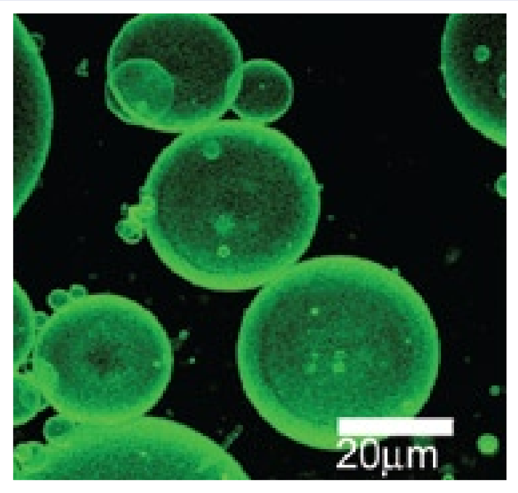
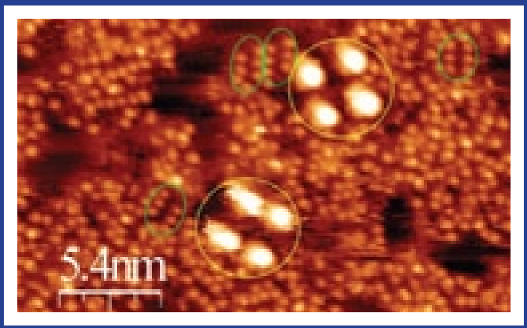
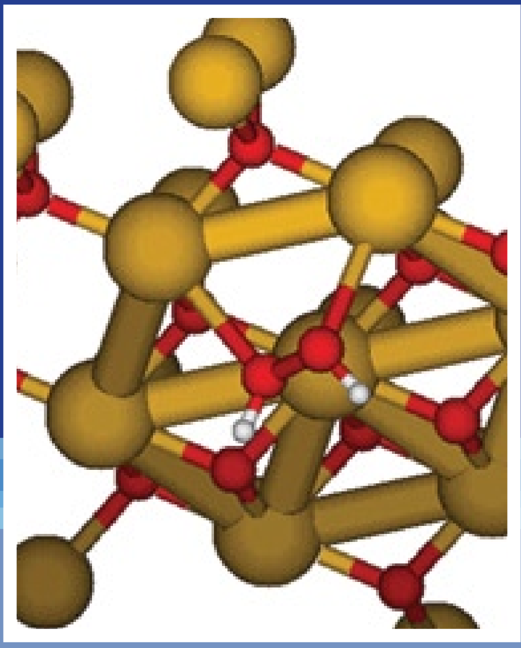
# 2008 NSF Nanoscale Science and Engineering Grantees Conference

December 3–5, 2008
NSF - Arlington, VA



## Cover Figures

Controlling Interfacial Activity of Nanoparticles: Robust Routes to Nanoparticle-Based Capsules, Membranes, and Electronic Materials (NIRT 0609107), T. Emrick, T.P. Russell, A. Dinsmore, N. Menon, and B.D. Freeman (p. 92).

Imaging and Actuation of Nanocar Molecules by Scanning Tunneling Microscopy (NIRT 0708765), A. J. Osgood, J. Zhang, T. Sasaki, J. Guerrero, J. M. Tour, and K. F. Kelly (p. 54).

Engineered Therapeutic Nanoparticles as Catalytic Antioxidants (NIRT 0708172), S. Seal, W. Self, A. Masunov, and J.McGinnis (p. 44).

# 2008 NSF Nanoscale Science and Engineering Grantees Conference

*December 3-5, 2008*
*National Science Foundation, Arlington, VA*

Organizing committee:

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## Centers and Networks

## Nano Highlights

**Panel Discussions**

# Preface

The NSF Nanoscale Science and Engineering (NSE) grantees conference highlights the research and education activities of ongoing NSE grant projects. Roundtable discussions promote new interdisciplinary partnerships and identify future directions for research, education, networking, business interactions, environmental health and safety, and societal impact. These interactions help to advance the goals of NSF (www.nsf.gov/nano), the U.S. National Nanotechnology Initiative (www.nano.gov), and the 21st Century Nanotechnology Research and Development Act. The goals include:

- Conduct of research and development to realize the full potential of nanoscale science and engineering;
- Development of the skilled workforce and supporting infrastructure needed to advance research and development;
- Better understanding of the social, ethical, health, and environmental implications of the technology; and,
- Facilitating transfer of the new technologies into commercial products.

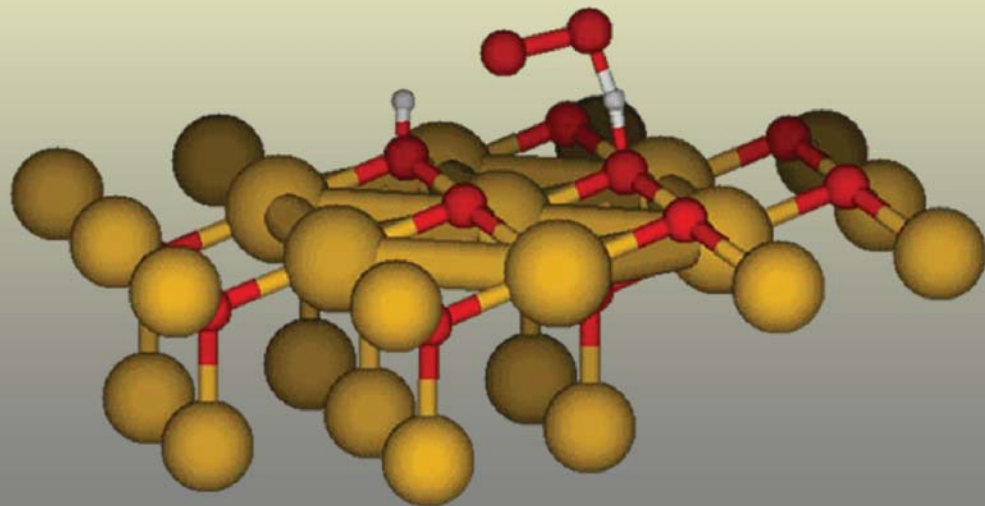
The 2008 conference was held at NSF headquarters (Arlington, VA) December 3 – 5, 2008. Some 138 attendees from academia, government, and industry met during this period to exchange views, report research progress, compare best practices in the management of NSF centers, and in other ways foster dissemination of the rapidly expanding knowledge base in all aspects of nanotechnology and its role in society. A particular highlight was the set of seven keynote presentations from leading research groups, providing overviews of significant contemporary NSE topics. This component of the conference was expanded somewhat from the previous year, partly in response to feedback from prior attendees. Other major portions of the program included intensive interactive sessions for poster viewing in several rooms adjoining the main conference presentation venue. Lunch hours were exploited to continue informative presentations, especially from NSF staff members concerning programmatic opportunities and social dimensions.

This Proceedings book serves as a summary of the conference contents. More information, including complete slide decks from the many presentations by keynote speakers and panel discussants, is available on the conference website, www.nseresearch.org.

Roderic Beresford
Brown University
Providence, RI

# 2008 NSF Nanoscale Science and Engineering Grantees Conference

## December 3-5, 2008



www.nseresearch.org

# *Nanotechnology at NSF*

**M.C. Roco**

**National Science Foundation**

**and National Nanotechnology Initiative**

NSF's Nanoscale Science and Engineering Grantees Conference
December 3, 2008

Benchmark with experts in over 20 countries

## "Nanostructure Science and Technology"

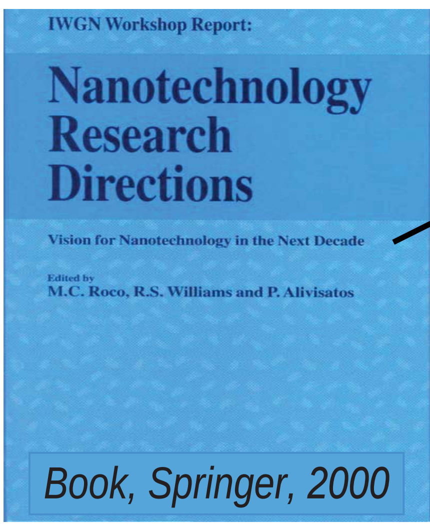
*Book Springer, 1999*

### *Nanotechnology*

is creation of materials, devices and systems by *control and restructuring of matter* at dimensions of roughly 1 to 100 nanometers,

- ⇨ at the transition from individual to collective behavior of atoms and molecules
- ⇨ where new phenomena
- ⇨ enable new applications

M.C. Roco, 12/03/08




## "Vision for nanotechnology in the next decade" (2001-2010)

*Systematic control of matter on the nanoscale will lead to a revolution in technology and industry*

- *Change the foundations from micro to nano*
- *Create a general purpose technology (similar IT)*

More important than miniaturization itself:

- Novel properties/ phenomena/ processes
- Unity and generality of principles
- Most efficient length scale for manufacturing
- Show transition from basic phenomena and components to system applications in 10 areas and 10 scientific targets

M.C. Roco, 12/03/08



NSF Overview
Mike Roco (2)

NSF Overview
Mike Roco (3)

# Generations of Products and Productive Processes

Timeline for beginning of industrial prototyping and nanotechnology commercialization (2000-2020)

**1st: Passive nanostructures** (1st generation products)
Ex: coatings, nanoparticles, nanostructured metals, polymers, ceramics

~ 2000

**2nd: Active nanostructures** Ex: 3D transistors, amplifiers, targeted drugs, actuators, adaptive structures

~ 2005

**3rd: Nanosystems, Revolutionary Products**
Ex: guided assembling; 3D networking and new hierarchical architectures, robotics, evolutionary

CMU

~ 2010

**4th: Molecular nanosystems**
Ex: molecular devices 'by design', atomic design, emerging functions

~ 2015-2020

**5th: Converging technologies**
Ex: nano-bio-info from nanoscale, cognitive technologies; large complex systems from nanoscale

Increased complexity

Reference: AIChE Journal, Vol. 50 (5), 2004

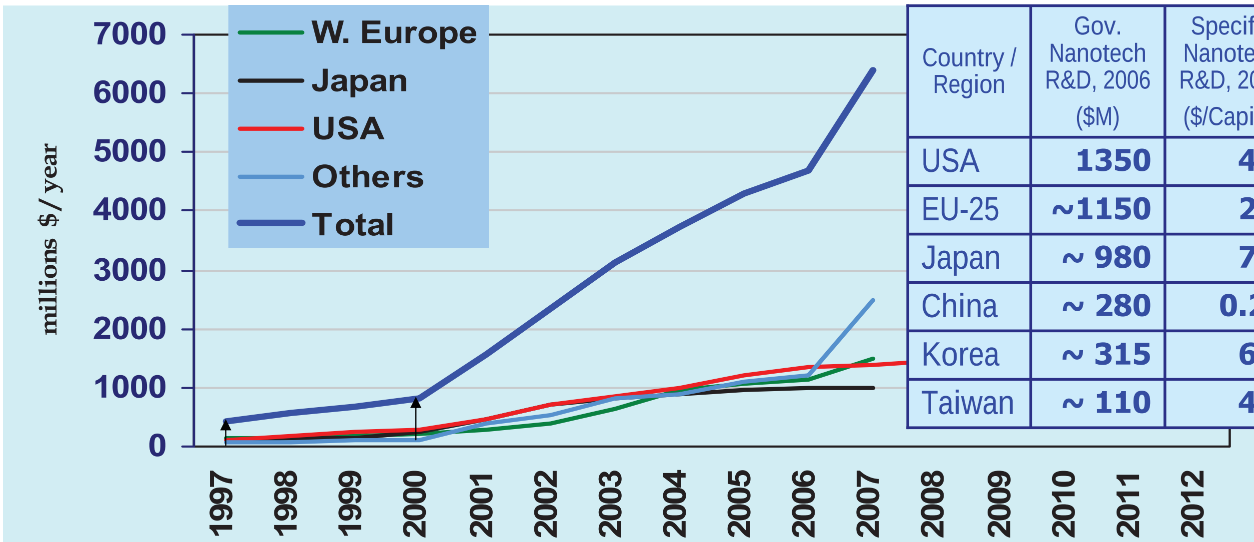
OSTP, OMB, NIH, NSF, DOD, DOE, NIST, FDA, NASA, USDA, NIOSH, USDA FS, DOS, EPA, DOTr, NRC, DOT, USPTO, ITIC, USGS, DOL, DOJ, DOEd, DOC TA, ITC, DOC BIS, DHS, CPSC

# National Nanotechnology Initiative

Collaborative, multi-agency, cross-cut program among 25 Federal agencies

# Context – Nanotechnology in the World

## National government investments 1997-2007 (est. NSF)




| Country / Region | Gov. Nanotech R&D, 2006 ($M) | Specific Nanotech R&D, 2006 ($/Capita) |
|---|---|---|
| USA | 1350 | 4.5 |
| EU-25 | ~1150 | 2.5 |
| Japan | ~ 980 | 7.6 |
| China | ~ 280 | 0.23 |
| Korea | ~ 315 | 6.5 |
| Taiwan | ~ 110 | 4.7 |

Seed funding (1991 - )

NNI Preparation (vision / benchmark)

1st Strategic Plan (passive nanostructures)

2nd Strategic Plan (active ns. & systems)

Industry R&D (~$7.3B) exceeded public R&D (~$6.5B) in 2007; total $13.8B

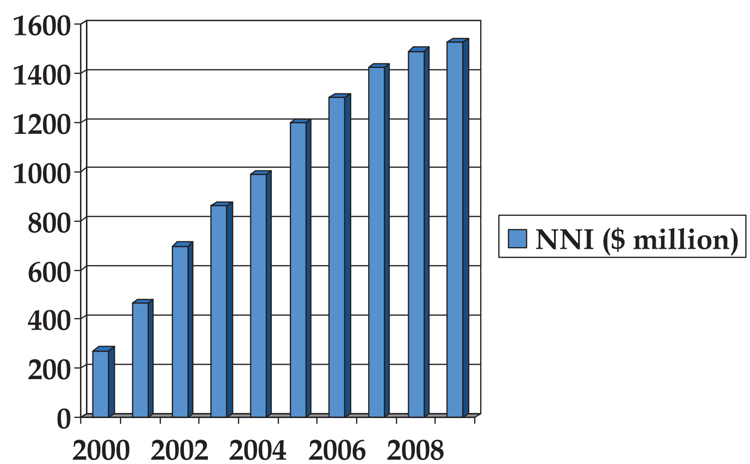
J. Nanoparticle Research, 7(6), 2005, MC. Roco



# Changing national investment

## FY 2009 NNI Budget Request - $1,527 million

| Fiscal Year | NNI |
|---|---|
| 2000 | $270M |
| 2001 | $464M |
| 2002 | $697M |
| 2003 | $862M |
| 2004 | $989M |
| 2005 | $1,200M |
| 2006 | $1,303M |
| 2007 | $1,425M |
| 2008 | $1,491M |
| R 2009 | $1,527M |




NNI / R&D ~ 1/4 of the world R&D

MC. Roco, 12/03/08

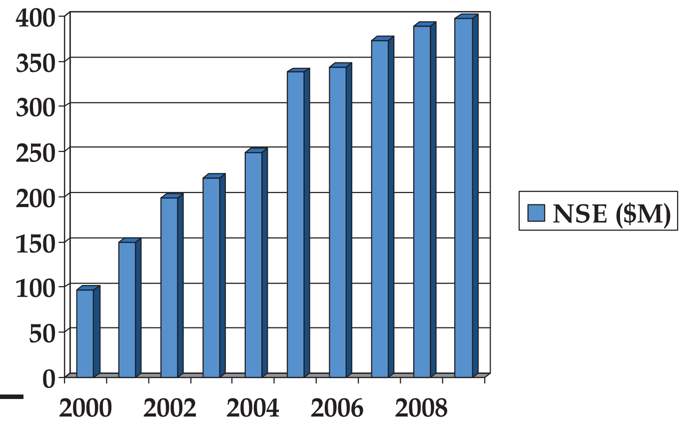
# NSF – discovery, innovation and education in Nanoscale Science and Engineering (NSE)

www.nsf.gov/nano , www.nano.gov

FY 2009 Request: $397M ~1/4 of Federal and ~1/12 of World Investment

– Fundamental research - seven PCAs with new priorities
– Establishing the infrastructure - over 4,000 active projects; 26 large centers, 2 user facilities (NNIN, NCN), multidisciplinary teams
– Training and education – over 10,000 students and teachers/yr

| Fiscal Year | NSF |
|---|---|
| 2000 | $97M |
| 2001 | $150M |
| 2002 | $199M |
| 2003 | $221M |
| 2004 | $254M |
| 2005 | $338M |
| 2006 | $344M |
| 2007 | $373M |
| 2008 | $389M |
| R 2009 | $397M |




MC. Roco, 12/03/08

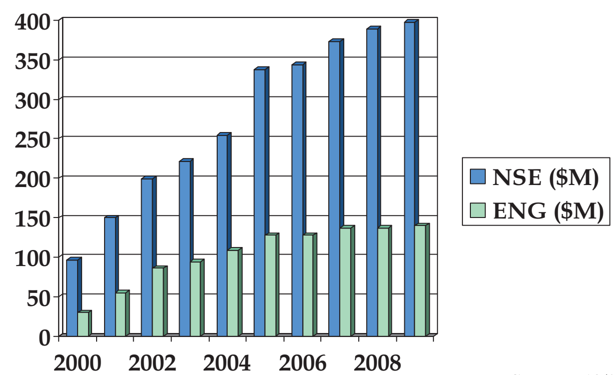
# NSE: Role of Engineering

**Engineering has a leading role in NSE because:**
- **nanotechnology deals with systems at nanoscale**
- **integrative, interdisciplinary**
- **transforming tool**

Collaboration with NSF Directorates: MPS, CISE, BIO, GEO, SBE, HER
Also, NNI - 24 departments and agencies (DOE,DOD, NASA, NIH, NIST, EPA, etc.)

Changing engineering disciplines (research, education, relevance)

| | | |
|---|---|---|
| 2000 | $97M | $30.0M |
| 2001 | $150M | $55.3M |
| 2002 | $199M | $86.3M |
| 2003 | $221M | $94.4M |
| 2004 | $254M | $108.9M |
| 2005 | $338M | $127.8M |
| 2006 | $344M | $127.8M |
| 2007 | $373M | $137.2M |
| 2008 | $389M | $137.2M |
| 2009 | $397M | $140.0M |




MC Roco, 12/03/08

NSF Overview
Mike Roco (5)

NSF Overview
Mike Roco (6)



# National Nanotechnology Initiative activities at NSF in FY 2008

## Actual budget : $389M

- **Program solicitations**
  - Nano-EHS with EPA and DOE
  - Nanotechnology Undergraduate Education (ENG and EHR)
- **Support in the "core" program with focus on single investigator & other core**
  - Research and education programs in all directorates
  - Interdisciplinary fellowships; NSEC, STC, MRSEC and ERC centers
  - Instrumentation (REG, MRI); Collaboration industry (GOALI, PFI)
  - Network for Computational Nanotechnology ($3.8M/yr)
  - National Nanotechnology Infrastructure Network ($14M/yr)
  - Nanoscale Informal Science and Education network
  - Interagency collaborations: Manufacturing, Societal Implic., EHS
- **SBIR/STTR** (additional ~ $17M/year)

MC. Roco, 12/03/08

## FY 2009 NSF Budget Request to Congress ($397 M) by Directorates and Program Component Areas

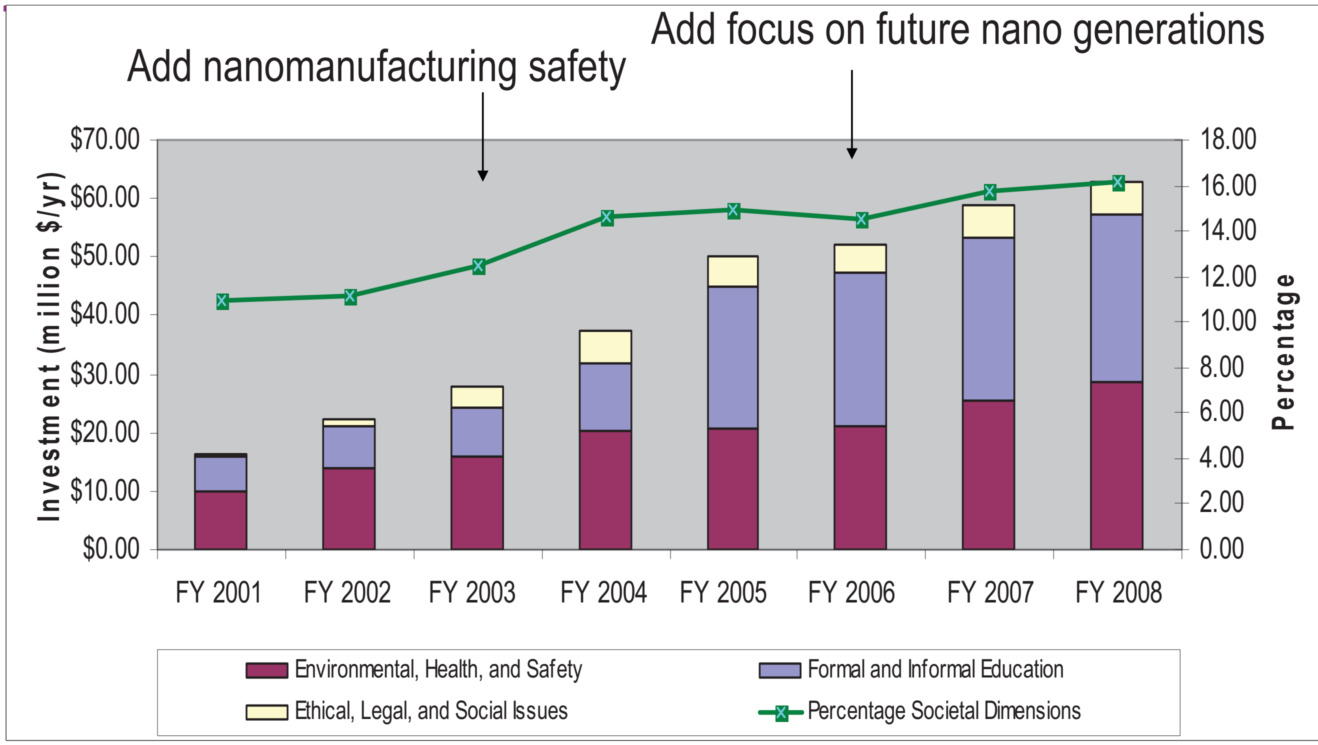
### Seven directorates participate

| (Dollars in Millions) | BIO | CISE | ENG | GEO | MPS | SBE | R&RA | EHR | Total, NSF |
|---|---|---|---|---|---|---|---|---|---|
| Program Component Area | 56.6 | 11.0 | 140 | 6.33 | $178 | 1.67 | 393.7 | $3.1 | 396.8 |
| Fundamental Nanoscale Phenomena & Processes | 39.5 | 1.00 | 19.2 | | 81.52 | | 141.2 | | 141.2 |
| Nanomaterials | 0.05 | | 16.0 | | 47.00 | | 63.05 | | 63.1 |
| Nanoscale Devices & Systems | 0.50 | 5.60 | 44.0 | | 1.50 | | 51.60 | | 51.6 |
| Instrumentation Rsch, Metrology & Stds for Nanotech | 6.00 | | 4.50 | | 5.50 | | 16.00 | | 16.0 |
| Nanomanufacturing | | 2.40 | 24.0 | | 0.50 | | 26.90 | | 26.9 |
| Major Rsch Facilities & Instrumentation Acquisition | 5.00 | 2.00 | 6.62 | | 18.47 | | 32.09 | | 32.1 |
| Societal Dimensions: Envir Health & Safety (EHS) | 5.05 | | 11.0 | 6.33 | 8.26 | | 30.64 | | 30.6 |
| Societal Dimensions: Education (EDUC) | 0.50 | | 12.0 | | 14.20 | | 26.70 | 3.1 | 29.8 |
| Societal Dimensions: Ethical, Legal & Others (ELSI) | | | 2.70 | | 1.12 | 1.67 | 5.49 | | 5.49 |

MC. Roco, 12/03/08

# NSF Investment in Societal Dimensions of NT

## Of FY 2008 NNI / NSF request of $390 M, $63 M or 16.1% is for SI, and $28.8 M (7.4%) for nano ENV/EHS

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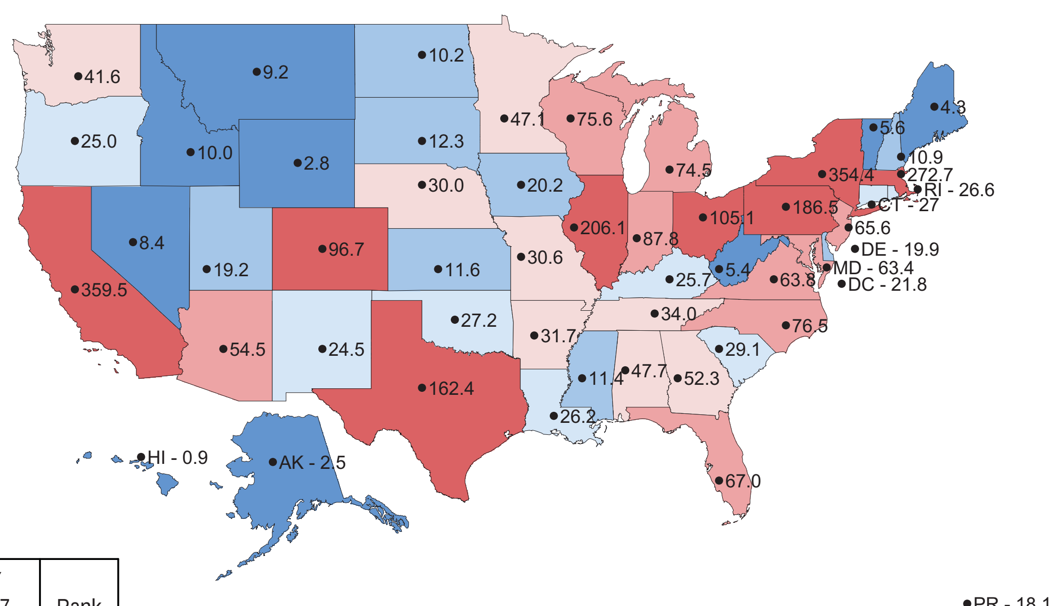
# Total Amount for NEW NS&E Awards FY 2001 – 2007 by State




| State | NEW FY 2001-2007 | Rank |
|---|---|---|
| CA | $359,529,514 | 1 |
| NY | $354,432,745 | 2 |
| MA | $272,681,724 | 3 |
| IL | $206,073,629 | 4 |
| PA | $186,473,981 | 5 |

**NEW Awd. Amt. FY01-07 ($10^6)**
- <= 10
- 10 - 20.2
- 20.2 - 29.1
- 29.1 - 52.3
- 52.3 - 87.8
- 87.8 - 359.5

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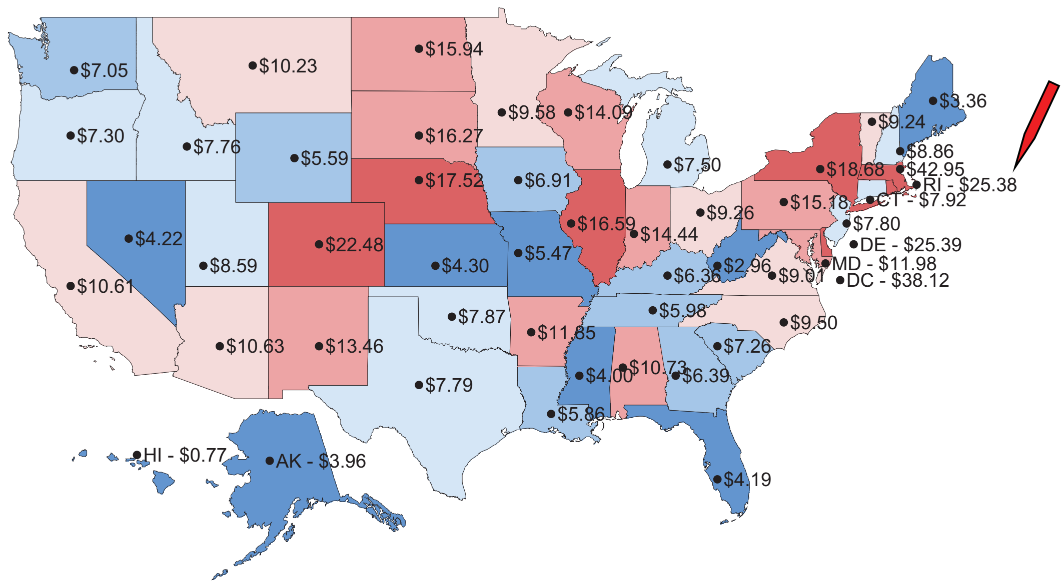
NSF Overview
Mike Roco (8)


## Per Capita Amount for NEW NS&E Awards FY 2001 – 2007 by State




| State | NEW FY 2001-2007 | $ Per Capita | Rank |
|---|---|---|---|
| MA | $272,681,724 | $42.95 | 1 |
| DC | $21,804,945 | $38.12 | 2 |
| DE | $19,893,702 | $25.39 | 3 |
| RI | $26,604,737 | $25.38 | 4 |
| CO | $96,677,354 | $22.48 | 5 |

**FY01-07 PerCapita NEW Amt.**

<= 5.466
5.466 - 7.262
7.262 - 8.859
8.859 - 10.63
10.63 - 16.27
16.27 - 42.95

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# Nanotechnology in 2008, still in an earlier formative phase of development

- Characterization of nanomodules is using micro parameters and not internal structure
- Measurements and simulations of a domain of biological or engineering relevance cannot be done with atomic precision and time resolution of chemical reactions
- Manufacturing Processes – empirical, synthesis by trial and error, some control only for one chemical component and in steady state
- Nanotechnology products are using only rudimentary nanostructures (dispersions in catalysts, layers in electronics) incorporated in existing products or systems
- Knowledge for risk governance – in formation

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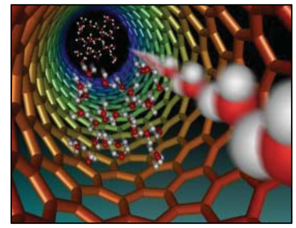
## FY 2009 NS&E Priorities Research Areas (1)

The long-term objective is building a foundation of fundamental research to understand and restructure matter at nanoscale in all areas of S&E



### A. Scientific challenges

- New theories at nanoscale
  Ex: transition from quantum to classical physics, collective behavior, for simultaneous phenomena
- Non-equilibrium processes
- Designing new molecules with engineered functions
- New architectures for assemblies of nanocomponents
- The emergent behavior of nanosystems

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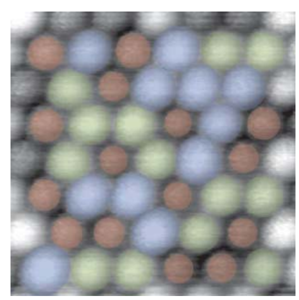
## FY 2009 NS&E Priorities Research Areas (2)



### B. Development of nanotechnology

- Tools for measuring and restructuring
  with atomic precision
  and time resolution of chemical reactions
- Understanding and use of quantum phenomena
- Understanding and use of multi-scale selfassembling
- Nanobiotechnology – sub-cellular and systems approach
- Nanomanufacturing hybrid, on site
- Systems nanotechnology

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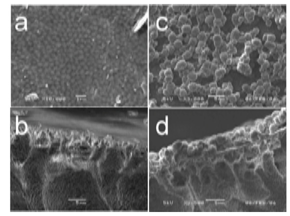
## FY 2009 NS&E Priorities Research Areas (3)

### C. Integration of nanotechnology in application areas

- Replacing electron charge as the information carrier in electronics
- Energy conversion, water filtration / desalinization using new principles




SEM micrographs of membranes (UIUC)

- Efficient nanomanufacturing and sustainable environment
- Nano-bio interfaces between the human body and manmade devices
- Nano-informatics for better communication and nanosystem design

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## From FY 2009 NSF priority research areas (4)

### Societal dimensions of nanotechnology

- Understanding and sustainable ENV, including research for natural/ incidental/ manufactured nanomaterials

  Key nano- EHS priorities at NSF
  - New instrumentation for nanoparticle characterization and nanotoxicity
  - Transport phenomena and physico- chem.- biological processes
  - Nano-bio interface: ecological and human health implications
  - Predictive models for interaction of nanomat. with cells/living tissues
  - Separation of nanoparticles from fluids
  - Safety of manufacturing nanoparticles

- Earlier formal and informal education
- Social issues and public engagement

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NSF Overview
Mike Roco (10)

# NSE program emphasis in FY 2009

- Increased focus on complex, large nanosystems
- Three-dimensional measurements of domains of engineering relevance with good time resolution
- Converging science, engineering and technology from the nanoscale (in manufacturing, information systems, medicine, environment, etc.)
- R&D themes on sustainable development (energy, water, food, climate)
- Expanded joint research program addressing societal implications of nanotechnology; partner with other agencies
- Earlier educational programs and teaching materials, including for K-12, by remote access to NSF educational networks (NU, NISE, NNIN)
- Expand partnerships of academic researchers with industry, medical facilities and states through GOALI, PFI and other programs

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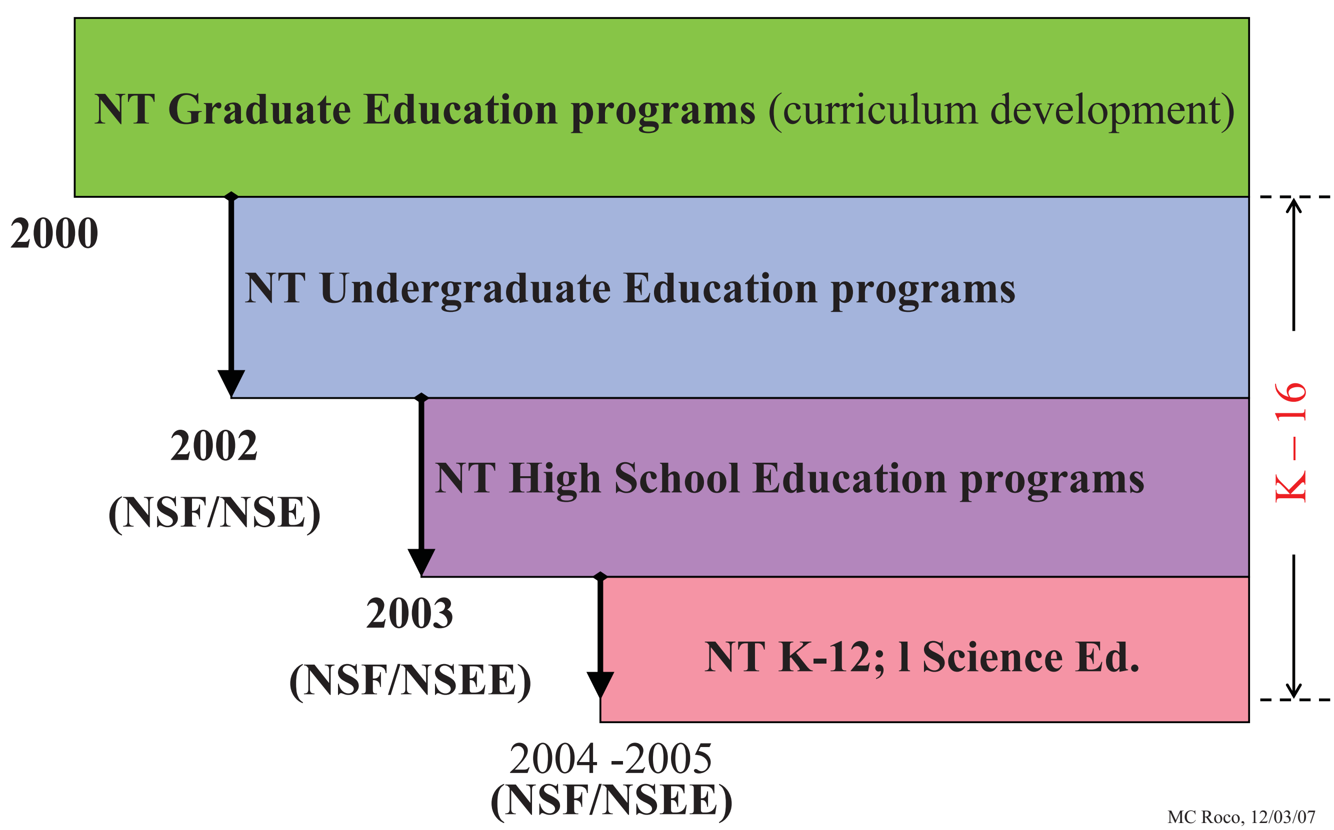
# Introducing earlier nanotechnology education
## (NSF: Nanoscale Science and Engineering Education)

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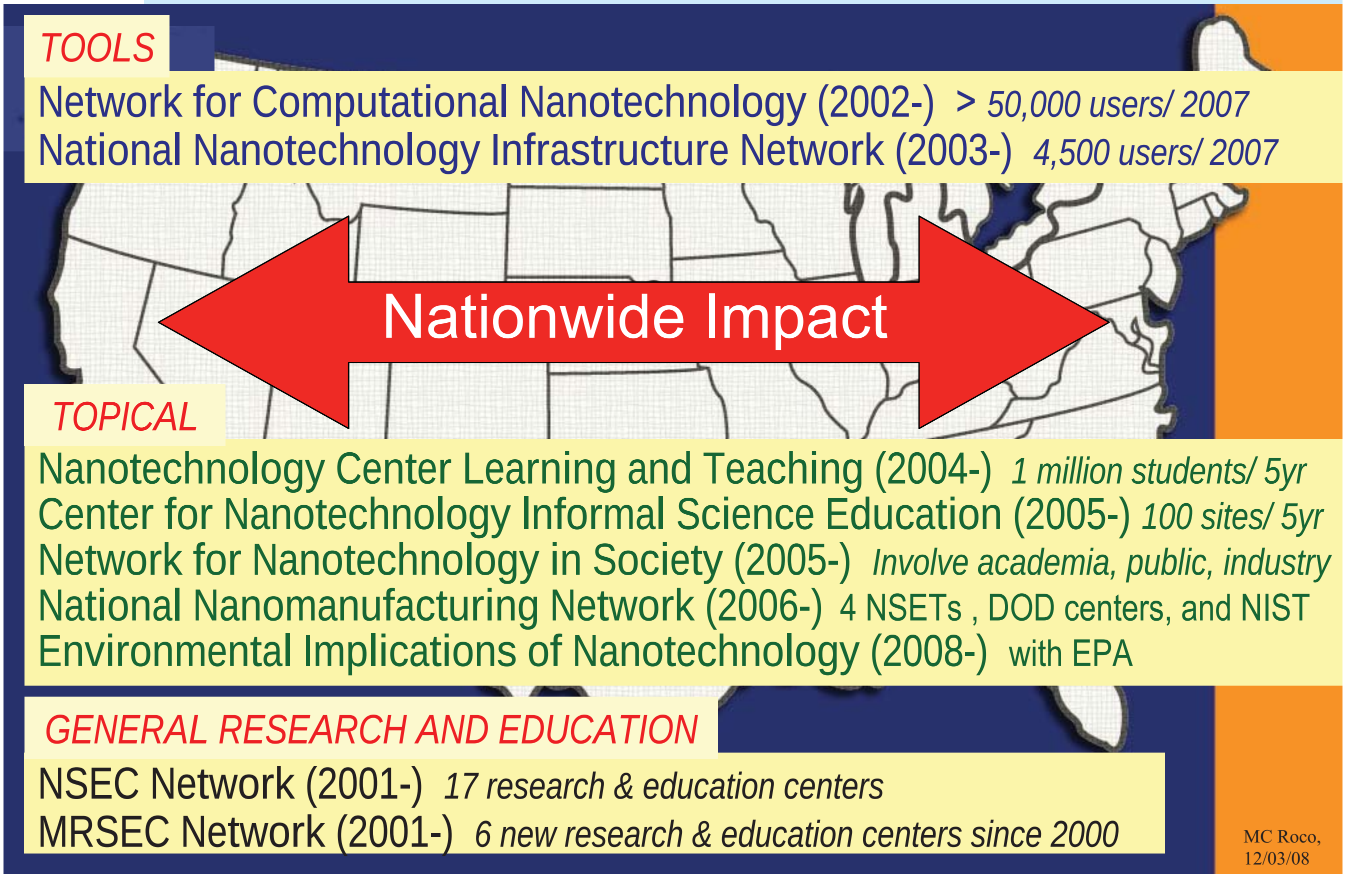
## Nine Nanoscale Science and Engineering networks with national outreach




*TOOLS*

Network for Computational Nanotechnology (2002-) > *50,000 users/ 2007*
National Nanotechnology Infrastructure Network (2003-) *4,500 users/ 2007*

*TOPICAL*

Nanotechnology Center Learning and Teaching (2004-) *1 million students/ 5yr*
Center for Nanotechnology Informal Science Education (2005-) *100 sites/ 5yr*
Network for Nanotechnology in Society (2005-) *Involve academia, public, industry*
National Nanomanufacturing Network (2006-) 4 NSETs , DOD centers, and NIST
Environmental Implications of Nanotechnology (2008-) with EPA

*GENERAL RESEARCH AND EDUCATION*

NSEC Network (2001-) *17 research & education centers*
MRSEC Network (2001-) *6 new research & education centers since 2000*

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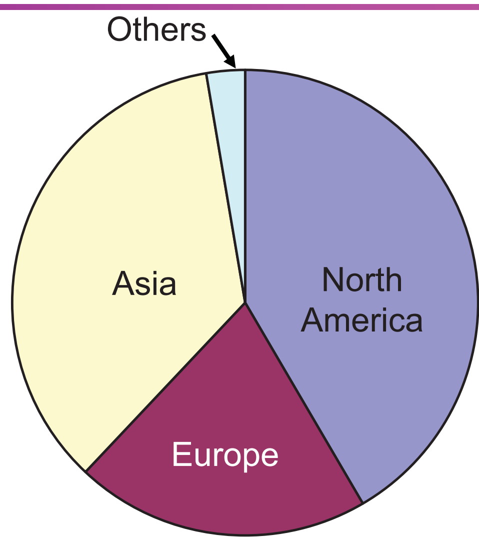
## Industry-academe-government <u>R&D partnerships</u> – increased relevance

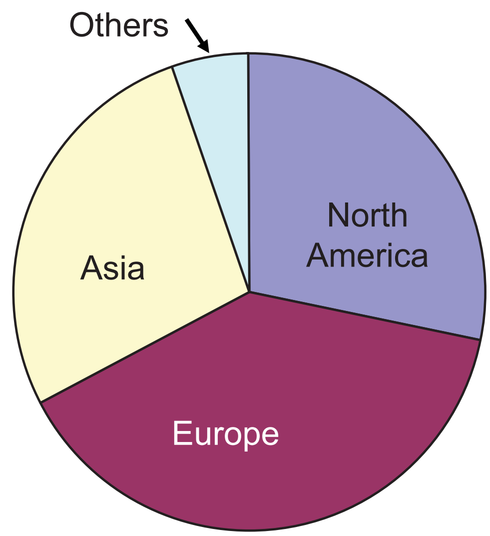
- Increased role of industry in funding nanotechnology R&D ; changes in gov. funding because other oblig.
- Special role of local governments (state, county) for infrastructure, education and small business
- Global partnerships for nanotechnology knowledge, markets and organizations
- Cross-industry R&D consortia for nano-platforms

M.C. Roco, 12/03/08

# Growing nanotechnology R&D investment - $13.8 billion in 2007




Private (Corp. + VC)
Total = $**7.3** billion




Public (National, regional, state)
Total = $**6.5** billion

National governments ~ $4.7 billion
Local governments and organizations ~ $1.8 billion

Source: Lux Research

## NNI-Industry Consultative Boards for Advancing Nanotech

Key for development of nanotechnology, Reciprocal gains

- **NNI-Electronic Industry (SRC lead), 10/2003 -**
  - Collaborative activities in key R&D areas
  - 5 working groups, Periodical joint actions and reports
  - NSF-SRC agreement for joint funding; other joint funding
- **NNI-Chemical Industry (CCR lead)**
  - **Joint road map for nanomaterials R&D; Report in 2004**
  - **2 working groups, including on EHS**
  - **Use of NNI R&D results, and identify R&D opportunities**
- **NNI – Organizations and business (IRI lead)**
  - **Joint activities in R&D technology management**
  - **2 working groups (nanotech in industry, EHS)**
  - **Exchange information, use NNI results, support new topics**
- **NNI – Forestry and paper products (AF&PA lead, 4/2007), 10/2004-** **Workshop / roadmap for R&D**
  - **Exchange information**

AF&PA American Forest & Paper Association

MC Roco, 12/03/07

# Several NNI Accomplishments

- Developed foundational knowledge for control of matter at the nanoscale: over 4,000 active projects in > 500 universities, private sector institutions and government labs in all 50 states
- "Created an interdisciplinary nanotechnology community" [1]
- R&D / Innovation Results: With ~25% of global government investments, the U.S. accounts worldwide for
  - ~ 50% of highly cited papers,
  - ~ 60% of USPTO patents[2], and
  - ~70% of startups[3] in nanotech.
  - Over 2,000 companies with nanotechnology products in 2007 (U.S.)
- Infrastructure: 82 new large nanotechnology research centers, networks and user facilities; over 50,000 users in 2 academic-based networks

([1]) NSF Committee of Visitors, 2004; ([2]) Journal of Nanoparticle Research, 2004; ([3]) NanoBusiness Alliance, 2004

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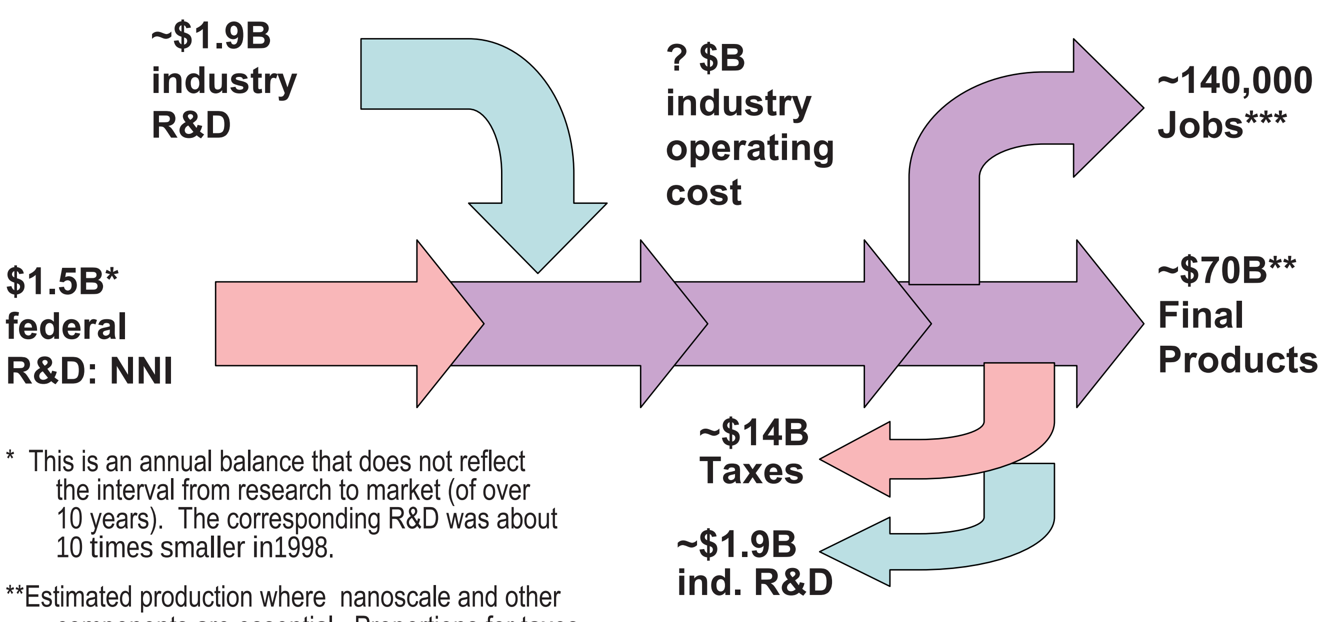
# Estimation of Annual Implications of Federal Investment in Nanotechnology R&D (FY 2008)




* This is an annual balance that does not reflect the interval from research to market (of over 10 years). The corresponding R&D was about 10 times smaller in1998.

**Estimated production where nanoscale and other components are essential. Proportions for taxes based on CCR estimation for chemical industry

***Estimated number of nanotechnology related jobs assuming $500,000/yr/job

M.C. Roco, 12/03/08

# FY 2008 NSF's Grantees Meeting

- Review selected NSE awards: FY 2007 NIRT, NSEC . .
  Posters, keynotes and panels to facilitate exchanges, partnerships, and research planning
- Presentations from the DOD, EPA and FDA
- Strengthen NSE trans-disciplinary community
  Prepare for increased complexity in research

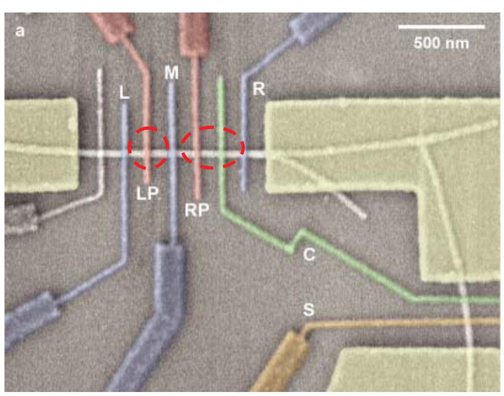
MC Roco, 12/03/07

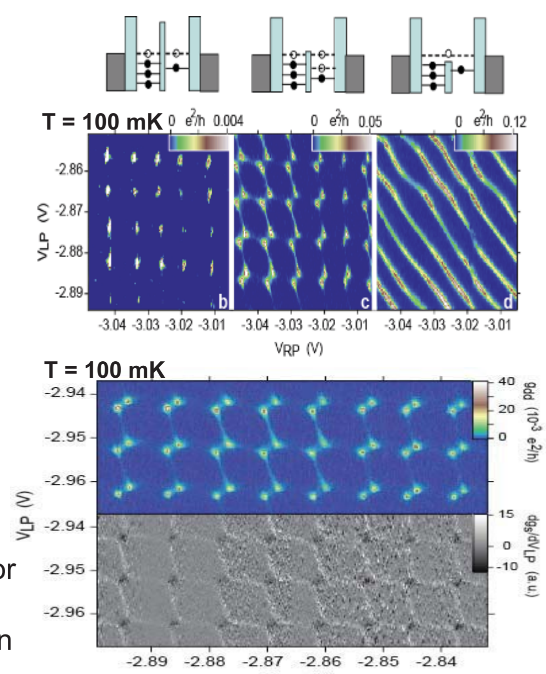
# Nanowires as a Platform

- ***Synthetic control of structure and composition on many length scales***
- ***Predictable and tunable electronic properties allow fundamental limits of nanodevices/1-dimensional systems to be addressed***
- ***Nanowires with controlled chemical and electronic properties represent an ideal building block for exploring new functional devices and hybrid materials.***
- ***Nanoscale wires/nanowires are of central importance to integrated nanosystems***

***Exploit to answer what is possible!***

# Double Quantum Dot with Integrated Charge Sensor Based on Ge/Si Nanowires




- Fully control of interdot coupling and barrier height by local top gates
- Plunger gates control charge number
- Double dot capacitively coupled to sensor dot on adjacent nanowire
- Charge sensing critical for single-electron double dots and spin control

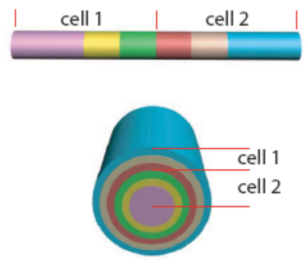
Hu, Churchill, Lieber & Marcus, *Nature Nano.* **2**, 622-625 (2007)

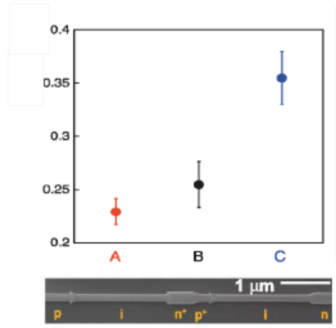


Nanowires: A Platform
Charles Lieber (1)

# Exploring Novel Nanostructure To Push Limits of Photovoltaic Efficiency

**I. Tandem Solar Cells**

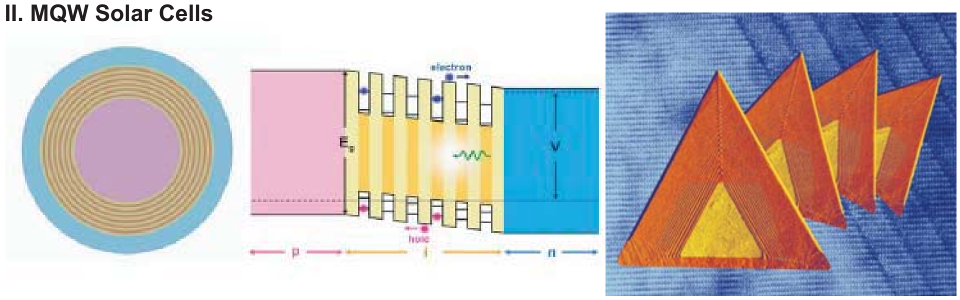



- Controlled synthesis enables integration of ≥2 p-i-n diodes in series with independent control of junctions.
- Substantial increase in open circuit voltage realized in 'tandem' axial single nanowire photovoltaic elements!

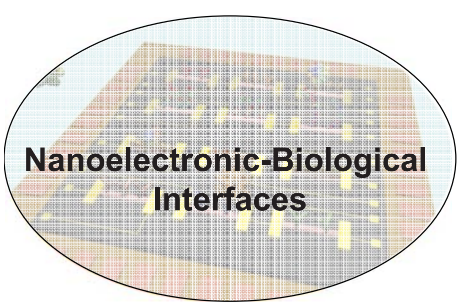
Kempa, Tian, Lieber & coworkers, *Nano Lett.* **8**, 3456 (2008)

**II. MQW Solar Cells**




Qian, Lieber & coworkers, *Nature Mater.* **7**, 701 (2008)

# Vision for Life Sciences




## Nanoelectronic-Biological Interfaces Enable:

- **Diagnostic devices for disease detection**
- General detection & kinetics platform
- New tool for single-molecule detection/biophysics
- **Powerful devices for electronic and chem/bio recording from cells, tissue & organs**
- Potential implants for highly functional & powerful prosthetics, as well as hybrid biomaterials enabling new opportunities

# NANOTECHNOLOGY

## THE BRIGHT! and THE DARK?

**Multiple Applications/Benefits**

- Structural Engineering
- Electronics, Optics
- Consumer Products
- Alternative Energy
- Soil/Water Remediation
- Nanomedicine:
  - *therapeutic*
  - *diagnostic*
  - *drug delivery*
  - *cancer*
  - *nanosensors*
  - *nanorobotics*

**Consumer Fears/Perceived Risks**

- Safety: Potential adverse effects
- Environmental Contamination
- Inadvertent Exposure *(inhalation, dermal, ingestion)*
- Susceptible Subpopulation
- Societal Implications
- Nanotoxicology:

  *supplies information for risk*
  *-assessment,*
  *-management,*
  *-communication*

## Rochester MURI (*Multidisciplinary Unversity Research Initiative*)

**Correlating Physico-Chemical and Toxicological Properties of Nanoparticles**

Synthesis
*Physico-chemical*
Characterization

Methods Development

**Collaborations:**
*NIOSH*
*Owens Corning*
*Health Canada*
*Airforce Research Lab.*
*Michigan State Univ.*
*GSF-Germany*

Testing
cell-free
cellular/subcellular
*Correlations?*
*in vivo*

? ? ?

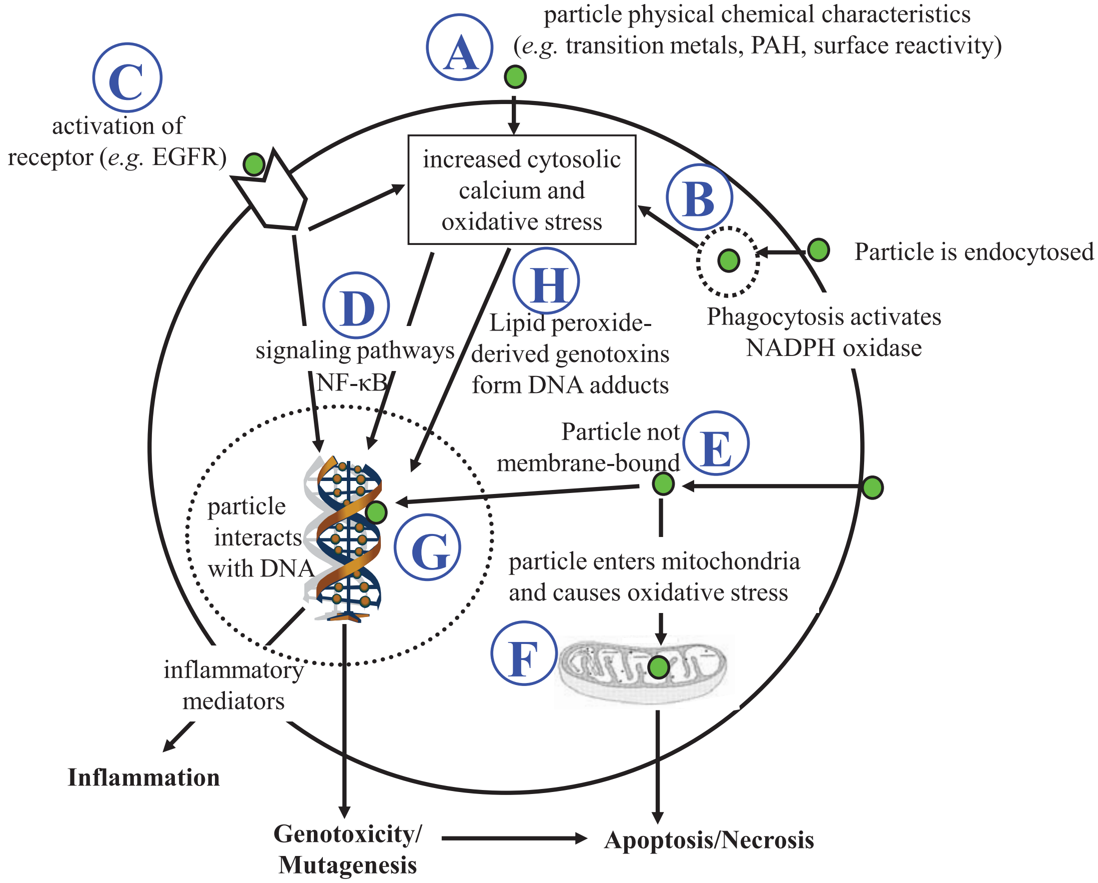
T o x i c i t y R a n k i n g

Benchmark NP
*low toxicity*

Benchmark NP
*high toxicity*

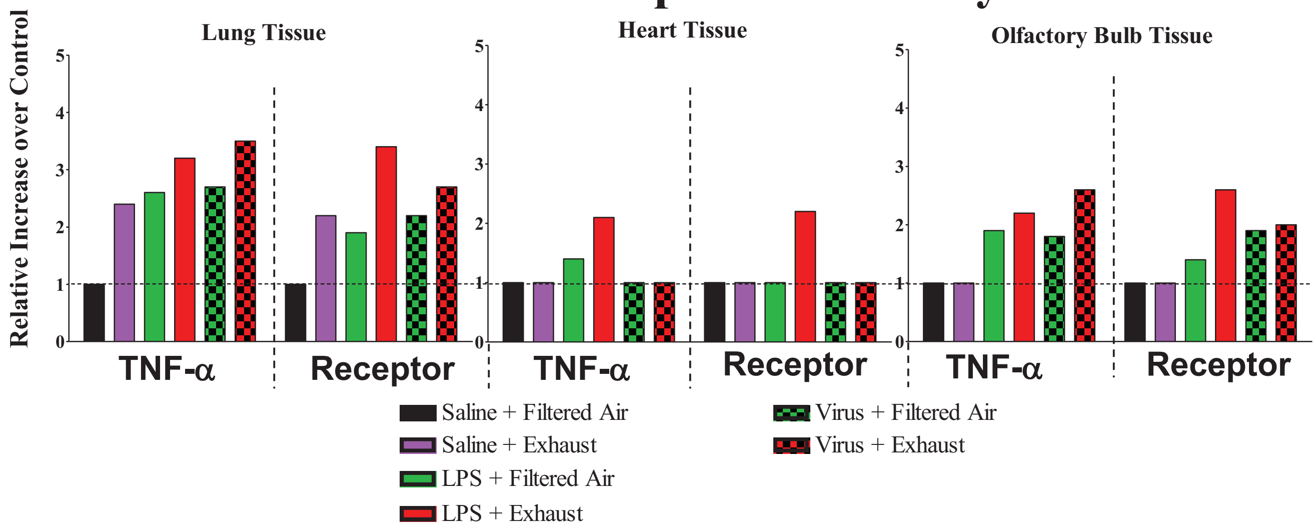
Bioinformatics
*Predicting nanostructure-induced responses*

# *Nanoparticle – Cell Interactions and Oxidative Stress*



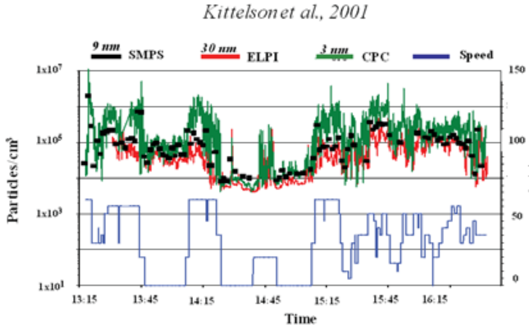

**Important to remember: *Dosis sola facit venenum***

# TNF-α and TNF-α Receptor I Gene Expression in 21 month-old Rats Exposed for 1 Day in MEL



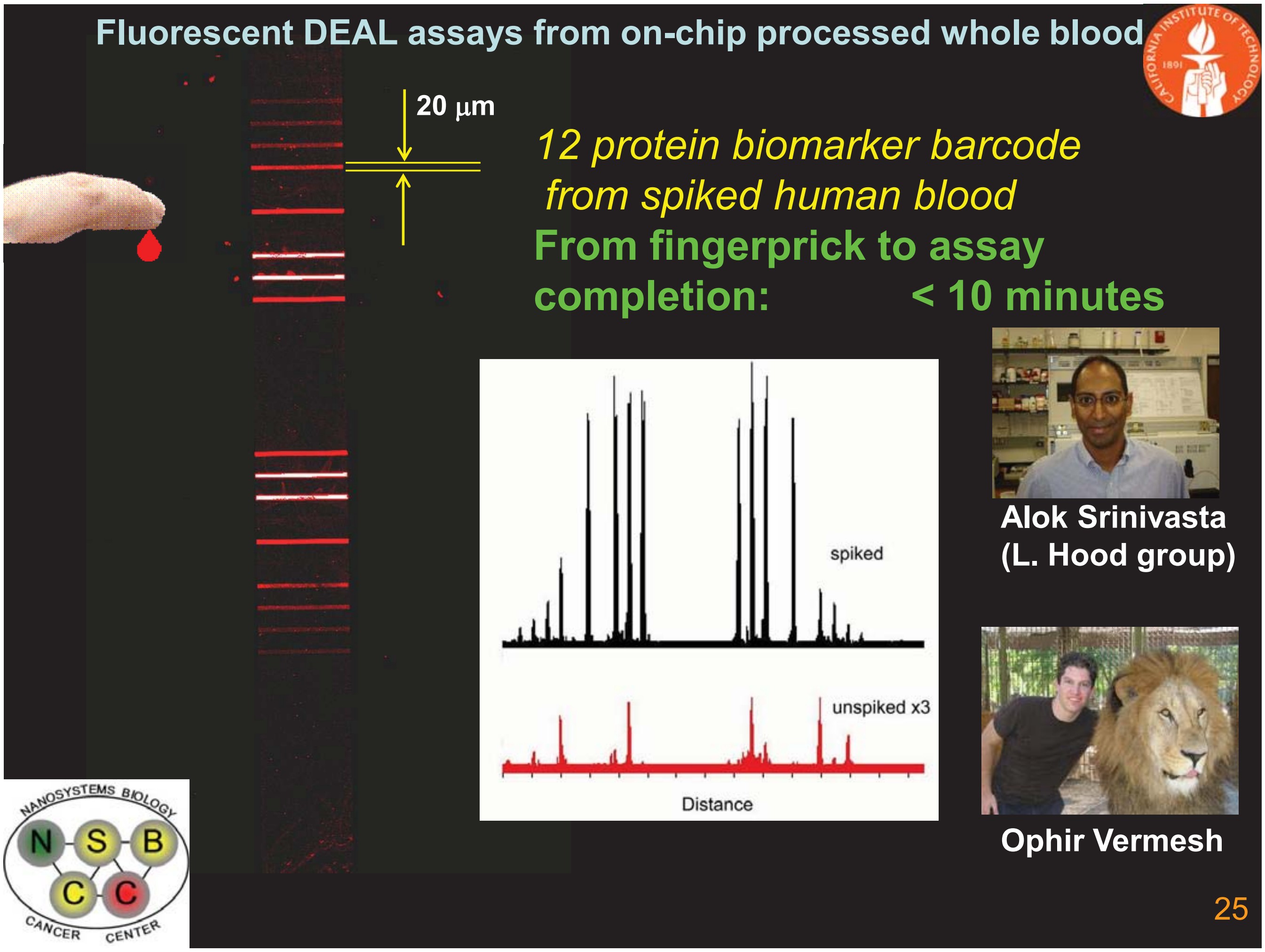

**Typical Roadway Data, Minnesota**

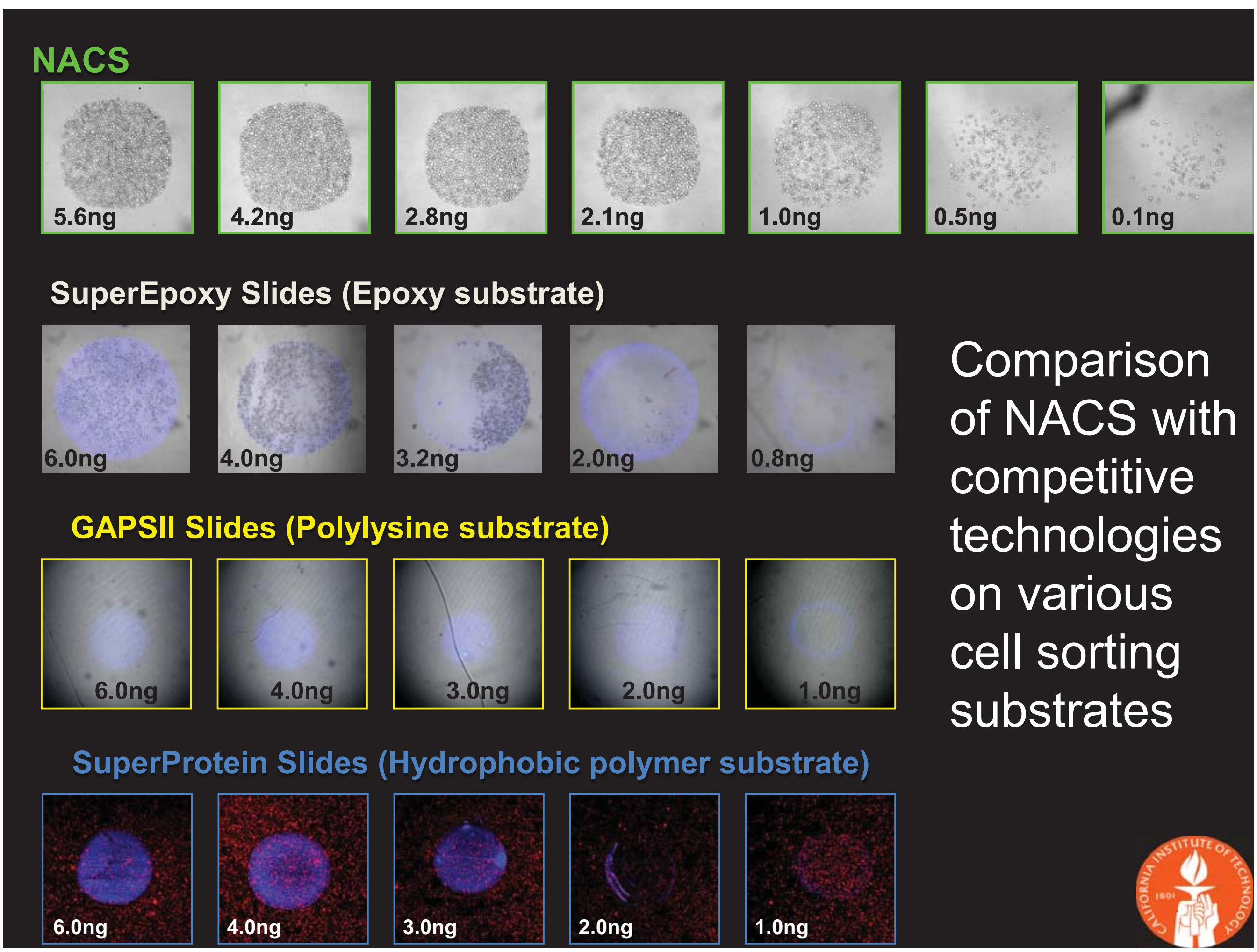
*Kittelson et al., 2001*





Toxicology of Nanoparticles
Gunter Oberdorster (2)

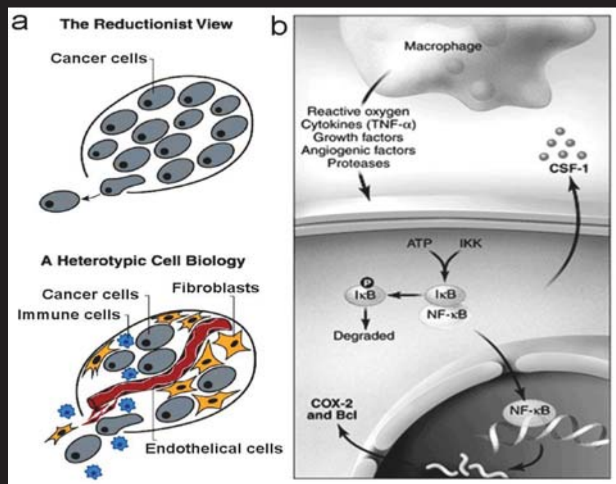

Fluorescent DEAL assays from on-chip processed whole blood
20 μm
12 protein biomarker barcode
from spiked human blood
From fingerprick to assay
completion: < 10 minutes
spiked
unspiked x3
Distance
Alok Srinivasta
(L. Hood group)
Ophir Vermesh
NANOSYSTEMS BIOLOGY
N S B
C C
CANCER CENTER
25


NACS
5.6ng
4.2ng
2.8ng
2.1ng
1.0ng
0.5ng
0.1ng
SuperEpoxy Slides (Epoxy substrate)
6.0ng
4.0ng
3.2ng
2.0ng
0.8ng
GAPSII Slides (Polylysine substrate)
6.0ng
4.0ng
3.0ng
2.0ng
1.0ng
SuperProtein Slides (Hydrophobic polymer substrate)
6.0ng
4.0ng
3.0ng
2.0ng
1.0ng
Comparison of NACS with competitive technologies on various cell sorting substrates

## NanoBio Interface: Multiplexed Measurements at the Single Cell Level

### The immune system & cancer

role of the immune system in tumor stroma





J. Marx, Nature 2006

*The Kavli Nanoscience Institute*

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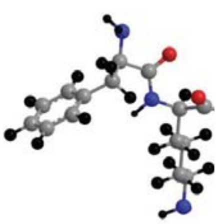
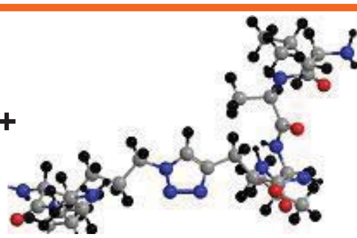
## Peptides Generalize the *In Situ* Click Chemistry Approach



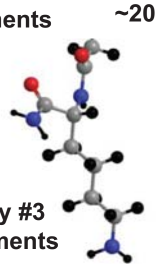
\+



Peptide Library #1
~20 million elements

Peptide Library #2
~20 million elements

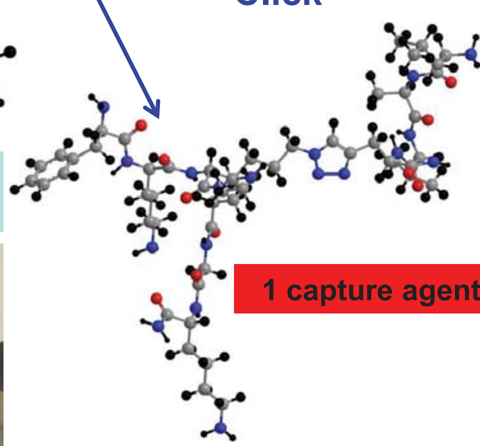
\+



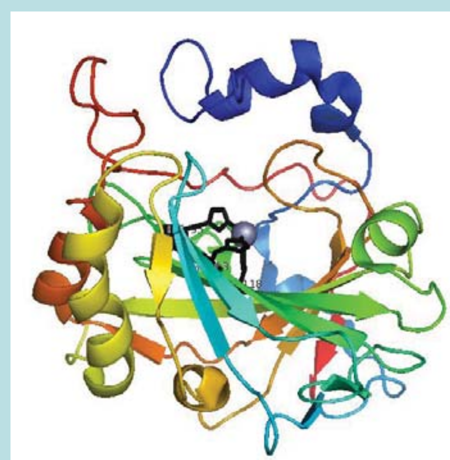
Peptide Library #3
~20 million elements

Protein catalyst

"Click"



1 capture agent



**Carbonic Anhydrase II**
metalloenzyme associated with renal, prostate, and other cancers; therapy target for melanoma & glial tumors

Rosemary Rohde &
*Heather Agnew*

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Nanoscale Building Blocks
Donald Tomalia (1)

# Outline

I. Lessons Learned from Traditional Chemistry - a "Central Dogma"

II. Recent Lessons Learned From Dendrimers/Dendrons:

"Proof of Concept" for a Nano-Chemistry *Central Dogma?*

*III.* *Atom Mimicry – Taken to the Nanoscale Level*:

(a) Nanomaterials Classification Roadmap
(b) Pervasive *Core-Shell Architectures/Outer Shell Reactivity*
(c) *Structure Controlled: Critical Nanoscale Design Parameters*

IV. Proposed Nano-Element Categories

V. Proposed Nano-Compounds/Assemblies

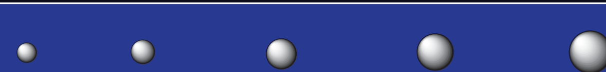
VI. Nano-Periodic Property Patterns

VII. Emergence of a "Central Dogma" for *Synthetic Nano-Chemistry*

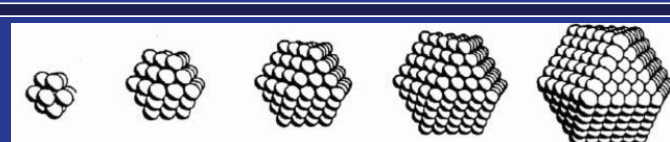
VIII. Conclusions

THE NATIONAL DENDRIMER & NANOTECHNOLOGY CENTER

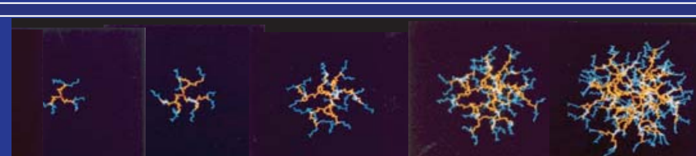
# Comparison of Atoms with Hard and Soft Nano-Matter



| | | | | | | |
|---|---|---|---|---|---|---|
| Picoscale Matter (Atoms) | Elements Exhibiting Noble Gas Configurations | He | Ne | Ar | Kr | Xe |
| Shell Components n (Electrons) | Electron shell levels: | 1 | 2 | 3 | 4 | 5 |
| | Diameters: | .064 nm | .138 nm | .194 nm | .220nm | .260 nm |
| | Saturation values (n): | 2 | 10 | 18 | 36 | 54 |
| | Atomic weights: | 4.00 | 20.17 | 39.94 | 83.80 | 131.30 |



| | | | | | | |
|---|---|---|---|---|---|---|
| Hard Nano-Matter (Gold Nanoclusters) | Full-Shell "Magic Number" Clusters | | | | | |
| Shell Components n (Au Atoms) | Atom shell levels: | 1 | 2 | 3 | 4 | 5 |
| | Diameters: | .864 nm | 1.44 nm | 2.02 nm | 2.59 nm | 3.17 nm |
| | Saturation values (n): | 12 | 54 | 146 | 308 | 560 |
| | Nano-cluster weights: | 2560 | 10833 | 28953 | 60861 | 110495 |

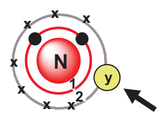
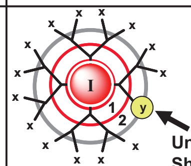
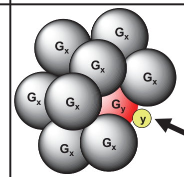
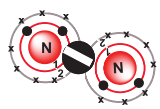
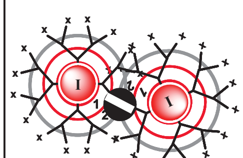
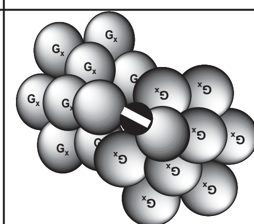


| | | | | | | |
|---|---|---|---|---|---|---|
| Soft Nano-Matter (Dendrimers) | Saturated Monomer Shells | | | | | |
| Shell Components n (Monomers) | Monomer shell levels: | G=1 | G=2 | G=3 | G=4 | G=5 |
| | Diameters: | 1.58 nm | 2.2 nm | 3.10 nm | 4.0 nm | 5.3 nm |
| | Saturation values (n): | 9 | 21 | 45 | 93 | 189 |
| | Nanostructure weights: | 144 | 2414 | 5154 | 10632 | 21591 |

D.A. Tomalia, *J. Nanoparticle Research, submitted* (2008).

THE NATIONAL DENDRIMER & NANOTECHNOLOGY CENTER

# Architectural Patterns Influencing Modular Reactivity (Picometer to Nanometer Dimensions)

| | Atoms | Dendrimers | Core–Shell Tecto(dendrimers) |
|---|---|---|---|
| Dimensions | 0.05–0.6 nm | 1–15 nm | 5.0 ≥ 100 nm |
| Valency (Reactivity) | Unfilled Outer Electron Shell | Unfilled Outer Branch Cell Shell | Unfilled Outside Dendrimer Shell |
| (Core–Shell) Architecture Induced Reactivity (Unfilled Shells) |  (e.g., fluorine) Unfilled Shell (x) |  Unfilled Shell (x) |  Unfilled Shell (x) |
| Functional Components Directing Valency | Missing One Electron (y) in Outer Shell (x) Penultimate to Saturated Noble Gas Configuration | Missing One Terminal Branch Cell in Outer Shell (x) Exposing Functionality (y) | Missing One Dendrimer Shell Reagent Exposing Functionality (y) |
| Chemical Bond Formation Leading to Saturated Outer Shell: Atoms, Dendrimers, Core-Shell Tecto(dendrimers) |  |  |  |

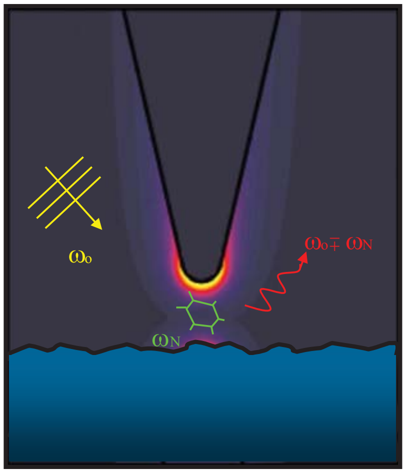
D.A. Tomalia, et al., *PNAS,* 99 (8) (2002) 5081-5087

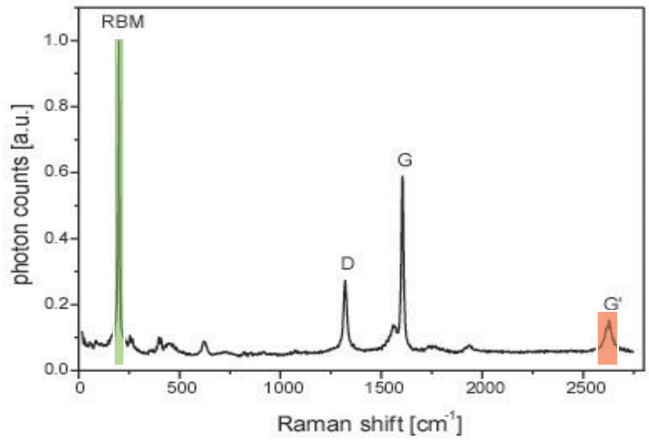
Nanoscale Building Blocks
Donald Tomalia (2)

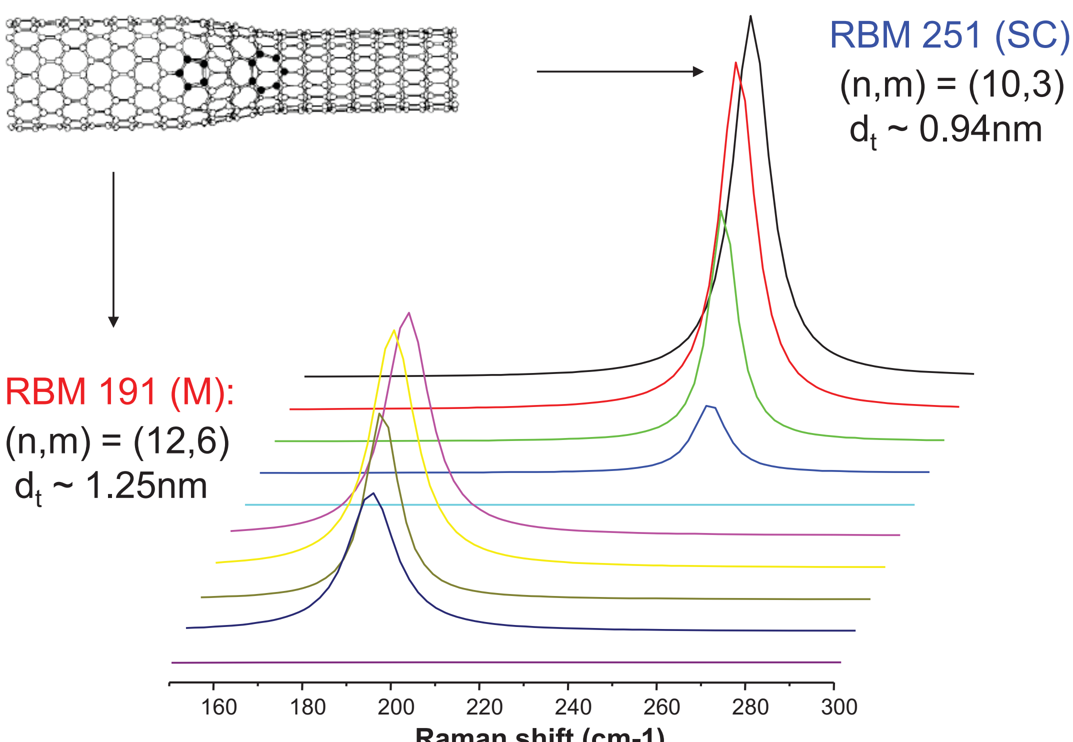
# Conclusions

- A New Hypothesis is Proposed for Unifying and Defining the Emerging Discipline: ***Synthetic Nano-Chemistry***
- It is Based on J. Dalton's Original Principles of ***Atom Mimicry***
- ***New Concepts are Introduced to Describe Published Examples of:***
  ***(a) Hard-Soft Matter Nano-Element Categories***
  ***(b) Hard-Hard, Soft-Soft, Hard-Soft Nano-Compound Categories***
  ***(c) Nano-Periodic Property Patterns***
- ***First Steps have been taken toward a "Central Dogma" for Unifying and Defining Synthetic Nano-Chemistry***
- ***There is Optimism for Evolving Nano-Periodic Tables for Predicting Nano-Element/Compound: (a) Reactivities, (b) Physical Properties, (c) Toxicology and (d) Environmental Impact, etc.***

# NEAR-FIELD RAMAN SCATTERING

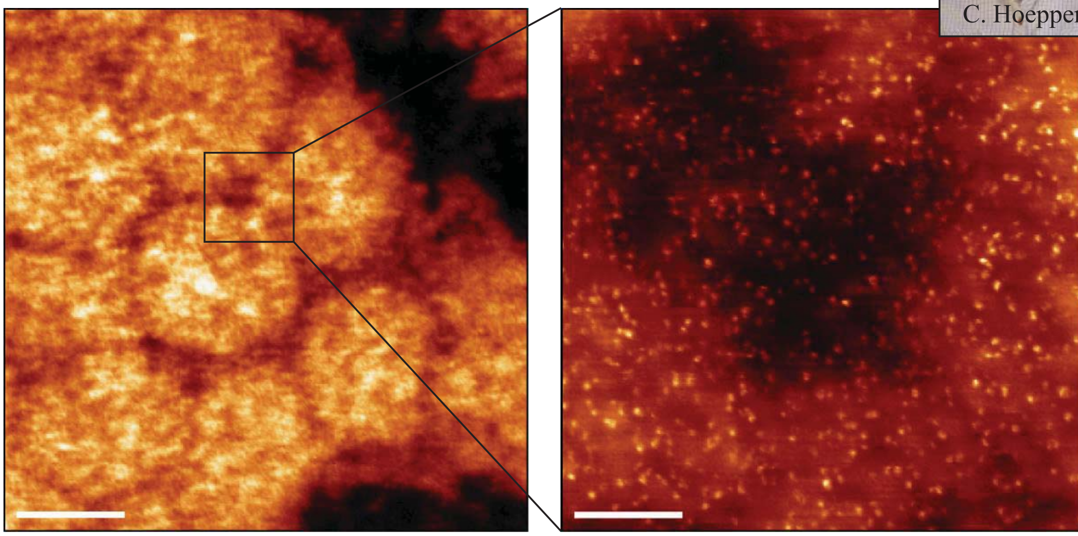




*Nano Lett.* **7**, 577 (2007)

## IMAGING OF SINGLE $Ca^+$ ION CHANNEL PROTEINS IN ERYTHROCYTE MEMBRANES

*Nano Lett.* **8**, 642 (2008)

## CONCLUSIONS

### Antenna-coupled light-matter interactions

- Spectroscopy with spatial resolution ~10 nm
- Opportunities for LEDs, photovoltaics
- Nonlinear plasmonics

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**Thanks:** Ado Jorio, Steve Cronin, Todd Krauss, Ernesto Joselevich, Lewis Rothberg, Alex Noy, Shanlin Pan, Brian Holmberg, Barbara Schirmer, Ryan Beams, Brian McIntyre,

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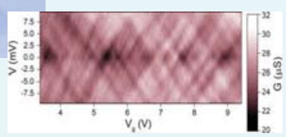
www.nano-optics.org

Atomically-Thin Carbon
Michael Fuhrer (1)

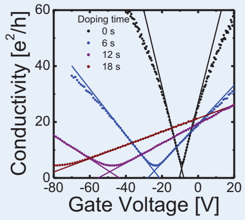
**Prof. Michael S. Fuhrer's Group**
Sungjae Cho
Chaun Jang
Shudong Xiao
Alexandra Curtin

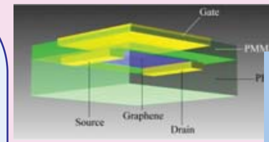

*MR in graphene*

*graphene Fabry-Pérot*



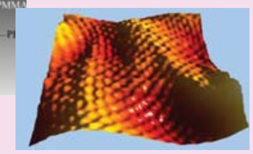

*UHV doping, dielectric expts.*




*transfer-printing*

*STM*



**Prof. Ellen D. Williams' Group:**
Dr. William Cullen
Prof. Masa Ishigami (now @ UCF)
Daniel Hines
Jianhao Chen

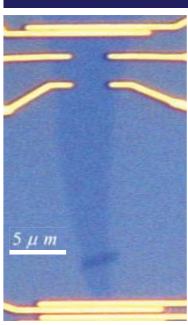
**Prof. Sankar Das Sarma's Group**
Dr. Shaffique Adam Dr. Euyheon Hwang
Dr. Enrico Rossi Wang-Kong Tse
**Theory**

*More Info:*

| | |
|---|---|
| *Fuhrer group:* | **www.physics.umd.edu/mfuhrer** |
| *Williams group:* | **www.physics.umd.edu/spg** |
| *Das Sarma group:* | **www.physics.umd.edu/cmtc** |



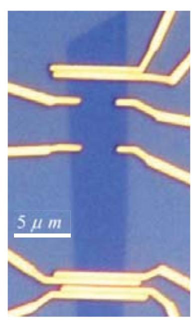
## Quantum Hall Effect: Single Layer vs. Bilayer




Single layer:

$$\sigma_{xy} = \nu \frac{e^2}{h} \qquad \nu = 4\left(n + \frac{1}{2}\right)$$

Berry's phase = π

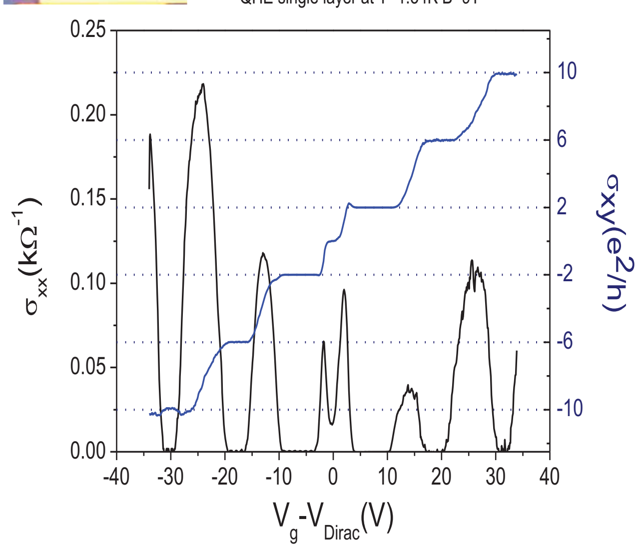



Bilayer:

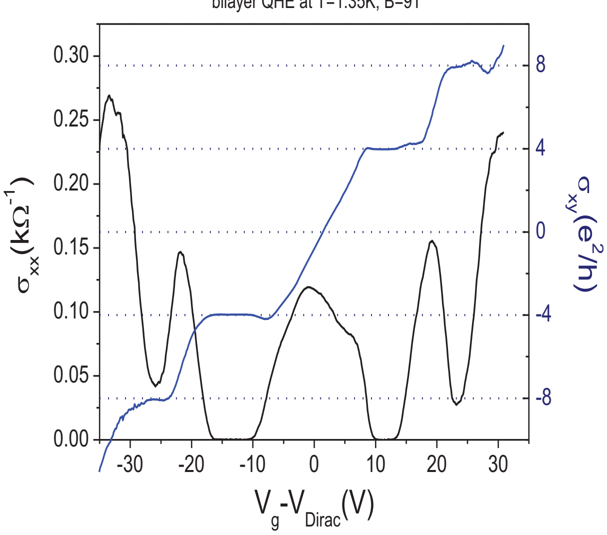
$$\sigma_{xy} = \nu \frac{e^2}{h} \qquad \nu = 4(n+1)$$

Berry's phase = 2π

QHE single layer at T=1.34K B=9T




bilayer QHE at T=1.35K, B=9T




See also: Zhang et al, 2005, Novoselov et al, 2005.

## Charged Impurity Scattering: Potassium Doping in UHV

J. H. Chen, et al. *Nature Physics* **4**, 377 (2008)

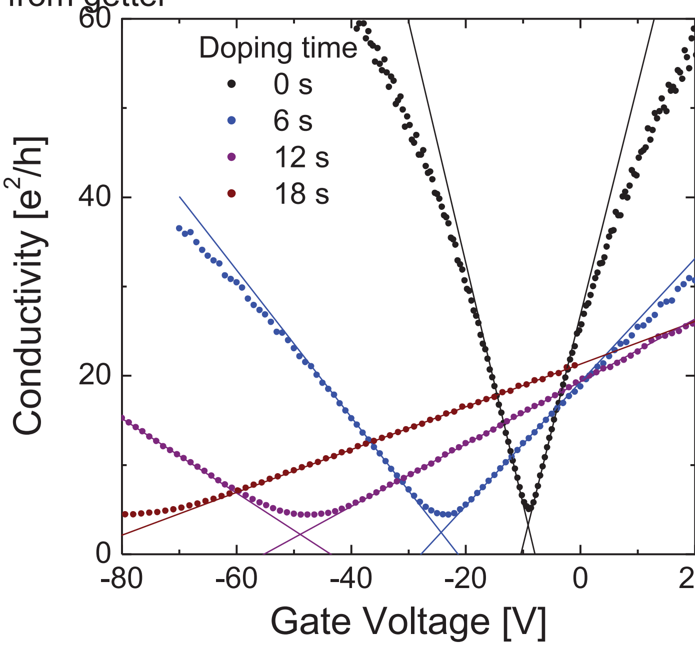
- Clean graphene in UHV at $T$ = 20 K
- Potassium evaporated on graphene from getter

Upon doping with K:

1) mobility decreases
2) $\sigma(V_g)$ more linear
3) $\sigma_{min}$ shifts to negative $V_g$
4) plateau around $\sigma_{min}$ broadens
5) $\sigma_{min}$ decreases (slightly)

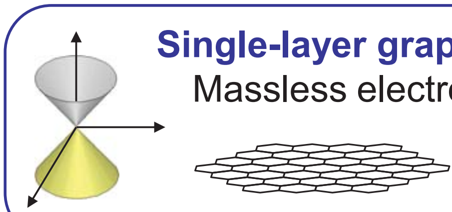
All these feature predicted for Coulomb scattering in graphene

Adam, et al., PNAS 104, 18392 (2007)

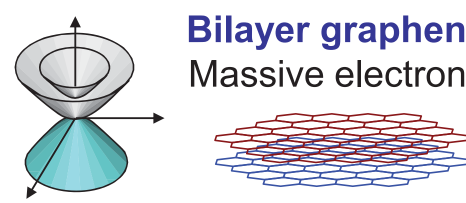




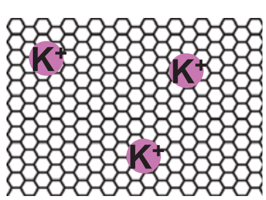

## Outlook



**Single-layer graphene**
Massless electrons

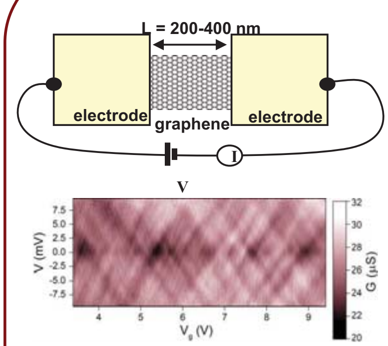


**Bilayer graphene**
Massive electrons



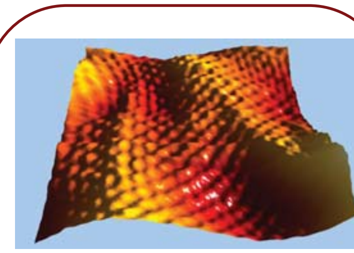

**Surface science expts. can tune:**
Dielectric constant
Charged impurities
Magnetic impurities
etc.

+




**Mesoscopic expts.**
Ballistic transport of wave-like electrons

+



**Scanned probe expts. can image:**
Atomic structure
Defects
Edges
Electron wavefunctions

Applying Physics Nano-technology to Biology
Harald Hess (1)

# Nanoscale measurement examples in biology: Sub-diffractive imaging & the fly brain challenge

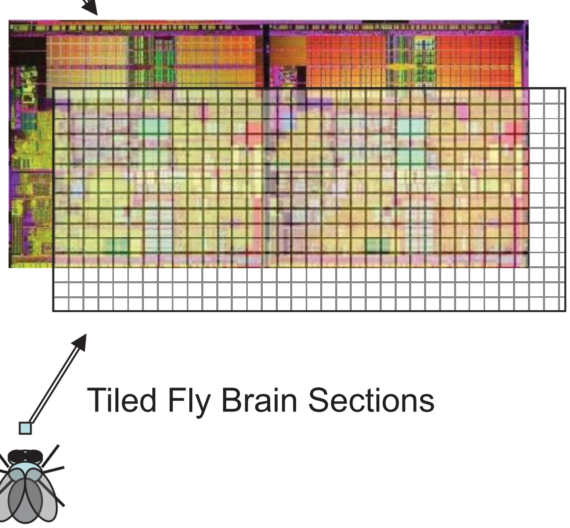
*Harald Hess, HHMI Janelia Farm*

- Introduction to HHMI Janelia Farms
- Sample: Nerves, Worm Brains, Fly Brains, Rodent Brains
  - The data challenge!
- Probes and Microscopies:
  - Existing
    - Electrophysiology
    - Fluorescent labels
    - Microscopes
  - Innovating Examples
    - Electrophysiology
    - Labels
    - Enhancing contrast
    - Improving Resolution
    - PALM & iPALM

HHMI janelia farm research campus

# Fly Brain Inspection : Semiconductor Chip Inspection

Pentium 4 Dual Core



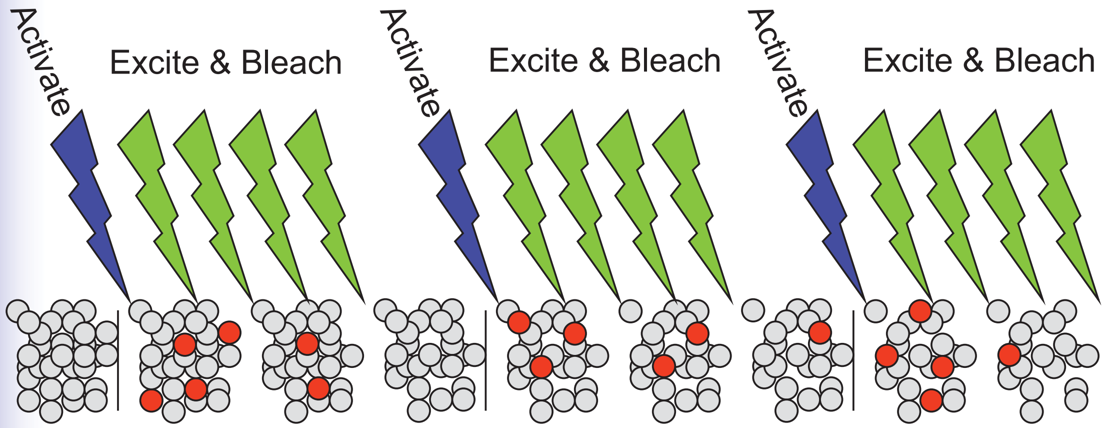
Tiled Fly Brain Sections

**If Fly Brain were sectioned to 0.07 micron and spread out**

| Die | | Fly |
|---|---|---|
| 5 $cm^2$ | | 5 $cm^2$ |
| | 65 nm | |
| Wire | | Axon |
| | 200 Million | |
| Transistors | | Synapse |
| | 200,000 | |
| CLB(FPGA) | | Nerve Cell |

janelia farm research campus

# 1) Establish Sparse Subset with Fractional Activation

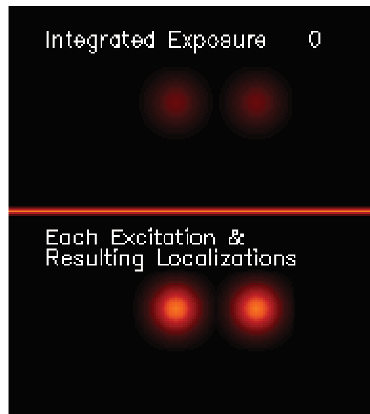



Switchable Flourescent Protiens:
Kaede, Eos

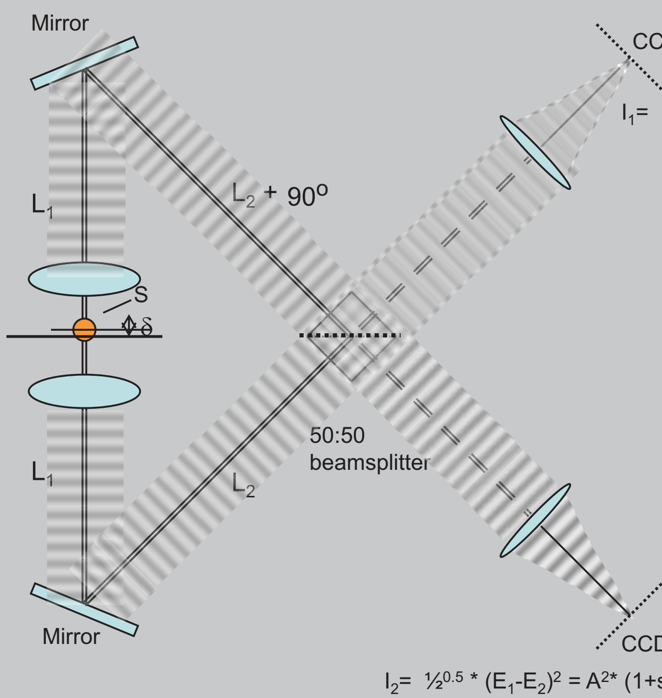
## 2)Localize:

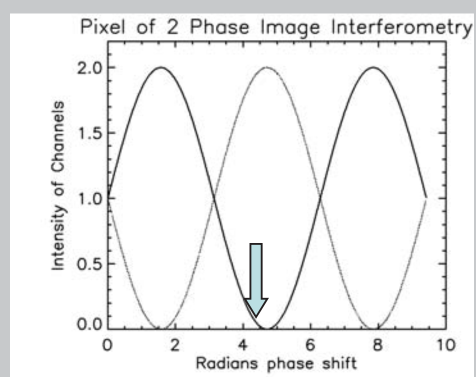
Fit Point Spread Function *s ~ 200 nm*

Center Location w Error $\sigma$ ~ *sεN ~ 10 nm*




# Single Photon Interferometric Fluorescence Imaging




0 - 300 nm

## *Exploiting Protein Cage Dynamics for Engineering Active Nanostructures*

*NSF NIRT CBET-0709358*
PIs: **Trevor Douglas (PI), Brian Bothner, Yves Idzerda, Mark Young**
Montana State University

The focus of this Montana State University (MSU) NIRT builds upon a strong multidisciplinary team in the development of protein cage architectures as size and shape constrained templates for nanomaterials synthesis [1]. A deepening understanding of these systems has led to an appreciation that protein cage dynamics plays an important role in the overall properties of the nanomaterials. *The central focus of this NIRT is to examine how particle confinement and protein cage dynamics at active interfaces controls nanomaterials synthesis and material functionality.* The long-term goal is to use this knowledge to guide the development of a new generation of active and responsive nanomaterials.

**The project is divided into three integrated components: *Active Interfaces*, *Cage Dynamics*, and *Confinement*.**

Protein cage architectures, such as viruses and ferritins have three active interfaces can be manipulated, both chemically and genetically. These include the exterior surface, the interior surface, and the interface between the subunits that comprise the protein cage architecture.

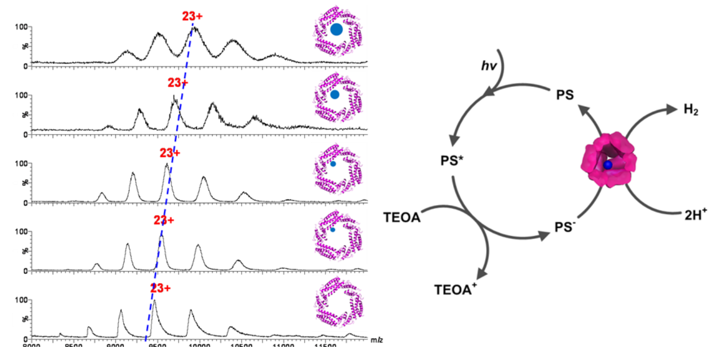


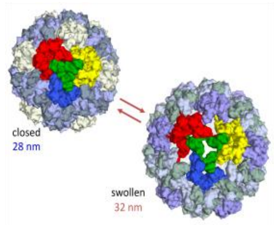

**Fig 1.** ESI Mass spectrometry was used to monitor Pt(II) ion binding and reduction to form Pt clusters. The clusters were active for $H_2$ formation when coupled to an Ir photosensitizer [2].

***Active Interfaces*** is focused on directing interactions for defined chemical synthesis using hard-soft interfaces, particle-surface interactions and controlled hierarchical assembly [2-4].

We have shown that we can use mass spectrometry to monitor metal ion binding and nanoparticle growth within a protein cage architecture. We have demonstrated that interactions between protein macromolecules and metal ions or nanoclusters can be preserved and metal deposition can be monitored by following mass increases of the protein-metal composite. Our state-of-art mass spectrometry has a sufficient mass accuracy and resolution to discriminate 2-3 metal ions depending on atomic masses of metal ions. Therefore, it is possible to concurrently detect multiple populations distributed within an ensemble and monitor their changes individually instead of averaging all signals. Using a combination of electrospray ionization (ESI) and time-of-flight (TOF) mass analyzer, the mass measurement of giant non-covalent macromolecular complexes has been possible and preservation of non-covalent interactions and solution structures in the gas phase inside mass spectrometer has been well demonstrated.

***Cage Dynamics*** is centered around understanding and directing inherent and engineered cage dynamics to control material confinement, directed self-assembly, and particle-particle interactions [5-6].

Protein cages are assembled from identical individual subunits to form the overall architecture. The dynamics of the cages can arise either from the collective motions of these individual subunits or from individual components of the structure. We have investigated the change in modulus that occurs when a virus capsid undergoes a structural transition between a closed and an open conformation resulting in a roughly 10% increase in diameter. Shown in Fig 2 is the structural transition and the modulus, measured by quartz crystal microbalance (QCM).




| Particle form | Shear Modulus | Young's Modulus | Diameter (AFM) |
|---|---|---|---|
| Swollen | 4907 | 12268 | 31.5 nm |
| Closed | 4547 | 11368 | 28.6 nm |
| Swollen | 4892 | 12230 | 31.5 nm |

Pascals

**Fig 2.** The CCMV virus undergoes a swelling transition, which has been probed by QCM to determine the elastic modulus of these two conformations. Environmental triggers (pH and [Metal ion] switch between these two conformations.

Using our ability to control the disassembly and reassembly of the cages from individual subunits we have made chimeric cages of multiple modified subunits. We analyzed the ensemble distribution of the cages by native mass spectrometry and found homogeneous populations that fit to a bimodal distribution of subunits (Fig 3). This approach now allows us to selectively modify subunits and assemble 'designer' cages in which the distribution of modified subunits is controlled by the input ratio in the re-assembly reaction [5].

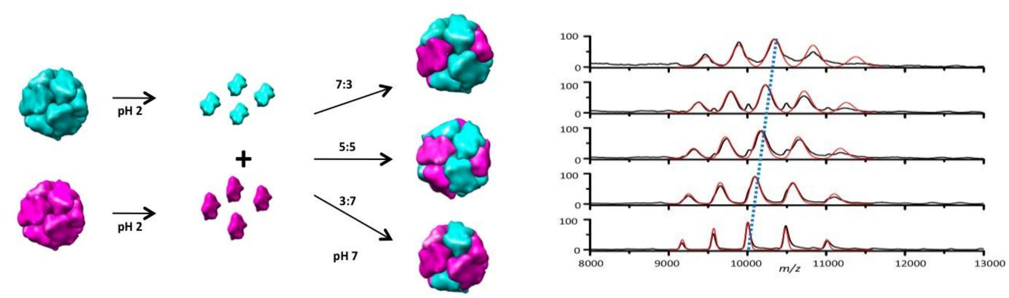



**Fig 3.** Using the Dps protein cage we have shown that we can differentially modify two subunits and reassemble into a chimeric cage, which follows a binomial distribution of subunits [5].

The ***Confinement*** thrust integrates the *Active Interfaces* and *Cage Dynamics* to explore their consequences on the physical properties of individual and collections of particles [7-12]. Confinement of mineralized particles in protein cages modifies the behavior of the surface spins by reducing the surface anisotropy. This directly affects the surface spin configuration, greatly enhancing the overall moment of the

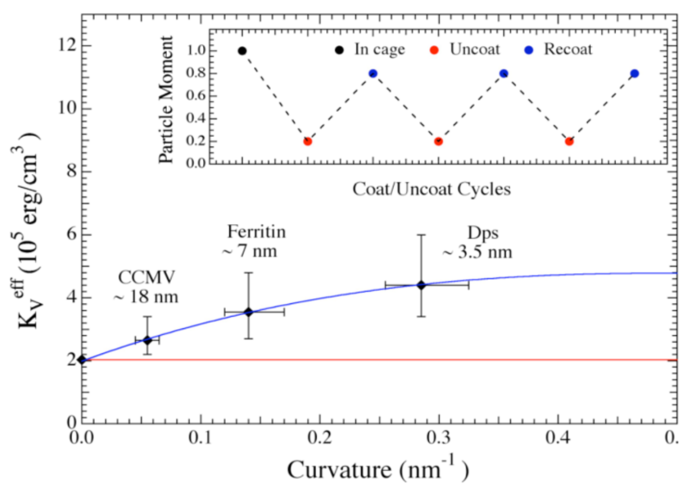



**Fig 4.** Confinement of magnetic nanoparticles within protein cages of different sizes. Removal of the protein results in loss of overall moment but recoating the particles restores most of the moment. This uncoating/coating can be cycled to reduce and restore the overall moment.

nanoparticle. Control would allow us to turn on and off catalytic activity, substantially reduce particle magnetic moment for new sensor applications, and modify optical properties. As an example, magnetic nanoparticle sensor applications typically rely on the attachment or detachment of the particle. By using active control of the surface anisotropy, the particle can remain attached, but the particle moment can be reduced by 80%, which would essentially remove the magnetic signal.

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**Single Molecule Detection in Living Cells using Carbon Nanotube Optical Probes**

*Michael Strano, Klaus Schulten, Taekjip Ha, and Thomas Eurell*

NSF Award 0708459

This proposal seeks to demonstrate real time, sustained optical signal transduction from living cells at the single molecule level. Nanotechnology is yielding new classes of materials with unique optical properties that can provide innovative engineering solutions to traditionally difficult biological problems. While single molecule detection techniques have significantly impacted our understanding of biology, limitations such as photobleaching, intermittent emission (blinking), unfavorable wavelengths and auto-fluorescence have restricted in-vitro and in-vivo single molecule studies to superficial regions of biological systems. The high electronic density of states of carbon nanotubes enables their spectroscopic characterization at the single nanotube level. Hence, it is now theoretically possible to transduce single molecule adsorption events at a nanotube surface. Furthermore, carbon nanotubes are unique in that they do not photo-bleach, show no intermittent blinking and are detectable at the single molecule level in the near infrared, where auto-fluorescent background is negligible. In this proposal, the research team will demonstrates the engineering of single walled carbon nanotubes by attaching recognition ligands, which modulate the optical properties in response to a specific molecular adsorption. Preliminary data has been shown for ultra sensitive detection of glucose and streptavidin using prototype carbon nanotube-based optical probes. In addition, the PI demonstrates that wrapping DNA oligonucliotides and other biomolecules around nanotube sensors can deliver them directly into the cytoplasm of murine myoblast stem cells. Thus they present, as proof of concept, the first nanotube spectroscopy from within a living cell.

# NIRT: Self-Assembled Nanohydrogels for Differential Cell Adhesion and Infection Control

*NSF NIRT Grant 0708379*

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Stevens Institute of Technology, Hoboken, New Jersey 07030

Among the possible complications associated with total joint replacement surgery, biomaterials-related infection is among the most common and most serious. Infection occurs in approximately 0.5 – 5% of the hip and knee replacements [1, 2] and is substantially higher in cases of trauma [3, 4]. Infection of an implanted device is a catastrophic problem, because there is currently no effective therapy to fully resolve an infected implant short of removing the implant altogether and pursuing a subsequent revision surgery.

At its core, the infection of an implant surface is a biomaterials problem. A number of materials modifications have been made to render such surfaces repulsive to bacteria – e.g. PEGylation [5-7] – but these bacteria-repulsive surfaces also repel eukaryotic cells. Instead, a surface is needed that is *differentially adhesive* such that it promotes osteoblast adhesion and proliferation while simultaneously inhibiting bacterial adhesion and proliferation (figure 1). This is a fundamental biomaterials problem that remains unsolved.

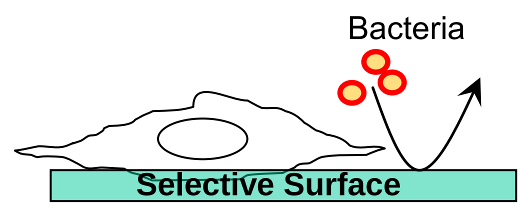


Fig. 1 – A differentially cell adhesive surface will enable osteoblast adhesion and proliferation for healthy healing while simultaneously minimizing bacterial adhesion and, hence, reducing the probability of infection.

Nanoscale science and engineering offers a compelling possible solution to the differential cell adhesion problem. This solution uses nanoscale hetero-features organized on surfaces in two dimensions at submicron length scales. Modulations of cell adhesiveness at 1-100 μm length scales have been extensively studied for the purposes of eukaryotic cell patterning. However, the idea of modulating nanoscale adhesiveness to achieve differential cell adhesion to repel bacteria yet attract eukaryotic cells based on fundamental differences in the length-scale properties of these cells is new.

Our approach involves the synthesis and surface self assembly of nanosized hydrogels that will mediate the adhesion of osteoblasts and staphylococcal bacteria. Osteoblasts, like most eukaryotic cells, are typically on the order of 10 μm in diameter, they have flexible cell walls that can conform to a substrate, and they adhere to surfaces by nanoscale integrin-mediated focal contacts [8-11]. Staphylococcal bacteria, on the other hand, are spherically shaped, they do not easily conform to a substrate, and they are only about 0.6-0.9 μm in diameter. We are thus developing synthesis and self assembly methods over a range of hierarchical length scales in order to modulate cell adhesion based on these differences.

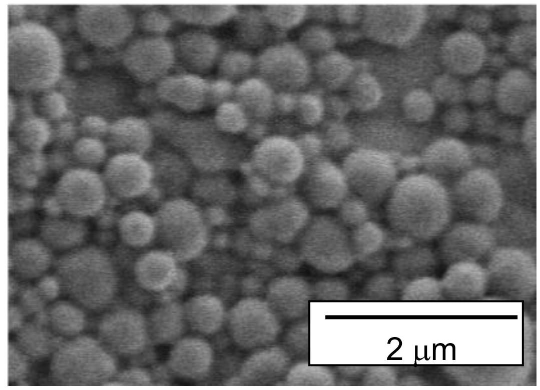


Fig. 2 - SEM image of dry PEGDA-AA hydrogel particles.

One focal point of our research effort uses inverse emulsion polymerization to synthesize copolymer hydrogel particles from PEG diacrylate (PEGDA 575) and acrylic acid (AA) precursors. The acid groups confer pH-dependent charge on the resulting gels and also provide sites for post-synthesis functionalization. After repeated cleaning and separation by centrifugation methods, gel particles with sizes ranging from about one micron down to tens of nanometers can be isolated (fig. 2). Zeta potential and dynamic-light-scattering measurements show that these gels undergo pH dependent charge and size changes as anticipated. Using established methods of electrostatic self assembly, we have successfully deposited sub-monolayer quantities of PEG-based nanohydrogels on poly(lysine)-primed silicon surfaces. As we move into our second year, our goals are to: (1) establish better control over the hydrogel particle size; (2) refine the electrostatic deposition parameters to control both the average inter-gel spacing and fractional coverage of surface; and (3) develop protocols to create cell-adhesive variants of the gel particles by the covalent grafting of adhesion-promoting protein moieties.

A second focal point of our research effort centers on the *in vitro* evaluation of the differential cell-adhesion properties of nanohydrogel-modified surfaces. Preliminary results using static cell culture indicate that the adhesion of *Staphylococcus epidermidis* is substantially reduced by sub-monolayer coverage of cell-repulsive gels on an otherwise cell-adhesive surface. To better assess differential cell adhesiveness, an important aim over the past year has been to establish a microfluidic platform and co-culture protocols as a novel means of evaluating the effects of nanohydrogel size and lateral organization on the differential adhesion of osteoblasts and *S. epidermidis* bacteria. We have designed and fabricated a microfluidic prototype (fig. 3) that can be used for *in-situ* imaging cell interactions with clinically relevant surfaces. Its key attributes are: (1) multiple cell culture chambers, (2) a clinically relevant Ti alloy substrate incorporated as the bottom surface of the device, (3) *in situ* confocal imaging of cell interactions with the biomaterial surface, and (4) embedded microvalves for time-controlled delivery of

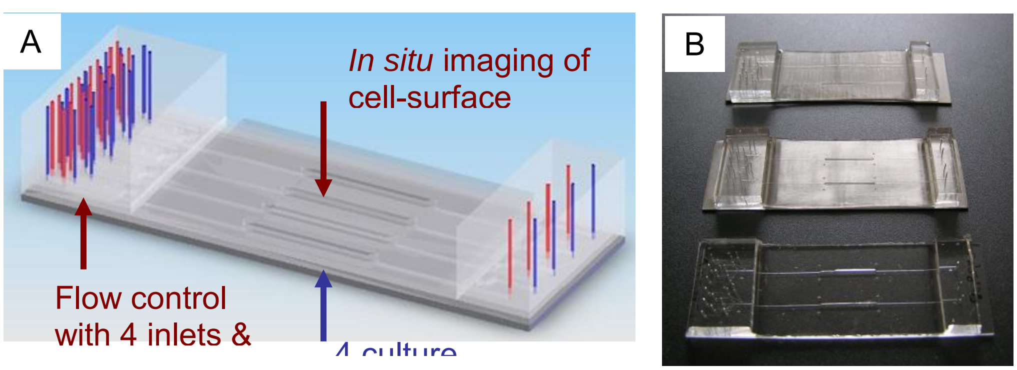


Fig. 3 - (A) Schematic co-culture microfluidic device (red and blue lines indicate punched holes for fluidic connections). (B) Prototype 2-chamber microfluidic devices fabricated with: (Top) Ti alloy surface roughened to 0.5 μm, (Middle) Ti alloy polished to 0.05 μm, and (Bottom) glass slide.

reagents and for preventing cross-contamination between the chambers. We have successfully developed cell co-culture protocols, and we are currently developing *in situ* imaging techniques to observe osteoblast response to a bacterial insult.

Our research activities are being integrated into a high-school outreach activity in collaboration with the Stevens Center for Innovation in Science and Engineering (CIESE). The objective is to develop, integrate, and pilot curriculum modules that will be taught in high school biology and chemistry classes and which incorporate themes related to the parent project. The curriculum modules were drafted during the summer of 2008 (fig. 4) and are now undergoing revision prior to being piloted in spring 2009. Teacher applications are being screened to select participants for this pilot. Additionally, broader dissemination began in October when a paper describing this aspect of the project was presented at the Fall 2008 Mid-Atlantic Section Conference of the American Society of Engineering Education (ASEE).

Fig. 4 - Stevens undergraduate Zareen Mobin working with Ms. Clare Kennedy from the Academies at Englewood / Dwight Morrow High School.

For additional in formation, email Dr. Matthew Libera at mlibera@stevens.edu

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**Nanostructured Bimetallic, Trimetallic and Core-Shell Fuel-Cell Catalysts with Controlled Size, Composition, and Morphology**

*Chuan-Jian Zhong, Bahgat Sammakia, and Susan Lu*

NSF Award 0709113

This research program focuses on the topic area of "Active Nanostructures" through design, synthesis, modeling, characterization, and optimization of multimetallic nanoparticles towards fuel-cell catalysts. Multimetallic nanoparticles promise advanced opportunities for the development of active, robust and low-cost catalysts. A major problem is the lack of the ability in controlling size, composition, and morphology at the nanoscale. The goal of the proposed research is to establish the fundamental correlation between the nanostructural parameters (size, shape, composition and morphology) and the catalytic properties (activity and stability). Our approach is nano-engineering of multimetallic nanoparticles with a combination of activity enhancing, stability-optimizing, and cost-reducing components. Nanoparticles with binary (M1nM2100-n), ternary (M1nM2mM3100-n-m) alloys, and core@shell (M1@M2) will be synthesized, modeled, and characterized.

This approach is significant because the development of multimetallic catalysts towards practical fuel cell catalysts requires a balanced understanding of activity-enhancement, stability optimization and cost reduction, which has not been addressed by the existing approaches. The proposed research will accomplish four specific objectives:

1. to synthesize, characterize and optimize multimetallic nanoparticles and catalysts with controllable size (1-10 nm), composition (e.g., M1nM2100-n, M1nM2mM3100-n-m, M1@M2, MOx@M, where M (1 or 2) = Pt, Co, Ni, V, Fe, Cu, Pd, W, Ag, Au, etc.), and morphology (e.g., alloy, core@shell, shape, etc.);
2. to evaluate the catalytic activities of the multimetallic nanoparticle catalysts in fuel-cell reactions for understanding the relationships between the catalytic activity and the nanostructural parameters;
3. to develop theoretical models for predicting and assessing the structural correlation of the multimetallic nanoparticles and catalysts; and
4. to carry out optimization analysis of the catalyst activity-stability and fuel cell testing of selected catalysts to determine the durability and degradation mechanism.

Fundamental questions concerning the synergistic activity of the surface sites and the relative surface arrangement of different metals or metal oxides in the nanoparticles will be addressed. The multidisciplinary team integrates the capabilities of PI/Co-PIs in nano-engineering, theoretical modeling and performance testing, including Prof. Zhong of the Department of Chemistry focusing on nanoparticle synthesis and characterization, Prof. Lu of Systems Science and Industrial Engineering focusing on optimization and reliability evaluation, Prof. Sammakia of Mechanical Engineering focusing on advanced characterizations and outreaching activities at State University of New York, and Prof. Wang of the Department of Chemistry & Biochemistry at Southern Illinois University focusing on theoretical modeling of the nanoparticles.

Intellectual Merits: At the fundamental level there is an outstanding need for the design and fabrication of multifunctional catalysts that exhibit synergistic activity and stability. The proposed approaches and methods in synthesis, processing, computation and optimization are expected to provide experimental, theoretical, and engineering insights into the catalysis of the nanostructured catalysts with controllable size, composition, and morphological properties. The fuel cell technology will be favorably impacted by such insights. Importantly, the methods and insights will also provide a useful knowledge base for many researchers in understanding and designing nanostructured catalysts.

Broader Impacts: The proposed research program encompasses nanoscale design, chemical synthesis, computational modeling, optimization analysis, fuel cell technology, and diverse physical and chemical measurements. The scope of the research activities is so broad and deep that the implementation of such a nanotechnology research program is expected to open up new opportunities in expanding the interdisciplinary explorations of nanotechnology. Our on-campus and cross-campus learning activities integrates nanotechnology and fuel cells into chemistry and engineering course modules that will be engage students, including undergraduate and high school students, in an interdisciplinary learning environment to become competitive in the nanotechnology-demanding job market.

**C-MEMS/C-NEMS for Miniature Biofuel Cells**

*Marc Madou, Leonidas Bachas, Sylvia Daunert, and Chunlei Wang*

NSF Award 0709085

In recent years, the quest for alternative sources that can autonomously power bioMEMS devices, especially those geared for in vivo applications, such as monitoring and drug delivery, has been the focus of research by scientists and engineers as new power sources will prove critical for the advancement of the field. Current batteries are still less than optimal and often present drawbacks related to safety, reliability and scalability. An ideal power source for implantable devices should take advantage of natural compounds present in the body of an individual and use them as fuel to produce power in a continuous and reproducible manner, as long as the patient's physiological functions remain steady. Biofuel cells, which are capable of converting biochemical energy into electrical energy, have been deemed as a potential solution to the drawbacks presented by conventional batteries, but the power density and operational lifetime requirements for implanted devices have not been met yet. To that end, we propose to integrate genetically engineered catalytic proteins and carbon-based 3 dimensional (3D) MEMS/NEMS structures to create new biofuel cells. The biofuel cell electrode surfaces, especially fractal electrode array, presents significantly increased surface area as compared to traditional architecture, increasing the biocatalyst loading capacity considerably for high power throughput. The genetically engineered enzymes inherently increase enzyme stability, consequently increasing biofeul cell lifetime. The scaled fractal electrode surface plays a role in wiring the enzymes to the biofuel cell anode, which increases the electron transfer efficiency from the enzyme to the electrode for an increase in the overall performance of the biofuel cells. Furthermore, C-MEMS/C-NEMS architectures will enable the reproducible fabrication of low cost carbon-based electrode structures.

We envision that this project will have an impact on the MEMS, NEMS and bioMEMS communities. Given that C-MEMS/NEMS technologies can be used in a number of fields as a substitute for siliconbased devices, the proposed technology should find applications not only in energy-related areas, such as biofuel cells, micro-batteries and super capacitors, but also in others, such as biosensing, drug delivery and actuators. The C-MEMS/NEMS approach gives the development engineers unprecedented freedom in the design and manufacture of high surface area conductive structures through the use of new materials and innovative fabrication techniques. The development of biofuel cells based on producing high aspect ratio 3D carbon structures in the mm to nm range by integrating ?top-down? and ?bottom-up? processing approaches and combining biological components with MEMS/NEMS structures should present advantages over traditionally used Si-based materials. Moreover, this could start a trend in the lithographic patterning of materials other than Si. Further, the proposed technologies could also have an impact on other industries and on the end-users. For example, the point-of-care diagnostic market, including implantable biosensors that track blood glucose levels and deliver insulin, is approximately a $7 billion to $8 billion market growing at around 10% per annum. Since our biofuel cells are ideal for use in miniaturized medical devices, we expect that they could have an impact both in in vivo as well as in vitro diagnostics and point-of-care situations.

The PIs have a well-established productive collaboration that has resulted in a good number of joint publications, grants, and advising of graduate and postdoctoral students. This project will further enhance the current interdisciplinary and collaborative effort of the groups of Dr. Madou at UCI, Dr.

Wang at FIU and Drs. Bachas and Daunert at UK. The proposed collaborative research will allow us to combine ?bottom-up? biotechnology with ?top-down? micro/nanomanufacturing techniques for bio MEMS/NEMS applications. Such work will foster interdisciplinary interactions and will train students with different backgrounds, i.e., chemical/materials engineering, mechanical engineering, electrical engineering, and chemistry, in the broad areas of micro/nano fabrication of novel biomedical sensing devices and high capacity miniaturized power sources. Workshops and outreach programs will be conducted to broadly disseminate the results of this work and raise awareness to students (undergraduates and K-12) and the general public in bioMEMS and Nanobiotechnology. Moreover, this project broadens the participation of women in multidisciplinary science and engineering.

# Functionalization of alloy metal nanoparticles for enhanced transport and catalysis in membranes

*NSF NIRT Grant 0708779*

PIs: **Benny D. Freeman[1], John W. Keto, Desiderio Kovar, Graeme Henkelman, Michael F. Becker**

*The University of Texas at Austin*

**Introduction and Objectives**

Membranes used in gas separations offer tremendously lower energy and capital costs when compared to technologies currently in use. A major challenge for using membranes in large-scale gas separations is developing materials that offer high purity and high flux of the desired gas. Our goal is to utilize metallic nanoparticles (NPs) to improve the transport properties of polymeric membranes. The main thrusts of the research are production and characterization of metallic NPs, simulation of kinetic and catalytic processes, and optimization of nanocomposite membrane transport properties. This project also provides a vessel for educational outreach through collaboration with Texas School for the Deaf (TSD) and Austin Children's Museum (ACM).

**Nanoparticle Production and Characterization**

We use the Laser Ablation of Microparticle Aerosol (LAMA) process to produce nanoparticles (NPs). In the LAMA process, uniformly sized microparticles are aerosolized in a gas stream. This aerosol stream is then passed through the path of a high-energy eximer laser, which breaks the micron-sized particles into many nano-sized particles for later collection. The LAMA process allows for larger scale production of NPs without the use of capping agents on the particle surface [2].

Increased NP production focuses more attention on economical selection of microparticle feedstock. Silicon dioxide NPs are of interest due to their catalytic nature. Initially these particles were produced from purchased silicon dioxide microparticles, but their cost is prohibitive for high volume NP production. Another route to silicon dioxide microparticles is the hydrolysis of tetraethyl ortho-silicate (TEOS) to form silicon dioxide and ethanol. SEM analysis was performed on the microparticles formed by hydrolysis and TEM analysis on the NPs made by the subsequent ablation of the microparticles. The TEM images show that the LAMA process can produce uniform $SiO_2$ particles <10nm from hydrolyzed TEOS.

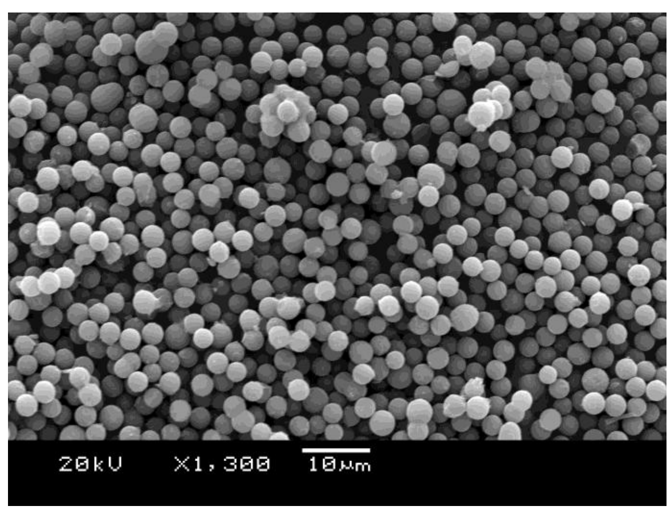


**Figure 1**: SEM of $SiO_2$ microparticles produced in our laboratory for use as feedstock for the LAMAA process..

**Figure 2**: TEM of $SiO_2$ NPs on carbon grid produced core/shell nanoparticle using our feedstock and the. shell LAMA process.

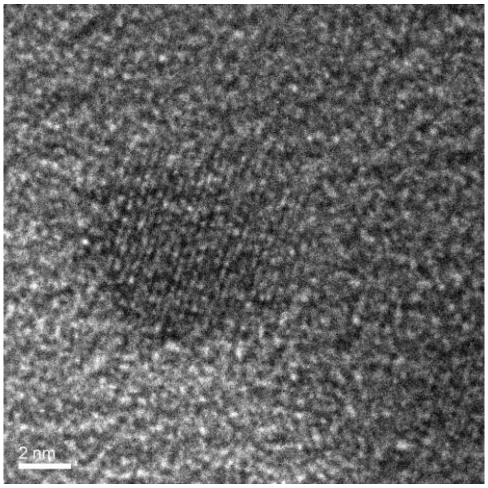


**Figure 3:** HRTEM micrographs of a CdSe/ZnS The spherical darker core of CdSe covering lighter ZnS shell can be observed.

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In an effort to utilize the properties of two different materials, we developed a process for making a core-shell NP. These NPs consist of two different semiconductors, using ZnS and CdSe for the core and shell, respectively. Producing ZnS NPs first, then feeding the CdSe microparticles into the ablation chamber along with the ZnS NPs yielded 20 nm NPs with ZnS core and CdSe shell [3]. We determined that the core-shell order could be reversed. This technique was also applied using silver or gold and oxides to produce nano-islands of gold on a NP of $SiO_2$.

**Optimization of Transport Properties**

In order to be commercially viable, gas separation membranes must be made from materials that have high flux and high purity of the desired product. When included in a polymeric membrane, the physical properties of the polymers limit separation performance. There exists a trade-off of increased gas flux and decreased gas selectivity and vice versa. The separation limitations of neat polymers are overcome by including other materials in the polymer matrix to “facilitate” transport of a desired species. Previous research has shown that the pi bond in olefins, such as ethylene and propylene, form a complex with a positively charged silver ion, whereas the analogous paraffins such as ethane and propane, form no such complex with the silver. Including ionized silver in a membrane dramatically increases the solubility for olefins compared to that of paraffins. The increase in olefin solubility leads to increased

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**Figure. 4**: Ethylene-ethane separation properties in conventional polymers and in XLPEO doped with **0.05** vol. % LAMA Ag NPs at 35°C. The AgNPs were nominally **8** nm dia..

olefin/paraffin selectivity without sacrificing permeability. Our group found that including very small amounts of (~0.1wt%) elemental silver NPs into the polymer matrix, achieved this same performance increase. The high surface-to volume ratio of the NPs makes a large area of silver available for complexing with minimal weight loading. Our membranes with silver NPs do not show the performance decline over time that is usually exhibited by membranes with silver ions.

**Modeling**

To bridge the gap between theory and experiment, we are modeling the facilitated transport of olefins and paraffins using a kinetic Monte Carlo (kMC) model. The model uses a two dimensional lattice in which gas molecules may diffuse via site-to-site hopping with a kinetic rate derived from their experimental diffusion constant in a PEG membrane. Lattice sites that contain a nanoparticle have a slower hopping rate with an Arrhenius form based on density functional theory (DFT)-calculated binding energy. The model demonstrates the relative importance of binding energies, pressure, and othertunable variables in achieving optimal olefin selectivity. In conjunction with the kMC model, we are using DFT to calculate the interaction of PEGDA with silver surfaces. The calculated vibrational spectra of PEGDA with nanoparticle flocs can be compared to surface enhanced Raman spectra (see Figure) to determine the binding geometry on the surface.

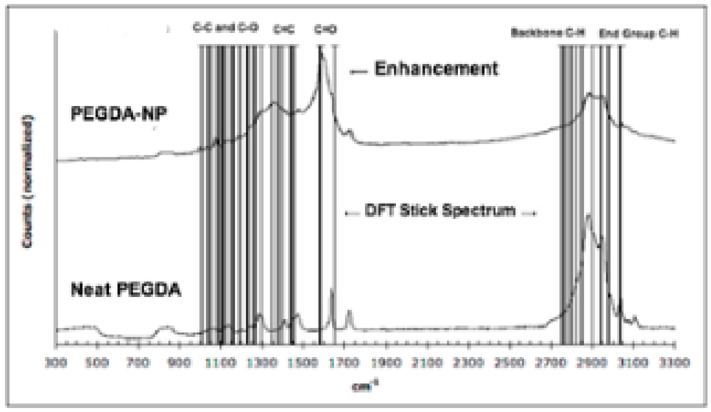



**Figure 5**: SERS data of neat PEGDA and PEGDA flocs showing spectral changes due to binding to silver surfaces. The DFT-calculated normal modes of PEGDA are shown as lines overlaying the spectra.

**Outreach**

In addition to the work being done in the lab, a significant portion of this project provides educational activities in the community. Our group established a relationship with the Texas School for the Deaf (TSD) by hosting a field trip to UT as well as recruiting a deaf high school student as an intern in our summer research program. Most recently, we have also initiated a monthly afterschool science club for TSD high school students, and discussions have begun with the prinicipal of the TSD elementary school to offer monthly science activities for third, fourth, and fifth graders. Other educational opportunities for the group are available through the Austin Children's Museum (ACM). Through ACM's *Science Sundays* program, we have offered activity clusters in energy, chemical changes, and polymers during the museum's no-admission period on Sunday afternoons. In all, the endeavors with both the Texas School for the Deaf and the Austin Children's Museum provide both a way for the next generation to explore science and a means by which our faculty and graduate students can make contributions to the broader community.

[1] For further information about this project email Benny Freeman at freeman@che.utexas.edu.
[2] Becker et al., *NanoStructured Materials,* 10, **1998,** 853-863
[3] Gallardo et al., *Applied Physics A,* accepted 2008

# NIRT: Engineered Therapeutic nanoparticles as catalytic antioxidants

*NSF NIRT Grant* **0708172**

PIs: **S. Seal,[1] W. Self,[1] A. Masunov[1] and J. McGinnis[2]**
[1]University of Central Florida, Orlando, and [2]University of Oklahoma

Rare earth nanoparticles have shown great potential for biological applications. Based on the ability undergo reversible redox reactions, these nanoparticles can effectively quench free radicals. We are developing engineered rare earth nanoparticles (cerium oxide nanoparticles and its hybrids) to mimic antioxidant enzymes in order to reduce accumulation of biological damage due to free radicals. This investigation will uncover and elucidate the molecular mechanism of the antioxidant nature of nanoceria as well as develop these materials into radical scavenging therapeutics. The NIRT team is studying the entire product cycle from synthesis, surface modification and characterization of the nanoparticles using advanced analytical tools, testing of their radical scavenging properties and their subsequent application in biological systems. In order to understand the details of the mechanism of functional activity, quantum chemical calculations are being performed on the ceria NPs. Although these NPs have shown excellent antioxidant and regenerative behavior in neurons, the details of cellular interaction mechanism are yet to be understood. In this program, we are developing engineered rare earth NPs to study their protective behavior in retinal cells. Furthermore, the computational data on the therapeutic characteristics of NPs are correlated with the experimental data. This will provide a solid foundation for further optimization and development of ceria and other rare earth nanostructures to enhance their biological activity. Based on the evaluation of experimental and theoretical data, ceria NPs will be tested *in vivo* in the albino rat light – damage model system.

Currently the team has produced engineered ceria nanoparticles, ranging between 2 and 10 nm in size, were introduced into organotypic rat brain cell cultures which consisted of neurons, glia and microglia. Cultures treated with nanoparticles not only maintained the normal physiology properties of the neurons, but the survival rate of such cultures exceeded that of control cultures by a factor of three. Nanoceria particles have shown to be preventing the increases in the intracellular concentrations of ROS in primary cell cultures of rat retina and the loss of vision *in vivo* due to light-induced degeneration of photoreceptor cells. We hypothesized that the nanoparticles increased longevity by reducing the free radical damage to the biological system. Furhter, we are working on simulations of lattice parameters and electronic structure of nanoceria: The team had shown that formation of subsurface vacancies is sufficient to explain the expansion of lattice parameter with decreasing size of the ceria nanoparticles. The biofocus team has discovered that nanoceria can catalyze SOD activity *in vitro*, and have been working to understand the molecular mechanism of this radical scavenging property of the material. Catalytic activity of nanoceria with higher level of $Ce^{3+}$ was shown to be superior in our preliminary work (Patent Pending). Finally the team in collaboration with U of Oklahoma has made significant contributions in preventing retinal degeneration. In one of the recent studies using albino rat *in vivo* light damage model, it has shown intravitreal administration of nanoceria in rat retina can prevent the damage of photoreceptors (1 patent issued, 1 Patent Pending).The team have shown that nanomolar concentrations of $CeO_2$ NPs in serum-free cell culture media is effective in scavenging free radicals to reduce damage to neurons in the model system. We have also found that the co-existence of both $Ce^{3+}$ and $Ce^{4+}$ oxidation states in $CeO_2$ NPs plays a critical role in its antioxidant behavior. Experimental data have shown that the reversal of oxidation state also continues over time in cell culture and therefore $CeO_2$ NP acts as a catalyst.

These can be a new version of regenerative nanomedicine and open an entirely new field of rare-earth based nanomedicines. Millions of people suffer from neurodegenerative disease including macular degeneration. Our current multidisciplinary combined with engineers and scientists have created novel nano-rare earths with regenerative capability in scavenging radicals and protecting mammalian cells. The research will train students from engineering, simulation and biomolecular eated unique partnership between University of Central Florida and /

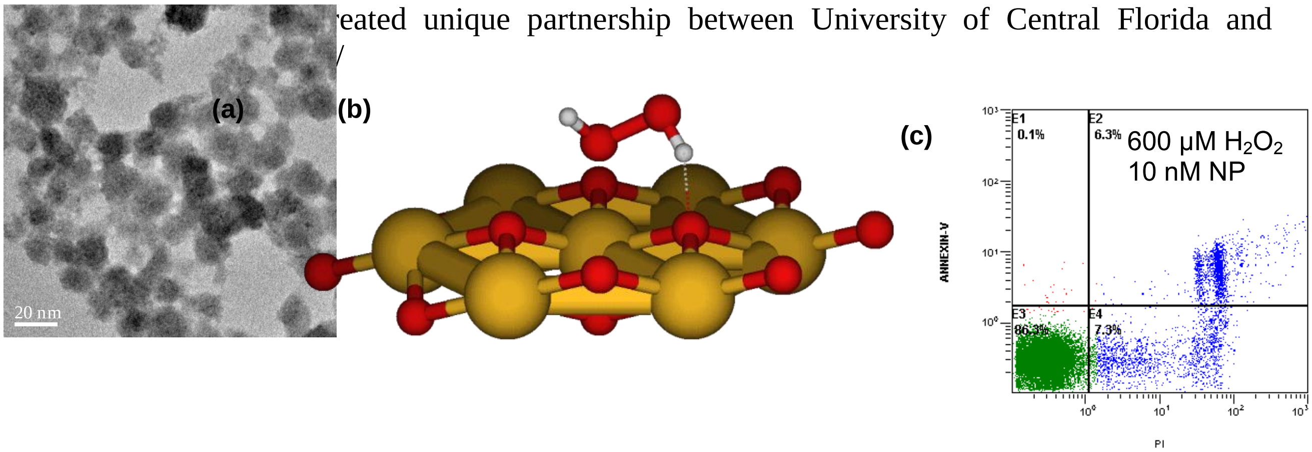



**Fig Highlight: (a) Engineered multivalent states in 5 nm ceria particles. (b) Ce – brown, O – red, H – white. First-Principle geometry optimizations of atomic clusters Ce7O14+H2O2 simulating hydrogen peroxide chemisorbed on the NP (111) oxygen-terminated surface used Density Functional Theory (BMK exchange-correlation functional) with Gaussian basis set and Effective Core potentials – showing the potential for SOD mimetic activity, (c ) Cerium oxide nanoparticles significantly decrease RPE cell death induced by hydrogen peroxide (600 micromolar concentration.**

This research successfully bridges nano and biotechnology, engineering, and molecular medicine to address the potential cure for glaucoma. The broader impact of this research is in the discovery of the novel regenerative rare earth nanomedicine using bioactive nanostructures. The highly multidisciplinary environment involves engineering, biomedical science, nanoscience and college of medicine researchers and provides a valuable research environment for undergraduate, graduate students, and postdocs. Furthermore, the research is integrated into undergraduate courses in nanoscience and technology. All the PIs will use material generated in this project as case studies to illustrate key concepts in materials engineering, chemistry, and nanotechnology and molecular medicine.

Almost 3 Million people from USA suffer from Glaucoma, and this research has potential solutions to understand and development of disease prevention, which can help to reduce medical cost and improve lives. Thus the science has enormous potential impact in creating regenerative nanomedicine using active nanostructures.

**The research is tranformatory because of the following key reasons:**

1. Potential treatment to prevent blindness using nanoparticles, prevention of neurodegeneration, hereditary blindness and macular degeneration – extending to Biomedical applications
2. Stability of nanoparticles as a function of aging contributing to the Colloidal science
3. SOD mimetic activity found in inorganics – e.g., nanoceria for the first time.
4. Atomic-level details of SOD mimetic activity as a function of nanoparticle aging and chemistry.
5. Development of regenerative nanomedicine
6. Providing valuable multidisciplinary training male and female students including minorities.

# Optics on a Nanoscale Using Polaritonic and Plasmonic Materials

*NSF NIRT Grant 0709323*

PIs: **Andrey Chabanov[1], Federico Capasso[2], Vinothan Manoharan[2], Michael Spencer[3], Gennady Shvets[4], Christian Zorman[5]**
[1]University of Texas-San Antonio, [2]Harvard University, [3]Cornell University, [4]University of Texas-Austin, [5]Case Western Reserve University

The goal of this project is to develop a novel approach to coupling optical energy to the nanoscale. Light diffraction prevents confinement of light in the regions smaller than half a laser wavelength, impeding the development of future nanophotonic devices and limiting future nanoimaging applications. Surface polaritons (phonons or plasmons), on the other hand, can have wavelengths that are orders of magnitude shorter than in vacuum. Thus plasmonic/ polaritonic components (waveguides, membranes, ultra-sharp tips) enable us to achieve unprecedented focusing of optical energy that can address the needs of nanophotonics, nanomanufacturing, NEMS, nanoscale thermal source development, and nanofluidics. Exotic optical devices such a "superlenses" capable of resolving sub-wavelength features are also enabled by plasmonic/polaritonic materials. Our project brings several unique approaches to bear on this subject.

**First**, we employ phonon-polaritonic materials, such as SiC and $TiO_2$, for mid-infrared (mid-IR) super-resolution imaging, which could potentially revolutionize label-free detection of biological and chemical substances. Building upon our recent demonstration [1] of mid-IR superlens-enabled subsurface imaging through SiO2 substrate (**Fig.1**), our goal is to demonstrate mid-IR imaging through water, paving the way to *in vivo* imaging of nanoscale biological objects transported through nanofluidics channels.

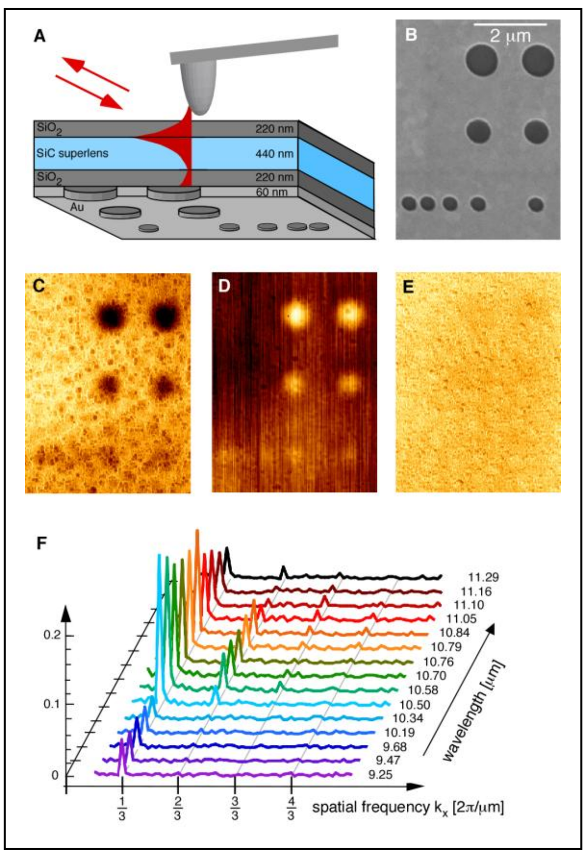



**Figure 1.** Near-field microscopy through a 880-nm thick superlens structure:

**A.** Sketch of the experimental setup.

**B.** Scanning Electron Micrograph of the object plane showing holes in a 60 nm thick Au film (1200/860/540 nm diameter).

**C.** IR amplitude map in the image plane at $\lambda$=10.85 μm, where superlensing is expected.

**D.** IR phase contrast map at $\lambda$=11.03 μm.

**E.** Control image of IR amplitude at $\lambda$=9.25 μm.

**F.** Fourier transforms of amplitude images of a grating. High spatial frequencies seen (up to the fourth diffracted order) are transmitted by the superlens at $\lambda$=10.84 μm.

**Second**, we take a significant step towards engineering liquid metamaterials, or *metafluids*, whose optical properties can be controlled by an external signal. Active control of optical and near-IR properties of water is demonstrated [2] by using a concept of Artificial Plasmonic Molecules (APMs) that are synthesized in emulsions and appropriately shaped to enable strong resonance response (**Fig.2**). Colloidal solutions of APMs can act as an optical medium with very large, small, or even negative effective permittivity and substantial effective magnetic permeability in the visible and near-IR spectral bands. This new metamaterials will be used as an actively controlled component in applications such as IR imaging and liquid-liquid waveguides that guide light owing to the change in both electric permittivity and magnetic permeability.

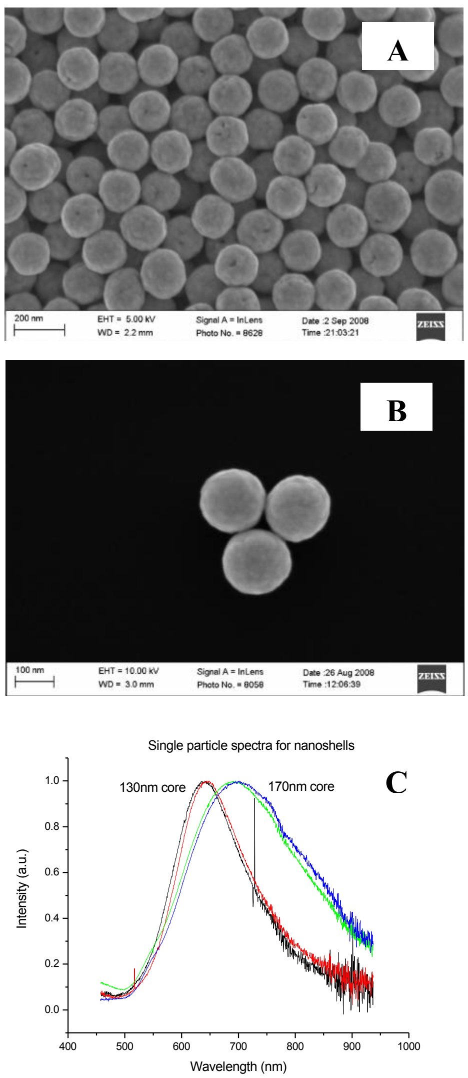



**Figure 2.** Artificial Plasmonic Molecules-based metafluid:

**A.** Silica cores are synthesized and functionalized with a silane linker. Gold nanoparticles are self-assembled onto the surface and gold shells with controllable shell thickness are created by electroless deposition

**B.** Gold 180-nm diameter nanoshells are assembled into trimers using capillary-force clustering or DNA-mediated adhesion

**C.** Single nanoshell absorption spectra of particles (130 and 170 nm core) are measured in air on a glass substrate

**Third**, we take advantage of the fact that SiC relies on the properties of its phonons to ensure its polaritonic properties. Therefore, there are no fundamental physical phenomena on a nanoscale that should prevent us from making SiC waveguides and tips as sharp as 10nm or less. This will result in incredible energy concentration at the tips and possibility of making active nanophotonic devices.

This research project brings together collaborators from several areas of physics and engineering who have complimentary strengths in synthetic chemistry and chemical engineering, materials science and growth, device physics, optical characterization, and computational modeling. Graduate students are involved in all stages of the project. We work with local university outreach offices to establish Mentorship Networks among minority students in the San Antonio/Austin area aimed at enhancing their interest and awareness of nanoscale science. Last summer we have organized first annual Nanoscience Summer School at Harvard for graduate and undergraduate students involved in the project research.

**References:**

[1] Taubner, Korobkin, Urzhumov, Shvets, Hillenbrandt, *Science* **313,** 1595, (2006).
[2] J Fan, D Aronzon, V Manoharan, and F Capasso, to be published.

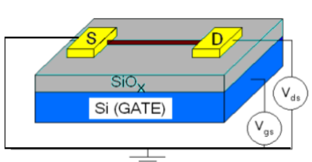
# NSF- NIRT: "Surface State Engineering"
# Charge Storage and Conduction in Organo-Silicon Heterostructures as a Basis for Nanoscale Devices

**John C. Bean (PI)[1], Avik Ghosh[1], Lloyd R. Harriott[1], Lin Pu[2], Keith Williams[3]**
[1]Dept. of Electrical and Computer Engineering, [2]Dept. of Chemistry, [3]Dept. of Physics
University of Virginia, Charlottesville Virginia

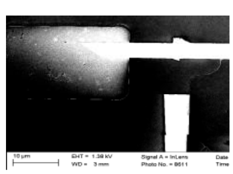
**Introduction:** Combining the lessons of molecular electronics with the needs of microelectronics, in this project we proposed the development of "Surface State Engineering." That is, we would attach organic molecules to silicon surfaces so strongly and intimately, that confined molecular electrons and free silicon electrons would be able to interact quantum mechanically. This could address the known statistical shortcomings of impurity doping processes in nanoscale FETs by offering the ability to fine tune electron transfer between molecule and Si. And, in the longer term, it would open the door to new devices based on quantum effects such as Fano and Kondo scattering, and on random telegraph signal phenomena. To achieve these goals, we proposed three enabling tools: 1) Modeling techniques that could realistically combine the very different physics of quantum dots and silicon layers; 2) Novel molecular self-assembly techniques that would allow for both molecular passivation and electrical activation of Si surfaces; 3) A quasi 1D Si on insulator FET structure that would serve both as a tool for molecular surface-state "fingerprinting" and as a device development platform.

**Strategy in the Project's First Year:** We anticipated that our complete e-beam lithography based device platform would take at least one year to fully develop. We therefore adopted a "concurrent engineering" strategy where one sub-team focused on fundamental modeling and characterization, while a second sub-team developed molecular self-assembly techniques on Si, while the third sub-team developed the complete nano Si FET device test bed.

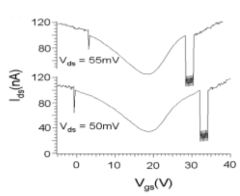
**a) Fundamental Modeling and Characterization:** This sub-team was driven by professors Ghosh and Williams. Ghosh's modeling strategy was to combine Density Functional Theory (for continuum Si electronic states) with Extended Hückel Theory (for confined molecular states) to model FET conduction within the framework of Non-Equilibrium Greens Functions. To provide up-front validation of this methodology, he analyzed prior data from Tour et al. [1] on "SURFET" devices. For a variety of molecules, he was indeed able to accurately model induced FET threshold voltage shifts in terms of molecular polarization and charge transfer.[2, 3]



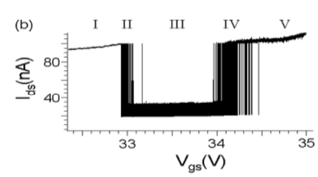

CNT FET Structure



CNT FET

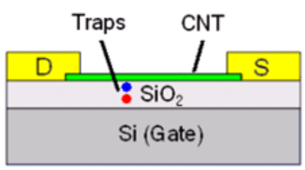



I-V



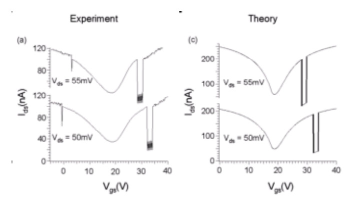

Enlarged overlapping RTS I-V

Williams and Ghosh then identified the shortest route to a testable quasi-1D FET as being one based on a single carbon nanotube (CNT). They developed such structures (as shown above left) and began testing these for Random Telegraph Signals (RTS). These signals occur when an available electronic level ("trap") occurs in close proximity to a quasi-1D FET device channel. In its charged state, that trap can act as a FET gate, pinching off channel conduction. As charge moves in and out of that level, FET conduction flickers, with the on-off duty cycle of that flickering depending on the local Fermi level position, which is in turn controlled by device gate, source and drain voltages. Analysis is straight-forward when only one charge-center/trap is active. But with molecules distributed along its channel, our proposed hybrid molecular-Si FET could easily have multiple active charge-centers/traps. This raised the question of whether molecular fingerprinting would still be possible in the presence of overlapping RTS signals. To answer this question, Williams and Ghosh were able to identify an anomalous overlap occurring in the signals of certain CNT FET devices (as shown above right). As shown below (left and center) they were able to model this as overlapping charge centers, producing excellent agreement between observed and modeled device I-V characteristics, reinforcing our plan to use interpreted RTS data our fundamental molecular "fingerprinting" tool.[4]

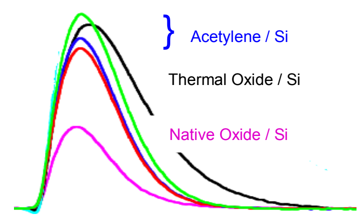



J.Chan *et al*, in review

Quasi 1D CNT FET with adjacent charge centers



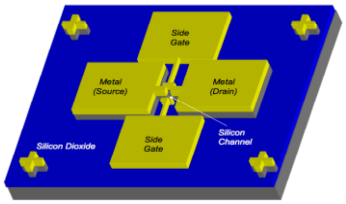

Successful comparison of experimental and modeled overlapping RTS signals



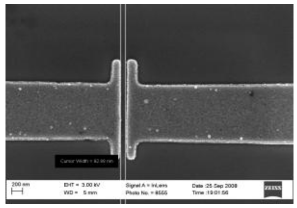

Pulsed photoconductance of Acetylene passivated Si

**b) Molecular Self-Assembly on Si:** In parallel, the sub-team led by professors Pu and Bean developed means of attaching highly pure, highly ordered molecular layers to Si. The approach was to use vacuum-based "hydrosilylation." In this approach, arriving molecules are terminated with a double or triple carbon-carbon bond which, under UV illumination will reduce in bond order, one carbon removing a hydrogen atom from the adjacent Si surface, freeing that Si atom for bonding with the second carbon. This process was validated through a number of techniques including attenuated-total-reflection FTIR and pulsed photoconductance. Photoconductance tested the crucial question of whether, after removing conventional $SiO_2$ passivating layers from Si surfaces, we could then restore inactivity solely based on molecular attachment. If this were achieved, surface recombination would be eliminated as a path for photo-induced minority carrier recombination, thereby extending photoconduction. As the data above right show, for hydrosilylated acetylene on Si we were indeed able to achieve pulsed photoconduction fully comparable to that of control Si samples passivated by state-of-the-art thermal oxidation. This sets the stage for the gradual substitution of the electrically active molecules as proposed in our 1D organo-silicon FETs.

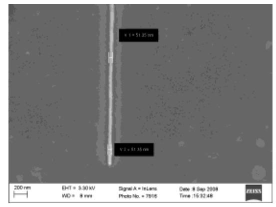
**c) Development of Nanoscale Quasi 1D Organo-Silicon FET**: For the development of the full quasi 1D silicon on insulator nano FET, professors Harriott, Bean and their students acquired and set up a new electron beam lithography system, and developed a device process based on double metal lift-off. The proposed structure (below left) incorporates not only a SOI backgate but also metal side gates on each side of the channel that can be used to further narrow the channel conduction path. Fabricated side gates with 92 nm separation are shown below at center left. Etched Si-on-insulator channels of both 50 nm and 29 nm width are then shown on the right. These components are now ready to be combined within the nano FET device test structure, which will then be available for full organo-Si device development.



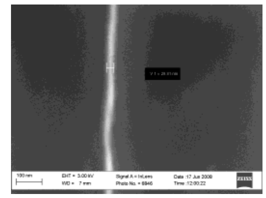

Quasi 1D SOI-FET



Side Gates w/ 92 nm separation



50 nm Si channel



29 nm Si Channel

**Education and Outreach** built upon earlier our NSF CCLI funded the "UVA Virtual Lab" science education website (www.virginia.edu) and our NSF NUE funded "Hands on Introduction to Nanoscience" class (www.virlab.virginia.edu/Nanoscience_class/Nanoscience_class.htm). That website has now accumulated over 4 ¼ million hits, and the combined projects led to PI Bean being named as the 2009 recipient of the IEEE Undergraduate Teaching Medal. In this NIRT project, those resources were combined with the expertise of the multi-site Science Museum of Virginia to develop nanoscience curricula for Virginia K-12 public schools. The highlight of this year's effort was a full class on "Teaching Nanoscience" taught for "southside" Virginia K-12 science teachers by Bean last August (for university credit), with ongoing activities continuing throughout this fall. Those activities included a successful partnership with Danville Community College to gain not one but two grants to fund their acquisition of STMs and AFMs as the foundation for building their own nanoscience AA degree program (to be modeled on the UVA NUE curriculum).

For further information about this project, contact John C. Bean: john-bean@virginia.edu

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[1] *Controlled Modulation of Conductance in Silicon Devices by Molecular Monolayers*, He, T.; He, J.; Lu, M.; Chen, B.; Pang, H.; Reus, W. F.; Nolte, W. M.; Nackashi, D. P.;Franzon, P.D.; Tour, J. M.; J. Am. Chem. Soc., 128, 14537-14541, (2006)

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[3] *Controlling transistor threshold voltages using molecular dipoles*, Smitha Vasudevan, Neeti Kapur, Tao He, Matthew Neurock, James M. Tour and Avik W. Ghosh
arXiv:0807.3378v1

[4] *Reversal of current blockade through multiple trap correlations*, Jack Chan, Brian Burke, Kenneth Evans, Smitha Vasudevan, Kamil Walczak, Mingguo Liu, Joe Campbell, Keith A. Williams and Avik W. Ghosh, submitted to Nature Nanotechnology

# NIRT: Photon and Plasmon Engineering in Active Optical Devices based on Synthesized Nanostructures

*NSF NIRT Grant ECCS-0708905*

**PIs: Marko Loncar[1], Mikhail D. Lukin[2], Hongkun Park[3,2]**

[1]School of Engineering and Applied Sciences, [2]Department of Physics, [3]Department of Chemistry and Chemical Biology, Faculty of Arts and Sciences, Harvard University

Our research focuses on the development of new class of light emitting devices that integrate state-of-the art nano-sized emitters with advanced structures for light localization. Our approach combines nanoscale light emitters synthesized bottom-up (as sources of photons) and optical structures fabricated top-down (for engineering propagation and control of photons and plasmons) to enable optical feedback and efficient coupling from nanostructures to optical fiber or free space. The central goals of our project include understanding of fundamental properties of light generation and control in active optical nanostructures, as well as development of novel devices and systems for optical and quantum information processing. We are also addressing important questions that pertain to complex nanostructures that incorporate bottom-up synthesis and top-down fabrication, including development of techniques and methodology to manipulate and position nanostructures and efficiently couple light in and out of nanostructures. Our work will enable the realization of robust, practical sources of single photons, nano-scale lasers, novel single photon switches, and methods for efficient light collection with sub-wavelength resolution. These devices and techniques are expected to have a wide variety of applications in the areas ranging from quantum cryptography and optical communications, to life sciences and advanced photolithography.

During the past year we focused on (i) efficient generation of surface plasmons via strong interaction between quantum emitters and proximal metallic nanowires (Figure 1), (ii) development of hybrid nanophotonic-plasmonic platform for efficient extraction of single-plasmons (Figure 2), (iii) direct electrical detection of surface plasmons using semiconductor nanowires (Figure 3), and (iv) design of photonic crystal cavities that operate in visible, suitable for coupling to nano-emitters. Our studies resulted in four publications [1-4], two manuscripts in preparation[5, 6], and number of conference talks.

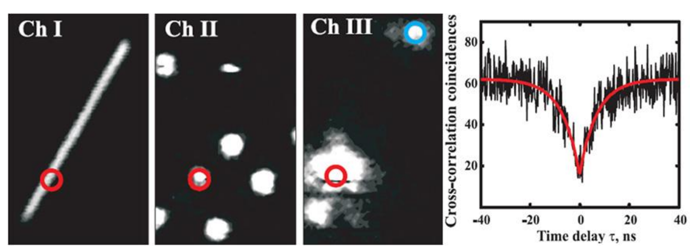


**Fig. 1.** Coupling of CdSe quantum dots to surface plasmons supported on Ag NW[1]. The leftmost panel shows a confocal reflection image of an Ag nanowire. ChII panel corresponds to a fluorescence image of quantum dots emitting at 655nm, while ChIII panel shows a coupled wire–dot system. The red circle corresponds to the position of the QD coupled to NW. The largest bright spot corresponds to the QD fluorescence, while two smaller spots correspond to SPs scattered from the NW ends. Blue circle indicates the end of the NW used for photon cross-correlation measurements shown in the right-most panel.

We developed a method to prepare a structure in which a crystalline Ag nanowire lies in close proximity to CdSe quantum dots, and used it to demonstrate a cavity-free, broadband approach for engineering photon-emitter interactions via sub-wavelength confinement of optical fields near metallic nanostructures. Specifically, coupled CdSe quantum dot/Ag nanowire samples were prepared by spin-coating a solution of chemically synthesized CdSe quantum dots (mixed with $Na_2B_4O_7$ and cysteine) onto a plasma-cleaned glass slide, followed by deposition of protective PMMA layer. A stamp with thiol-modified silver nanowires was placed on top of the slide leaving nanowires on the PMMA. Finally, another cap PMMA layer was deposited onto nanowires. Figure 1 summarizes our results and demonstrates that the single-photon emission of a quantum dot can be directed into guided surface plasmons in metallic waveguides: when the proximal quantum dot (circled in red) was excited by the laser, the nanowire ends lit up. The light emission at the nanowire ends is a result of single, quantized surface plasmons scattering off the ends of the nanowire. Results from a large number of devices show that efficient coupling is accompanied by more than a 2.5-fold enhancement of the quantum dot spontaneous emission.

In order to further improve the efficiency of our system, that is increase photon collection efficiency, it is important to minimize losses associated with propagation of surface plasmons and maximize photon out-coupling efficiency. The platform that we are developing, that combines nanophotonics and plasmonics, is shown in Figure 2. Owing to large density of optical (plasmon) modes associated with silver nanowire, quantum dot coupled to the nanowire emits single plasmons. Plasmons are then converted into photons via directional coupler formed between overlapping sections of the nanowire and $SiN_x$ waveguide. Finally, photons are coupled into tapered optical fiber using spot size converter made form polymer (SU-8 photoresist). Our system represents powerful interface between macro-world (optical fiber) and quantum world (quantum dot) that allows for strong interaction between light and matter by progressive reduction of the size of propagating optical field

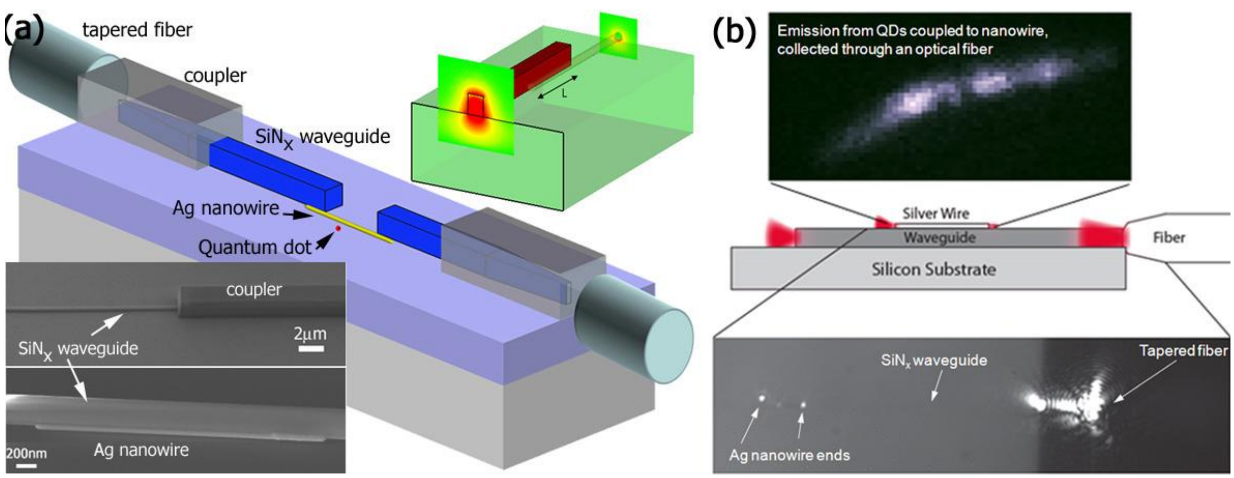


**Fig. 2.** (a) Schematic of the system used for efficient generation and extraction of single photons emitted from quantum emitters. Insets show fabricated structures as well as theoretical results for nanowire-waveguide coupler. (b) Experimental results.

The nanowire-waveguide coupler was optimized using three-dimensional finite-difference time-domain modeling, and efficiencies ~ 70% were obtained. The same method was used to design fiber-waveguide coupler resulting in efficiencies as high as 90%. The fabrication process that we used to realize our $SiN_x$ photonics platform that operates in visible consists of electron beam lithography and dry etching, followed by additional e-beam step to define fiber couplers (2μm thick SU-8 resist) at the end of tapered section of $SiN_x$ waveguides. Finally, bottom-up synthesized Ag nanowires are positioned next to the waveguides. Using this platform and tapered optical fibers we were able to efficiently launch light into silver nanowires. Alternatively, by exciting quantum dots coupled to Ag nanowire, using an additional objective lens, we were able to collect the emission from these quantum dots through tapered optical fibers (Figure 2). We are presently investigating emission properties of single quantum dot coupled to Ag nanowire in order to realize efficient room temperature source of single photons.

In this grant period, we have also started to work on the demonstration of plasmon detection using near-field detectors incorporating semiconductor nanowires. Figure 3 shows the preliminary data obtained from a device that is composed of an Ag nanowire in contact with a Ge nanowire plasmon detector. As it can be seen, the Ge nanowire detector exhibited a measurable current when a laser light was coupled to the end of the Ag nanowire, indicating that plasmons propagating in the Ag nanowires causes the electron-hole pair generation within the Ge nanowire. This initial result demonstrates that the electrical detection of plasmons is indeed feasible and points to the exciting possibility of generating a compact, on-chip quantum photonic/plasmonic circuit.

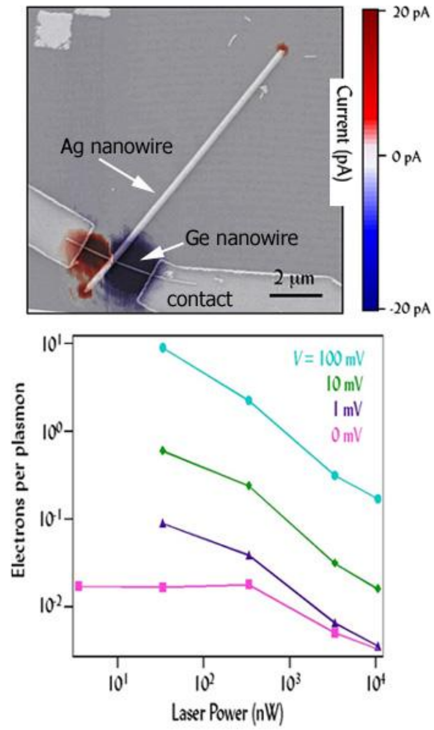


**Fig. 3.** Composite image: SEM micrograph and detected current when laser beam is scanned across the structure. Red spots on Ag nanowire ends correspond to 20pA current signal when laser is focused on Ag nanowire ends. Efficiency as high as 10 electrons per plasmon can be obtained under bias. . The intrinsic gain mechanism is due to transiently trapped charges modulating the conductivity of the Ge nanowire.

In addition to strong research component, our interdisciplinary team provides powerful educational opportunities for students in our groups, by exposing them to a broad collaboration that encompasses theoretical calculations, nanostructure synthesis, and device design, fabrication and characterization. Our team holds bi-weekly meetings where we discussed our interdisciplinary research that spans physics, chemistry and engineering. We have also organized several seminars in the general area of nanophotonics/ plasmonics. The team members have all been actively involved in the science and engineering outreach efforts at Harvard by giving public lectures, mentoring high school students and working with high school teachers through NSF supported Research Experience For Teachers Program.

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**Synthesis, Actuation and Control of Single-Molecule Nanocars**

*James Tour, Anatoly Kolomeisky, and Kevin Kelly*

NSF Award 0708765

The objective of this research is to develop external electronic and optical methods for controllably imaging, sensing, propelling and actuating nanocars and nanotrucks and to devise theoretical models for predicting the motion and output from these diminutive structures. The approach is to synthesize new nanocar entities that are suitable for rolling motion and susceptible to electronic manipulation, imaging using a host of microscopies and devising theoretical models for predicting the mechanisms, range of motion and work output extractable from truly nano-sized single-molecule machines.
Intellectual merit:Transport of goods and materials between points is at the heart of all engineering and construction in real-world systems. As researchers delve into the arena of the nano-sized world, it beckons that they learn to manipulate and transport nanometer-scale materials in a similar manner. This proposed work outlines a method to control the motion of nanocars at the nanoscale level, and thereby pave the way for future bottom-up nanoscale construction.

Broader Impact: The research plan outlined above will be leveraged with education and outreach efforts using the NanoKids program, thereby multiplying this program's impact on grades 6-12 students and teachers, undergraduate students, graduate students, and traditionally underrepresented groups in the sciences and engineering. This uses the attractiveness of nanoscale science to introduce fundamental concepts in chemistry, physics and biology including how those concepts eventually make their way into the marketplace thus impacting everyday life. Funding this work will provide a path to future construction while laying groundwork for education from middle school to post graduate studies.

# Active Nanostructures with Giant Piezo-Response

*NSF NIRT Grant ECCS-0708759*

PIs: **Chang-Beom Eom[1], Robert Blick[1], Mark S. Rzchowski[1], Darrell G. Schlom[2], Long-Qing Chen[2], Xiaoqing Pan[3], Vladimir Aksyuk[4]**

[1]University of Wisconsin-Madison; [2]Penn State University; [3]University of Michigan;
[4]Bell Laboratories, Lucent Technology

Major challenges are emerging as electromechanical systems move to the nano-scale (nanoelectromechanical systems, or NEMS), with an integration density that demands faster and larger relative motion range. Our recently developed giant piezoelectric epitaxial thin-films directly on silicon can drastically increase the motion range and speed, with even potentially greater response by using engineered nanoscale strain distributions and domain structures. We will integrate epitaxial thin film heterostructures of giant piezoelectric materials directly on silicon (see Figure 1) to make *hyper*-active nano-electromechanical systems. These heterostructures are compatible with silicon nanofabrication processes, can be integrated with silicon-based electronics, and have large enough response to revolutionize active NEMS actuators. This research will develop a fundamental scientific understanding of nanoscale piezoelectric phenomena in active nanoscale electromechanical devices, with applications in high performance signal processing, communications, sensors, and nano-positioning actuators. The relationship between piezo-response and nanoscale strain and domain configurations developed here can be applied to multifunctional materials to develop new NEMS devices.

This research will resolve the fundamental issues that control nanoscale performance of piezoelectric materials in NEMS devices. Future generations of NEMS devices enabled by this research are likely to find wide-ranging applications and bring technological advances to many parts of society. Our **Education** goal is a broad experience for all students. This includes first-year student rotation through research groups, working in international and industrial laboratories, research interactions with individuals of diverse backgrounds, and participating in outreach programs. In **Outreach**, secondary school science teachers from Mayagüez, Puerto Rico will be brought to UW-Madison each summer for a nanotechnology learning/research experience. They will develop classroom material in both English and Spanish, and put in place programs for implementation secondary schools across the country. Graduate students will be involved as mentors to the teachers.

**References**

[1] For further information about this project email **<eom@engr.wisc.edu>**

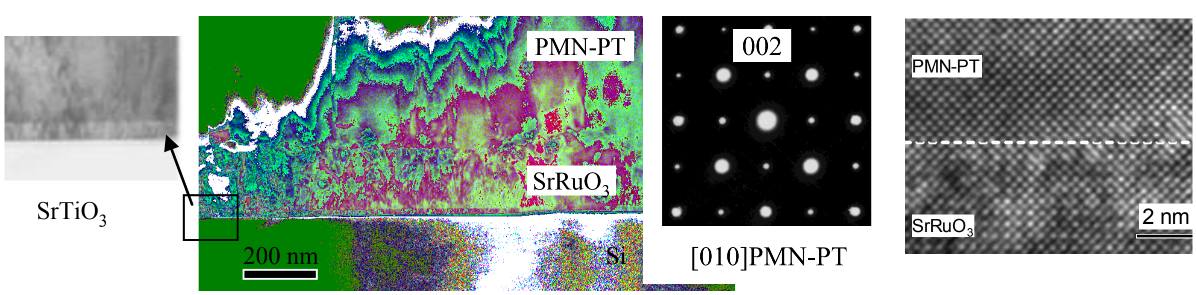


Figure 1: (a) Cross-sectional TEM micrograph, (b) selected-area electron diffraction (SAED) pattern of giant piezoelectric $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ (PMN-PT) layer, and (c) high resolution image at the interface between PMN-PT and $SrRuO_3$ of PMN-PT/$SrRuO_3$ thin film heterostructures on $SrTiO_3$/Si substrate.

**Molecular Electronic Devices with Carbon-based Electrodes on Active Substrates**

*Colin Nuckolls, Kenneth Shepard, Qiao Lin, Philip Kim, and Matthew Francis*

NSF Award 0707748

The objective of this research is to develop a new class of nanoscale biosensors based on molecular electronic devices that utilize carbon nanotube and graphene-based electrodes. The approach centers around using chemistry to incorporate biological macromolecules as recognition domains on molecular bridges and to further develop these molecular-electronic devices as sensors. These biosensors will be fabricated on active complementary metal-oxide-semiconductor microelectronic substrates to provide true single-molecular sensitivities with potentially submicrosecond temporal resolution.

The intellectual merit of the proposed effort is centered on the sensitivity and specificity that can be achieved using this approach. Because these sensors do not rely on temporal or ensemble averaging to achieve sensitivity, they monitor individual events at a true single-molecule level, providing measurement of rich stochastic dynamics of probe-target interactions. In particular, the research effort involves new scientific investigations involving nucleic acid hybridization, protein-protein interactions, and protein conformation changes with single-molecule sensitivity, yielding new insight into processes such as folding and catalysis. These highly integrated devices will have broad practical application in medical diagnostics (genomics and proteomics), drug discovery, and environmental monitoring.

This integrated program of research and education has broad impact in training graduate and undergraduate students in a cross-disciplinary research environment. The research has broad impact to a range of science and technology including medicine, pharmacology, semiconductors, homeland security, and environmental monitoring. Significant effort will be made for K-12 outreach by systematically training highly motivated high school students within the program and also enhancing the interaction with local K-12 educators.

# NIRT: Chemically Directed Surface Alignment and Wiring of Self-Assembled Nanoelectrical Circuits

*NSF NIRT Grant CBET0708347*

PIs: **J.N. Harb[1], A.T. Woolley[2], R.C. Davis[3], M.R. Linford[2] and D.R. Wheeler[1]**
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## Introduction

The goal of this project is to create nanocircuits by self assembly of circuit templates in solution followed by chemically directed surface placement and metallization of circuit templates and active elements. To accomplish this goal, an interdisciplinary research group, ASCENT (ASsembled nanoCircuit Elements by Nucleic acid Templating), has been formed at Brigham Young University. Research efforts have been focused on the development and refinement of four key technologies: (1) solution-phase assembly of structures and templates, (2) high-resolution chemical surface patterning, (3) high-precision metallization of molecular templates, and (4) chemically-directed assembly and integration of nanostructures on surfaces as described below.

## DNA Circuit Templates

We are assembling DNA into designed structures for nanoelectronic circuit templates. We use DNA origami[1] to fold molecules into predetermined shapes by means of many short, complementary "staple" strands that hybridize to a longer, single-stranded "scaffold" piece of DNA and hold it in a designed structure. After being assembled in solution, the molecular templates will be chemically directed into place on a surface and metallized.

We have carried out initial DNA origami work to design an 11 nm X 64 nm rectangular motif (Figure 1a). We have assembled these DNA nanostructures and characterized them by atomic force microscopy (AFM), as indicated in Figure 1b. We are presently focusing on methods for high-yield scaffold strand generation, and the extension to more sophisticated DNA origami designs.

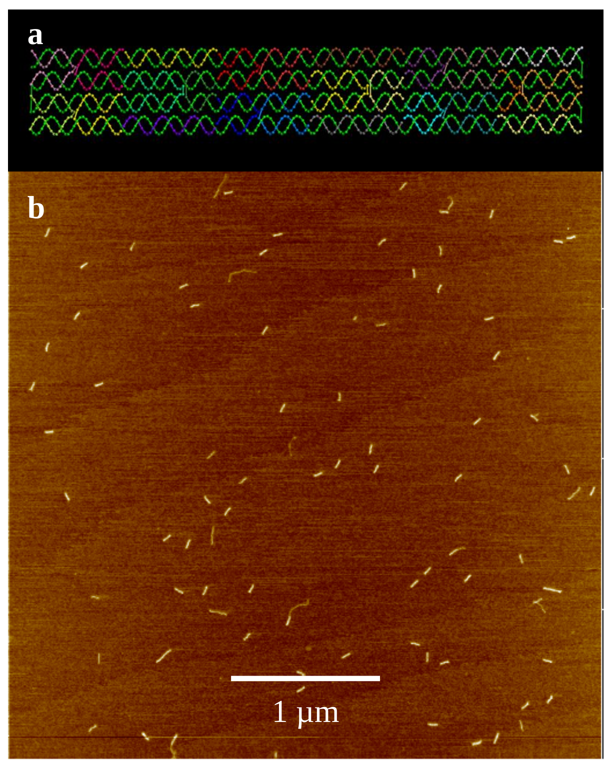


***Figure 1.** (a) DNA origami model showing individual pieces of DNA as different colors. (b) AFM image of the assembled DNA origami in (a); height scale is 4 nm.*

## High-resolution Chemical Surface Patterning

Nanoscale chemical surface patterning is needed both as a path for nanowire plating and as an anchor for the placement of DNA templates. We are exploring several different methods of chemically patterning the surface including polymer nanografting, chemomechanical patterning and self assembled layers. In polymer nanografting a positively-charged polymer is attached by electrostatic interactions to a silane monolayer on an oxide surface. We then use an AFM tip (NSC12/Pt50/AlBS, Mikromasch) to scribe off the original polymer (see Figure 2), and deposit a fluorescently-tagged polymer on the surface. With this technique, we were able to generate box and line patterns in the positively-charged polymer, the smallest lines having a half-pitch of 12nm (Figure 3).

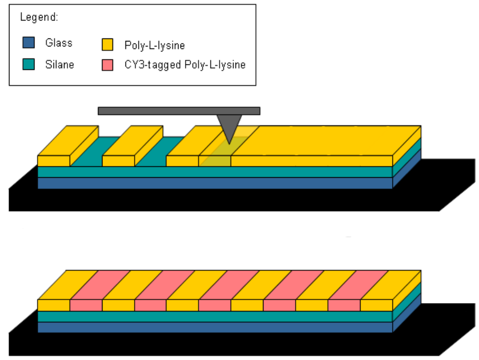


***Figure 2.*** *Polymer nanografting.*

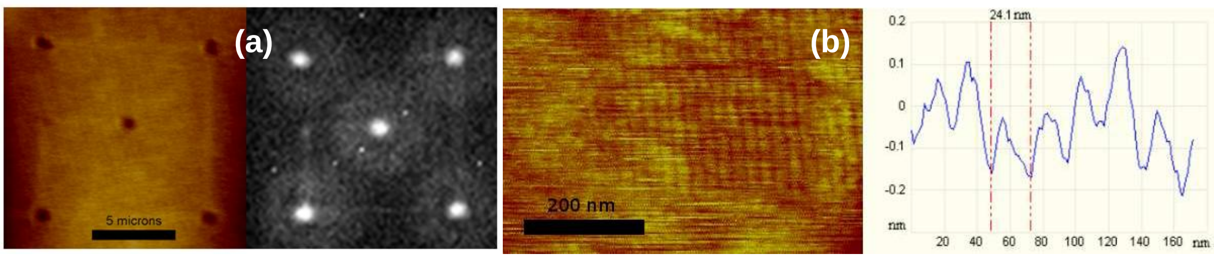


***Figure 3.*** *(a) Tapping-mode AFM height image (left) and fluorescence micrograph (right) of a five dot pattern. The faint rings around the dots in the optical image are imaging artifacts; (b) Tapping-mode image of scribed lines with half-pitch of 12nm.*

A similar procedure has been used to pattern an aminopropyltriethoxysilane (APTES) monolayer by depositing polystyrenesolfonate (PSS) on the monolayer and then nanoshaving with AFM. The resulting lines were metalized with copper via electroless plating.

Self-assembled gold nanodots have also been formed as possible anchors for molecular circuits. A poly(styrene-b-2-vinylpyridine) block copolymer in toluene forms micelles which preferentially adsorb a gold salt when it is added to the solution.[3] A monolayer of the loaded micelles is then deposited in a hexagonal array on a clean oxide surface by dip coating. A subsequent oxygen etch removes the polymer and leaves bare gold nanoparticles on the substrate (Figure 4). A procedure for chemical functionalization of the gold nanodots is being developed to facilitate alignment and placement of the molecular circuit templates.

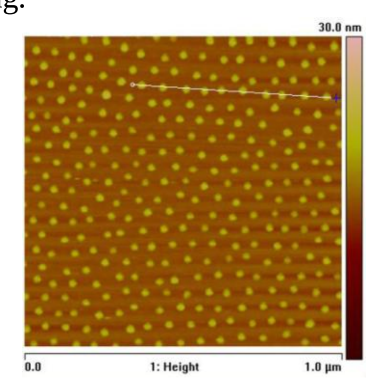


***Figure 4****. Gold nanodots formed from a self-assembled micelle array.*

## Metallization

Our aim in this area is to provide selective, continuous metallization of DNA templates for the formation of nanoelectronic devices and connection of those devices to other circuit elements. Both wet electroless plating and vapor phase deposition has been examined. The electroless plating chemistry that produced the best results was a silver chemistry that was adapted from the literature.[2] Figure 5 shows highly selective plating that is nearly continuous. Efforts are underway to understand the influence of plating variables such as bath composition, temperature,

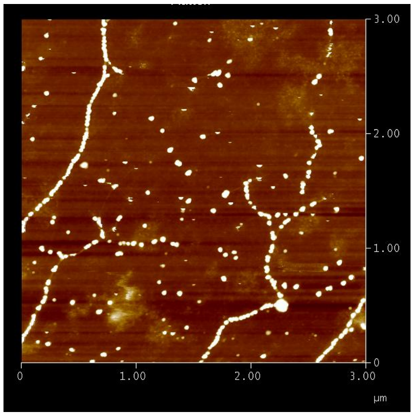


*Figure 5: AFM height image of silver nanowires formed on DNA templates.*

and additives on the selectivity and continuity of the deposits. Experiments with additives for palladium plating have examined the effect of mercaptopropane-sulfonic acid (MPS), propanedisulfonic acid (PDS) and sulfanilic acid (SA). Plated samples that had been treated with these additives were analyzed with XPS to determine if there was acceleration of metallization on the surface. Initial results are encouraging and show that the use of accelerating additives may provide a means of improving continuity. The most effective additive to date for Pd plating was SA.

We are also exploring gas-phase DNA metallization as an alternative method for improving selectivity. Our approach involves exposure of aligned DNA on surfaces to organometallic compound vapor at elevated temperatures. AFM data showed selective metal deposition on DNA strands for a model Ni(acac)$_2$ system, as illustrated in Figure 6. Future work will entail optimization of the metallization process through improved control of temperature and the generation of organometallic compound vapor.

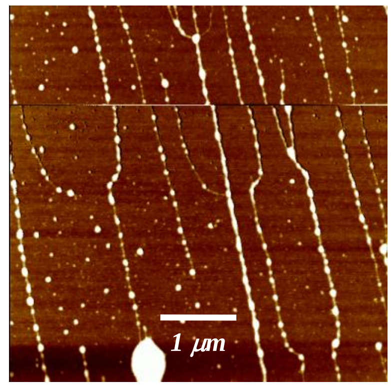


***Figure 6.*** *AFM images of DNA deposited on a silicon surface and exposed to Ni(acac)$_2$ for 5 min at 180 ºC; height scale is 10 nm.*

## Directed Assembly and Integration of Nanostructures on Surfaces

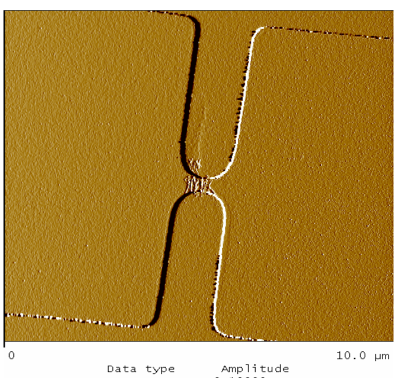


***Figure 7.*** *Carbon nanotubes placed between two electrodes by dielectrophoresis.*

Efforts in the area of assembly and integration have been focused on carbon nanotube alignment and selective placement in nanowire gaps. E-beam patterned structures have been used for the work to date, although smaller metallized molecular circuit templates will eventually be used. After separation, semiconducting nanotubes are placed in the narrow gaps by dielectrophoresis (Figure 7). The process has been optimized to the point that we have been able to deposit one or two nanotubes per gap simultaneously for multiple structures.

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**NanoManufacturing and Analysis of Active Hierarchical Nanofilamentary Nanostructures**

*Yuris Dzenis, Xiao Cheng Zeng, Joseph Turner, and Qiming Zhang*

NSF Award 0709333

The research objective of this Nanoscale Interdisciplinary Research Team (NIRT) project is to develop and study novel hierarchical nanofilamentary materials and structures based on active continuous nanofibers. Ferro/piezoelectric materials represent a technologically important class of active materials and ferro/piezoelectric fibers and fiber-reinforced composites have distinct advantages for applications. However, current manufacturing techniques result in thick fibers with diameters in the tens to hundreds of microns leading to their poor processability and mechanical properties. In this project, hierarchical nanofilamentary materials and structures based on novel active continuous nanofibers will be nanomanufactured, studied, and developed. The project will build on the recent discovery of a nanomanufacturing technique capable of producing nearly perfectly aligned and dense bundles and yarns of continuous nanofilaments. Nanomanufacturing method will be further developed and optimized to produce hierarchical nanofilamentary structures from ferro/piezoelectric ceramic and polymer nanofibers. Mechanical and physical properties of these novel materials will be characterized and correlated to their multiscale architecture. Multiscale modeling and analyses will be performed and used to understand their behavior and to correlate it with their structure and processing parameters. This research will have impact on nanomanufacturing, characterization, and modeling of active materials, nanofibers, and nanofiber assemblies and composites. This project will further advance our knowledge and understanding of nanofiber nanomanufacturing and behavior. Continuous nanofiber technology is attracting rapidly increasing interest in many fields and industries. The new materials and nanomanufacturing methods to be developed in this project will be used in a broad variety of applications. Educational component includes multidisciplinary research training of several PhD students and development of relevant new courses. Societal and ethical issues associated with nanomaterials research will be also explored in conjunction with the nanomanufacturing, characterization, and modeling research.

# NIRT: Composition Graded, Epitaxial Oxide Nanostructures: Fabrication and Properties

*NSF NIRT CMMI -0709293*

PIs: **Efstahios I. Meletis**[1], **Jiechao Jiang**[1], **Chonglin Chen**[2], **Amar S. Bhalla**[2], **and Gemunu Gunaratne**[3]

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**Introduction and Objectives:** Perovskite oxides are of enormous fundamental interest and technological importance due to their intriguing properties which can be tailored for a wide range of applications in magnetic, magnetoelectronic, photonic, and spintronic technology. Such oxides have been synthesized in the past in bulk form or as thin films. Compositionally gradient thin films and nanostructures of these oxides are expected to offer enormous opportunities to explore intriguing physics and applications. However, major challenges exist in the synthesis of such structures since their fabrication by self-organization has not yet been attempted. Recently, we achieved fabrication of ordered arrays of coherent, orthogonal one-dimensional epitaxial (La, Sr)$MnO_3$ nanopillars on (001) $LaAlO_3$ substrate by pulsed-laser deposition (PLD), which to the best of our knowledge, has been the first report on the fabrication by self-organization of such epitaxial oxide nanopillars. The formation of the nanopillars depends strongly on the processing temperature and oxide composition. Such nanopillars exhibit novel magnetic properties different from those of their bulk, thin film, or nanoparticle counterparts. This research focuses on fully exploiting the enormous potential of these self-organized nanostructures by adding a novel and challenging dimension to their nanomanufacturing: to fabricate such nanopillars with a high perpendicular anisotropy arising from variation in composition, either continuously (graded) or discretely (composite, modulated layers) using PLD and investigate the effects of processing and material parameters on their formation by self-organization; to characterize their magnetic properties and morphological, structure and interface structures using newly developed HRTEM

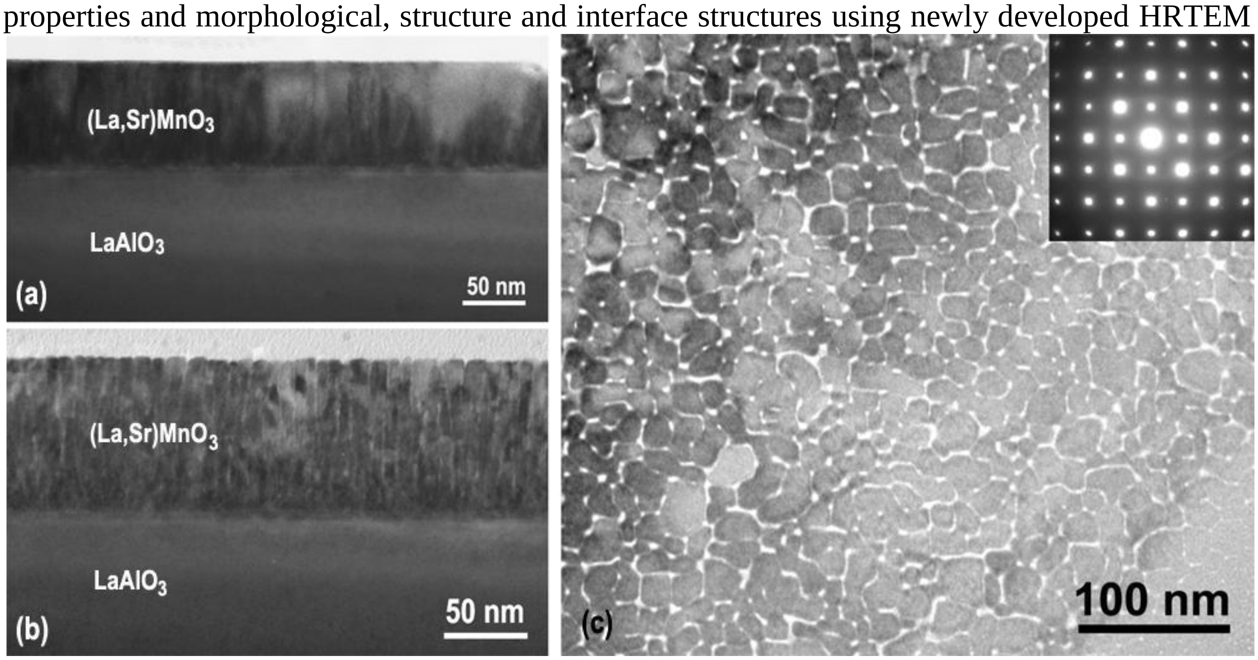


**Figure 1.** XTEM image of epitaxial (La,Sr)$MnO_3$ continuous film (a) and nanopillars (b) on (001) $LaAlO_3$ substrate. (c) Plan-view TEM of epitaxial (La,Sr)$MnO_3$ nanopillars.

methods [1,2] and other complementary analytical techniques; to perform finite element modeling and physical property (ferroelectric, piezoelectric, ferromagnetic, ferroelastic, etc.) measurements on designed new ferroic composites and to conduct theoretical modeling of the self-organization process in conjunction with the experimental findings.

**Results:** We have systematically investigated the effects of processing parameters (temperature, pressure, laser energy and frequency) during deposition and post-annealing on the formation of epitaxial (La,Sr)$MnO_3$ continuous films and nanopillars. We are able to fabricate (La,Sr)$MnO_3$ continuous epilayer (Fig. 1a) and discrete epitaxial nanopillars (Figs. 1b and c) by manipulating the experimental conditions and parameters and confirmed the repeatability for achieving a variety of designed nanostructures. A roadmap for fabricating various distinct epitaxial nanostructures has been established. Knowledge obtained from these series of investigations is used for theoretical modeling for precisely controlling and predicting the formation of the nanopillar structures. Structures formed during the growth of an epilayer on a substrate are determined by minimizing the energy of the configuration, which consists of (i) elastic energy of the epilayer, due to the requirement that it be commensurate with the substrate, (ii) the surface energy of the epilayer, and (iii) the wetting potential [3]. We assume that the substrate lattice is unchanged, and hence that there is no associated energy. The spatio-temporal dynamics of the epilayer is typically described using the evolution of its height h(x,y) via

$$\frac{1}{\sqrt{1+|\nabla h|^2}}\frac{\partial h}{\partial t} = \mathcal{D}\nabla_S^2\left[\mathcal{E}(h)+\gamma\kappa+\Phi\right]$$

where the diffusion is along the surface h(x,y) [3]. Unfortunately, the expressions for the terms on the right (the free energy density, curvature, wetting energy etc.) in terms of h(x,y) and its derivatives are very complicated. The analysis can be simplified by using the "small slope" expansion, which will be valid close to the Stransky-Krastonow instability, where the homogeneous solution destabilizes to a patterned array [4]. Under these conditions, the previous equation reduces to

$$\frac{\partial h}{\partial t} = g\nabla^2 h + \nabla^4 h + \nabla^6 h + \nabla^2\left[h\nabla^2 h + p(\nabla h)^2 + qh^2\right]$$

In deriving this equation, we have scaled h(x,y) by the height L at which the homogeneous layer destabilizes. The control parameters L, g, p, and q can be evaluated n terms of the mechanical parameters of the substrate and the epilayer.

Under the model dynamics, a uniform (but noisy) deposition of atoms on a substrate gives self-assembled quantum-dot arrays. In order to form large-scale perfect arrays, we use a technique that we proposed previously; namely masking of the deposition [5]. Properties of the mask can be determined from the spatio-temporal dynamics of the formation of a disordered pattern in the absence of the mask [5]. Figure 2 shows such a large-scale ordered quantum-dot array.

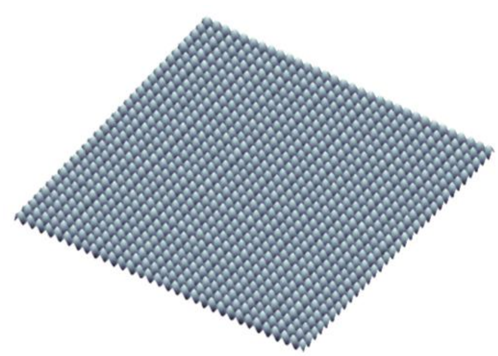

**Figure 2**. Ordered quantum-dot array.

We also recently identified non-lead ferroelectric material, Barium titanate ($BaTiO_3$) and its modified materials, such as (Ba, Sr)$TiO_3$ and Ba(Zr,Ti)$O_3$, based thin films as another counterpart for the composition graded nanostructures. These thin films exhibit high dielectric constant, relatively low dielectric loss tangent and large electric field tunability that have attracted considerable attention for dynamic random access memories (DRAM), bypass capacitors, IR detectors, and tunable microwave applications in tunable filters, phase shifter, antennas, etc. We have recently successfully fabricated "microstructure" graded $Ba(Zr,Ti)O_3$ thin

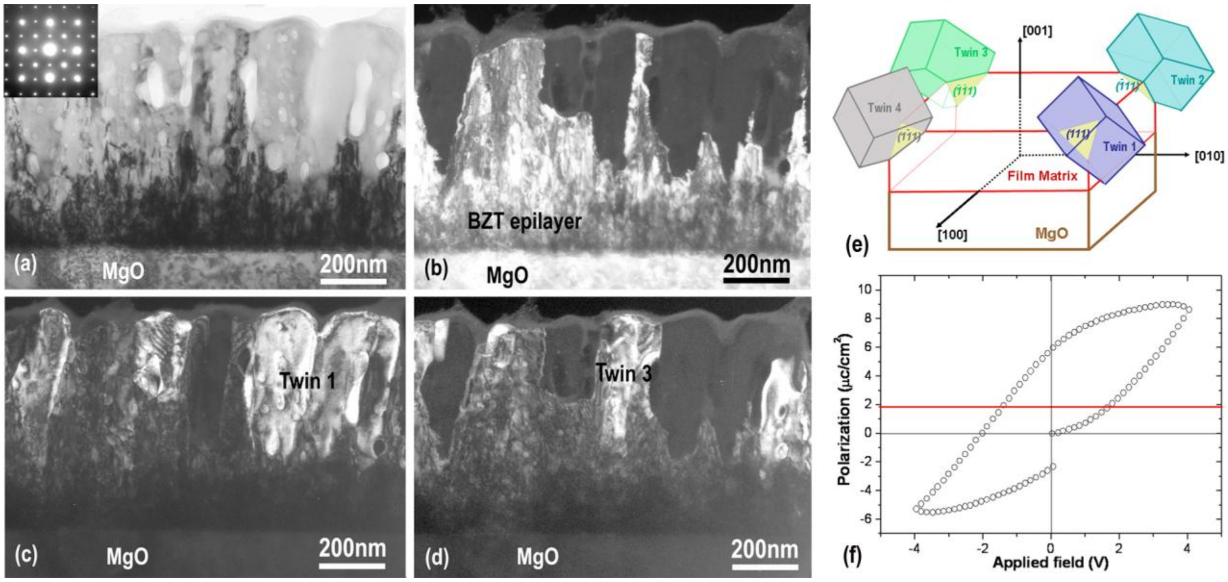


**Figure 3.** XTEM image of twin-coupled structure on epitaxial $Ba(Zr,Ti)O_3$ film on (001) MgO substrate. (a) bright-field image, (b), (c) and (d) dark-field images showing presence of BZT epilayer and two twins, (e) schematic illustration showing coexistence of the twins with the epilayer, (f) hysteresis loop measurement of BZT film exhibiting interesting abnormal properties due to the formation of the twins in the films.

films on (001) MgO substrate (Figs. 3a-d). $Ba(Zr,Ti)O_3$ thin films were first epitaxially grown on the substrate. On the top of the $Ba(Zr,Ti)O_3$ epilayer, multi-oriented twins were formed by sharing their {111} planes with the epilayer, as schematically illustrated in Fig. 3e. Such microstructure graded thin films show interesting abnormal ferroelectric properties (Fig. 3f) that do not exist in their bulk counterpart.

We expect that this synergistic effort will yield new fundamental knowledge on self-organization of 1-D, epitaxial oxide nanostructures with graded composition. Variation in chemical composition opens up various new possibilities of designing new multiferroic nanoscale structures with unusual cross coupled properties.

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**Hierarchical Manufacturing and Modeling for Phase Transforming Active Nanostructures**

*Dimitris Lagoudas, Kenneth Gall, Ibrahim Karaman, Jun Kameoka, and Xinghang Zhang*

NSF Award 0709283

This proposed research was submitted in response to the Active Nanostructures and Nanosystems initiative, NSF 06-595, category NIRT. Active nanoscale structures and nanosystems capable of actuation and sensing are needed for a wide range of applications in nanomedicine, nanoelectronics, space exploration, homeland security and defense. An integrated team of co-PIs from Texas A&M University and Georgia Tech proposes, as a combined research effort, a comprehensive interdisciplinary program in hierarchical manufacturing and modeling for phase transforming magnetic shape memory alloys (MSMA).

Technical: The main goal of the proposal is to establish a hierarchical framework that will combine the fabrication of MSMA nanolayers with the extrusion of nanowires. These monolithic and hybrid nanowires will then be used in the fabrication of fibers, by coaxial electrospinning, to be used as devices that can be activated by temperature, stress, and remotely by magnetic field. The first level of nanomanufacturing will focus on thin films, composed of nano to micron size layers of conventional shape memory alloys (SMA), magnetic materials and MSMA using magnetron sputtering. Thin films will then serve as precursor for nanowire fabrication by using a cost effective hydraulic pressure extrusion technique. The higher level nanomanufacturing will involve the use of a novel coaxial electrospinning whereby nanowires will be aligned in selected matrices such as silica for the purpose of making biosensors, remotely controlled nano/micro actuators, and active mesoporous ductile membranes. To support the nanomanufacturing effort, selective multiscale modeling will involve atomistic simulations to address phase transformation phenomena at nanoscale, and microstructural mechanism-based continuum level constitutive models to address the functionality of the nanostructures and nanodevice behavior.

Nontechnical: The proposed research will attempt to develop a multilevel fabrication methodology for nanowires with combined shape memory and magnetic properties. This hierarchical fabrication methodology will be assisted by a parallel multiscale modeling effort, and also by multiscale state-of-the-art characterization techniques. These unique multifunctional nanowires will be utilized in the manufacturing of biosensors using a novel coaxial electrospinning method. The proposed research is scientifically significant because it will reveal the effect of nanoscale phenomena occurring at crystallographic length scales on larger scale functionality through hierarchical nanomanufacturing. The proposed research will also result in well-structured hierarchical fabrication methodologies and architectures for new multifunctional materials and devices to be used as sensors and actuators in engineering applications, facilitating the design of micro-actuators, biosensors, valves and active mesoporous structures. The knowledge generated from these studies could revolutionize the design of active nano and micro-scale systems and components capable of undergoing very fast reversible deformations, and exhibiting high actuation, sensing and promising power generation characteristics. The proposed project activities will include the development of teaching modules in multifunctional materials for incorporation into undergraduate courses; enrichment of graduate and undergraduate research experiences through summer collaborative exchange programs between Texas A&M and Georgia Tech; development of a graduate course in active thin films, nanowires and active nanostructures; involvement of underrepresented groups through participating regional minority serving universities, and injection of laboratory demonstration models in educational material for secondary educational programs, which will be coordinated with the newly established NSF Nanoscale Undergraduate Education (NUE) program at Texas A&M.

**Protein-Aided Nanomanufacturing**

*Daniel Schwartz, Mehmet Sarikaya, Francois Baneyx, Karl Bohringer, and David Ginger*
NSF Award 0709131

This research was received in response to the Active Nanostructures and Nanosystems initiative, NSF 06-595, category NIRT. Manufacturing at the nanometer-scale has the traditional challenges associated with ensuring superior quality, cost, speed, and production flexibility, as well as added constraints on the precise molecular/atomic configuration of the product. This research seeks to develop the molecules, hardware, and software needed to meet the challenges of hierarchical nanomanufacturing. Precise control of solution processed inorganic materials will be achieved using inorganic synthesizing proteins (ISPs) that are identified via combinatorial biology. ISPs are growth 'seeds' that can nucleate the target inorganic materials when brought into contact with an engineered aqueous electrolyte. Hardware for ISP seed 'planting' will rely on the protein-compatible patterning techniques dip-pen nanolithography, micro-contact printing, and thermo-responsive protein adsorption. New software algorithms are being developed to compute the optimal locations for planting ISP seeds on a surface to produce the highest accuracy object with the fewest number of tool moves. The final step in the protein-aided manufacturing process is to immerse the seeded surface in the growth electrolyte to spontaneously grow the object. Several scientific issues will be addressed. Rapidly identifying ISPs with selective affinity for specific inorganic polymorphs is key to understanding and controlling the growth of materials with desired crystallinity. The impact of protein patterning method on the molecular orientation and synthesis activity of ISPs will be studied, as will the scale-dependence of patterning and growth. Robust geometric modeling and tool path planning software will be developed to ensure good build fidelity for both isotropic and anisotropic crystal growth over hierarchical geometries.
This research addresses key societal challenges associated with alternative energy, sustainability, and the development of scientific and engineering human resources. The technology test bed for this research is the fabrication of ZnO solar cells, where new nanomanufacturing approaches offer the potential for significant improvements in performance and cost of solar energy conversion. Currently, solar cells and most electronic devices are made using high temperature, low pressure, and toxic reagents. The room temperature, water-based protein-aided manufacturing process proposed here demands modest energy inputs and uses low toxicity precursor reagents, thereby impacting the sustainability and efficiency of our economy. The graduate students working on this project will be integrated into nanotechnology-oriented programs aimed at improving the diversity of scientists and engineers, as well as a global partnership where they will have the opportunity to gain international experiences.

# NIRT/GOALI: Development of a Multiscale Hierarchical Nanomanufacturing Tool

*NSF NIRT Grant 070781*

PIs: **Xianfan Xu, Okan K. Ersoy, Arvind Raman, Minghao Qi**
Purdue University
**William A. Challener**
Seagate Technology LLC

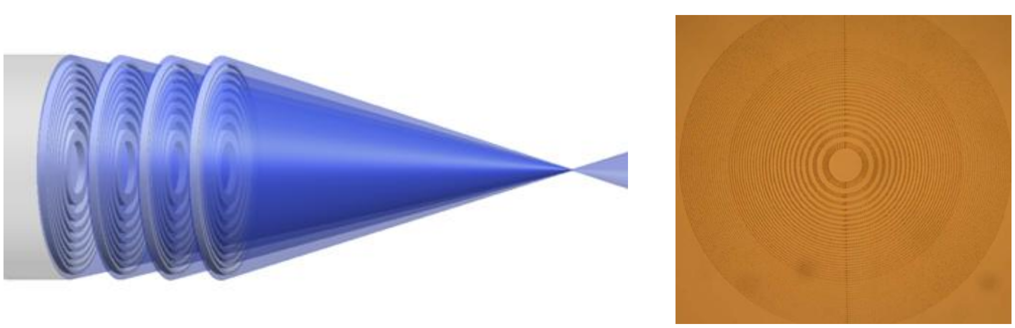
The ***objective*** of this project is to develop a low-cost, high throughput, hierarchical nanomanufacturing tool that allows mass production of components and devices with feature dimensions across several length scales, from nanometers to centimeters and above.

The key component of the manufacturing system is a nanoscale optical antenna aperture which concentrates light into a nanometer size domain with high transmissivity (or efficiency). The concentrated radiation from the antenna is used as a nanoscale light source for nanomanufacturing. To develop multiscale, hierarchical manufacturing tool, we incorporate micrometer resolution radiation sources, a volume zone plate, for fabricating micrometer size features. This will greatly speed up the manufacturing process. We also design and integrate optical and mechanical components, and develop computer-aided-manufacturing algorithms for multiscale, hierarchical manufacturing.

This is a collaborative project involving researchers in manufacturing, optics, dynamics and control, and semiconductor device fabrication. We also collaborate with Seagate Technology LLC to investigate the performance of the optical antenna apertures, who is interested in using these antennas for hybrid (optic-magnetic) data storage.

Notable results obtained so far include:
(1) Design and fabrication of volume zone plate.
(2) Design and fabrication of optical nano antenna.
(3) Construction of the nanolithography system.

(1) Volume zone plate design and fabrication. Volume zone plate produces a micrometer size light spot for fabricating micrometer size structures. It also allows integration with nano-optical antenna for fabricating nanometer size features. Figure 1a illustrates the schematic of a four layer



(a) (b)

**Fig. 1: (a) Schematic of a four layer volume zone plate as a focusing element. (b) Femtosecond laser fabricated volume zone plate inside quartz. Outer ring diameter is 0.7 mm.**

zone plate. We use femtosecond laser to fabricate these volume zone plates (patent pending). Additionally, we have carried out optical computations to optimize the design of volume zone plates [1]. Based on computational design, we demonstrated that the efficiency of focusing can be as high as 80%, compared with a normal zone plate focusing element which has a maximum efficiency of about 40%.

(2) Design and fabrication of optical nano antenna. The optical nano antenna aperture is the key element for producing a nanoscale light spot for nanomanufacturing. Figure 2 shows a schematic of the bowtie aperture. For antenna optimization, we carried out 3D FDTD (finite difference time domain) and FEFD (finite element frequency domain) calculations of 3-dimensional bowtie structures.[2] The 3D bowtie structures are better approximation to the structure that can be fabricated using focus ion beam milling. The performance of focusing of nano antenna aperture is characterized using a home-built near field scanning optical microscopy (NSOM).

(3) Construction of the nanolithography system. A micro and nanomanufacturing system using micro and nano optical elements have been designed and built (Fig. 3). In addition to the optical components, it also has high precision motion control system for creating high precision patterns, optical metrology system for measuring the relative positions of the optical elements with respect to the substrate, computer interface, and clean air handling system. Current it is being tested for fabricating various micro and nano-structures.

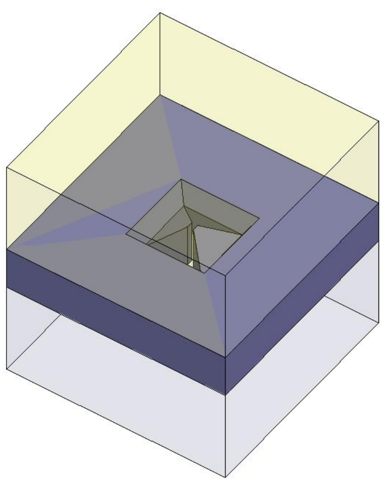


**Fig. 2: 3D view of the simulation setup**

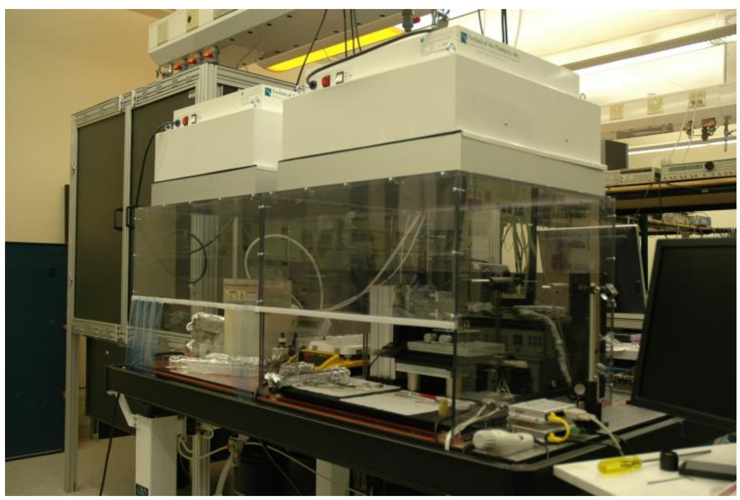


**Fig. 3: The nanomanufacturing system.**

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# Precise Building Blocks for Hierarchical Nanomanufacturing of Membranes with Molecular Resolution

*NSF NIRT Grant CMMI-0707610*

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**Background** One of the most promising developments in the field of separations using membranes is that of molecular sieve or zeolite membrane technology. Zeolites and other molecular sieves are crystalline inorganic framework oxides with micropores capable of recognizing molecules by shape and size. This ability along with their thermochemical stability and catalytic activity has led to their use in a broad variety of applications as catalysts, adsorbents and ion exchangers. The desire of incorporating these materials in thin film devices with molecular resolution can be traced back in the 1940's. However, it is only about a decade that the first commercial zeolite membranes, targeting small scale distributed applications, i.e., membrane modules of about ten square meters, became available. Since then, commercialization progress has been stagnant, hampered by problems in scale up from lab to commercial scale.

It has become evident that zeolite membrane technology for large scale processes depends on reliable manufacturing that can generate large membrane areas while achieving essential film characteristics: film continuity with low defect density, appropriate pore orientation and small membrane thickness – well under the micrometer range. This NIRT team undertakes the challenge to make the leap forward towards developing such a process.

Studies by members of this team and others have shed new light on the nucleation and growth mechanisms of templated zeolites from metastable precursor nanoparticles. A set of mechanistic principles has been identified and phenomenological models have been formulated for certain systems.[1] These principles motivated the proposed experimental efforts which attempt to control the size and shape of zeolite nanoparticles to an unprecedented level and utilize these nanoparticles as precisely engineered building blocks for molecular sieve thin films made by hierarchical nanomanufacturing.[1]

**Hypothesis and Proposed Work** It was hypothesized that synthesis in a confined environment will enable manipulation and control of undesirable aggregation steps and will ultimately yield the desirable perfection in zeolite particle shape and the needed monodispersity in size. Three confined environments, two of which have been introduced by the co-PIs, are being used: reverse opal carbon, block copolymer reverse micelles and nanoporous plastics. The precisely shaped nanoparticles will be used subsequently as building blocks to form closed packed crystallographically aligned monolayers using reactive attachment. In this approach, the zeolite particles are functionalized so that they can strongly bond with appropriately treated substrates. Following secondary growth, the developed continuous films will be tested for permeation properties, and their microstructure and performance will be compared with the current state-of-the-art. It is anticipated that by using the novel nanoscale building blocks, the thickness of highly selective molecular sieve membranes will be reduced from the currently feasible 1,000 nm level to 100 nm or less. Consequently, significant molecular sieve membrane capital and operating cost benefits are the expected outcome of the proposed work. These improvements will be a leap forward for wider use of energy efficient molecular sieve membrane separation technology.

**Collaborations** In addition to enabling the thinnest, and consequently most productive, zeolite membranes ever made, the proposed hierarchical film processing technology may impact other technologies, like microelectronics and sensors. One of these potential uses, i.e., low-k dielectrics for microprocessors, is being evaluated in collaboration with another NIRT team lead by Professor Yushan Yan at UC Riverside. The educational experience of the graduate students and the research productivity of the team are enhanced by two international collaborations from leading groups in the areas of catalysis (Prof. A. Corma) and particle attachment by molecular linkages (Prof. KB Yoon). Moreover, interactions with Chevron and Ecolab provide a connection with industrial practice.

**Notable Results**

Hydrothermal synthesis of uniform zeolite particles in 3DOM reactors.[2] The siliceous zeolite, silicalite-1 was grown in the confinement of three-dimensionally ordered macroporous (3DOM) carbon or 3DOM sulfated zirconia, in which 100–300 nm macropores were interconnected through windows, permitting complete penetration of precursor solutions. The macropores therefore acted as massively parallel arrays of hydrothermal reactors. Both materials were stable to growth conditions for silicalite. Uniform products with varying morphologies were obtained, including zeolite microspheres with smooth or corrugated surfaces or geode-like hollow zeolite spheres (Figure 1).[2] Upon calcination of the carbon reactors in air, the products could be dispersed in solvents to form discrete spherical particles, which could then be reassembled on planar surfaces into close-packed layers.

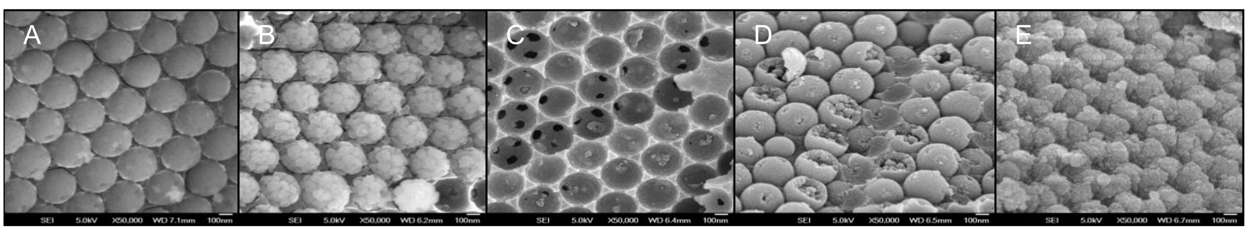


**Figure 1.** Scanning electron microscopy images of silicalite particles hydrothermally grown in the confinement of 3DOM reactors under different processing conditions. (A) Smooth spheres were obtained for a negatively charged reactor surface after five infiltration steps. (B) Spherical agglomerates of silicalite nanoparticles were formed for a negatively charged reactor surface after two infiltration steps. (C) Discrete silicalite nanoparticles were attached to the walls of a positively charged reactor surface after one infiltration step. (D) Geode structures formed after multiple infiltrations in a positively charged reactor surface. (E) When the positive surface charge was very high (here on 3DOM sulfated $ZrO_2$), the silicalite surface layer blocked pore entrances.

Synthesis of silicalite-1 nanocrystals by confined growth in 3DOm carbon replicas.[3] Confined crystal growth of silicalite-1 zeolite has been carried out within the 3DOm carbon replicas of colloidal crystals composed of ca. 10, 20 and 40 nm silica particles. As shown in Figure 2a, TEM of the 40 nm 3DOm carbon following confined synthesis reveals isolated particulate domains (e.g., arrows) of approximately 200-300 nm in size dispersed throughout the replica for the synthesis compositions and conditions described herein. WAXS (Figure 2f, trace A) measurements taken of the sample depict signature reflections of silicalite-1, with high crystallinity of the particulate domains confirmed following their isolation from the 3DOm carbon template (Figure 2f, trace B). Faceted zeolite crystals (Figure 2b, arrow) that appear to protrude through the pore cavity can be found among the particles. SAXS analysis reveals signature mesoporosity before (Figure 2e, trace A) and after (Figure 2e, trace B) isolation of the particulate templates from the 3DOm carbon. The isolated particulate domains remain intact initially, but can be dispersed into primary particles (Figure 2c) by mild sonication (i.e., 5 minutes). *This represents the identification of a facile means for realizing highly uniform and dispersed nanocrystalline zeolites, an elusive task with other confined synthesis approaches.*

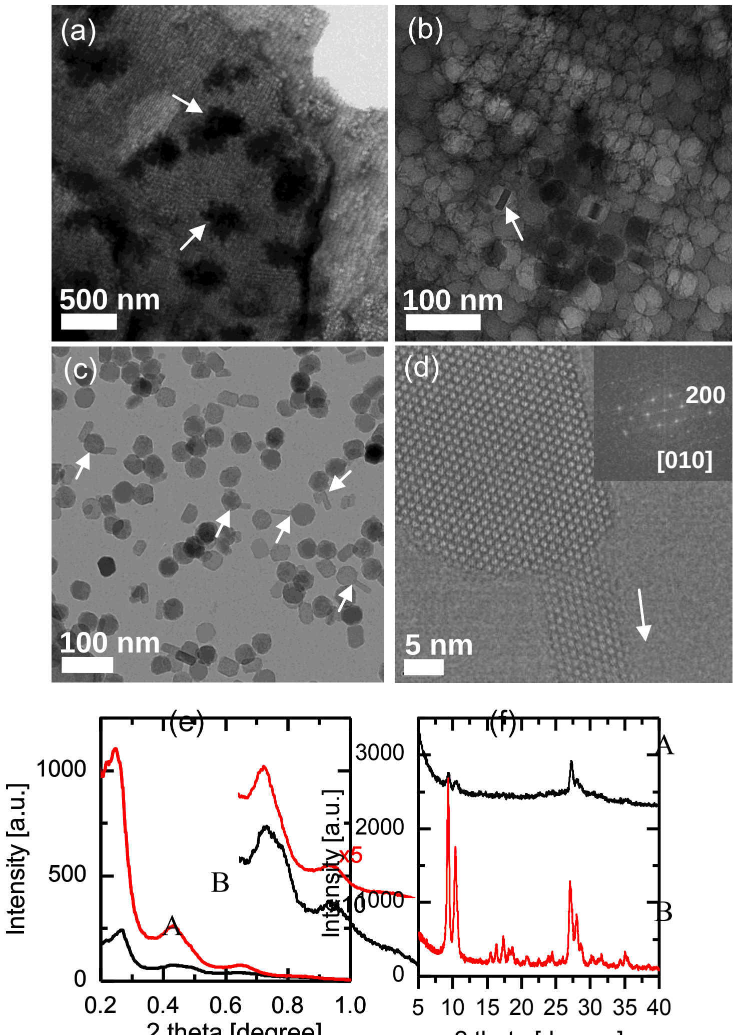


**Figure 2.** TEM characterization of confined silicalite-1 crystal growth carried out in a 40 nm 3DOm carbon template before (a,b) and after (c,d) carbon removal, with high resolution TEM in (d) of uniquely shaped crystals observed in (c, arrows). The inset displays the diffraction pattern collected from the crystal interface, and the solid arrow in (d) denotes the c-axis of the crystal. SAXS (e) and WAXS (f) data before (trace A) and after (trace B) carbon removal are also shown.

While both smooth and subtly faceted particles are observed after dispersion that have clearly been templated by individual ca. 40 nm cavities of the 3DOm, unique faceted, rod-like outgrowths (arrows, Figure 2c) on some particles are also observed. A representative high-resolution image of the junction between the base particle and the outgrowth is shown in Figure 2d, suggesting that the particle is single crystalline. This is consistent with seeded growth occurring at the surface of a well-formed crystal and propagating, along the dominant crystal axis (the c-axis in the case of silicalite-1, denoted by the solid arrow in Figure 2d), through pore window constrictions connecting adjacent cavities of the 3DOm carbon replica. *This identification of crystal propagation through constrictions supports the notion that confined growth may occur by rare and dispersed single nucleation events in the 3DOm replica, followed by crystal growth to fill the pore cavities, and eventual propagation through the constricting pore windows.*

Current work focuses on film formation using the precisely shaped zeolite particles, investigation of the catalytic performance of the 3DOm zeolites, and further studies of confined crystal growth. Moreover, we initiated efforts on the synthesis of porous polymers that we currently attempt to use for confined zeolite growth.

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For more information link to: [http://www.cems.umn.edu/research/tsapatsis/NIRT_ZGCS/index.php](http://www.cems.umn.edu/research/tsapatsis/NIRT_ZGCS/index.php) or
email: tsapatsi@cems.umn.edu

# Active Nanofluidic Manufacturing and Hierarchical Assembly of Anisotropic Nanocolloids

*NSF NIRT 0707383*

**Mark A. Burns, Sharon C. Glotzer, Joanna Mirecki Millunchick and Michael J. Solomon**
University of Michigan Ann Arbor

## Introduction

This NSF NIRT project seeks to advance the rapidly expanding research frontier of the fluidic manufacture of anisotropic particle building blocks [1]. Simultaneously, we aim to exploit the tremendous potential for encoding information into the sequence, shape and symmetry of anisotropic particle building blocks so they can assemble into complex three-dimensional (3D) structures [2]. Taken together, these two areas each represent one level of a new hierarchical assembly paradigm that can input spherical nanocolloidal precursors and, by way of anisotropic building blocks, output complex 3D terminal structures with a range of new, active functionalities. Yet, to date, the two levels of the assembly hierarchy have advanced independently on the different scales of microparticles (fabrication) and molecules (anisotropic assembly) rather than together at the nanoscale.

In this project we seek to address the key fundamental scientific challenges needed to realize this hierarchical paradigm at nanoscale dimensions. At this scale there is rich new potential for applications requiring active functionality for materials in photonics, electronics and energy management. In this aim we are supported by our recent discovery that fluidic processing can be used to assemble microparticles into permanently bonded anisotropic building blocks with high sequence and shape fidelity. Our prior research has additionally shown vis simulation that anisotropic building blocks are a key foundation from which 3D terminal structures can be assembled. Our objective is addressed through an integrated research program that brings to bear our state-of-the-art capabilities in nanofabrication, fluidic manufacturing, nanocolloid assembly, direct visualization by confocal and electron microscopy and computer simulation of anisotropic building block interactions and assembly. Simultaneously, by developing new data repository and wiki cyber tools we create a clear conduit for dissemination of our discoveries so as to contribute to training and education of students.

To illustrate the project focus, in Fig. 1 we depict two kinds of nanocolloids with differing interactions (e.g. type "A" and type "B" due e.g. to different surface chemistries). To permanently bond the constituent nanocolloids, we execute fusing reactions that yield permanent interparticle bonds. The particular sequence of "A" and "B" constituents is actively controlled by fluidic control mechanisms. Because the concept is general, it can be applied to produce a range of nanocolloidal building blocks for hierarchical assembly. We will thus discover how to optimally design a set of anisotropic buildings with interactions that can be exploited to assemble a particular 3D terminal structure targeted for assembly.

## Project Objectives

A number of important fundamental challenges arise in the hierarchical assembly of anisotropic building blocks. First, when fabricating building blocks by fluid manufacturing, we should better understand the effect of particle-channel interactions and apply that understanding to better design fluidic networks to fabricate complex structures. Second, when assembling building blocks into complex 3D terminal structures, we should better understand how to optimally design building blocks for programmable assembly into a target structure and then apply that understanding to better design self-and guided assembly processes. Thus, we pursue two key objectives:

Objective 1: Investigate key issues needed to extend the paradigm of nanofluidic processing to manufacture anisotropic building blocks of programmable sequence, shape and chirality as the constituent particle size is progressively decreased. Target in particular: (i) anisotropic building block – surface interactions in fluidic channels of complex design; (ii) design of fluidic networks for complex building block fabrication.

Objective 2: Investigate key issues needed to assemble complex, three-dimensional terminal structures from anisotropic building blocks with interactions encoded in the building blocks. Target in particular: (i) optimal decomposition of 3D terminal structures into anisotropic building blocks programmed for assembly; (ii) design of self- and guided- assembly processes.

**Methods and Results**

In pursuit of the research objectives, we are applying four principal methods. The interactions among these methods are shown in Fig. 2.

Microfluidic production of anisotropic particles with configurable anisotropy. We perform continuous synthesis of anisotropic particles with features such as alternating bond angles, configurable patchiness and uniform roughness [1]. The sequence and shape of the anisotropic particles are configured by exploiting a combination of confinement effects and microfluidics to pack precursor colloids with different properties into a narrow, terminal channel. The precursors are permanently bonded into particles by thermal fusing. Particles produced have precisely configured, repeatable bond angles. Sequence and shape anisotropy are combined to yield microparticle analogues of surfactants, tri-blocks and patchy particles. With this method we can produce particles at a high frequency (up to 1 Hz), and isolate the products in a microfluidic device for further use.

Field-assisted assembly of anisotropic particles. We efficiently generate assemblies of anisotropic nanocolloids with controllable order by application of applied fields. Using rod shaped colloids as a model material we have investigated the effect of centrifugation on their assembly. Dispersions of colloidal rods are subjected to different centrifugation speeds in custom made cells. 3D image volumes of sediment structure are collected by confocal laser scanning microscopy. We use image-processing algorithms [3] to quantify the nematic order parameter (*S*) of the materials formed by field-induced assembly. We find that the nematic order parameter (*S*) increases with increasing Peclet number for rods of aspect ratio 3.6. Here the Peclet number is computed from the single rod rotational diffusivity. The enhancement in orientational ordering is a consequence of the interplay between a thermodynamically-driven order-disorder transition and transport-driven alignment effects.

Theory and simulation of anisotropy effects. We apply a variety of simulation techniques to investigate the synthesis and self-assembly of anisotropic nanocolloidal systems. Brownian dynamics simulations have been carried out to ascertain the effect of rectilinear channel confinement on bond angles in anisotropic particles [4]. To examine the phase behavior and self-assembly of the anisotropic nanocolloids, we use several methods including equilibrium molecular dynamics, Metropolis Monte Carlo, and a variety of energy minimization techniques such as Monte Carlo minimization("basin-hopping") and numerical algorithms. We also employ an algorithm recently developed to search for low-energy structures of arbitrary colloidal building blocks.

Characterization of functional properties of nanocolloidal assemblies. We have developed a MEMS-based fluidic device for characterization of the conductivity properties of nanocolloidal structures. FIB (focused ion beam) methods were used to prototype and test design ideas. Thin film fabrication techniques were then applied to progress from design ideas to device implementation. In the device shown schematically in the figure, colloids are propagated into the device, and the voltage-current response of the resulting assemblies is obtained as output. The aim is to investigate the influence of nanocolloidal packing and confinement on the electrical properties of terminal nanocolloidal assemblies.

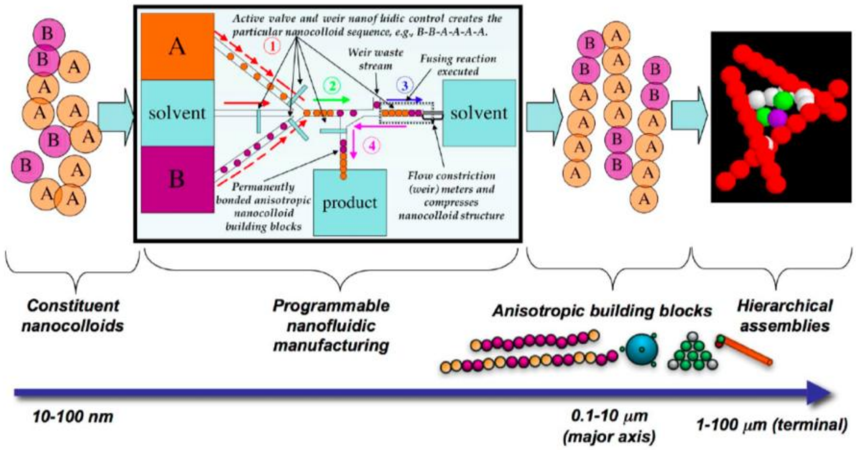


Figure 1. Schematic of the hierarchical assembly paradigm for production of complex 3D structures by nanofluidic manufacturing and anisotropic building block assembly.

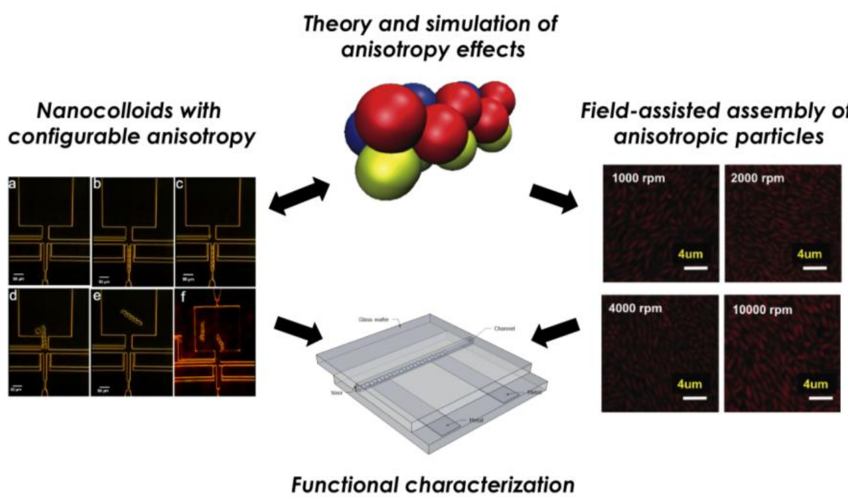


Figure 2. Interactions among the four research methods. Please see text for additional discussion.

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# Interfacial Forces in Active Nanodevices

*NSF NIRT Grant 0709187*

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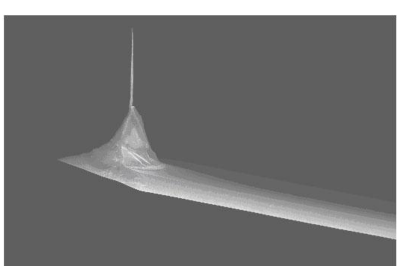
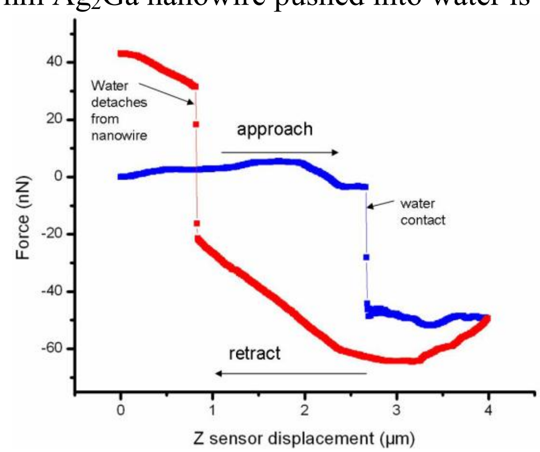
Johns Hopkins University

**Project Objectives:** As device dimensions shrink towards molecular scales, interfacial forces become increasingly important. At the same time, traditional theories of interfacial forces become inadequate, and fundamentally new phenomena appear. The goals of our project are to determine the limits of traditional theories, identify new interfacial phenomena, develop general models for interfacial forces at the nanometer scale, and explore processes that may enable new active nanodevices. To achieve these goals we are developing and applying new experimental and theoretical methods that allow measurement of interfacial forces on nanowires and in nanometer gaps between solid surfaces and control of these forces using electric fields and light. Progress on specific projects is outlined below [1].

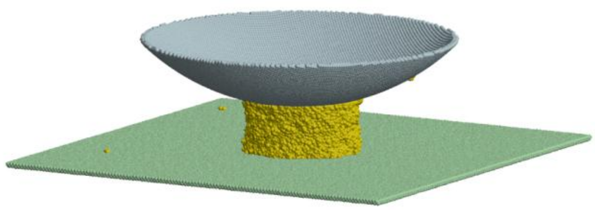
**New Simulation Algorithms:** Simulations of interfacial forces are difficult because of the wide range of length and time scales and the presence of long-range interactions. The team has developed new algorithms that address these challenges. The first addresses time scale separation in hybrid atomistic/continuum models that treat interfacial regions atomistically, while using a more efficient continuum model in the larger surrounding regions. While this greatly decreases the number of atoms that must be followed, their motion must still be integrated on femtosecond time scales. This becomes inefficient as the size of the continuum region, and the associated time scale, grow. The new algorithm [2] follows atomic motion over short intervals and extrapolates the results to the characteristic time scale of continuum regions. This allows a substantial speed up with an accuracy that grows as the time scale separation increases. The second algorithm uses a multigrid approach to obtain the long-range contribution of Coulomb interactions [3]. This allowed the studies of electrowetting described below.

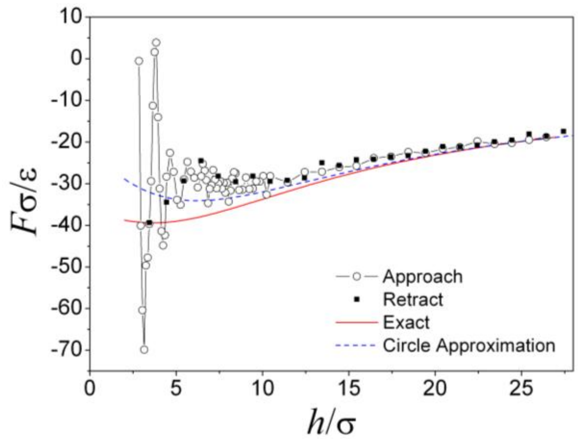
**Capillary Effects at the Nanoscale:** The atomic force microscope (AFM) is being used to measure capillary forces on nanowires as they are pulled through an air/liquid interface. The effects of surface chemistry, roughness, nanowire radius, and velocity are being studied. Si, InAs, and $Ag_2Ga$ nanowires with 50nm to 250 nm radius have already been mounted on AFM cantilevers (below). A measured force curve of a 200 nm $Ag_2Ga$ nanowire pushed into water is shown to the right. Surface tensions and contact angles can be obtained from such curves and compared to macroscopic values [4]. Future work will examine changes induced by electric fields and light, and the potential for switching the interface between different states.



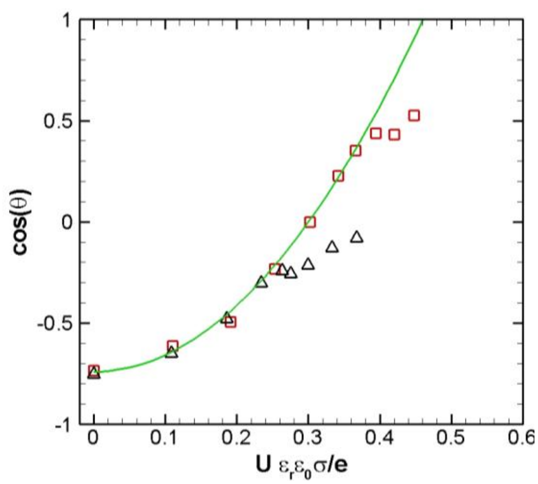


Simulations are examining static and dynamic capillary forces at nanometer scales to help interpret and guide the above experiments. Simulation results for capillary adhesion between a spherical tip and a flat plate (below) are plotted on the right. For separations greater than about 10 molecular diameters, continuum theory is accurate. Molecular layering and disjoining pressure effects lead to pronounced deviations at smaller scales. Nanowire studies are in progress.






**Electrowetting at the Nanoscale:** Experiments are examining electrowetting in nanometer scale gaps between surfaces in the Surface Force Apparatus [5]. Simulations have provided the first test of continuum theories in nanoscale drops. The figure below shows the change in contact angle θ with voltage U for model systems with a very thin dielectric layer, and the prediction of the Lippmann equation (solid line) [6]. The drop radius is only about 15 molecular diameters and yet the change in contact angle follows the continuum prediction at low voltages. At higher voltages the contact angle saturates. This is also observed in macroscopic experiments and there has been debate over its origin [7]. Our results suggest that saturation is associated with charged molecules leaving the drop. The barrier for this is larger for longer chains (squares) than shorter chains (triangles), leading to a higher saturation voltage.

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# NIRT: Reversible Frictional Adhesion of Natural and Bio-Inspired Multi-Scale Structures

*NSF NIRT Grant 0708367*

PIs: **Kimberly Turner**, **Jacob Israelachvili, Mark Cutkosky*, Thomas Kenny***
UC Santa Barbara, *Stanford University

This team is working to better understand the gecko adhesion and dynamics, and to carry over this understanding into the design and fabrication of hierarchical analogues. There are three main goals this interdisciplinary team plans to achieve over the project duration: 1.) Improved fundamental understanding and development of models describing 'frictional adhesion', 2) Development of adhesion metrics and test standards for natural and artificial adhesive systems, and 3.) Design and fabrication of bio-inspired articulated reversible adhesives integrating nano-, micro- and macro-scale components for adhesion and micro-robotic applications. By addressing the system through three cohesive goals, the team hopes to make significant gains into understanding and mimicking this unique and useful system.

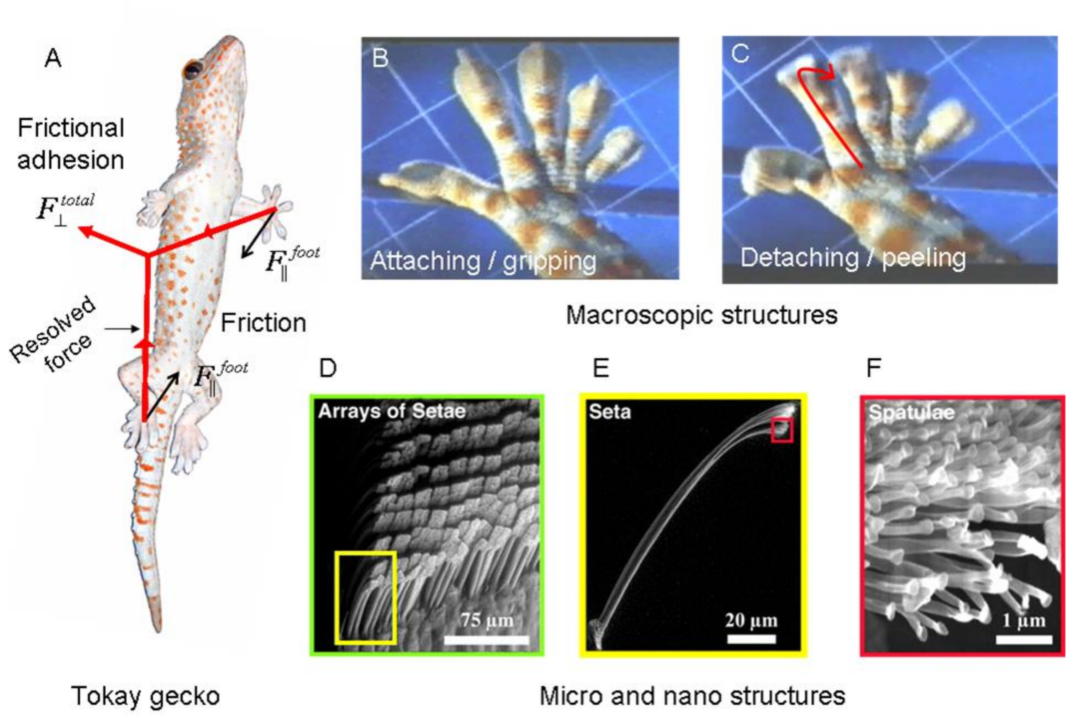


**Figure 1.** Hierarchical structures of the Tokay gecko from the macroscopic (the feet and toes, A-C) to the microscopic setae (D, E), to the nanoscopic adhesive pads or spatulae (F). A gecko generates both normal $F_{\perp}$ (adhesion,) and lateral $F_{\|}$ (friction,) forces along different directions that together enable it to climb on walls and run on ceilings. (B) Toe configuration during attachment; (C) toe configuration during detachment, showing the unusual peeling back action of the toes.

The gecko's dynamic adhesive mechanism has many features that could be mimicked for fabricating new types of controllable synthetic dry adhesive systems and articulated robots. Our aim is to carry out experiments on the different hierarchical structures of the gecko adhesive system (Fig. 1) coupled to theoretical modeling to establish criteria for the design and fabrication of synthetic adhesive systems employing materials that can rapidly attach and detach. As a synergistic team, we hope to achieve breakthroughs in the understanding and creation of synthetic nature-inspired adhesives.

**Specific project objectives are:**

1. To understand the interplay between friction and adhesion, specifically how friction can be exploited to enhance adhesion forces ('frictional adhesion').
2. To understand the mechanism(s) by which geckos can strongly attach then detach their foot pads, all within 20 milli-seconds.
3. To use the Surface Forces Apparatus to measure the dynamic friction and adhesion forces between gecko setal arrays and compare the results with those obtained on specially designed synthetic surfaces.
4. To understand the role of humidity and bulk water on the surface chemistry of the β-keratin structures that make up the adhesive gecko pads.
5. To develop predictive models for such systems.
6. To use our experimental and theoretical findings to create a functioning synthetic dry adhesive system. We are extending the current application to a more diverse set of surfaces and scaling the results to larger areas and higher levels of adhesion.

Reversible, reusable adhesives have applications in many areas including health and medicine, robotics and manufacturing. The general area of adhesion science is one that can be successfully utilized to excite and motivate students of many levels. A website and experiments are planned to not only bring together the scientific community studying this problem, but also to excite students of all levels, which demonstrate the basics of adhesion science. The website has been created, and can be viewed at http://www.engr.ucsb.edu/~tmems. In addition, we propose the creation of a nano-art show to bring the realm of nanotechnology to the public. Samples of gecko and gecko-inspired art created by our group currently hangs in the UCSB Engineering Science Building breezeway, and gets lots of interest. Finally, students (graduate and undergraduate) have traveled between the three collaborative institutions as part of internship/exchange programs. We held the 1st annual NIRT Gecko workshop on July 10-11 of this year. This workshop was attended by not only NIRT PI's and graduate students, but also international collaborators from Australia and Germany. During the two-day workshop, talks were given on progress of each team, and there were also brainstorming sessions. The workshop was a success, and it has enabled better communication between the teams. Copies of the workshop presentations and agenda items can be found on our NIRT website.

(For samples, see the "Overview" documents posted on the conference website, http://www.nseresearch.org/)

**References**

[1] For further information about this project link to http://www.engr.ucsb.edu/~tmems or email: Turner@engr.ucsb.edu.

# NIRT: Active Electromechanical Nanostructures Without the Use of Piezoelectric Constituents

*NSF NIRT Grant 0708096*

PIs: **Pradeep Sharma, Boris Yakobson, Ramanan Krishnamoorti, Zoubeida Ounaies**
University of Houston, Rice University, Texas A&M University

The objective of this NIRT grant is to promote a multi-disciplinary collaboration between theorists and experimentalists to understand and develop active nanostructured architectures such as nanocomposite skins and films that do not require any piezoelectric materials as constituents and in principle can be designed with any material combination. Modeling methods ranging from *ab initio* atomistic calculations to enriched continuum models will be employed to enhance understanding of flexoelectricity at the nanoscale and provide guidelines to select materials and engineer highly optimized, apparently piezoelectric nanostructures with the requisite symmetry, topology and size. The different topologies will be fabricated by precisely controlling the dispersion of suitably shaped nanoparticles in a polymer matrix (from soft elastomers to hard thermoplastics and thermosets) with external fields (flow, electrical & magnetic) as a means to tune the symmetry and provide the necessary 3-dimensional arrangement of the nanoinclusions.

The expected benefits of the program will be both educational and societal. Anticipated research outcomes are an independence from Nature's limited selection of active electromechanical materials and an ability to design multifunctionality by assembling arbitrary non-active material combinations. Apart from resolutions of fundamental scientific questions related to piezoelectricity at the nanoscale, technological applications of the proposed research are anticipated in next generation actuators, sensors, MEMs and NEMs with consequent impact on diverse industries such as, Electronics, Space and Aerospace, Biomedical, Defense among others. The educational impact is that undergraduate and graduate students will be trained in emerging and interdisciplinary scholarly research. Research and education will be integrated by focusing on the education, outreach and recruitment through (1) Undergraduate summer research opportunities, (2) High School outreach using our existing NSF RET, REU and AGEP, and (3) Middle/High School student demonstrations. Research findings will be incorporated into courses, and broadly disseminated through conference presentations, scholarly publications, and the PIs's websites.

We have obtained several notable results and here we highlight just one. We are able to show that if suitably shaped pores are fabricated in non-piezoelectric (cubic) phase of $BaTiO_3$, for nanoscale sized pores, a significant “apparent” piezoelectric effect results----comparable to materials that are intrinsically piezoelectric. This major result is summarized in the Figure below.

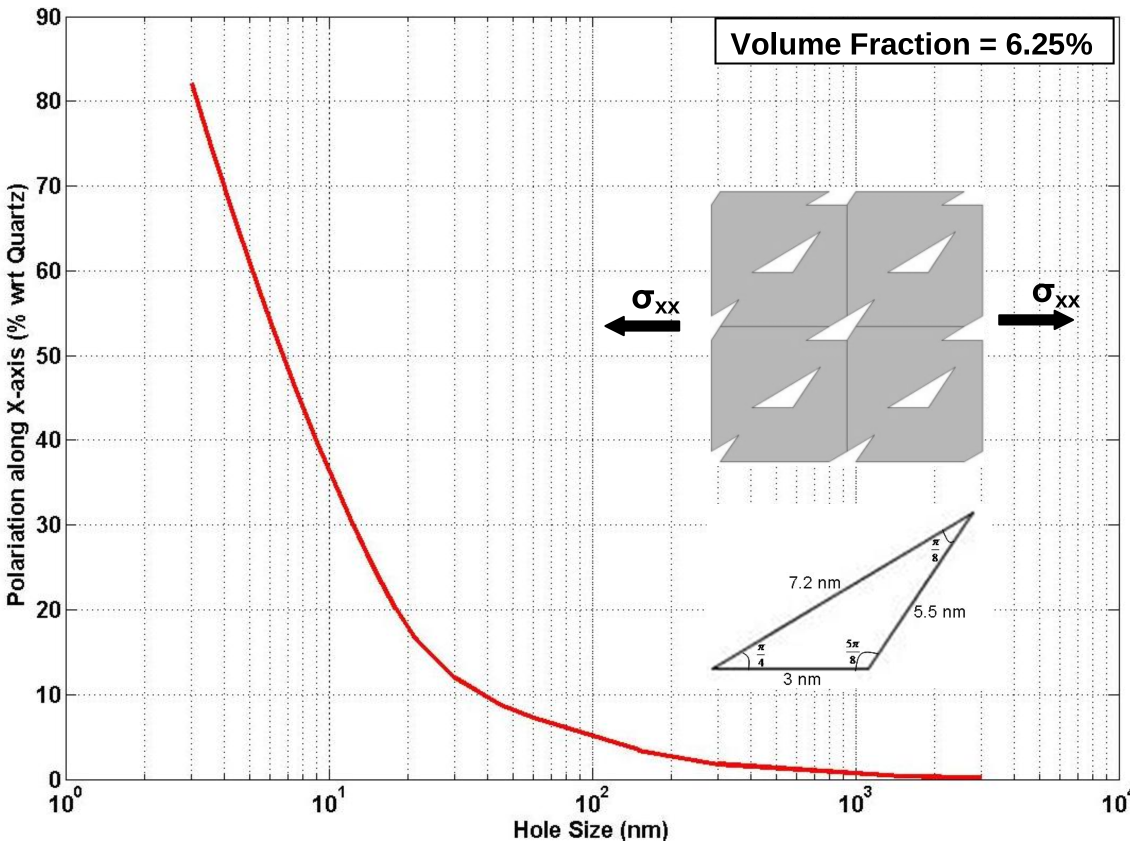


**Fig. 1:** The X-component of the polarization (normalized with respect to quartz) as a function of pore size for a $BaTiO_3$ film (in paraelectric phase) with triangular holes subjected to uniaxial stress as shown. The composite exhibits induced polarization close to 80 % of Quartz for hole-size of 3nm.

**Intuitive Toxicology and Public Engagement**

*David Berube, Jennifer Kuzma, Dietram Scheufele, Kevin Elliott, Pat Gehrke*

NSF Award 0709056

Introduction. It is well documented that inexpert audiences reason and react differently than experts when exposed to information about toxicological risks, but almost none of the existing studies have examined how the public and experts react differently to risks associated specifically with the applied nanosciences. To address this weakness, we propose to reveal which factors are most significant in affecting public perception of the risks of applied nanosciences and what, if any, relationship exists between the modes of public deliberation, sources of information (e.g. use of new media), and the effects of new information on risk perception. Five methodological stages are proposed: refine and develop key variables and instruments (stage 1), determine the contribution of variables to perceived risk (stage 2), elucidate the effect of civic engagement and new media on risk perception (stage 3), verify key variables related to risk perception (stage 4), and provide outreach to the public (stage 5). Stage 1 will be accomplished by hosting an interdisciplinary conference to isolate key variables and to produce appropriate instruments with which we can assess public perceptions of the risks of applied nanosciences. After refining our methodology based on the proceedings of the conference, we will conduct a set of Delphi rounds to determine what are the differences between public and expert perceptions of the risks of applied nanosciences (stage 2), paying particular attention to differences based on sources of information and variables that amplify or attenuate perceptions of risk. Drawing on the findings of the Delphi rounds, the research team will hold civic engagement events (stage 3), bringing together non-expert citizens and a variety of experts. Observation and coding of the events will address the effect of civic engagement on public and expert perceptions of risk. We will test whether a relationship exists between modes of deliberative interaction and changes in perceptions of risk, as influenced by the new media as a source of information on risk and deliberative interaction. For stage 4, focus groups on the use of nanoscience in food preparation and packaging) will verify and narrow the key variables that affect public perception of the risk of applied nanosciences. For the final stage (5), this project concludes with a workshop to report conclusions and generate criticisms and future directions for research.

Intellectual Merit. This project will produce an especially timely heuristic for the projection of public responses to applied nanosciences, given issues of toxicity, roles of new media, and applies its theoretical findings to a case instant examining public perception to nanotoxicity issues and agri-food.

Broader Impact. The results will reveal specific variables and combinations of variables that affect public perceptions of the risks of applied nanosciences equipping policymakers, researchers, industry, and public participants with a greater capacity for productive public engagements and discussions about how to respond to those risks. This work will impact public awareness and provide us with the essential guidance to better enable future communication on the risks of nanotechnology and models for effective civic engagement. This project examines the educational, economic, social, organization, and ethical changes associated with support for, design of, and results from inventions and innovations involve active nanostructures and nanosystems.

# Gated Transport through Carbon Nanotube Membranes

**NSF NIRT Grant** # 0709090

**Costas Grigoropoulos**, UC Berkeley; **Olgica Bakajin**, *UC Davis*; **Michael Colvin**, *UC Merced*; **Aleksandr Noy**, *UC Merced*; **David Sholl**, *Georgia Tech*

## Summary

Our interdisciplinary team is using a combination of experimental and simulation tools to conduct a study that would greatly improve our understanding of the nature and control of molecular transport through carbon nanotubes. Our project explores the following two broad topics:

- Fundamentals of molecular interactions with CNTs and the effects of spatial confinement on the molecular structure, dynamics and transport.
- Active regulation and control of molecular selectivity and transport through carbon nanotubes using highly specific DNA-based molecular gating.

**Intellectual Merit:** The proposed research will broaden and enhance the fundamental science of nanofluidics. We will not only investigate the effect of confinement that has implications for understanding ionic and water transport in living cells, but also lay the foundation for the development of membrane-based transformational technologies. The newly discovered phenomenon of fast transport through carbon nanotubes will be exploited to enable improvements in the performance of membranes for desalination, gas separation as well as other applications such as protective gear and drug delivery.

**Broader Impacts:** Beyond the training of graduate and undergraduate students on nano-bio-fluidics and the strengthening the course curricula at the partner institutions, we will design and implement co-taught graduate level courses. We will also place special emphasis on the recruitment of minority and underrepresented students.

**Activities and Findings:**

Our research focused in three main areas:

1) Understanding of the growth of aligned carbon nanotubes
2) Understanding of ion exclusion mechanisms of carbon nanotube membranes
3) Understanding of gas transport mechanisms through a comparison between simulation and experiements

### 1) GROWTH OF ALIGNED NANOTUBE ARRAYS

Catalytic CVD growth, in which a mixture of the carbon feedstock gases flows over the metal nanoparticle catalyst at high temperatures, readily produces vertically aligned carbon nanotube arrays in laboratory conditions, yet the growth mechanism is still poorly understood. As the result, synthetic control over nanotube diameter, chirality, and length is either limited or non-existent.

We found that systematic variations of process pressure and water concentration in our CVD system results in large fluctuations in the yield and quality of the carbon nanotube arrays. The important role played by these two parameters is not surprising, as the total pressure affects the partial pressures of the reaction species, and thus ultimately determines the incoming flux of carbon to the catalyst. The primary role of the water is to oxidize and remove amorphous carbon on the catalyst, but it could also etch the graphitic carbon Under our growth conditions there is a very stable region in the pressure and water content parameter space that maximizes the CNT growth rate and routinely and reproducibly produces nanotube arrays of up to 1 mm in height at high yield. The height of the array grown at these conditions was extremely uniform and varied by only 1-2% over the sample. Significantly, array height was also reproducible from run to run: nanotube array height measured after 13 different 10-minute-long growth runs over the course of 8 months using three different catalyst depositions showed standard deviation of only 7.8%. The TEM analysis shows that growth in the optimal region of the parameter space produces high quality multi-wall carbon nanotubes (MWNTs) with well-graphitized sidewalls and low concentration of defects.

Kinetics of carbon nanotube growth shows a relatively long initial stage during which the CNT arrays grow at constant rate, followed by a very abrupt growth stoppage. This behavior, although regularly observed in CNT growth experiments, has not been explained by any microscopic growth model. Moreover, it contradicts the widely-used exponential growth model by Iijima and co-workers. We present a new model that combines a microscopic mechanism for growth poisoning by amorphous carbon with the mass transport limitations considerations to provide a description of the growth kinetics that matches experimental data with high precision.

Reproducible growth of nanotube arrays under controlled conditions that we have demonstrated removes many obstacles to the technological applications of carbon nanotube arrays. Tight control over array dimensions should enable their incorporation into the MEMS and NEMS devices using processes and architectures that require close matching of the components. We also showed that the kinetics of CNT array growth can be described quantitatively using a simple model that considers carbon pyrolysis equilibrium, carbon diffusion through the catalyst particle and poisoning of the catalyst surface. This model enables better understanding of the molecular mechanisms of carbon nanotube growth and also provides a strong foundation for the future growth process optimization efforts.

## 2) ION EXCLUSION BY NANOTUBE PORES

Biological pores regulate the cellular traffic of a large variety of solutes, often with high selectivity and fast flow rates. These pores share several common structural features: the inner surface of the pore is frequently lined with hydrophobic residues and the selectivity filter regions often contain charged functional groups. Hydrophobic, narrow diameter carbon nanotubes can provide a simplified model of membrane channels by reproducing these critical features in a simpler and more robust platform. Previous studies demonstrated that carbon nanotube pores can support a water flux comparable to natural aquaporin channels. We investigated ion transport through these pores using a sub-2-nm, aligned carbon nanotube membrane nanofluidic platform. To mimic the charged groups at the selectivity region, we introduced negatively charged groups at the opening of the carbon nanotubes by plasma treatment.

Pressure-driven filtration experiments, coupled with capillary electrophoresis analysis of the permeate and feed, were used to quantify ion exclusion as a function of solution ionic strength, pH, and ion valence. We showed that carbon nanotube membranes exhibit significant ion exclusion that can be as high as 98% under certain conditions. Our results strongly support a Donnan-type rejection mechanism, dominated by electrostatic interactions between fixed membrane charges and mobile ions, while steric and hydrodynamic effects appear to be less important.

## 3) GAS TRANSPORT STUDIES

The experimental efforts focused on the following thrusts: (i) assembly of a multi-component gas permeation system,, (ii) membrane characterization, including single-component gas permeation studies, and (iii) binary gas permeation studies using the multi-component gas permeation system. We have explored transport and selectivities for various gas mixtures as a function of temperature and gas mixture composition.

Atomistic simulations are a useful tool to complement our experimental studies of CNT membranes, as they bring the possibility of exploring in great detail the physical mechanisms that control molecular flux through nanopores. Previous simulations by Sholl and co-workers have explored diffusion of gas mixtures through individual CNTs. Real membranes, however, inevitably contain a polydisperse distribution of carbon nanotube pore sizes. We are currently using atomistic simulations to explore the influence of pore diameter polydispersity on the performance of CNT membranes for gas separations. Understanding these effects is nontrivial because the separation accomplished by each individual nanotube in a membrane is coupled with every other nanotube through the gas mixture present on the feed and permeate side of a membrane. We have tackled this task by performing detailed atomistic simulations of individual nanotubes of several different pore diameters, then using these results to define a continuum-level description of gas transport through these pores. This continuum description is suitable for describing the overall performance of a collection of coupled nanotubes acting as a complete membrane. Preliminary results from these calculations indicate that in membranes that are dominated by carbon nanotubes with diameter < 2 nm, as we see in our experimental studies, the contributions due to the presence of a small fraction of nanotubes with diameters of 2-4 nm define only a small correction to the overall performance of the membrane.

## PUBLICATIONS

- *Review:* Noy et. al., Nano Today, 2, 22 (2007)
- *Ion Exclusion:* Fornasiero et. al. Proc. Natl. Acad. Sci USA, **105**, 17217 (2008)
- *CNT Growth:* Stadermann et. al., *Nano Letters*, in revision (2008)

**Active Nanophotofluidic Systems for Single Molecule/Particle Analysis**

*David Erickson, Kara Bren, Michal Lipson, l·ýŘ Todd Krauss*
NSF Award 0708599

This NSF-NIRT award is centered around the active integration of nanophotonics, nanofluidics, nanomaterials and single molecule physics into a new field, refered herein as ''Nanophotofluidics''. The assembled team consists of researchers from Cornell University and the University of Rochester bringing distinct individual expertise to form the integrated, multidisciplinary research program to exploit the extremely high optical intensities achievable in our newly developed 50nm wide exposed mode ?slot waveguides? to perform optofluidic tweezing and propulsion (by exploiting polarization and scattering/adsorption forces) and demonstrate a series of new active nanoscopic single molecule and multi-particle analytical tools.

Intellectual Merit: This program is divided into three focused research areas: 1) develop a better fundamental understanding of the coupling of electromagnetics and hydrodynamics on the nanoscale to demonstrate the core elements of a broader nanophotofluidic transport architecture, 2) demonstrate the most resolute separation mechanism developed to date, and 3) develop a new mechanism for investigating single protein folding dynamics in solution.

Broader Impacts: Integrating photonic elements as active components in micro- and nano-fluidic devices represents a largely unexplored area that could have significant impact that could be extended into a broad new class of photonically driven microfluidic devices where rapid, network based particle manipulation is performed using the high-speed components already developed by the telecommunications industry. Such platforms may find application in emerging fields such as nano-assembly (offering all the advantages of optical tweezing but more rapidly and with sub-wavelength precision). A fundamental part of this program is an outreach and education strategy consisting of: 1) The development of a series of integrated educational units distributed to K-12 classrooms nationwide through the Cornell Main Street Science program and 2) An interdisciplinary nanoscience and engineering seminar series for the upstate New York area. This seminar series will attract attendees from both universities as well as undergraduate institutions in upstate New York. The talks will also be posted on a dedicated website for download. Students from the target institutions will also be given the opportunity to post questions on a dedicated website which will be answered directly by the speaker or the PIs.

**Ultra-Low-Power Wireless Transmitter with Passive Bragg Oscillator**

*Edwin Kan*

NSF Award 0725688

Intellectual Merits: The proposed effort seeks to make a fundamental breakthrough in realizing the ultra-low-power wireless transmitter for low-bit-rate communication in millimeter-size systems. In conventional radio link, the small antenna size constrained by the overall system geometry will require high carrier frequency, but a lower limit of the power consumption will be set by the parasitic capacitance of the radio circuits. There are several previous efforts to resolve this basic conflict, including an extended dormant mode, ultra-wide-band pulse systems, and the carrier-based impulse radio. However, either the physical antenna is difficult to realize, or the power can not be sufficiently reduced. The proposed transmitter requires only a narrow-band antenna, but generates the carrier oscillation from a passive Bragg lattice. The digital base band is operated at a low frequency close to the specified bit rate of communication, and can be readily implemented in the digital wrist watch fashion. The signal rise and fall time can be first sharpened by a buffer, and then be further sharpened with enlarged magnitude in nonlinear transmission lines. When the wave front contains a large signal with characteristic frequency exceeding the Bragg lattice frequency, single-tone oscillating waves are generated with high power conversion efficiency to drive the millimeter-size antenna.

Broader Impacts: Inexpensive millimeter-size autonomous systems have many important applications such as environmental monitoring, body implants for disease screening and detection with minimal intrusion, the creation of intelligent spaces, and structural health monitoring. The key missing technology is the low-power wireless link. The success of this research effort will bring forth major impacts on senor network and biomedical implants. The miniature autonomous system design will also serve as the main example for outreach to high-school female and minority students to boost their aptitude towards engineering as a socially relevant career direction.

# Nanotube-array based lithography

*NSF NER, Grant #0609349*


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**Collaborators:** Sami Aouadi (Department of Physics) and Haibo Wang (Department of Electrical Engineering) Southern Illinois University; Horacio Espinosa (Department of Mechanical Engineering) Northwestern University; Christina Trautmann (GSI, Germany)


Nano-lithography has proven to be one of the leading approaches for a controllable patterning of molecules at nano- and micro-scale levels. Though many other methods for patterning molecules and nanoparticles at the nanoscale are currently available, they have some limitations such as high throughput rate, simultaneously patterning of different molecules, and relatively expensive instrumentation. Here we show a novel method for fabricating a conical pore in a glass matrix (called chip) which was used to pattern a FITC-tagged DNA onto a gold coated substrate using electrophoretic transport mechanism. The fabricated chips were mounted on a home-made 3-D piezoelectric motors for demonstration of patterning of nucleic acids. Our deposition system may find many potential applications from patterning semiconductors to performing reactions at molecular level.

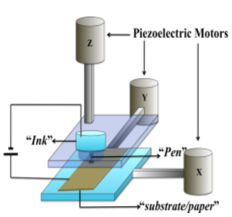


**Figure 1**. Schematic of Instrumentation

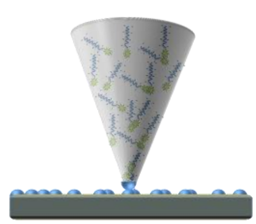

**Figure 2**. Schematic of Pen with DNA writing

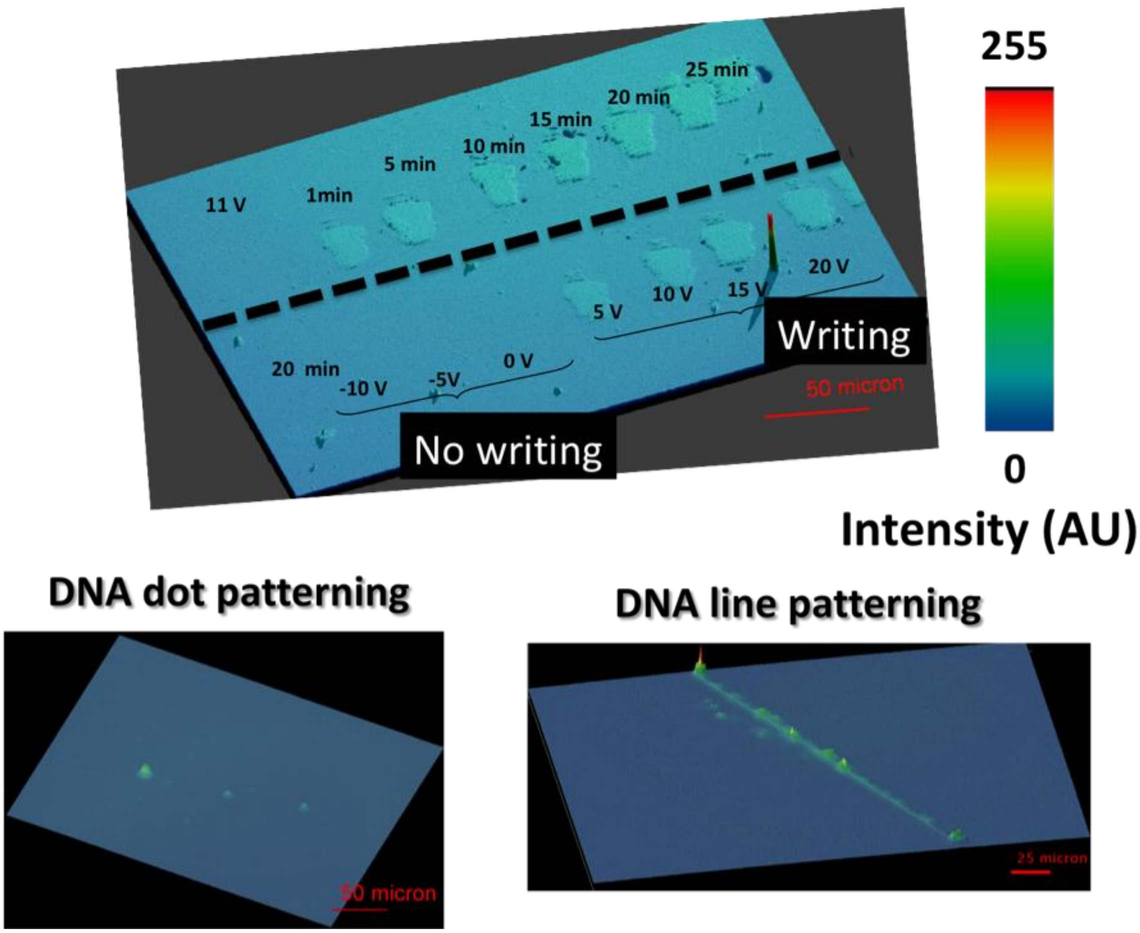


**Figure 3**. Different types of DNA patterns formed on substrates with the application of positive potential. Top figure shows that patterning does not occur when negative potential is applied and occurs only when positive potential is applied.

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**NIRT: Nanometer Stoichiometric Particle Compound Solutions and Control of their Self-Assembly into the Condensed Phase**

*Christopher Sorensen, Kenneth Klabunde, Amitabha Chakrabarti, Bruce Law, and Christer Aakeroy*

NSF Award 0609318

This proposal was received in response to Nanoscale Science and Engineering initiative, NSF 05-610, category NIRT. The goal is to create a new family of nanometer "stoichiometric particle compounds," or what could also be called nanoparticles of all the same size, and to control their active assembly into condensed phases. In order to do this, understanding and control of solution phase and interfacial properties is needed. Understanding of particulate self-assembly to yield two and three dimensional superlattices, films and gels is also needed. To achieve this goal a series of nanomaterials will be synthesized in large amounts and will be "nanomachined" (digestively ripened) to molecular stoichiometry and stabilized with selected surface ligands. The ligands will be chosen for their tendencies to be hydrophobic or hydrophilic, their ability to form ordered monolayers, and to hydrogen bond and/or interdigitate with neighbors. In this way solution phase behavior, aggregation, crystallization to form superlattices, and assembly into various structures will be controlled. The physical chemistry of solutions, their phase diagrams, interfacial phenomena, and transitions to other phases is very well understood. Moreover, much is known about colloid phase stability and what happens when the colloid is destabilized. The new nanometer size stoichiometric particle compounds to be studied lie between solutions and colloids, and their phase behavior, interfacial phenomena, transitions to other phases, and controlled assembly have not been explored with experiment or theory. This research will attempt to rectify this lack of experimental data and understanding, and hence bind all these systems with one universal description. Therecently developed supramolecular building techniques will be extended to assembly of particles rather than molecules. The idea is to view these nearly uniform in size and composition nanoparticles as stoichiometric compounds with behavior, perhaps in some novel manner, analogous to "normal" atomic and molecular systems. Creation of materials based on single-sized nanoparticles, rather than atoms and molecules that actively assemble into superlattices, films, gels and supermolecular entities would yield a whole new class of materials with which it could rebuild or recreate all our modern marvels. Stoichiometric particle compounds can produce a particle-based world. Thus, from a broad perspective, this is an attempt to develop and then use the concept of a three-dimensional periodic table where size is the third dimension. The PIs will develop a streamlined set of course options to allow our students to achieve a broad training across physics, chemistry, materials science and engineering without significantly adding time to their training experience. The program will introduce teen women to nanoscience and technology through a recently established and very successful summer workshop series. The PIs will include undergraduates in the research year round.

**NER: Design and Study of Non-Classical Optical Phenomena in Self-Assembled Nanophotonics**

*Michael Bartl*

NSF Award 0609244

The object of this research is to experimentally realize and study novel non-classical optical phenomena through the combination of nanoscale photon sources with specifically engineered nanophotonic structures. In particular, the proposed work strives to investigate the effect of photonic band structure crystals on spontaneous emission. The approach is based on activating high-quality 3-dimensional titania inverse opal photonic crystals with nanocrystal emitters using molecular linkers with nanocrystal-specific functional groups. The core of the proposed research is a systematic investigation of the optical properties of such nanoemitter-activated photonic crystals, utilizing an arsenal of micro-spectroscopy techniques including polarization-dependent and angle-resolved photon dynamics and statistics measurements.

The defining goals of this proposal are to obtain detailed insights into photonic crystal/nanoemitter coupling for non-classical manipulation of spontaneous emission and to realize novel optical phenomena such as cavity-less photonic band-edge lasing and the creation of stable optical qubits. If successful, the proposed work should lead to breakthroughs in information technology and thus should have significant economic and social impacts. Ultra-fast photon-based information processing lies in the heart of future technologies and therefore can be expected to deeply impact our faster-is-better society. In addition, the multidisciplinary nature of this proposal is also an excellent research area for undergraduate and graduate students, who will be trained in the interdisciplinary aspects of this project, including laser spectroscopy, electron and optical microscopy, and materials chemistry. To further broaden the impact, special efforts will be focused towards the recruitment of minority and female students/trainees.

**NIRT: Nanostructure Components for Terahertz Spectroscopy on a Chip**

*Andrea Markelz, S. James Allen, Jonathan Bird, Lev Murokh, and Gregory Aizin*

NSF Award 0609146

This NIRT proposal focuses on the implementation of frequency-tunable terahertz (THz) sources and detectors based on nanostructured semiconductor systems. The common fea-ture of these active nanostructures is that the energy scales of their characteristic excita-tions lie within the THz range. To address the needs for technology over a wide fre-quency range, we explore devices that achieve their functionality by making use of plas-mons in confined geometries, as well as photoexcitation of electrons in quantum-point-contacts. These devices should be suitable for integration into large-scale arrays, provid-ing the capability to perform sophisticated temporal and spatial signal processing. The team assembled to pursue this research consists of faculty from the University at Buffalo, UC Santa Barbara, Queens College and Kingsborough Community College. It has wide expertise in the fabrication, DC and THz characterization, and theoretical modeling of semiconductor nanodevices. The group is complemented by collaborators at the Institute of Physical and Chemical Research (RIKEN, Japan) and Sandia National Laboratories.

Intellectual Merits: This work should lead to the development of novel THz sources and detectors that are fully integrable with conventional microelectronics. These devices should show several improvements over existing technology, such as widely-tunable response frequency, low power consumption, and enhanced sensitivity. They should find use in many applications, including signal processing, homeland defense, pharmaceutical science and biomedicine.

Broader Impacts: This NIRT provides training for graduate and undergraduate students in nanoelectronic sensors, a vital area to the economic and defense interests of the nation. It also increases the exposure of community-college students to nanotechnology, by means of internships and mini workshops. Opportunities to engage high-school teachers in the research are also planned.

**NIRT: Hierarchical Nanomanufacturing of Carbon Nanotube Sheets and Yarns and their Applications for Active Nano-Materials Systems**

*Ray Baughman, John Ferraris, Karen Lozano, Anvar Zakhidov, and Mei Zhang*

NSF Award 0609115

This proposal was received in response to Nanoscale Science and Engineering initiative, NSF 05-610, category NIRT. One objective of this work is to provide science and technology enabling eventual commercial production of carbon nanotube yarns and sheets having close to the mechanical, electrical, and thermal transport properties of the component individual nanotubes. The approach taken is solid-state processing, since this is the only method that is applicable for the ultra-long nanotubes needed for realizing the spectacular inherent properties of individual nanotubes. Another objective is to add higher levels of hierarchal assembly that are optimized for active device applications. While applications focus will be on artificial muscles, project advances will benefit diverse applications demonstrated for these nanotube yarns or sheets: light emitting diodes, organic and electrochemical solar cells, polarized sheet incandescent light sources, cold electron emission displays and lamps, transparent conducting applique's, thermal electrochemical harvesting, and yarn supercapacitors. The last objective of developing a rational synthetic route to carbon nanotubes of one type, by crystal-based reactions that are an alternative to poorly controllable gas-phase-based nanotube growth processes, will increase fundamental understanding of crystal-controlled solid-state polymerization reactions, chemical transformations dominated by three-dimensional covalent connectivity, and enable bulk property characterizations for nanotubes of one type.

Nano@Border, NanoScout, NanoExplorer, and NanoInventor programs will benefit minorities, very young students, the retired and unemployed, as well as encourage people with quite different backgrounds to work together on interdisciplinary teams in frontier areas. Project funding will expand these educational activities, and bring women and Hispanics to work on the project. Our project collaborations with Raytheon, Lockheed Martin, Nokia, the NASA Ames Center for Nanotechnology, the Naval Undersea Warfare Center, Carbon Nanotechnologies Inc., Hyperion Catalysts International, Eeonyx Corporation, and other companies will both accelerate project progress, and help provide clear paths for commercialization of project discoveries.

**NIRT: Controlling Interfacial Activity of Nanoparticles: Robust Routes to Nanoparticle-based Capsules, Membranes, and Electronic Materials**

*Todd Emrick, Thomas Russell, Narayanan Menon, and Anthony Dinsmore*

NSF Award 0609107

Intellectual Merit: This proposal was received in response to Nanoscale Science and Engineering initiative, NSF 05-610, category NIRT. The objective of this research is to prepare robust materials from nanometer-scale particles, termed nanoparticles. Gaining an understanding of the structure and physical behavior of nanoparticles is crucial for fully understanding their properties, but a significant challenge given the very small size of the particles. The approach is to prepare nanoparticles in unique ways, and with unique surface properties, that allow them to self-organize in the absence of external forces. This self-organization gives assembled nanoscale materials, such as ultra-thin sheets and capsules, where the thickness of the sheet or capsule wall is five nanometers or less. Performing chemical reactions on these assemblies converts them from nano-assemblies, with no mechanical integrity, into nano-materials that are surprisingly robust given their very small dimensions.

Broader Impact: The research carries critically important features that pertain both to technological advances and educational activities. Nanoscale devices, such as encapsulant and release systems used in therapeutic drug treatments, can be improved and refined through the use of nanoparticles as components of the therapy. In addition, nanoparticles, when used in conjunction with conventional membranes for water purification, can help remove water-borne contaminants, leaving clean drinking water following filtration. Finally, the self-organization of nanoparticles in solution provides stunningly beautiful microscopic images. These images convey the physical importance and visual appeal of the science done in the laboratories to the broader public, providing a source of science education in concert with artistic appeal.

# Nanotechnology in the Public Interest: Regulatory Challenges, Capacity, and Policy Recommendations

*Nanotechnology Interdisciplinary Research Team (NIRT), SES #0609078*
**C. Bosso (PI); J. Isaacs, W. Kay, R. Sandler, and A. Busnaina (co-PIs)**
**Northeastern University [1]**

**Project Goals**: This project evaluates federal and state government capacity -- defined here as sufficiency in scientific expertise, legal authority, organizational design, and relevant regulatory frameworks -- to address societal and policy challenges posed by nanoscale innovations and products, and, where appropriate, make recommendations for building capacity to address these challenges. Particular attention is paid to developing capacity in the Commonwealth of Massachusetts, a state currently at the forefront of nanotechnology research and development with requisite expectations about the centrality of nanotechnology to its future economic health, as well as in various cities in the Commonwealth where issues of facilities siting, health and safety concerns, and first responder expertise are paramount.

**Methods employed**: Analysis of scholarly literature; review of government documents and studies; assessment of survey data; interviews with public officials and other policy stakeholders.

**Fields of Impact**: Political Science; Public Administration and Public Policy; Public Health; Journalism; Law; Philosophy; Engineering and Materials Science.

**Collaborations**--NSF Center for High-rate Nano-manufacturing (Northeastern University; University of Massachusetts, Lowell; University of New Hampshire); Boston Museum of Science; Massachusetts Technology Collaborative; Massachusetts Department of Environmental Protection; City of Cambridge (MA); City of Boston; Environmental Law Institute (Washington, D.C.); Toxics Use Reduction Institute (University of Massachusetts, Lowell); other regional nanotechnology related research projects (e.g., University of Massachusetts, Amherst).

## <u>Current Projects</u>

**1. Environmental Regulation Under Uncertainty:** a set of papers organized around the question of how government can ensure effective and responsive environmental protection under conditions of rapid technological change, attendant lack of clarity on effects, information asymmetries, and, by extension, the greater direct role for business in regulatory outcomes. The papers form the basis of an edited volume, *Environmental Regulation Under Uncertainty*, to be published in Spring 2009 by Resources for the Future Press (Washington, D.C.).

**2. FDA Capacity:** This project focuses on the challenges facing the U.S. Food and Drug Administration as it expects to grapple with an array of new nano-enabled technologies, in particular human therapeutics, enhancements, sensors, drug delivery systems, and, even, cosmetics.[2] Comparisons with activities in the European Union and Canada, among others, are to be included. As with Project 1, we are selecting an array of leading scholars in the field who will present papers in a research workshop, tentatively set for Fall 2009, followed by publication in an edited volume, among other venues.

**3. Capacity Building Project:** This project seeks to develop a comprehensive account of how public institutions can develop, improve, and upgrade their capabilities and overall performance. It is to some extent modeled after the research into High Reliability Organizations (HRO) undertaken during the 1990s at the University of California, Berkeley. In that study, researchers were sent to a variety of settings – e.g., emergency rooms, flight control centers, etc. – that combine catastrophic potential with high levels of uncertainty and unexpected events. Over time, these teams observed a number of similarities in organizational structure, operating procedures, and management practices that have come to be commonly recognized as features of an HRO.[3] In much the same way, this project explores cases wherein government agencies must acquire or develop the capacity to address the challenges produced by new technologies, whether as a consequence of technological development or as a need to address the side effects of some product or application. The cases, selected from federal, state, and local levels, are designed cumulatively to shed light on how respective agencies and units adapt themselves – or are forced to respond to – new technologies, new missions, and new challenges. These include:

- NASA and the development of space science
- Creation of Atomic Energy Commission and its transformation into the NRC [4]
- The Food and Drug Administration revises its drug approval process
- Massachusetts DEP responds to a perchlorate problem on Cape Cod
- The City of Cambridge and rDNA rules

**4. Patent Policy:** assess institutional capacity of U.S. Patent and Trademark Office and evaluate intellectual property issues related to patent reform and commercialization of nanotechnologies.

**5. Ethical and Justice Issues:** evaluate applications of nanotechnology on their likelihood to promote or compromise environmental values, e.g., ecological integrity, biodiversity, and environmental justice. [5]

**6. Local and state regulatory capacity in Massachusetts:** The Commonwealth of Massachusetts is in the top tier of the states for research and development in nanoscale technologies, and expects nanotechnology to be a major component of its economy for decades to come. As a consequence, there is considerable shared strong interest in ensuring a smooth transition from R&D to commercial scale production, as well as in developing the local and state institutional capacity to handle any social and environmental effects of technology development and commercialization as this sector matures and grows. Projects under way include assessments of the Commonwealth's biotechnology regulatory system, rules on nanoparticle research reporting explored by the City of Cambridge, the state's response to perchlorate contamination in groundwater on Cape Cod, and controversies over the siting of a Level 4 infectious disease research laboratory in the City of Boston. The research team also has a working relationship with an interagency working group on nanotechnology, an informal network of career staff from an array of state environmental, public health, and occupational safety agencies whose purpose is to provide a forum for discussion about the potential challenges posed by emerging technologies, including nanotechnology. These projects will produce a range of papers to be combined into a report on Massachusetts and the regulation of emerging technologies and made available as case studies for use in undergraduate and graduate courses in public policy and administration, science and technology studies, and related fields.[6]

## Outreach and Education

Education and outreach efforts address the parallel need to build capacity among current and future policymakers, particularly administrative professionals in relevant federal, state, and local agencies and offices, as well as journalists who cover nanotechnology related issues.

**1. Professional association meetings:** posters and presentations at meetings in political science (APSA), public administration, and engineering (ASEE, IEEE). [7]

**2. Graduate and Undergraduate Research** positions for students in philosophy, political science and public administration, environmental studies, and engineering. [8]

**4. Cooperative education and internship opportunities:** full time 6-month research positions for undergraduate students at the Environmental Law Institute (Washington, D.C.) and the Massachusetts Department of Environmental Protection (Boston).

**5. Content rich website and bi-weekly *NSRG e-newsletter*** [http://nsrg.neu.edu]

**6. Sponsored lectures**: C. Kelty (Rice U.); M. Kurath (Harvard U.); R. Masters (Dartmouth).

**7. Courses and modules:** Technology and Human Values (Sandler, undergrad); lectures and modules in a wide array of NEU courses, including nanomedicine, philosophy, business administration, political science and public administration, and engineering.

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# NIRT: Full Spatio-Temporal Coherent Control on Nanoscale

*NSF NIRT Grant CHE-0507147*

PIs: **Mark Stockman[1], Keith Nelson[2], and Hrvoje Petek[3]**
[1]Department of Physics and Astronomy, Georgia State University
[2]Department of Chemistry, MIT
[3] Department of Physics and Astronomy, University of Pittsburgh

Optical processes on the nanoscale are of great importance both fundamentally and for applications in science, engineering, technology, and defense. Among the fundamental problems of the nanoscale optics and nanoplasmonics is delivery if the optical radiation to the nanoscale. The conventional methods with tapered optical fibers and sharp metal tips can produce high enough enhancements of he local optical field by the price of a very low efficiency o the energy transfer. A goal of this project is to find much more efficient ways to transfer energy to the nanoscale using tapered nanoplasmonic structures. The concentration of the optical energy in the nanoplasmonic structures is coherently controlled using spatio-temporal pulse shapers.

We have developed theory of a plasmonic portal: a nanowedge where the propagation of the surface plasmon polaritons toward the tip leads to the transfer of the optical energy and its concentration on the nanoscale at the sharp edge of the wedge [1]. The concentration in the direction normal to the wedge surface and along the propagation direction is possible with the sizes less than 10 nm, which are determined by the minimum thickness of the wedge. The localization in the plane of the wedge normally to the propagation direction is determined by the thickness of the wedge at the site of the polariton launching and is typically on order of 20 nm. Separately, we have established that for plasmonic waveguides tapered stronger than the adiabaticity would allow, a very efficient concentration is possible [2].

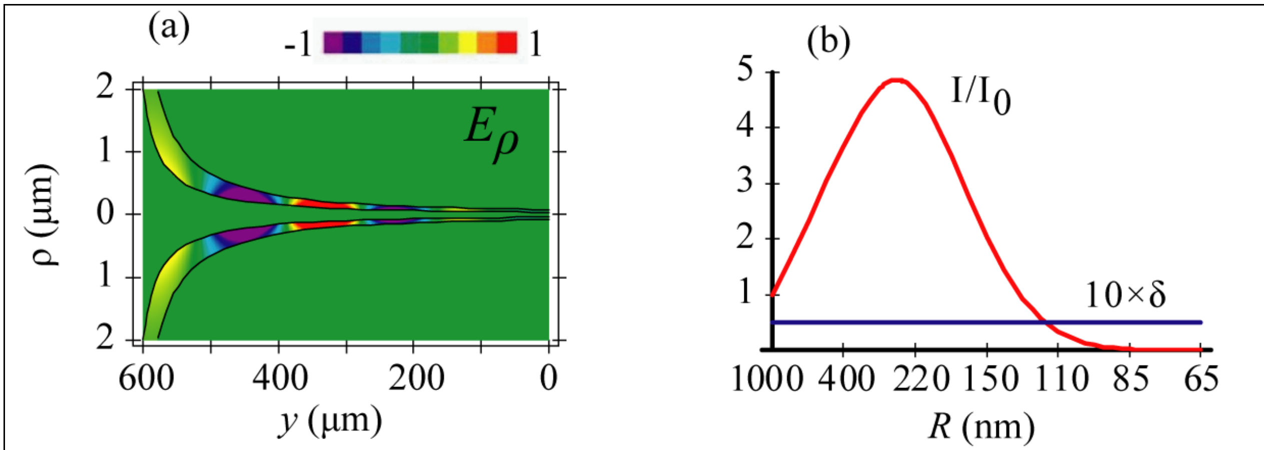


Fig. 1. (a) Electric field amplitude of THz wave in plasmonic metal waveguide. The waveguide is a funnel-like coax where the field is concentrated between the center tapered silver wire and the thick silver shell. The radial field amplitude is shown in relative units using color coding. (b) The red line depicts the relative intensity of the THz radiation as a function of the inner radius *R* of the shell (the outer radius of the waveguide). The blue line shows the value of the adiabatic parameter (multiplied by a factor of 10) as a function of *R*.

We have also developed theory of the terahertz (THz) radiation compression into nanoscale regions [3]. The wavelength of the THz radiation is from tens to hundred microns and exceeds the size of the concentration region by two to three orders of magnitude. The nanoscale concentration of the THz radiation is extremely important for applications, including nonlinear THz spectroscopy, and sensing and detection of submicron objects of the biological origin (viruses, spores, bacteria) for biomedical and defense purposes. We have established that the principal limitation and scale of the spatial concentration of the THz radiation is imposed by the skin effect: the penetration of the THz radiation into the metal of the waveguide and its absorption by the metal, which are the plasmonic phenomena. The skin depth in the THz region is from 30 to 100 nm. We found that the adiabatic compression to the nanoscale is possible in optimally tapered, funnel-like metal plasmonic waveguides [3].

This adiabatic nanocompression of THz radiation is illustrated in Fig. 1, where the THz intensity is increased by a factor of ~5 with respect to the initial intensity at *R*=220 nm. Even for the compression radius of *R*=100 nm, the intensity is still comparable with the initial one. The efficient adiabatic compression of the THz radiation to the nanoscale regions will find application for THz ultramicroscopes with ~100 nm resolution, for detection, sensing and spectroscopy of submicron biological objects (viruses, spores, etc.) for biomedical and defense needs, etc.

We have carried out experimental studies of subwavelength focusing of surface plasmon polaritons (SPPs) on metal surfaces controlled by phased arrays of nanoparticles and by phase-controlled, shaped laser pulses [4, 5], see also [6]. Using PEEM, we have been able to observe the patterns of diffraction, interference and focusing, which are dynamically controlled by the relative phase between the individual pulses in the pair.

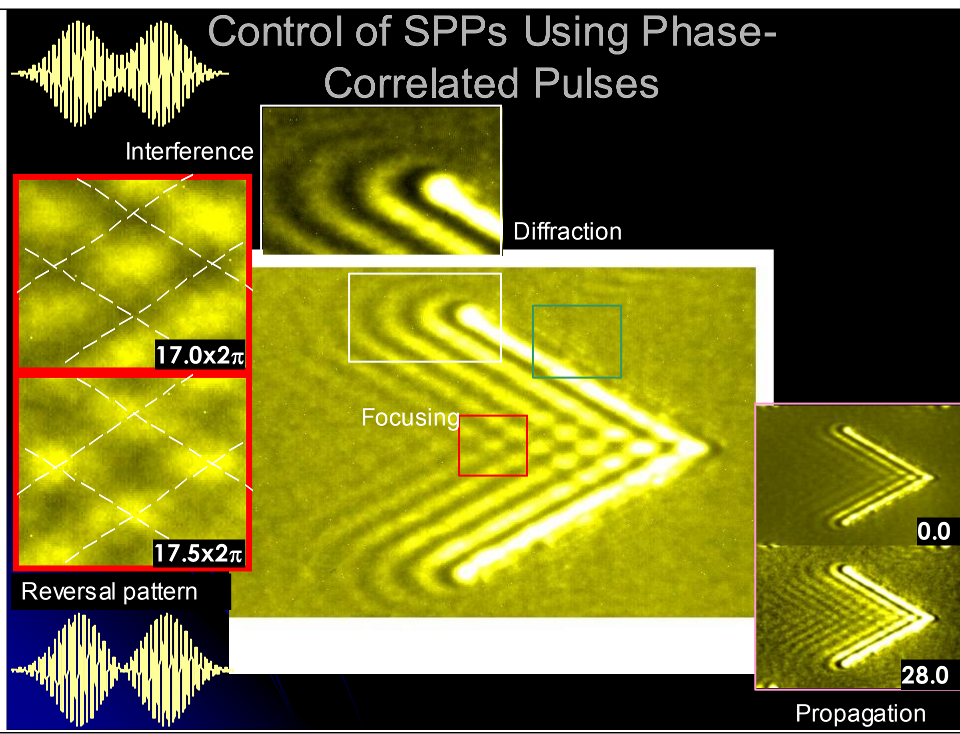


Fig. 2. Coherent control of SPP focusing using phased correlated pulse pairs. Patterns of focusing, interference, and diffraction are observed.

Finally, we have theoretically considered the renormalization of the Coulomb interaction on the nanoscale [7]. One of the manifestations of this effect is the transfer of the optical energy across a nanoplasmonic particle mediated by localized surface plasmons (SPs) [7]. in Fig. 3, we illustrate the transfer of optical excitation energy in the near field across a silver-dielectric nanoshell of aspect ratio *x*. Ad these results show, in the infrared region, the energy transfer rate is very efficient. It is comparable with the quenching rate by the metal, occurring during times on the picosecond scale.

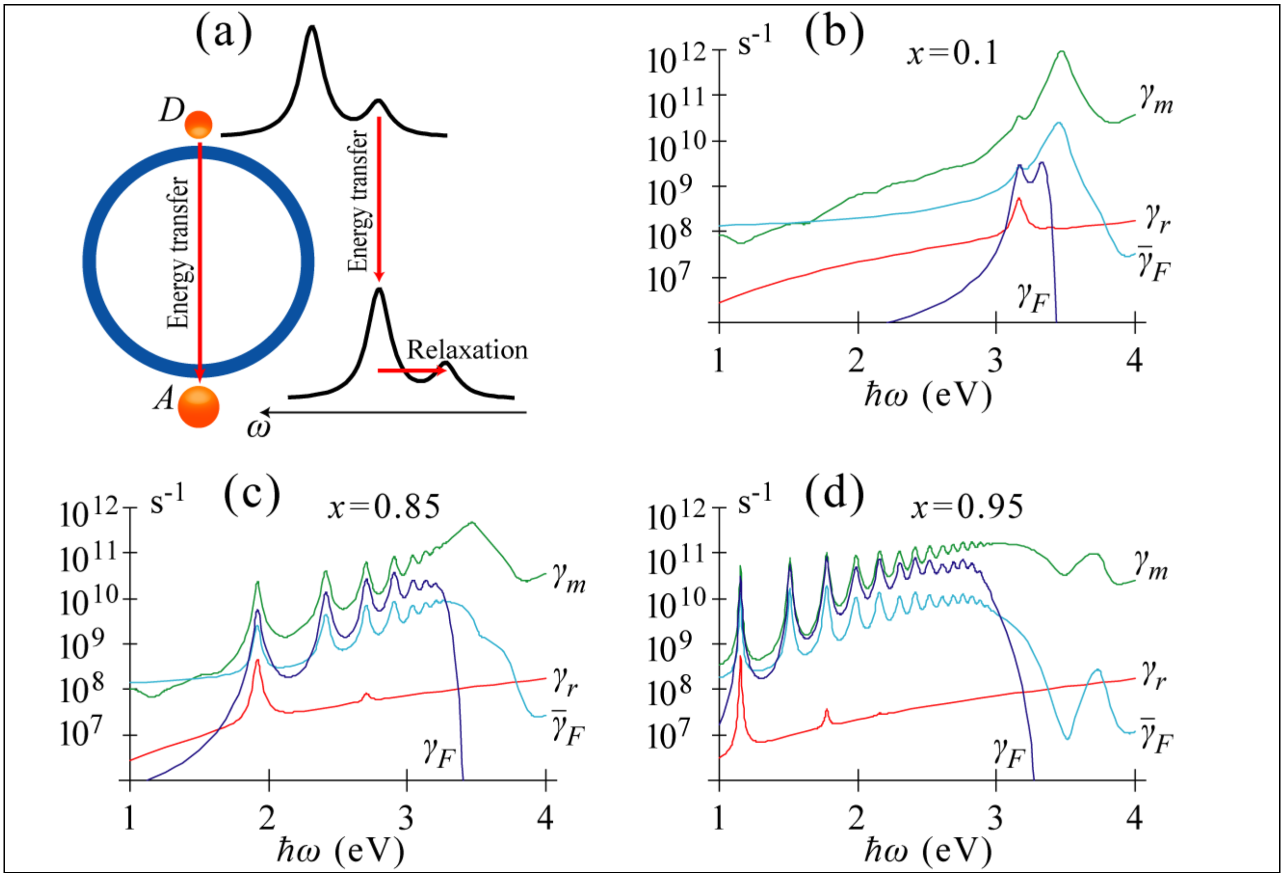


Fig. 2. Transfer and relaxation rates for nanocrystal quantum dots (NQDs) at the outer surface of silver nanoshell, modified and enhanced by SPs. (a) Schematic of the system and energy transfer processes. A nanoshell is indicated by a blue circle, and the donor and acceptor NQDs are labeled by D and A, correspondingly. The frequency distributions of the transition oscillator strengths of the donor and acceptor NQDs are shown by bold black curves. The energy transfer between NQDs and subsequent relaxation are indicated by red arrows. (b)-(c) The nonradiative and radiative relaxation rates (in the logarithmic scale) for NQDs on nanoshells for the aspect ratios x specified in the panels. The FRET rate for two NQDs situated on the opposite poles of a nanoshell [cf. panel (a)] is shown by the blue curves. The SP-mediated FRET rate averaged over the position of the acceptor on the nanoshell is shown by the light-blue curves. The rate of transfer to the metal is plotted by the green curves. The radiative rate for a NQD at the surface of the nanoshell is depicted by the red curves.

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**NIRT: Collective Computation with Self Assembled Quantum Dots, Nanodiodes and Nanowires: A Novel Paradigm for Nanoelectronics**

*Supriyo Bandyopadhyay, Kang Wang, Koray Karahaliloglu, Wei Lu, Pinaki Mazumder, and Jianping Sun*

NSF Award 0506710

The project aims to synthesize nano-structures for cellular neural networks capable of signal processing and collective computational activity. Additionally, speed-power analysis, network abstraction tools and simulators will be developed, and efficient approaches to data input and output will be explored.

The approach is to fabricate and test nanowire and quantum dot arrays using self-assembly and MBE growth. These structures are known to exhibit the desired circuit behavior. A recently observed phenomenon, whereby the negative differential resistance in the structures can be modulated with infrared excitation, is being explored in an effort to create a paradigm for optical programming.

The potential impacts of this research are in revolutionizing alternate approaches to computation and signal processing, and developing a neruromorphic paradigm based on simple self assembled structures capable of ultrafast and ultra low power computation.

# UC Center for the Environmental Implications of Nanotechnology

*NSF Cooperative Agreement Number EF 0830117*

PIs: **Andre Nel, Arturo A Keller, Hilary Godwin, Yoram Cohen, Roger Nisbet**
University of California

**__Vision and overarching description of the Center__**: A recent report[1] by the National Research Council (NRC) of the National Academy of Sciences (NAS) set forth a vision of dramatic change in toxicological testing from individual testing to a predictive high-throughput paradigm premised on the established mechanisms and pathways of toxicity. This report was endorsed in a *Science* policy forum on toxicology[2] and is in accordance with the implementation of high-throughput screening efforts by the US EPA[3] and the National Toxicology Program.[4] The NAS report cites the work at UCLA in the fields of air pollution and engineered nanoparticle (NP) research as an example of how a mechanistic paradigm can be used to build a predictive platform for NP hazards.[1,5,6] In addition to the paradigm of oxidant injury through reactive oxygen species (ROS) generation, which is relevant to environmental toxicology, other mechanisms of injury are emerging, allowing high-throughput screening (HTS) approaches to be implemented to make predictions about biocompatible and bio-hazardous nanomaterial (NM) properties.[5,7–12] Establishing a predictive science is a timely approach for nanotechnology-based enterprises wishing to avoid the problems faced by the chemical industry, where only a few hundred of the *ca*. 40,000 industrial chemicals[13] have undergone toxicity testing, making it very challenging to control the toxicological impact of chemicals in the environment. Building on this seminal concept, we will conduct *predictive toxicological science for NMs* through the founding of the UC Center for Environmental Implications of Nanotechnology (UC CEIN) at UC Los Angeles (UCLA) in partnership with UC Santa Barbara (UCSB), UC Davis (UCD), UC Riverside (UCR), Columbia University (New York), University of Texas (El Paso, TX), Nanyang Technological University (NTU, Singapore), the Molecular Foundry at Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratory (SNL), the University of Bremen (Germany), University College Dublin (UCD, Ireland), and the Universitat Rovira i Virgili (URV, Spain).

__The goal of the Center__ is to develop a *broad-based model of predictive toxicology* premised on quantitative structure–activity relationships (QSARs) and NM injury mechanisms at the biological level. Our *predictive scientific model* will consider: (i) the NMs most likely to come into contact with the environment; (ii) their distribution in the environment, as governed by modes of release, physicochemical and transport properties, interactions with biological substrates, and bioaccumulation; (iii) representative ecological life forms serving as early sentinels to monitor the spread and bio-accumulation of hazardous NMs; (iv) biological screening assays allowing QSARs to be developed based on the bio-physicochemical properties of NMs; (v) HTS of a combinatorial NM library; and (vi) a self-learning computational system providing a framework for predictive risk analysis. These research activities will be combined with educational programs informing the public, future generations of scientists, public agencies, and industrial stakeholders of the importance of safe implementation of nanotechnology in the environment. The overall impact will be to reduce uncertainty about the possible consequences of NMs in the environment, while at the same time providing guidelines for their safe design to prevent environmental hazards.

**Intellectual Merit:** The UC CEIN integrates and advances knowledge from multiple disciplines required tounderstand the complex intersection of nanotechnology with the environment. The Center will unite recognized experts in the fields of engineering, chemistry, physics, materials science, ecology, cell biology, marine biology, bacteriology, particle and chemical toxicology, computer modeling, HTS, and risk prediction to establish the foundation of a new scientific discipline: Environmental Nanotechnology and Nanotoxicology. This team combines resources of several major US research universities and national laboratories—including the California NanoSystems Institute (CNSI), LLNL, SNL, the Center for Nanotechnology in Society (CNS), and the National Center for Ecological Analysis and Synthesis (NCEAS)—with those of international collaborators and industrial partners in the USA, Asia, and Europe. This effort is centered on the creation of a new scientific platform on which diverse disciplines will be integrated into a predictive toxicological science to determine the novel physicochemical properties of NMs and their interactions with ecological life forms at the nano–bio interface. Our predictive toxicological paradigm and QSAR-based analysis of the bio-physicochemical properties of NMs also provides the logical entrée into the knowledge generation, self-learning, and risk predictions that are required for safe implementation of nanotechnology in the environment. Thus, we envisage that predictive toxicological science will grow in step with expansion of the nanotechnology industry, thereby making it possible to act preemptively, rather than retroactively.

**Broader Impact:** Traditional and current toxicity testing in humans and the natural environment relies mainly on a complex set of whole-animal-based toxicity testing strategies. This approach cannot handle the rapid pace at which nanotechnology-based enterprises are generating new materials and ideas. The UC CEIN will address these challenges of scale by implementing a scientific platform that will be updated as nanotechnology evolves from single- to multitasking and, ultimately, to highly complex hybrid products that might include engineered NMs linked to biological components. In addition, the UC CEIN will train the next generation of nanotechnologists in this science-based, paradigm-shift approach toward determining toxicity in the environment. The UC CEIN's creation of a comprehensive computational risk model will allow powerful risk predictions to be made for and by the academic community, industry, the public, and regulating agencies. Our partner centers (CNS, CSNI, NCEAS, LLNL, SNL) will be powerful portals for the dissemination and integration of our research findings to the scientific, educational, and industrial communities, both nationally and internationally—as will be our annual International Summit. Our outreach activities will serve to inform both experts and the public at large about the safety issues surrounding nanotechnology and how to safely produce, use, and dispose NMs.

**Activities in research, education, and their integration***:* Our research goal of developing a predictive risk model for NM impact on the environment will be executed through seven IRGs. To develop an understanding of the QSARs, IRG 1 will establish a physical *library of standard reference NMs* representing the major classes of commercial products; it will also use advanced NM design and synthesis methods to develop a *combinatorial library* that enables our study of the interfacial properties responsible for biocompatible and bio-adverse responses. These NMs will be characterized to determine the physicochemical properties (IRG 1) that are associated with cellular, tissue, and systemic injury in aquatic and terrestrial life forms (IRG 2). These ecological life forms will be chosen to represent a hierarchy of trophic levels in the environment and will be used for assessment of NM uptake, clearance, bioaccumulation, and dose–response relationships (IRG 3). The engineered NPs will be compared with naturally existing congeners to determine their transport, aggregation, stability, and fate in soil, water, and air (IRG 4). We propose to use the key interfacial properties governing interactions at the nano–bio interface (size, surface area, wettability, aggregation, dispersibility, charge) to develop HTS approaches (IRGs 1 & 5) allowing contemporaneous testing of batches of NMs in representative cellular systems (*e.g.*, bacteria, yeasts) for hazard prediction according to a variety of cellular endpoints (oxidant stress response, proliferation, ATP production, mitochondrial dysfunction, apoptosis).[1,5,6] To train novel cognitive neural networks for risk prediction, the physicochemical, biological, toxicological, exposure, and dose–response data will ultimately be integrated into a comprehensive environmental multimedia assessment model for NPs and NP-bound toxicants (IRG 6). This computational risk model will interface with the CNS and NCEAS at UCSB to responsibly convey the risks to industry, the public, and regulatory agencies, and to set environmental safety guidelines (IRG 7).

A major goal of the UC CEIN will be to train the next generation of nano-scale scientists, engineers, and regulators to anticipate and mitigate potential future environmental hazards associated with nanotechnology. These educational programs will broaden the knowledge base of the environmental implications of nanotechnology through academic coursework, world-class research, training courses for industrial practitioners, and a journalist–scientist communication program. We will expand representation and access to this knowledge base through an internship program directed at California community colleges serving underrepresented groups. Our partner centers (CNS, CSNI, NCEAS) will be powerful portals for the dissemination and integration of knowledge to the scientific, educational, and industrial communities, both nationally and internationally.)

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# Center for the Environmental Implications of NanoTechnology (CEINT)

*NSF Cooperative Agreement Number EF-0830093*

PIs: **Mark R. Wiesner[1], Gregory V. Lowry[2], Kimberly Jones[3], Michael Hochella[4], Richard Di Giulio[1]**

[1]Duke University, [2]Carnegie Mellon University, [3]Howard University, [4]Virginia Tech

The Center for the Environmental Implications of NanoTechnology (CEINT) unites world-class groups at four core universities several US university partners, international collaborators, and government labs in a single vision: *to elucidate general principles that determine nanomaterial behavior and translate this knowledge into the language of risk assessment to provide guidance in assessing existing and future concerns surrounding the environmental implications of nanomaterials.*

This is a grand challenge, as the potential diversity of nanomaterials is staggering, with countless variations in size, shape, surface chemistry, chemical composition, coatings and composites. CEINT responds to the challenge of relating a vast array of nanomaterial properties to their potential environmental exposure, biological effects, and ecological consequences. Fundamental questions motivating our research include:

- What nanomaterial properties and environmental conditions control the spatial and temporal distribution of nanomaterials in the environment?
- Are there true "nano" effects on transport, bioavailability, toxicity, and other environmental endpoints that go beyond the effect of very high specific surface area?
- Are there fundamental differences between natural nanomaterials that are ubiquitous in the environment and those that are manufactured? If so, are there evolutionary consequences of these differences?
- Can the effects of nanomaterials on the environment be predicted from first principles such that fully exploiting the benefits of nanotechnology and managing the risks of these materials on the environment becomes tractable?
- What educational, technical, and social impediments must be overcome to ensure that nanotechnology evolves as a tool for sustainability rather than an environmental liability?

Our overarching objective is to unravel the role of nanoparticles in ecosystems, their movements through the environment, their interactions with organisms, the mechanisms by which they exert their influence, and thus, their environmental impacts. CEINT accomplishes these vital tasks through an extensive, highly interdisciplinary, and tightly networked community of scientists and laboratories with a shared educational mission and connection to society through exceptional outreach programs.

**Bridging Disciplines, Geography, and Stakeholders**

Headquartered at Duke, the Center for the Environmental Implications of Nanotechnology (CEINT) integrates the activities of ecologists, cell and molecular biologists, geochemists, nanochemists, materials scientists, ecotoxicologists, environmental engineers, and mathematicians. Faculty and students from Duke, Carnegie Mellon, Howard, Virginia Tech, Stanford, and the University of Kentucky work together with government laboratories and facilities of the **EPA**, **NIEHS**, **NIST**, and **DOE.** Our Center has extensive links to other Nanotechnology Science and Engineering Centers and national ecological research facilities. Our international partners span three continents and include some of the most prominent groups working abroad on implications of nanomaterials for ecosystems and human health. To be an effective center and realize the synergies inherent in this large network of researchers, disciplinary and geographical distances must be overcome. We bridge disciplines and distances in our research and educational program using a multi-institutional team-based model we have developed and tested through our experience with international collaborations. *This model places students at the center of the collaborative process as powerful catalysts for interdisciplinarity.* Our university program includes undergraduate and graduate student fellowships, seminar series, internships, Center and NNIN lab rotations, international and service learning experiences, and annual workshops. Of particular importance to the CEINT is the dialogue that must occur with policy makers, regulators, NGOs and industry. To this end, our Center includes a dedicated policy-translation infrastructure on the ground in Washington, DC. The combination of state-of-the-art facilities for nanomaterials characterization and fabrication, outstanding facilities for ecosystem research, virtual reality tools, and policy-translation groups in Washington DC are uniquely powerful assets for the CEINT. More broadly, our educational program is inspired by a convergence of disciplines at the nano-scale that sets the stage for a new approach to interdisciplinarity that we envision transforming education from grade school through doctoral study. Research and education are seamlessly connected with our outreach efforts in transferring the knowledge generated within the Center to society at large.

***Broader Impacts.*** The CEINT touches virtually every level of the educational enterprise. Specifically, CEINT currently includes innovative formal curricula development G9-12 and REU experiences. Our recruitment effort will establish a diverse cadre of graduate students through aggressive efforts that will engage traditionally underrepresented minorities and women. Howard University's status as an HBCU—where approximately 88% of the chemistry, biology, and engineering enrollment is African American—provides a direct path to engage historically under-represented minority students in cutting edge research and nanotechnology policy-making activities. Laboratory rotations of students *to* Howard from other CEINT partner institutions will further support Howard's research mission. We link active programs across the Center to enhance the recruitment of URM graduate students, provide connections with other HBCUs and HSIs (Hispanic Serving Institutions), establish relationships with undergraduate research programs, and provide services that enhance the professional preparation of all students associated with this center.

**Multi-scale, Interdisciplinary Research**

To accomplish the Center objectives, we draw on a core of internationally recognized leadership in five areas of expertise: 1) environmental toxicology and ecosystem biology, 2) nanomaterial transport, transformation, and fate in the environment, 3) biogeochemistry of nanomaterials and incidental airborne particulates, 4) nanomaterial chemistry and fabrication and, 5) environmental risk assessment, modeling, and decision sciences. Grouped into *three primary research themes* and *three crosscutting core activities*, each of these areas of expertise is vital to a comprehensive investigation of environmental implications of nanomaterials (**Figure 1**). CEINT research is grouped into three interconnected Themes: 1) Exposure: Transport and Transformations in Laboratory Systems, 2) Cellular and Organismal Responses and, 3) Ecosystem Responses. This research is supported in turn by work in three crosscutting Cores: A) Manufactured Nanomaterials, B) Natural and Incidental Nanomaterials and, C) Modeling, Risk Assessment, and Societal Impacts.

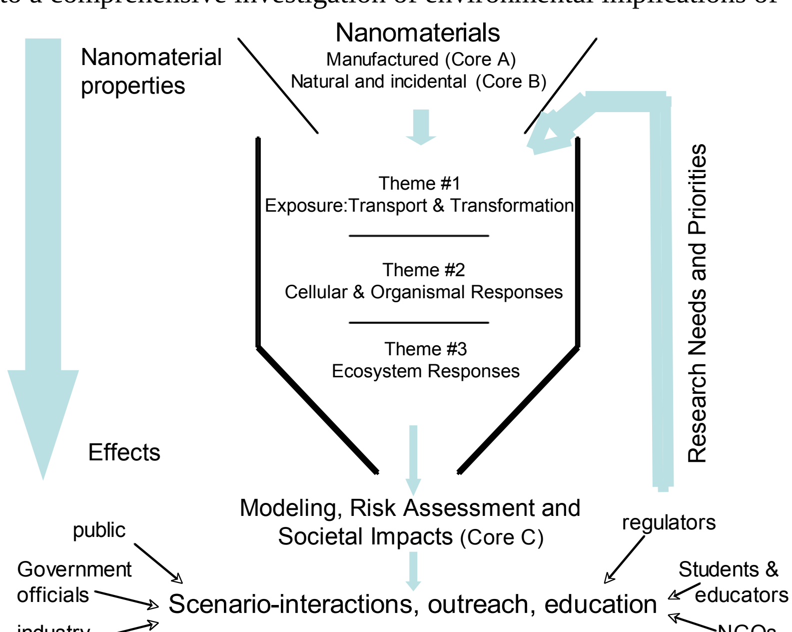


**Figure 1.** Themes, Core areas and activities.

Research advances through multiple scales and at increasing levels of complexity (**Figure 2**). Beginning with work in **Theme 1**, we determine how the physical and chemical properties of nanomaterials of defined structure, composition and size dictate their distribution and persistence in the environment (exposure), as well as the effects of biological and chemical transformations on exposure processes. In **Theme 2,** we examine how these variations in exposure affect bioavailability and single organism endpoints, including hazards such as toxicity. Finally, in **Theme 3,** we consider how complex interactions in microcosms, mesocosms, and field sites combine to produce exposure and hazards that include large-scale endpoints such as alterations to ecosystem services like nutrient cycling. From beaker to ecosystem, these studies are bound together by a consideration of types of nanomaterials and the transformations they undergo. Our approach is thus both reductionist and constructionist, allowing observations made in complex systems to be interpreted in the context of fundamental mechanisms elucidated in controlled laboratory systems.

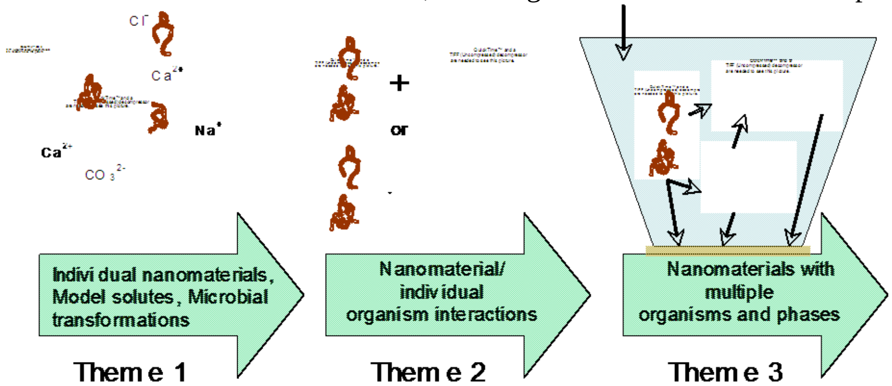



**Figure 2.** Increasing complexity of experimental systems: from controlled laboratory experiments to ecosystems with multiple organisms and phases.

***Intellectual Merit.*** Our research addresses the influence of nanomaterials on processes ranging in scale from the subcellular to ecosystems. We will elucidate factors controlling nanomaterial exposure, persistence, bioavailability, toxicity, metabolism, trophic transfer, and impacts on population evolution, and critical ecosystem functions. *A distinctive element of our Center is the synthesis of this information into a rigorous risk assessment framework and an accompanying infrastructure to transfer these results into the policy-making community and society at large.* Manufactured nanomaterials will be studied not only as possible emerging contaminants, but also as laboratory models that will allow for systematic manipulation of size, functionality, composition, and shape to reveal the relationships that may exist between the properties of nano-scale materials and their bio-chemical interactions.

The systematic study of nanoparticle properties and their relationships to environmental transport and endpoints will be the foundation for the next generation of risk assessment. By this we mean the ability to relate particle descriptors to environmental function, as opposed to the labor and time consuming paradigm of case-by-case risk assessment. Our research on manufactured, naturally occurring, and incidental nanoparticles recognizes that *if data on nanoparticle risk are to be meaningfully interpreted, it is critical to quantify the relative exposures presented by these various sources of nanomaterials.* This, and other basic information developed by CEINT, may redefine environmental risk assessment for nanomaterials. Social scientists in CEINT will study the emergence of an industry whose economic benefits are propelling a major expansion in the face of unquantified environmental implications.

For further information about this project link to **www.ceint.duke.edu** or email **wiesner@duke.edu**

**NSEC: Center for Scalable and Integrated Nanomanufacturing (SINAM)**

*Xiang Zhang*

NSF Award 0751621

This award provides for the continuation of the Nano Science and Engineering Center for Scalable and Integrated Nanomanufacturing (SINAM) for an additional five years. The center focuses on a manufacturing paradigm that offers to transform laboratory science into industrial applications in nano-electronics, biomedicine, and in traditional industries. The center includes a team of scientists and engineers from six institutions, UCLA, UC Berkeley, Stanford, UCSD, University of North Carolina and HP Labs. Research will focus on a nano-manufacturing paradigm that includes plasmonic imaging lithography (PIL) using engineered surface plasmons with extremely short wavelength and ultra-molding lithography. Both aim at nanomanufacturing at the 1-10 nanometer scale. SINAM will further develop a novel hybrid approach, in combining the top-down and bottom up technologies to achieve massively parallel integration of heterogeneous nanoscale components into higher-order structures and devices. SINAM will develop system engineering strategies to scale up the technologies developed and work with industry to develop the next generation of nanomanufacturing tools that will be used for commercial product design and development. The center?s goal over the next five years is to fully develop and scale up the nanomanufacturing technologies that enable the transition to industrial applications.

SINAM's broader impacts includes education and training for a high tech workforce, and societal outreach for general public benefits. Special efforts will be made with California schools to reach out to minority and female students. These educational activities include: (1) Grades 7-12, Discover Nanotechnology where SINAM researchers will make use of an inquiry module on Nanotechnology for students; (2) a Nano-Manufacturing Summer Academy that will provide six weeks summer training for undergraduates students and K-12 school teachers; and (3) "Graduate Young Investigator (GYI)" and Industrial Internships for Graduate Students. To build awareness of the opportunities and impact of nano manufacturing, center personnel will work with California Science Museums and the California State Economic Strategy Panel, and they will work through professional organizations such as ASME, SME, and IEEE in organizing symposia. The SINAM Industrial Consortium, established during the first five years of the center, will work closely with the center?s industrial partners, such as HP and IBM, to transfer new technologies to industrial applications. The new manufacturing paradigm resulting from this research will impact the society through the acceleration of the emergence of new technologies and industries based on nanotechnology

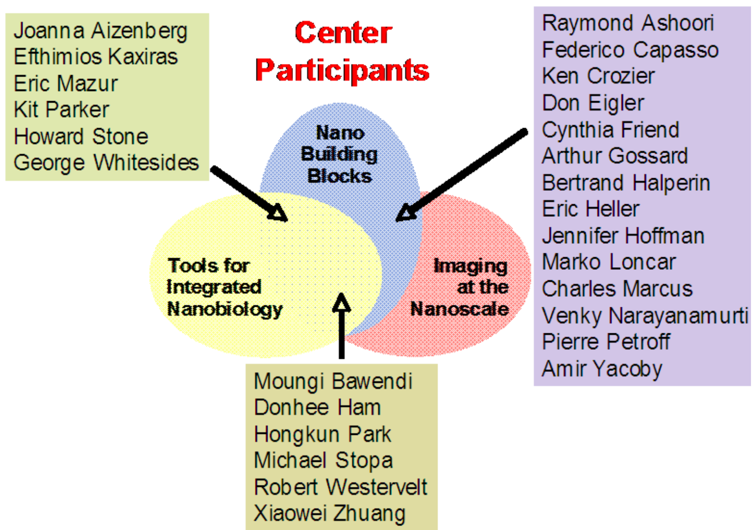
# Science of Nanoscale Systems and their Device Applications


*NSF NSEC Grant PHY-06046094*

PIs: **R.M. Westervelt** and **B.I. Halperin**

Harvard, Massachusetts Institute of Technology, University of California Santa Barbara, & Museum of Science, Boston

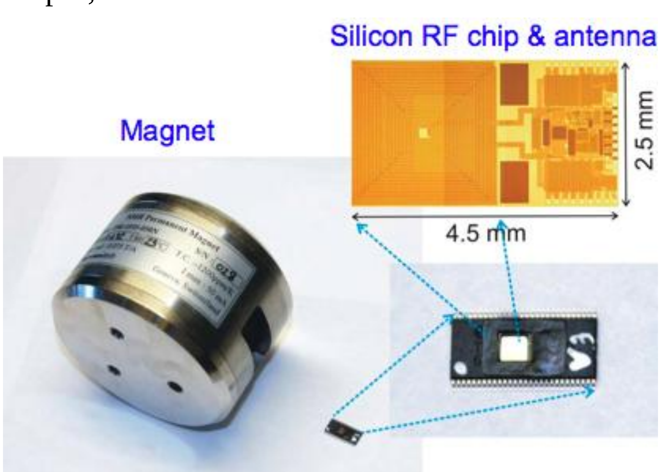

Our Nanoscale Science and Engineering Center develops tools to study nanoscale systems. We would like to control electrons and photons in nanostructures for nanoelectronic and nanophotonic devices. The Center plans to do this by synthesizing nanoscale building blocks and by developing new imaging techniques. We would also like to understand how biological systems function at the nanoscale by developing tools based on the Physical Sciences.




Three Clusters address these goals:

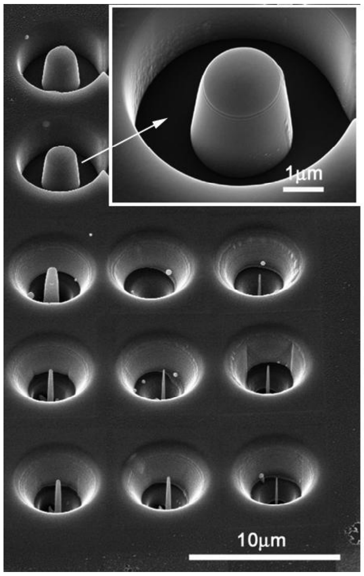
**Cluster I: Tools for Integrated Nanobiology** builds bridges between the Physical Sciences, Biology, and Medicine. The Physical Sciences offer powerful new tools for manipulating and testing biological cells and tissues, based on microfluidics, semiconductor technology and biological probes. In turn, Biology and Medicine offer an enormous range of engaging problems in functional biological systems, and the opportunity to think about "hybrid" systems that combine biological and non-biological components.

**Cluster II: Nanoscale Building Blocks** addresses the synthesis of new classes of nanostructures that exhibit size-dependent properties. An emphasis is placed on structures with unconventional shapes, as well as on zero- and one-dimensional nanoparticles and nanowires. Techniques are being developed to synthesize nanostructures from new materials, including oxide semiconductors and metal chalcogenides. These nanoscale building blocks provide new approaches for nanoelectronics and nanophotonics as well as sensors for biological systems.




One-chip NMR relaxometer for biodetection. (**Ham**)

**Cluster III: Imaging at the Nanoscale** explores new ways to image the quantum behavior of electrons and photons in nanostructures using custom-made cooled scanning probe microscopes for capacitive probing of electrons and near-field




Diamond nanowires fabricated from a single crystal (**Loncar**).

scanning optical microscopes for subwavelength imaging with custom tips. Imaging is an essential tool for the development of nanoelectronics, nanophotonics, and qubits for quantum information processing. New types of semiconductor heterostructures are grown for this work using Molecular Beam Epitaxy.

The **Center for Nanoscale Systems (CNS)** is a major investment by Harvard to create and maintain the facilities needed for research in this nanoscience and technology. A new building, the **Laboratory for Integrated Science and Engineering,** completed in fall 2007, houses **CNS** facilities for imaging, nanofabrication, and materials growth. Harvard and UC Santa Barbara provide facilities to outside users through the **National Nanotechnology Infrastructure Network (NNIN)**.

Connections with **Industry** are built by Harvard's **Office of Technology Development** and by the **Industrial Outreach Program** of the School of Engineering and Applied Sciences. Our Center is funded by the **Nanoelectronics Research Initiative** (**NRI**) of the **Semiconductor Reseaerch Corporation** to develop new oxide materials for future logic switches. Many Center participants collaborate with industry.

Our Center promotes **Education** in nanoscale science and engineering and develops **human resources** at the pre-college, undergraduate, graduate, and postdoctoral levels through a range of activities including REU and RET programs, a Harvard course *Applied Physics 298r — Interdisciplinary Chemistry, Engineering and Physics,* and workshops including annual *Industry Partnership Program* workshops and *Frontiers in Nanoscale Science and Technology* workshops held with our international collaborators.

Our Center aims to increase **Diversity** by recruiting a more diverse group of graduate students and postdocs, increasing the diversity of participating faculty, recruiting members of under-represented groups through our REU program, introducing public school students to science and engineering, and developing long-term partnerships with predominantly female and minority-serving institutions.

The **Museum of Science, Boston** informs the public about advances in nanoscience and technology in an entertaining and informative way. Larry Bell and Carol Lynn Alpert at the Museum help direct the **National Informal Science Education (NISE)** network in partnership with The Exploratorium in San Francisco and The Science Museum of Minnesota. The NISE network is designed to foster public awareness, engagement and understanding of nanoscale science, engineering and technology.

For further information, please see our website **http://nsec.harvard.edu**.

The **Laboratory for Integrated Science and Engineering** at Harvard houses **Center for Nanoscale Systems** shared facilities.

## Nanoscale Science and Engineering Center for Directed Assembly of Nanostructures

*NSF NSEC Grant 0642573*

PI: **Dr. Richard W. Siegel**
Rensselaer Polytechnic Institute

The NSF *Nanoscale Science and Engineering Center for Directed Assembly of Nanostructures* (www.nano.rpi.edu) was founded in September 2001 at Rensselaer Polytechnic Institute, the University of Illinois at Urbana-Champaign, and Los Alamos National Laboratory. Our NSEC addresses the fundamental scientific issues underlying the design and synthesis of nanostructured materials, assemblies, and devices with dramatically improved capabilities for many industrial and biomedical applications. Directed assembly is the fundamental gateway to the eventual success of nanotechnology. Therefore, our NSEC strives to discover and develop the means to assemble nanoscale building blocks with unique properties into functional structures under well-controlled, intentionally directed conditions. We combine theory and computational design with experimentation to focus on discovery of novel pathways to assemble functional multiscale nanostructures with junctions and interfaces among structurally, dimensionally, and compositionally different building blocks. Our NSEC integrates research, education, and technology dissemination to serve as a leading national and international resource for fundamental knowledge and applications in nanoscale science and technology. The NSEC *research program* consists of three coordinated interdisciplinary and inter-institutional thrusts.

*Thrust 1: Nanoparticle Gels and Polymer Nanocomposites* focuses on the synthesis, phase behavior, structure, and assembly of organic and inorganic nanoparticles with homogeneous or heterogeneous surfaces by means of chemical and / or physical control. Its goal is to guide the organization of nanoscale building blocks to create 3-D hierarchical materials with novel properties. We continue to focus on two primary research areas: nanoparticle gels and polymer nanocomposites, which are closely integrated through shared intellectual threads and a highly collaborative and interdisciplinary research team. During the past several years, we have synthesized organic and inorganic nanoscale building blocks with controlled size, composition, and surface functionality, studied the viscoelasticity, phase behavior, and structure of model nanoparticle-polymer mixtures, created 3-D hierarchical structures by means of direct-write assembly of nanoparticle inks, and synthesized, assembled, characterized, and modeled the behavior of polymer nanocomposites.

*Thrust 2: Nanostructured Biomolecule Composite Architectures* is focused on the incorporation of biological macromolecules into nanocomposite materials to enable specific applications, including directed assembly based on biorecognition and biocatalysis, which impact tissue engineering, biosensing, self-cleaning and self-repair capabilities, and the design of novel lamellar structures. Its goal is to enable the efficient and selective interaction of biomolecules with synthetic nanoscale building blocks to generate functional assemblies. Achieving fundamental understanding, both experimental and computational, of the molecular events that govern biological function and selectivity in nonbiological nanoscale environments is crucial to developing nanostructured biomolecule composite architectures.

Our research team is well positioned at the interface of biological and material sciences, which enables us to integrate our extensive interdisciplinary expertise in biomolecular engineering; nanomaterial preparation, characterization, and functional assembly; and theory and simulation. During the past several years, we have focused on the preparation, fundamental understanding, and potential applications of biomolecule / nanomaterial hybrid composites with tailorable structures and functions.

*Thrust 3: Serving Society through Education and Outreach* has as its goal to serve society by: (i) raising public science literacy through informal and formal education, and reaching a diverse audience to broaden the technical reach of our NSEC through programs that are carefully designed to integrate nanotechnology research with education, and (ii) enhancing the responsible, safe, and efficient transfer of nanotechnology developments to industry, the primary route through which society can benefit from the fruits of our research. Hence, our continuing vision encompasses research, education, and outreach through interactions with students of all ages and researchers in universities, national laboratories, and industry. Our Molecularium® project (www.molecularium.com) continues to be highly successful in the important area of public science literacy. We have reached thousands of people so far, and are on our way to reaching ever-wider segments of society.

Through our industry outreach program, we have already entered into several pre-commercial trials of technology developed in our NSEC laboratories. We are continuing our strong industry interactions, which not only provide a mechanism for transferring technology to benefit society, but also broaden the education of our undergraduate and graduate students. To better understand how technology is used by industry, we initiated a study of socioeconomic impacts that is providing an understanding of the role of industry, the role of collaborations, and the role of public perception in the development of nanotechnology.

Examples of major accomplishments in our NSEC program reported in the last year have been:

- Room Temperature Assembly of Germanium Nanoparticle-based Photonic Crystals: Through a rapid and low-cost self-assembly process, a nanoparticle-based photonic crystal, a three-dimensionally periodic material with unique and powerful optical properties, was formed. Our photonic crystals exhibited the greatest photonic strength to date of any nanoparticle- based systems, and in addition, we demonstrated, for the first time, that germanium nanoparticles could be directly used to create a photonic crystal. Reflectance spectroscopy, in conjunction with appropriate theoretical models was used to determine that the germanium photonic crystal had a refractive index contrast of 2.05, the largest refractive index contrast obtained to date for any nanoparticle-based system.
- Chain Conformations and Bound Layer Correlations in Polymer Nanocomposites: A combined experimental and theoretical approach has been employed to address the open question of chain conformation and adsorption in polymer nanocomposites. Small angle neutron scattering (SANS) on mixtures of polystyrene and nanosilica has unequivocally shown that polymers adopt random coil shapes, whose sizes are independent of molecular weight and nanofiller concentration. Our novel microscopic statistical mechanical theory of polymer nanocomposites also predicts the existence of a thin thermodynamically stable bound layer of polymer surrounding dispersed fillers. The experimental polymer scattering signature of this phenomenon is a peak in the SANS spectrum, whose intensity and location are controlled by nanoparticle size and volume fraction. The neutron scattering data are consistent with these predictions thereby providing the first evidence for the existence of nanoscale layers that play a critical role in promoting miscibility and good filler dispersion.

- Enzyme-catalyzed Directed Assembly of Organogels: Organogelators with excellent ability to gel a broad range of organic solvents as well as natural oils (olive and vegetable oils) were synthesized using all natural building blocks (sugars, fatty acids, and enzymes). This is an example of exquisitely selective enzyme-catalyzed directed assembly – chemical synthesis of the gelators results in poor gel properties due to the lack of selectivity. With their ability to assemble at the nanoscale, and to be prepared from all natural building blocks (sugars, fatty acids, and enzymes), these gelators may be used to encapsulate pharmaceutical, food, and cosmetic products and to build 3-D biological scaffolds for tissue engineering.

- Cellulose Nanotube Composites as Flexible Power Sources: Nanocomposites have been developed that have enhanced biocompatibility while still exhibiting important properties associated with nanomaterials. Nanoporous cellulose-heparin composites were prepared as blood compatible membranes for kidney dialysis and as electrospun fibers for woven vascular grafts. Of significant interest in combining biological and materials applications, cellulose-oriented carbon nanotube composites have been prepared, which contain ionic liquids as batteries and supercapacitors and a patent application filed. These flexible, biocompatible devices are being evaluated in a number of applications including as implantable and wearable power sources for medical assist devices.

- Self-Assembly of Decorated Nanoparticles in Polymer Nanocomposites: The self-assembly of nanoparticles into complex superstructures with precise geometrical form is typically controlled through particle shape or directional interparticle interactions. A more subtle issue is the creation of anisotropic structures from isotropically interacting spherical particles. While one-dimensional strings can be formed from such particles at high particle loadings, the formation of extended assemblies (cylinders, sheets) at low particle loadings is typically attributed to particles with directional interactions. We have shown that spherical nanoparticles uniformly grafted with polymer chains dispersed in a homopolymer matrix with the same chemistry as the “brush” can self-assemble into highly anisotropic sheets even at low particle loadings. This self-assembly process, which is analogous to the behavior of block copolymers and other surfactants in selective solvents, can have profound implications for applications in which it is well established that a small amount of highly anisotropic filler can lead to improved properties.

- Nanotube-Assisted Protein Deactivation: There is currently substantial interest in understanding and achieving remote control over protein function on nanomaterials. We have demonstrated for the first time the remote and specific nanotube-mediated deactivation of proteins using near-infrared irradiation (wavelengths 700-1100 nm). The observed deactivation is mediated by a photochemical reaction involving free radicals generated on irradiation of the carbon nanotubes. Such an event has been used to design polyvalent nanotube-peptide conjugates that target and destroy anthrax toxin and to design optically transparent nanotube coatings that possess “self-cleaning” activity following either near-infrared or visible irradiation. Nanotube-assisted deactivation, therefore, represents a general and facile strategy for the targeted destruction of proteins, pathogens, and cells, with applications ranging from antifouling coatings to proteomics and novel therapeutics.

# Electron Transport in Molecular Nanostructure

*NSF NSEC CHE-0641523*

PIs: **James T. Yardley**, **Ronald Breslow**, **Tony Heinz**
Columbia University

The Columbia University Nanoscale Science and Engineering Center (NSEC) is dedicated to developing the highest level of fundamental understanding for many important phenomena of electron transport through single molecules, carbon nanotubes, graphene, and nanoscale molecular assemblies [1]. Our research program is exploring three broad scientific propositions:

- Molecular Conduction: The fundamental phenomena for electron transport through a single molecule represent an exciting opportunity for scientific discovery.
- Molecular Assembly: Through combination of “bottom up” creation of specific chemical systems and “top down” fabrication, we can explore transport properties of two dimensional nano-structures.
- Nanoscale Characterization: Characterization of nanoscale molecular assemblies closes the functional design loop linking molecular properties, pathways for assembly and electrical function.

Our interdisciplinary program pursues the synthesis, fabrication, and characterization of three different types of nanoscale molecular systems in intimate contact with electrical contacts: (1) single walled carbon nanotubes, (2) two-dimensional molecular systems including graphene and (3) single molecules. The Nanocenter program brings a common intellectual approach to create a fully integrated multidisciplinary program built upon these molecular systems.

*Electron Structure and Dynamics in Single Walled Carbon Nanotubes*. We have made significant advances toward the characterization and understanding of isolated single walled carbon nanotubes. We have developed a unique form of Rayleigh Scattering Spectroscopy which provides rapid spectral signatures for individual nanotubes. This discovery has dramatically influenced how the entire scientific community explores the fascinating phenomena associated with carbon nanotubes. These capabilities are allowing us to explore the electronic properties of carbon nanotubes and carbon nanotube devices that have been structurally identified. These fundamental measurements will open up new perspectives in our understanding of the electronic transport properties of carbon nanotubes and corresponding devices.

*Two Dimensional Molecular Nanostructures*. We have begun to develop methodology for the fabrication and electrical characterization of two dimensional planar graphene. We have confirmed the theoretical predictions based on band structure of the ideal system and we have begun to define the practical capabilities for this system. These discoveries form the basis for extensive explorations of these exciting new two dimensional systems. Thus we are exploring the electronic properties on nano-scale ribbons of graphene as potential new electronic devices which can be fabricated using planar processing techniques. We are examining the role of defects and edges on the electronic properties. We are also examining the implications of chemical modifications of graphene.

*Single Molecule Conduction*. The fundamental characterization of conduction phenomena in single molecules has proven to be a major scientific challenge. Our discovery of diamine-gold systems has allowed us for the first time to undertake systematic explorations of the influence of chemical structure on molecular conductance. These experiments thus point the way toward a definition of chemical "design rules" for molecular conduction phenomena. Our demonstration of direct measurement of conductance for a single molecule covalently bonded across a nanometer-scale carbon nanotube junction has created a new platform for single molecule conductance studies. These experiments are already demonstrating a rich variety of behavior and should become a primary tool for explorations of molecular conductance.

*New Paradigms for Multidisciplinary Research*. Within the communities of Columbia University, Barnard College, City College of New York, and Rowan University, we have created a new paradigm for multidisciplinary research. Our program has been extremely effective in generating excitement about nanoscale science and engineering and the rewards of interdisciplinary research. We have generated new perspectives to the graduate and undergraduate student body through examples of successful interdisciplinary research, strong and vital seminar programs, new courses and major changes in existing or basic courses. The Columbia Nanocenter has made major impact on the research infrastructure and methodology for carrying out interdisciplinary research in the university setting.

**References**

[1] For further information about this project visit the internet web site: www.cise.columbia.edu/nsec/ or email James Yardley at jy307@columbia.edu.

# Network for Computational Nanotechnology – nanoHUB.org

*NSF Award EEC-0634750*
PI: **Mark S. Lundstrom, Director**
**George B. Adams III, Deputy Director**
**Gerhard Klimeck, Associate Director for Technology**
Purdue University, West Lafayette, IN

The Network for Computational Nanotechnology (NCN) is an NSF infrastructure and research network established in September 2002 to support the National Nanotechnology Initiative. NCN operates **nanoHUB.org**, a cyber-resource for nanotechnology theory, modeling and simulation. Our vision is to grow and support a diverse nanotechnology discovery and learning community via shared research and educational resources.

**We encourage all NSF-funded nanotechnology research projects to make the most of nanoHUB.org as a dissemination vehicle.**

85,000 people used nanoHUB.org in the past 12 months. This large audience means content contributors realizing impressive returns. Two examples are Prof. Supriyo Datta, Purdue University and Prof. Dragica Vasileska, Arizona State University. See http://www.nanohub.org/com_usage/?task=contributors

Datta has published his graduate-level Nanoelectronics lectures on nanoHUB.org and to date they have been viewed or downloaded over 130,000 times. Such massive influence on graduate education lead to his being awarded the 2008 IEEE Leon K. Kirchmayer Graduate Teaching Award.

Vasileska published her nanoelectronics simulation tool SCHRED on nanoHUB.org. As she continues to use SCHRED, and has published nine papers of her group's work based on it, over 1300 other nanoHUB users have run 32,500 SCHRED simulations leading to over 70 papers in the research literature, all citing Vasileska.

Datta's and Vasileska's experiences illustrate the value of placing quality content online before a very large, active academic community of users. The usage data reported here, and much more, is available for any content hosted on nanoHUB.org. As an NSF-funded effort ourselves, we appreciate the value of such data for understanding your outreach success and documenting your impact.

Publishing of seminars, videos, and simulation tools on nanoHUB.org is about as difficult as posting a video on YouTube. NCN staff are ready to assist you. There is no charge to upload content or to host it. Sign up for a free account at **nanoHUB.org** and get started.

# Nanoscale Informal Science Education Network


Grant *0532536*

PIs: **Larry Bell**, **Carol Lynn Alpert, Paul Martin, Rob Semper, Tom Rockwell**

Museum of Science, Boston; Science Museum of Minnesota; Exploratorium

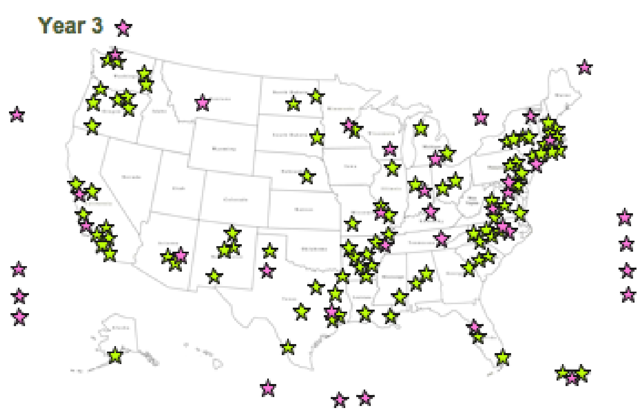

The Museum of Science, the Exploratorium, and the Science Museum of Minnesota are working together to lead a national Nanoscale Informal Science Education Network, in order to:

- Research, develop, implement, and disseminate educational products and experiences that inform, inspire, and engage public, youth, and professional audiences in nanoscale science, engineering, and technology, and their societal implications.
- Create a sustainable service-oriented infrastructure that can nurture ongoing professional development and innovation in nanoscale informal science education and also grow and adapt to reach new audiences in collaboration with new partners.
- Build lasting bridges between research institutions and their communities through museum and research center collaborations focused on enhancing public engagement with research.

In it's first two years the NISE Net, then comprised of 15 organizations, built the capacity of a core set of institutions and individuals to develop and present informal nano educational experiences by working together to develop and evaluate a broad range of new programs, exhibits, forums, media and visualizations that address various aspects of nanoscale science and technology. It also worked to create new connections between various researchers and informal science educators. The goal was to have public nano education activities at 100 sites nationally, but research within the informal science education community in the first two years, showed little institutional commitment or capacity to include nanoscale science and engineering within science museum exhibits and programs. And so the NISE Net strategy was redirected in year three toward creating both commitment and capacity within science museums to offer nanoscale informal science education.

**NanoDays 2008**

As a concrete step toward building the number of institutions engaged in offering educational experiences about nanoscale science and technology to the public, the NISE Net launched NanoDays March 29-April 6. The original intention was to get 30 institutions to participate, but when initial recruitment efforts demonstrated greater interest than expected, the NISE Net produced and distributed 100 NanoDays kits to sites across the U.S. and provided additional access to materials included in the kit over the NISE Net website.



Students compare diameters of nanofibers and human hair using SEM at UPR-Humacao

Students build virus models during the NanoDays events at Montana State University. Photo by Martha Peters.

NanoDays activities occurred throughout the U.S. March 29- April 6, 2008

**Network Building**

For many institutions NanoDays was an introduction to providing educational activities to the public about nanoscale science and technology. For others it was the first time nano researchers and science museum staff partnered in a program of public education. NanoDays was not intended to be an end in itself, but rather a means to building capacity for nano education in a larger network of institutions. And so NanoDays has been followed by regional workshops conducted at seven network expansion nodes across the country. These workshops have been designed to further the commitment and capacity for nano education of many of the 2008 NanoDays participant institutions. The regional network expansion nodes serve as hosts and guides to new network members, helping them to learn about and access the NISE Net's educational resources. Two additional network expansion nodes focus on children's museums, which have expressed an unexpected interest in NanoDays materials, and organizations with particular emphasis on diversity, access, and equity. Two large professional organizations – the Materials Research Society and the Association of Science-Technology Centers have also worked to build the number of researchers and science museums involved in the activities of the NISE Net.

**Catalog**
The Network's website (www.nisenet.org) includes a catalog of informal educational products developed by the members of the NISE Net using a process of formative evaluation to improve their effectiveness. These education products range from the table top demonstrations included in the NanoDays kits, to individual exhibits and exhibit packages, to educational programs of various kinds, to media products, graphic products, and all the materials needed to conduct forums that focus on dialogue and deliberation around the societal and environmental implications of various applications of nanotechnology.


Media, exhibits, and programs of various kinds are available from the catalog - www.nisenet.org

The catalog is currently being built. The online infrastructure is in place and the various educational products are now being loaded into the site. All materials developed by the NISE Net are freely available, including fabrication drawings for exhibits and everything that can be transmitted electronically. In the next phase of catalog development, processes for third party contributors will be developed. NISE Net products will be accompanied by evaluation results and all catalog entries will include a mechanism for user comments. Users of NISE Net educational products are encouraged to adapt them as appropriate to their needs and audiences and to contribute their modifications to the catalog so they are available to other users.

**RISE** (Research – Informal Science Education partnerships)
NISE Net is working to foster the development of effective, sustainable educational outreach partnerships primarily between NSF-funded nanoscale science and engineering research centers and informal science education institutions, in order to increase the capacity of these institutions to work together to further the long-term public engagement goals of the NISE Network and of the national research and education communities. Contact Carol Lynn Alpert – calpert@mos.org if you want to get involved.

Participate in NanoDays 2009
March 28 - April 5

www.nisenet.org

# Building Capacity for Public Engagement through Research Center – ISE Partnerships

**Case Study**: Center for High-rate Manufacturing NSEC and
Science of Nanoscale Systems and their Device Applications NSEC
with the Museum of Science, Boston (MOS)

*NSF Grant #s 06046094, 0425826, 0117795, 0532536*

PIs: **Carol Lynn Alpert,* Larry Bell,* Ahmed Busnaina,^ Robert Westervelt[o]**
*with J. Antill,*C. Barry,[a] A. Fiorentino,* K. Hollar,[o] J. Isaacs,^ T. Miller,**
*J. Neely,* L.Regalla,* J. Rosenberg,* A. Swint**

*Museum of Science, Boston ^Northeastern University [o]Harvard University
[a]University of Massachusetts at Lowell

**Summary:** The Nanoscale Informal Science Education Network (NSF ESI 0532536) seeks to foster partnerships between research centers and informal science education institutions, in order to increase their capacity to work together to engage public and K-12 audiences in learning and thinking about nanoscale science and engineering, potential applications and impacts. This effort, led by NISE Net Co-PI C. L. Alpert, and based at the Museum of Science, Boston, is partly informed by long-standing education outreach collaborations between the two Boston/Cambridge based Nanoscale Science and Engineering Centers and the Museum of Science, Boston (MOS). These collaborations are being presented at the 2008 NSF NSE Grantees Meeting as a case study of the productivity and impact that can be reached through such partnership efforts.

**Background:** The two NSECs each included extensive five-year education outreach partnership plans with MOS in their initial proposals to NSF and allocated funds for them through subawards. MOS hired dedicated education associates and multimedia producers to develop and deliver a diverse portfolio of public engagement and professional development programs and media in collaboration with the researchers and students associated with the two research centers on an ongoing basis.

**Outcomes:** The partners have produced an extensive portfolio of exhibits, videos, multimedia, live daily museum presentations, guest researcher events, forums, NanoDays events, a juggling show, cable news stories, podcasts, science communication workshops for early career researchers and educator symposia. Audience reach is in the hundreds of thousands. The partnerships help educators and their audiences become more familiar with nanoscale research and helped researchers develop new skills in engaging broad audiences. These activities and their audiences are detailed on the accompanying poster.

**Research & Evaluation:** The partners participate in an extensive program of evaluation of all major activities. Activities are improved based on formative evaluation by the MOS Research & Evaluation team and then re-assessed by an independent evaluation firm, Multimedia Research.

**For more information or consultation on forming**
*a research center –informal science education partnership, contact rise@nisenet.org*

# Center for Nanotechnology in Society

*NSF NSEC Grant 0531184*

PIs: **Barbara Herr Harthorn, Rich Appelbaum, Bruce Bimber,**
**W. Patrick McCray, Christopher Newfield**
University of California, Santa Barbara

The Center for Nanotechnology in Society at UCSB promotes the study of societal issues connected with emerging nanotechnologies in the US and around the globe. It serves as a national research and education center, a network hub among researchers and educators concerned with societal issues about nanotechnologies, and a resource base for studying these issues in the US and abroad. The work of the CNS-UCSB is intended to include diverse communities in the analysis of nanotechnologies in society and in discussion through outreach and education programs that include students and teachers and extend to industry, community and environmental organizations, policymakers, and the public.

The intellectual aims of CNS-UCSB are twofold: to apply knowledge of human behavior, social systems, and history to identify societal implications of nanotechnologies; and to deepen basic knowledge about the global human condition in a time of sustained technological innovation through close examination of the emergence of nanotechnologies. These aims motivate research from many theoretical and methodological perspectives, provide the basis for industry-labor-government-academic-NGO dialogue, and organize the mentoring of graduate, undergraduate, and postdoctoral students. The Center draws on UCSB's renowned interdisciplinary climate to integrate the work of nanoscale engineers and physical and life scientists with social scientists studying nanotechnology in society. Close ties with the internationally prominent nanoscale researchers connected with the California NanoSystems Institute and with social science research centers at UCSB focused on relations among technology, culture, and society are enhanced by social science collaborators at UC Berkeley, the American Bar Foundation, the Chemical Heritage Foundation, Duke University, Rice University, SUNY Levin Institute, SUNY New Paltz, and University of Washington in the US, and Cardiff University, UK, University of British Columbia, Canada, University of East Anglia, UK University of Edinburgh, UK, and a number of institutes and centers in China and East Asia.


CNS-UCSB researchers address a linked set of social and environmental issues regarding the domestic US and global creation, development, commercialization, production, consumption, and control of specific nanoscale technologies. The center addresses questions of nanotech-related societal change through research that encompasses three areas:

- **Working Group 1. Historical Context of Nanotechnologies** studies the historical underpinnings of nano policy, the nano enterprise, and their social context
- **Working Group 2. Innovation, Intellectual Property, and Globalization** develops a comprehensive understanding of processes of innovation, commercialization, and global development and diffusion of nanotechnology with an emphasis on E and S Asia.
- **Working Group 3**. **Nano Risk Perception and the Public Sphere** seeks to understand amplification and attenuation of nanotech risk perception in US and comparative other societies and how elite organizations are forming, interacting, and framing discourse about nano and

society; and to develop methods for engaging diverse US publics in upstream deliberation about nanotechnologies' near and long-term futures.

The **Historical Context of Nanotechnologies** group (**WG-1**) has studied the history of molecular electronics and spintronics; they have also begun examining quantum dot research in conjunction with **WG-2**'s research. Another focus traces public commercial interest in nanotechnology to futurist imaginings of nano's potential applications through analysis of historical overlap between different pro-technology groups in the 1980s. Recent findings:

- "Hidden histories" of MBE (molecular beam epitaxy) and spintronics [McCray, *Technology & Culture,* 2008; Choi & Mody, *Soc Studies of Sci*, 2008; McCray, *Nature Nanotech* 2007]

The **Innovation, Intellectual Property, and Globalization (WG-2)** team combines two streams of research to develop a comprehensive understanding of the processes of innovation, diffusion, and commercialization of nanotechnology. The **Innovation Group** involves interdisciplinary collaboration with UC Berkeley and the University of Washington to examine core elements of the nanoscale innovation system. One project explores the interactions of nano-scale research with technology transfer at the university-industry interface. They are using quantum dot research as a test case to link patents, publications, researchers, and R&D centers to track technology threads, identify patterns in industry licensing, and assess reports of nanoscale patent "hold-up." A second project conducts survey research on nano-scale laboratories about their cross-institutional innovation practices. The **Globalization Group**, in collaboration with Duke University, focuses on global emergence and diffusion of nanotechnologies, with a strong emphasis on the role of international collaboration in nano R&D in China and Taiwan. Recent findings:

- Enhanced nanotechnology research capacity and marketable innovation are key to the Chinese government's strategy for future commercial success, economic competitiveness, and continued economic growth; US-China collaboration a vital part of the innovation system [Appelbaum & Parker, 2008, *Sci & Public Policy*]
- Chinese nano materials publications are rapidly increasing in quantity (if not quality) to the near-equivalent level of US publications [Appelbaum & Parker, 2008, *Sci & Public Policy*]
- A survey shows evidence that nanoscale researchers are more likely than others to collaborate across disciplinary lines, "nano" is not gaining momentum as a researcher identity [Newfield & Alimahomed].

The **Risk Perception and Nano in the Public Sphere** (**WG-3**) groups are pursuing several streams of linked research. The **Risk Perception** team from UCSB, Cardiff, UBC, American Bar Foundation, SUNY New Paltz, and UEA has completed a novel 2 x 2 cross-national, cross-application comparative public deliberation of the US and UK with separate groups focused on nano health and energy applications and are currently disseminating results. They continue a study of experts' risk perceptions among academic and industry nanoscientists and engineers, nanotoxicologists, and regulators, for comparative analysis with the public's concerns. The team conducted a new national risk perception survey in the US in Summer, 2008, and expect to complete data analysis and begin dissemination in 2009. The **Nano in the Public Sphere** team examines "elite" reaction to nanotechnology in global civil society, by focusing on the way nano messages are being framed by elite media, policy makers, and other shaping policy discussions. The team has collected the most exhaustive database available anywhere that tracks English-language media coverage of societal impli-cations of nano-technologies. Recent findings:

- US and UK publics view new nanotechnologies benefits as outweighing risks so far; they view energy applications as more urgent and more beneficial than medical applications [Pidgeon, Harthorn, Bryant, & Rogers Hayden, *Nature Nanotech,* in press, 2008]
- During 2006 and 2007, there was no upward trend in media coverage of nano risks; major nano news events that did occur tended to focus on regulatory actions and issues of governance [Bimber & Weaver 2008]
- An international survey of nanofirms' safe handling practices documents unmet needs for regulatory guidance. [Conti et al. *Env Sci & Tech,* 2008]

**Education and Public Engagement programs at CNS-UCSB** aim to nurture an interdisciplinary community of nanoscale scientists & engineers (NSE), social scientists, and educators, and to achieve *broader impacts* through engagement of diverse audiences in dialogue about nanotechnology and society. CNS-UCSB provides a unique fellowship and joint education program for graduate students in both social sciences and NSE. In Summer 2008, the Center hosted its 3rd 8-week Undergraduate Research Internship program for UCSB and California community college students, the latter recruited through a partnership with the INSET (Internships in Nanosystems Science, Engineering and Technology) program at the UCSB CNSI. The CNS interns generated group projects that traced the travels of nanotech materials and products through the Global Value Chain.

Through the weekly seminar, speakers series, conferences, visiting scholars, informal science education events for the public (Nano-Meeters), and wide electronic dissemination of a popular nano and society-related Weekly News Clips service, the CNS engages with campus, local, and national and international media, as well as government, industry, NGOs, and the general public. The November 2008 Nano-Meeter on **Nano Energy Applications** features 2000 Nobel laureate Alan Heeger, UCSB MRSEC Director Craig Hawker and Dan Colbert, Exec Director of the new UCSB Institute for Energy Efficiency. In Fall 2009, CNS-UCSB will host a major international conference in Washington DC on "**Emerging Technologies/Emerging Economies: Nanotechnology for Equitable Development.**" Co-sponsors include the Woodrow Wilson International Center for Scholars and the University of California Washington Center.

**International Collaborations –**International collaboration is central to CNS-UCSB's work, with formal collaborations in place with universities in Canada, the UK, and China. CNS-UCSB has indirect representation on the International Risk Governance Council (IRGC), and through the International Nanotechnology and Society Network (INSN), is fostering dialogue among nano and society researchers in North America, the EU, Central and South America, and East Asia. CNS-UCSB is a founding member and lead partner in the Nano in Society Network and its newly forming international professional society.

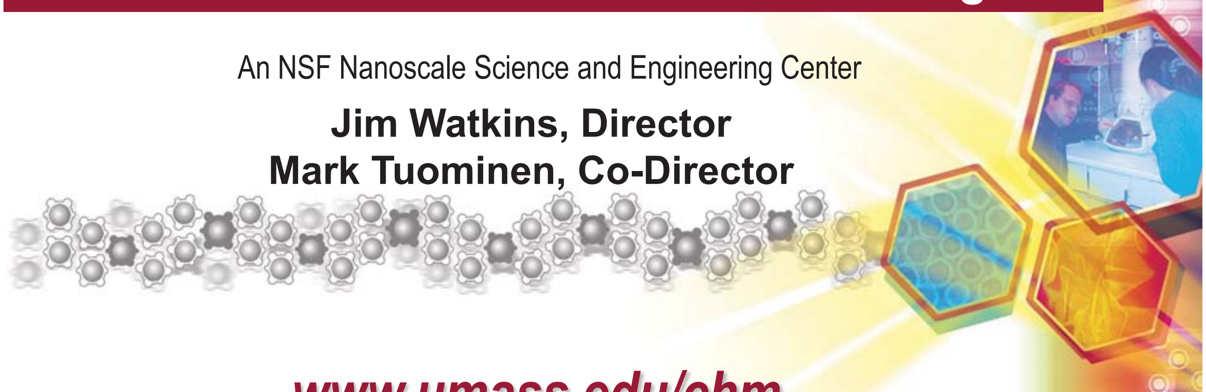
**References** [1] For further information about this project please see our website at <**http:cns.ucsb.edu**> or email **<harthorn@cns.ucsb.edu>**

CHM
Center for Hierarchical Manufacturing
University of Massachusetts Amherst

# Center for Hierarchical Manufacturing

An NSF Nanoscale Science and Engineering Center

**Jim Watkins, Director**
**Mark Tuominen, Co-Director**



***www.umass.edu/chm***

Contact: Jim Watkins, 413-545-2569, watkins@polysci.umass.edu

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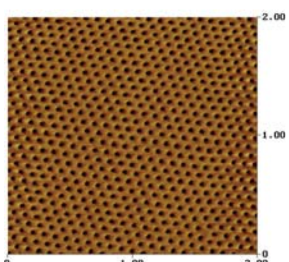
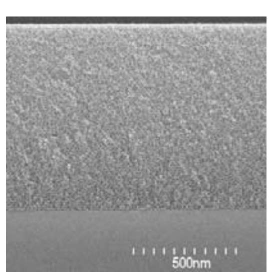
# Technical Research Group 1

## Nanoscale Materials and Processes

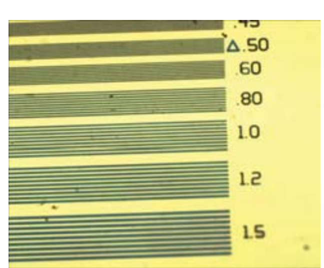
| | |
|---|---|
| *Co-Leaders:* | James J. Watkins, Thomas P. Russell |
| *Participating Faculty:* | C. Cabrera (UPR) K. Carter, A. Crosby, T. Emrick, T. McCarthy J. Rothstein, S. Thayumanavan |
| *Partners/Collaborators:* | Hitachi, Lucent-Alcatel, Molecular Imprints, NIST, Novellus Systems, Seagate, IBM, SCMaterials, TIAX LLC |
| *Goal:* | **Focus on fundamental processes that underpin techniques for the fabrication of nanostructured materials that can be integrated with existing large-scale manufacturing processes** |



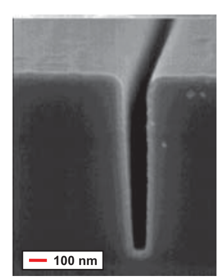

**Block copolymer template arrays**




**Robust 3-D nanoporous films by 3-D BCP replication**




**Device elements from nanocontact molding**




**Conformal metal oxide deposition**

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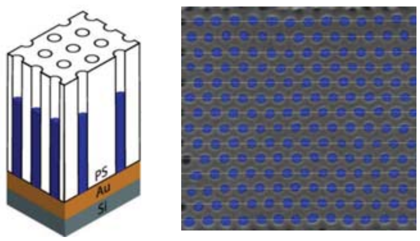
# Technical Research Group 2

## Nanoelectronics

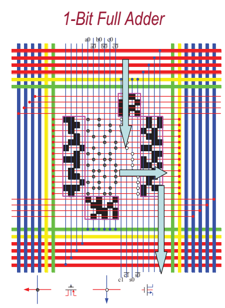
*Co-Leaders:* Andras Moritz, Mark Tuominen

*Participating Faculty:* M. Achermann, M. Barnes, K. Carter, J. Hudgings (Mount Holyoke College), A. Moritz, L. Mountziaris, M. Rotea, T. Russell, M. Inoue (Toyohashi), R. Katiyar (UPR Rio Piedras)

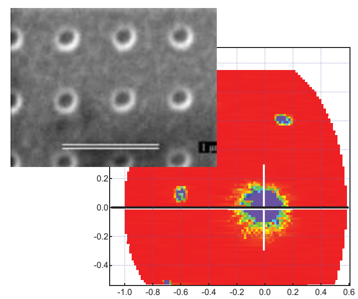
*Goal:* Hierarchical nanoelectronics for future high performance data storage and processing systems, energy conversion devices and sensors




Perpendicular Magnetic Media




Nano Circuits



Nano Photonics

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# Technical Research Group 3

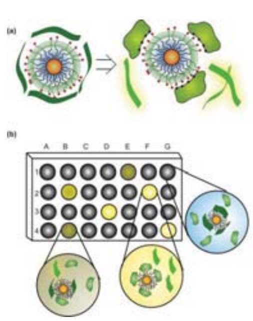
## Bionanotechnology

*Co-Leaders:* Surita Bhatia and Vince Rotello

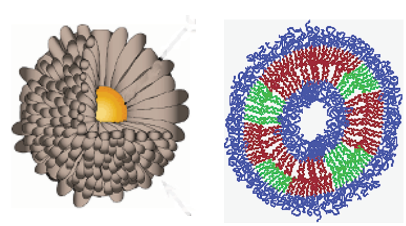
*Participating Faculty:* H. Bermudez, T. Emrick, T. Mountziaris, M. Muthukumar, G. Tew, S. Thayumanavan

*Partners and Collaborators:* University of Puerto Rico, SUNY Buffalo, UMass-Baystate Biomedical Research Institute

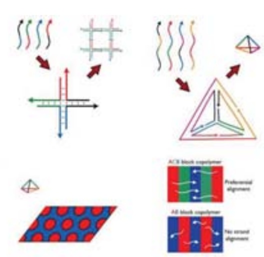
*Goal:* Creation of new nanostructured materials through bioassembly and development of new biosensors and biodevices



Chemical nose



Functionalized nanoparticles, vesicles and assemblies



DNA directed assemblies

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**MRSEC: Genetically Engineered Materials Science and Engineering Center**

*Mehmet Sarikaya l·yŘ Francois Baneyx*

NSF Award 0520567

The University of Washington MRSEC supports innovative research and education that integrates modern molecular biology with state of the art chemical synthesis to construct hybrid materials exhibiting properties that cannot be achieved through either traditional biological or chemical routes. By engineering modular biomolecular components with tailored recognition, structural, and informational properties and interfacing them with specific molecular and inorganic nanoscale components the MRSEC will impart materials with photonic / electronic / catalytic / chemical functionality that can be reorganized, addressed, and reconfigured on demand in response to external stimuli. The center will develop coordinated activities in graduate and undergraduate education and outreach, establish an international network of laboratories sharing a common interest in molecular biomimetics, and partner with industry and national laboratories to translate fundamental discoveries into new products realities. The MRSEC will conduct a unique outreach program to Native Americans in the Seattle area.
The MRSEC, consisting of one Interdisciplinary Research Group - Polypeptides as genetically engineered building blocks for functional hybrid materials - will create protein-based molecular building blocks with tailored functionalities and use them for the synthesis and assembly of nanostructured hybrid materials exhibiting novel or improved properties.

Participants in the Center currently include ten senior investigators, four postdoctoral associates, and five graduate students from seven departments and two partner universities - New York University and the Istanbul Technical University. Professor Mehmet Sarikaya directs the MRSEC.

# Stanford University Center for Probing the Nanoscale

*NSF NSEC Grant 0425897*

PI: **Kathryn A. Moler, Co-PI: David Goldhaber-Gordon, Stanford University**

The joint Stanford University/IBM Center for Probing the Nanoscale (CPN) at Stanford University is a research and education center with goals to **develop and apply novel nanoprobes**. These novel instruments dramatically improve our capability to observe, understand, manipulate and control nanoscale objects and phenomena. The CPN **disseminates its knowledge** among the scientific community and works closely with industrial partners to **transfer technology** for adaption into commercial products. The CPN has developed several science outreach and education programs that **educate and inspire** the community about nano science. Middle school students and their teachers are especially targeted. All outreach activities will promote and encourage a healthy growth of the next generation of scientists and engineers.

With the rapid and exciting progress in producing new and advanced nanomaterials, capabilities for probing and analyzing these materials have lagged behind. Motivated by fundamental questions in nanoscience and technology, CPN research and development focuses on making available novel probes that open windows into the nanoscale,. The past years of the CPN have enhanced and leveraged Stanford's and IBM's distinguished histories and strong programs in nanoprobes, resulting in substantive achievements in nanoprobe research and education with an emphasis on nanoelectronics and photonics, nanomagnetics, and molecular mechanics.

Future CPN work will concentrate research efforts in tightly knit, focused theme groups dedicated to collaboratively advance nanoprobe technologies. The five theme groups are described in the following paragraphs:

***1) Plasmonic Scanning Tunneling Microscopy***

The study of light-sensitive, dynamic processes in molecular-scale objects is at the core of understanding phenomena governing the electronic structure of materials such as photochromic molecules and semiconductor quantum dots. The plasmonic scanning tunneling microscope will perform local electronic and optical imaging and spectroscopy. The pivotal goal is to combine the exquisite spatial resolution inherent in high-resolution scanning tunneling microscopy and spectroscopy with the detailed information on high-frequency excitations of materials yielded by optical channels. Theory will provide input on combined electronic and excitation spectra in materials. At spatial resolutions of 0.1 – 10 nm and frequency ranges of $10^{12}$ – $10^{15}$ Hz, we will map local density of states, while also directly and coherently probing infrared to optical band phenomena in nanostructured materials and devices.

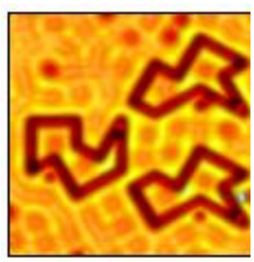

**Figure 1**
Carbon monoxide atoms assembled into structures that confine electrons, to study quantum phase of single electron wavefunctions.

***2) Individual Nanomagnet Characterization***

Magnetic nanoparticles have a number of present and proposed applications spanning various areas in information technology, biology and medicine. For example, magnetic nanoparticles are crucial in increasing the density of information storage, have been clinically approved for use as

MRI contrast agents and have the potential to be successfully used for treatment and removal of cancer cells. The properties of magnetic nanoparticles are inherently sensitive to small variations in volume, shape, and structure, and therefore it is vital to characterize them individually. Our theme group will develop and advance a variety of nanoprobes with the spatial resolution and magnetic sensitivity to detect and characterize individual nanomagnets for nano-biotechnology applications. We will demonstrate the feasibility of characterizing the magnetic moment and dynamics of individual nanomagnets and apply these techniques in collaboration with chemists and biologists working to realize the potential of nanomagnets for nanobiotechnology.

***3) Nanoscale Electrical Imaging***

With the rapid advancement in electronic devices, lithographically-patterned structures such as transistors now commonly have electronic properties that vary on scales of a few to tens of nanometers. Novel materials also exhibit local electronic variations, due to patterns in the underlying atomic structure, inhomogeneity in structure or doping, or spontaneous organization of electrons. These local variations have important implications for the behavior of the materials or structures and ultimately determine the properties and performance of advanced electronic devices. We propose to develop and apply a suite of techniques to measure electronic properties such as dielectric constant, conductivity, and carrier density of materials at the 10 nm scale, with sensitivity to variations deep beneath a sample surface.

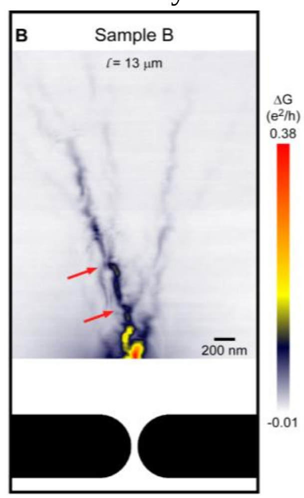


**Figure 2**
Electron Flow in a GaAs/AlGaAs-based two-dimensional electron gas. Electron flow originates from a narrow orifice (quantum point contact) formed between the two depletion regions, schematically indicated in black below the image.

***4) Nanoscale Magnetic Resonance Imaging***

Extending the sensitivity of magnetic resonance imaging to the level of individual nuclear spins would enable the development of a "molecular structure microscope" capable of imaging the atomic structure of molecules in three dimensions. Such a capability would have revolutionary impact on structural molecular biology since it would allow atomic structures to be obtained for proteins that cannot be crystallized for x-ray diffraction analysis. Recent work sponsored by CPN has proven that magnetic resonance force microscopy (MRFM) can achieve three-dimensional imaging with spatial resolution below 10 nm. We will focus now on extending MRFM resolution to below 1 nm – or roughly an order of magnitude improvement over today's capability. If sub-nanometer can be achieved, then MRFM's true 3D imaging capability, lack of radiation damage and elementally specific contrast could make it a powerful tool for structural biologists.

***5) BioProbes: Nanoscale Cantilevers***

Understanding the principle and processes that govern the functions of cell membranes will help us tailor drugs to effectively penetrate the membrane for efficient treatment. The novel nanoprobes will directly study the membrane and measure the forces, mechanical stiffness, electrostatics, and sequence of biological processes to replace and complement more traditional remote sensing techniques. Our theme will adapt unique cantilever designs for aqueous solution, based on recently invented torsional and dual-cantilever AFM cantilevers that have extremely high force sensitivity together with kHz sampling frequencies, ideal for biological samples. We will apply these cantilevers for solution phase biological imaging and time-resolved measurements. Functionalized probe tips on the cantilevers will provide specific biomolecular functionality, enabling us to attack the biologically important processes of viral peptide penetration and ion channel activity. Ultimately, we plan to simultaneously measure nanoscale electrical potential and membrane stiffness of active ion channel clusters using cone-shaped coaxial core-shell electrochemical probes. These metrologies will unlock the real time mechanical and electronic processes at and within biological membranes that are currently inaccessible by any other technique.

The CPN includes thirteen core faculty-level Investigators (including three IBM Investigators who also serve as Consulting Professors at Stanford), twenty-eight affiliated faculty members and dozens of students and postdocs in eight academic departments. We maintain active collaborations and information exchange with other non-formally-affiliated groups.
Seed grant opportunities are widely advertised and seed grants are competitively awarded. CPN Graduate Prize Fellowships are competitively awarded on the basis of advisor recommendations and student-written proposals, and provide graduate students with a full stipend to initiate a novel nanoprobe research project.
Nanotechnology is being increasingly adopted by industry, and future generations will encounter a significant amount of nanotechnology in day-to-day products. Educating the public about nanotechnology is therefore at the core of CPN's outreach activities. It is known that middle school students lose interest in science and therefore CPN's outreach program is targeting this particular age group to retain and foster students' interest and excitement about nanotechnology and nanoscience.
A successful approach for reaching middle school students has been the **Summer Institute for Middle School Teachers** (SIMST). Middle school teachers participate in an intensive week-long program of content lectures, hands-on activities and curriculum development exercises. The CPN helps the teachers to apply their new knowledge by having them create nanoscience lessons that are shared among participants for use during the school year. Furthermore, these activities and lessons will be compiled for broader dissemination through future workshops and made available as online education resources. To provide continuing support for teachers and to assess the effectiveness of SIMST, CPN members keep in close contact with program alumni, including conducting classroom visits. The CPN has also held **teacher development workshops** to help pre-service teachers enrolled in the Stanford Teacher Education Program (STEP) incorporate nanoscience into their curriculum from the beginning of their teaching careers. The **Annual Nanoprobe Workshop, which features 8-10 world-class nanoscience researchers as speakers,** provides an excellent opportunity for academic and industrial scientists to exchange knowledge and ideas and to broaden the horizons of our students. The workshop grows in popularity each year and attracted about 200 participants in 2008. Future outreach activities of the center will build on the established structure and will increasingly **target populations historically underrepresented in the physical sciences** to encourage their participation in nanoscience. These activities will be performed in close collaboration with Stanford's Office of Science Outreach and will focus on local schools that serve large numbers of the targeted populations.

**References**

[1] For further information about this project visit www.stanford.edu/group/cpn/

# Center for Templated Synthesis and Assembly at the Nanoscale

*NSF NSEC Grant DMR- 0425880*

PI: **Paul F. Nealey**
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The UW NSEC on Templated Synthesis and Assembly at the Nanoscale was founded in September 2004 with the mission to revolutionize nanomanufacturing and foster exploration and discovery of new materials and material architectures through directed assembly. The UW NSEC has become a fertile ground for collaboration, interdisciplinary research, and discovery that has truly changed the nature and scope of research at the University of Wisconsin, particularly at the interface of chemistry and engineering. To date, the UW NSEC has been characterized by its high productivity, its impact on technology and fundamental science, its success in incorporating underrepresented groups into scientific pursuits and, perhaps most importantly, the intellectual environment that it has created for well over a hundred undergraduate and graduate students, faculty, and industrial and academic collaborators. The activities of the NSEC are crafted to evolve the mission of the center on all fronts, including technology, innovation, discovery, societal implications, public engagement, and education at all levels. To that end, the NSEC includes four research Thrusts, Societal Implications research, and a focused Education and Outreach group.

**Thrust 1:** *Directed Assembly of Block Copolymer Materials:* Block copolymers have tremendous potential for patterning and assembling functional material architectures at the nanoscale because their constituent, compositionally distinct blocks spontaneously form ordered structures (domains) with dimensions of 3 to 50 nm. The dimensions and shapes of the structures in the bulk represent a delicate balance of interfacial energy between blocks ($\gamma_{a\text{-}b}$) and the configurational entropy of the polymer chains. Unfortunately self-assembly results in the creation of features riddled with imperfection and non-uniformities. Intervention is required to overcome trapping of low energy defects. In our primary research approach, block copolymer films are equilibrated in the presence of chemical surface patterns that 1) have dimensions similar in size to individual domains, and 2) illicit strong differing interfacial interactions between the surface and the blocks of the copolymer film ($\gamma_s$). By manipulating the geometry of the chemical patterns, and the magnitude of $\gamma_s$ in comparison to $\gamma_{a\text{-}b}$, we can direct the block copolymer to assemble into essentially defect free arrays over arbitrarily larger areas. Assembly is relatively insensitive to the details of the underlying chemical pattern with respect to dimensional uniformity of the domains and inter-domain roughness. Furthermore, systems can be designed to induce the domain structure of the block copolymer film to assemble into morphologies not observed in the bulk, including the canonical set of structures used in the fabrication of integrated circuits or more complicated three-dimensional architectures. The same strategies may be used to assemble functional materials such as block copolymer-nanoparticle composites. In a second approach, block copolymer films are graphoepitaxially assembled on chemically and topographically patterned surfaces to induce well-ordered cylindrical and lamellar domains that are oriented perpendicular to the substrate and are therefore amenable for pattern transfer. Based on these achievements and their relationship to the most critical issues facing the continued development of lithographic materials and processes, which remains the enabling technology for semiconductor and related industries (dimensional uniformity of patterns, line edge roughness, and resolution), Thrust 1 has adopted a test-bed approach to investigate the insertion point of block copolymer lithography in nanomanufacturing.

**Thrust 2:** *Directed Assembly of Sequence-Specific Heteropolymeric Nanostructures* revolves around investigations of the design, directed assembly and functional properties of organic nanostructures synthesized from a class of non-natural amino acids called $\beta$-peptides. Research in Thrust 2 has revealed that oligomers of $\beta$ -peptides provide access to organic nanostructures with exact control over shape and complex surface nanopatterns of chemical groups. This level of control over chemical patterning is made possible through specification of the sequence of the $\beta$-amino acids within the folded oligomers. Using β-peptides that fold into "nanorods" as a prototypical system, Thrust 2 has exploited exact and systematic manipulation of the surface chemical patterning of nanostructures to (i) yield insights into the mechanical and thermophysical properties of individual patterned nanorods, (ii) advance our understanding of the ways in which nanoscopic chemical patterns mediate interactions on the nano-scale, (iii) unmask a range of unexpected and rich assembly behaviors in the bulk and at interfaces that are directed by surface nanopatterns, and (iv) reveal a high level of control over the functionality of these nanostructures, including activity in biological systems. This progress has been made possible through the combined participation of faculty with expertise in synthetic organic chemistry, nanostructure characterization tools, spectroscopic methods, statistical mechanics and computational methods, single molecule force spectroscopy, and microbiological and biotechnology.

**Thrust 3:** *Driven Nano-Fluidic Self Assembly of Colloids and Macromolecules* relies on driven, nanoscale assembly at equilibrium and beyond equilibrium. Nanoscale assembly and self-assembly processes have traditionally relied on thermodynamic equilibrium to reach desirable end states. By focusing on driven assembly beyond equilibrium, Thrust 3 has sought to expand the accessible states and strategies available for nanofabrication. Research in Thrust 3 has systematically considered the use of fields to drive the assembly of different nanoscale elements, including nanoparticles and macromolecules, in a variety of media. The emphasis has been to identify and understand the general, underlying principles that govern driven assembly across a wide range of complex fluids and materials. To that end, Thrust 3 has developed equilibrium and non-equilibrium theories, multiscale formalisms, and models that capture the coupling between external fields and the structure and dynamics of systems of interest, and has engaged experimentalists in a complete cycle of prediction, validation and exploration that has led to rapid fundamental and technological advances that capitalize on such couplings. These advances have been transformative, and include development of the fastest algorithms for calculation of the coupling between hydrodynamic forces and macromolecular structure out of equilibrium, development of optical mapping platforms for high-throughput analysis of entire genes, and development of liquid-crystal plasmonic based sensors for toxicants and biomolecules.

**Thrust 4:** *Environmental Health and Safety Implications of Nanomaterials* seeks to reduce uncertainty about the environmental health and safety implications of nanotechnology by elucidating fundamental principles governing biological responses to engineered nanomaterials and investigating the environmental behavior of nanomaterials. Thrust 4 research focuses on *in vivo* biological responses to nanocomposite materials before and after environmental "weathering". While the majority of prior studies examining biological responses to nanomaterials have relied on cell culture systems (*in vitro*), such studies cannot capture the diversity of biological processes that may lead to adverse outcomes in whole organisms (*in vivo*). Thrust 4 seeks to identify and understand the properties of nanomaterials that contribute most significantly to *in vivo* biological responses using the zebrafish (*Danio rerio*) embryo as a model. Genes, receptors and molecular processes are highly conserved across animal phyla. Studies with zebrafish have a high probability of being representative for other animals, including humans. Once released into the environment, nanomaterials may undergo biogeochemical processing, or weathering. Almost nothing is currently known about the biogeochemical processing of engineered nanomaterials. Thrust 4 aims to elucidate the fundamental degradation chemistry of polymer-modified nanoparticles and nanocomposite materials and how such transformation may alter their effects on the embryonic development of zebrafish.

Thrust 1 examines situations and processes in which the self-assembly of mesoscopic materials and the resulting nanostructures can achieve a state of thermodynamic equilibrium. Thrust 2 considers synthetic routes that are also governed by thermodynamic equilibrium and nanoscale templates, but this time at the level of individual atoms and chemical reactivity. Thrust 3 is concerned with nanoscale self-assembly far from equilibrium, driven by the influence of external fields and severe confinement. Thrust

4 considers environmental implications of the development, design, reception, and uptake of self-assembling nanotechnological systems. Each group integrates the five essential elements required for forefront research in nanoscale science and engineering: synthesis, theory, structural characterization, property evaluation, and applications. An aggressive Seed program operates in a manner to foster innovation and promote growth and evolution into new, unexplored areas of opportunity. The established Thrusts and Seed projects share a common view, namely the precise synthesis of nanoscale elements, their assembly into nanostructured systems through the use of templates, self-organization and confinement, and the creation of materials, devices, and processes with hitherto unattainable functions.

Societal Implications research has focused on developing effective mechanisms for actively engaging citizens, scientists, and government agencies in dialogues and decision-making about nanotechnology's benefits and risks. Successful projects include: (1) Six highly innovative and unique Nano Cafes, engaging nearly 300 lay citizens and many NSEC scientists; (2) Two comprehensive nanotechnology information websites used worldwide by citizens, government, researchers, and industry; (3) a highly successful and well-attended nanosafety workshop and two pilot projects to better understand nanotechnology EHS issues in workplaces; and (4) the development of an inter-agency government working group involving six state and federal agencies and NSEC scientists.

NSEC Education and Outreach activities are designed to educate teachers, students, and the general public about nanoscience. Programs for teachers include Research Experience for Teachers, professional development workshops offered through the Wisconsin Summer Science Academies program, and an annual conference for teaching science to students with visual impairments. NSEC supports programs directed toward K-12 students including projects that help build diversity within the scientific community. The Sci EN*Count*Er*s* program partners with the local Boys and Girls clubs to excite teenagers and middle school students about science and engineering. The NSEC has developed a novel method to produce large scale tactile models of nanoscale surfaces for teaching blind and visually impaired students about nanoscale science and engineering. For undergraduates NSEC hosts an annual Research Experience for Undergraduates program in nanotechnology to train our next generation of nanoscientists and engineers. NSEC programs for the general public include an active collaboration with the Discovery Center Museum to build and distribute museum exhibits on nanoscience and engineering incorporating the large scale tactile models developed by the UW-Madison NSEC.

The NSEC activities include the establishment of a Graduate Fellowship Program to recruit the most talented young scientists and engineers to the interdisciplinary field of nanoscale science and engineering and to foster a community of diversity. We have also established links to international laboratories on three continents that support living expenses of our students while they participate in substantive collaborative co-supervised research projects.

The shared experimental facilities of the UW NSEC serve internal and external users in academia and in industry and include the only open-access extreme ultra violet lithography tools in the nation and a new soft materials synthesis and characterization facility (SML). The number of users of the SML has increased by a factor of three in the last year. This facility will house a new Bio-AFM/Fluorescent microscope instrument that will provide optically guided AFM imaging with direct correlation of fluorescence and sample topography. It will be equipped for nano-mechanical studies on cells, surfaces and tissues, including: elasticity, molecular (un)folding, ligand-receptor interactions, etc.).

For further information about this project link to **www.nsec.wisc.edu** or email **nealey@engr.wisc.edu**

**NSEC: The Center for High-rate Nanomanufacturing (CHN)**

*Ahmed Busnaina, Nicol McGruer, Glen Miller, Carol Barry and Joey Mead*

NSF Award 0425826

The Nanoscale Science and Engineering Center entitled New England Nanomanufacturing Center for Enabling Tools is a partnership between Northeastern University, the University of Massachusetts Lowell, the University of New Hampshire, and Michigan State University. The NSEC unites 34 investigators from 9 departments.

The NSEC is likely to impact solutions to three critical and fundamental technical problems in nanomanufacturing:

- Control of the assembly of 3D heterogeneous systems, including the alignment, registration, and interconnection at three dimensions and with multiple functionalities,
- Processing of nanoscale structures in a high-rate/high-volume manner, without compromising the beneficial nanoscale properties,
- Testing the long-term reliability of nano components, and detect, remove, or prevent defects and contamination.

Novel tools and processes will enable high-rate/high-volume bottom-up, precise, parallel assembly of nanoelements (such as carbon nanotubes, nanorods, and proteins) and polymer nanostructures. This Center will contribute a fundamental understanding of the interfacial behavior and forces required to assemble, detach, and transfer nanoelements, required for guided self-assembly at high rates and over large areas.

The Center is expected to have broader impacts by bridging the gap between scientific research and the creation of commercial products by established and emerging industries, such as electronic, medical, and automotive. Long-standing ties with industry will also facilitate technology transfer. The Center builds on an already existing network of partnerships among industry, universities, and K-12 teachers and students to deliver the much-needed education in nanomanufacturing, including its environmental, economic, and societal implications, to the current and emerging workforce. The collaboration of a private and two public universities from two states, all within a one hour commute, will lead to a new center model, with extensive interaction and education for students, faculty, and outreach partners. The proposed partnership between NENCET and the Museum of Science (Boston) will foster in the general public the understanding that is required for the acceptance and growth of nanomanufacturing.

The Center will study the societal implications of nanotechnology, including conducting environmental assessments of the impact of nanomanufacturing during process development. In addition, the Center will evaluate the economic viability in light of environmental and public health findings, and the ethical and regulatory policy issues related to developmental technology.

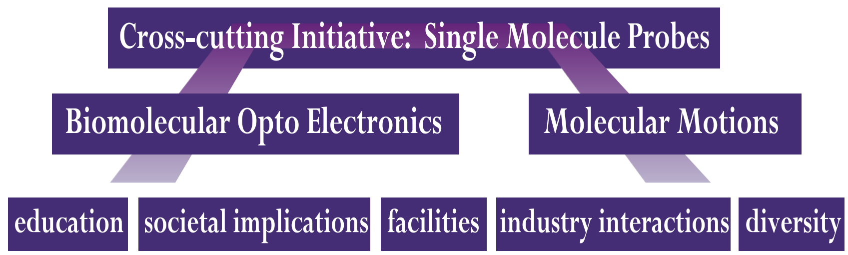
# The Nano/Bio Interface Center

*NSF NIRT (or NSEC) Grant 010425780*

**Director: Dawn Bonnell, Associate Director: Yale Goldman**

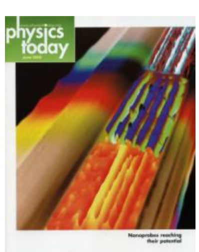
The University of Pennsylvania

The Nano/Bio Interface Center exploits Penn's strengths in design and control of molecular functionality, quantifying behavior of individual molecules, and interactions at organic/inorganic interfaces to establish the foundation for understanding the interface of physical and biological systems. Two multi disciplinary research teams are focused on aspects of the fundamental scientific issues; a cross cutting initiative develops ideas integral to all projects. The research themes are: optoelectronic function in ***biomolecule-nanostructure hybrids*** and ***mechanical motion of proteins***. The Cross Cutting Initiative develops the ***single molecule probes*** necessary to accomplish these goals by combining near field optical probes with mechanical and electronic probes. Each theme has a strong fundamental component and obvious technological impact that ranges from nanoelectronics to medical diagnostic devices.

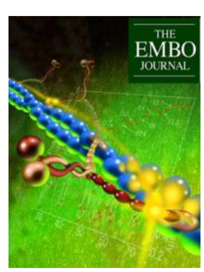


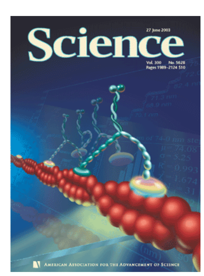

The NIBC engages the local community in several forums. Professional development activities for teachers are held at high schools that serve under represented minority populations, the NBIC sponsors the annual Nanotechnology@Penn day which engages over 150 high school students and a summer academy course for high school students is held on Nanotechnology. A joint RET program with Drexel University is extremely successful. In NBIC controlled programs (RET, REU, teacher development) diversity is substantially above the national averages. The NBIC engaged the global community by establishing an International Nano/Bio Network involving Enrollment in the Nanotechnology Minor and graduate Certificate programs both doubled over last year.

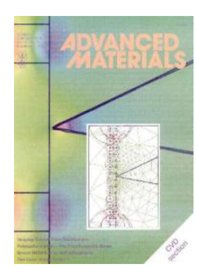
Several recent exciting research advances characterize the activity of the NBIC Research Team 1 designed and synthesized a new family of $\alpha$-helix based compounds that allows molecular length, electron hopping distance and interface attachment to be systematically controlled. Protocols were developed for probing opto electronic properties of individual molecules. Assemblies of nanoparticles-chromophore hybrids have been patterned by Ferroelectric Nanolithography and demonstrate optoelectronic function. Research Team 2 designed microfluidic hydrodynamic mixing chambers and developed numerical models to describe interactions in these liquid systems. New phase transitions in block copolymers are being exploited to control surface properties and position

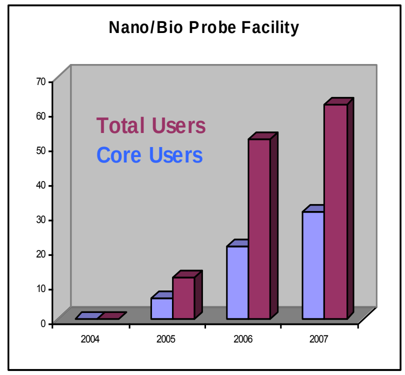




actin filaments. The helical tracks of molecular motors on actin filaments were measured and the kinetics of myosin filament self-assembly determined. Forced unfolding and temperature induced relaxations in proteins were quantitatively compared. A physical theory of dynamics of particles tethered by long nucleic acids was constructed. The Cross-cutting Initiative has demonstrated simultaneous fluorescent imaging and AFM on single ribosomes and NBIC beta site activity on the Veeco Bioscope has resulted in the evolution of this technology. Two new variants of multiple modulation SPM were developed to probe local electronic structure and a combined SPM-optical measurement was shown to yield local dielectric properties of molecules. 3-D optical tomography was demonstrated at the 100 nm length scale and analytical solutions for new configurations developed.




The Nano/Bio Probe Innovation Facility develops next generation probes of local phenomena, making these available to the research community long before they become commercialized and works with industry to transition discoveries to products to allow wider dissemination. The facility is being developed within the framework of a 3-phase plan. Phase one developed first generation probes and prototypes, provided immediate access to the community and installed the necessary management infrastructure. The second phase developed additional resources and expanded these capabilities. Currently the instrumentation is housed in the Edison (primary site), Towne and Richards buildings. The third phase involves consolidating this facility to one location in the new Krishna P. Singh Nanotechnology Building. The continued increase in the number of users attests to the value of the facility to the research community.

**References**

**[1]** www.nanotech.upenn.edu
**[2]** www.nanoprobenetwork.upenn.edu

**NNIN: National Nanotechnology Infrastructure Network**
*Sandip Tiwari*
NSF Award 0335765

The National Nanotechnology Infrastructure Network (NNIN) is a partnership of 13 institutions (Cornell University, Georgia Institute of Technology, Harvard University, Howard University, North Carolina State University (affiliate), Pennsylvania State University, Stanford University, University of California at Santa Barbara, University of Michigan, University of Minnesota, University of New Mexico, University of Texas at Austin, and University of Washington) that provides multi-faceted, interdisciplinary, and broadly-accessible infrastructure supporting both near-term and long-term needs identified in the National Nanotechnology Initiative. The partnering facilities are open laboratories providing outstanding service to the external user, comprehensive training and staff support, and support of interdisciplinary and emerging areas of research, with openness to new materials, techniques, and applications.

Some of the key scientific, educational, and societal needs supported by the network are:

- Easy implementation of nanotechnology experiments through integration of knowledge and coordination of large numbers of different types of patterning and processing steps, together with the complex tasks of synthesis and assembly at the molecular scale
- Specialized techniques for characterization and metrology at the atomic scale
- Support of advanced and robust modeling and simulation through software and hardware resources with strong technical support
- Technology transfer and the sharing of new techniques through in-person and web-based interactions
- Education and technical training of new users who will be the leaders in nanotechnology
- Public education about the opportunities and challenges of nanotechnology
- Promotion of research in the social sciences so that future developments lead to the greatest possible societal benefits, and societal and ethical studies that focus on research, infrastructure, and the impacts of nanotechnology.
- Nation-wide outreach across age groups and technical interests, with special efforts to reach non-traditional users and under-represented groups.
- Active coordination and knowledge dissemination on safety, environment and health benefits and risks of nanotechnology

Specifically, the network provides:

Infrastructure for Research: The network provides on-site and remote access for users, from academia, small and large industry, and government, to advanced top-down patterning and processing and bottom-up synthesis and self-assembly, comprehensive integration capabilities for multi-step processes, state-of-the-art characterization for hard and soft materials, the development of tools and techniques, and a comprehensive web and computation infrastructure in support of nanotechnology. The network has easy user access that enables a diversity of projects efficiently and at low cost: e.g., molecular-scale electronic contacts; use of functionalized nanotubes; integrated mechanical, electronic, fluidic, and bio-systems; advanced types of microscopy; and a large ensemble of other projects. The network also develops tools in support of future research and nano-manufacturing, including imprint and soft-lithography with applications in electronics, microfluidics, and nanobiotechnology.

Infrastructure for Network Web and Computation: The network's computation and web-based infrastructure provides a centralized resource for organizing and distributing the rapidly-growing knowledge base at the foundation of nanoscience and engineering. It includes training in tools, processing, and synthesis techniques; classes; discussion groups; an open text-book with links to the technical resources and data-bases; and technical support for robust computational tools for design, simulation, and modeling. The web-based infrastructure also comprehensively links our initiatives in education, outreach, and societal and ethical studies in order to provide nation-wide access.

Collaboration and External Interactions: The network employs connections and extensive collaborations with national and industrial laboratories, and with foreign institutions. Through these partnerships and joint meetings and workshops, we share expertise and perspectives, provide specialized training opportunities, coordinate access to unique instrumentation, and transfer newly developed technologies.

Infrastructure for Education, Human Resource Development, Outreach, and Societal and Ethical Studies: Education, human development, outreach, and societal and ethical studies components are thoroughly integrated throughout the network. Our goals are to spread the benefits of nanotechnology to new disciplines, to educate a dynamic workforce in advanced technology, and to become a teaching resource in nanotechnology for people of all ages and educational backgrounds. Network-based education and information tools and comprehensive local hands-on activities towards these goals include: development of a hyper-linked Open Textbook for advanced students, web-based education and virtual research with introductory material for "K-to-gray" distance learning, outreach to 2- and 4-year colleges, a web-based magazine (a mini Scientific American/New Scientist) to interest 6-10 year olds in science, modular teaching packages for nanoscience and for laboratory experimentation in schools, experience-providing programs for undergraduates and teachers, and specialized programs for outreach to women, African-Americans, and Hispanics.

The network also supports an infrastructure and research environment to promote consideration of the societal and ethical consequences of nanotechnology, covering economic, political, educational, environmental, health, safety, legal, security, and cultural implications. A network of scholars in these fields are embedded within the NNIN, with coordinated efforts to foster exchange and discussion, development of web-based resources for research and education, public outreach through the media, and an online archive of technical documents, analysis, transcripts and policy recommendations. The research orientation of the effort explores issues of ethics, communication, workforce change, industrial innovation, and other social implications of nanotechnology.

# Center for Nanoscale Chemical-Electrical-Mechanical-Manufacturing Systems (Nano-CEMMS)

*NSF NSEC Grant 0328162*

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**Abstract:** The Center for Nanoscale Chemical-Electrical and Mechanical Systems is a NSF-sponsored Nanoscale Science and Engineering Center (NSEC) that is focused on developing the science and engineering of processes, tools and systems for manufacturing at the nanoscale along with the human resources to enable it. Started up in September of 2003, Nano-CEMMS is a partnership between four institutions: Caltech, North Carolina A&T, Stanford and the University of Illinois at Urbana Champaign.

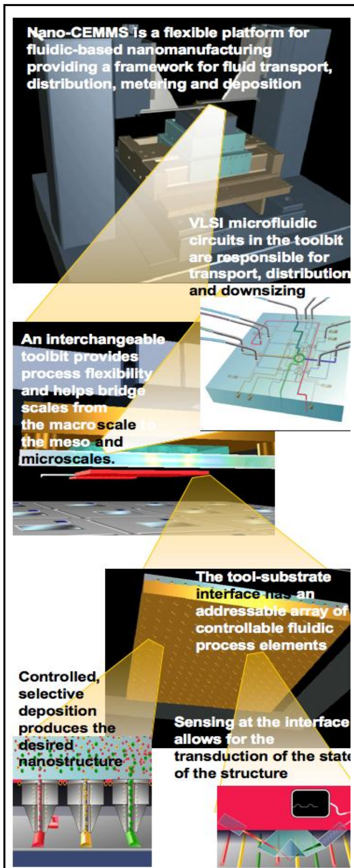



**Figure 1:** Schematic of the different scales & subsystems in the Nano-CEMMS Platform.

## 1. Introduction

The *vision* of the Nano-Chemical-Electrical-Mechanical Manufacturing Systems (Nano-CEMMS) Center[1] is to make the most basic elements of manufacturing, *transcription* of matter and the *transduction* of its state, a practical reality at the nanoscale. Therefore, its *mission* is to: (a) Explore and develop new methodologies and tools that exploit chemical, mechanical and electronic phenomena and processes for 3-D manufacturing at the nanoscale; (b) Create viable technologies that integrate nanoscale manufacturing methodologies into scalable, robust and cost-effective operational systems for manufacturing devices and structures at larger length scales; and (c) Develop diverse human resources to enhance the scientific research, education, and industrial nanotechnology workforce the country.

The programs within the Center concentrate on two main areas (a) Research and (b) Education and Outreach. The Center integrates the work of roughly 21 faculty (from 7 disciplines), 4 post-doctoral researchers, 25 graduate students, 17 undergraduate students and 6 staff members into a number of cross-disciplinary research projects with strong components of education and outreach.

## 2. Research

Nano-CEMMS' strategic research vision is *to explore and exploit fluidic and ionic transport phenomena at the nanoscale to create a fundamentally new manufacturing paradigm to enable nanoscale heterogeneous integration.* If a fundamentally new manufacturing paradigm is possible, then nanoscale fluidics, rich in efficient and tunable transport, is an obvious domain in which to begin. Therefore, the Nano-CEMMs primary strategic goals are to:

**Goal 1** – Explore and characterize nanoscale fluidic or ionic transport and phenomena to increase the knowledge of fluid-material-structure-field interactions, for the purpose of creating new approaches to manufacturing at the nanoscale. This goal is addressed by *Thrust 1 – Micro-Nano Fluidics.*

**Goal 2** – Develop and extend the basic technology infrastructure required in a manufacturing process (such as sensing, positioning, microfabrication tooling, and micro-nanofluidics) beyond the current state-of-the-art to support fluid and ionics-based manufacturing at the nanoscale. This goal is addressed by *Thrust 2 – Nanoscale Sensing and Positioning and Fabrication.*

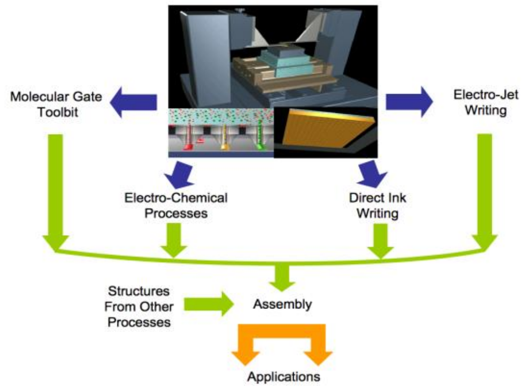



**Figure 2** The Nano-CEMMS manufacturing strategy integrates fluidics-based processes with an assembly process to create a manufacturing pathway to heterogeneously integrated products.

**Goal 3** – Combine the results of basic exploration of nanoscale fluidic transport and phenomena in a new nanomanufacturing modality and merge these capabilities into an integrated set of processes for nanomanufacturing, addressed by *Thrust 3 – Manufacturing Processes and Systems.*

**Goal 4** – Demonstrate how the new manufacturing processes being developed (i) produce new routes to heterogeneous integration in electronics, optoelectronics and microfluidics, with capabilities at the nanoscale; and (ii) create new capacity to support specific testbed applications. This goal is addressed by *Thrust 4 – Applications and Testbeds.*

To integrate these goals, Nano-CEMMS uses a manufacturing platform depicted in Figure 1. Figure 2 shows how the basic scheme underlies a set of processes and assembly mechanisms for heterogeneous integration, enabling broad material coverage, nanoscale resolution capabilities and flexibility in the geometries, from flat to full three-dimensional layouts. The vision of a fluidic and ionic-based nanomanufacturing platform includes developing physical realizations of the manufacturing processes in configurations that enable high throughput, high resolution, flexibility, robustness and high yield, via positioning platforms, embedded sensing, and localized control arrays of process elements and interchangeable toolbits.

Research teams within Nano-CEMMS have made significant progress with respect to each of the goals and reported in 235 peer-reviewed journal papers and 16 patent applications. For example, recently,

- The Sweedler, Bohn and Shannon groups have been experimentally studying transport in nanopores or molecular gates so as to develop a number of capabilities important to manufacturing. Important accomplishments for the last year include the capability to manipulate small sample volumes using a new and novel injection method, floating injection, for improved injection plugs and better subsequent separation analysis in

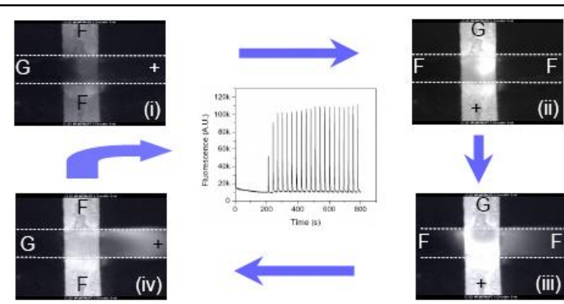



**Figure 3:** Images showing the floating injection process with cetyltrimethylammonium bromide (CTAB)-modified phosphate buffer (20 mM phosphate plus 50 μM CTAB). (i) initial state; (ii) floating injection is on; (iii) ~10 s later; and (iv) separation is initiated. 30 nm pore NCAM. The electropherogram shows 20 repeated injections.

hybrid PMMA micro/nanofluidic devices, shown schematically in Figure 3. Reproducibly transporting sample plugs from one microfluidic channel to another through the interconnected NCAM is important for many of the Nano-CEMMs printing strategies in addition analytical/bioanalytical applications. [2].

- After demonstrating the highest resolution printing using an electro-hydrodynamic jet, Rogers and Park (visiting from KAIST, Korea) Georgiadis and Ferreira have developed scaling relations models for dimensional ranges in which the size of the nozzle is much less than one micron and droplet size is ~100 nm at which point the scaling relationships developed for conventional EHD sprays are no longer applicable. [3].
- Addressing the problem of high-sensitivity detection, Lu has developed an approach based on three important steps, a) precise immobilization of DNA stands on a substrate, b) site-specific docking of nano-particle probes on DNA strands along with their use in enhancing spectroscopic detection signals and c) use of specific binding/cleavage reactions to detect presence of certain analyte molecules (Figure 4).

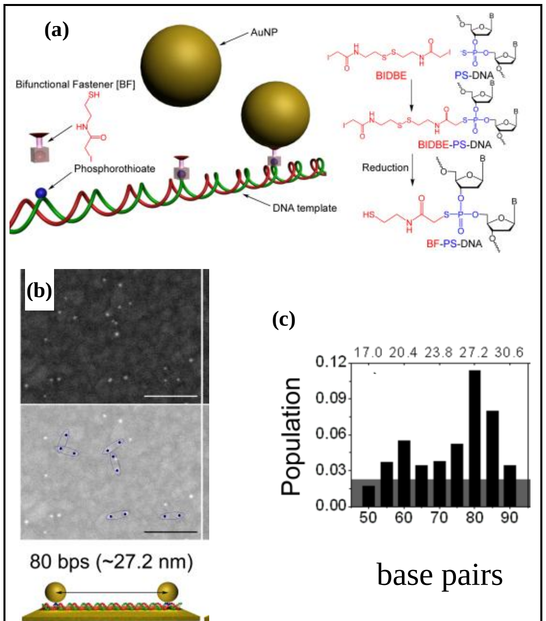



**Figure 4** **(a)** Schematic of approach to site-specific docking of Au nanoparticles on DNA, **(b)** SEM, optical micrograph and schematic of two gold particles docked 80 basepairs away, and **(c)** statistics of distances between the Au nanoparticles in the micrograph.

- Yu has developed whole new process modes to create long wires using controlled evaporation at the minuscus to create rolls of micro-fibers of various salts such as CuSO4 and metals such as copper, silver, gold and platinum as shown in Figure 5 [4, 5].

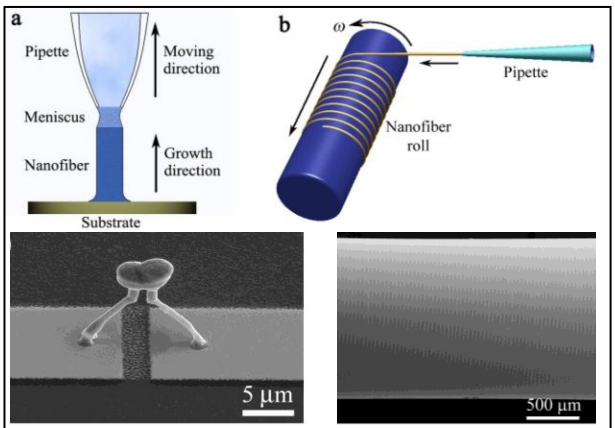



**Figure 5**: **(Top)** Schematics showing deposition schemes based on the evaporation from a confined nanoscale meniscus. **(Bottom left):** SEM of a 3-D bridging structure. **(Bot. Right)** The SEM of 850 nm $CuSO_4$ microfiber 45 cm long rolled onto 1.58-mm diameter shaft.

## 3. Education and Outreach

The broader mission of the Center involves advancing education in nanoscience and technology, and developing diverse human resources in science and engineering in general and nanomanufacturing in particular. A solid HRD program infrastructure supports programs for pre-college, undergraduate, and graduate students, as well as teaching professionals. Over these years, new courses based on Center research were taught at UIUC and NCA&T. In the last year, 10 Ph.D. and 7 M.S students graduated, 16 REU students participated in the Center, 254 high and middle school teachers attended institutes and workshops, 3,949 middle and high school students attended Center programs, and 1,213 students used classroom learning modules developed by the Center. Components aimed at increasing diversity were embedded in all facets of the Center. Evaluations of all education and outreach activities were conducted by faculty and staff from the Departments of Education at UIUC and NCA&T. The Center's education program has also leveraged its budgets through collaborations with the Illinois State Board of Education for the development and delivery of teacher education programs and also with fund from private foundations.

## 4. Summary

In the four years since its inception, Nano-CEMMS has developed into a vibrant, interdisciplinary research and education environment. Tangible results of this integrated environment are evident from its ability to leverage funds from other agencies and industry. The productivity of the environment is visible in the number of publications (around 235) with more than half published with two or more Center researchers and Patents (16 applications). The Center has graduated 15 PhD and 15 MS students and this number is expected to increase steadily.

## 7. References

[1] http://www.nano-cemms.uiuc.edu/
[2] Kim, B. Y., Swearingen, C. B., Ho, J. A.., Romanova, E. V., Bohn, P. W., and Sweedler, J. V. "Direct Immobilization of Fab' in Nanocapillaries for Manipulating Mass Limited Samples," J. Am. Chem. Soc. 129, 7620-7626, 2007.
[3] E.N. Gatimu, J.V. Sweedler, P.W. Bohn, "Nanofluidics and the Role of Nanocapillary Array Membranes in Mass-Limited Chemical Analysis," The Analyst 131, 2006, 131, 705-709.
[4] Suryavanshi A. P. and Yu, M.F. "Electrochemical Fountain Pen Nanofabrication (ec-FPN) of Vertically Grown Platinum Nanowires," Nanotechnology, 18, 105305, 2007.
[5] Suryavanshi, A.P., Hu, J., and Yu, M.F. "Meniscus-Controlled Continuous Fabrication of Arrays and Rolls of Extremely Long Micro- and Nano-fibers," Advanced Materials, 20, 793-796, 2008.

**NANO HIGHLIGHT** NSF NIRT Grant **0708172**

# NIRT: Engineered Therapeutic nanoparticles as catalytic antioxidants

PIs: **S. Seal,[1] W. Self,[1] A. Masunov[1] and J. McGinnis[2]**

[1]University of Central Florida, Orlando, and [2]University of Oklahoma

Almost 8 million people in the USA have Age Related Macular Degeneration, over 5 million have diabetic retinopathy and almost 3 Million people from USA suffer from Glaucoma. Therefore, this research project has the potential both to better understand these blinding diseases as well as to develop novel therapeutics for treatment or prevention, all of which can help to improve the quality of lives and reduce medical costs. Thus this NIRT program has enormous potential impact in creating regenerative nanomedicine using active nanostructures. Based on the ability to undergo reversible redox reactions, nanoceria nanoparticles (NP) can effectively scavenge reactive free radicals. We are developing engineered rare earth NPs to mimic antioxidant enzymes in order to reduce accumulation of biological damage due to free radicals. Although these NPs have shown excellent antioxidant and regenerative behavior in neurons, the details of cellular interaction mechanisms are yet to be understood. In the current program, we are studying the protective behavior in retinal cells. Furthermore, the computational data on the therapeutic characteristics of NPs are correlated with the experimental data.

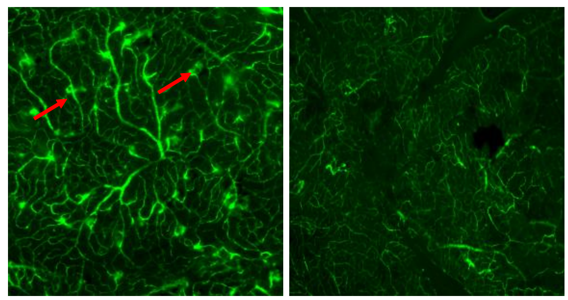


Fig 1. Nanoceria prevent inherited leaky retinal vasculature in mutant mice.

Thesse NPs have found to prevent the increase in the intracellular concentrations of ROS in primary cell cultures of rat retina and the loss of vision *in vivo* due to light-induced degeneration of photoreceptor cells. Using a fluorescent assay that detects leaky blood vessels (red arrows) in mutant mouse retinas, our data showed that a single injection of nanoceria given 21 days prior to the assay, greatly reduced (estimate 85%) retinal edema in the mutant mouse retina (Fig 1). We hypothesized that the nanoparticles increased longevity by reducing the free radical damage to the biological system. We have further discovered that nanoceria can catalyze SOD activity *in vitro*, and have been working to understand the molecular mechanism of this radical scavenging property of the material. Catalytic activity of nanoceria with a higher level of $Ce^{3+}$ was shown to be superior in our preliminary work. We have also found that the co-existence of both $Ce^{3+}$ and $Ce^{4+}$ oxidation states in $CeO_2$ NPs plays a critical role in its antioxidant behavior. Experimental data have shown that the reversal of oxidation state also continues over time in cell culture and therefore $CeO_2$ NP acts as a catalyst.

Our current multidisciplinary strategy combined with engineers and scientists have created novel nano-rare earths with regenerative capability in scavenging radicals and protecting mammalian cells. The research will train students from engineering, simulation and biomolecular engineering and has created unique partnership between University of Central Florida and University of Oklahoma.

Some news highlights: Sights set on nanoparticles" – *Materials Today*, 9(12), 2006, "Trouble with Photons", New York Times, Oct 31, 2006, BBC News (http://news.bbc.co. uk/1/hi/health/ 6749707.stm), Key papers from the Team: McGinnis et al., *Nature Nanotech*, 1(2), 2006. Self, Seal, et al., *Biomaterials*, 29, 2008, *Chem Comm*, 10, 2007. *Patent*: 7,347,987, McGinnis, Seal et al. For more information: Contact sseal@mail.ucf.edu

# NANO HIGHLIGHT
# NIRT: Photon and Plasmon Engineering in Active Optical Devices based on Synthesized Nanostructures

*NSF NIRT Grant ECCS-0708905*

**PIs: Marko Loncar[1], Mikhail D. Lukin[2], Hongkun Park[3,2]**
[1]School of Engineering and Applied Sciences, [2]Department of Physics, [3]Department of Chemistry and Chemical Biology, Faculty of Arts and Sciences, Harvard University

The central goals of our project are understanding and engineering of fundamental properties of light generation and control in active optical nanostructures, and development of novel devices and systems for optical and quantum information processing. This is accomplished by integrating bottom-up synthesized nano-emitters with top-down fabricated structures for light confinement. Our work will enable the realization of robust, practical single photons devices (e.g. sources and switches), nano-scale lasers, and methods for photon harvesting with sub-wavelength resolution**.** These devices and techniques are expected to have a wide variety of applications in the areas ranging from quantum cryptography and optical communications, to life sciences and advanced photolithography.

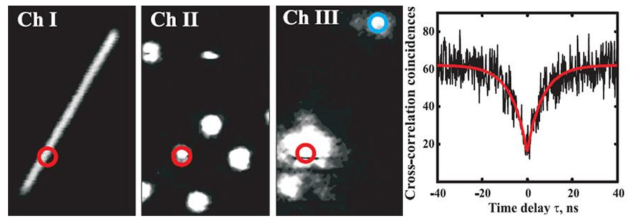



**Fig. 1.** Coupling of CdSe quantum dots to surface plasmons supported on single crystal Ag nanowire[1]. CH I and CH II show a confocal reflection image of an Ag nanowire, and fluorescence image of quantum dots emitting at 655nm, respectively. Ch III shows a coupled wire–dot system. The red and blue circle corresponds to the position of the dot coupled to nanowire and the end of the nanowire, respectively, used for photon cross-correlation measurements (the right-most panel).

Similar to conventional dielectric fiber that can guide photons, metal nanowire can guide propagating surface plasmon modes (charge density waves coupled to photons) localized transversely to dimensions comparable to the wire diameter. However, as opposed to dielectric waveguides, fundamental plasmon mode of nanowire exists even when nanowire diameter is much smaller than the optical wavelength. Such sub-wavelength localization is accompanied by a dramatic concentration of optical fields, and reduced propagation velocities of plasmon modes. This, in turn, significantly increases the emission rate of a nanoscale optical emitter placed in the proximity of the nanowire, and channels the majority of its spontaneous radiation into the guided surface plasmon mode of the nanowire (Figure 1). Non-classical photon correlations (anti-bunching) between the emission from the quantum dot and the ends of the nanowire demonstrate that the latter stems from the generation of single quantized plasmons. The collection efficiency of our system can be further improved by coupling the nanowire to a dielectric waveguide (Figure 2). In this way, plasmons generated by quantum dot can be efficiently collected by an optical fiber.

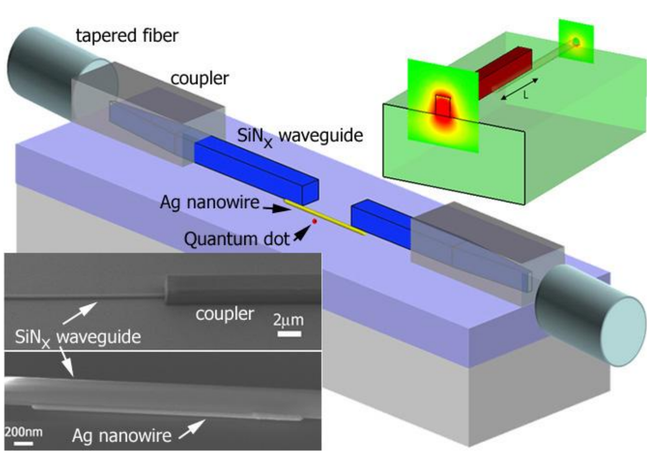



**Fig. 2.** Platform used for efficient extraction of quantum dot emission. Insets: fabricated structures and model of nanowire-waveguide coupler.

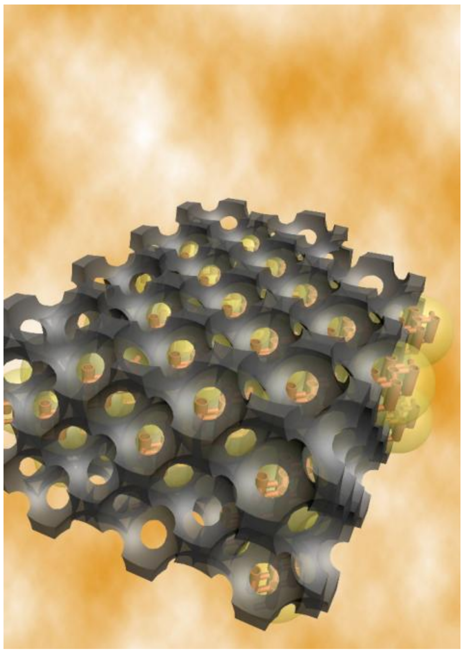
1. A. V. Akimov, et al, *Nature* **450**, 402 (2007)
2. Further information: loncar@seas.harvard.edu, lukin@fas.harvard.edu, Hongkun_Park@harvard.edu

# NANO HIGHLIGHT

## Precise Building Blocks for Hierarchical Nanomanufacturing of Membranes with Molecular Resolution

*NSF NIRT Grant CMMI-0707610*

PIs: **Michael Tsapatsis, Marc Hillmyer, Alon V. McCormick, R. Lee Penn, Andreas Stein**
Department of Chemical Engineering and Materials Science and Department of Chemistry,
University of Minnesota, Minneapolis, MN



Zeolites are microporous materials that find numerous applications in catalysis, separations, ion exchange, etc. They have pores of the order of 1nm and can discriminate molecules based on size and shape. However, because of this small pore size they also exhibit mass transfer limitations (diffusion of molecules is slow).

The combination of *ordered microporosity and mesoporosity* is a possible solution in order to obtain materials that exhibit the molecular sieving properties of zeolites without the mass transfer limitations. An analogy would be that of freeways and streets, with the mesopores being freeways and the zeolite micropores being the streets. All the action takes place at the streets. However, in the absence of freeways, access to the streets and the corresponding action may be difficult. Therefore, numerous efforts in the last 15 years are aiming in this direction.

Recently published work[1] form this team shows that ordered mico-meso-porous materials can be made by growing zeolite crystals in an ordered porous carbon scaffold (see schematic). After the zeolite is grown, the scaffold can be removed to generate larger highly interconnected pores precisely located to allow for fast transport of molecules to the molecular sieving areas. It is expected that these three dimensionally ordered mesoporous (3DOm) zeolites will exhibit faster reaction rates for reactions involving molecules that diffuse slowly in the zeolite pores.

The team demonstrated not only the imprinting of ordered mesoporosity, but also the synthesis, under appropriate conditions, of single isolated nanocrystals bearing size and shape perfection as well as unusual morphologies that cannot be accomplished otherwise. These precisely shaped zeolite nanoparticles can be used to form coatings for molecular sieve membrane applications.

**Reference**

W. Fan, M. Snyder, S. Kumar, P.-S. Lee, W.C. Yoo, A.V. McCormick, R.L. Penn, A. Stein and M. Tsapatsis, ***Nature Materials***, Published Online, DOI:10.1038/nmat2302

For more information link to: http://www.cems.umn.edu/research/tsapatsis/NIRT_ZGCS/index.php or
email: tsapatsi@cems.umn.edu

# NANO HIGHLIGHT

## Nano-Pen

*NSF NER, Grant #0609349*

PI: **Punit Kohli,** Department of Chemistry and Biochemistry, Southern Illinois University, Carbondale IL 62901.

**Students:** Pradeep Ramiah Rajasekaran, Justin Wolff, Rashid Zakeri, Bojan Mitrovic, Charvi Patel and Kashyap Tadinisa. **Collaborators:** Sami Aouadi (Department of Physics) and Haibo Wang (Department of Electrical Engineering) Southern Illinois University. Horacio Espinosa (Department of Mechanical Engineering) Northwestern University. Christina Trautmann (GSI, Germany)

Patterning at submicron/nanometer resolution has a wide range of applications in a variety of fields. It is difficult to make these nanometer patterns with conventional photolithography. Making patterns in nanometer scale usually involves expensive and complex instrumentation. Some of the present techniques involve Atomic Force Microscopy (AFM), Dip Pen Lithography (DPN) etc. Here we propose a relatively simple and inexpensive technique for patterning at submicron- and nano-scale level. We use electric potential to force charged molecules through a "nanopen" that is made from glass. The electroosmotic/electrophoretic effects draw the charged molecule (DNA) on to the substrate for patterning purposes. This set up is attached to a set of XYZ piezoelectric motors which can be controlled with computer to make patterns on the surface.

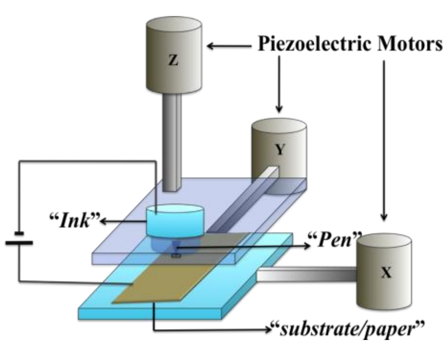



**Fig. 1** Schematic of Pen

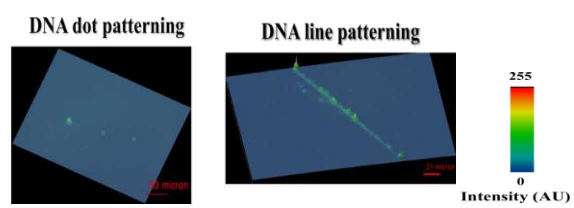



**Fig. 2** DNA Patterning

**Reference**:

1. Ho, Andrea M.; Rim, Jee; Kohli, Punit; Patankar, Neelesh; Espinosa, Horacio D. "*Electric-field Induced Direct Delivery of Proteins by a Nanofountain Probe*" *PNAS*. **2008**. 105. 16438-16443.
2. Pradeep, Ramiah Rajasekaran; Wolff, J.; Zakeri, R.; Mitrovic, B.; AouadiS.; Trautmann,C.; Kohli, P. "Lithography using Nanotubes", JACS (in preparation).
3. Mirkin, C. *et al*. Science, **1999,** 283, 661-663.

# NANO HIGHLIGHT

## From Biotechnology to Nanotechnology: Parallels in State Regulatory Review

*Nanotechnology Interdisciplinary Research Team (NIRT), SES #0609078*

**C. Bosso (PI); J. Isaacs, W. Kay, R. Sandler, and A. Busnaina (co-PIs); K. McCarty (RA)**

**Northeastern University [1]**

The Commonwealth of Massachusetts is in the top tier of the states for research and development in nanoscale technologies. As a consequence, there is considerable shared strong interest in ensuring a smooth transition from R&D to commercial scale production, as well as in developing the local and state institutional capacity to handle any social and environmental effects of technology development and commercialization as this sector matures and grows. This project examined the formulation of state environmental and permitting regulations relevant to the biotechnology industry and assesses implications for nanotechnology development broadly understood.

Massachusetts, like many states, has invested heavily in the economic development promise of biotechnology, which as a sector now employs thousands of people with the potential to create more new jobs as more companies move to commercial production. Of course, any company or operation in Massachusetts that emits particles into the air or water, or that creates hazardous chemical or biological waste during or as a result of production processes are subject to a matrix of local, state, and federal environmental, health, and safety (EHS) laws and regulations. While such regulations are designed to protect workers, the public, and the environment, out of date or inappropriate rules and procedures can add burdens to businesses seeking to speed new products to new markets. For smaller companies in particular, opaque state and local permitting processes and environmental regulations can hamper progress to market by imposing unforeseen and possibly high additional resource burdens. The prospect of navigating a convoluted regulatory system may prompt companies to look elsewhere to site their manufacturing and production operations.

In 2002 the biotechnology industry in Massachusetts criticized the Commonwealth's regulatory matrix as burdensome, complicated, and a direct barrier to economic growth. In response the Department of Environmental Protection (DEP), working directly with a wide array of stakeholders, reviewed and ultimately streamlined a set of air pollution, wastewater treatment, and hazardous waste regulations. In some cases the changes applied to specific processes and known pollution thresholds for biotechnology operations, while in others DEP found reason to extend the revised regulations to all industries.

The analogy of this case to the nanotechnology sector, broadly understood, is clear. States are critical players, both as primary enforcers of federal EHS regulations and as regulatory innovators in their own right. States also seek a balance between encouraging economic development and ensuring public and environmental health and safety. The role of states as regulatory agents will loom larger as applications move to commercial production. This case study of the process by which Massachusetts revised regulations pertaining to the biotechnology industry provides useful insights into the potential regulatory issues facing the nanotechnology sector and lessons about how industry representatives may need to work with state officials to adapt regulatory frameworks to sector-specific needs.

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[1] NIRT, "Nanotechnology in the Public Interest: Regulatory Challenges, Capacity, and Policy Recommendations." For more information see the Nanotechnology and Society Research Group website http://nsrg.neu.edu. This research was also supported by the Center for High-rate Nanomanufacturing (EEC #0425826), A. Busnaina, Director.

# Laboratory for Integrated Science & Engineering

*NSEC NSF/PHY 06-46094*
**Robert M. Westervelt**
Harvard, MIT, USCB, MOS

New shared facilities operated by the Harvard's Center for Nanoscale Systems located in our new Laboratory for Integrated Sciences building new provide world-class, centralized facilities and technical support for research on nanoscale systems:

- Nanofabrication - e-beam, optical and soft lithography.

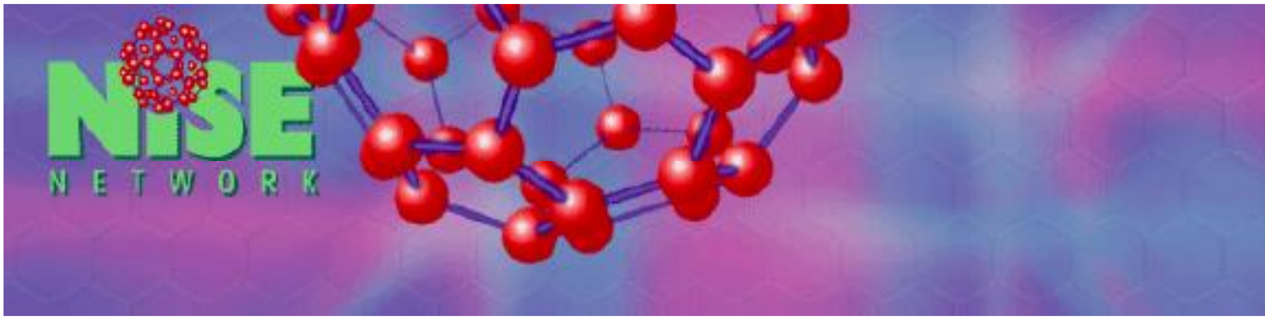
- Imaging - TEM, STEM, & SEM, as well as AFM and confocal microscopy.

Advanced Materials Synthesis

# Nanoscale Informal Science Education NISE Network

*NSEC NSF/PHY 06-46094*

**Carol Lynn Alpert, Larry Bell, Kathryn Hollar, Eric Mazur, Robert M. Westervelt, George Whitesides**
Harvard, MIT, USCB, MOS

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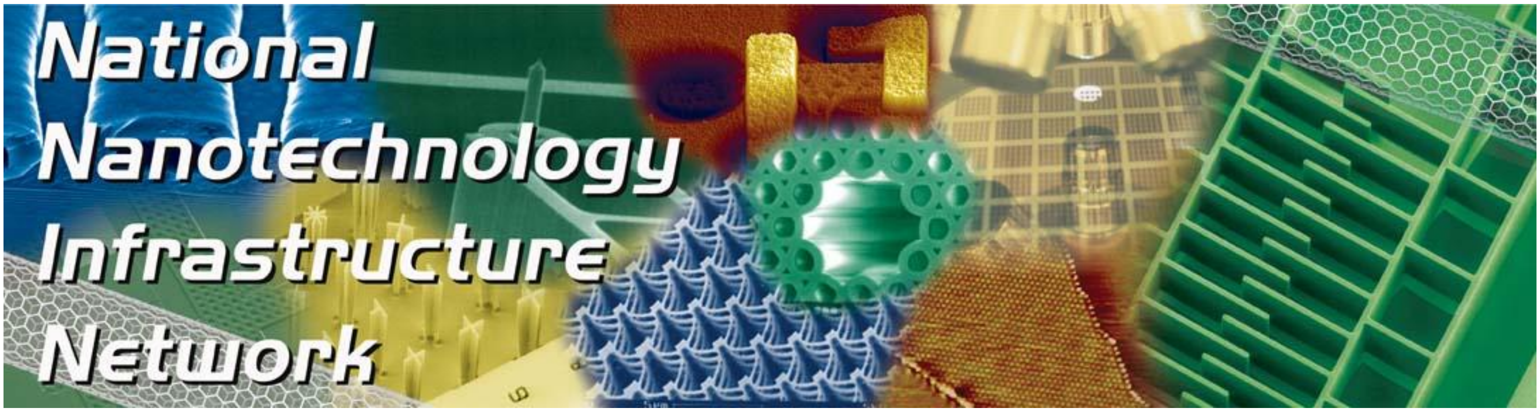
TIFF (Uncompressed) decompressor
are needed to see this picture.

Our NSEC is a strong partner in the Nanoscale Informal Science Education (NISE) Network that links science museums, educational organizations and research institutions. The Center's faculty and students, guided by our Education Director **Kathryn Hollar**, develop interactive demonstrations and help set up NanoFutures Forums at the Museum of Science, Boston, as well as particpate in the NISE Nanoscale Education Outreach (NEO) Workshops at the Exploratorium in San Francisco.

## National Nanotechnology Infrastructure Network

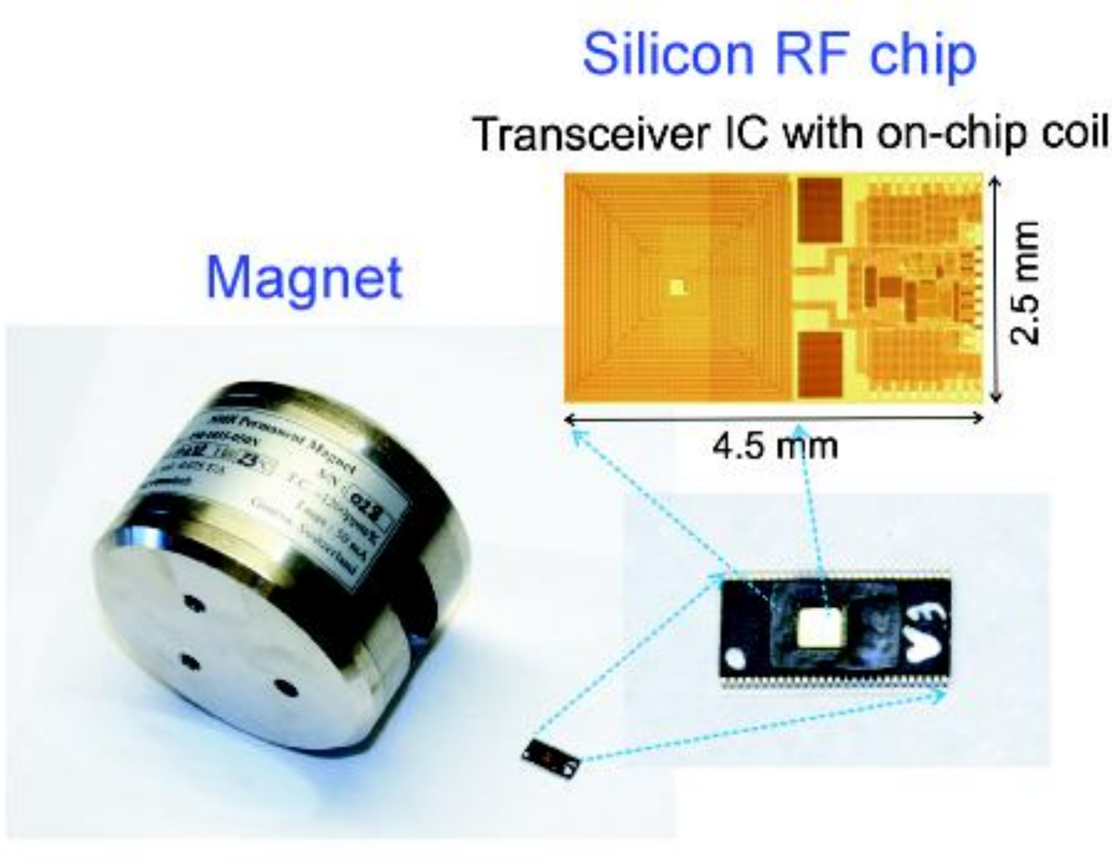
*NSEC NSF/PHY 06-46094*
**Robert M. Westervelt**
Harvard, MIT, USCB, MOS




Harvard and UC Santa Barbara are two of an integrated partnership of thirteen user facilities led by Cornell and Stanford that provide opportunities for nanoscience and nanotechnology research. At Harvard, the NNIN provides expertise in computation and in soft lithography through the Center for Nanoscale Systems. At UCSB, the NNIN provides expertise in optics and electronic materials.

# 1-Chip CMOS NMR System

*NSEC NSF/PHY 06-46094*
**Donhee Ham**
Harvard, MIT, USCB, MOS

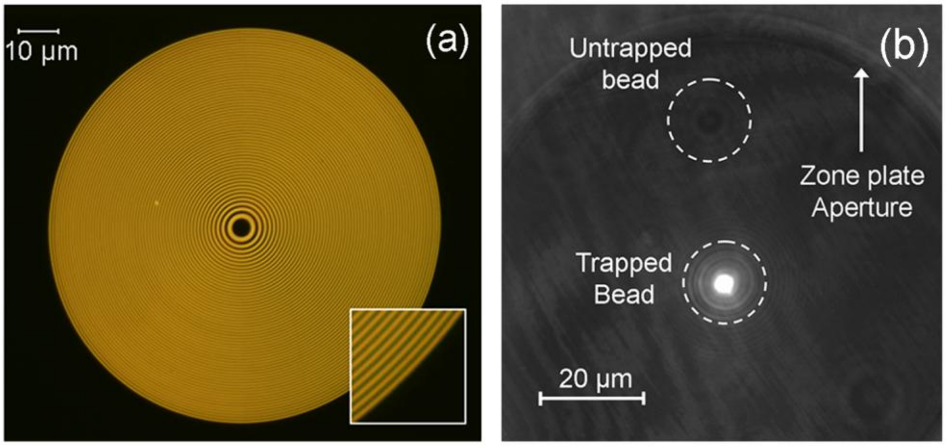



A 1-chip NMR relaxometry system that is 80x smaller, 60x lighter, yet 60x more mass sensitive than a commercial benchtop system. This is possible through CMOS integration of a highly sensitive RF transceiver, which controls and monitors nuclear spins in a sample. This system is a low-cost, portable diagnostic tool that can detect biomolecules (e.g., cancer marker proteins) by monitoring nuclear spin relaxation times, in conjunction with magnetic nanoparticles.

# Microfabricated Fresnel Zone Plate Optical Tweezers

*NSEC NSF/PHY 06-46094*

**Kenneth Crozier**
Harvard, MIT, USCB, MOS

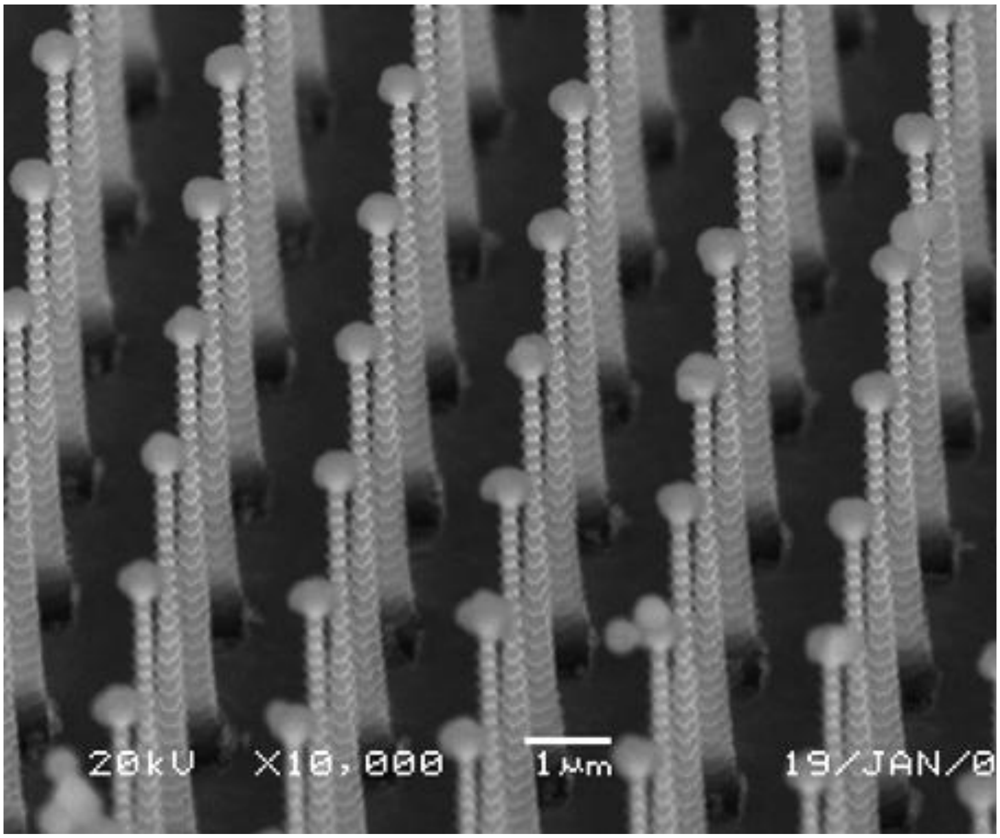



(**a**) Photograph of microfabricated Fresnel-Zone-Plate optical tweezer, consisting of concentric gold rings (50 nm thick) on a microscope slide. The Zone Plate outer diameter is 100 µm, and the focal length is 8 µm. **(b)** CCD camera image of a fluorescent bead (2µm diameter) trapped in Zone Plate focus.

Optical tweezers incorporated in microfluidic chips, could carry out many functions, including particle sorting and manipulation, and biophysical-force measurements. **Crozier** has demonstrated a Fresnel zone plate as an optical trap. The device, shown in **(a)**, consists of concentric gold rings on a glass substrate. It focuses a collimated laser beam to a submicron spot. In (**b**), a photograph of a 2 µm bead trapped by the Zone Plate is shown.

# Materials Deposition on a Nanowire Array: Nanoscale Building Blocks

*NSEC NSF/PHY 06-46094*
**Joanna Aizenberg**
Harvard, MIT, USCB, MOS

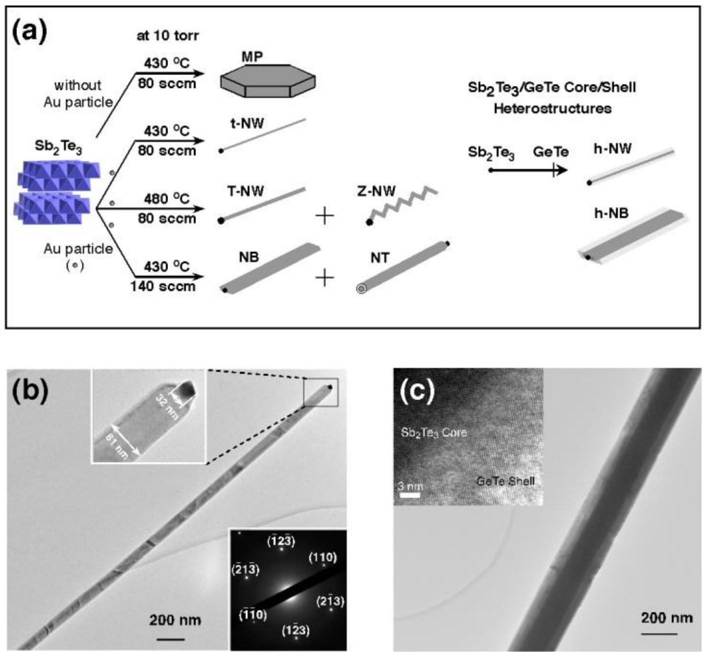



A new approach to fabricate nanowire arrays has been developed, in which a guest material is deposited at one end of each nanowire, due to the super-hydrophobic character of the surface. Highly uniform deposition of particles with controlled size, geometry and structure occurs, as shown for calcium carbonate particles. This method could be applied quite generally to produce novel functionalized nanowire arrays and 3-D nanostructures for applications in electronic and optical materials, actuators, biological sensors, functional "barcode" designs, and self-organization.

# Phase-change Nanowires and Nanowire Heterostructures

*NSEC NSF/PHY 06-46094*

**Hongkun Park**
Harvard, MIT, USCB, MOS

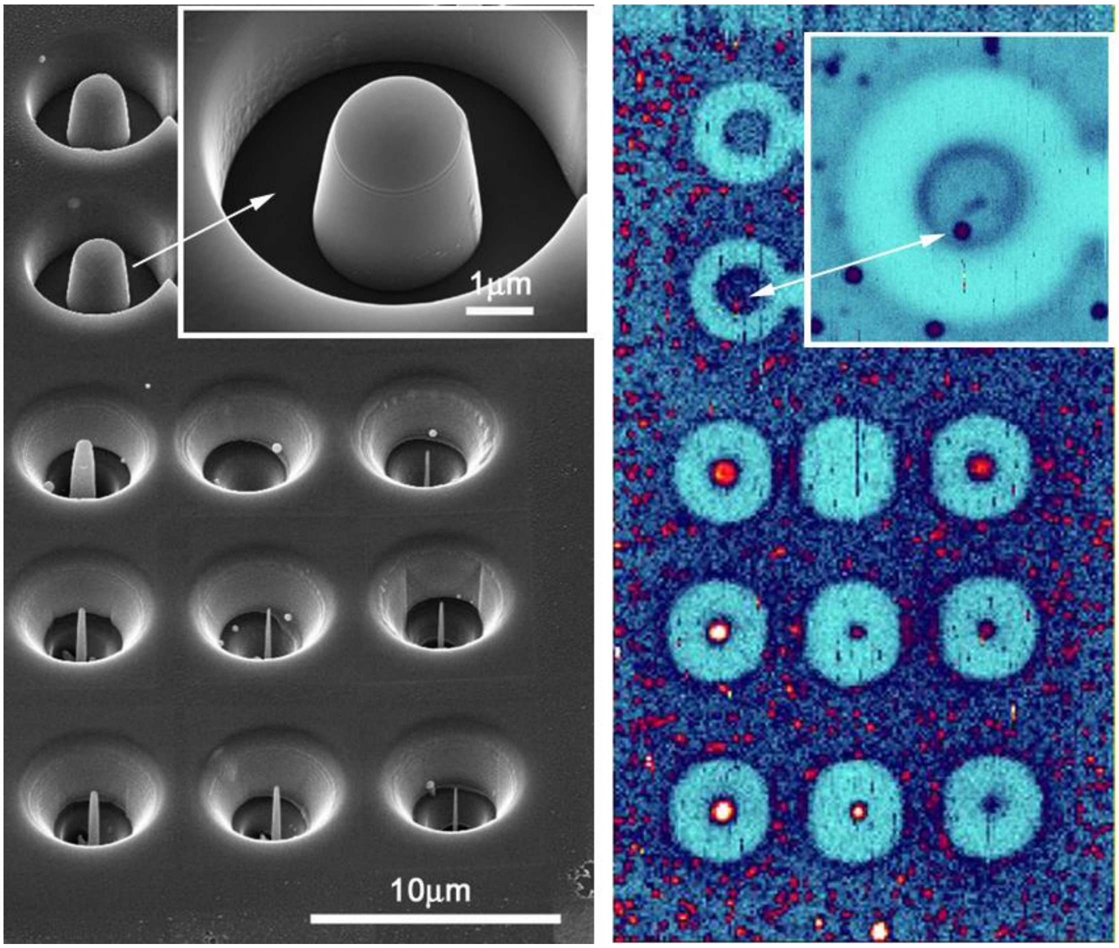



Chalcogenides exhibit a reversible crystalline-amorphous phase change induced by temperature or electric field, and form the material bases for data storage media such as CD/DVD and phase-change random access memory (PRAM). The intrinsic properties of chalcogenide materials and their size-dependent variations determine the speed, stability, and miniaturization of PRAM, highlighting the importance of studying these phase-change materials in a nanostructured form. **Park** has synthesized single-crystalline phase-change $Sb_2Te_3$ and GeTe nanowires and nanowire heterostructures.

# Diamond Nanowires

*NSEC NSF/PHY 06-46094*

**Marko Loncar**
Harvard, MIT, USCB, MOS



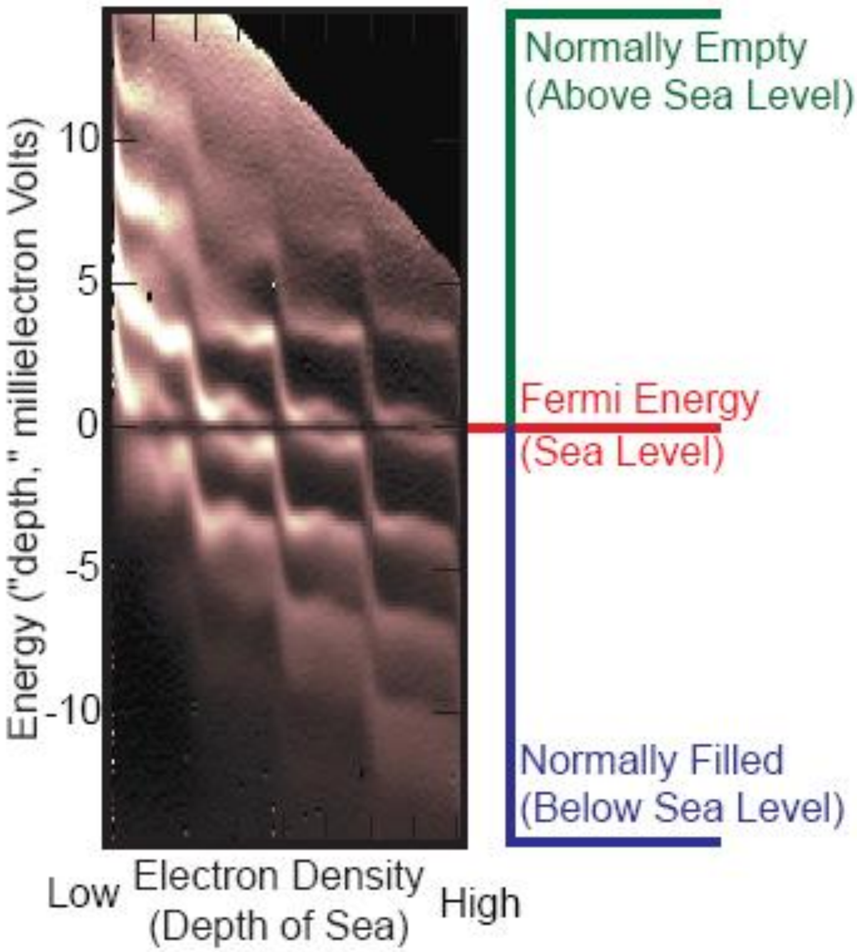

(left) SEM micrograph of an array of diamond nanowires and microposts fabricated in single crystal CVD-synthesized diamond. (right) Confocal photo-luminescence image shows presence of single NV color centers (small red dots) inside nanowires, as well as in the large posts (inset).

# Spectroscopy of Quantum Hall Systems


*NSEC NSF/PHY 06-46094*

**Raymond Ashoori**

Harvard, MIT, USCB, MOS


A new technique developed by **Ashoori** allows measurement of the energy spectrum of electrons in a two-dimensional electron gas with 1000 times better energy resolution than was previously possible. Electrons tunnel into an energy level in the 2D system much more quickly than they would otherwise, allowing the spectrum to be mapped by measuring the tunnel rate *vs.* electron energy. These spectra provide the first glimpse of these systems and show what a beautiful and interesting view that can be.

# NANO HIGHLIGHT

## Chasing a $3 Trillion Industry: China's Bid to Become a Major Nano Player

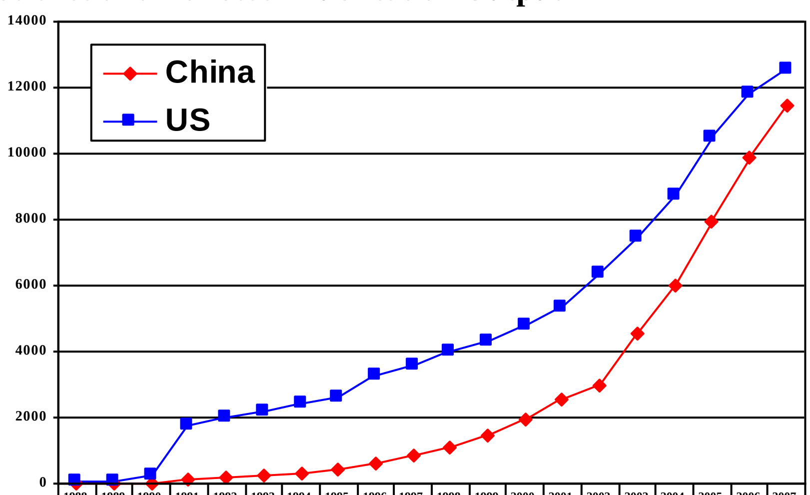
*NSF NSEC Grant 0531184*

PIs: **Barbara Herr Harthorn, Rich Appelbaum[1,2], Bruce Bimber, W. Patrick McCray, Christopher Newfield**
University of California, Santa Barbara

Researchers at UCSB's Center for Nanotechnology in Society, Duke University's Center on Globalization, Governance & Competitiveness and SUNY's Levin Institute have examined China's efforts to become first movers in the projected $3 trillion global nanotechnology industry. Analysis of Chinese nanotechnology publication data, Chinese government documents, and over sixty interviews with Chinese Academicians, scientists, engineers, and policy-makers finds that while the combination of international collaboration and public funding of nanotechnology R&D and commercialization holds promise, China remains – in the words of the head of its National Center for Nano-Science and Technology – "in the rear of the first echelon or the front of the second echelon, ranking fifth or sixth in the world."

Like many countries involved in catch-up development[1], China is convinced that manufacturing prowess alone is insufficient to becoming a leading economic power in the 21st century. National Long and Medium Term Scientific and Technological Development Plan (2006-2020): nanotechnology is one of 4 "science Megaprojects." One area where this effort has clearly manifested itself is in nanotechnology publication output[2]. Based on a linear projection of the current publication data, Chinese nanotechnology publications are predicted to surpass the US in number by 2012.

**China and US Nanoscience and Nanotech Publication Output**




| | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| China | 4 | 5 | 10 | 99 | 178 | 238 | 312 | 435 | 612 | 857 | 1083 | 1469 | 1944 | 2544 | 2964 | 4542 | 6000 | 7954 | 9863 | 11432 |
| US | 49 | 90 | 263 | 1764 | 1981 | 2190 | 2417 | 2620 | 3264 | 3552 | 3974 | 4302 | 4762 | 5341 | 6346 | 7484 | 8712 | 10492 | 11813 | 12546 |

**References**

[1] Richard P. Appelbaum, Rachel A. Parker, Cong Cao, and Gary Gereffi "China's (Not So Hidden) Developmental State: Becoming a Leading Nanotechnology Innovator in the 21st Century" *Half Empty and Half Full: Perspectives on U.S. Innovation Policy 1969-2009* Fred Block and Matthew R. Keller, eds. Forthcoming, 2009
[2 ]Richard P. Appelbaum and Rachel A. Parker, "China's Bid To Become a Global Nanotech Leader: Advancing Technology Through State-Led Programs and International Collaborations," *Science and Public Policy* June 08

# NANO HIGHLIGHT

## Health and Safety Practices in the Nanomaterials Workplace: Results from an International Survey

*NSF NSEC Grant 0531184*

PIs: **Barbara Herr Harthorn[1], Rich Appelbaum[1], Bruce Bimber, W. Patrick McCray, Christopher Newfield**
University of California at Santa Barbara

Researchers at University of California, Santa Barbara, in a study funded by the International Council on Nanotechnology (ICON), surveyed 82 nanomaterials firms and labs in 14 countries regarding their environmental health and safety (EHS) programs, practices, and risk beliefs about nanomaterials.

Most nano-specific EHS programs were found to build upon general EHS programs, but also included nano-specific workplace engineering controls, and recommendations for protective clothing, gloves, eye protection and respirators. However, workplace monitoring and nano-specific waste disposal were only found in the subset of organizations believing in special risks related to nanomaterials. A majority of organizations expressed need for toxicological information and EHS guidance. Improved risk communication is thus needed to further implementation of related programs. The study concludes that organizations that are wholly inattentive to EHS would likely engage in nano-specific EHS upon implementing a staffed, general EHS program.

(Photo: Paul Schulte, NIOSH)

**References**
[1] Conti, J.A., [1] K. Killpack,[2] G. Gerritzen,[2] L. Huang,[2] M. Mircheva,[2] M. Delmas,[2] B.H. Harthorn,[3] R. Appelbaum,[3] & P.A. Holden.[2] *Environ. Sci.Technol* 42 (9), 3155-3162, 2008. 10.1021/es702158q Web Release Date: Apr 1, 2008. American Bar Foundation 1; Donald Bren School of Environmental Sci & Management, UCSB 2; CNS-UCSB, UCSB 3.

# NANO HIGHLIGHT
## Traveling Nanotechnologies: An Undergraduate Internship Program in Nanotechnology and Society

*NSF NSEC Grant 0531184*

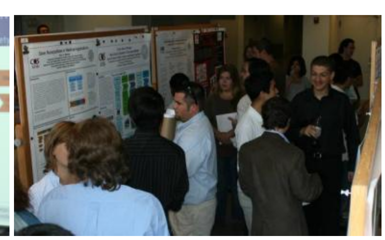
PIs: **Barbara Herr Harthorn, Rich Appelbaum, Bruce Bimber, W. Patrick McCray, Christopher Newfield**
University of California, Santa Barbara

Education and Public Engagement is a critical component of the Center for Nanotechnology in Society at UCSB. This highlight reports on our eight-week Summer Internship Program for undergraduates from UCSB campus as well as California community colleges who are recruited through a partnership with the INSET (Internships in Nanosystems Science, Engineering and Technology) program at the California NanoSystems Institute at UCSB.

In summer 2008, five social science and humanities undergraduates traced the 'travels of a nanotechnology' through the Global Value Chain and consumer products' life cycles at the Center for Nanotechnology in Society (CNS) at UCSB. Mentored by CNS Graduate Fellows in the social sciences and NSE and faculty researchers, one team of interns investigated nanosilver in washing machines, plush toys, and first aid applications, and another team researched solar technology companies in China and Italy. They used a Global Value Chain approach to consider all the inputs and activities that go into creating a product or an industry – from R & D, design, and raw materials, to production, manufacture, marketing and distribution, including all the people or companies involved. At the end of the program, interns presented their results in a poster and presentation, and created information cards for their product. The results of this project were presented to social science community college teachers at a UCSB CNSI-CNS Educators' Conference in Sept, 2008.

As a model for undergraduate research on societal implications of nanotechnology, this project was successful in three primary ways:

- working with commercial products in everyday use or on the cutting edge of technology motivated students
- interns were able to be self-directed and make research decisions based on a guiding framework and theoretical foundations
- the project integrated nanoscale science and engineering with societal implications, giving students a 'big picture' around which they could tell the story of their nanomaterial

**References** [1] For further information about this project please see our website at <**http:cns.ucsb.edu**> or email CNS-UCSB Education Coordinator, Julie Dillemuth **<julie@cns.ucsb.edu>**

# NANO HIGHLIGHT
# Context Matters Too: First Ever US-UK Cross-National Comparison of Public Deliberation

*NSF NSEC Grant 0531184*

PIs: **Barbara Herr Harthorn[1], Rich Appelbaum, Bruce Bimber, W. Patrick McCray, Christopher Newfield**
University of California at Santa Barbara

While "size matters" is a ubiquitous theme in nanotech research, this comparative study found that the context, both national/cultural and type of application, matters a great deal in determining public response to specific nanotechnologies.

The goal of this study was to devise a cross-cultural protocol for studying public deliberation of nanotechnology applications. Four parallel deliberative workshops were conducted in February 2007, two in the US and two in the UK. The workshops focused upon nanotechnology applications in energy and human health and enhancement and recruited diverse groups matched in composition to local demographics. The 4.5 hour single session meetings included balanced presentations of known and potential benefits and risks, and a "world café" type session for self-directed learning.

Public views in both countries focused on benefits rather than risks. Application context was more salient than nation as a source of difference, with nanotech energy viewed in a more positive and urgent light than health and human enhancement technologies. Subtle differences across countries emerged in views about equitable distribution, trustworthiness, and in consumerist attitudes. Overall, societal implications trumped concerns about technological implications for risk.

Example of World Café session (photo credit: www.notio.com)

**References**

[1] N Pidgeon (Cardiff), B. Harthorn (UCSB), K Bryant (SUNY-NP), T. Rogers-Hayden (East Anglia). In press, *Nature Nanotechnology.*

# NANO HIGHLIGHT
## Density Multiplication and Improved Lithography by Directed Block Copolymer Assembly

*NSF NSEC Grant DMR-0425880*

PIs: **J. J. de Pablo, P. F. Nealey**
University of Wisconsin-Madison

Electronic devices such as computer chips and future data storage drives that are the heart of products from laptops to cell phones to digital cameras are manufactured using photolithography. This process allows for the patterning of billions of nanoscopic structures and parts of the devices with virtually no defects over areas of square centimeters. As we look into the future, limitations related to the tools and materials used in the lithographic process may preclude the realization of future generations of high-performance products. A team of researchers at the University of Wisconsin Nanoscale Science and Engineering Center and Hitachi Global Storage Technologies have recently developed the technology to dramatically improve the quality and decrease the cost of patterning at nanoscopic length scales. Self-assembling block copolymers, materials that spontaneously form structures at length scales of 5 to 50 nm, assembly on surfaces patterned with lithography so as to markedly improve both the quality and resolution of the process. In comparing the assembled structures to the lithographically defined chemical pattern (see Figure) , the density is increased by a factor of four and the dimensional uniformity is vastly improved. These results have profound implications for augmenting and advancing the performance and capabilities of lithographic patterning and the many essential modern devices that rely on this nanomanufacturing process.

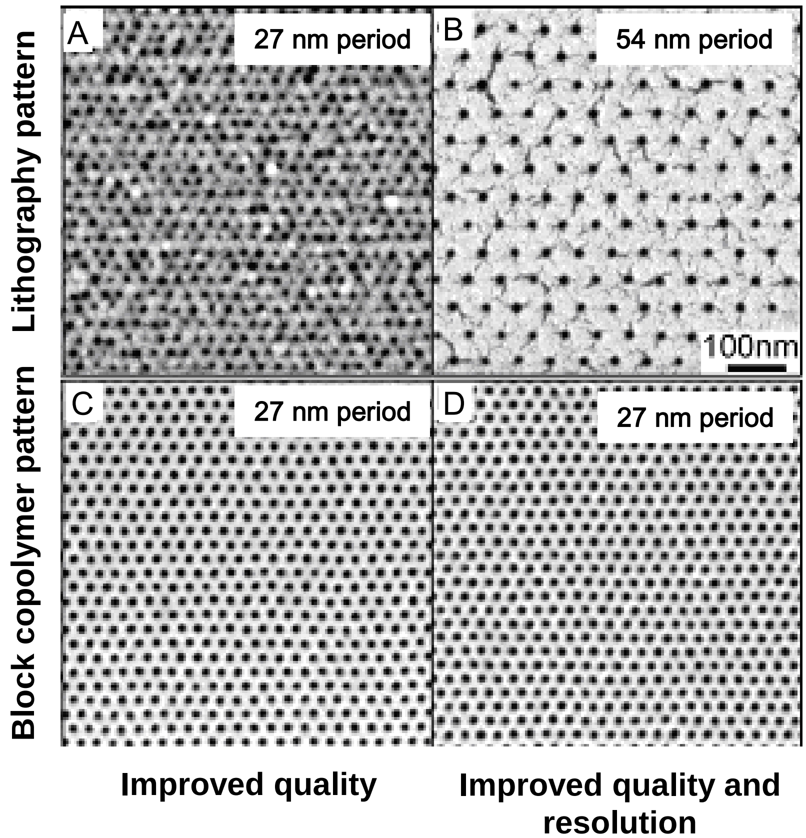



**Figure 1.** Comparison of the quality and resolution of patterns created by lithographic tools using current materials and processes (A and B) versus patterns created using the same tools but with self-assembling block copolymer materials (C, D).

[1] For further information about this project email nealey@engr.wisc.edu
[2] Ruiz et al., *Science*, 321: 936-939, **2008**.

# Panel Discussion:

# Legacy of the NSEC Programs



# Agenda

**Bob Westerveld**
  **Scientific Legacy**
**Dick Siegel**
  **Technological Development Legacy and Future**
**Ahmed Busnaina**
  **NSECs and industry: Legacy and Future**
**Placid Ferreira**
  **Manufacturing Legacy and Future**
**Barbara Harthorn**
  **Societal Impact Legacy and Future**
**Jim Yardley**
  **Comments and Discussion**

Nano Centers --- Present and Future
James Yardley panel (2)

# Yardley's Observations…..NSEC Legacy

- **Students and postdocs who understand and have experienced truly collaborative interdisciplinary research.**
- **Science and Technology that transcends what would have happened without a center-level environment.**
- **Creation of a community for interdisciplinary research in nanoscale science and technology.**
- **Creation and rapid development of new interdisciplinary fields of endeavor.**
- **Nurture of new faculty (and some non-new faculty) who understand and indeed champion interdisciplinary research.**

- **New level of diversity in scientific endeavor – especially in university faculty.**
- **Higher level of inquisitivity in research – research on a higher intellectual plane.**
- **Establishment of culture for collaborative interdisciplinary research in universities, but also industry and national laboratories.**
- **New technological and business concepts and basis for application to the benefit of society.**
- **Paradigm for national (and indeed international) focused science and technology development program.**

Nano Centers --- Present and Future
James Yardley panel (3)


## Some discussion points:

- **What legacies did we leave out?**
- **How can these legacies be quantified?**
- **How could we make the case for legacies that are seemingly difficult to quantify?**
- **Would the funds have been better expended to support research grants to individuals?**

## Scientific Legacy of NSEC Program

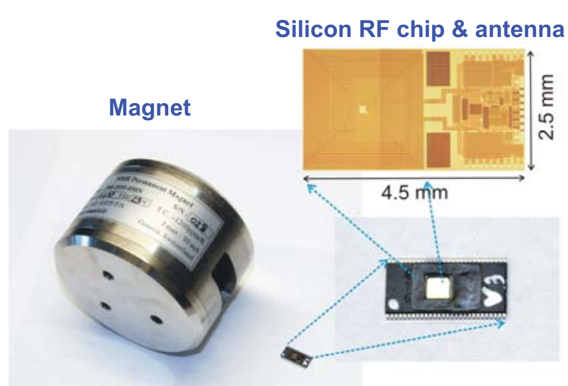
### R.M. Westervelt (Harvard)

- **Smaller, Faster, More Powerful, Less Expensive**
- **Nanodevice → Device Science → Applications**
- **NSEC Joins Separate Fields**
  - **Materials Science, Electrical & Mechanical Engineering, Physics, Chemistry, Health & Medicine**
- Example: **Low-cost Integrated Biosensors for Health**

**1-chip NMR Relaxometer**
(D. Ham & R. Weissleder)

"Magnetic switch" biosensor - clumping of magnetic particles reduces NMR T2 relaxation time.

Conventional NMR relaxometer
$80,000 + 250 lb
1-chip NMR relaxometer
disposable chip + magnet



Nano Centers --- Present and Future
James Yardley panel (4)

NSF NSEC

# NanoCenters – Present and Future

## *Technological Development*

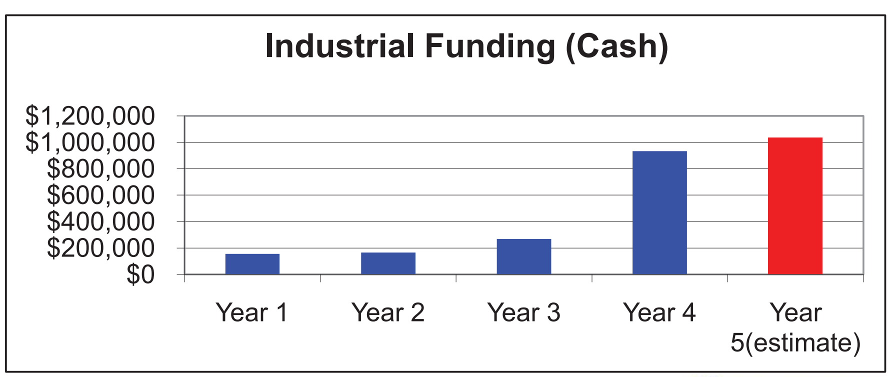
- ***strong, scratch- and wear-resistant polymers***
- ***wavelength-dependent transparent coatings***
- ***electrically conductive insulator systems***
- ***wide dynamic range, selective sensors***
- ***lightweight, flexible energy-storage devices***
- ***enhanced tissue regeneration surfaces***
- ***selective and tunable filtration systems***
- ***novel public science education media***

**Rensselaer Nanotechnology Center** **R. W. Siegel**
**3 December 2008**

## NSF Nanoscale Science and Engineering Center for High-rate Nanomanufacturing (CHN) Industrial Partnerships

**31 Companies**

***Companies Contributing Financially:***
**Amberwave, EMC, Intel, Konarka , Kuraray, MKS Instruments, Nanodynamics, Nantero, Nypro, Raytheon, Textron Systems, Triton Systems, Velcro**




Center for High-rate Nanomanufacturing

Nano Centers --- Present and Future
James Yardley panel (5)

**The Legacy and Future of Social Impacts Centers**

*Barbara Herr Harthorn*
PI and Director, Center for Nanotechnology in Society at University of California at Santa Barbara

The NNI (Sept 2008:3) promotes a vision for"…a future in which the ability to understand and control matter at the nanoscale leads to a revolution in technology and industry that benefits society." NSF stands alone among the 25 members of the NNI in its solid commitment to societal implications research and the knowledge it can provide about the complexities of this unfolding revolution and the factors driving and constraining its possibilities for shared benefit in the 21st century.

The legacy of NSF's societal nano Centers? First, the funding of Centers—the two 3-yr-old NSECs that are Centers for Nanotechnology in Society at UCSB and ASU—represents a relatively rare way to organize and implement social research (outside the health sciences). Because center support offers larger scale of operation, longer timelines for research, and flexible planning, and because we were founded relatively upstream in the R&D process, the CNS has created a demonstrable "ripple effect," rapidly generating a significant cluster of multidisciplinary collaborative research on a large range of social, economic, cultural, historical, political, & psychological dimensions of technological change. At NSF's instigation, the Centers have also taken the lead in development of a national network of societal implications researchers [this map shows extent in US in 2008 alone]; in less than 3 years the network has organized itself into a new international scholarly organization-S-NET—the first conference will be held in Seattle in Sept 2009 and you're all invited to join us.

Most important, the multidisciplinary collaborative research that centers enable and a flourishing network extends is generating new understandings—in our UCSB center alone this work spans policy history, many facets of the complex, new and rapidly changing globalized innovation system, and the contending, shifting, and only sometimes coalescing views held by key societal actors in nanotechnological change—NGOs, media new and old, and a multicultural public. These latter are engaging with emerging nanotechnologies through a bundle of often contradictory views, the understanding of which is essential for risk governance. They, like we, are conflicted about the US's slumping economy and job security at home, our place in the global economy, competition for access to new commodities, urgent need for new energy efficiencies and alternatives, concerns about health and health care, educational hopes for themselves and their children, and desire for a better future here and abroad (or at least not a significantly worse one). The NNI comes with a special mandate for public involvement, one the Obama administration is likely to reinforce and extend, and our research on means for multi-cultural engagement and debate will be an increasingly useful resource for the NSE world as well as policymakers and industry.

Our Center has launched new mechanisms to bridge that age old division between science and social science, and these new bonds are leading in unexpected directions as we co-educate and train a new generation of NSE and social scientists about the social, cultural, environmental, economic, and political contexts and value systems around the globe in which new technologies are emerging. In these educational and training programs and other contexts, we see an unprecedented mutuality of interaction beween physical sciences and social sciences that center status has both demanded and enabled; we are continuing to forge new and deeper ties with the NSE—some of them with those of you in the room. To name just a few—we've been involved from the start w/ the UCSB CNSI and its former director Evelyn Hu; UCSB MRSEC and MRL director Craig Hawker has just joined the CNS-UCSB Executive Committee; Bob Westervelt has been a valued member of our National Advisory Board from the start; CNS-UCSB is a partner and I am directly involved with the new UC CEIN led by Andre Nel that you'll hear about on Fri; UCSB colleague Nobel Laureate Alan Heeger just led a public outreach event for us last month in Santa Barbara on nano energy applications; and our major international conference planned for Nov 2009 here in Washington DC on Emerging Economies/Emerging Technologies: Nanotechnology for Equitable Development is partnered with the Woodrow Wilson IC and co-sponsored enthusiastically by our UCSB College of Engineering and the new Institute for Energy Efficiency led by John Bowers. NSF Center support is directly responsible for many of these synergies and the relatively new involvement of social scientists in them. Predicting the future is beyond my capacity, but I can say that this enterprise is headed on a course that aligns well with the direction of change in Washington, the US and the global society. (And I'd like to add that to that end, we've generously donated our National Advisory Board chair, Tom Kalil, to the Obama administration in science and technology policy.)

Nano Centers --- Present and Future
James Yardley panel (6)

Semiconductor Research Corporation
PIONEERS IN COLLABORATIVE RESEARCH®

nanoelectronics RESEARCH INITIATIVE

# SRC Nanoelectronics Research Initiative

Overview for NSF Grantees Meeting
December, 2008

Jeffrey Welser
Director
jeff.welser@src.org



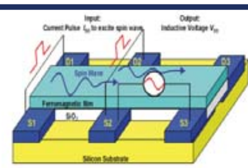
## NRI Mission Statement

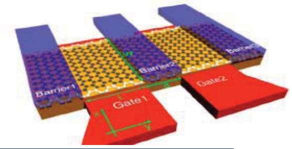
- **NRI Mission: Demonstrate novel computing devices capable of replacing the CMOS FET as a logic switch in the 2020 timeframe.**
  - These devices should **show significant advantage over ultimate FETs** in power, performance, density, and/or cost to enable the semiconductor industry to **extend the historical cost and performance trends** for information technology.
  - To meet these goals, NRI pursues **five research vectors**, focused on discovering and demonstrating new devices and circuit elements for doing computation.
  - Finally, it is desirable that these technologies be **capable of integrating with CMOS**, to allow exploitation of their potentially complementary functionality in heterogeneous systems and to enable a smooth transition to a new scaling path.

Nanoelectronics Research Initiative
Jeff Welser and Ralph Cavin (2)

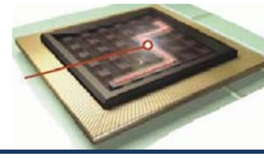
# NRI Primary Research Vectors

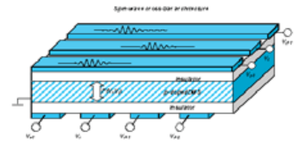
- NEW DEVICE
  Device with alternative state vector



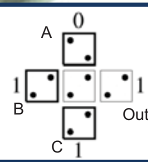


- NEW WAYS TO CONNECT DEVICES
  Non-charge data transfer

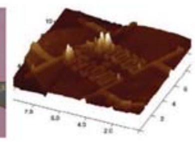




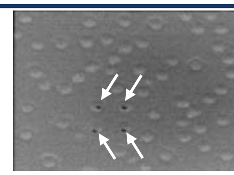
- NEW METHODS FOR COMPUTATION
  Non-equilibrium systems




- NEW METHODS TO MANAGE HEAT
  Nanoscale phonon engineering



- NEW METHODS OF FABRICATION
  Directed self-assembly devices



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# NRI Centers

NIST

- Leveraging industry, university, and both state & fed government funds, and driving university nanoelectronics infrastructure

WIN Western Institute of Nanoelectronics · INDEX Institute for Nanoelectronics Discovery and Exploration · SWAN Southwest Academy of Nanoelectronics · Nanoelectronics • Architectures MIND Midwest Institute for Nanoelectronics Discovery

| | | | |
|---|---|---|---|
| **WIN**<br>Western Institute of Nanoelectronics | **INDEX**<br>Institute for Nanoelectronics Discovery & Exploration | **SWAN**<br>SouthWest Academy for Nanoelectronics | **MIND**<br>Midwest Institute for Nanoelectronics Discovery |
| **UCLA**, UCSB, UC-Irvine, Berkeley, Stanford, U Denver, Iowa, Portland State | **SUNY-Albany**, GIT, RPI, Harvard, MIT, Purdue, Yale, Columbia, Caltech, NCSU, UVA | **UT-Austin**, UT-Dallas, TX A&M, Rice, ASU, Notre Dame, Maryland, NCSU, Illinois-UC | **Notre Dame**, Purdue, Illinois-UC, Penn State, Michigan, UT-Dallas |
| Theme 1: Spin devices<br>Theme 2: Spin circuits<br>Theme 3: Benchmarks & metrics<br>Theme 4: Spin Metrology | Task I: Novel state-variable devices<br>Task II: Fabrication & Self-assembly<br>Task III: Modeling & Arch<br>Task IV: Theory & Sim<br>Task V: Roadmap<br>Task VI: Metrology | Task 1: Logic devices with new state-variables<br>Task 2: Materials & structs<br>Task 3: Nanoscale thermal management<br>Task 4: Interconnect & Arch<br>Task 5: Nanoscale characterization | Theme 1: Graphene device: Thermal, Tunnel, and Spin<br>Theme 2: Interband Tunnel Devices<br>Theme 3: Non-equilibrium Systems Model / Meas.<br>Theme 4: Nanoarchitecture |

7

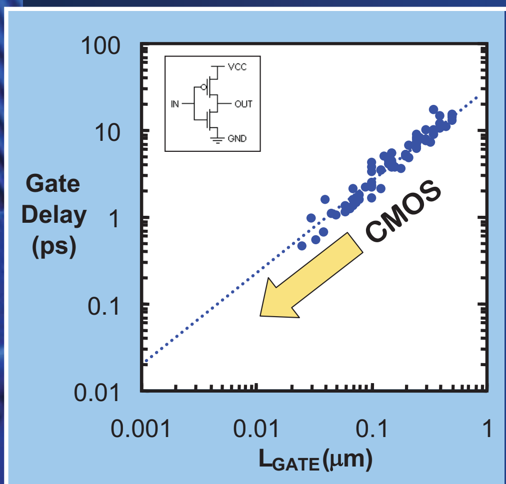
Nanoelectronics Research Initiative
Jeff Welser and Ralph Cavin (3)

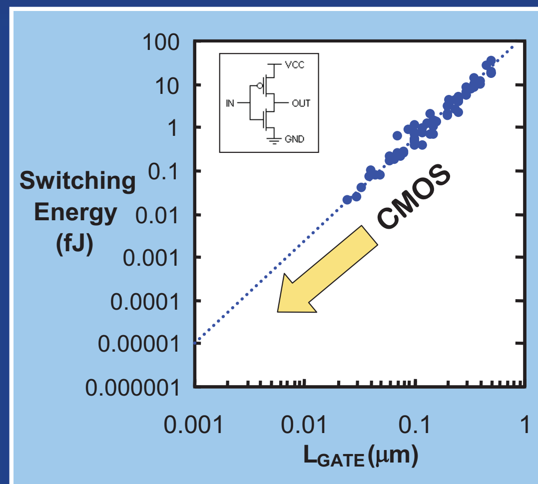
## CMOS Limitation # 1 — Size

It is important to continue shrinking device dimensions:

- To further increase speed and reduce switching energy
- To increase functionality and reduce manufacturing cost per bit

But as gate dimensions approach **atomic size**, tunneling and quantum effects degrade device operation.

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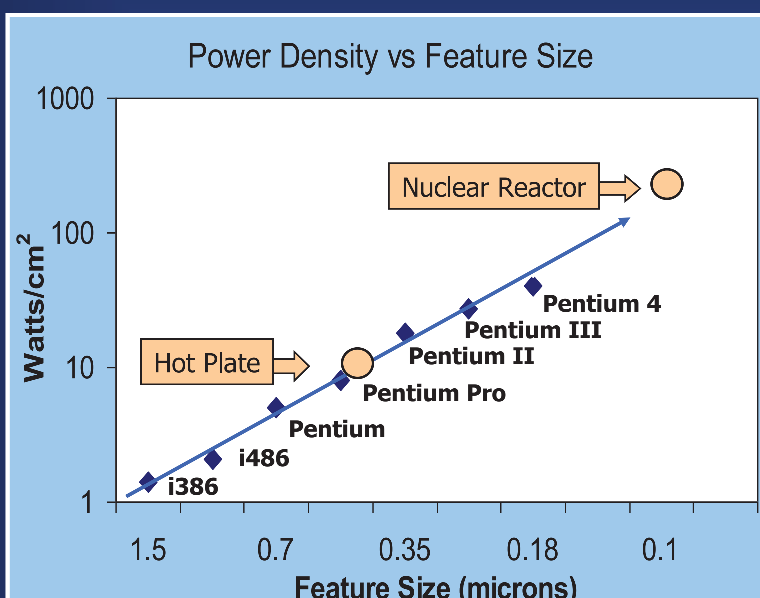
## CMOS Limitation # 2 — Heat

As dimensions continue to shrink, high-performance ICs will generate inordinate amounts of heat — **to the point of self destruction!**

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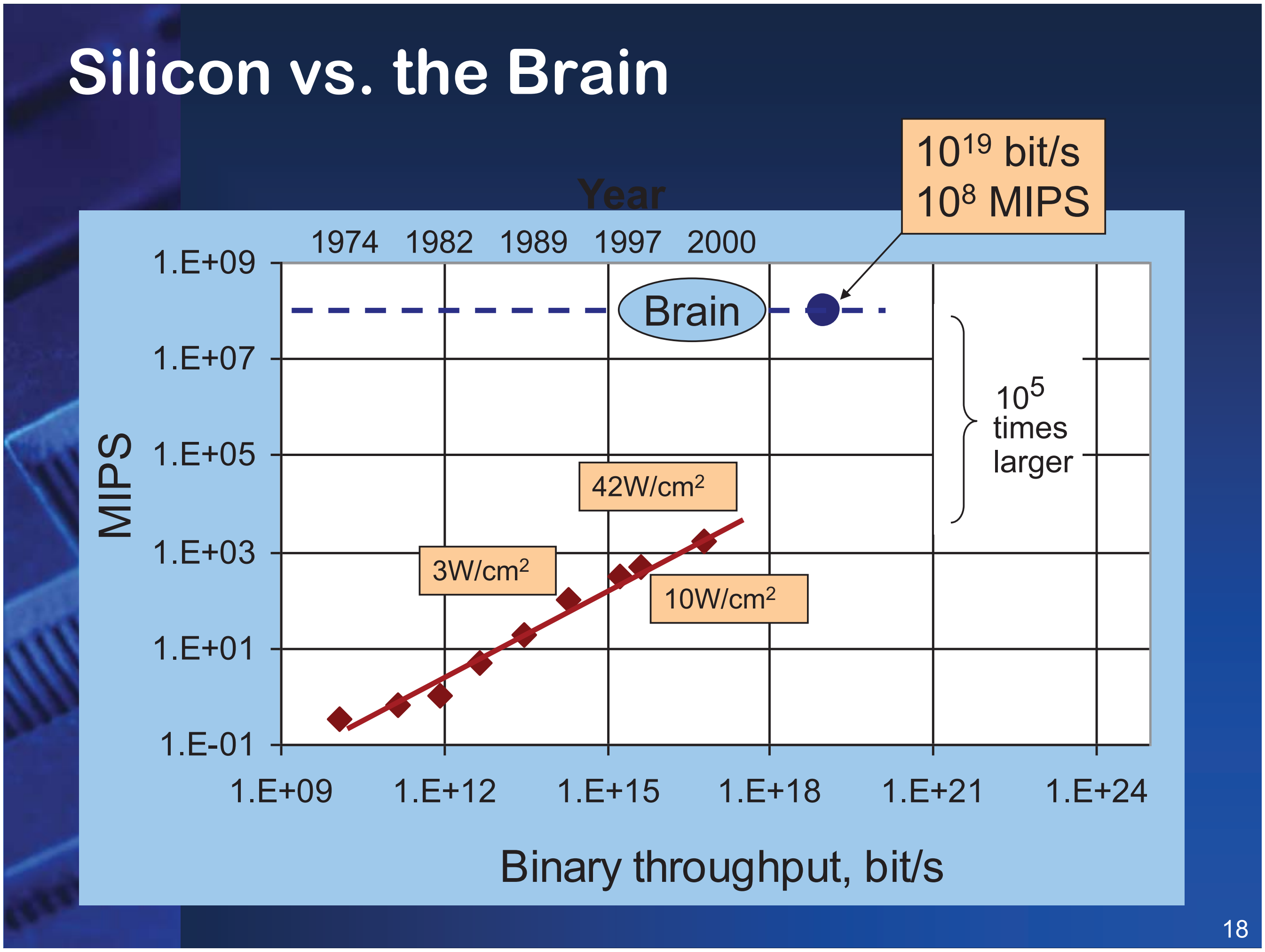
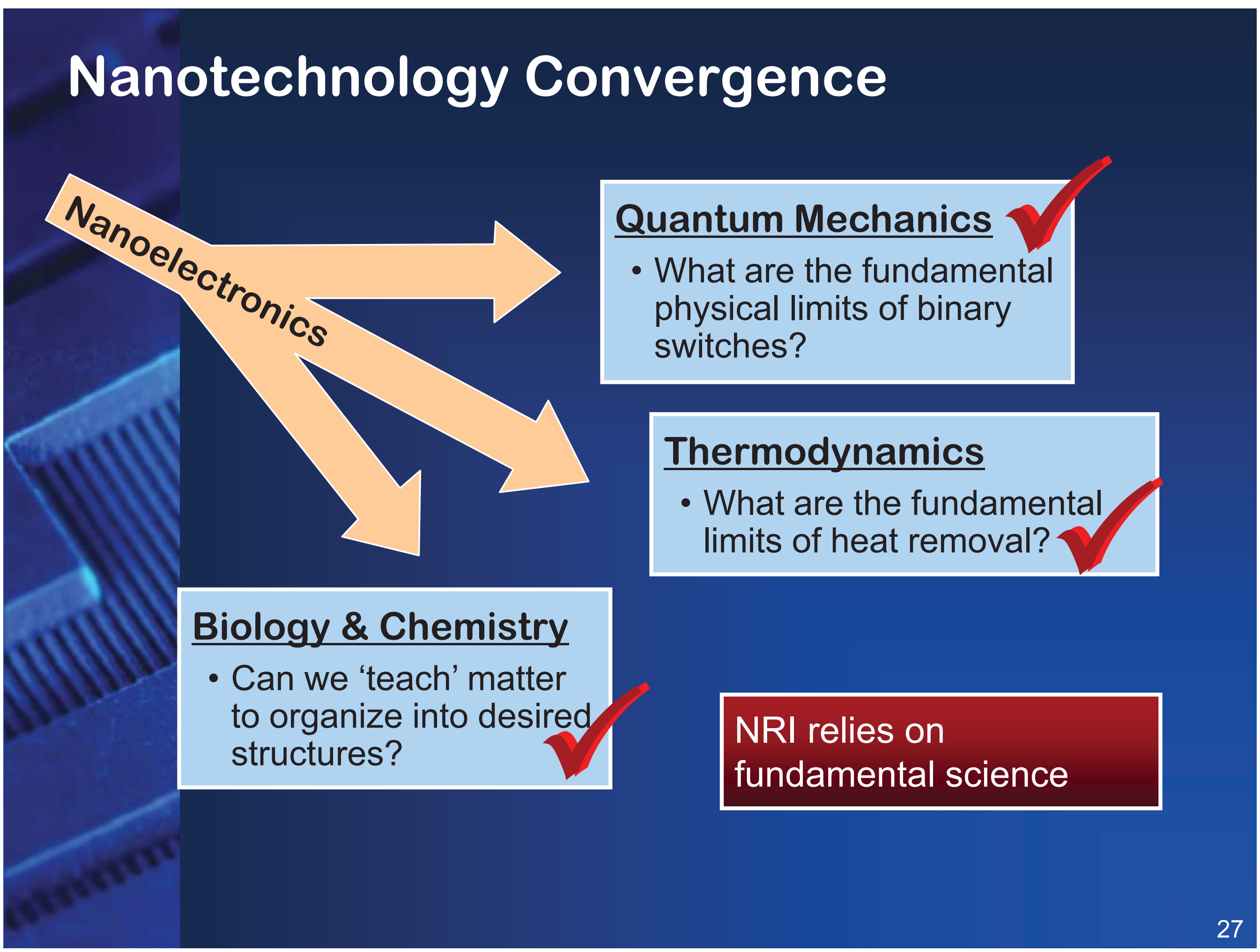


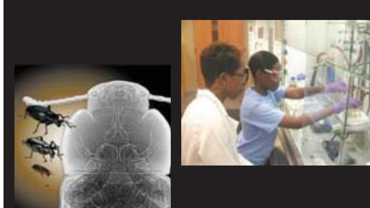

Nanoelectronics Research Initiative
Jeff Welser and Ralph Cavin (4)

# Office of International Science & Engineering

## 2008 NSE Grantees Conference

**<u>OISE's Central Role</u>: to ensure that NSF and the U.S. research and education community thrive in the changing landscape of global science and engineering through international collaboration**

- International programs that are innovative, catalytic and responsive to NSF's mission
- Priorities: promote U.S. research excellence through international collaboration and develop globally engaged researchers





International Opportunities
Mark Suskin (1)

# OISE & International Activities at NSF

- **OISE supports international activities Foundation wide:**
  - Co-fund new proposals submitted to NSF disciplinary programs
  - Co-fund supplements to existing NSF grants
  - New proposals to OISE
- **Key elements for OISE co-funding:**
  - Intellectual collaboration
  - Leverage expertise and resources
  - U.S. junior researchers and students

# Partnerships for International Research and Education (09-505)

***Program Objectives:***

- **Enhance research excellence via international partnership and collaboration.**

  ***cutting edge research that leverages unique, complementary expertise of US and foreign partners***

- **Promote the development of a diverse, globally engaged U.S. scientific and engineering workforce.**

  ***Innovative international research/education opportunities for students***

- **Strengthen the capacity of U.S. institutions to engage in and benefit from international research and education collaborations.**

  ***Enhance internationalization above level of research lab***

International Opportunities
Mark Suskin (2)

NSE Centers in Society
Tom Rieker panel (1)

RICE
Unconventional Wisdom

# Nano Good Practices Wiki

*An Introduction to a Novel Concept*

CBEN
RICE UNIVERSITY

ICON

## What is a Wiki?

A Wiki is central, shared repository of online information

*Wikis for Dummies*

- Anyone can edit the pages
- Editing is easy and requires no special tools
- Formatting is simple
- Changes are easily tracked

WIKIPEDIA
The Free Encyclopedia

OPEN WETWARE

Wikia Astronomy

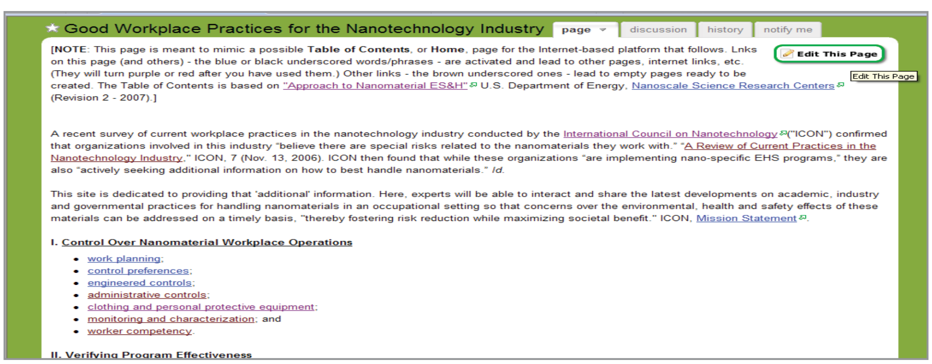
Quantiki Portal

# Why a Wiki for Nano Handling Practices?

| Features | Policy Document | Research Paper | Wiki Entry |
|---|---|---|---|
| Describes a specific practice | No | Maybe | **YES** |
| Written by practitioners | Maybe | Maybe | **YES** |
| Written for practitioners | Maybe | No | **YES** |
| Short lead time to publication | No | No | **YES** |
| Engages global community | No | Maybe | **YES** |
| Provides a forum for dialog | No | No | **YES** |
| Easily accessed | **YES** | No | **YES** |

Policy document = Guidance document usually produced by a government agency, intended to convey principles of safe handling. Publicly available on the Internet.
Research paper = Peer-reviewed publication on e.g., effectiveness of personal protective equipment, aerosolizability, etc.
Wiki entry = Page in the Good Practices Wiki that communicates practices that are followed when working with a specific material or process.

# Nano Good Practices Wiki



★ Good Workplace Practices for the Nanotechnology Industry | page | discussion | history | notify me

Edit This Page

[**NOTE**: This page is meant to mimic a possible **Table of Contents**, or **Home**, page for the Internet-based platform that follows. Lnks on this page (and others) - the blue or black underscored words/phrases - are activated and lead to other pages, internet links, etc. (They will turn purple or red after you have used them.) Other links - the brown underscored ones - lead to empty pages ready to be created. The Table of Contents is based on "Approach to Nanomaterial ES&H" U.S. Department of Energy, Nanoscale Science Research Centers (Revision 2 - 2007).]

A recent survey of current workplace practices in the nanotechnology industry conducted by the International Council on Nanotechnology ("ICON") confirmed that organizations involved in this industry "believe there are special risks related to the nanomaterials they work with." "A Review of Current Practices in the Nanotechnology Industry," ICON, 7 (Nov. 13, 2006). ICON then found that while these organizations "are implementing nano-specific EHS programs," they are also "actively seeking additional information on how to best handle nanomaterials." *Id.*

This site is dedicated to providing that 'additional' information. Here, experts will be able to interact and share the latest developments on academic, industry and governmental practices for handling nanomaterials in an occupational setting so that concerns over the environmental, health and safety effects of these materials can be addressed on a timely basis, "thereby fostering risk reduction while maximizing societal benefit." ICON, Mission Statement.

**I. Control Over Nanomaterial Workplace Operations**

- work planning;
- control preferences;
- engineered controls;
- administrative controls;
- clothing and personal protective equipment;
- monitoring and characterization; and
- worker competency.

**II. Verifying Program Effectiveness**

## Features

- Protected Internet site on occupational practices for the safe handling of nanomaterials
- Multiple stakeholders contribute, share and discuss information
- Modern, interactive, up-to-date
- Editorial board ensures quality

**http://icon.rice.edu/projects.cfm?doc_id=12207**

**Administrator**
**ICON**
**Faciltators**
**Matthew Jaffe (C&M)**
**Kristen Kulinowski (Rice U)**
**Chairs**
**Bruce Stockmeier (Argonne Nat'l Lab)**
**Michael Riediker (Institute for Work and Health, Switzerland)**
**Planning Team**
**Crowell & Moring, LLP**
**Nanotech BC**
**NIOSH**
**U Wisc NSEC**
**U Mass Amherst NSEC**
**ILO**
**IOM (UK)**
**RTI**
**Evonik DeGussa**
**Nanotech Industries Assoc (UK)**
**Boeing**

NSE Centers in Society
Tom Rieker panel (3)

# NS&E Centers in Society: Collaboration with Industry

## – Partnership in Nanotechnology –

*Richard W. Siegel*
*Director*

**NSF Nanoscale Science and Engineering Center for Directed Assembly of Nanostructures**

*Rensselaer Polytechnic Institute*
*University of Illinois at Urbana-Champaign*
*Los Alamos National Laboratory*

NYSTAR NEW YORK STATE OFFICE OF SCIENCE, TECHNOLOGY & ACADEMIC RESEARCH

NATIONAL SCIENCE FOUNDATION

Rensselaer

**National Science Foundation NSE Grantees Conference** **3 December 2008**

---

## Center Mission and Approach

Education Industry RPI and UIUC LANL

### MISSION STATEMENT

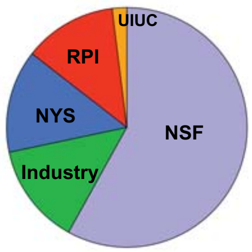
**We will integrate research, education, and technology dissemination, and serve as an international resource for fundamental knowledge and applications, in the directed assembly of nanostructures.**

- ♦ Combine computational design with experimentation to discover novel pathways to assemble functional multiscale nanostructures with junctions and interfaces between structurally, dimensionally, and compositionally different nanoscale building blocks
- ♦ Excite and educate a diverse cadre of students of all ages from K-12 through postdoctorate in nanoscale science and engineering
- ♦ Work hand-in-hand with industry to develop nanotechnology for the benefit of society

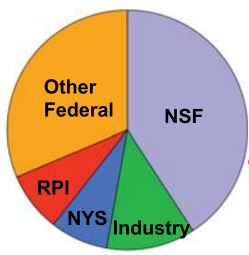
NSE Centers in Society
Tom Rieker panel (4)



## Strategic Plan for the Future




NSEC ~$3.5M pa




RNC ~$6M pa


## Industry Partnership – MS&E Distinguished Lectureships

***ABB Corporation:***

**Ivar Giaever** ***(Nobel Laureate, RPI)***
**Pierre Wiltzius** ***(UIUC)***
**William A. Goddard III** ***(Cal Tech)***
**John Silcox** ***(Cornell)***
**Louis Brus** ***(Columbia)***
**Matthew Tirrell** ***(UCSB)***
**Barbara Baird** ***(Cornell)***

***Eastman Kodak Company:***

**William D. Nix** ***(Stanford)***
**Catherine Bréchignac** ***(CNRS)***
**Noel C. MacDonald** ***(UCSB)***
**John H. Weaver** ***(UIUC)***
**Robert K. Sekerka** ***(CMU)***
**Ali A. Argon** ***(MIT)***

***Albany International:***

**Gareth Thomas** ***(UCB)***
**Rustum Roy** ***(Penn State)***
**A. W. Castleman, Jr.** ***(Penn State)***
**Sheldon M. Wiederhorn** ***(NIST)***

***IBM:***

**James D. Meindl** ***(Georgia Tech)***
**Joseph E. Greene** ***(UIUC)***
**Robert O. Ritchie** ***(UCB)***
**Edward J. Kramer** ***(UCSB)***
**Robert W. Balluffi** ***(MIT retired)***
**Phaedon Avouris** ***(IBM)***

***Philip Morris USA:***

**Roberto Car** ***(Princeton)***
**Dieter Gruen** ***(Argonne)***
**Robert W. Cahn** ***(Cambridge)***
**Knut Urban** ***(FZJülich)***

## *Industry-named Graduate & Postdoctoral Fellowships*

**85 graduate fellows and 11 postdoctoral fellows (in person-years)**

NSE Centers in Society
Tom Rieker panel (5)



# How can NSE Centers impact Society through education and outreach?

**R.P.H. Chang**

Director, National Center for Learning and Teaching in Nanoscale Science and Engineering (NCLT)

Northwestern University

NCLT NU • UM • PU • UIC • UIUC • ANL • AAMU • FU • HU • MC • UTEP • PSS

## Students must learn to:

1. Think critically and make sound judgments
2. Solve complex, multidisciplinary, open-ended problems
3. Create and to launch new enterprises
4. Communicate and collaborate effectively
5. Make innovative use of knowledge, information and opportunities
6. Take charge of financial, health and civic responsibilities

** Source: 21st Century Skills, Education & Competitiveness Report by Partnership for 21st Century Skills (2008)*

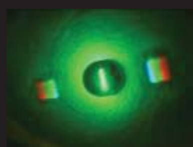
**Our Role as researchers? Connect teachers and students with the latest research findings and discoveries through education programs and laboratory experiences: REU, RET, IGERT, GK-12, NCLT, NISE, NIMD, NUE, etc.**

NCLT NU • UM • PU • UIC • UIUC • ANL • AAMU • FU • HU • MC • UTEP • PSS

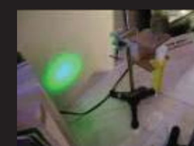
# National Center for Learning and Teaching in Nanoscale Science and Engineering

**Mission: *Build national capacity*** in Nanoscale Science & Engineering (NSE) Education

**Vision:** Develop a ***globally competitive*** NSE workforce and train a national cadre of leaders in NSE education

Learning and teaching through ***inquiry and design*** **of nanoscale materials** and applications



- **Developing Curricula**
- **New Learning Standards**
- **NSE Education Knowledge Base**

NCLT NU • UM • PU • UIC • UIUC • ANL • AAMU • FU • HU • MC • UTEP • PSS

# Challenges in STEM Education

- **Students lack motivation** and confidence in learning STEM subjects – We must build "science esteem".
- **Demographic changes will exacerbate achievement gaps** among many subgroups – racial and ethnic minorities will comprise the majority of the nation's population by 2042 – We must reach under-represented students and their teachers.
- **New generation of digitally-minded students** have a different approach to learning – We must develop content and methods that engage them and hold their interest.
- **A paucity of well-trained STEM teachers** – We must offer professional development.
- **Lack of interdisciplinarity** - Subjects are taught in a compartmentalized manner and teachers are isolated within discipline-based departments – We must lead a cultural shift towards interdisciplinarity.

NCLT NU • UM • PU • UIC • UIUC • ANL • AAMU • FU • HU • MC • UTEP • PSS

NSE Centers in Society
Tom Rieker panel (7)

# NSE Centers: Nanomanufacturing Role

Mark Tuominen
*Director, National Nanomanufacturing Network*
*Co-Director, Center for Hierarchical Manufacturing*
*Professor of Physics*
*UMass Amherst*

CHM Center for Hierarchical Manufacturing University of Massachusetts Amherst

NSF

National Nanomanufacturing Network

*www.nanomanufacturing.org*

*NSF NSE Grantees Meeting, December 3, 2008*



## Issues Influencing the Implementation of Nanomanufacturing Processes

- Built on robust science and technology
- Value of physical properties and impact on performance
- Statistical distributions of properties
- Knowledge of process-property relationships (for design and mfg)
- Reproducibility and reliability
- Useful standards (ISO & others)
- Availability of process and metrology tools
- Compatibility of NM process with surround mfg processes
- Trained workforce
- Manufacturing cost and mode (in-house or outsource)
- EHS throughout life cycle
- Scalability and extensibility

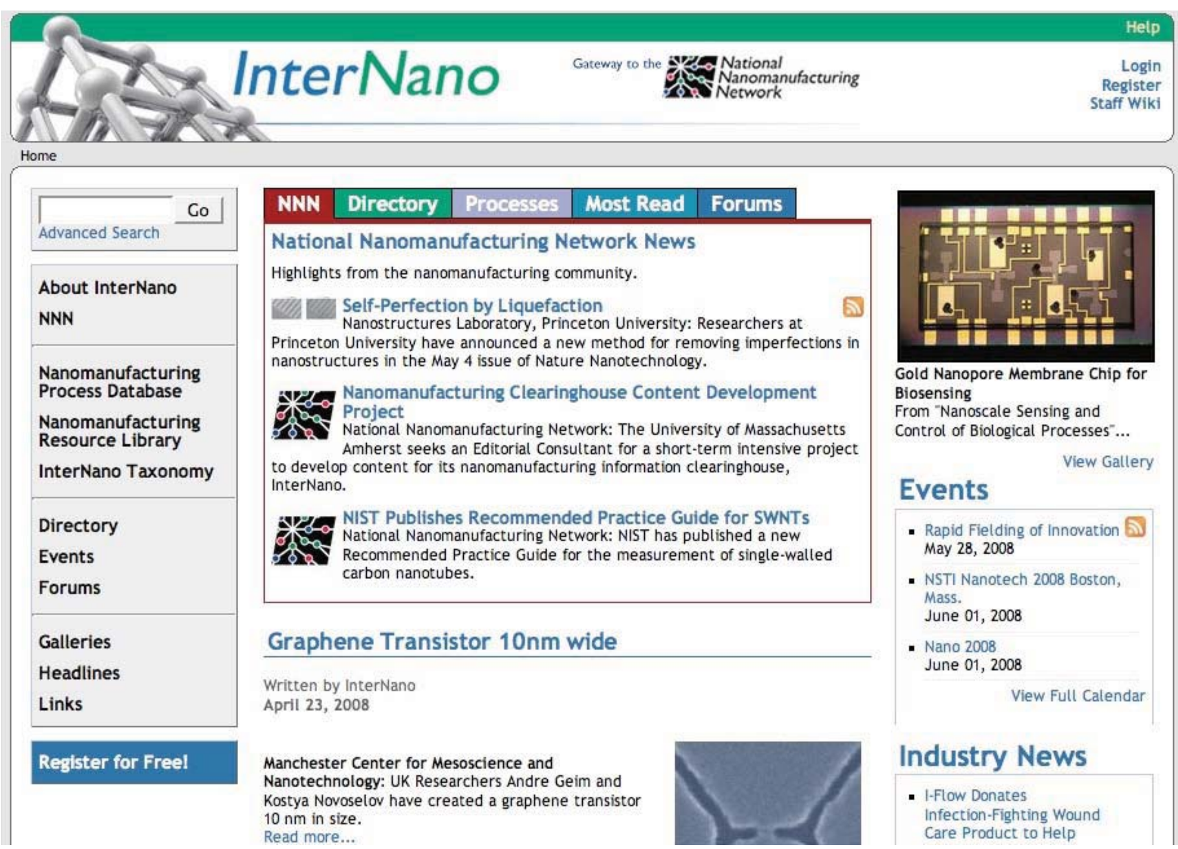
  - Current NM technologies are at varied levels of maturity
  - Many at infancy; data/information is sparse

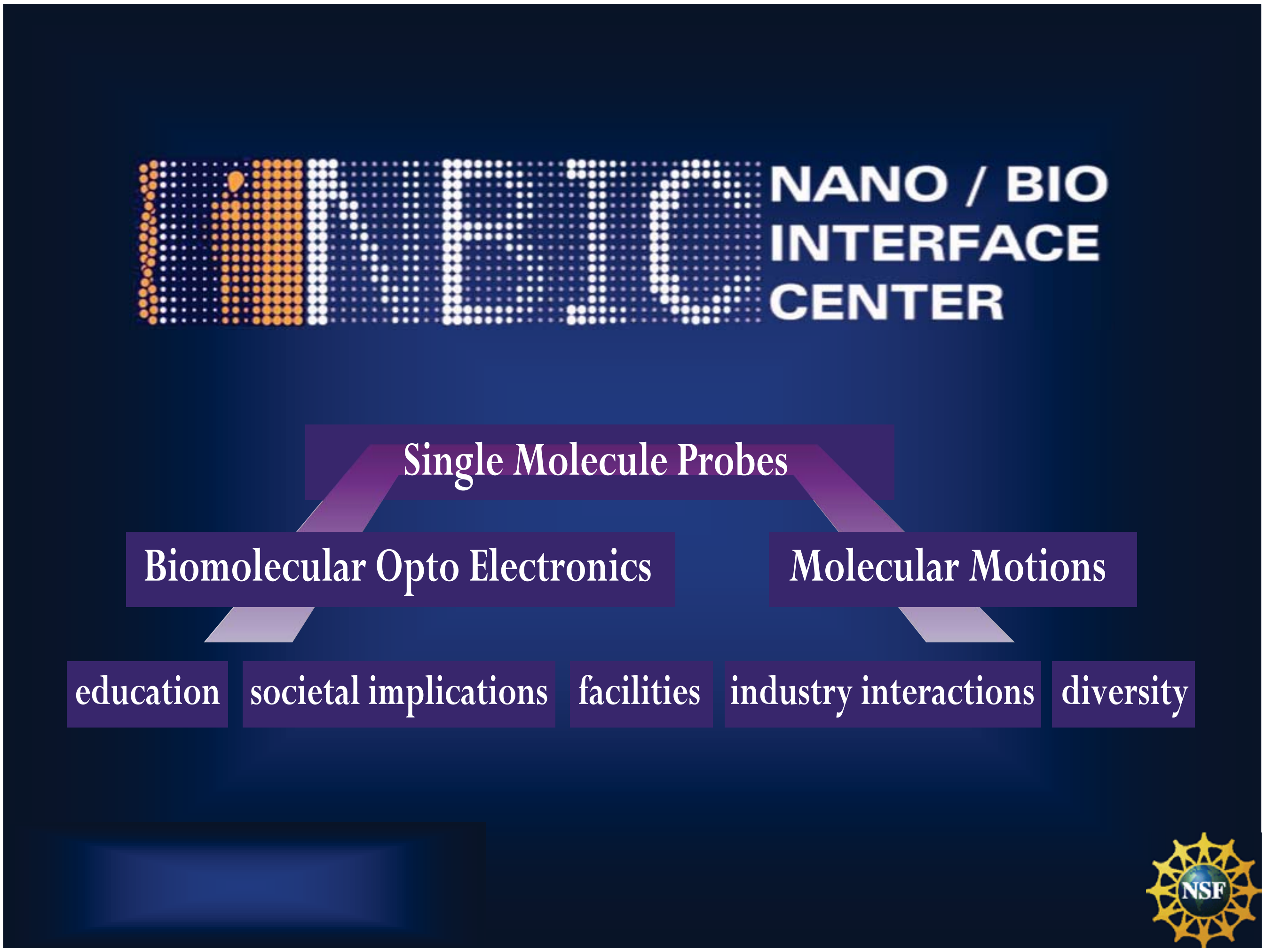
National Nanomanufacturing Network

# Origins of the NNN: Four Nanomanufacturing NSF NSECs

- **Center for Hierarchical Manufacturing** (CHM)
  - UMass Amherst/UPR/MHC/Binghamton
- **Center for High-Rate Nanomanufacturing** (CHN)
  - Northeastern/UMass Lowell/UNH
- **Center for Scalable and Integrated Nanomanufacturing** (SINAM)
  - UC Berkeley/UCLA/UCSD/Stanford/UNC Charlotte
- **Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems** (Nano-CEMMS)
  - UIUC/CalTech/NC A&T

National Nanomanufacturing Network






## Impact in terms of research and education

**Enabling new directions in research**

**Expanding resources for research and education**
**$8M in core grant expenditures → $5.1M new revenue**

**Recruitment of faculty across school boundaries**
**$900k investment → $922k new support for junior faculty**

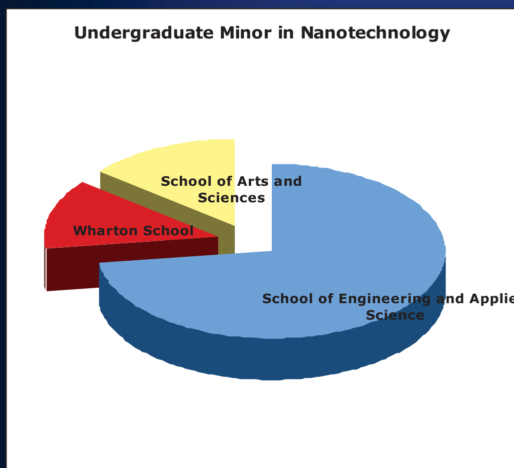
**Developing Infrastructure**
**justification for new nanotech building**
**direct and leveraged investment of $2.1M in infrastructure**

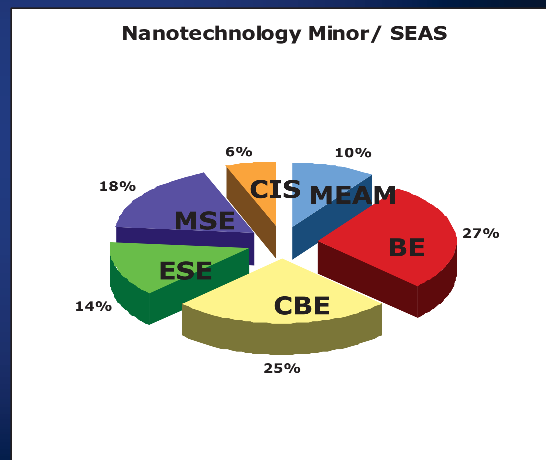
NANO / BIO INTERFACE CENTER
NSF

Center Management and Stewardship
Bruce Kramer panel (1)

# Impact in terms of educational programs

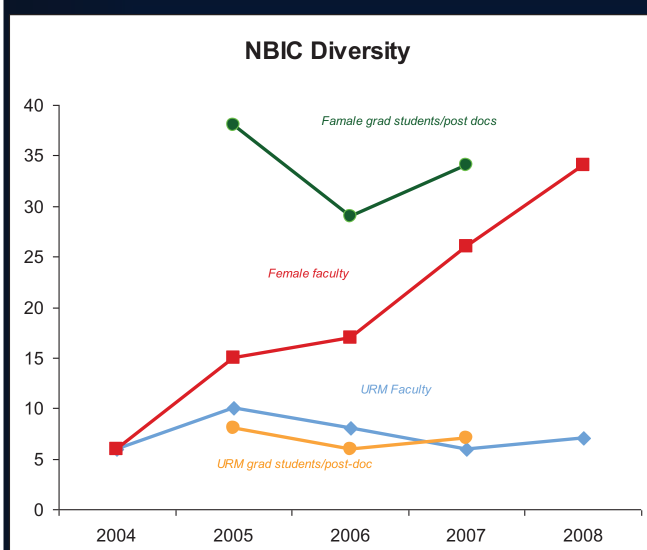
## Undergraduate Nanotechnology Minor

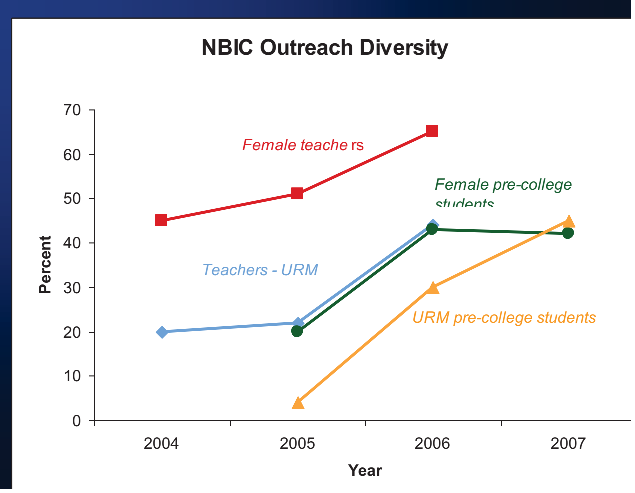



NANO / BIO INTERFACE CENTER

# Leadership by Example: Diversity in NBIC Programs



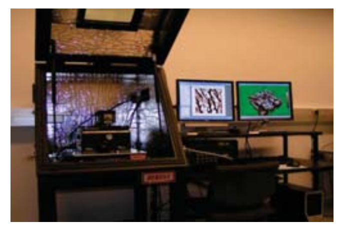

NANO / BIO INTERFACE CENTER

Center Management and Stewardship
Bruce Kramer panel (3)

MRFN Materials Research Facilities Network

# Statement of Purpose

The vision of the Materials Research Facilities Network (MRFN) is to develop a cohesive network of user facilities that allows the significant investment by the NSF in MRSEC facilities to be fully leveraged and made available to the wider materials community



MRFN Materials Research Facilities Network

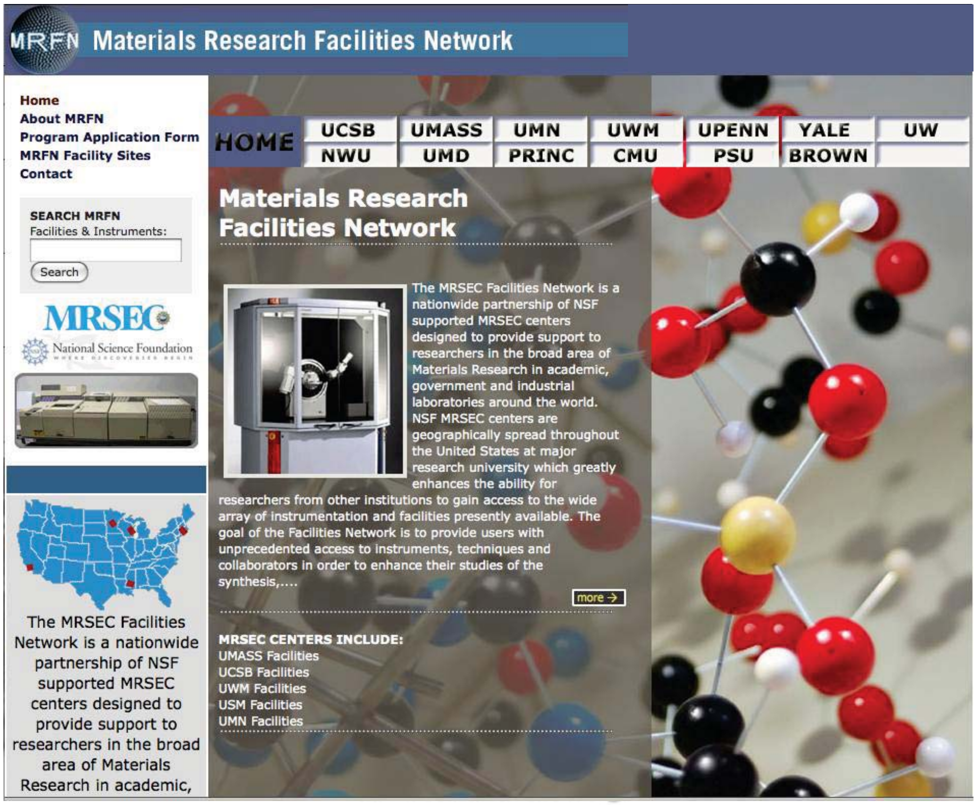
# Developing Character of MRFN

- **Advantages**
  - Easy access-wide geographical distribution
  - Established co-ordination among centers
  - Coordination with educational and diversity programs
  - Large instrument base with wide range of materials emphases
- **Challenges**
  - Promoting participation of new users
  - Cyber infrastructure
  - Longevity of participants
  - Personnel support

www.mrfn.org

MRFN Materials Research Facilities Network

# WWW.MRFN.ORG




MRFN Materials Research Facilities Network

# Results

| Contact | Large University | Small University | Instrument |
|---|---|---|---|
| Faculty | 10 | 8 | All |
| Student | 5 | 15 | AFM, TEM |
| Industry | 4 | | XPS, NMR |
| Technician | 3 | | NMR, LC |

Center Management and Stewardship
Bruce Kramer panel (4)

# *Center Management and Stewardship;*

## *the National Nanotechnology Infrastructure Network experience*

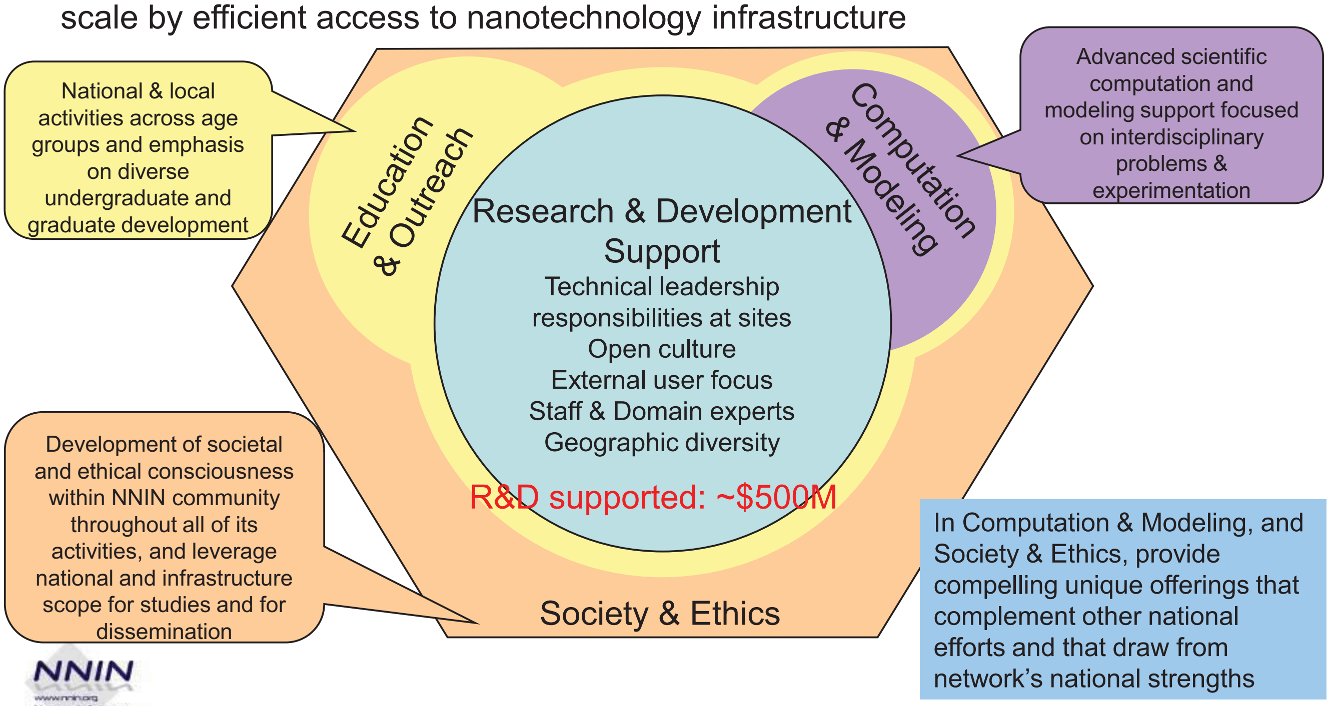
Network
- research/service/breadth
- broader mission
- openness, learning, complementarity, …

Challenges?
- Science and engineering in the modern world
- World and the Academy
- Academy and Change
- Scope

*Sandip Tiwari*
*NNIN Director*

## *NNIN*

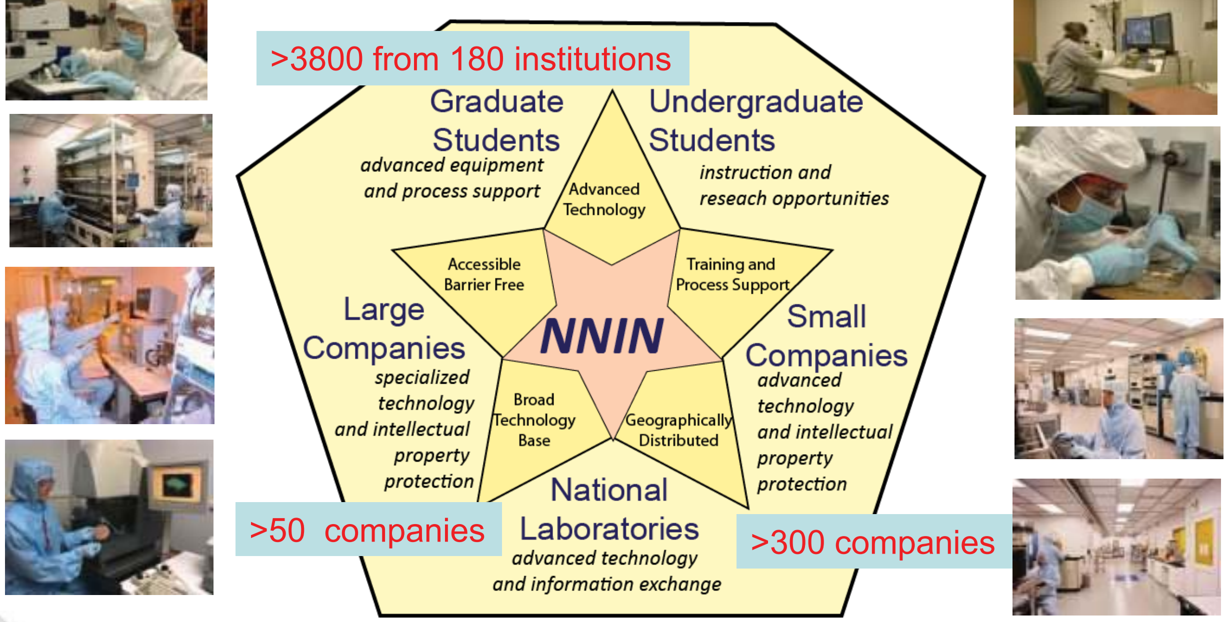
**NNIN Research Infrastructure Mission:**
Enable rapid advancements in science, engineering and technology at the nano-scale by efficient access to nanotechnology infrastructure



Center Management and Stewardship
Bruce Kramer panel (6)

# NNIN Research Users

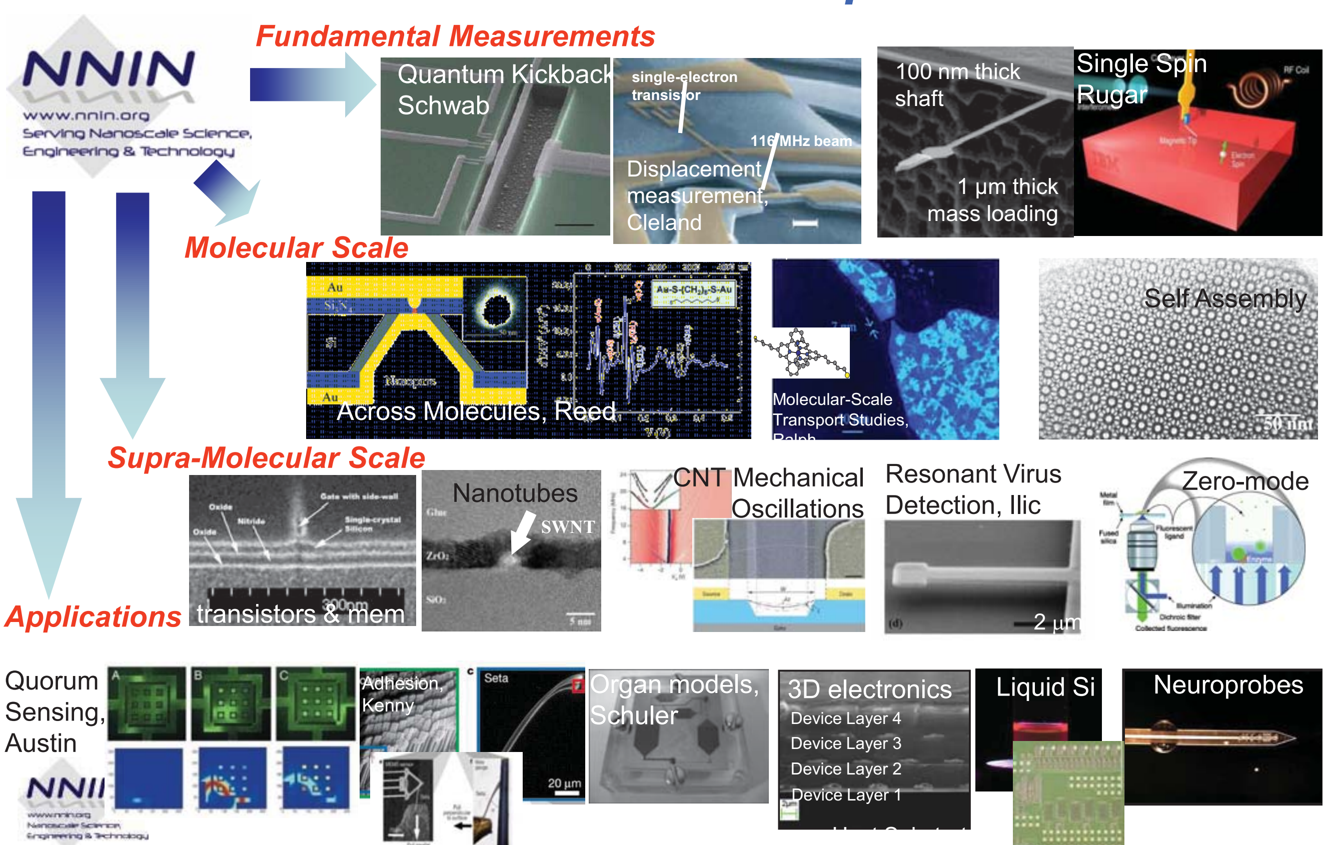
- Users from diverse disciplines
- Users with different specialized and integrated technical needs
- Users from diverse institutions




NNIN network model permits effective & efficient service



# NNIN's Scientific Impact



NSF Grantees Meeting, December 3, 2008

Panel on Center Management and Stewardship

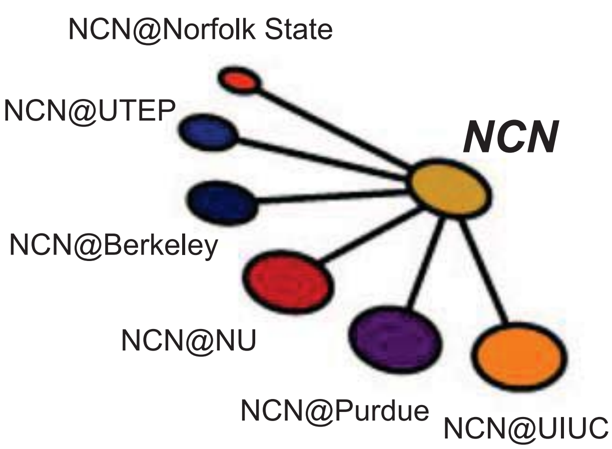
# NCN

Mark Lundstrom, Director
Network for Computational Nanotechnology
Discovery Park, Purdue University
West Lafayette, IN

PURDUE UNIVERSITY

1

## Network for Computational Nanotechnology




***Mission:***

***Research*** *that helps move nanoscience to nanotechnology to nanomanufacturing.*

***Infrastructure*** *that:*

- *connects simulation developers with users*
- *disseminates research methods*
- *promotes education*
- *fosters collaboration*

*an NSF 'infrastructure and research network'*

Center Management and Stewardship
Bruce Kramer panel (8)

# challenges

- getting people's attention
- developing a shared vision
- role of professional staff vs. faculty and students
- financial stewardship / reporting
- staying on track
- moving people / universities out and in
- having impact

NCN
nanoHUB.org

4

# things that have worked

- annual site visits with clear review criteria
- strategic planning / annually updated
- regular communication: monthly web meetings, mid-year review, all-hands meeting, EAB meeting
- fixed (short) duration funding / external review
- close financial oversight
- finding the key people and directing resources to them
- continually thinking about your legacy will be

5

# Nanotechnology in the SBIR/STTR Programs at NSF

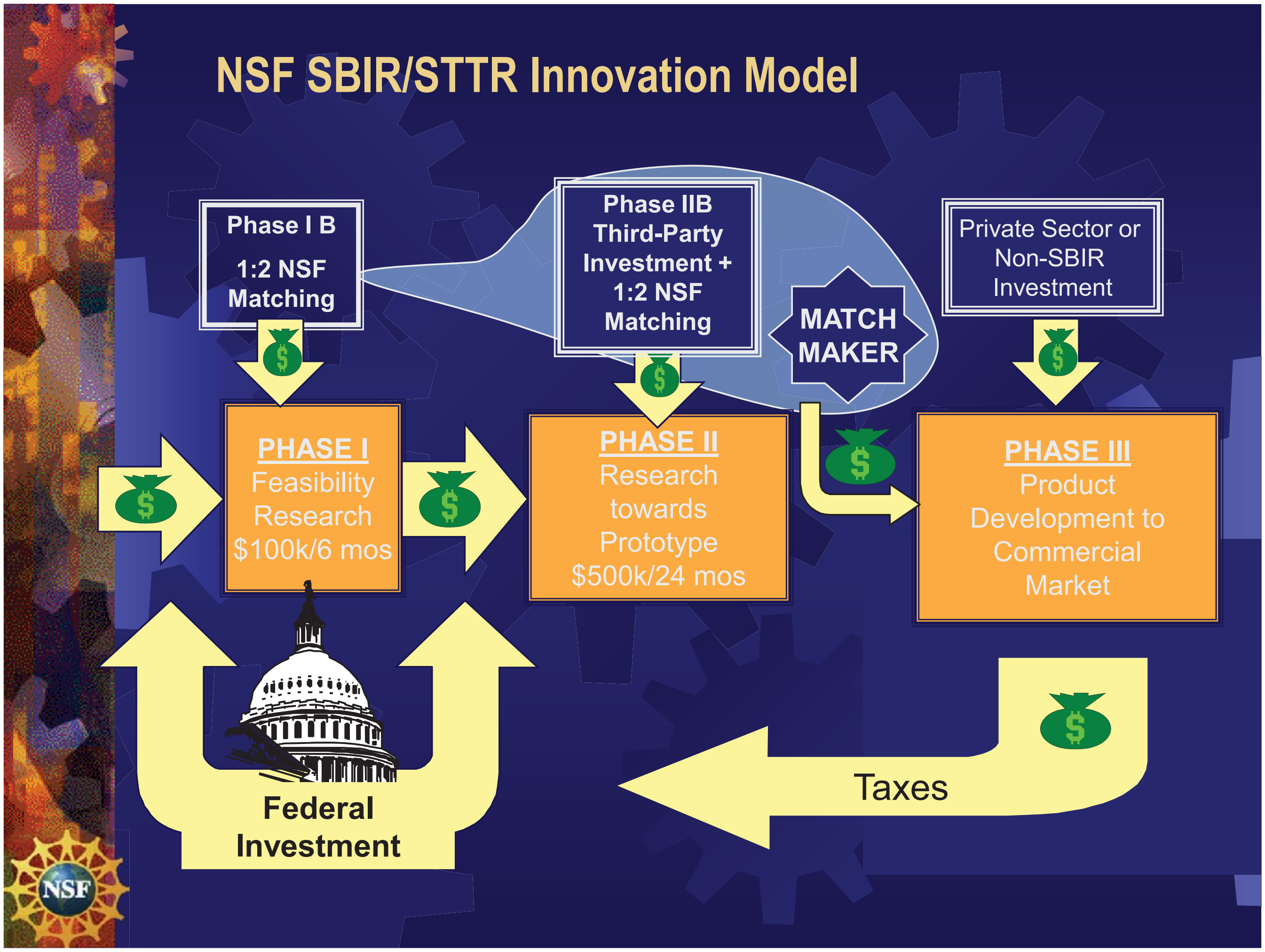
T. James Rudd
Industrial Innovation and Partnerships
Engineering Directorate
National Science Foundation

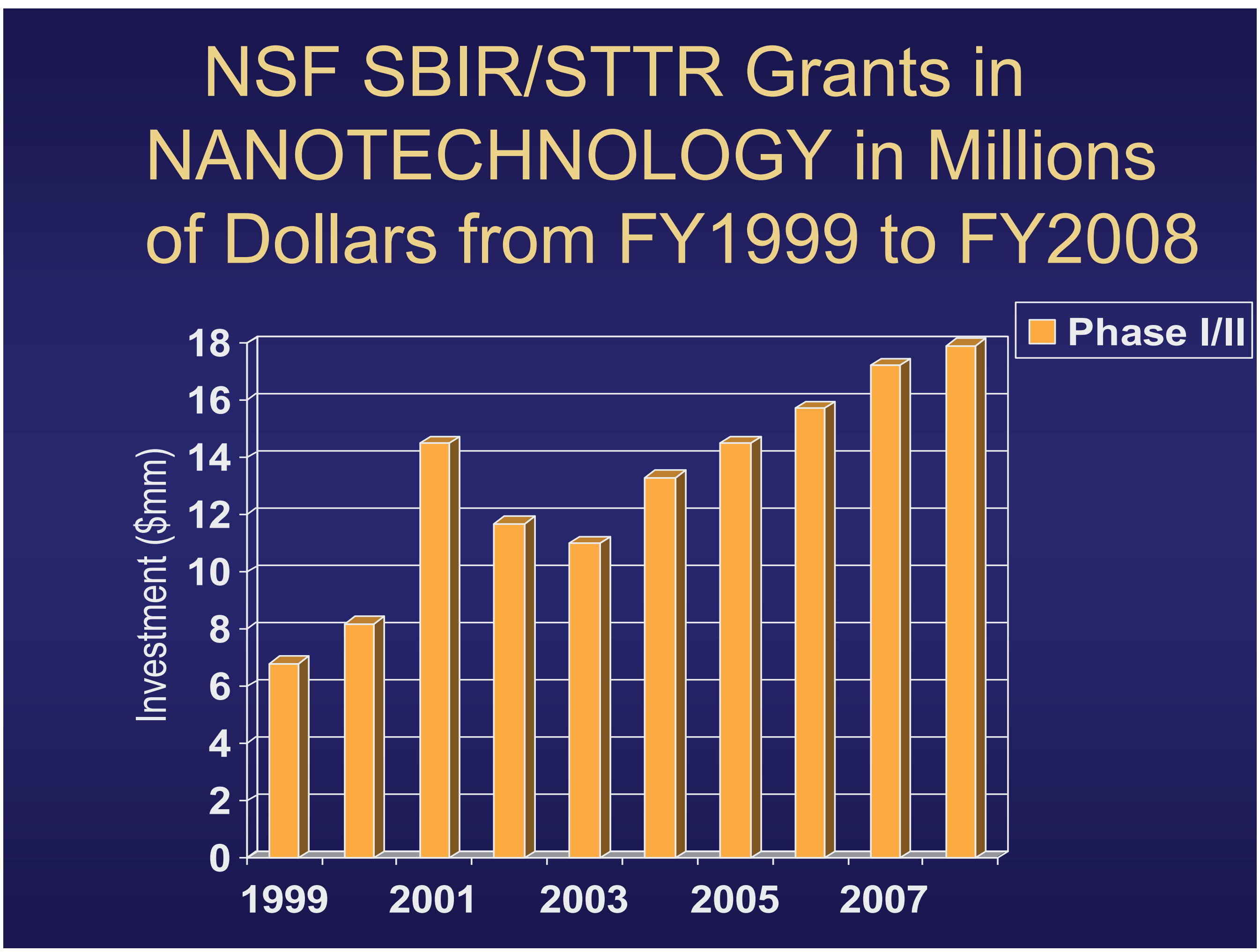
**Nanoscale Science and Engineering Grantees Conference**
**December 4th, 2008**

## Nanotechnology Thrusts in SBIR/STTR at NSF

- **Synthesis and Processing** - techniques for synthesis, fabrication, and processing of nanostructures
- **Materials, Devices, Systems, and Architectures** - techniques for processing and converting molecules and nanoprecursors into functional nanostructures; nanostructured materials, nanocomponents and nanodevices
- **Nanomanufacturing** - techniques for synthesis and scale-up of structures, devices and systems employing nanostructured materials and processes with nanoscale control

Nanotechnology in the SBIR/STTR Programs
James Rudd (1)




Nanotechnology in the SBIR/STTR Programs
James Rudd (2)

Nanotechnology and Media
Josh Chamot (1)

PEW / INTERNET
PEW INTERNET & AMERICAN LIFE PROJECT

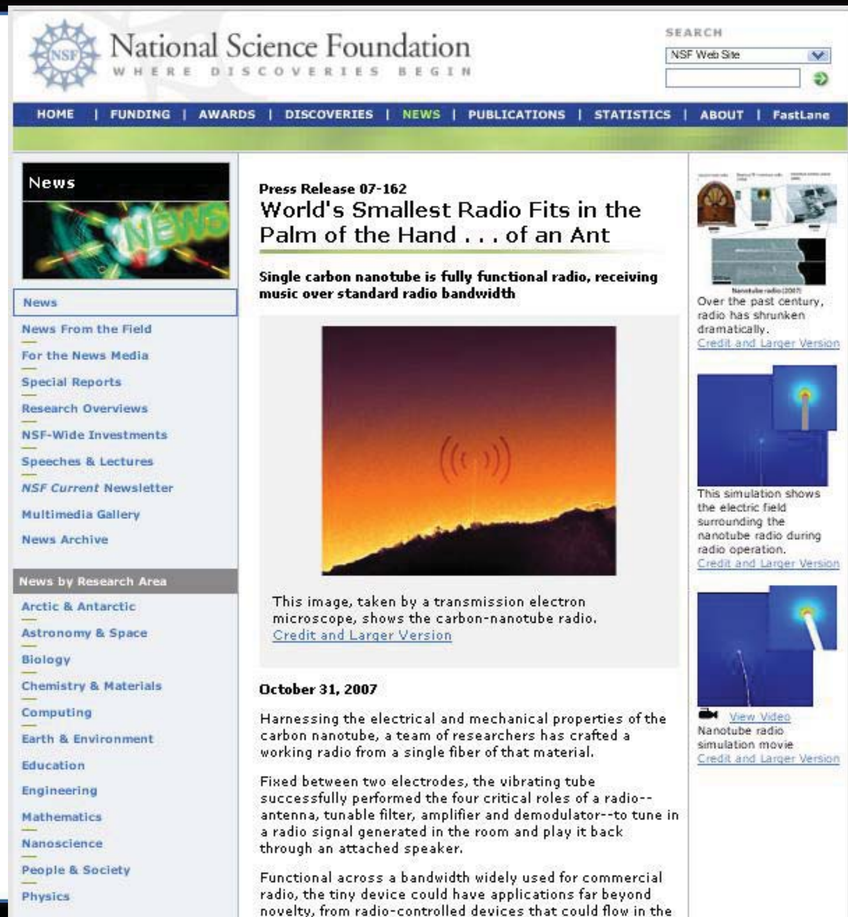
**FACT: Nearly 40 million Americans rely on the internet as their *primary source* of news about science.**

- *Television is first (41%) as a science news source.*
- *The internet is now second (20%)*
- *Newspapers and magazines are third (14%)*
- *In homes with broadband, 44% of young adults get their science news from the internet.*

*Pew Internet and American Life Project survey*
*Funded by the National Science Foundation*

## LiveScience.com

- **Behind the Scenes:** Weekly feature stories that highlight the work of university scientists and engineers. It is syndicated to top 10 consumer news sites like Yahoo!News and MSNBC.
- **Research in Action:** An image-of-the-week feature with much longer captions that is now part of LiveScience's syndication efforts.
- **ScienceLives:** Ten-question profiles that have proved so popular with PIOs and researchers that we now run the profiles every week.




## NSF's Studio 8

Located in the Arlington, VA, satellite office of NCSA's ACCESS GRID facility.

A high-definition studio for interviews and other events intended for distribution on the Internet, radio and television.

Remote participants are linked in one of two ways: via the Internet Access Grid or a video teleconferencing (VTC) facility.

Nanoscience Activities at Other Agencies
Jonathan Porter, Jeff Morris, and Norris Alderson (1)

# Defense Nanotechnology Research and Development

Dr. Jon Porter
jonathan.porter@osd.mil

December 4, 2008



# DoD Perspective and Nanotechnology

- **History of support for pre-“nano” nanoscience research**
- **Increasing emphasis on manufacturing technology, producibility, sustainability**
- **Increasing emphasis on Environment, Health, and Safety aspects**
  - **Research, Acquisition, ESOH communities collectively engaged**
- **NNI accelerates high-potential nanotechnology-based capabilities**
- **For details see “Defense Nanotechnology Research and Development Program”**
  **www.nano.gov/html/res/pdf/DefenseNano2007.pdf**

Nanoscience Activities at Other Agencies
Jonathan Porter, Jeff Morris, and Norris Alderson (2)

# Examples of Potential DoD Applications of Nanotechnology

- **Electronics and Sensing**
- **Power and Energy**
- **Structural Materials**
- **Coatings**
- **Multifunctional Materials and Devices**
- **Materials and Systems Prognosis**
- **Energetics**

# S&T Budget Estimates

(Includes Congressional Adds for FY07 and FY08)

(*All numbers rounded to nearest $M)

| **Program Component Area (PCA)** | **FY2007** | **FY2008** | **FY2009** |
|---|---|---|---|
| 1. Fundamental Nanoscale Phenomena and Processes | $210M | $ 259M | $ 228M |
| 2. Nanomaterials | $ 86M | $ 69M | $ 55M |
| 3. Nanoscale Devices and Systems | $120M | $ 120M | $ 108M |
| 4. Instrumentation Research, Metrology, and Standards | $ 4M | $ 8M | $ 4M |
| 5. Nanomanufacturing | $ 8M | $ 5M | $ 13M |
| 6. Major Research Facilities and Instrumentation Acquisition | $ 22M | $ 25M | $ 22M |
| 7. Environment, Health, and Safety | | $ 2M | $ 2M |
| 8. Education and Societal Dimensions | | | |
| **TOTAL** | **$450M** | **$487M** | **$431M** |

Nanoscience Activities at Other Agencies
Jonathan Porter, Jeff Morris, and Norris Alderson (3)



EPA United States Environmental Protection Agency

# Nanomaterials: Research to Support Environmental Decisions

**Jeff Morris**
**National Program Director for Nanotechnology**

*Presentation to the NSF NSE 2008 Grantees Conference*

**Arlington, VA**
4 December 2008

**Office of Research and Development**

EPA United States Environmental Protection Agency

## Nanomaterials and Environmental Decision Making: A Few "Simple" Questions

What nanomaterials, in what forms, are most likely to result in environmental exposure?

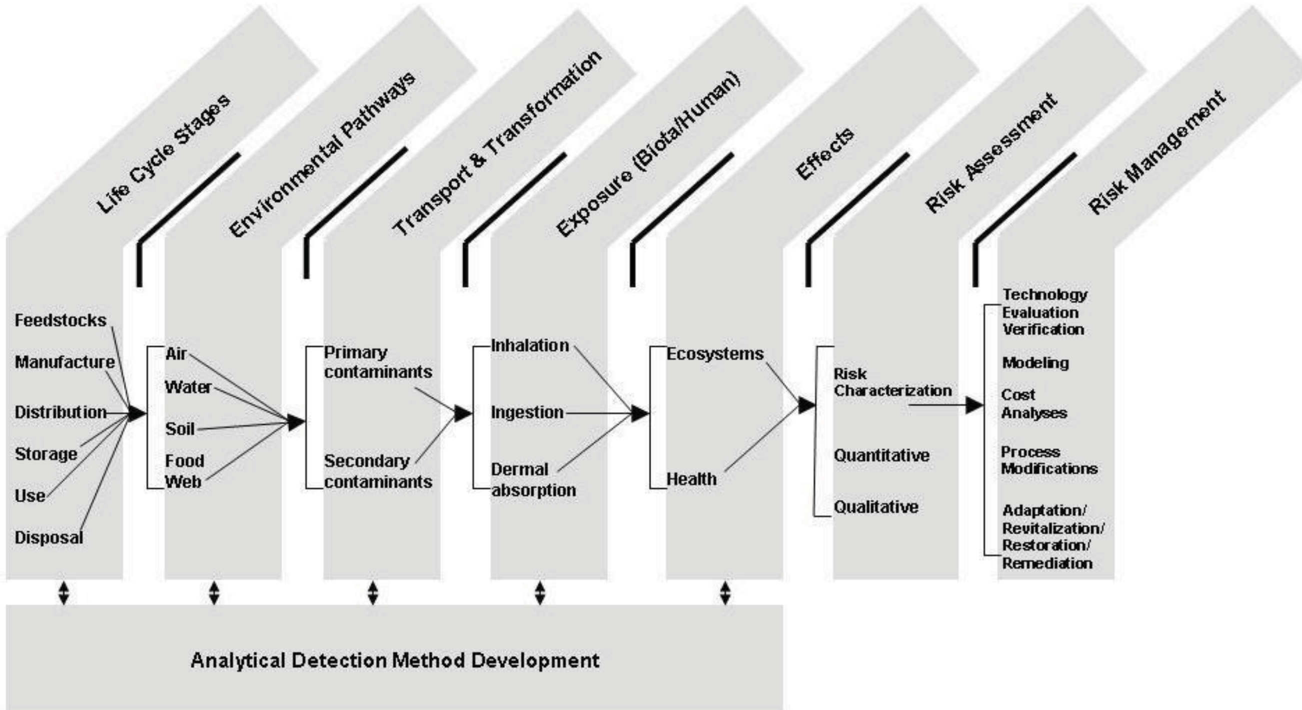
What particular nanomaterial properties may raise toxicity concerns?

→ Are nanomaterials with these properties likely to enter environmental media or biological systems at concentrations of concern, and what does this mean for dose-response and risk?

→ If we think yes, can we change properties or mitigate exposure?

United States Environmental Protection Agency

## Comprehensive Environmental Assessment






Based on Comprehensive Environmental Assessment (Davis and Thomas, 2006)



United States Environmental Protection Agency

## Key Points

- Decision makers need information grounded in reality, and nanotechnology EHS researchers should understand decision makers' needs.
- A life-cycle perspective is important.
- Avoiding risk is better than managing risk. What information can researchers provide to decision makers that can prevent hazards and unintentional exposures?

Nanoscience Activities at Other Agencies
Jonathan Porter, Jeff Morris, and Norris Alderson (5)

U.S. Food and Drug Administration
Protecting and Promoting Public Health
www.fda.gov

# RESEARCH NEEDS AT FDA

**2008 NSF Nanoscale Science and Engineering Grantees Conference**

December 4, 2008

Norris E. Alderson, PhD
Associate Commissioner for Science

U.S. Food and Drug Administration
Protecting and Promoting Public Health
www.fda.gov

# FDA Mission

The FDA is responsible for **protecting the public health** by assuring the safety, efficacy, and security of human and veterinary drugs, biological products, medical devices, our nation's food supply, cosmetics, and products that emit radiation.

The FDA is also responsible for **advancing the public health** by helping to speed innovations that make medicines and foods more effective, safer, and more affordable; and helping the public get the accurate, science-based information they need to use medicines and foods to improve their health.

3

## Nanoscale Materials in FDA Products

- Drugs and food ingredients
- Sunscreen materials
- Filler or bonding agents for bone and tooth repair
- Drug delivery materials
- Medical imaging
- Food and beverage containers
- Implant materials

U.S. Food and Drug Administration
Protecting and Promoting Public Health
www.fda.gov

## Research Needs

- Tools and methodologies to:
  - Assess product chemistry and unique characteristics of product
  - Enhance quality control measures
  - Produce consistent formulations with low batch-to-batch variability
  - Link product quality to performance

Global NSEE
Bob Chang (1)

# Global Nanoscale Science and Engineering Education

**R.P.H. Chang**
Director, National Center for Learning and Teaching in Nanoscale Science and Engineering (NCLT)
Northwestern University

NCLT NU • UM • PU • UIC • UIUC • ANL • AAMU • FU • HU • MC • UTEP • PSS

## About the GNSEE Workshop

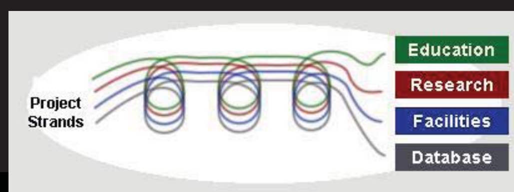

- Goal of this Workshop - Develop a global NSEE community that will greatly enhance NSEE learning and teaching in formal and informal settings.
- Vision - use this community to work together to train the next generation of nanotechnology workers and global leaders to solve the challenges facing our world.

NCLT NU • UM • PU • UIC • UIUC • ANL • AAMU • FU • HU • MC • UTEP • PSS

# Global Nanotechnology Network

- Partner Networks in Africa, Asia, Europe, and the US
- GNN development workshops – 2001 (Mexico), 2003 (Japan), 2005 (Germany), 2009 (Rio de Janeiro)
- Diverse stakeholders in academia, industry, and government

**Education** is a major project strand of the GNN!





NCLT NU • UM • PU • UIC • UIUC • ANL • AAMU • FU • HU • MC • UTEP • PSS

# Global Nanotechnology Network

- A 4th GNN Development Workshop is planned during the IUMRS-ICAM 2009 conference in Rio de Janeiro


- Global partners are invited to help us:
  - Identify leading nanotechnology researchers, educators and policy makers from your countries and regions
  - Identify / obtain funding for them to attend the Workshop
  - Support student participation at the Workshop
- For more information, please contact mri@northwestern.edu

NCLT NU • UM • PU • UIC • UIUC • ANL • AAMU • FU • HU • MC • UTEP • PSS

Best Practices for Advancing NSE Education
John Bradely panel (1)

*NSF Nanotechnology Grantees*

*Dec. 5, 2008*

# *National Nanotechnology Infrastructure Network*

## *Education and Outreach Program Best Practices*

*Nancy Healy*
*NNIN Education Coordinator*

*Lynn Rathbun, Ph.D*
*NNIN Program Manager*

NNIN Semi-Annual Meeting Oct 2006

## *Scope of NNIN Education and Outreach*

| | Site Specific Activities | Network-wide Activities |
|---|---|---|
| Local | Local Activities – Site Specific | Network Activities - Local Scope |
| | Facility tours<br>Community days<br>Open house<br>Seminars/Public lectures<br>School programs | User support & training<br>Diversity<br>K-12 education- school programs<br>Summer & after school camps |
| National Scope | Site Activities - National Scope | Network Activities - National Scope |
| | Workshops<br>Technical Training<br>Teacher Training<br>Research Experience for Teachers<br>(initial program)<br>K-12 instructional materials<br>Hands-on demos & experiments<br>Undergraduate education | National Conferences & Meetings<br>Research Experience for Undergrads<br>RET (NSF award)<br>NNIN Education portal<br>User support<br>Diversity<br>Open Textbook<br>*Nanooze* |

**NNIN programs reached > 15,000 individuals in 2007**

NNIN Semi-Annual Meeting Oct 2006

# Research Experience for Undergraduates

An Activity of the NNIN Education & Outreach Program

Strong, Diverse Applicant Pool

75-90 participants
12-14 sites
10 weeks

High Quality, Diverse Projects

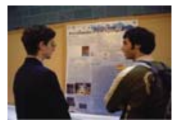
Instruction ,Mentoring & Advanced Instrumentation

End of Program Network Convocation

REU Research Accomplishments

Presentations Publications

**iREU**



Longitudinal Study of REU Outcomes

**Degrees** **Type of Career**

- Highly Coordinated Among Sites
- Common on-line application
- Central award process
- Common expectations and procedures

NNIN
www.nnin.org
Nanoscale Science, Engineering & Technology

NNIN Semi-Annual Meeting Oct 2006

## *Research Experience for Teachers in Nanotechnology*

***An Activity of the NNIN Education and Outreach Program***

- REU-like experience for teachers
  - leverage
- 5 NNIN sites
- Research and Activity development
  - Activities are distributed via NNIN education web site
  - Major portion of the available NNIN resource material
  - Shared among sites


NNIN
www.nnin.org
Nanoscale Science, Engineering & Technology

*An activity of the Education Program of NNIN, the National Nanotechnology Infrastructure Network*
*Funded by the National Science Foundation as part of ECS-335765 Sandip Tiwari , Cornell, PI , and as RET site award EEC-0601939, Nancy Healy, Ga. Tech, PI.*

# MRSEC Education Directors Network

Daniel Steinberg
Princeton University
December 5, 2008

NSF NSE 2008 Grantees Conference

PCCM

# Action

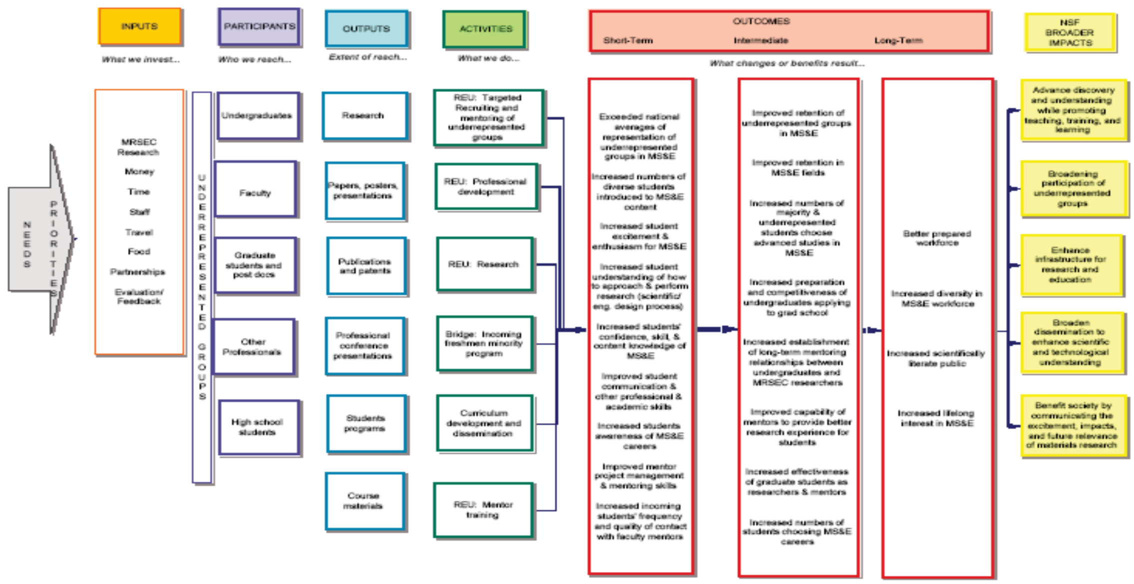
- Conducted Working Meeting 9/14-9/17 2008
- Agenda set in part by results from work groups
- Goals: increase collaboration nationally among MRSECs
- Improve evaluation, show impact
- Diversity strategies for MRSECs and Materials Science
- Build Cross-center logic models (1st step in sharing data and resources)
- Ultimately – collaboration between MRSEC education programs at all levels, share data

PCCM

Best Practices for Advancing NSE Education
John Bradely panel (3)

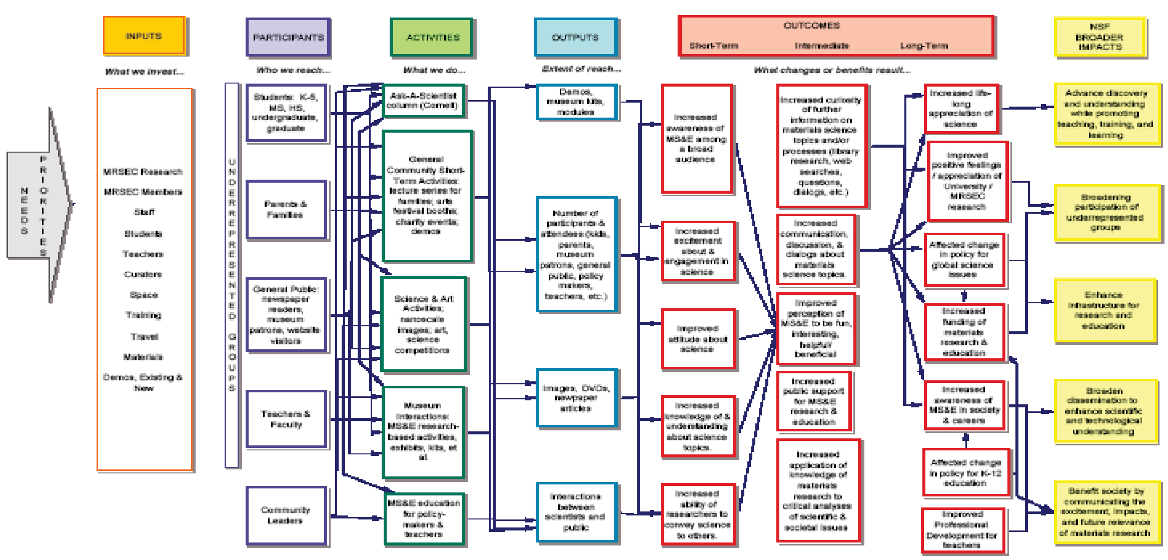
MRSEC E/O LOGIC MODEL

## Undergraduate Research Experiences




MRSEC E/O LOGIC MODEL

## Public Interactions



nanoHUB.org ONLINE SIMULATION AND MORE

## BEST PRACTICES FOR ADVANCING NSE EDUCATION

George B. Adams III, Deputy Director
Network for Computational Nanotechnology (NCN), Purdue University

- Working with Profs. David Radcliffe, Sean Brophy, George Bodner and CoE Dir. of Assessment, Dr. Diane Beaudoin

Areas of investigation –
- Identify effective pedagogical methods for using nanoHUB resources for learning
- Understanding the dynamics of knowledge generation and usage on nanoHUB

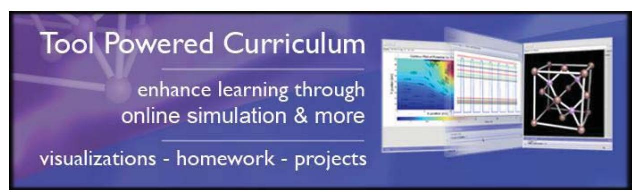
Methods –
- Instructor and student surveys
- In-depth instructor and student interviews
- nanoHUB usage data

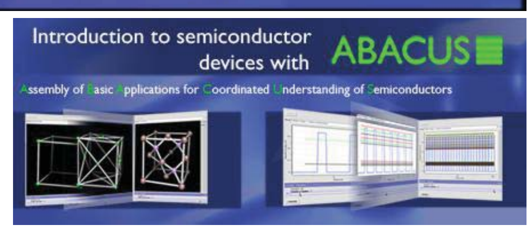
PURDUE UNIVERSITY

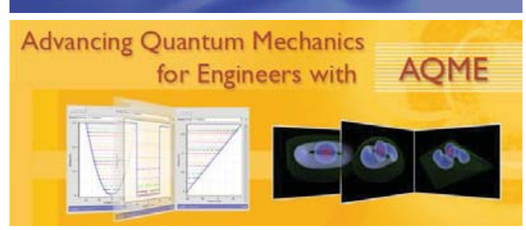
nanoHUB.org ONLINE SIMULATION AND MORE

## New Education Support

- Tool-powered curricula
  - Turn-key simulation
  - Instructor-created custom tool bundles
  - Visualizations
  - Homework and project assignments
  - Interactive seminars by leading researcher







Best Practices for Advancing NSE Education
John Bradely panel (5)

Best Practices for Advancing NSE Education
John Bradely panel (6)

nanoHUB.org ONLINE SIMULATION AND MORE

Key characteristics of nanoHUB.org –

- Supports student exploration
- Supports active and collaborative learning
  - However, students taxed to be “intellectually present” and “on task”; they may push back
- On-line is engaging for “Digital Natives”
- Crossover of formal/informal environments
  - Positive for K-12

Observations

- With laboratories it is fairly easy to distinguish research and education use
- Discovery and Learning form a continuum with cyber-environments

PURDUE UNIVERSITY



## Nanoscience for the Public

**R.M. Westervelt**

***Science of Nanoscale Systems and their Device Applications***

**NSEC (Harvard, MIT, UCSB, MOS Boston)**

School of Engineering and Applied Sciences &
Department of Physics
Harvard University

NSEC Harvard, MIT, UCSB, MoS

NISE network NANOSCALE INFORMAL SCIENCE EDUCATION

NRI

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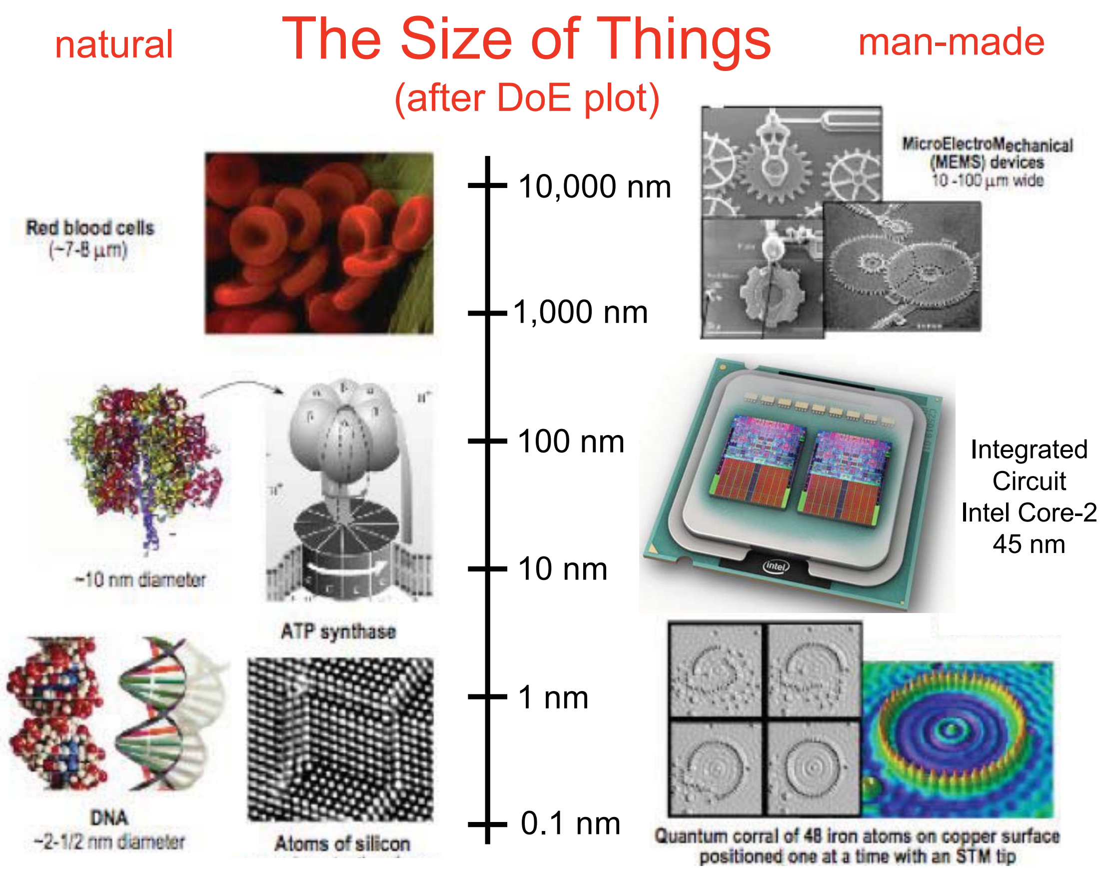



# NSEC Course - Nanoscale Science and Engineering

**Applied Physics 298r**

**Interdisciplinary Biology, Chemistry, Engineering and Physics: Seminar**

**Mon. & Wed. 12:00-1:30, Pierce Hall Room 209**

**Spring 2007**

| | | |
|---|---|---|
| 1/31/07 | Robert Westervelt | Overview of NSEC research |
| 2/5/07 | Donhee Ham | Soliton electronics & Biolab-on-IC |
| 2/7/07 | George Whitesides | Tools for integrated nanobiology |
| 2/12/07 | Kevin (Kit) Parker | The Heart: From womb to doom |
| 2/14/07 | Howard Stone | Cellular-scale hydrodynamics |
| 2/21/07 | Xiaowei Zhuang | Single-molecule imaging of molecular and cellular processes |
| 2/26/07 | Efthimios Kaxiras | Multiscale theory for complex materials |
| 2/28/07 | Hongkun Park | Oxide and chalcogenide nanostructures |
| 3/5/07 | David Bell | How to see the needle in the haystack, microscopy on the nanoscale |
| 3/7/07 | Joseph Mizgerd | Opportunities for fighting lung infection using nanosciences |
| 3/12/07 | Moungi Bawendi | Nanoscale building blocks |
| 3/14/07 | Eric Mazur | Manipulating light at the nanoscale |
| 3/19/07 | Cynthia Friend | Synthesis and stability of surfaces in nanoscale materials |
| 3/21/07 | Shriram Ramanathan | New paradigms for nanoscale ultra-fast devices |
| 4/2/07 | Ray Ashoori | Imaging at the nanoscale |
| 4/4/07 | Jenny Hoffman | Magnetic force microscopy of superconducting vortices |
| 4/9/07 | Eric Heller | Imaging of electron flow in GaAs-AlGaAS semiconductors |
| 4/11/07 | Charles Marcus | Quantum information using spin in quantum dots |
| 4/16/07 | Federico Capasso | Surface plasmon photonics |
| 4/18/07 | Marko Lončar | Nanolasers and single-photon sources based on photonic crystal cavities |
| 4/23/07 | Ken Crozier | Plasmonics: Confining electromagnetic fields to subwavelength dimensions with metallic nanostructures |
| 4/25/07 | Mike Stopa | Modeling the nanoscale world: The need for computation in nanoscience |
| 4/30/07 | Venky Narayanamurti | Ballistic electro-photonics |
| 5/2/07 | Marc Kastner | Single electron counting spectroscopy of excited states in quantum dots |

nsec.harvard.edu Course website: http://www.courses.fas.harvard.edu/colgsas/7500

For more information, please contact Fawwaz Habbal: habbalf@deas.harvard.edu or Naomi Brave: brave@deas.harvard.edu



Best Practices for Advancing NSE Education
John Bradely panel (7)

Best Practices for Advancing NSE Education
John Bradely panel (8)


# Museum of Science Boston

**Carol Lynn Alpert and Larry Bell**

## 2004 Zagat U.S. Family Travel Guide:

"Extraordinary to Perfection"

#16 Top-Rated U.S. Attraction (and the ONLY New England institution in the top 50 list)

Highest-ranked science museum

NISE network
NANOSCALE INFORMAL SCIENCE EDUCATION

**NSEC Advisors**
**Robert Westervelt**
**Kathryn Hollar**
**Eric Mazur**
**George Whitesides**

**Core Partners:**

**Museum of Science** - Larry Bell & Carol Lynn Alpert
**Science Museum of Minnesota** - Paul Martin
**The Exploratorium** - Rob Semper & Tom Rockwell

NISE Network is designed to foster public awareness, engagement, and understanding of nanoscale science, engineering, and technology.

The Network will innovate, prototype, and test new approaches to communicating the nanoscale world to the public.

http://www.nisenet.org

# Building Capacity for Public Engagement through Research Center - ISE Partnerships

NSEC
Harvard, MIT, UCSB, MoS

Center for High-rate Nanomanufacturing

Carol Lynn Alpert
Director, Strategic Projects
Museum of Science, Boston
Co-PI, NISE Network

Museum of Science

NISE network
NANOSCALE INFORMAL SCIENCE EDUCATION

## Main Points:

- Science-literate public
- Informed and intelligent citizen/electoral engagement
- Open doors for young people to seek higher education
- Provide enrichment beyond the classroom
- Leverage impact through partnerships -
  research centers working together with ISEI's.
- Capacity-building flows in both directions.

⟺

Informal Science Education
Larry Bell and David Ucko panel (1)

Informal Science Education
Larry Bell and David Ucko panel (2)

# Case Study

Museum of Science, Boston

*in partnership with*

Center for High-rate Nanomanufacturing

Northeastern, UMass-Lowell, UNH

Center for High-rate Nanomanufacturing

Science of Nanoscale Systems and their Device Applications NSEC

Harvard, MIT, UCSB, MOS

## What makes partnerships work?

- Advance planning
- Funding
- Mutual respect
- Buy-in at highest levels
- Dedicated staff / Frequent communication
- Cross - cultural understanding
- Evaluation and constant improvement

Nanoscale Science and Engineering
2008 NSF Grantees Conference
Arlington (VA), December 3-5, 2008

11:15 (Dec 3, 2008) Panel: Informal Science Education
Moderators: Larry Bell (Museum of Science, Boston)
and David Ucko, NSF

Wendy Crone, Univ. Wisconsin
Carl Batt, Cornell Univ.
Akhlesh Lakhtakia, Penn State Univ.
Carol Lynn Alpert, MOS

**Remarks by Akhlesh Lakhtakia**

Dear Colleagues,

Thank you for inviting me to participate, and thank you for listening to me.

The National Science Foundation has been very successful in having universities and other research institutions devise programs to improve the technoscientific knowledge of schoolteachers and principals. Websites and brochures have been designed. Short-term camps have been and are being conducted by universities to imbue primary and middle-school children with a fascination for science and technology. These are important activities that must continue and even be enhanced.

Incorporation of scientific understanding in everyday life by laypersons is not easy. Let me take the case of the National Science Foundation. Newspapers are full of scientific reports on the obesity epidemic sweeping our country. Yet all breakfast items served today by NSF promote obesity. If scientific personnel working for NSF cannot translate scientific knowledge into everyday practice, imagine how difficult must it be for laypersons! Informal science education is therefore necessary.

I became formally involved in informal science education as one of three technoscientific faculty members from Penn State in the NSF-funded three-university Center for the Integration of Research, Teaching and Learning centered at the University of Wisconsin-Madison. In devising my activities as part of that five-year project (2003-2008), I interpreted informal science education as community science education.

Community science education is absolutely important in any technologically advanced democracy such as ours. National legislatures and elected executives routinely consult technical and scientific experts before setting the parameters of industrial policies and technoscientific expenditures. Even state legislatures and elected executives have the financial wherewithal and constitutional authority to create and run technoscientific agencies for consultations as well as for the implementation of legislated decisions.

However, the march of technoscience is so relentless, its spread is so pervasive and its scope so widely-encompassing that decision-making by local legislatures such as school boards and municipal councils and elected executives such as mayors needs to be technoscientifically informed as well. This is where community science education is needed.

My activities as part of CIRTL were focused on improving the communication abilities of graduate students. Five batches of 6 graduate students each went through an intensive workshop to develop 20-minute power-point presentations on their own research for presentation to lay audiences. Some of the presentations were put on the web. My department instituted the requirement of a nontechnical abstract in addition to the usual technical abstract. Nontechnical abstracts are put on the web. We beefed up the student╒s experience during graduate seminars by adding the requirement of a reflective element in their seminar reports.

These activities were undertaken with the hope that our graduate students will, in time, not only advise national and state leaders, but also local community leaders. Indeed, some of them would even become local community leaders.

The presentation workshops made me realize that a different type of community science education activity is needed. We technoscientists must not imagine that lay audiences comprise people who can only be passive recipients of technoscientific information. Just because they do not have doctorates in technosciences does not mean that they cannot think. Many of them can think more acutely about technoscientific issues than many technoscientists. What they do not have, as the Wizard of Oz would say, is a proper tool! Scenario planning is that tool.

Technoscientific activities do not occur in isolation. Every one of these activities has societal consequences that may lie far beyond the abilities of many of us to think of. These consequences cannot be viewed through the narrow prism of this or that set of equations. Instead, they must be viewed as possible moves in a game of chess.

Let me give you an example. Suppose that municipal councilors in some city are debating in 2011 the need for refurbishment of IT devices two years later. Some of them have come to know that OLED technology is advancing rapidly could soon overtake LCD technology. If OLED monitors are expected to appear in the market by 2015, should new LCD monitors be installed in schools and the local airport in 2013 as scheduled? Will there be a reduction or increase of power consumption thereby? What hazardous materials and processes are involved in the manufacture of OLEDs as against the manufacture of LCDs? Is it easier to repair OLED monitors than LCD monitors? Is it easier to recycle parts from OLED monitors than from LED monitors? Is it



possible to incinerate OLED monitors safely or not? Where would incineration occur? And, so on.

Technical information needs to be collected and digested in order to answer various questions. Guesses have to be made when hard information is not available. The interrelationships of various factors have to be identified and classified in some order of importance. And then several scenarios must be constructed to project 10 or 20 years into the future.

The creation of a scenario is similar to modeling a physical, biological or engineered system by a technoscientist. But there is an interpretative element to social systems. Different people interpret factual data about the world differently, depending on the context of a situation as well as how a specific person comprehends the world. Different interpretations generally imply different outcomes.

Scenario planning is a method to simplify the complexity and understand why different outcomes are possible. The aim is to learn more about how social, political, economic and technological factors interact to create the current state of our society, and how these factors may create future states of the society. It is a way to describe how the society is and then to develop hypotheses about how the society may be. Investigation of how the society is and consideration of how it may be together enable discussions about how the society ought to be.

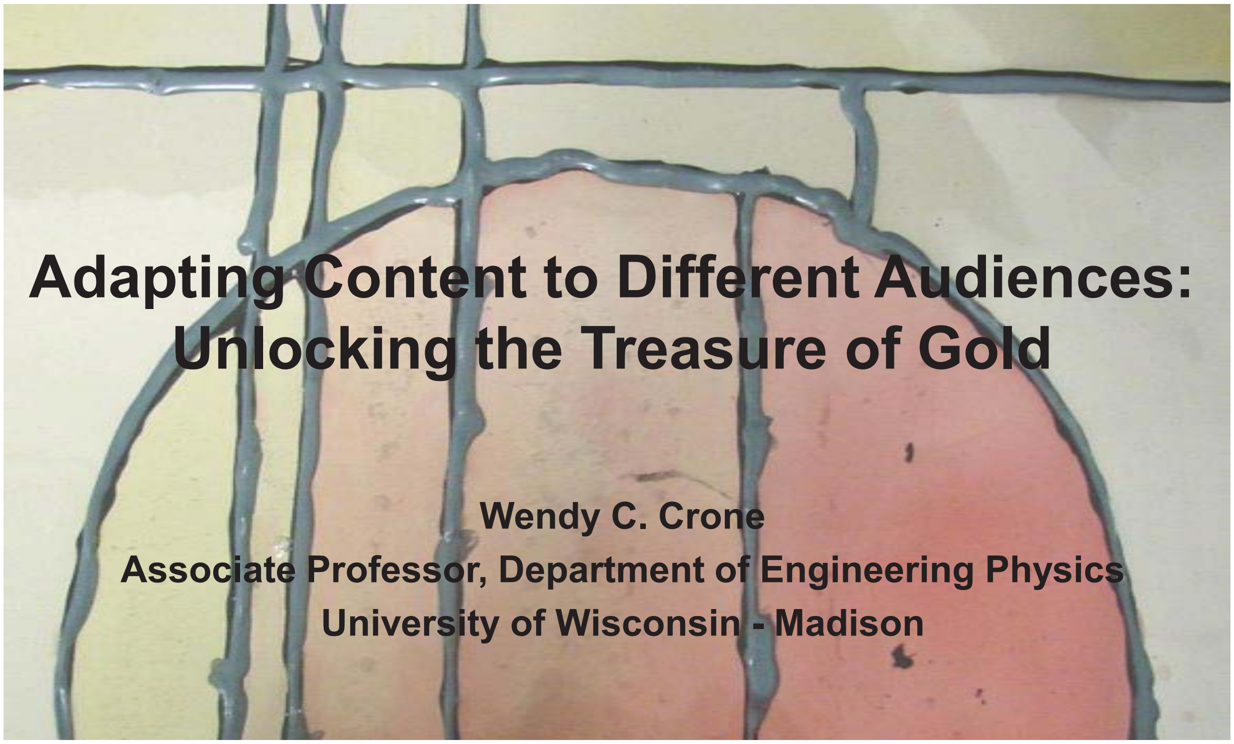
Scenario planning may be an effective tool for creating a common language among different stakeholders and thereby bridging two cultures: that of science and technology on the one hand, and that of social studies and the humanities on the other. Scenario planning thus is likely to be an excellent vehicle for community science education, because it will reach out to the intellects of the community leaders and involve them in a grand activity.

Informal Science Education
Larry Bell and David Ucko panel (5)



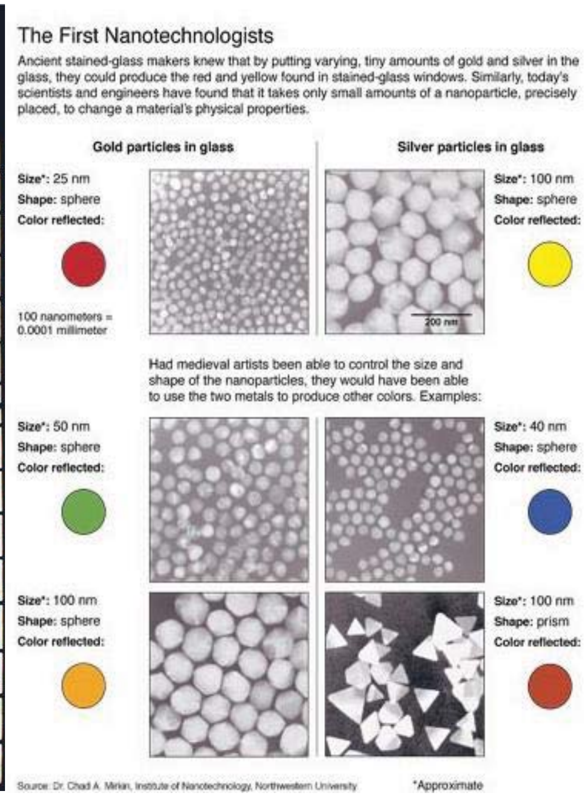
NISE network
NANOSCALE INFORMAL SCIENCE EDUCATION

Interdisciplinary Education Group
of the University of Wisconsin - Madison
**Materials Research Science and Engineering Center (MRSEC)**
on Nanostructured Interfaces



# Adapting Content to Different Audiences: Unlocking the Treasure of Gold

**Wendy C. Crone**
**Associate Professor, Department of Engineering Physics**
**University of Wisconsin - Madison**



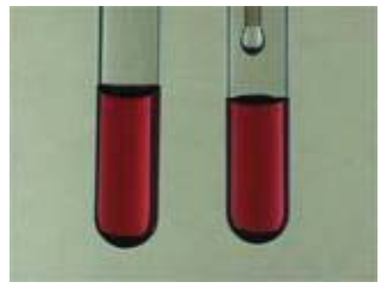

Chang, Kenneth. "Tiny is Beautiful:Translating 'Nano' Into Practical." New York Times 22 Feb 2005: Science.



www.mrsec.wisc.edu/nano

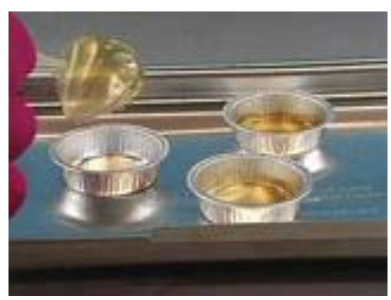
# Synthesis of Colloidal Gold Lab

- Video Lab Manual at: http://www.mrsec.wisc.edu/Edetc/nanolab/gold/index.html
- The synthesis procedure adapted from A. D. McFarland, C. L. Haynes, C. A. Mirkin, R. P. Van Duyne and H. A. Godwin, "Color My Nanoworld," *J. Chem. Educ*. (2004) **81**, 544A.

www.mrsec.wisc.edu/nano

# Synthesis of Colloidal Silver and Encapsulation in Polyvinyl Alcohol (PVA)

- Video Lab Manual at: http://www.mrsec.wisc.edu/Edetc/nanolab/silver/index.html
- The synthesis procedure adapted by Steve Ng and Chris Johnson from a procedure developed by S.D. Solomon, M. Bahadory, A.V. Jeyarajasingam, S.A. Rutkowsky, C. Boritz, and L. Mulfinger, *Journal of Chemical Education*, **84**, 322-325, (2007).


www.mrsec.wisc.edu/nano

www.nanooze.org
or just 'google' nanooze

Cornell University
Tamarack Design
Emily Maletz Graphic Design
Earth & Sky
NNIN
National Science Foundation

Chronicles of a Science Experiment

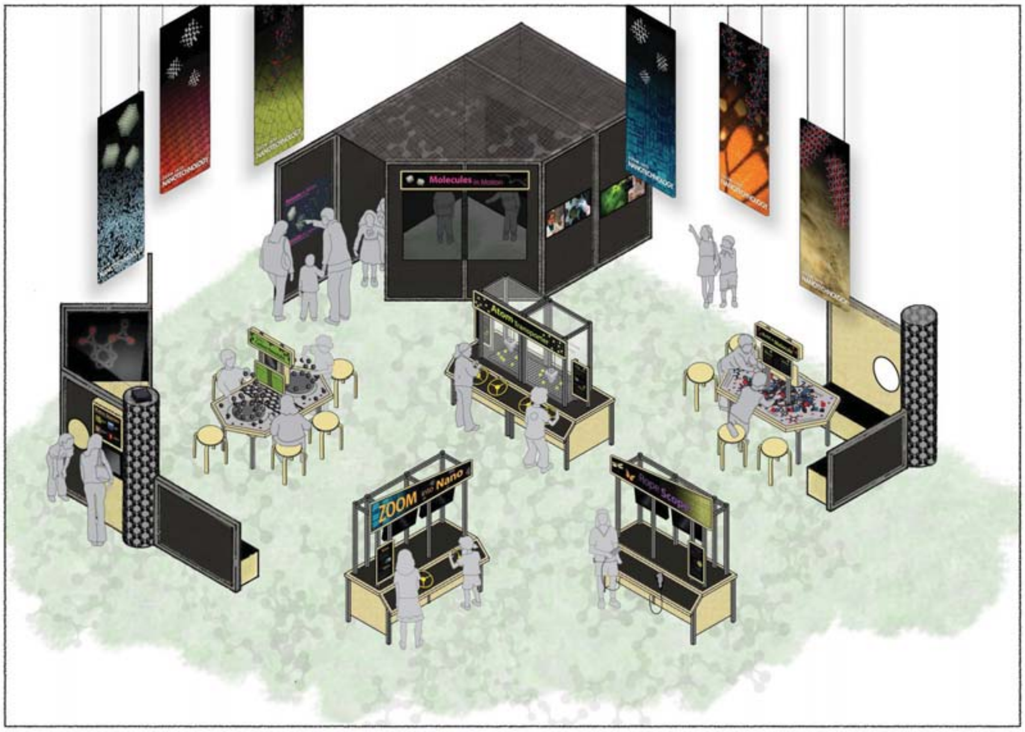
- All things are made of atoms.
- Molecules have size and shape.
- At the nanometer scale, atoms are in constant motion.
- Molecules in their nanometer scale environment have unexpected properties



Informal Science Education
Larry Bell and David Ucko panel (7)

Informal Science Education
Larry Bell and David Ucko panel (8)

## Too Small to See-2



# Our mission

- The mission of Nanooze is to excite, educate, and challenge both students and their teachers. Our overall goal is to get them engaged in science and engineering through fun, informative and science-based learning activities.

# Societal Dimensions of Nanotechnology 2008 Grantees Meeting

28-29 July, 2008

- Attended by 30 grantees representing 22 NSF funded projects
- 3 main topical areas – to be discussed in subsequent slides
- In 2008, over $4.1 million of NSF funding was directed to research on societal dimensions of nanotechnology
- About half of this funding supports two societal dimensions NSECs at Arizona State and University of California, Santa Barbara

# Topical Areas Addressed at the Meeting

1. Historical precedents and the capacity for "upstream" or "midstream" social shaping of nanoscience and nanotechnology
   - Historical context for emergence of nano S&T
   - Historical precedents for regulation and governance of nanotechnologies
   - Capacity for social shaping at upstream or midstream
   - Development of methodologies for upstream and midstream shaping
   - Safety and ethics practices and standards in labs and nanomanufacturing firms

NSF Grantees Meeting on Social Dimensions
Steve Zehr and Rita Teutonico (1)

NSF Grantees Meeting on Social Dimensions
Steve Zehr and Rita Teutonico (2)

Topical Areas

## 2. Public perceptions, risk communication, & media representations

- Work that monitors public perceptions of nanotechnology (surveys, focus groups)
  - Still relatively low level of public knowledge or interest in nanotechnology
  - Overall, relatively little public concern about potential nanotechnology risks
  - Comparing populations of nano scientists and public: Public perceives slightly more risk in all areas (e.g., loss of privacy, loss of jobs) with the exception of pollution and health risks where scientists perceive more risk.

Topical Areas

## 3. Nanotechnology Diffusion, Ethics and Cultural Values, Governance

- Nanotechnology Development and Diffusion:
  - Development of nano-districts in U.S., Europe, and Asia where research & commercialization are concentrated
  - Rapid growth of research & development in China – doesn't yet match the quality of work in U.S. or EU

# IGERT
## and Nanoscience

Carol Van Hartesveldt, Ph.D.
Program Director, IGERT
National Science Foundation

## Universities with Nano IGERTs

- Cornell (2)
- Drexel University
- Johns Hopkins University
- Northeastern
- Ohio State University
- Rutgers University (2)
- Tuskegee University
- UC-Berkeley
- UC-Los Angeles
- University of Central Florida
- University of Delaware
- University of Massachusetts Amherst
- University of Minnesota
- University of New Mexico (2)
- University of Texas Austin
- University of Utah
- University of Washington
- Vanderbilt University
- William Marsh Rice University



NSE in IGERT and Centers for Learning
Mike Roco panel (1)

# Educational Features of IGERT Projects

- New curricula
  - Interdisciplinary courses, laboratories, seminars, often team-taught
  - Student-taught interdisciplinary courses
  - Distance learning, videoconferencing
- New integrative experiences
  - "boot camps," workshops, retreats
  - Team projects and teamwork exercises
  - Student-lead and -organized meetings
  - Laboratory rotations; co-advising
- Internships
  - Industry, national laboratory, research institute
  - International

# Find Out More About IGERT

- http://www.IGERT.org
  - Searchable site maintained by grantee
- http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=12759&org=DGE&from=home
  - IGERT home page at NSF
  - Program solicitation
  - Video presentation
- http://www.nsf.gov/pubs/2006/nsf0617/index.jsp
  - Impacts of IGERT evaluation
- http://www.nsf.gov/pubs/2008/nsf0840/index.jsp
  - IGERT 2006-2007 Annual Report

NSE in IGERT and Centers for Learning
Mike Roco panel (2)

NSE in IGERT and Centers for Learning
Mike Roco panel (3)

# Science of Learning Centers

## Nanoscale Science and Engineering Grantees Conference

December 3-5, 2008

Soo-Siang Lim Ph.D
Program Director and Chair of Coordinating Committee
Science of Learning Centers Program
National Science Foundation

# Application…

## Each SLC offers "bridge supports" to translate knowledge into practice

- Stable, long term partnerships of researchers and teachers that:
  - ✓ Better align research agendas to education issues
  - ✓ Bring teacher input to research - and encourage new ideas
  - ✓ Build capacities of a new breed of researchers and teachers
- Evaluation over long term and development of standards for quality control.

**A NATIONALL RESOURCE FOR ALL!!!**

Science of Learning Centers
SCIENCE OF LEARNING CENTERS

# Current SLC Portfolio

## 2004 Cohort

- **CELEST**: Center for Cognitive and Educational Neuroscience (Boston U)
- **LIFE**: Learning in Informal and Formal Environments (U of Washington)
- **PSLC**: Pittsburgh Science of Learning Center (Carnegie-Mellon U)

## 2006 Cohort

- **SILC**: Spatial Intelligence and Learning Center (Temple U)
- **TDLC**: Temporal Dynamics of Learning Center (UC-San Diego)
- **VL2**: Visual Language and Learning Center (Gallaudet U)

SCIENCE OF LEARNING CENTERS

# SLC Network of Six Centers

**Another Level of Collaboration, Synergy & Synthesis**

- Across centers in research, training, knowledge transfer and dissemination
- Increased access to experts, materials and training opportunities
- Timely exchanges coordinated via a web of:
  - 30 + academic institutions
  - 60 + non-academic institutions
  - More than 450 participants
- Framework that sustains continuous education and training in interdisciplinary Science of Learning

SCIENCE OF LEARNING CENTERS

## Poster Group I: NIRT A and B (Room 365)

| | | | | |
|---|---|---|---|---|
| | **NIRT A. Biological Phenomena** | | | |
| 1 | Trevor | Douglas | Montana State University | NIRT07: Exploiting Protein Cage Dynamics to Engineer Active Nanostructures |
| 2 | Matthew | Libera | Stevens Inst. of Technology | NIRT07: Self-Assembled Nanohydrogels... |
| 3 | Michael | Strano | MIT | NIRT07: Single molecule detection in living cells... |
| 4 | Edwin | Kan | Cornell University | NIRT: Molecular Sensing and Actuation by CMOS Nonvolatile Charges... |
| 5 | Brij | Moudgil | University of Florida | NIRT: Multimodal Quantum Dot Based Probes for Non-Invasive Bioimaging |
| | **NIRT B. Catalysis** | | | |
| 6 | Benny | Freeman | Unversity of Texas Austin | NIRT07: Functionalization of Alloy Metal Nanoparticles for Enhanced... |
| 7 | Ajay | Karakoti | University of Central Florida | NIRT07: Engineered therapeutic nanoparticles as catalytic antioxidants |
| 8 | Chuan-Jian | Zhong | SUNY Binghamton | NIRT07: Nanostructured Bimetallic, Trimetallic and Core-Shell Fuel-Cell... |
| 9 | Marc | Madou | UC Irvine | NIRT07: C-MEMS/C-NEMS for Miniature Biofuel Cells |
| 10 | Israel | Wachs | Lehigh University | NIRT: Tuning the Electronic and Molecular Structures of Catalytic Active Sites... |

## Poster Group II: NIRT C, D, G, and H (Room 370)

| | | | | |
|---|---|---|---|---|
| | **NIRT C. Devices** | | | |
| 11 | Avik | Ghosh | University of Virginia | NIRT07: Surface State Engineering — Charge Storage and Conduction... |
| 12 | Chang-Beom | Eom | Univ. of Wisconsin Madison | NIRT07: Giant Piezoelectric Nanosystems |
| 13 | Kenneth | Shepard | Columbia University | NIRT07: Molecular electronic devices with carbon-based electrodes... |
| 14 | Kevin | Kelly | Rice University | NIRT07: Synthesis, Actuation and Control of Single-Molecule Nanocars |
| 15 | Marko | Loncar | Harvard University | NIRT07: Photon and Plasmon Engineering in Active Optical Devices... |
| 16 | Christian | Zorman | Case Western Reserve U. | NIRT07: Optics on a nanoscale using polaritonic and plasmonic materials |
| 17 | Andrea | Markelz | University at Buffalo, SUNY | NIRT:Nanostructure Components for Terahertz Spectroscopy on a Chip |
| 18 | Supriyo | Bandyopadhyay | Virginia Commonwealth U. | NIRT: Colective Computation with Self Assembled Quantum Dots... |
| 19 | Michael | Bartl | University of Utah | NER: Design and Study of Non-Classical Optical Phenomena... |
| 20 | Akhlesh | Lakhtakia | Pennsylvania State Univ. | Towards Circularly-Polarized Light Emission from Vertical-Cavity... |
| | **NIRT D. EM, Energy Materials** | | | |
| 21 | John | Harb | Brigham Young University | NIRT07: Chemically Directed Surface Alignment and Wiring of Self-Assembled... |
| 22 | Chris | Sorensen | Kansas State University | NIRT: Nanometer Stoichiometric Particle Compound Solutions and Control... |
| 23 | Mark | Stockman | Georgia State University | NIRT: Full Spatio-Temporal Coherent Control on Nanoscale |
| | **NIRT G. Societal** | | | |
| 24 | David | Berube | Univ. of Southern California | NIRT07: Intuitive Toxicology and Public Engagement |
| | **NIRT H. Transport** | | | |
| 25 | Costas | Grigoropoulos | UC Berkeley | NIRT07: Gated Transport through Carbon Nanotube Membranes |
| 26 | David | Erickson | Cornell University | NIRT07: Active Nanophotofluidic Systems for Single Molecule/Particle Analysis |

## Poster Group III: NIRT E and F (Room 380)

| | | | | |
|---|---|---|---|---|
| | **NIRT E. Manufacturing** | | | |
| 27 | Daniel | Schwartz | University of Washington | NIRT07: Protein-aided nanomanufacturing |
| 28 | Michael | Tsapatsis | University of Minnesota | NIRT07: Precise Building Blocks for Hierarchical Nanomanufacturing... |
| 29 | Efstathios | Meletis | Univ. of Texas Arlington | NIRT07: Composition Graded, Epitaxial Oxide Nanostructures: Fabrication... |
| 30 | Yuris | Dzenis | Univ. of Nebraska Lincoln | NIRT07: Nanomanufacturing and Analysis of Active Hierarchical... |
| 31 | Xianfan | Xu | Purdue University | NIRT07/GOALI: Development of a Multiscale Hierarchical Nanomanufacturing... |
| 32 | Joanna | Millunchick | University of Michigan | NIRT07: Active nanofluidic manufacturing and hierarchical assembly... |
| 33 | Xinghang | Zhang | Texas A&M University | NIRT07: Hierarchical Manufacturing and Modeling for Phase Transforming... |
| 34 | Ray | Baughman | University of Texas Dallas | NIRT: Hierarchical Nanomanufacturing of Carbon Nanotube Sheets & Yarns |
| 35 | Pradeep | Rajasekaran | Southern Illinois University | Nanotubes-Array based Lithography |
| 36 | Todd | Hastings | University of Kentucky | NIRT/GOALI: An Electron-Beam Based Microscale Nano-manufacturing... |
| 37 | Todd | Emrick | Univ. of Massachusetts | NIRT:  Controlling Interfacial Activity of Nanoparticles |
| | **NIRT F. Materials** | | | |
| 38 | Pradeep | Sharma | University of Houston | NRT07: Piezoelectric nanostructures without using piezoelectric materials |
| 39 | Mark | Robbins | Johns Hopkins University | NIRT07: Interfacial Forces in Active Nanodevices |
| 40 | Kimberley | Turner | UC Santa Barbara | NIRT07: Reversible Frictional Adhesion of Natural and Bio-Inspired Multi-Scale... |
| 41 | Traian | Dumitrica | University of Minnesota | CAREER: Nanomechanics from First principles: A Symmetry-Adapted... |
| 42 | Petra | Reinke | University of Virginia | SGER: Manganese Nanostructures on Si(100): Linking Structure... |

## Poster Group IV: Centers and Networks (Room 390)

| | | | | |
|---|---|---|---|---|
| 43 | Ahmed | Busnaina | Northeastern University | NSEC: The NSF Nanoscale Science and Engineering Center for High-rate... |
| 44 | Jacqueline | Isaacs | Northeastern University | NSEC: Center for High-rate Nanomanufacturing |
| 45 | Li | Zeng | UC Berkeley | NSEC: Center for Scalable and Integrated Nanomanufacturing |
| 46 | Mark | Tuominen | UMass Amherst | NSEC: Center for Hierarchical Manufacturing |
| 47 | Robert | Westervelt | Harvard University | NSEC: Science of Nanoscale Systems and their Device Applications |
| 48 | Matthew | Gilbert | Univ. Illinois | NSEC: Center for Probing the Nanoscale |
| 49 | Andrew | Greenberg | Univ. of Wisconsin Madison | NSEC for Templated Synthesis and Assembly at the Nanoscale |
| 50 | Barbara | Harthorn | UC Santa Barbara | NSEC: Center for Nanotechnology in Society at UC Santa Barbara |
| 51 | Robert | Chang | Northwestern University | NCLT: National Center for Learning & Teaching in Nanoscale Science and... |
| 52 | Carol Lynn | Alpert | Museum of Science | NSEE: Nanoscale Informal Science Education Network |
| 53 | Larry | Bell | Museum of Science | NSEE: Nanoscale Informal Science Education Network |
| 54 | Mehmet | Sarikaya | University of Washington | MRSEC: Genetically Engineered Materials Science and Engineering Center |
| 55 | Sandip | Tiwari | Cornell University | NNIN: National Nanotechnology Infrastructure Network |
| 56 | World | Nieh | USDA Forest Service | Public–Private Partnership for Nanotechnology Research and Development... |

**2008 Conference Program**

December 3: Focus on Centers
December 4: Focus on NIRTs (with invitees from other agencies)
December 5: Focus on integration of research and education

**Day 1: Wednesday, December 3, 2008**

Focus on Centers
Room 375, Stafford I, NSF

- 7:15 Coffee and continental breakfast
- 8:30 **Conference welcome and introduction**
  **Rod Beresford**, Brown University, Academic Conference Organizer
- 8:40 Day 1 Agenda Overview
  **Mark Tuominen**, University of Massachusetts Amherst
- 8:45 **Nanoscale Science and Engineering at NSF**
  **Mike Roco**, NSF
- 9:15 Panel: **Nano Centers - Present and Future**
  Moderator: **Jim Yardley**, Columbia University
  Scientific Legacy, **Robert Westervelt**, Harvard University
  Technological Development Legacy and Future, **Richard Siegel**, RPI
  NSECs and Industry: Legacy and Future, **Ahmed Busnaina**, Northeastern University
  Manufacturing Legacy and Future, **Placid Ferreira**, University of Illinois
  Societal Impact Legacy and Future, **Barbara Harthorn**, University of California Santa Barbara
- 10:00 Refreshment break
- 10:15 **Keynote: "Nanowires: A Platform for Nanoscience and Nanotechnology"**
  **Charles Lieber**, Harvard University
- 11:15 Panel: **Nanoelectonics Research Initiative**
  With an overview of the grantees meeting on December 1-2, 2008
  **Jeff Welser** (NRI and IBM) and **Ralph Cavin** (NRI and SRC)
- 12:15 Working lunch
  **Discussion on International Opportunities**
  with **Mark Suskin**, NSF
- 1:00 Posters: **Focus on NSF Centers**
  Introduction of the authors

Visiting the posters (includes refreshments)
Moderator: **Mark Tuominen**, University of Massachusetts Amherst

- 2:30 Panel: **NS&E Centers in Society**
  Moderator: **Tom Rieker**, NSF
  EHS aspects, **Kristen Kulinowski**, Rice University
  Interactions with Industry, **Richard Siegel**, RPI
  Education and Outreach, **Bob Chang**, Northwestern University
  Nanomanufacturing Role, **Mark Tuominen**, University of Massachusetts Amherst

- 3:30 **Keynote: "Physico-chemical Properties and Toxicology of Nanoparticles"** - abstract
  **Günter Oberdörster**, University of Rochester

- 4:30 Panel: **Center Management and Stewardship**
  Moderator: **Bruce Kramer**, NSF
  Illustrations from:
  NSEC, **Dawn Bonnell**, University of Pennsylvania
  MRSEC, **Ellen Williams**, University of Maryland
  NNIN, **Sandip Tiwari**, Cornell University
  NCN, **Mark Lundstrom**, Purdue University

- 5:30 Adjourn

- 6:30 Dinner

**Day 2: Thursday, December 4, 2008**

Focus on Nanoscale Interdisciplinary Research Team Projects
(Required for FY 2007 NIRT awardees)
Room 375, Stafford I, NSF

- 7:15 Coffee and continental breakfast

- 8:30 Day 2 Agenda Overview
  **Rod Beresford** and **Bob Hurt**, Brown University

- 8:45 **Keynote: "Nano-Bio Interface and Potential Science and Engineering Advances"**
  **James Heath**, California Institute of Technology

- 9:45 Posters: **Focus on NIRT (1)**
  Introduction of the authors
  Visiting the posters (includes refreshments)
  Moderator: **Bob Hurt**, Brown University

- 11:30 **Nanotechnology in the SBIR/STTR programs**
  **James Rudd**, NSF

- 12:00 Working Lunch
  **Discussion on Nanotechnology and Media**
  with **Josh Chamot**, NSF

- 1:00 **Nanoscience activities at other agencies**
  Nanotechnology Research at DoD - **Jonathan Porter**, DoD
  Nanotechnology Research at EPA - **Jeff Morris**, EPA
  Research Needs at FDA - **Norris Alderson**, FDA

- 2:00 **Keynote: "Nanoscale Spectroscopy with Optical Antennas"**
  **Lukas Novotny**, University of Rochester

- 3:00 Posters: **Focus on NIRT (2)**
  Continue introduction of the authors
  Visiting the posters (includes refreshments)
  Moderator: **Ken Chong**, NSF

- 4:30 **Keynote: "Periodic Patterns and Categories of Nanoscale Building Blocks"**
  **Donald Tomalia**, Central Michigan University

- 5:30-6:15 Movie: **"Molecules to the MAX"**
  presented by NSEC, RPI (**Richard Siegel**)

- 6:45 Dinner (suggested area restaurants)

**Day 3: Friday, December 5, 2008**

Focus on integration of research and education
Room 375, Stafford I, NSF

- 7:15 Coffee and continental breakfast

- 8:30 **Day 3 Agenda Overview**
  **Bob Chang**, Northwestern University and **Larry Bell**, Museum of Science
  Including poster introduction on education and outreach

- 8:45 Panel: **Global NSEE**
  Moderator: **Bob Chang**, Northwestern University

- 9:15 Panel: **Best Practices of NSEC and MRSEC for advancing NSE education**
  Moderator: **John Bradley**, NSF
  Participants: Education Coordinators of NSECs, MRSECs, and NNIN
  **Lynn Rathbun**, Cornell University, NNIN
  **Dan Steinberg**, Princeton University, MRSEC
  **George Adams**, Purdue University, NCN
  **Robert Westervelt**, Harvard University, NSEC

- 10:00 Refreshment break
- 10:15 **Keynote: "Massless and Massive Electrons in Atomically-Thin Carbon"**
  **Michael Fuhrer**, University of Maryland
- 11:15 Panel: **Informal Science Education**
  Moderators: **Larry Bell**, Museum of Science and **David Ucko**, NSF
  **Carol Lynn Alpert**, Museum of Science - poster
  **Akhlesh Lakhtakia**, Pennsylvania State University
  **Wendy Crone**, University of Wisconsin
  **Carl Batt**, Cornell University
- 12:15 Working Lunch
  **Overview of the NSF Grantees Meeting on Social Dimensions**
  **Steve Zehr** and **Rita Teutonico**, NSF
- 1:15 **Keynote: "Applying Physics Nano-technology to Biology"**
  **Harald Hess**, Howard Hughes Medical Institute
- 2:15 **Centers on Environmental Implications of Nanotechnology**
  Moderators: **Alan Tessier**, NSF and **Nora Savage**, EPA
  **Andre Nel**, University of California Los Angeles
  **Mark Wiesner**, Duke University
- 3:00 **NSE in IGERT, REU Programs, and Centers for Learning**
  Moderator: **Mike Roco**, NSF
  IGERT, **Carol Van Hartesveldt**, NSF
  Science of Learning Centers, **Soo-Siang Lim**, NSF
- 4:00 Closing remarks

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