State of Nanomanufacturing & Overview of Day 3 Goals

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www.nano.neu.edu
Focus on Current and Future Trends in Nanomanufacturing

Goals of Day 3 Program

- The goal of the conference is to discuss research trends, needs and barriers in nanomanufacturing and articulate the community’s vision for the future.

- Talks will provide background and set the stage for the discussion, talks will about 12 minutes to leave sufficient time for discussion.

- Each panelist should address and state technical fundamental barriers as they see it based on their research as well as research conducted by others. These barriers will be collected in a report to enable this conference to articulate the fundamental barriers that need to be addressed in future research projects.
Focus on Current and Future Trends in Nanomanufacturing

Summary of Day 3 Program

9:00   Panel 8: New Concepts for Nanomanufacturing
       New and Novel concepts that could be used for nanomanufacturing

10:30  Panel 9: Scalable Nanomanufacturing
       Scalability of newly developed nanomanufacturing processes

12:20  Nanomanufacturing at NSF, Khershed Cooper, NSF

12:40  Innovation I-Corps Program Rathindra "Babu" DasGupta, NSF

1:00   Panel 10: Nano-enabled Integrated Systems
       Nano-enabled products and systems and role of Nanomanufacturing

2:30   Panel 11: Advances in Modeling Nanomanufacturing Processes
       Addressing fundamental challenges in nanomanufacturing through modeling
Considerable investment and progress have been made in nanotechnology, but integration of nanoscale materials and processes into products have been considerably slow.

Commercial electronics device manufacturing is still mostly silicon-based, top-down and expensive, with factories costing billions and requiring massive quantities of water and power.

Most current nanoscale devices do not as yet incorporate actual nanomaterials (nanotubes, quantum dots, nanoparticles, etc.) and thereby miss on the much-anticipated superior performance and unique properties.
Printing offers an excellent approach to making structures and devices using nanomaterials.

Current electronics and 3D printing using inkjet technology, used for printing low-end electronics, flexible displays, cell phone RFIDs, are very slow (not scalable) and provide only micro-scale resolution.

Screen printing is also used for electronics but only prints 100 microns or larger patterns.

Even with these limitations, the cost of a printed sensor is 1/10th to 1/100th the cost of current silicon-based sensors.
Printed Electronics and Sensor

Flexible Electronics
Qing Cao et al., Nature, 2008

Flexible Display
http://www.adzuna.co.uk/blog/2011/11/14/where-the-future-jobs-lie/460-cpi-printed-electronics/

Electronic Books

Flexible biosensor using nanoparticle
Richard S. Gaster et al., Nature Nanotech., 2011
The end point for most applications is for the creation of disposable devices on low cost flexible substrates.

The most difficult combination to achieve retaining yield, lifetime and manufacturing ease, but opening up the largest markets.
For printed electronics and devices to compete with current silicon based nanoscale electronics, it has to print nanoscale features at:

- orders of magnitudes faster than inkjet based printers and
- at a small fraction of today’s cost of manufacturing Si electronic.

This will make nanomanufacturing accessible:

- to millions of new innovators and entrepreneurs and
- could produce a wave of creativity in the same way as the advent of the personal computer did for computing.
Bottom-up/top down Nanomanufacturing Utilizing Directed Assembly

- **Top-down Fabrication techniques**
  - Requires major facilities
  - Control below 30 nm is a challenge
  - Can not obtain high aspect ratio
  - Expensive process and facilities
  - Scalability to true nanoscale is still a question

- **Bottom-up Synthesis**
  - No standard 3D morphological control
  - Handling and alignment are difficult

Directed Assembly based nanomanufacturing involves adding materials selectively.
Directed Assembly

- Nanoparticles
- Nanotubes
- Nanowires
- Nanoflakes

- Electrostatic Forces
- van der Waals Forces
- Capillary Forces
- Electric Field
- Magnetic field

Directed Assembly

NANOELEMENTS

- Nanoparticles
- Nanotubes
- Nanowires
- Nanoflakes

- Electrostatic Forces
- van der Waals Forces
- Capillary Forces
- Electric Field
- Magnetic field

TEMPLATES

- Conductive-Insulating
- Flexible-Hard
- Patterned-Flat
Electric Field Directed Assembly

**Electrophoretic Directed Assembly**

- Simple, fast
- Large scale

**Dielectrophoretic Directed Assembly**

- Electrodes needed for assembly
- Assembly may result on a conductive surface

WM Choi et al. Nanotechnology, 2006, 17, 325–329
Advantageous

- Gives precise and good assembly
- Assembly on conductive or insulating substrates

Disadvantageous

- Slow and not suitable for high rate manufacturing
Fabrication rate for different assembly techniques

<table>
<thead>
<tr>
<th>Assembly Method</th>
<th>Fabrication rate (cm$^2$/h)</th>
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<tbody>
<tr>
<td>Template Guided Fluidic Assembly</td>
<td>10</td>
</tr>
<tr>
<td>Surface Functionalization</td>
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</tr>
<tr>
<td>Convective Assembly</td>
<td>10</td>
</tr>
<tr>
<td>Layer by Layer</td>
<td>1</td>
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<tr>
<td>Electrophoretic Deposition</td>
<td>100</td>
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</tbody>
</table>
## A comparison between Different Approaches

<table>
<thead>
<tr>
<th>Assembly technique</th>
<th>Speed</th>
<th>Material of surface</th>
<th>External force</th>
<th>Scalability</th>
<th>Resolution</th>
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<tbody>
<tr>
<td>Fluidic</td>
<td>Very slow</td>
<td>C/NC</td>
<td>No</td>
<td>No</td>
<td>nm</td>
</tr>
<tr>
<td>Evaporation/convective</td>
<td>Very slow</td>
<td>C/NC</td>
<td>No</td>
<td>No</td>
<td>nm</td>
</tr>
<tr>
<td>Gravure</td>
<td>Fast</td>
<td>C/NC</td>
<td>Yes</td>
<td>Yes</td>
<td>&gt;10 μm</td>
</tr>
<tr>
<td>LBL</td>
<td>Medium</td>
<td>C/NC</td>
<td>No</td>
<td>No</td>
<td>μm</td>
</tr>
<tr>
<td>Dielectrophoresis</td>
<td>Fast</td>
<td>C</td>
<td>Yes</td>
<td>No</td>
<td>nm</td>
</tr>
<tr>
<td>Electrophoresis</td>
<td>Fast</td>
<td>C</td>
<td>Yes</td>
<td>Yes</td>
<td>nm</td>
</tr>
</tbody>
</table>
How could we print at the nanoscale?

Johannes Gutenberg, 1395-1468

wooden printing press in 1568, 240 prints per hour

Stanhope press from 1842

Modern Offset Printing
Leveraging the directed assembly and transfer processes developed at the CHN, Nanoscale Offset Printing has been developed. The system is similar to conventional offset printing.

- The ink is made of nanoparticles, nanotubes, polymers or other nanoelements that are attracted to the printing template using directed assembly.

- This approach will be accomplished by integrating multiple directed assembly processes, printing and semiconductor manufacturing.

This novel approach offers 1000 times faster printing with a 1000 times higher resolution.
How Does it Work?
Beyond 3-D & Electronic Printing: Nanoscale Offset Printing Advantages

- Additive and parallel
- Scalable high throughput (much faster than 3-D printing)
- Printing down to 20nm
- Room temperature and pressure
- Prints on flexible or hard substrates
- Multi-scale; can print nano, micro and macro structures on the same layer
- Little use of chemicals (uses mostly water)
- Material independent
- Very low energy consumption
- Very low capital investment (equipment)
What Could We manufacture with Multiscale Offset Printing?

- Assembly of CNTs and NPs for Batteries
- Directed Assembly and Transfer
- CNTs for Energy Harvesting
- Flexible Electronics
- SWNT & NP Interconnects
- SWNT NEMS & MoS2 devices
- Multi-biomarker Biosensors
- Multi-scale Offset Printing
- Antennas, EMI Shielding, Radar, Metamaterials
- Drug Delivery
- Materials
- Energy
- Electronics
- Bio/Med

Nanoscale Science
Nanomaterials-based Manufacturing

Nanoscale Offset Printing
Printing of Nanoparticles

2D Assembly

(a)

(b)

(c)

(e)

copper

fluorescent PSL

fluorescent silica

fluorescent PSL

fluorescent silica

3D Assembly

fluorescent PSL

fluorescent silica

gold

50 nm

50 nm

100nm

100nm

Printing of Carbon Nanotubes

2D Assembly

3D Assembly
Printing of Heterogeneous Polymers

Multiple polymer systems, Rapid Assembly, multi-scales

3D Assembly

Square arrays

Circle arrays

90° bends

T-junctions

PMMA (Light)

PS (Dark)

2D Assembly

Center for High-rate Nanomanufacturing
Micro/nanowire Template

- Potential drop along the nanowire.
- Non-uniform assembly results.
- Peeling off from the substrate due to the poor adhesion.

Most of nanoparticles were assembled on the micro pad

Non uniform electric field across the wire
Damascene Template

- All features are connected to the conductive film underneath the insulating layer.
- Uniform electric field on all nano/micro features.
- Strong adhesion force between the conductive patterns and substrate.
- No indentation mark on the flexible substrate after transfer process.
- The template can be reused in the cycle without any additional process.
IBM invented copper damascene process for interconnect in 1998.

Semiconductor industries use damascene structure for copper interconnect on all electronics we use today.

- Originates from Damascus, from the 3rd to 17th century.
- For multilayer of two different steel and decoration of sword surface using gold.

What is Damascene?
Offset Printing Procedure

The template can be reused more than 100 times without any additional process.

Assembly "inking"

Pulling direction

Transfer "printing"

Biosensor

Chemical Sensor

Electric devices
Damascene Templates for Nanoscale Offset Printing

PEN

PI

Silicon-based Hard Templates
Electrical Properties of Printed Aligned SWCNT Networks

Two-terminal I-V Properties

- Alignment gives the network semiconducting behavior

Electronics
- Flexible transparent n-type MoS$_2$ transistors

- Heterogeneous SWNTs and MoS$_2$ complimentary invertors through assembly

- Rose Bengal Molecular Doping of CNT$_x$ Transistors
  - RB-Na doping shifts the threshold voltage of CNTFETs up to ~6V, lower the sub-threshold swing for 4 times, and increase the effective field-effect mobility
Sensors
In vivo Nano Biosensor

- Multiple-biomarker detection
- High sensitivity
- Low cost
- Low sample volume
- In-vitro and In-vivo testing

Image of the in-vivo biosensor (0.1 mm x 0.1 mm) after animal testing

Incubated with human plasma spiked with CEA
Detection limit: 15 pg/ml
Current technology detection limit is 3000 pg/ml

Langmuir, 27, 2011
Lab on a Chip Journal, 2012
Flexible CNT Bio sensors for Glucose, Urea and Lactate

Functionalized SWNTs

Gold

PEN

250 μm

4 μm

200 nm

1 μm

D-glucose (mM)

Current (mA)

0.000

0.005

0.010

0.015

0.020

0.0

0.1

0.2

0.3

0.4

0.5 mM

0 60 120 180 240 300 360

Time (s)
Chemical Sensors

Functionalized SWNT Chemical sensor

- Developed, fabricated and tested a micro-scale robust semiconducting SWNT based sensor for the detection of H₂S, simple alkanes, thiole, etc.
- Working in harsh environment (200°C; 2500Psi).
- Specific in various environments (N₂, Air, Water vapor, Water, alkanes, etc.)
- Resistance based operation
- Simple inexpensive 2-terminal device High sensitivity ~ppm.
Energy Harvesting
Energy Harvesting

SWNT based infrared energy harvesting device

- Developed rectifying SWNT antennas having the potential for absorption of far and mid-Infrared incident light.
- Developed both Zig-Zag and linear designs.
- Rectifying circuit consists of commercially available MIM diodes operating in the W band.
- Harvesting energy wherever there is temperature difference of ~5 degrees

CNT Infrared Energy Harvester
Multifunctional Structures
Lightweight Structural Materials for Shielding and Composite Multifunctional Structures

**SEM Images of Cross-bar Structure**

- **(a)** SWNTs Cross-bar Structure
- **(b)** Assembled SWNTs
  - SiO$_2$
  - High magnification of SWNTs
- **(c)** Patterned and aligned carbon nanotubes
- **(d)** SiO$_2$
Where do we go from here?
Enabling from Nano to Macro; from Electronics to Medicine; from Energy to Materials

- This technology is a great enabler and equalizer
- A nanofactory could be built for under $50 million, a small fraction of today’s cost
- Nanotechnology accessible to millions of innovators and entrepreneurs
- Unleash a wave of creativity in the same way as the advent of PC technology did for the computing industry.
What’s Next?

• How to commercialize nanomanufacturing?
• What are the application requirements? (application driven process and scalability)
• How to do we get industry interested and engaged in making products using the developed processes.
Questions and Discussion?