The Semiconductor Industry’s Nanoelectronics Research Initiative

Jeff Welser, Director SRC NRI
December, 2007
NRI Milestones

- **2001-2004: Defining Research Needs**
  - ITRS-Emerging Research Device Technical Working Group
  - NSF-SRC Industry-Academia-Government Silicon Nanoelectronics and Beyond (SNB) Workshops
  - SIA Technology Strategy Committee workshops
  - *Defined 13 Research Vectors of primary importance for finding the next switch*

- **March 2004:**
  - SIA White Paper on Post-CMOS presented to SIA Board
  - SIA Board Resolution for formation of **NRI**

- **March 2005:**
  - Six Companies sign NRI Participation Agreement
    - **AMD, Freescale, IBM, Intel, Micron, TI**
  - **NERC** incorporated to manage NRI
  - Governing Council (GC) and Technical Programs Group (TPG) formed with one representative per participating company

- **September 2005:** First NRI and NSF Solicitations released
- **January 2006:** Research Programs started

- **September 2007:** NIST joins NRI
SRC Global Research Collaboration

GRC – Global Research Collaboration
FCRP – Focus Center Research Program
NRI – Nanoelectronics Research Initiative
TRC – Topical Research Collaboration
• 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 is focused primarily on research on devices utilizing new computational state variables beyond electronic charge. In addition, NRI is interested in new interconnect technologies and novel circuits and architectures, including non-equilibrium systems, for exploiting these devices, as well as improved nanoscale thermal management and novel materials and fabrication methods for these structures and circuits.

• 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.
Five Research Vectors

- **Computational State Vector other than Electronic Charge**
  - (e.g. “bits” represented by spins)
    - New scaling path

- **Non-equilibrium Systems**
  - Lower power, less heat

- **Novel Data Transfer Mechanisms**
  - Overcome RC limits

- **Nanoscale Thermal Management**
  - Cooler operation, manage power density

- **Directed Self-assembly of such structures**
  - Less variability, higher density, more reliable, lower cost

➤ *Strong Focus in NRI on the first Research Vector*
Leveraging industry, university, and both state & fed government funds, and driving university nanoelectronics infrastructure

<table>
<thead>
<tr>
<th>WIN</th>
<th>INDEX</th>
<th>SWAN</th>
<th>NSF NSEC / MRSEC / NCN Supplemental Funding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western Institute of Nanoelectronics</td>
<td>Institute for Nanoelectronics Discovery &amp; Exploration</td>
<td>SouthWest Academy for Nanoelectronics</td>
<td>Funding 12 projects at 10 NSF centers</td>
</tr>
<tr>
<td><strong>UCLA, UCSB, Berkeley, Stanford</strong></td>
<td>SUNY-Albany, GIT, Harvard, MIT, Purdue, RPI, Yale</td>
<td><strong>UT-Austin, UT-Dallas, TX A&amp;M, Rice, ASU, Notre Dame, U of MD</strong></td>
<td></td>
</tr>
<tr>
<td>Theme 1: Spin devices</td>
<td>Task I: Novel state-variable devices</td>
<td>Task 1: Logic devices with new state-variables</td>
<td>Broad work on various topics – also leverages other work in the centers</td>
</tr>
<tr>
<td>Theme 2: Spin circuits</td>
<td>Task II: Fab &amp; Self-assembly</td>
<td>Task 2: Materials &amp; structs</td>
<td></td>
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<tr>
<td>Theme 3: Benchmarks &amp; metrics</td>
<td>Task III: Modeling &amp; Arch</td>
<td>Task 3: Self-assembly &amp; thermal mgmt</td>
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<tr>
<td></td>
<td>Task IV: Theory &amp; Sim</td>
<td>Task 4: Interconnect &amp; Arch</td>
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<tr>
<td></td>
<td>Task V: Roadmap</td>
<td>Task 5: Nanoscale characterization</td>
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</tbody>
</table>
SRC NRI Management Structure

SRC NRI Governing Council

SRC NRI Director: Jeff Welser
SRC NRI TPG (Industry Reps)

Center Executive Committee:
- Lead University Professors
- SRC NRI Director
- Industry / TPG representatives

Industry Assignees

Theme N: PI Leader

NIST Interaction

Project 1

Project 2

Theme 1

Theme 2

Theme N

SRC NRI Project(s)

Industry Liaison Team

NRI Project(s)

NSEC

MRSEC

NSF Centers:
- NSECs / MRSECs / NCN /...

SRC NRI Project(s)

Industry Liaison Team

NRI Project(s)

NIST Participants

NRI Centers: WIN / INDEX / SWAN /...
Key challenge for NRI: Creating a directed, basic science research program

Research results presented at first on-site annual reviews indicate strong progress already in three key areas to achieve this:

- Studying new science phenomena with device potential
  - Several promising new effects shown (e.g. Pseudospintronics, BAMR)
- Linking the scientists to the engineers, to insure research focus is on the key device issues
  - Even for new phenomena, presentations included topics like potential logic gate structure, prospects for room temperature operation, power dissipation, connecting devices, etc.
- Linking work across groups / universities / centers to maximize progress
  - Modeling of the Spin Hall effect at Purdue to understand the experimental results from UCB

Points to initial success in focusing the science towards switch technology

- Getting the right information early, to direct research along most promising paths
WIN Technical Roadmap

**THEME/Category** | **Focus** | **Task/Project**
--- | --- | ---
Spin Devices | Spin Wave Devices | - Gated Spin Wave Devices
- Spin wave devices
- Multiferroic based Spin logic
- Theoretical studies of SW switching and propagation

Magnetic Quantum Dot Logic | - Controlling Magnetic Coupling and Switching in Chains of Magnetic Nanoparticles.
- Interaction of Magnetic QD with FET for low power logic

Spin write devices | - High-Frequency Spin-Torque Devices
- Spin FET based on DMS nanowires
- Spin Hall Effect devices

Spin read devices | - Spin devices based on nanowire CMOS structure
- Spin valves
- Iron silicide for Si-based spin electronics

Device/Device Coupling & Interconnect | Resonant Coupling | - Frequency-controlled spin coupling using superconducting resonators
- Cavity Control of Spin Interaction

Spin Wave Bus | - Spin Wave interconnects

Metrics and Benchmarks | Fundamental limits of Spintronics | - Benchmarking and Criteria for Magnetic Logic Devices
- Metrics for New Switch concepts Evaluation

Spintronics Performance Metrics | - Circuit Design and Performance Metrics for Spintronics
In Resonance
\[ \Delta E_R = h \omega \]

Out of Resonance
\[ \Delta E_R = h \omega \]

OFF State
\[ V_{g_{off}} \]

ON State
\[ V_{g_{on}} \]

Single Electron Spin Devices
Raynolds et al (UAlbany)

Ballistic Spin Devices
Labela et al (UAlbany)

Quantum Dot Devices
Oktyabrsky et al (UAlbany)

Quantum Dot Modeling
Shur et al (RPI)

Molecular Excitons Spintronics
Baldo et al (MIT)

Magnetoelectronic Devices
Ross et al (MIT)

Logical Switches based on Complex Oxides
Ahn et al (Yale)

Reconfigurable One-Dimensional (1D) Switch (R1DS)
Ji Ung Lee (UAlbany)

Graphene Nanowire Switches
Murali and DeHeer (GT)

Molecular Nanowire Switches
Kaloyeros et al (UAlbany)

Graphene based Quantum Devices
Charles Marcus (Harvard)

Magnetoelectronic Devices
Multi bits logic

Post CMOS Switches

Graphene Nanowire Switches

Logical Switches based on Complex Oxides
Novel Transistor Research

**MOTIVATION:** Finding New Logic Switch

- Spin Hall Effect
- Pseudospintronics
- Dilute Magnetic Semiconductors
- Quantum Point Contacts
- Quantum Wires
- Quantum Wire Transistors
- Magnetic Nanoparticles
- Thin Film / FIB Characterization
- Nanophotonic Waveguides
- Nanomagnets

**GOAL:** Fundamentally New Device Concepts, Implementations, and Tools

- Non-Dissipative Response
- Dramatic Change in Current Voltage Relationship
- Spin-Momentum Transfer
- Exchange Interactions for Logic
- Spin Manipulation for Computation and Logic
- New Characterization Techniques for Devices
- Device-Device Interaction for Quantum Logic Gates
- Reduced Interactions for Near Ballistic Response
- Interaction Induced Switching
- Tunneling Enhanced Switching

**Tasks:**

1. Novel Devices
2. Novel Materials
3. Novel Transfer
4. Novel Interconnect
5. Novel Metrology
Task 1: Logic Devices based on alternate computational state variables

Task 2,3: Novel materials and structures

Task 4: Novel interconnect and architectures

Task 5: Nanoscale Characterization

DMS MQCA Phasetronics

Pseudospintronics on Graphene

NanoPlasmonics

Nano Manipulator/Probe system
# NSF NSEC/ MRSEC Nanoelectronics Areas*

<table>
<thead>
<tr>
<th>Institution</th>
<th>Alternative State variables</th>
<th>Non equilibrium devices</th>
<th>Novel information transfer</th>
<th>Phonon engineering</th>
<th>Self assembly</th>
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<tbody>
<tr>
<td>Electronic Transport in Molecular Nanostructures, NSEC</td>
<td>Columbia University</td>
<td>1</td>
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<td>Nanoscale Systems and their Device Applications, NSEC</td>
<td>Harvard University</td>
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<td>Integrated Nanopatterning and Detection, NSEC</td>
<td>Northwestern University</td>
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<td>Center for High Rate Nanomanufacturing</td>
<td>Northeastern University</td>
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<td>Stanford Center for Probing the Nanoscale</td>
<td>Stanford</td>
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<tr>
<td>Center for Nanoscale Electrical-Mechanical Manuifacturing Systems</td>
<td>UIUC</td>
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<td>Nanoscience in Biological and Environmental Engineering (CBEN)</td>
<td>Rice University</td>
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### NSEC Centers

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<thead>
<tr>
<th>Institution</th>
<th>Alternative State variables</th>
<th>Non equilibrium devices</th>
<th>Novel information transfer</th>
<th>Phonon engineering</th>
<th>Self assembly</th>
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<tr>
<td>Biomaterial microstructures</td>
<td>UCSB</td>
<td>2</td>
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<td>Grain boundaries, metals / ceramics; simulations</td>
<td>CMU</td>
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<td>Princeton Center for Complex Materials</td>
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<tr>
<td>Center for Nanostructured Materials</td>
<td>Cornell</td>
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<td>Nanomagnetisms -fundamental interactions and applications</td>
<td>U of Nebraska</td>
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<tr>
<td>Nanoscopic design, quantum dots, surfaces</td>
<td>U of Virginia</td>
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<td>Transport in nanostructured magnetic materials</td>
<td>U of Alabama</td>
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<tr>
<td>Molecular motors</td>
<td>Penn State University</td>
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<td>2</td>
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<tr>
<td>The Center for the Science and Engineering of Materials (CSEM), Laboratory for Research on the Structure of Matter</td>
<td>California Institute of Technology</td>
<td>2</td>
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<tr>
<td>The Center for Materials Science and Engineering (CMSE)</td>
<td>U of Pennsylvania</td>
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<tr>
<td>Directed Assembly of Nanostructures, NSEC</td>
<td>MIT</td>
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<td>Structural integrated films containing nanoparticles</td>
<td>Rensselaer Polytech Inst</td>
<td>2</td>
<td>1</td>
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<tr>
<td>Structural integrated films containing nanoparticles</td>
<td>Columbia University</td>
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### MRSEC Centers

*NSF-funded centers, capabilities self-assessed by Center directors*
Joint program established with NSF to fund NRI-related research at NSF centers

<table>
<thead>
<tr>
<th>PI</th>
<th>Institution</th>
<th>Center</th>
<th>Center Name</th>
<th>Title of Supplement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lundstrom, Mark</td>
<td>Purdue U</td>
<td>NCN</td>
<td>Network for Computational Nanotechnology</td>
<td>Exploratory Theory, Modeling, and Simulation for the NRI</td>
</tr>
<tr>
<td>Yardley, James T.</td>
<td>Columbia U</td>
<td>NSEC</td>
<td>Columbia Center for Electronic Transport in Molecular nanostructures</td>
<td>Non-equilibrium Quantum Coherent Devices in 1-D materials</td>
</tr>
<tr>
<td>Westervelt, Robert</td>
<td>Harvard U</td>
<td>NSEC</td>
<td>Science of Nanoscale Systems and their Device Applications</td>
<td>Ultrasmall Nanowire and Oxide Switches</td>
</tr>
<tr>
<td>Hawker, Craig</td>
<td>UCSB (Stanford, U Mass)</td>
<td>MRSEC</td>
<td>MRSEC at UCSB</td>
<td>Development of Next Generation Devices using Nanolithographic Techniques</td>
</tr>
<tr>
<td>Hull, Robert</td>
<td>U Virginia (Notre Dame)</td>
<td>MRSEC</td>
<td>Center for Nanoscopic Materials</td>
<td>Directed Assembly of Epitaxial Semiconductor Nanostructures for Novel Logic Switches</td>
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<tr>
<td>Johnson, Matt</td>
<td>U. Arkansas/ U Oklahoma</td>
<td>MRSEC</td>
<td>Center for Semiconductor Physics in Nanostructures</td>
<td>Nanoferroelectric Random Access Memory</td>
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</table>
### New NSF-NRI Projects: 2007-2009

- NSF and NRI selected six new projects at NSF centers for 2007-2009

<table>
<thead>
<tr>
<th>PI</th>
<th>Institution</th>
<th>NSF Center Type</th>
<th>Center Name</th>
<th>Title of Supplement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tsymbal, Evgeny / Sellmyer, David; Belashchenko, Kirill; Sabirianov, Renat</td>
<td>U.Neb-Lincoln (U.Neb-Omaha)</td>
<td>MRSEC</td>
<td>Q-SPINS: Quantum and Spin Phenomena in Nanomagnetic Structures (<a href="http://www.mrsec.unl.edu">www.mrsec.unl.edu</a>)</td>
<td>&quot;Multiferroic interfaces: new paradigms for functional switching&quot;</td>
</tr>
<tr>
<td>Hull, Robert / Wolf, Stuart; Floro, Jerrold; Awschalom, David; Snider, Greg</td>
<td>U. Virginia (UCSB / Notre Dame)</td>
<td>MRSEC</td>
<td>Center for Nanoscopic Materials Design (<a href="http://www.mrsec.virginia.edu">www.mrsec.virginia.edu</a>)</td>
<td>&quot;Coherent Spin Dynamics in Single Ion doped Semiconductors: Towards a Coherent or Quantum Spin Switch&quot;</td>
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<tr>
<td>Lundstrom, Mark / Alam, Muhamad; Datta, Supriyo; Klimeck, Gerhard; Roy, Kaushik</td>
<td>Purdue</td>
<td>NCN</td>
<td>The Network for Computational Nanotechnology (<a href="http://www.ncn.purdue.edu">www.ncn.purdue.edu</a>)</td>
<td>&quot;Exploratory Theory, Modeling, and Simulation for the Nanoelectronics Research Initiative&quot;</td>
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<tr>
<td>Ahn, Charles (Tully, John)</td>
<td>Yale</td>
<td>MRSEC</td>
<td>Center for Research on Interface Structures and Phenomena (<a href="http://www.crisp.yale.edu">www.crisp.yale.edu</a>)</td>
<td>&quot;Design and fabrication of magnetic-based devices with complex oxide materials&quot;</td>
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<td>MacDonald, Allan / DasSarma, Sankar (Williams, Ellen)</td>
<td>UMD (UT-Austin)</td>
<td>MRSEC</td>
<td>Materials Research Science and Engineering Center (<a href="http://mrsec.umd.edu">http://mrsec.umd.edu</a>)</td>
<td>&quot;Pseudospintronics&quot;</td>
</tr>
<tr>
<td>Kan, Edwin (Buhrman, Robert)</td>
<td>Cornell</td>
<td>NSEC</td>
<td>Center for Nanoscale Systems in Information Technologies (<a href="http://www.cns.cornell.edu/">http://www.cns.cornell.edu/</a>)</td>
<td>&quot;Controlled Orbital Hybridization in the Carbon Nanotube Quantum Modulated Transistor (CNT-QMT)&quot;</td>
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</table>
Overview of Current NRI Projects

Initial Focus: Device/Switch

Expanding Focus: Logic Gate

- Spin/Magnetoelectronic devices
- Electron charge devices
- Non-equilibrium systems
- Data transfer
- Thermal management
- Self assembly
- Patterning
- Others

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Questions? More Information?

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