Semiconductor Research Corporation

PIONEERS IN COLLABORATIVE RESEARCH®

nanoelectronics RESEARCH INITIATIVE

The Semiconductor Industry's Nanoelectronics Research Initiative

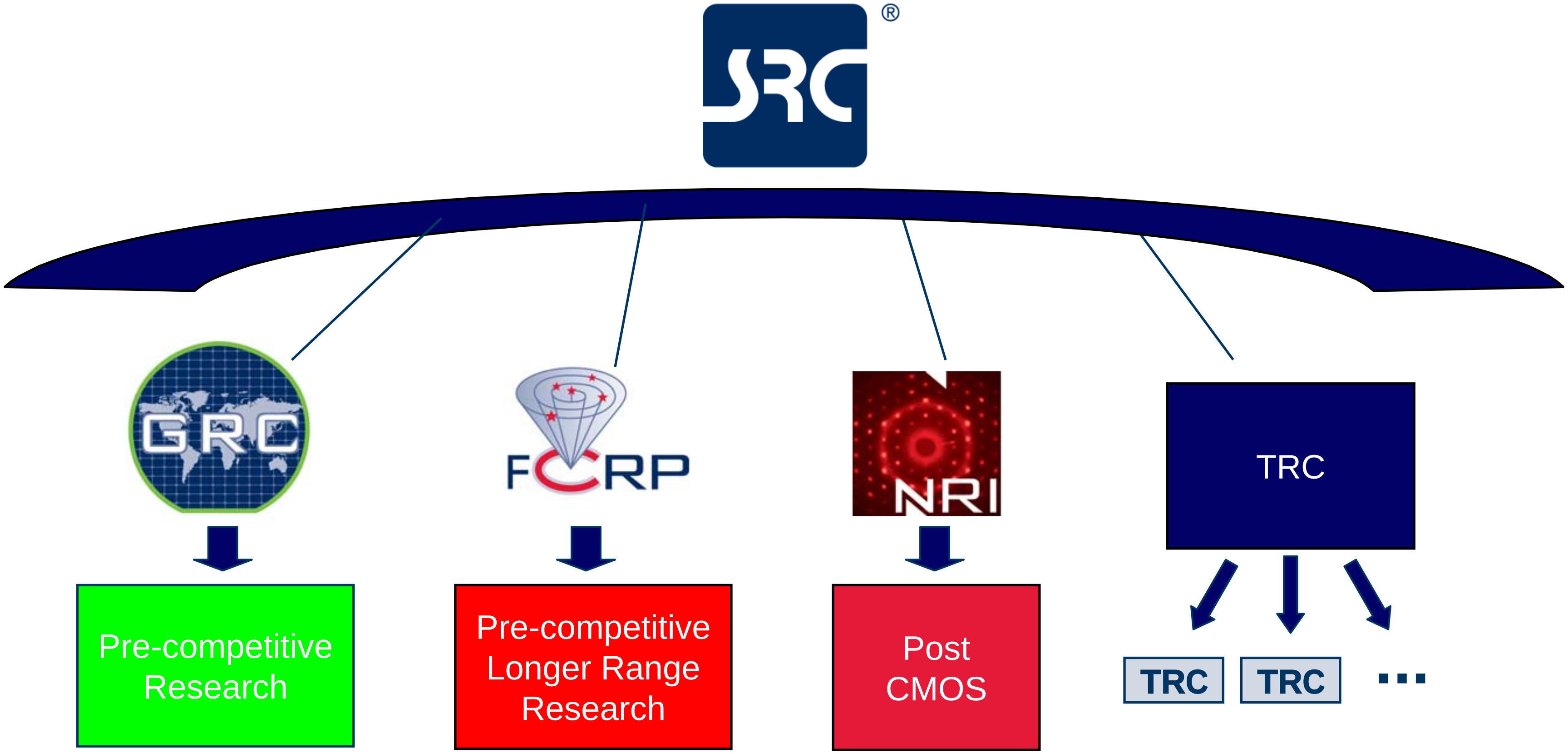
Jeff Welser, Director SRC NRI

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 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 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***

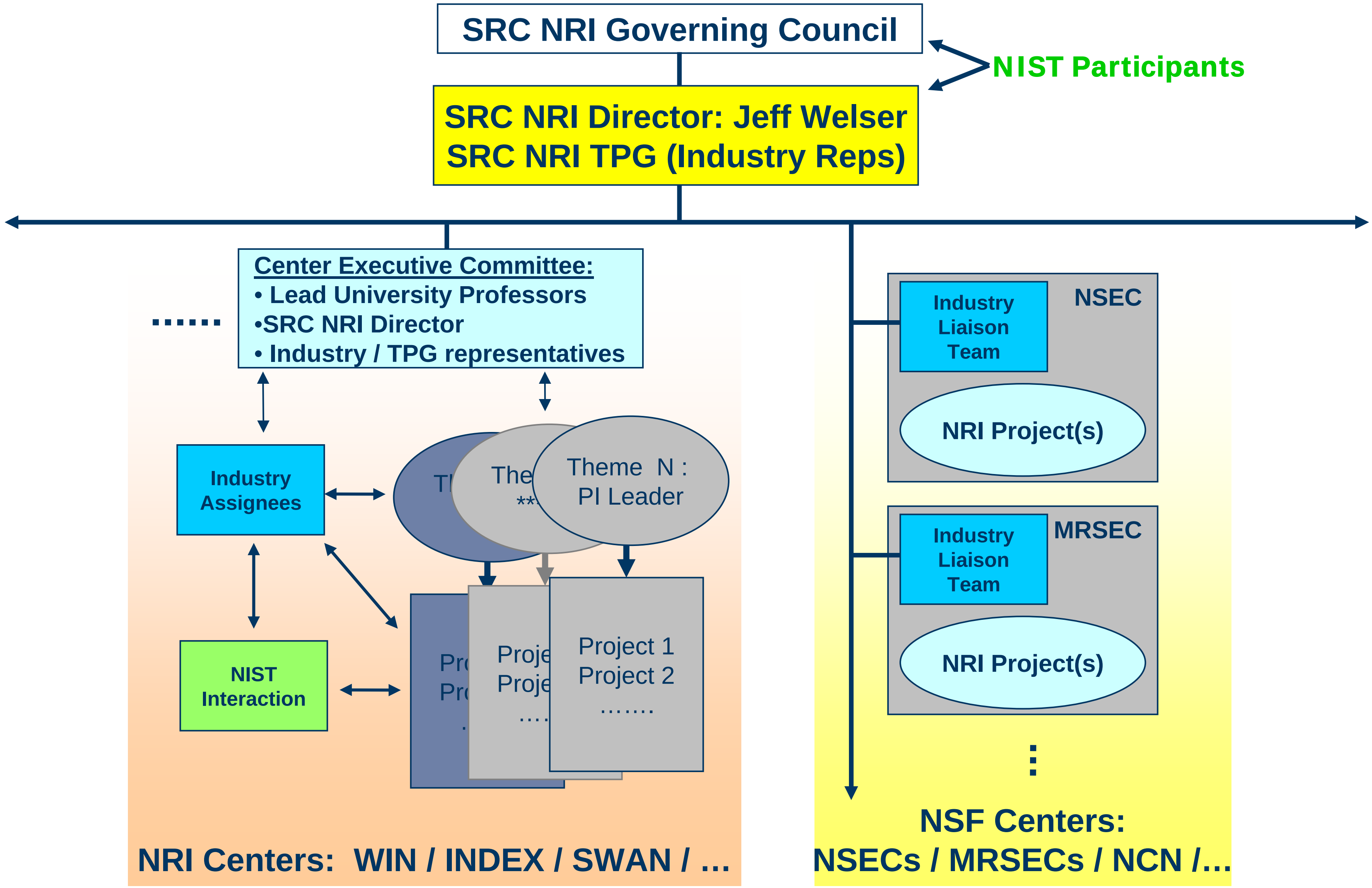
NRI Sponsored Research Programs

- 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 — NSF

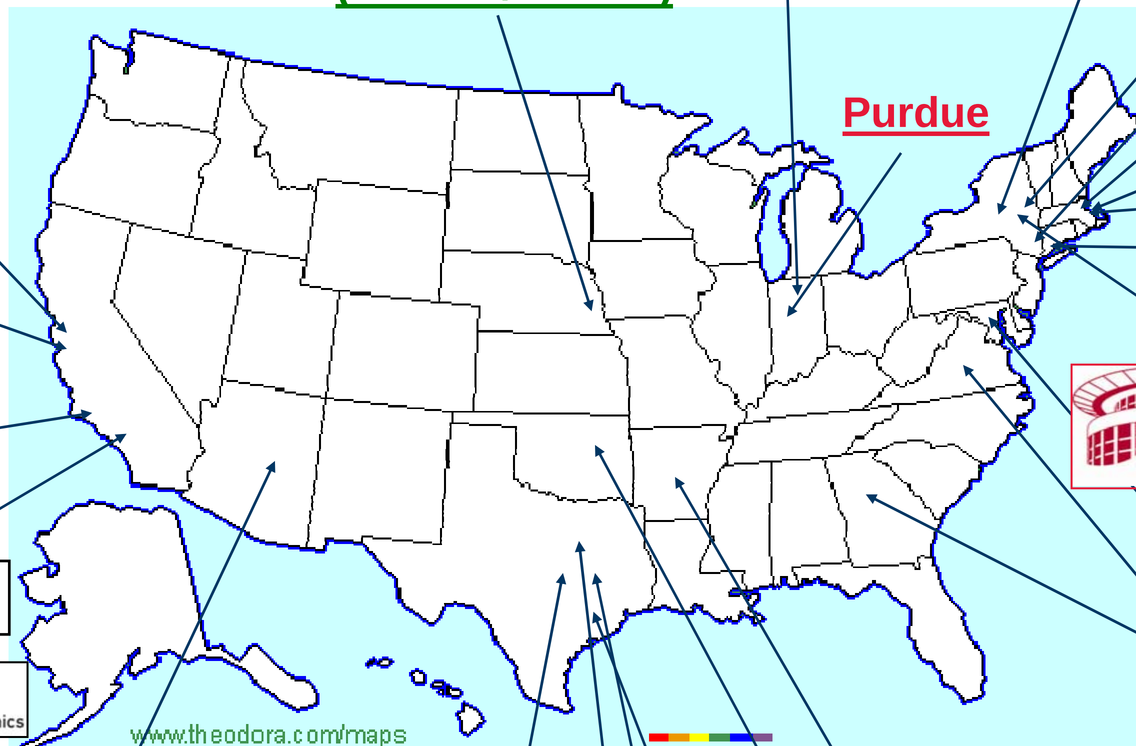
WIN Western Institute of Nanoelectronics	**INDEX** Institute for Nanoelectronics Discovery & Exploration	**SWAN** SouthWest Academy for Nanoelectronics	**NSF NSEC / MRSEC / NCN** Supplemental Funding
UCLA, UCSB, Berkeley, Stanford	**SUNY-Albany**, GIT, Harvard, MIT, Purdue, RPI, Yale	**UT-Austin**, UT-Dallas,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

SRC NRI Management Structure



NRI Funded Universities

25 Universities



UC Berkeley

Stanford

UC Santa Barbara

UC Los Angeles

WIN Western Institute of Nanoelectronics

Arizona State

UT Austin

SWAN Southwest Academy of Nanoelectronics

U Neb (Lincoln/Omaha)

Notre Dame

Cornell

RPI

Purdue

Columbia

U Mass

MIT

Harvard

Yale

SUNY Albany

INDEX Institute for Nanoelectronics Discovery and Exploration

U of MD

U of Virginia

GIT

Rice

TX A&M

UT Dallas

U of Arkansas

U of Oklahoma

INDEX

SWAN

WIN

NSF-NRI

Research Progress

- 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

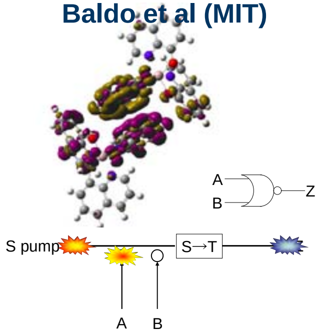
Western Institute of Nanoelectronics

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 super-conducting 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 Spintronic

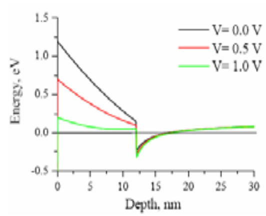
Post CMOS Switches

INSTITUTE FOR NANOELECTRONICS DISCOVERY AND EXPLORATION (INDEX)

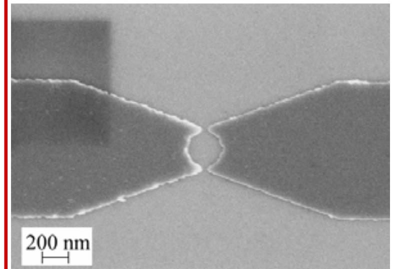
Molecular Excitons Spintronics
Baldo et al (MIT)



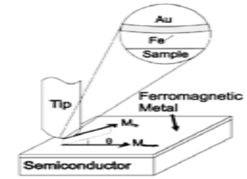
Quantum Dot Modeling
Shur et al (RPI)



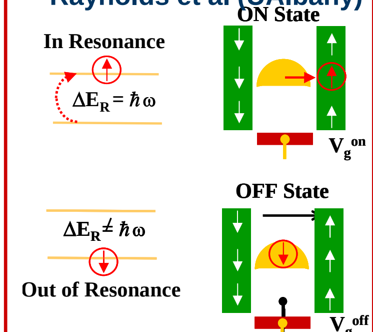
Quantum Dot Devices
Oktyabrsky et al (UAlbany)



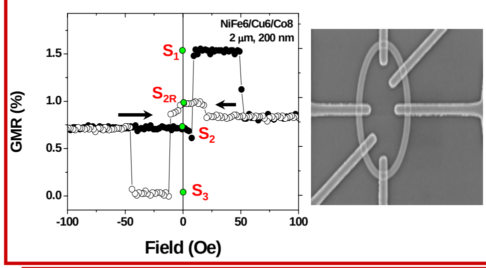
Ballistic Spin Devices
Labella et al (UAlbany)



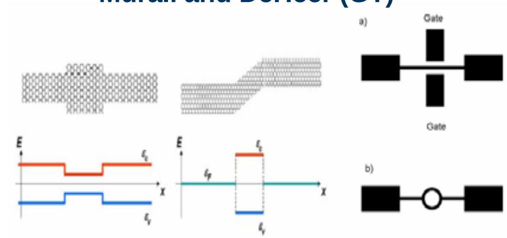
Single Electron Spin Devices
Raynolds et al (UAlbany)



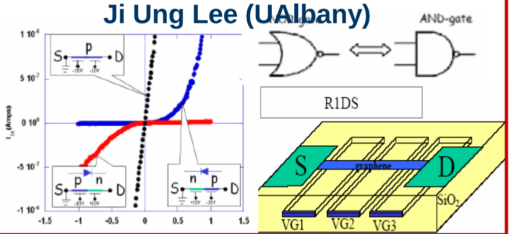
Magnetoelectronic Devices
Multi bits logic Ross et al (MIT)



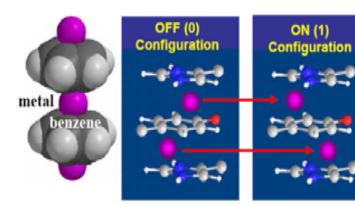
Graphene Nanowire Switches
Murali and DeHeer (GT)



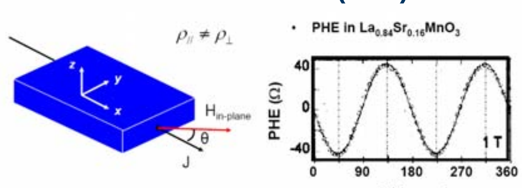
Reconfigurable One-Dimensional (1D) Switch (R1DS)
Ji Ung Lee (UAlbany)



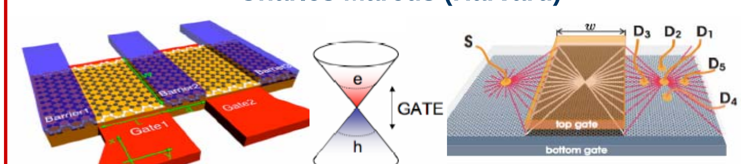
Molecular Nanowire Switches
Kaloyeros et al (UAlbany)



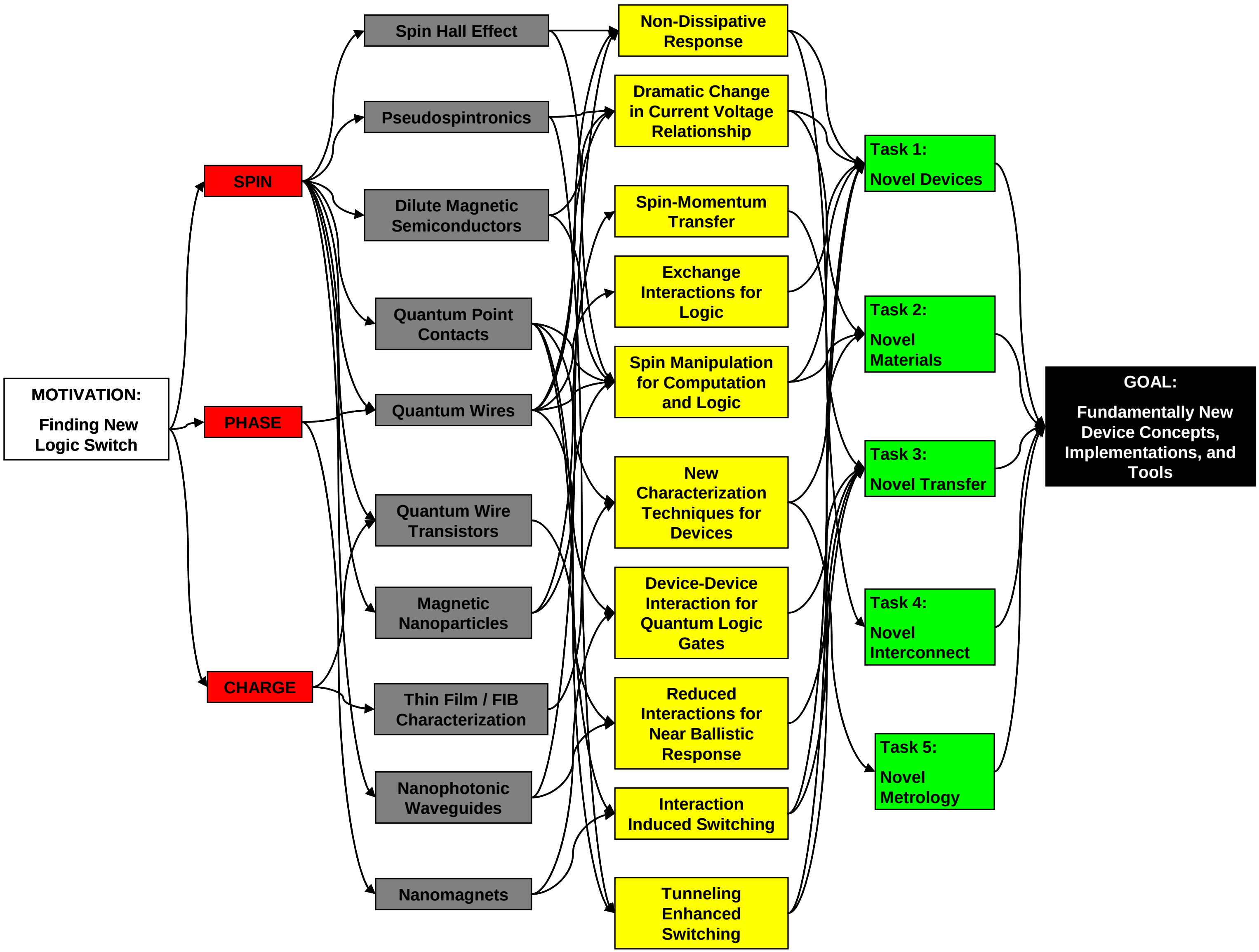
Logical Switches based on Complex Oxides
Ahn et al (Yale)



Graphene based Quantum Devices
Charles Marcus (Harvard)

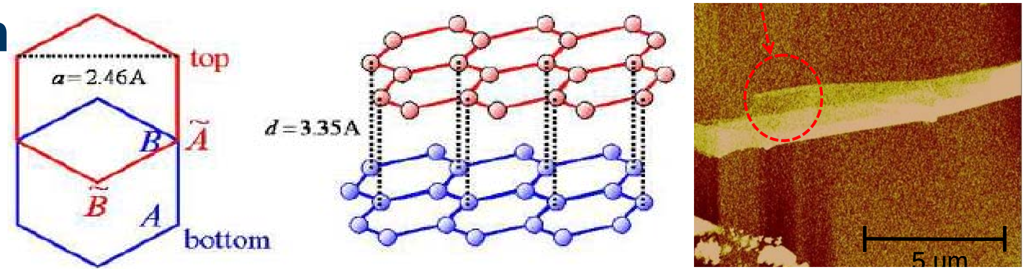


Novel Transistor Research



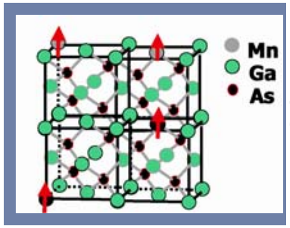
SWAN Task Highlights

Task 1: Logic Devices based on alternate computational state variables

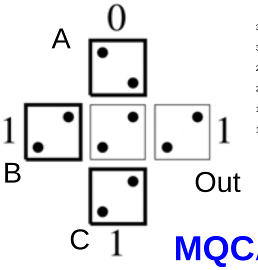


Pseudospintronics on Graphene

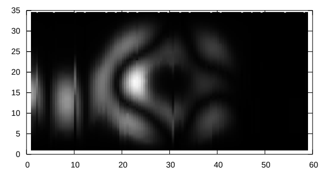
Task 2,3: Novel materials and structures

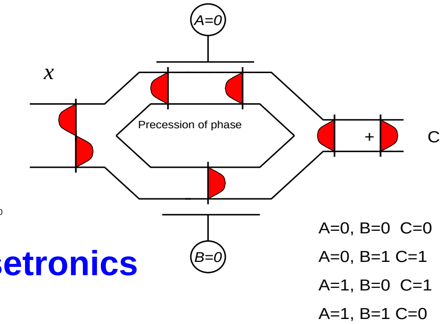


DMS



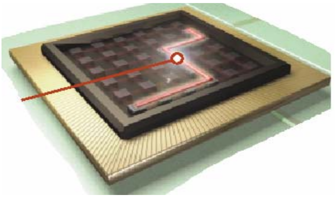
MQCA





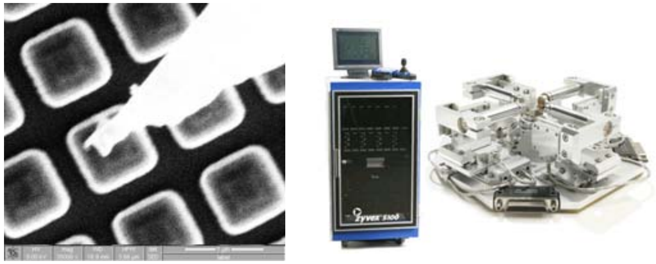
Phasetronics

Task 4: Novel interconnect and architectures



NanoPlasmonics

Task 5: Nanoscale Characterization



Nano Manipulator/ Probe system

NSF NSEC / MRSEC Nanoelectronics Areas*

3	**Primary focus**
2	**Secondary focus**
1	**Very little or no focus**

Question number		1	2	3	4	5
Institution		Alternative State variables	Non equilibrium devices	Novel information transfer	phonon engineering	self assembly
NSEC Centers						
Electronic Transport in Molecular Nanostructures, NSEC	Columbia University	1	2	1	2	2
Nanoscale Systems and their Device Applications, NSEC	Harvard University	3	3	3	3	3
Integrated Nanopatterning and Detection, NSEC	Northwestern University	1	2	1	1	3
Center for High Rate Nanomanufacturing	Northeastern University	2	1	1	1	3
Stanford Center for Probing the Nanoscale	Stanford	2	1	1	1	1
Center for Nanoscale Electrical-Mechanical Manuffacturing Systems	UIUC	1	1	1	2	2
Nanoscience in Biological and Environmental Engineering (CBEN)	Rice University	1	1	1	1	1
MRSEC Centers						
Biomaterial microstructures	UCSB	2	1	1	1	3
Grain boundaries, metals / ceramics; simulations	CMU	1	1	1	1	1
Princeton Center for Complex Materials	Princeton	3	1	1	1	3
Center for Nanostructered Materials	Cornell	2	1	1	1	2
Nanomagnetisms -fundamental interactions and applications	U of Nebraska	2	1	1	1	2
Nanoscopic design, quantum dots, surfaces	U ov Virginia	2	1	1	1	3
Transport in nanostructured magnetic materials	U of Alabama	3	3	1	1	2
Molecular motors	Penn State University	1	1	2	1	3
The Center for the Science and Engineering of Materials (CSEM),	California Institute of Technology	2	2	3	2	1
Laboratory for Research on the Structure of Matter	U of Pennsylvania	1	1	1	1	1
The Center for Materials Science and Engineering (CMSE)	MIT	2	1	1	1	2
Directed Assembly of Nanostructures, NSEC	Rensselaer Polytech Inst	2	1	1	2	3
Structural integrated films containing nanoparticles	Columbia University	1	1	1	1	3

*NSF-funded centers, capabilities self-assessed by Center directors

NRI-NSF Centers: 2006-2008

- Joint program established with NSF to fund NRI-related research at NSF centers

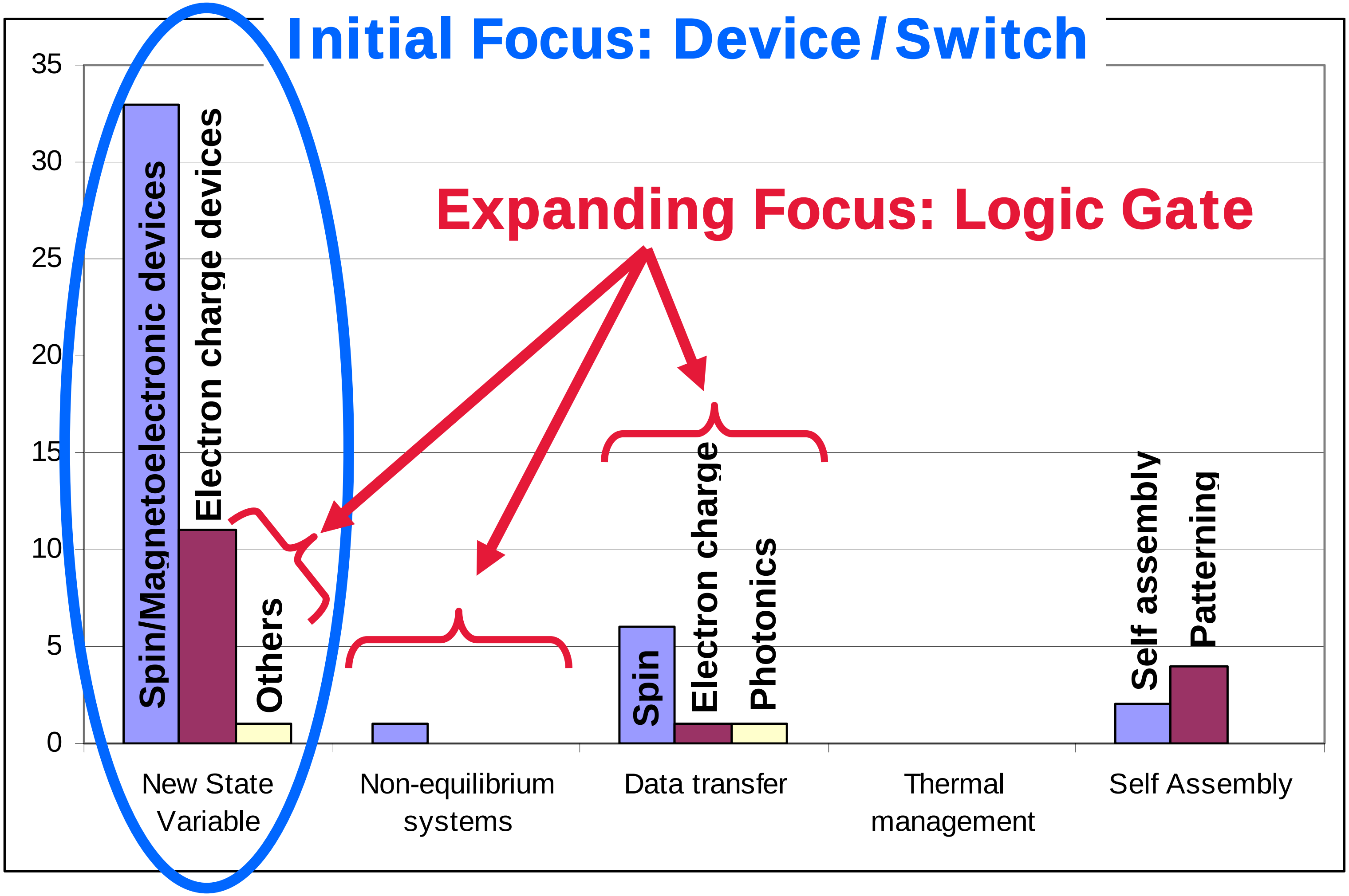
PI	Institution	Center	Center Name	Title of Supplement
Lundstrom, Mark	Purdue U	NCN	Network for Computational Nanotechnology	Exploratory Theory, Modeling, and Simulation for the NRI
Yardley, James T.	Columbia U	NSEC	Columbia Center for Electronic Transport in Molecular nanostructures	Non-equilibrium Quantum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

New NSF-NRI Projects: 2007-2009

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

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

Overview of Current NRI Projects



Questions? More Information?

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