Semiconductor Research Corporation

PIONEERS IN COLLABORATIVE RESEARCH®

Economic Impact of Nanotechnology in Electronics: (Semi) Quantitative Assessments

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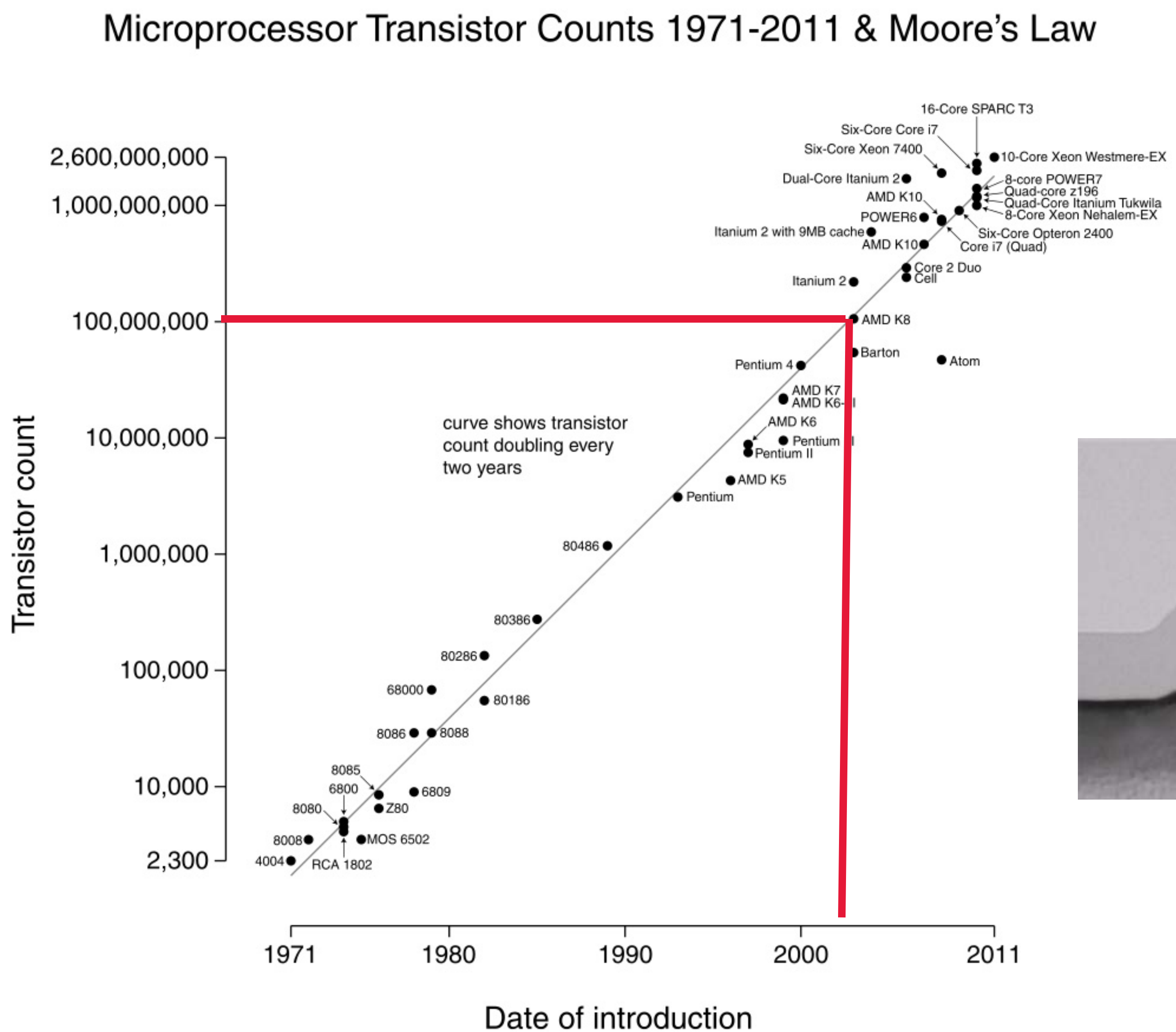
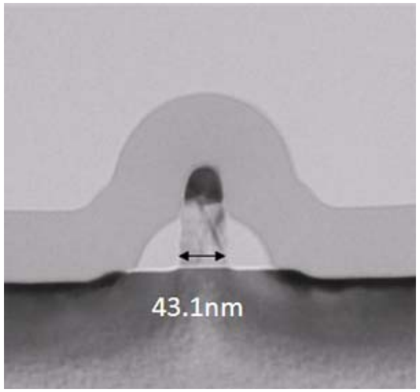
VP for Innovative Partnerships

International Symposium on Assessing the Economic Impact of Nanotechnology * Washington DC

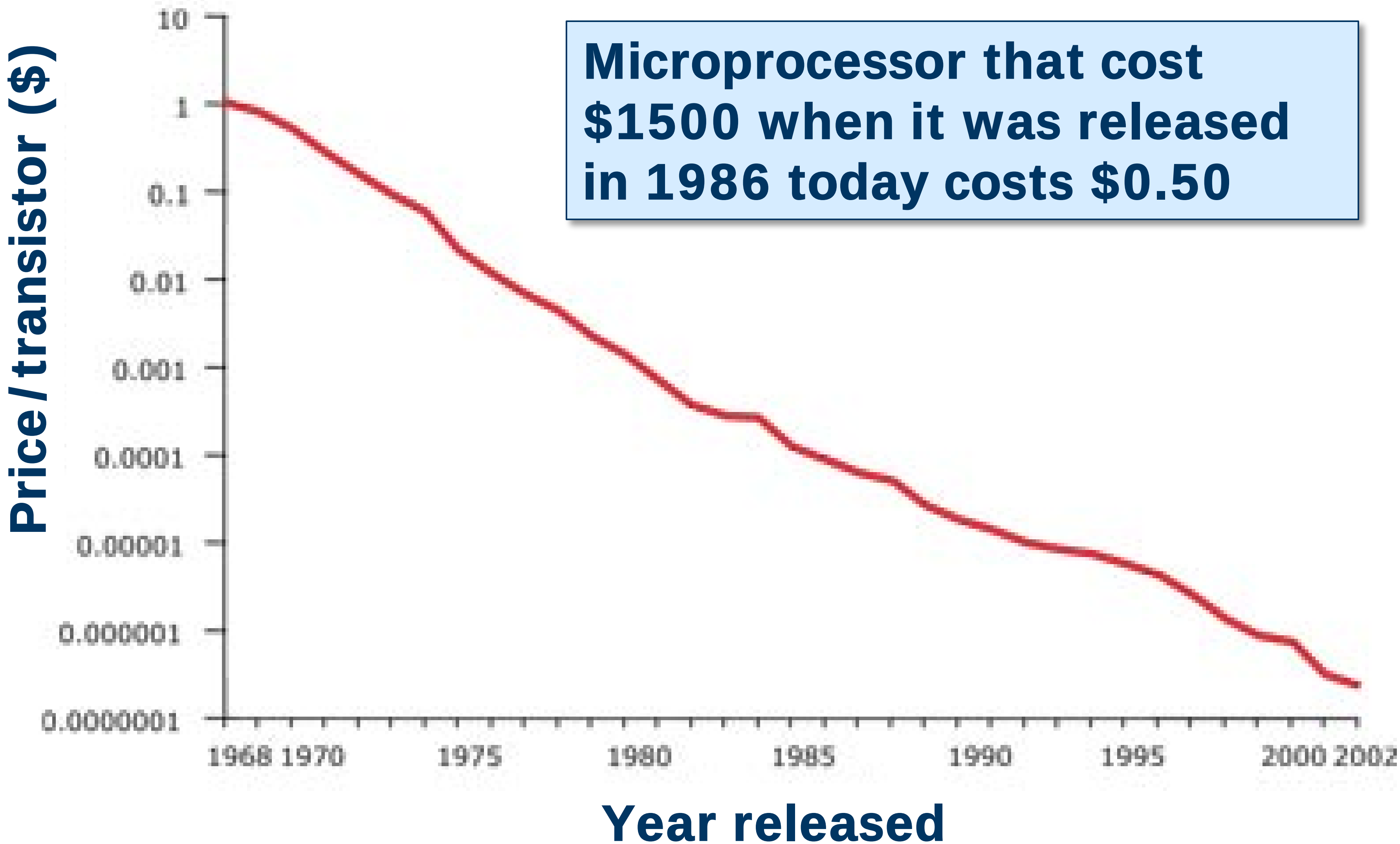
27-28 March 2012

Moore's Law Predicted Nano-Featured Integrated Circuits





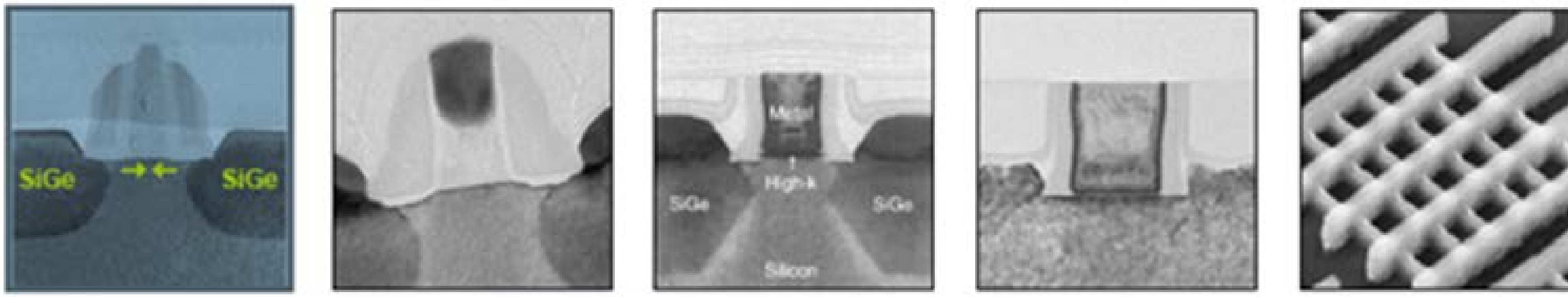
Transistor/chip ↑ = Price/transistor ↓



Microprocessor that cost $1500 when it was released in 1986 today costs $0.50

Nanotechnology + Electronics = Today's "Semiconductor" Industry

2003	2005	2007	2009	2011
90 nm	65 nm	45 nm	32 nm	22 nm



nested PMOS

Invented SiGe Strained Silicon	2nd Gen. SiGe Strained Silicon	Invented Gate-Last High-k Metal Gate	2nd Gen. Gate-Last High-k Metal Gate	First to Implement Tri-Gate

Strained Silicon

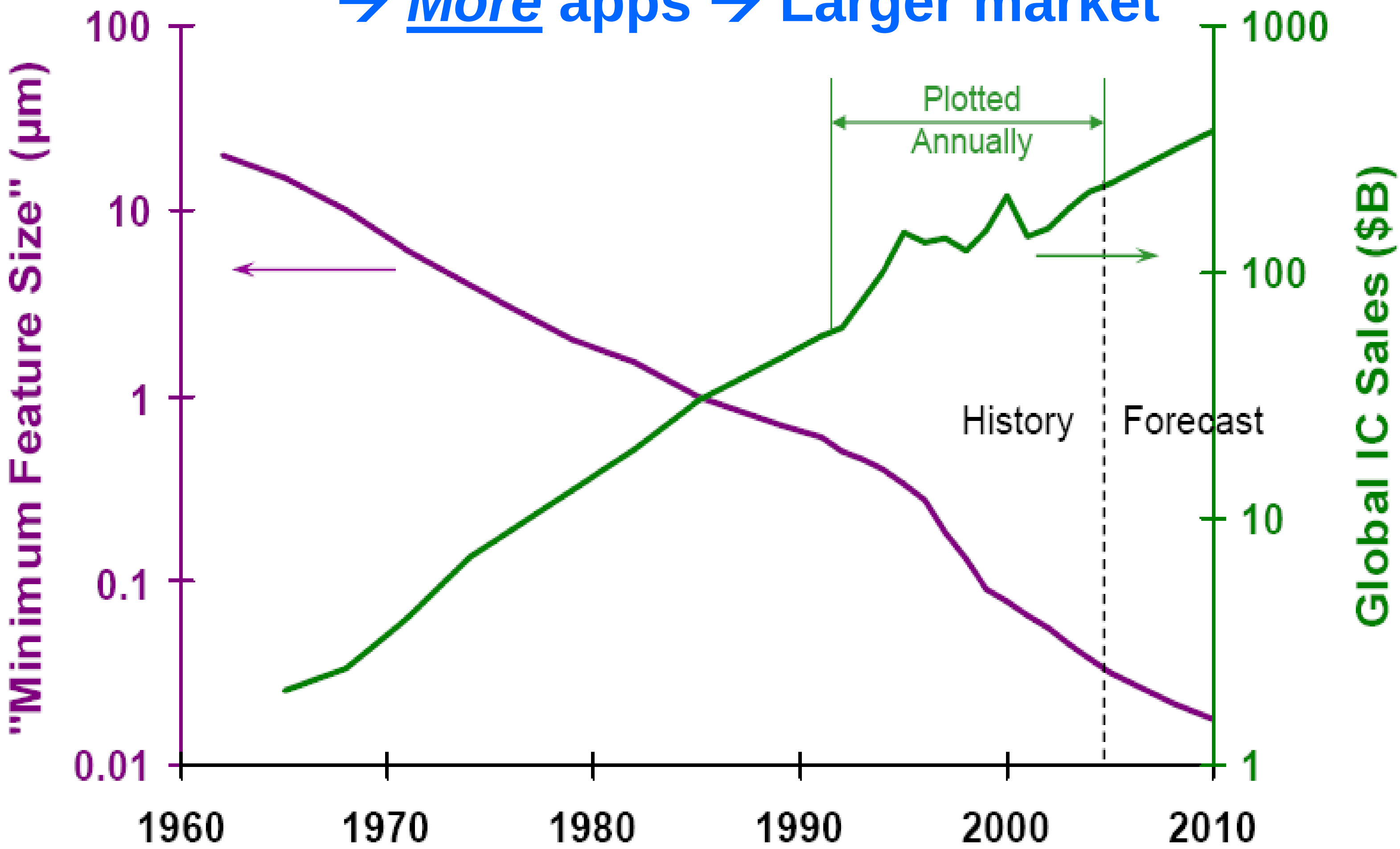
High-k Metal Gate

Tri-Gate

Shrinking Transistors

Scaling Drives the Industry

Smaller features → Better performance & cost/function → *More* apps → Larger market



Economic Impact of Semiconductors

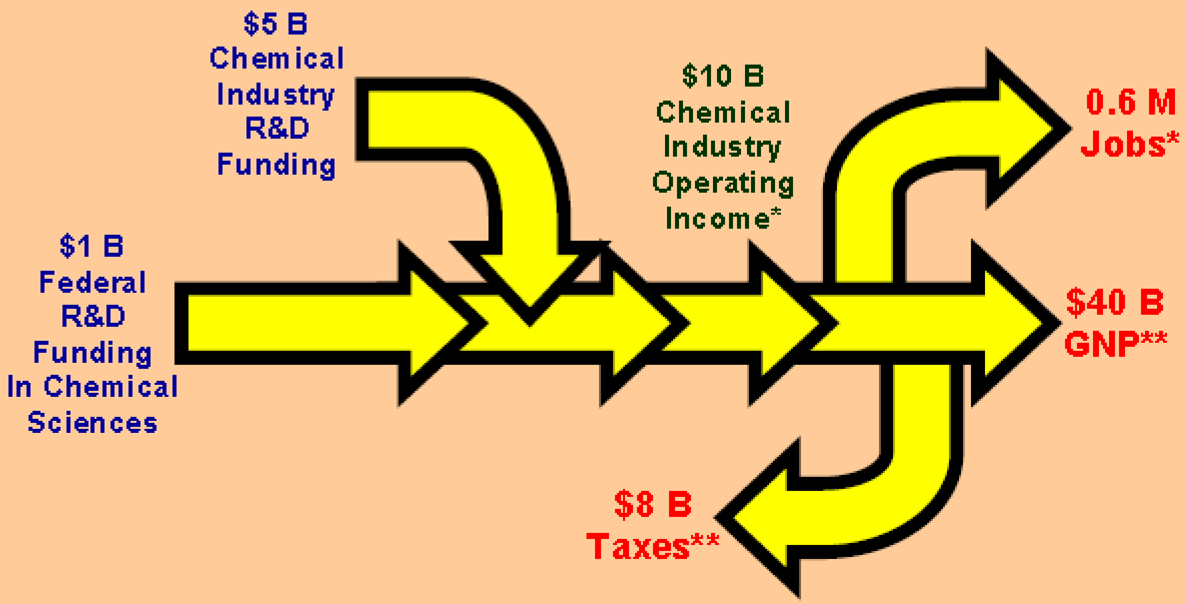
- Direct
  - $300 billion/year worldwide
  - 182,000 jobs in the U.S.
  - #1 U.S. exporting industry over past 6 years
- Indirect
  - Supports ~6 million U.S. jobs
  - Semiconductor industry represents <2% of GDP, but semiconductor-enabled ICT accounts for 25% increase in productivity (Jorgenson et al., 2007)

Economic Impact Measured by Growth Accounting: Semiconductors

- Difference in output vs. input is due to "innovation"
- In 1960-2007 Semiconductor industry output grew 22 times faster than the US economy as a whole
- Semiconductors are largely an intermediate input to other industries (like nano)
- Semiconductor use accounts for growth in many other industries.
  - 37% of growth in Communications (1960-2007)
  - 40% of growth in Primary Metals (1960-2007)
  - 48% of growth overall (1995-2000)
  - Increased Labor Productivity in Education Services, Federal Govt, Wholesale, etc.

Macroeconomic modeling of ROI from chemical research investment

"Measure for Measure: Chemical R&D Powers U.S. Innovation Engine", Council for Chemical Research, 2005



Basis:
*estimated from CCR study
**extrapolated from LANL study by Thayer, et al., April 2005 using REMI economic model

http://www.ccrhq.org/publications_docs/CCRPhaseIIStudyReport.pdf

Research for Economic Benefit: The SRC Model

- Industry **consortium** established by visionary leaders in 1982 to invest in **pre-competitive university research**.
- **Objectives**
  - Explore novel, relevant technologies
  - Promote collaboration
  - Create a pool of knowledgeable faculty and a pipeline of talent
- SRC has supported more than **2000 faculty** and **9,000 students** at **200+ universities** worldwide.


Robert Noyce


Erich Bloch


Jack Kilby

SRC's "Enhanced" Research Processes

- Develop research needs & priorities with industry
  - Builds upon the International Roadmap for Semiconductor Technology (www.itrs.org)
- Engage world-class researchers globally
  - Good faculty attract good students
- Provide industry "liaisons"
  - Provide input/feedback and sometimes access to samples, facilities, etc.
  - Mentor students
  - Transfer results to the company
- Connect people, transfer technology

Semiconductor Research Corporation:
A Family of Distinct, Related Program Entities

SRC

Global Research Collaboration
Ensuring vitality of current industry

Focus Center Research Program
Breaking down barriers to extend CMOS to its limits

Nanoelectronics Research Initiative
Beyond CMOS – identifying next information element

Energy Research Initiative
Emphasis on Photovoltaic and Smart Grid technologies

New Research Initiatives

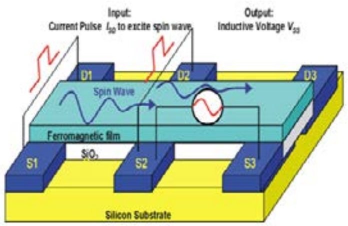
Education Alliance
Attracting and educating the next generation of innovators and technology leaders

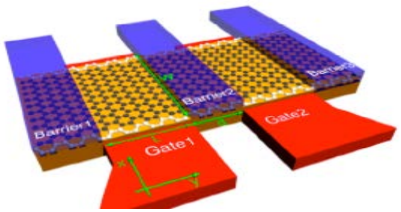
Beyond CMOS= “Nanoelectronics”

- Nanoelectronics Research Initiative (NRI) launched in 2005
  - Industry Members: GlobalFoundries, IBM, Intel, Micron, TI
  - Federal partners: NSF & NIST
  - State/local partners: California, Indiana (+South Bend), New York, Texas, and Virginia
- Mission: *Demonstrate novel computing devices capable of replacing the CMOS FET as a logic switch in the 2020 timeframe*.

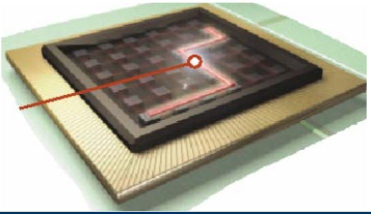
NRI Primary Research Vectors

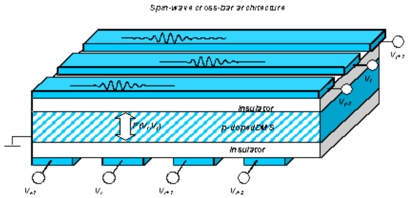
- NEW DEVICE
  Device with alternative state vector



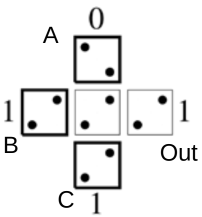


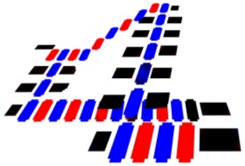
- NEW WAYS TO CONNECT DEVICES
  Non-charge data transfer



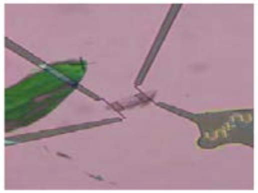


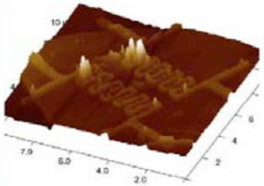
- NEW METHODS FOR COMPUTATION
  Non-equilibrium systems



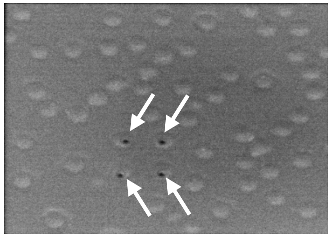


- NEW METHODS TO MANAGE HEAT
  Nanoscale phonon engineering



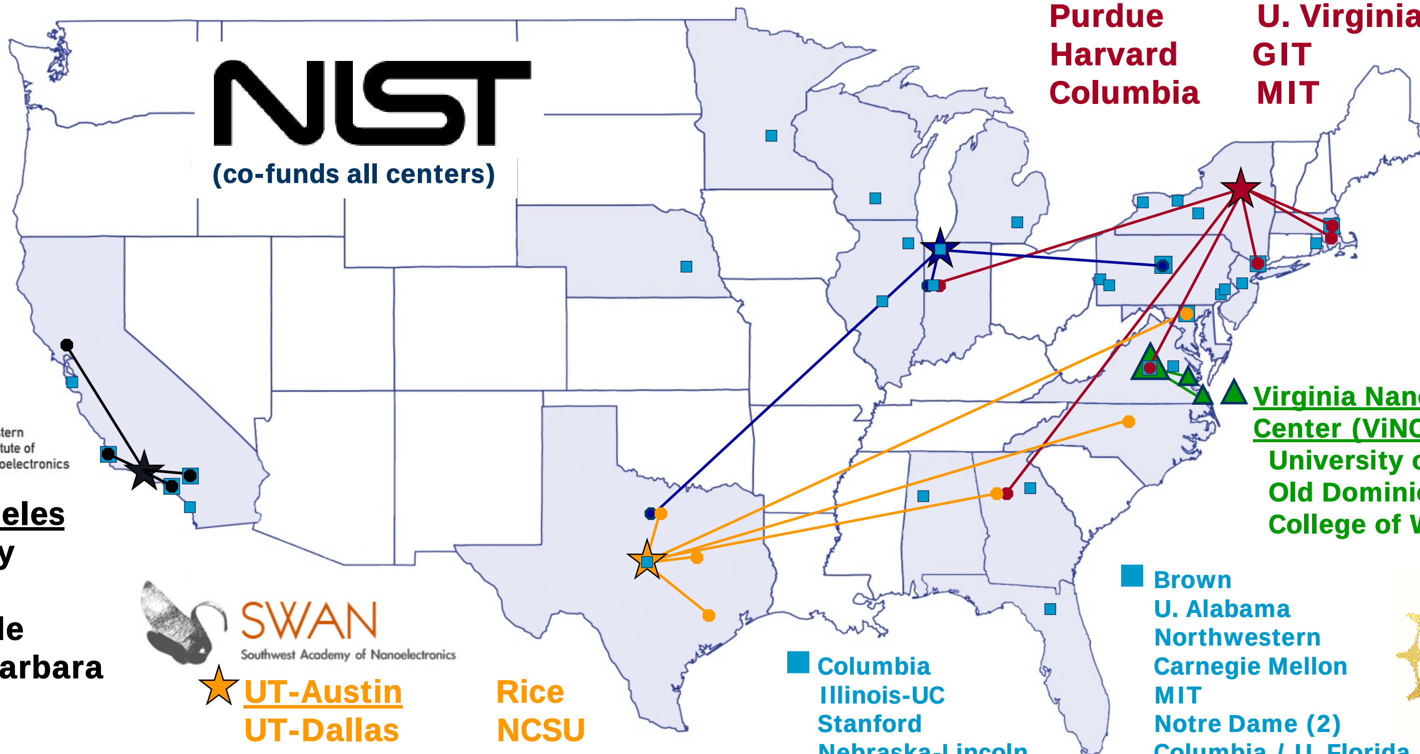


- NEW METHODS OF FABRICATION
  Directed self-assembly devices



NRI Funded Universities

Finding the Next Switch



Nanoelectronics • Architectures
MIND
MIDWEST INSTITUTE FOR NANOELECTRONICS DISCOVERY

★ **Notre Dame**
Penn State
Purdue
UT-Dallas

INDEX
INSTITUTE FOR NANOELECTRONICS DISCOVERY AND EXPLORATION

★ **SUNY-Albany**
Purdue
Harvard
Columbia
U. Virginia
GIT
MIT

NIST
(co-funds all centers)

Virginia Nanoelectronics Center (ViNC)
University of Virginia
Old Dominion University
College of William & Mary

WIN
Western Institute of Nanoelectronics

★ **UC Los Angeles**
UC Berkeley
UC Irvine
UC Riverside
UC Santa Barbara

SWAN
Southwest Academy of Nanoelectronics

★ **UT-Austin**
UT-Dallas
U. Maryland
GIT
Rice
NCSU
Texas A&M

NSF

■ **Columbia**
Illinois-UC
Stanford
Nebraska-Lincoln
Penn State
Princeton / UT-Austin
UC-Santa Barbara
UC-Riverside / Georgia
Virginia Commonwealth / UC-R / Michigan / U. Virginia
UC-Riverside / UC-I / UC-SD / Rochester / SUNY-Buffalo
U. Pittsburgh / U. Wisconsin-Madison / Northwestern

■ **Brown**
U. Alabama
Northwestern
Carnegie Mellon
MIT
Notre Dame (2)
Columbia / U. Florida
U. of Minnesota
Cornell / Princeton
Drexel University / UI-UC / U. Penn

Over 40 Universities in 19 States

SRC Numbers

SRC Research Programs*

- ✓ Over $1.6B invested
- ✓ 3,225 contracts
- ✓ 9,195 students
- ✓ 2,025 faculty members
- ✓ 261 universities

Deliverables*

- ✓ 43,070 technical documents
  - 377 patents granted
  - 908 patent applications
  - 677 software tools
- ✓ 2,944 research tasks/themes
- ✓ 9,195 students

Assessing Impact of SRC: Direct Outputs

- Technical documents
  - Publications
  - Presentations (conferences, reviews, etc.)
  - Reports
- Patents
- Students graduated/hired
- Startup companies

IEEE Journals: Citation Statistics

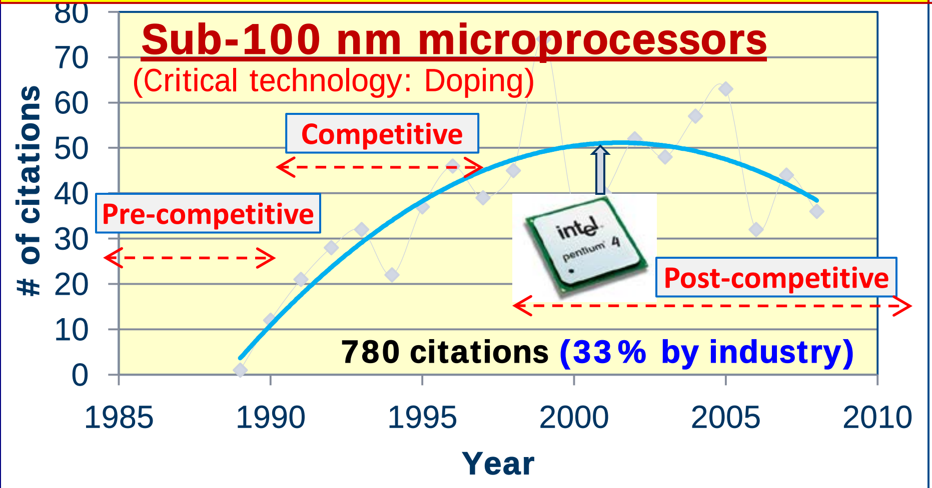
	Totals (through 2010)			Average per year				
IEEE Journal	**Papers**	**Citations**	**100+**	**Papers**	**Citations**	**100+**	**% of 100+**	**Avg. cit/pub**
Transactions	16,807	245,899	304	357.60	5,232	6.47	1.8%	14.6
Proceedings of the IEEE	19,949	279,959	548	231.97	3,255	6.37	2.7%	14.0
Electron Device Letters	6,433	103,644	111	207.52	3,343	3.58	1.7%	16.1
Journal of Solid State Circuits	8,813	158,184	218	195.84	3,515	4.84	2.5%	17.9
Circuits and Devices Magazine	615	1,522	2	61.50	152	0.20	0.3%	2.5
Trans. on CAD of Integrated Circuits and Systems	3,952	51,897	52	146.37	1,922	1.93	1.3%	13.1
Transactions on Computers	7,324	124,501	184	166.45	2,830	4.18	2.5%	17.0
Transactions on Nanotechnology	820	9,076	8	91.11	1,008	0.89	1.0%	11.1
Transactions on Reliability	4,165	31,444	20	88.62	669	0.43	0.5%	7.6
Averages	**7,653**	**111,792**	**161**	**171.89**	**2,436.35**	**3.21**	**1.60%**	**12.7**

Technology Transfer Indicator: Citations by Industry

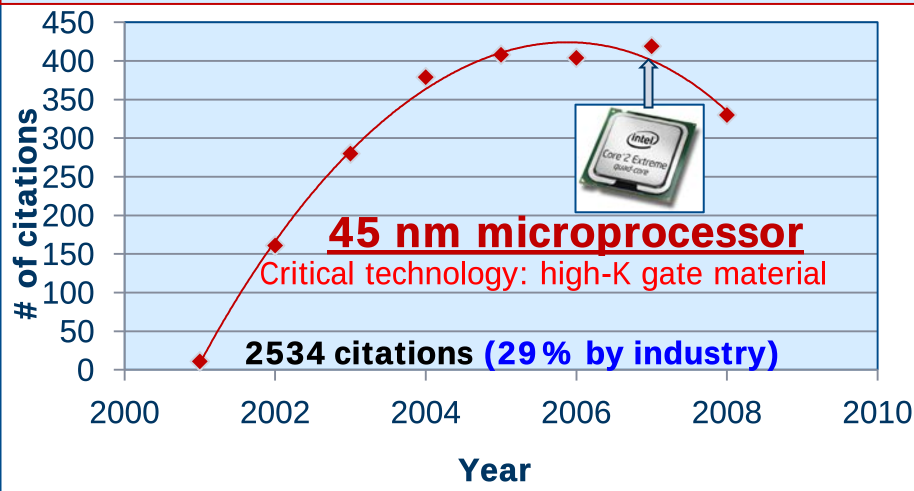
Est. Res. Start	Research/Influential Article	Total Cit. (% by Ind.)	Commercial Application		
			Technology	Year	Company
1984	"BSIM - Berkeley Short-Channel IGFET Model for MOS-Transistors", Sheu et al., *IEEE J. S-State Cir* 22 (1987) 558	200 (28%)	Compact Modeling Tools; Formal Verification Tools; Logic Synthesis Tools; Simulation Tools	1992	Synopsis; Cadence
1983	"Graph-based algorithms for Boolean function manipulation", Bryant, *IEEE Trans on Comput.* 35 (1986) 677	1754 (18%)			
1987	"Asymptotic wave-form evaluation for timing analysis", Pillage and Rohrer, *IEEE Trans Computer-Aided Design* 9 (1990) 352	762 (27%)			
1990	"Threshold voltage model for deep-submicrometer MOSFET's", Liu, Hu et al., *IEEE Trans Electron Dev* 40 (1993) 86	209 (35%)			
1986	"Point-Defects and Dopant Diffusion in Silicon", Fahey and Plummer *Rev Mod Phys* 61 (1989) 289	847 (31%)	Sub-100 nm MPU and Flash	2001	Intel; AMD; GF; Freescale; TI; NORTEL; IBM; Digital Equlp. Corp
1994	"Making silicon nitride film a viable gate dielectric", Ma, *IEEE Trans on Electron Dev* 45 (1998) 680	220 (25%)			

Citation trajectories peak about time of product introduction

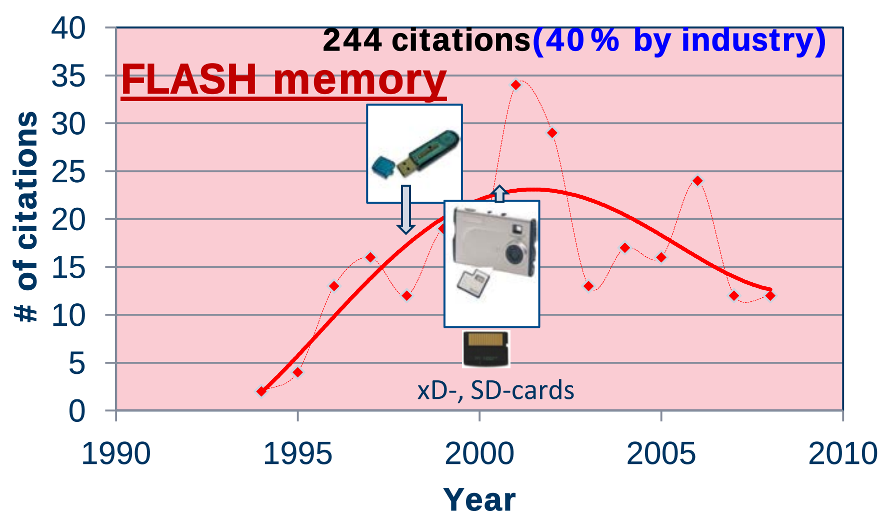
"Point Defects and Dopant Diffusion in Silicon", by Plummer et al. (1989)



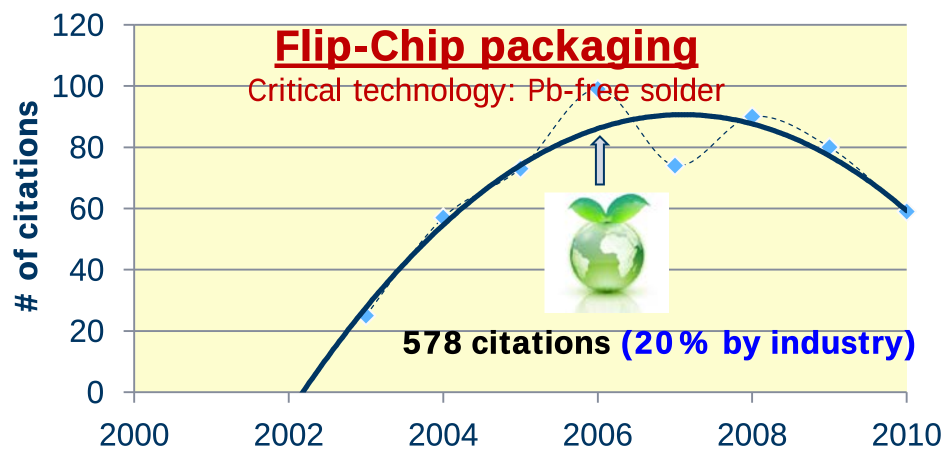
"High-k gate dielectrics: current status and materials properties considerations" by Wilk, Wallace and Anthony (2001)



"Hole injection SiO2 breakdown model for very low voltage lifetime extrapolation" , by Schuegraf and Hu (1994)



"Six cases of reliability study of Pb-free solder joints in electronic packaging technology", by Zeng and Tu (2002)

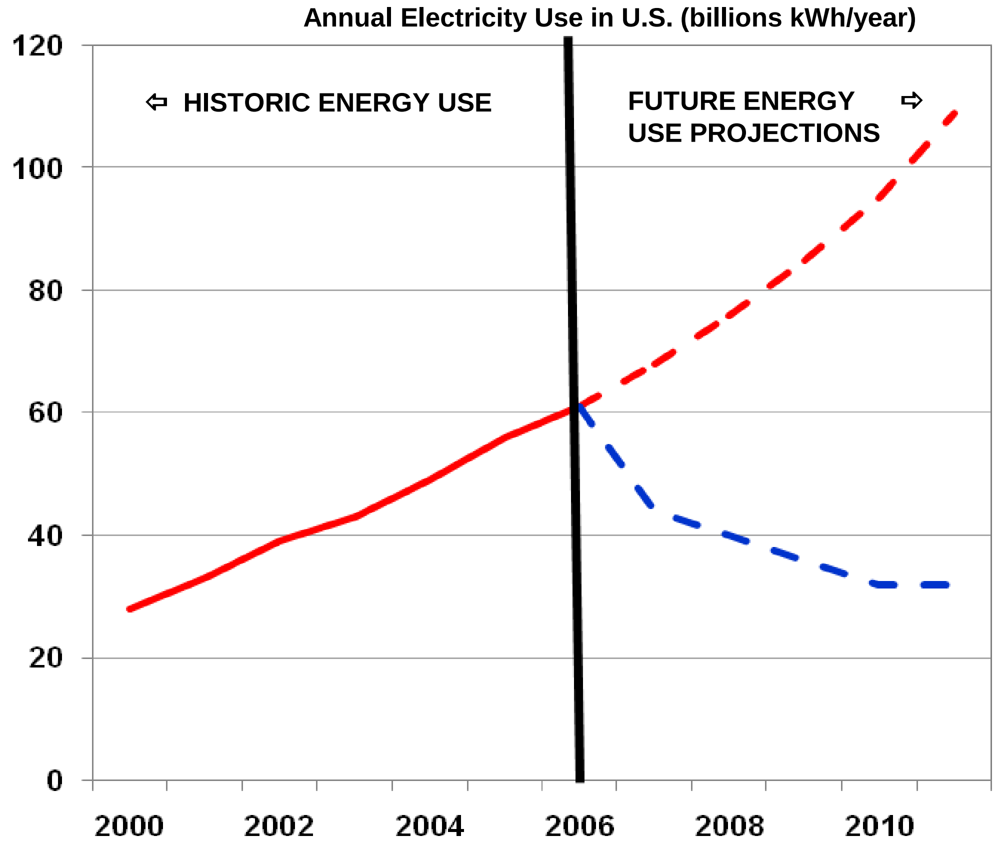


Semiconductors Enable IT Energy Efficiency

Server and Data Center Energy Savings

- **U.S. energy consumption by servers and data centers could nearly double again in five years.**
- **Through energy-smart technologies, it could be halved!**

Aggressive Actions on Servers and Data Centers Can Have Dramatic Results

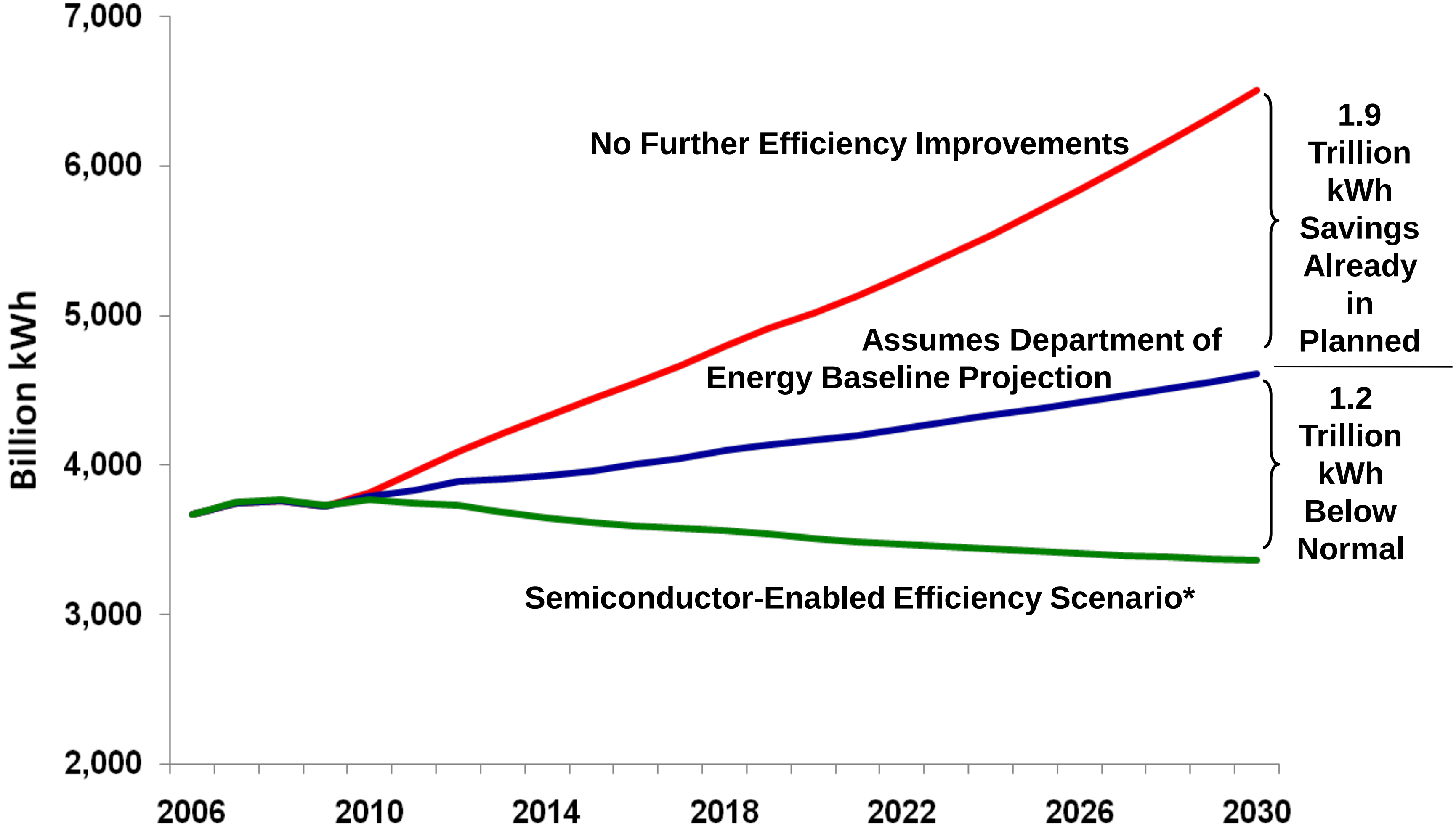


US Environmental Protection Agency, "Report to Congress on Server and Data Center Energy Efficiency Public Law 109-431", August 2, 2007

SIA SEMICONDUCTOR INDUSTRY ASSOCIATION

Semiconductors Enable Broad Energy Efficiency

Save 1.2 Trillion kWh, Reduce CO2 emissions by 733 MMT in 2030



*Note: Accelerated investments in semiconductor-related technologies stimulated by smart policies.
Source: American Council for an Energy-Efficient Economy, "Semiconductor Technologies: The Potential to Revolutionize U.S. Energy Productivity," (2009).

SIA SEMICONDUCTOR INDUSTRY ASSOCIATION

National Academies Review of NNI Statement of Task

- Examine the role of the NNI in maximizing opportunities to transfer selected technologies to the private sector, provide an assessment of how well the NNI is carrying out this role, and suggest new mechanisms to foster transfer of technologies and improvements to NNI operations in this area where warranted;
- Assess the suitability of current procedures and criteria for determining progress towards NNI goals, suggest definitions of success and associated metrics, and provide advice on those organizations (government or non-government) that could perform evaluations of progress;
- Review NNI's management and coordination of nanotechnology research across both civilian and military federal agencies.

Metrics of economic impact of nanotechnology

- Nano research patents and publications (resulting from govt funding) highly cited by industry
- # of jobs (tracked via online job sites)
- “nano producer” growth
- “nano user” growth

- Why? How? When?