Industry and Sustainable Nanotechnology

How can nanotechnology make industry more sustainable?

A semiconductor industry perspective

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VP for Innovative Partnerships

Semiconductor Research Corporation

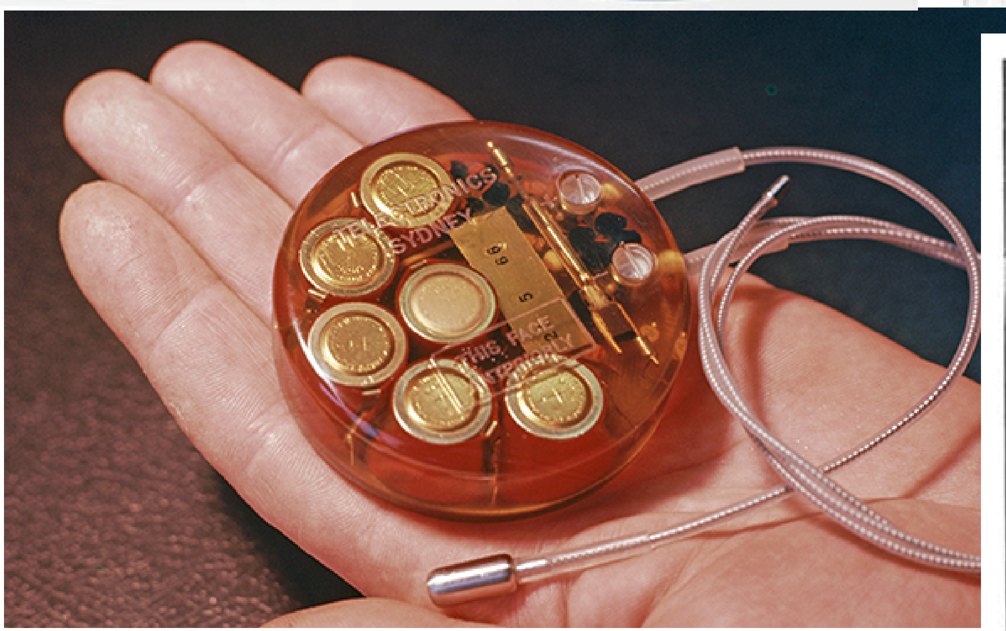
Sustainable Nanotechnology Organization Conference

November 5, 2012 * Arlington VA

General ways nano impacts industry sustainability

- Green(er) synthesis of (nano)materials and (nano)structures
  - Bottom up or additive fabrication
  - Improved sensing and filtration
- Synthesis of green(er) (nano)materials and (nano)technologies
  - Less is more, e.g. surface-driven applications
- Improved functionality, often in a smaller package

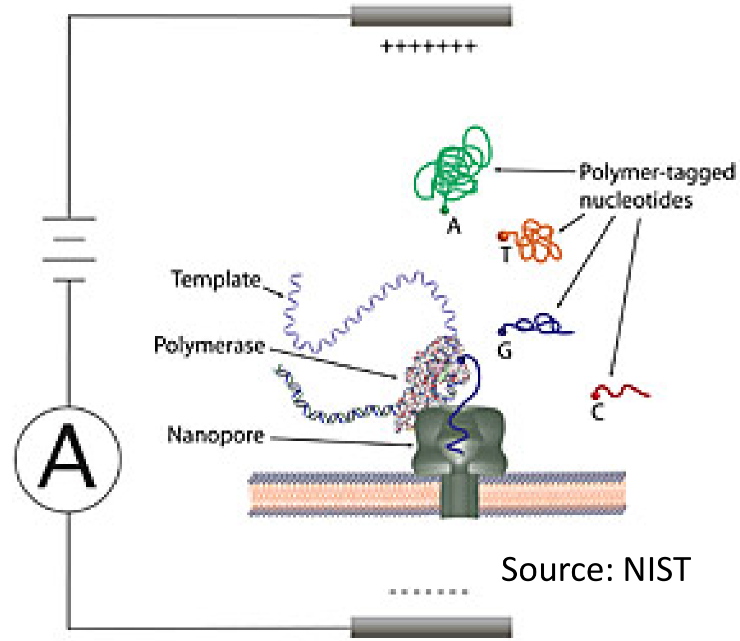




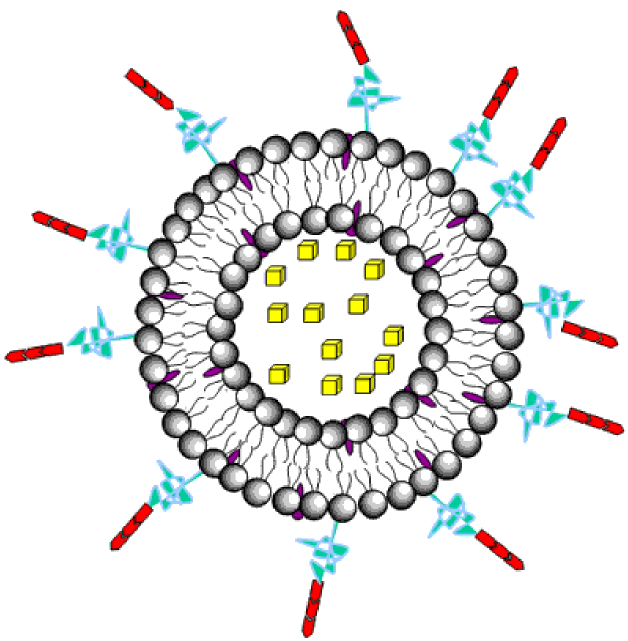
IS-1
Legend ™
SSIR MODEL 8416
XT 1100000R
MEDTRONIC

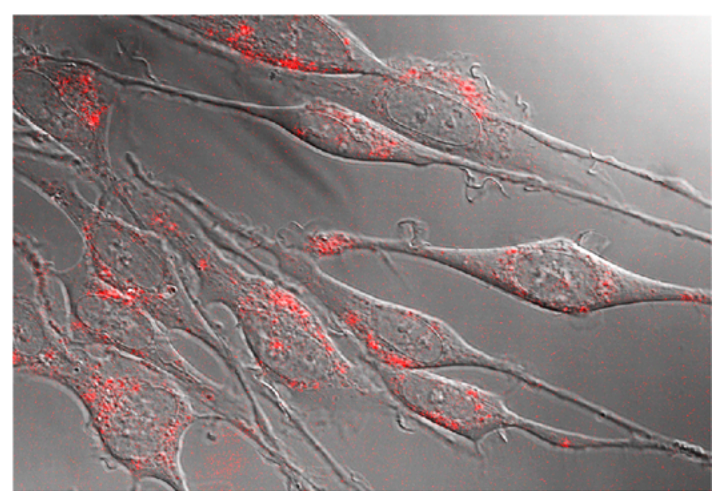
Nanotechnology for Medicine

- Imaging
- Diagnostics
- Therapeutics



Source: NIST





http://www.azonano.com/article.aspx?ArticleID=1538

Credit: J. Chang, Vanderbilt

Total Health Care Expenditures Percent of GDP, 1960-2008

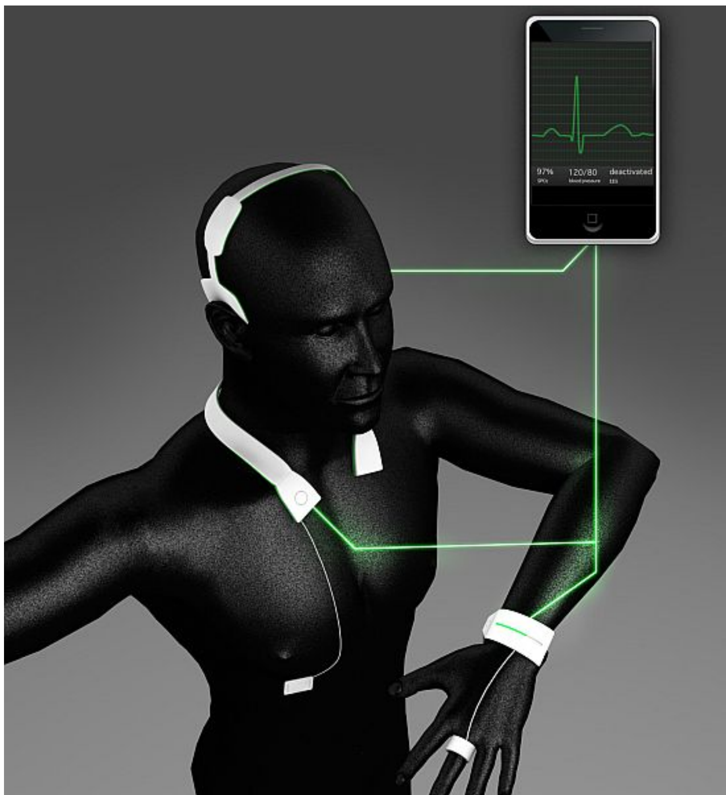
Most drugs

…don’t work for most people

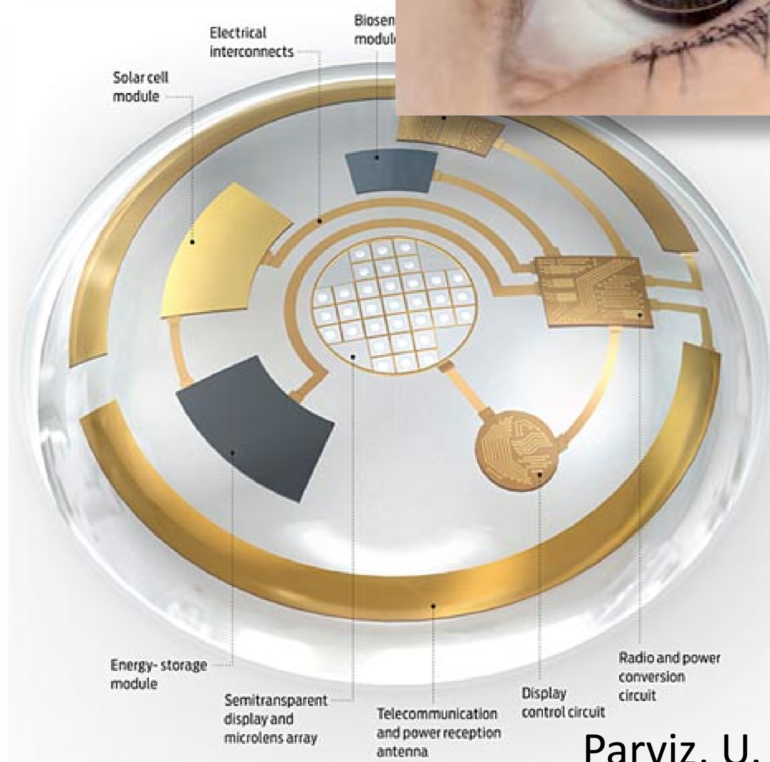
…most of the time.

Nanotechnology for Living

- Assistive Technologies
- Health monitors



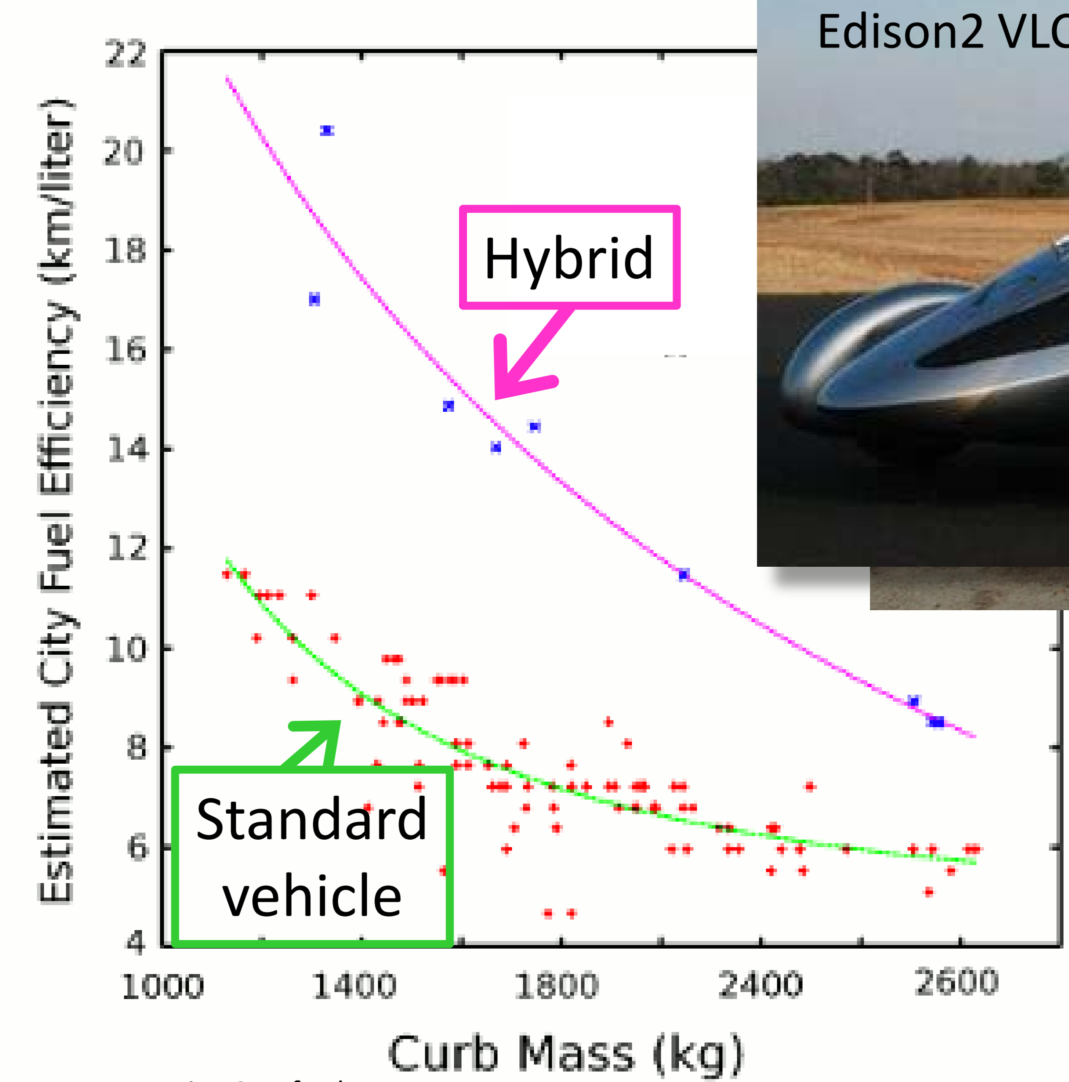
http://www.greendiary.com/healthpals-body-heat-powered-wearable-health-monitoring-system.html



Parviz, U. Washington

http://www.elementalled.com/academy/blog/innovative-technology/led-lights-make-augmented-vision-a-reality/

Nanotechnology for Automotive



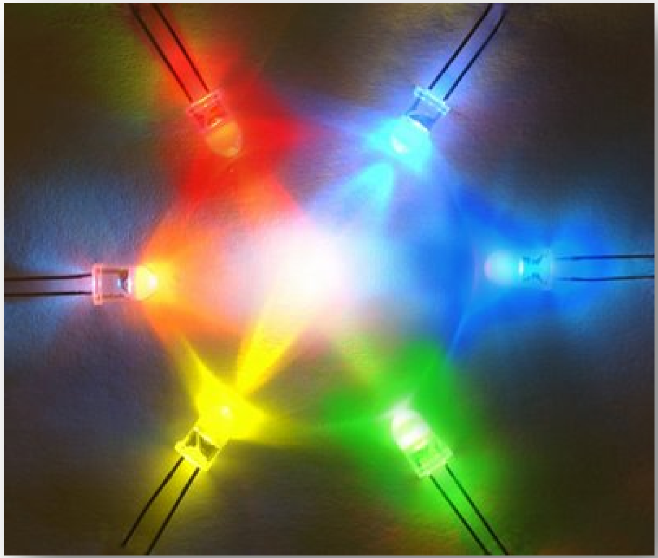
Danowitz, Stanford

"Edison2 combines sound physics with innovative design to produce workable and ***sustainable*** transportation solutions."

http://www.edison2.com/

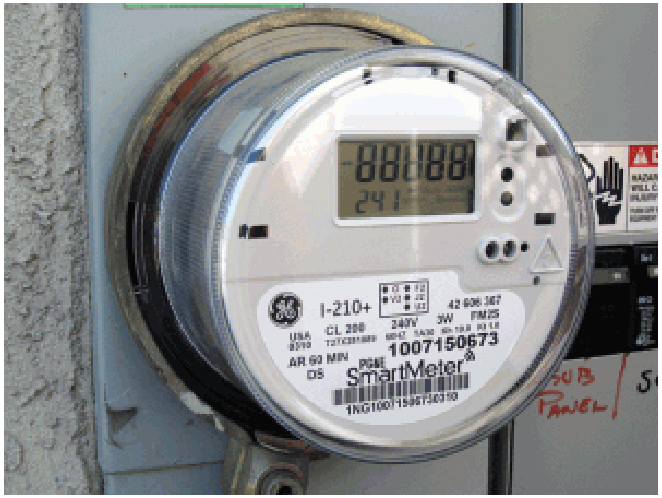
Nanotechnology for Energy

- Solid state lighting
- Solar cells
- Batteries



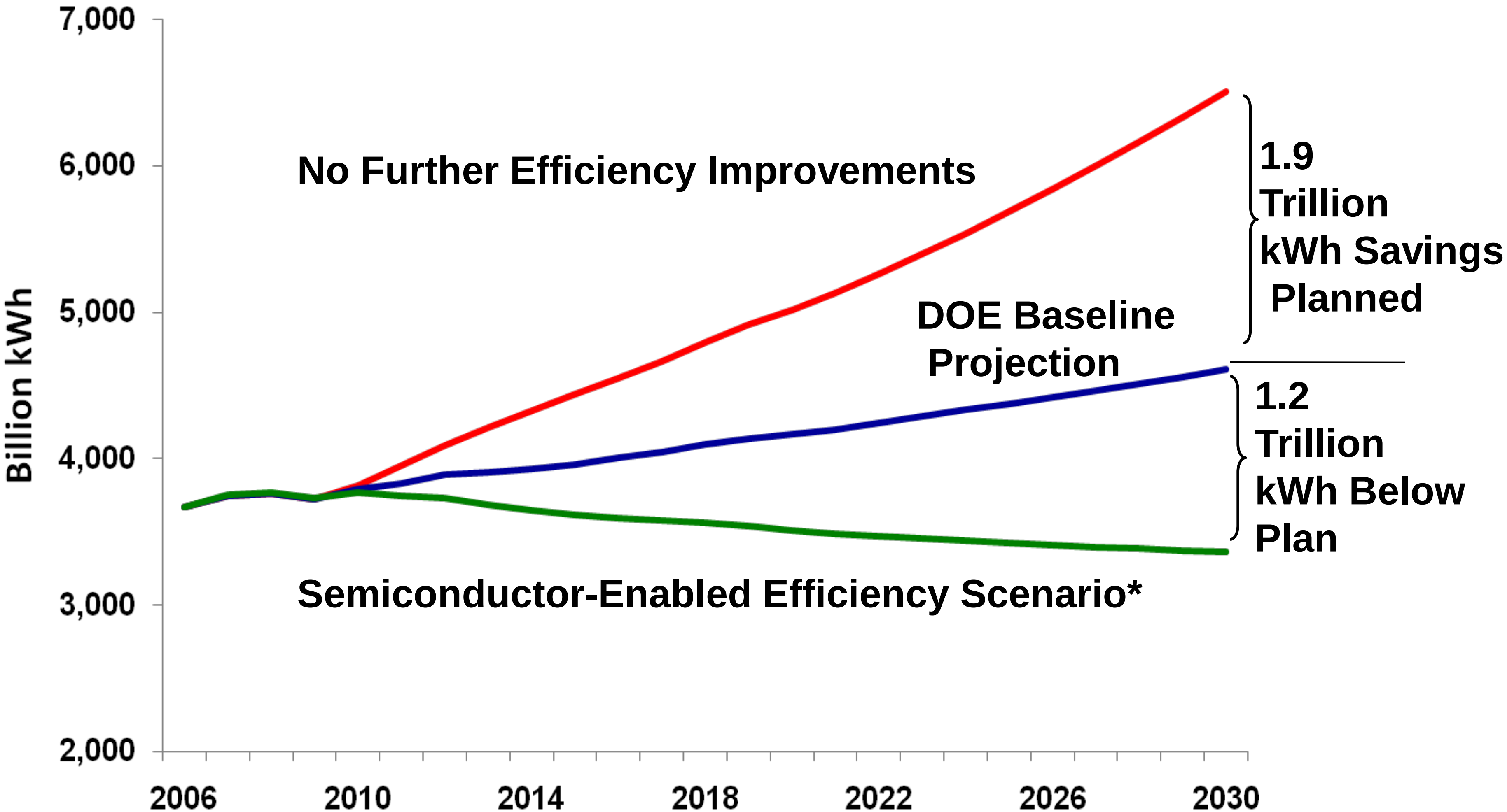
Nanotechnology for ITC & Electronics

- More connected
- More mobile
- More data = more knowledge
- More "intelligent" environment



Semiconductors Enable Broad Energy Efficiency

Save 1.2 Trillion kWh, Reduce CO_2 emissions by 733 MMT in 2030

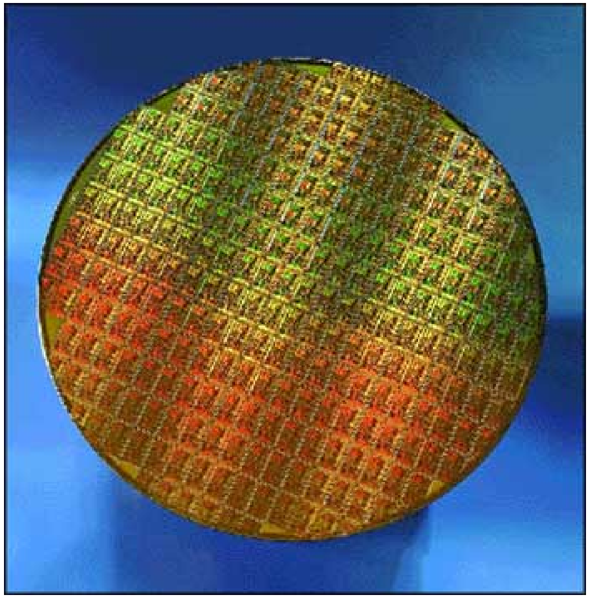


*Note: Accelerated investments in semiconductor-related technologies stimulated by smart policies.
Source: American Council for an Energy-Efficient Economy, “Semiconductor Technologies: The Potential to Revolutionize U.S. Energy Productivity,” (2009).

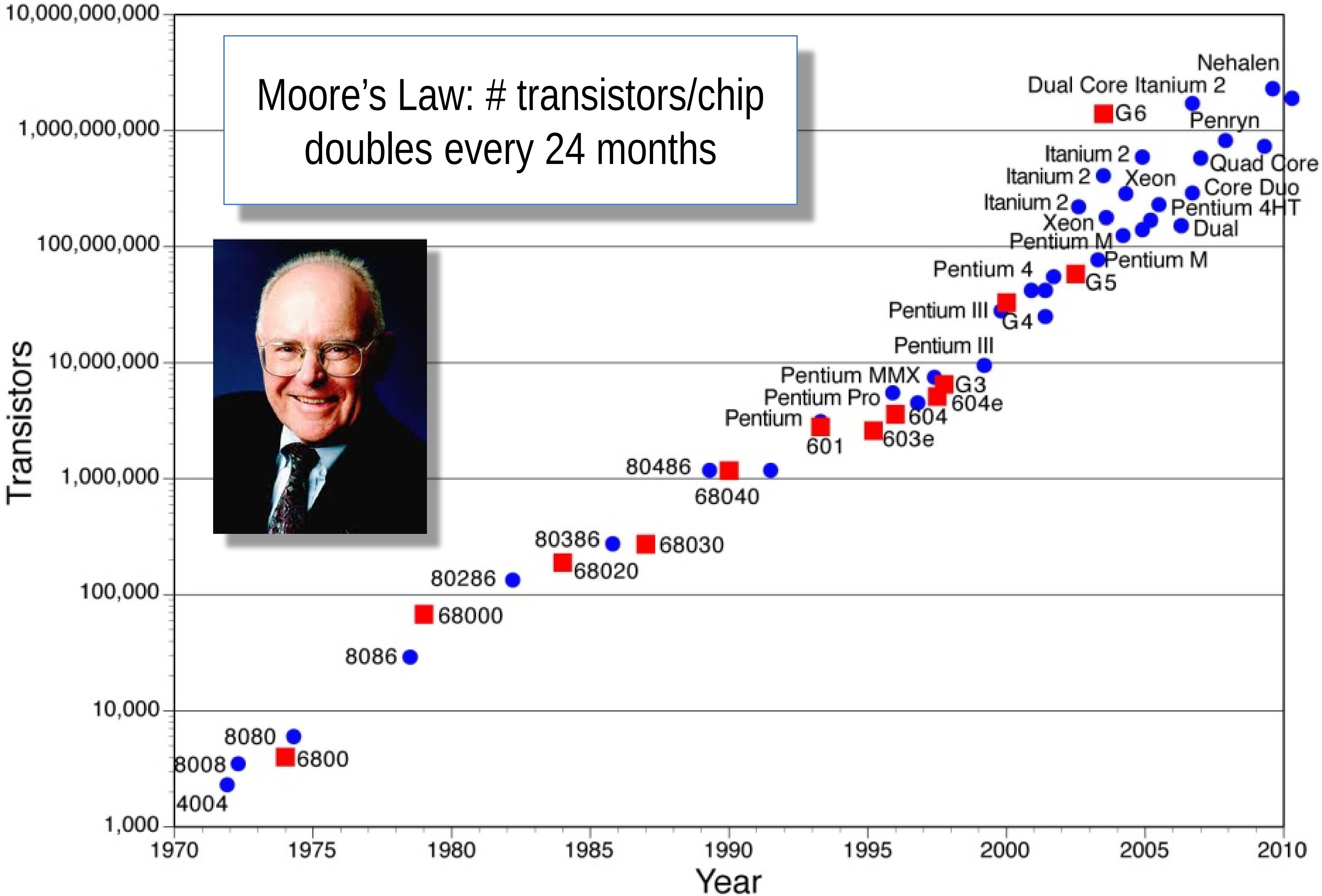
SIA SEMICONDUCTOR INDUSTRY ASSOCIATION

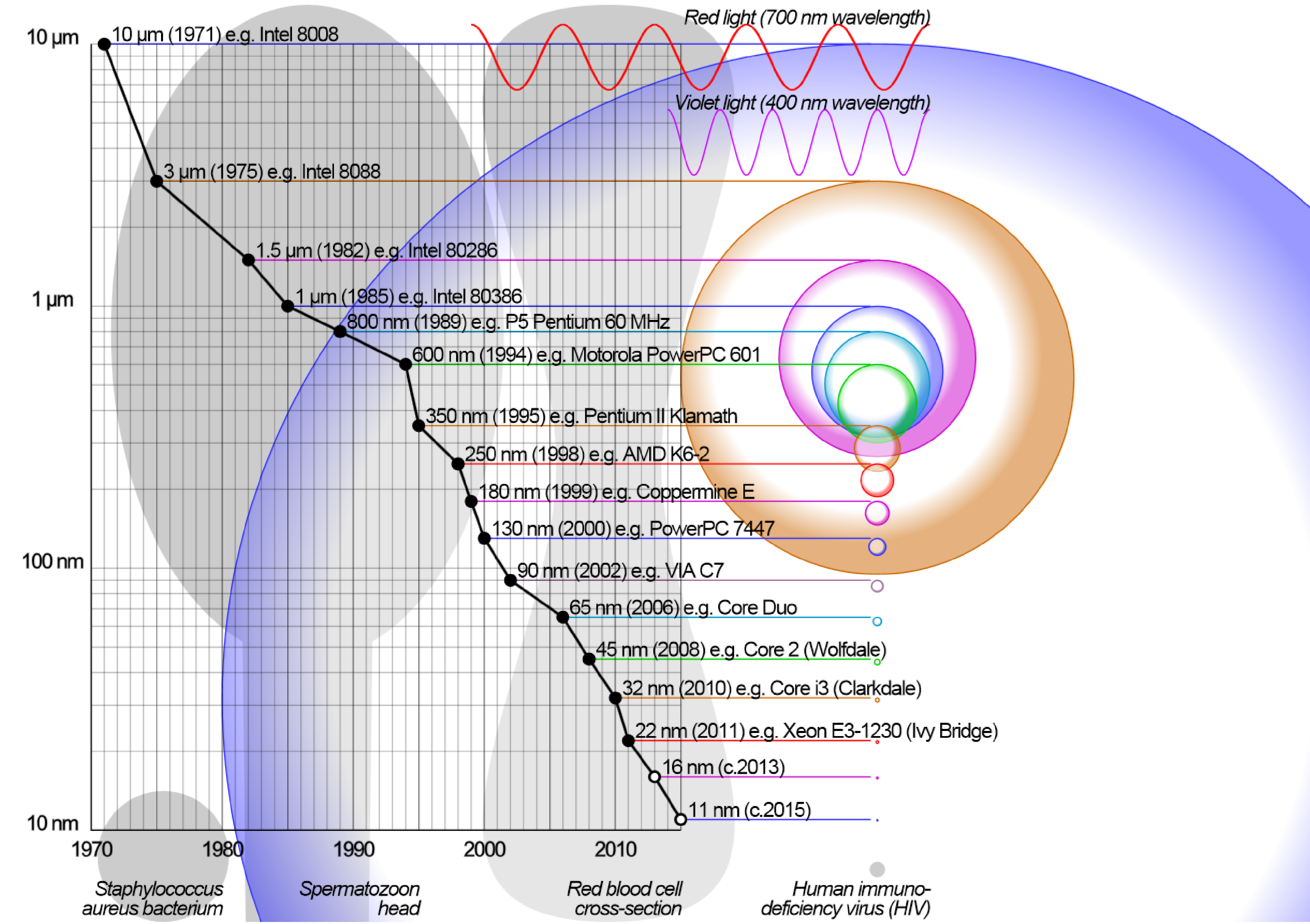
Nanotechnology for Semiconductors

- Nanomaterials
- Nanostructures
- Nanomanufacturing
- Nano metrology & characterization



Moore’s Law: # transistors/chip doubles every 24 months

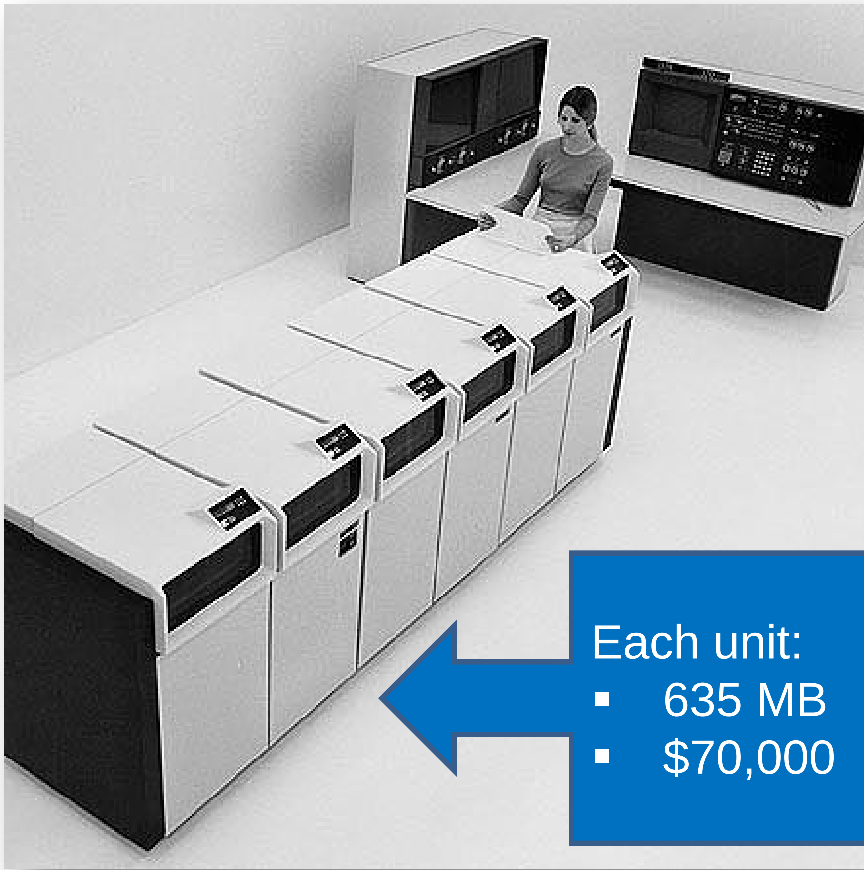




10 µm
1 µm
100 nm
10 nm
1970
1980
1990
2000
2010
10 µm (1971) e.g. Intel 8008
3 µm (1975) e.g. Intel 8088
1.5 µm (1982) e.g. Intel 80286
1 µm (1985) e.g. Intel 80386
800 nm (1989) e.g. P5 Pentium 60 MHz
600 nm (1994) e.g. Motorola PowerPC 601
350 nm (1995) e.g. Pentium II Klamath
250 nm (1998) e.g. AMD K6-2
180 nm (1999) e.g. Coppermine E
130 nm (2000) e.g. PowerPC 7447
90 nm (2002) e.g. VIA C7
65 nm (2006) e.g. Core Duo
45 nm (2008) e.g. Core 2 (Wolfdale)
32 nm (2010) e.g. Core i3 (Clarkdale)
22 nm (2011) e.g. Xeon E3-1230 (Ivy Bridge)
16 nm (c.2013)
11 nm (c.2015)
Red light (700 nm wavelength)
Violet light (400 nm wavelength)
Staphylococcus aureus bacterium
Spermatozoon head
Red blood cell cross-section
Human immuno-deficiency virus (HIV)

What Moore's Law Has Enabled

1982: Best available storage technology was the IBM 3350



Each unit:
- 635 MB
- $70,000

80Gb cost
$9,000,000 !!!
in 1976 dollars

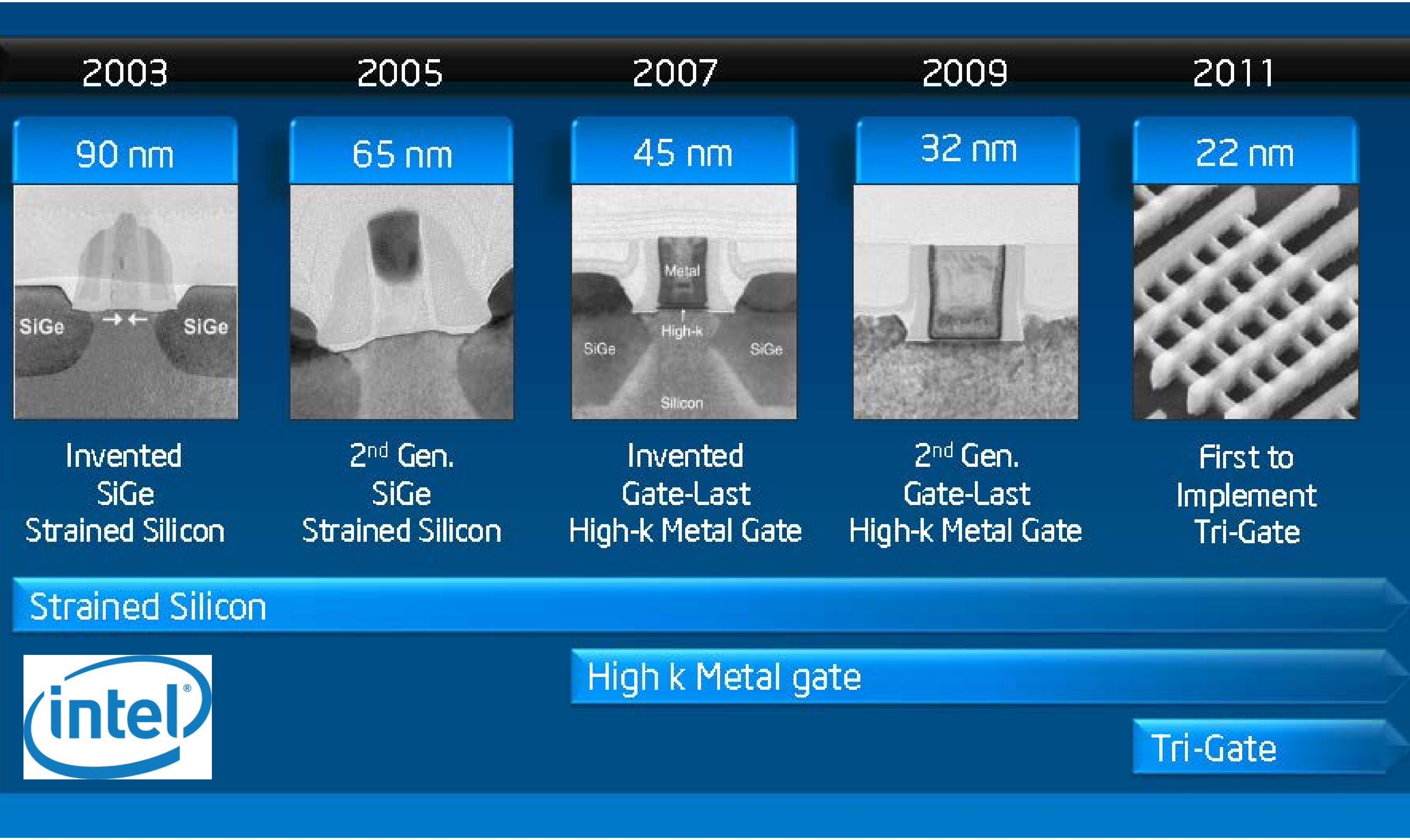
126 IBM 3350's = storage in 1 iPod

2012

iPod(5G)
80GB

80Gb cost
$100
in 2012 dollars

Nanotechnology + Electronics = Today's Semiconductor Industry



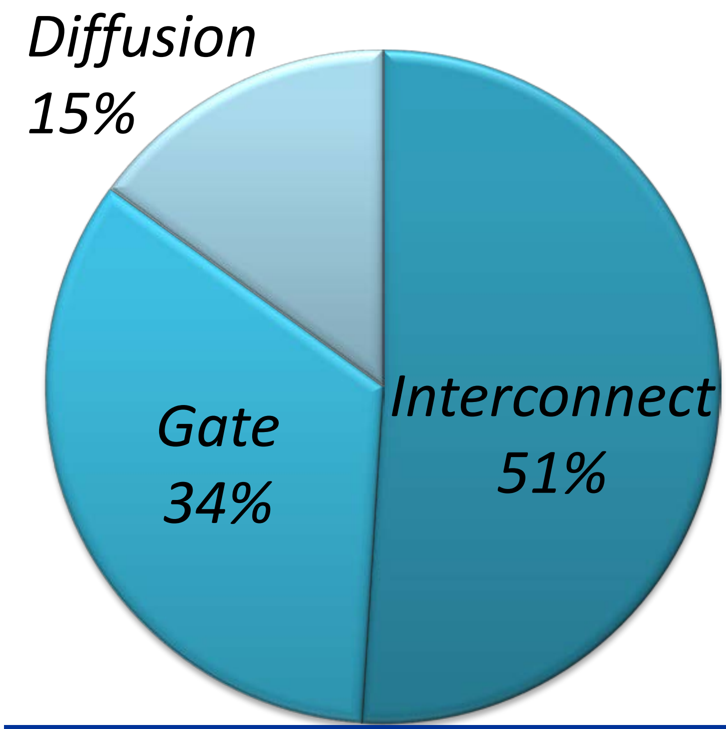
Nano-thick Gate Oxide Layer Requires New High-K Material

	K	Gap (eV)	CB offset (eV)
Si		1.1	
SiO_2	3.9	9	3.2
Si_3N_4	7	5.3	2.4
Al_2O_3	9	8.8	2.8 (not ALD)
Ta_2O_5	22	4.4	0.35
TiO_2	80	3.5	0
$SrTiO_3$	2000	3.2	0
ZrO_2	25	5.8	1.5
HfO_2	25	5.8	1.4
$HfSiO_4$	11	6.5	1.8
La_2O_3	30	6	2.3
Y_2O_3	15	6	2.3
a-$LaAlO_3$	30	5.6	1.8

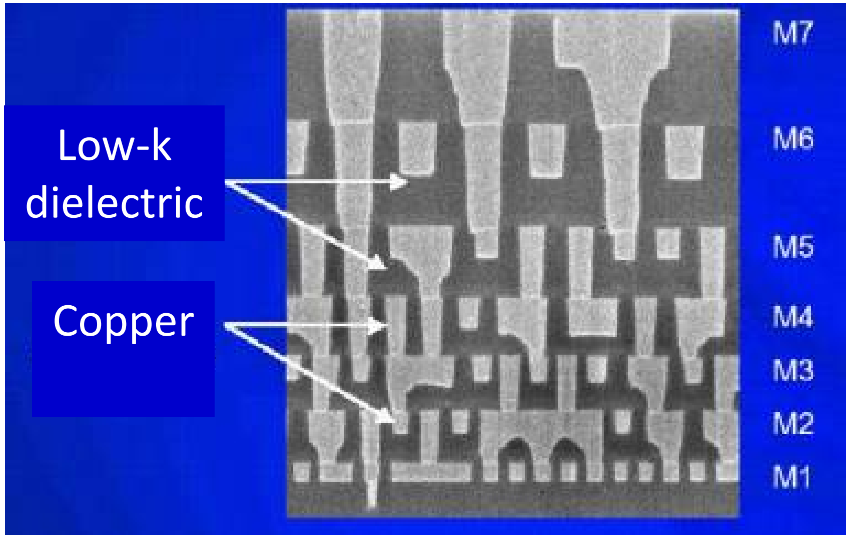
Source: Robertson, Eur Phys J Appl Phys, 28 (2004) 265

As Transistors Shrink, So Do Interconnects

Half of microprocessor power goes to interconnects (> 1 billion transistors; total budget= 200 watts)



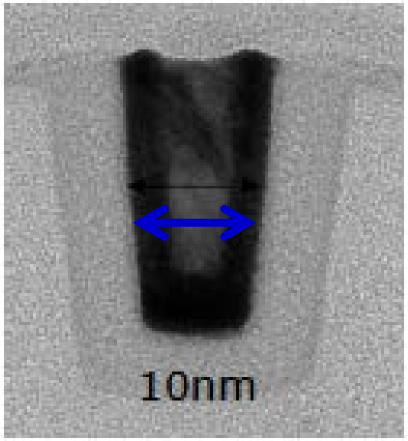
New conductive and insulating (nano)materials are needed



Source: NIST

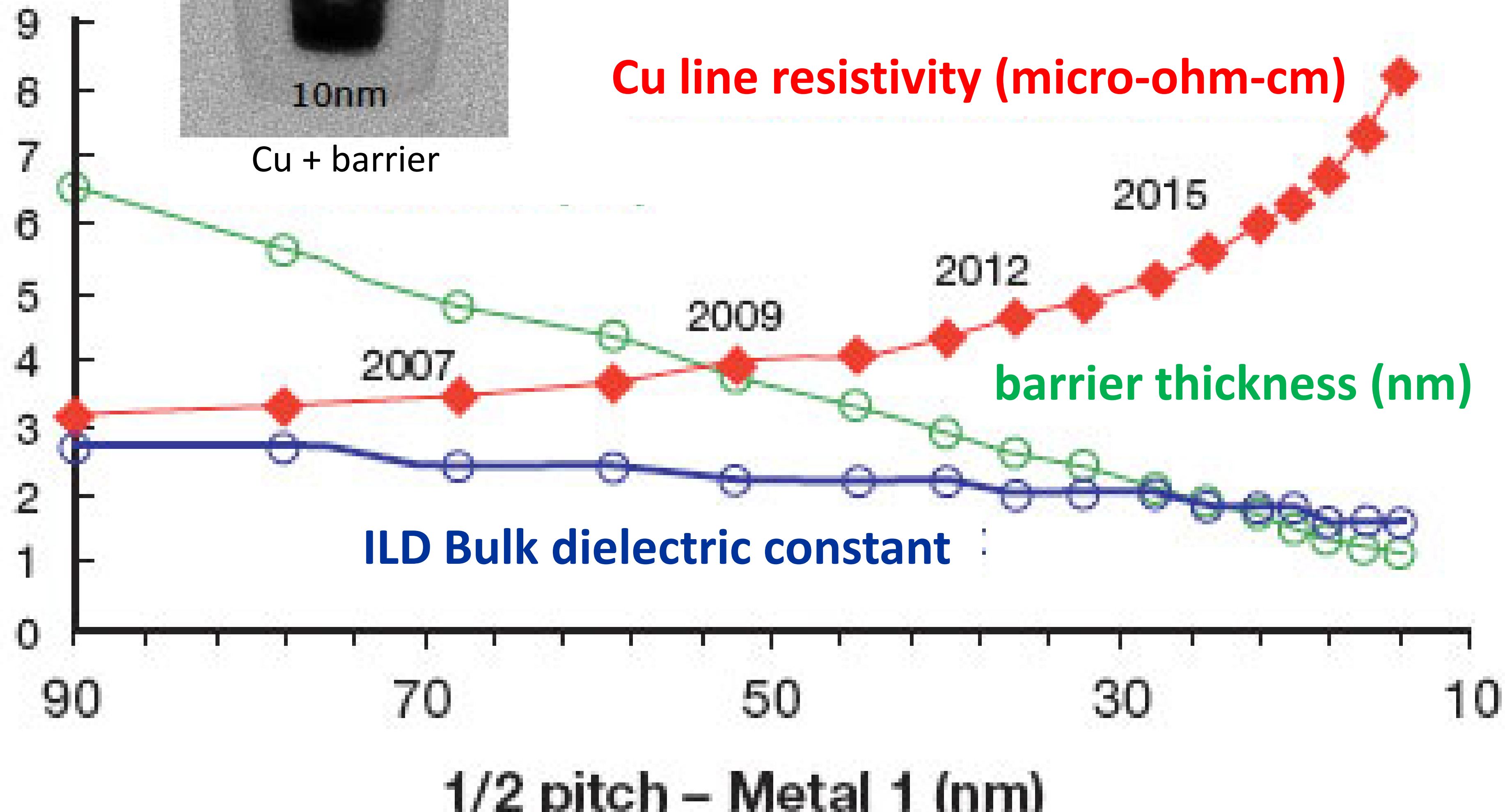
Length of interconnects in a microprocessor = 36 miles

Source: J. Clarke, Intel



Cu + barrier

Interconnect Triple Challenge



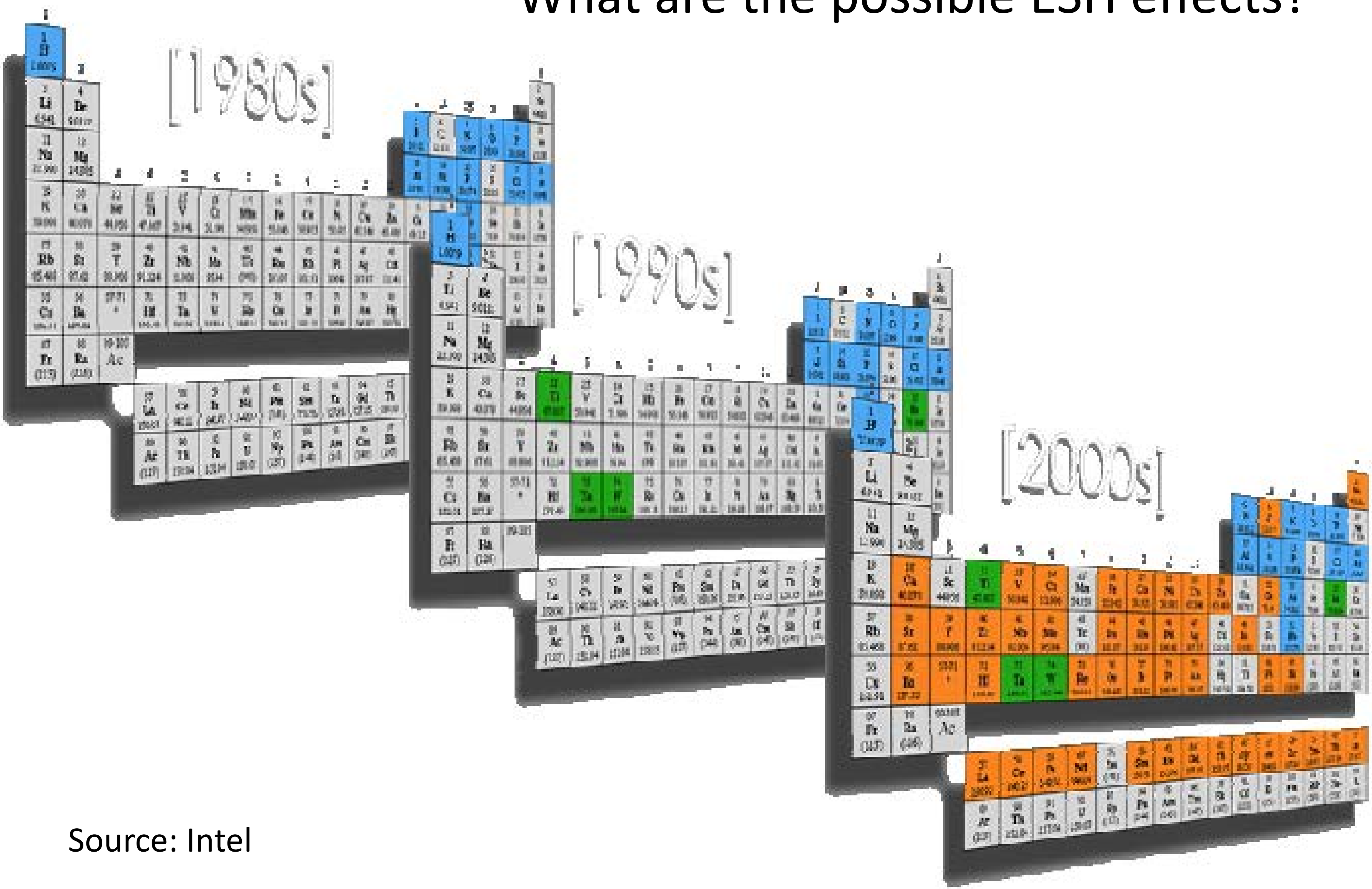
Source: http://www.future-fab.com/documents.asp?d_ID=4414

Need Better (Nano)Insulators: Low-k Dielectric Materials

Dielectric	Value of k (@ 1 MHz)
$SiO_x F_y$	3.2 - 3.5
Hydrogen silsesquioxane	3.0
Polysiloxane	2.89
Fluropolyimide	2.8
Benzo-cyclo-butane	2.7
Black diamond	2.7
Polyethylene	2.4
Polypropylene	2.3
Fluoropolymer	2.24
Perylene	2.2
Dupont PTFE-based copolymer AF 2400	2.06
Xerogels	1.2
Air	1.0
Carbon dioxide	1.0

“Silicon” Chips are Complex Nanomaterials

What are the possible ESH effects?



Source: Intel

2011 ITRS*: Addressing Increasing Complexity, ESH & Sustainability

- ESH strategies
  - To understand (characterize) processes and materials during the development phase
  - To use materials that are less hazardous or whose byproducts are less hazardous
  - To design products and systems (equipment and facilities) that consume less raw materials and resources
  - To make the factory safe for employees

* International Technology Roadmap for Semiconductors available at www.itrs.org

2011 ITRS: ESH Difficult Challenges (examples)

- Chemicals & materials
  - Assessment/characterization tools & methods
  - Comprehensive ESH data
- Process & equipment
  - "Greener" processes (more benign & less materials)
  - Exposure management
- Facilities
  - Improve efficiency (electricity, water, HVAC)
- Sustainability
  - Design for ESH (similar to other DFX)
  - Need for metrics

2011 ITRS: ESH & Emerging Nanomaterials

- Developing effective ***monitoring tools to detect nanomaterials' presence*** in the workplace, in waste streams, and in the environment
- Evaluating and developing appropriate ***protocols to ensure worker health and safety***
- Evaluating and developing ***emission control equipment*** to ensure effective treatment of nanomaterials-containing waste streams
- ***Understanding new nanomaterials' toxicity*** as it may differ from the bulk forms; involves developing rapid nanomaterials toxicity assessment methods as well as nanomaterials toxicity models

Industry's Voluntary Steps toward Sustainability

- World Semiconductor Council initiatives to reduce environmental impact
  - ***Reduce GHG emissions*** per area of Si wafer by 30% by 2020 from 2010 levels
  - ***Eliminate PFOS*** (perfluorooctyl sulfonates) from non-critical applications and research alternatives for critical uses
- Industry goal to keep energy/water use and air emissions constant per wafer during transition from 300 mm to 450 mm (more than 2X area)

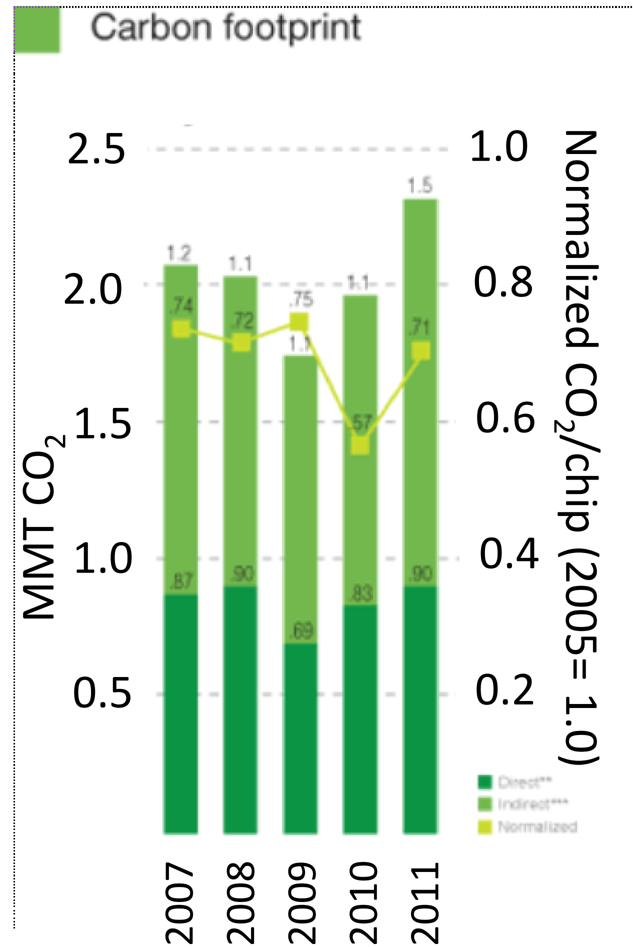
Individual Companies Setting Goals: Intel's 2012 Environmental Goals

- ***Reduce water use*** per chip below 2007 levels by 2012
- ***Reduce absolute global-warming gas footprin***t by 20% by 2012 from 2007 levels
- ***Reduce energy consumption*** per chip 5% per year from 2007 through 2012
- ***Reduce generation of chemical waste*** per chip by 10% by 2012 from 2007 levels
- ***Recycle 80% of chemical and solid waste*** generated per year
- Achieve engineering and design milestones to ensure that Intel products ***maintain the energy-efficiency lead*** in the market for next two product generations

Individual Companies Setting Goals: TI 2012 Environmental Goals

Texas Instruments

- Reduce GHG emissions per chip produced 30% by 2015 from 2010 level
- Raise waste efficiency (recycling) rate to 95% (currently 92%)
- Reduce chemical use in manufacturing by 3%

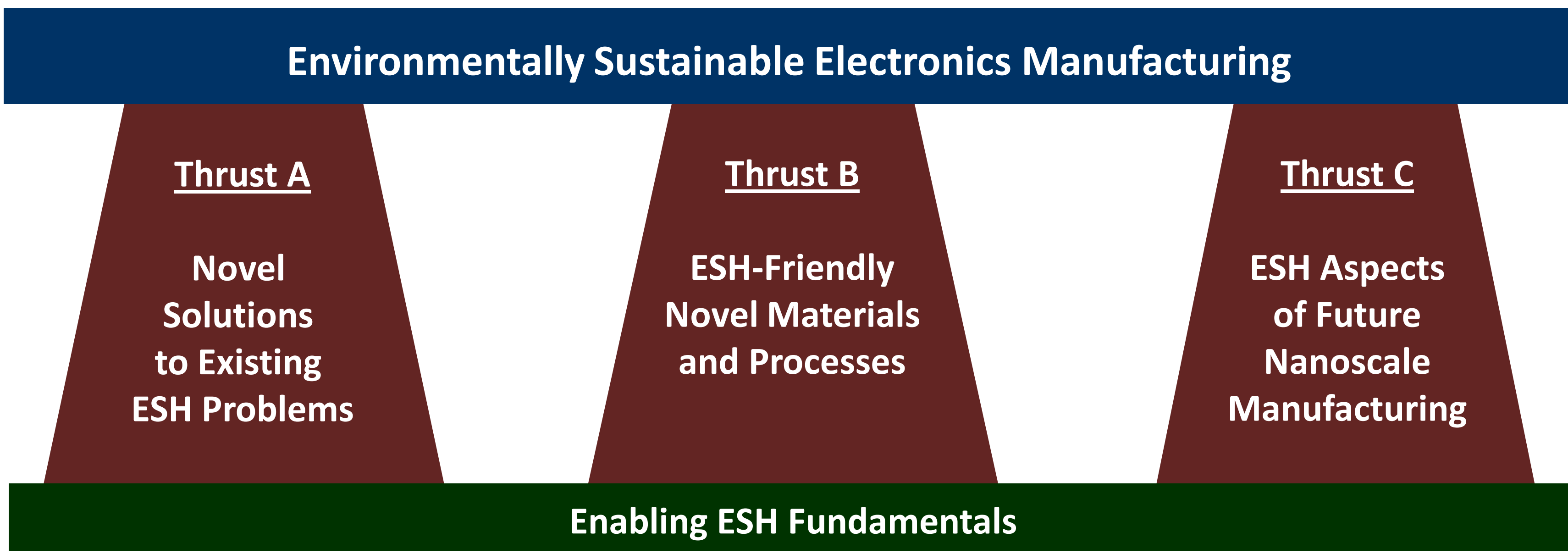


Center for Environmentally Benign Semiconductor Manufacturing

NSF ERC; co-funded with industry (SRC and SEMATECH) for 10 years; industry funded since 2006

APPROACH

- ✓ Focus on fundamental research to address manufacturing needs and technology gaps
- ✓ Transfer results to commercial application
- ✓ Create synergy and partnership with industry in <u>funding</u> and <u>conduct of research</u>



Founding Universities

- U Arizona
- U California – Berkeley
- MIT
- Stanford

Other University members

- Arizona State U (1998-)
- Columbia (2006-2009)
- Cornell (1998-)
- Georgia Tech (2009-)
- U Maryland (1999-2003)
- U Massachusetts (2006-2009)
- UNC-Chapel Hill (2009-)
- Purdue (2003-2008)
- U Texas-Dallas (2009-)
- Tufts (2005-2008)
- U Washington (2008-)
- U Wisconsin (2009-)
- UCLA (2011-)
- Johns Hopkins (2011-)
- NC A&T (2011-)

CEBMS Stats

Cumulative Data:

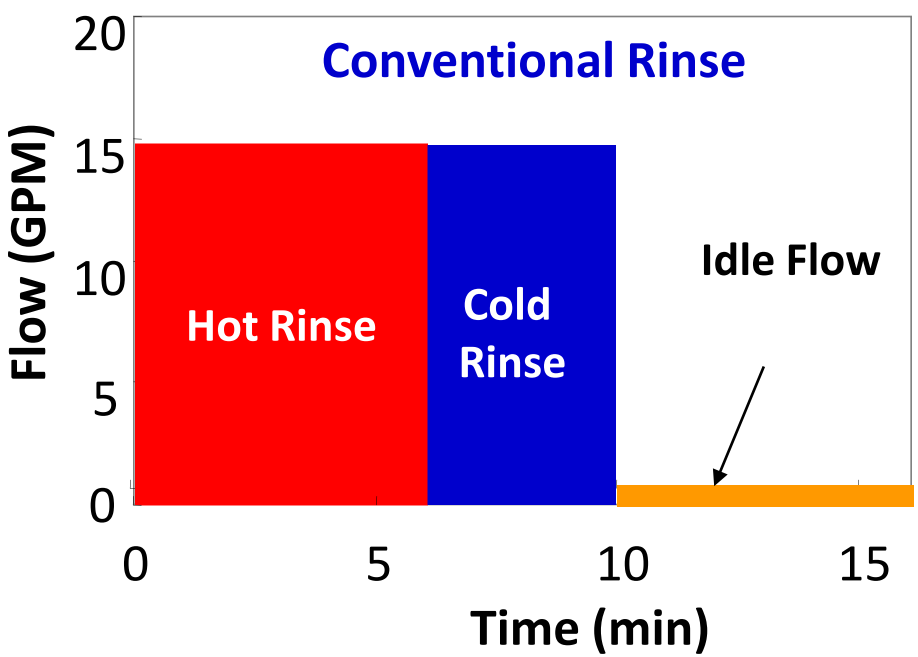
19	Core member Universities
243	PhD and MS
205	Undergraduates (reported)
13	Academic disciplines

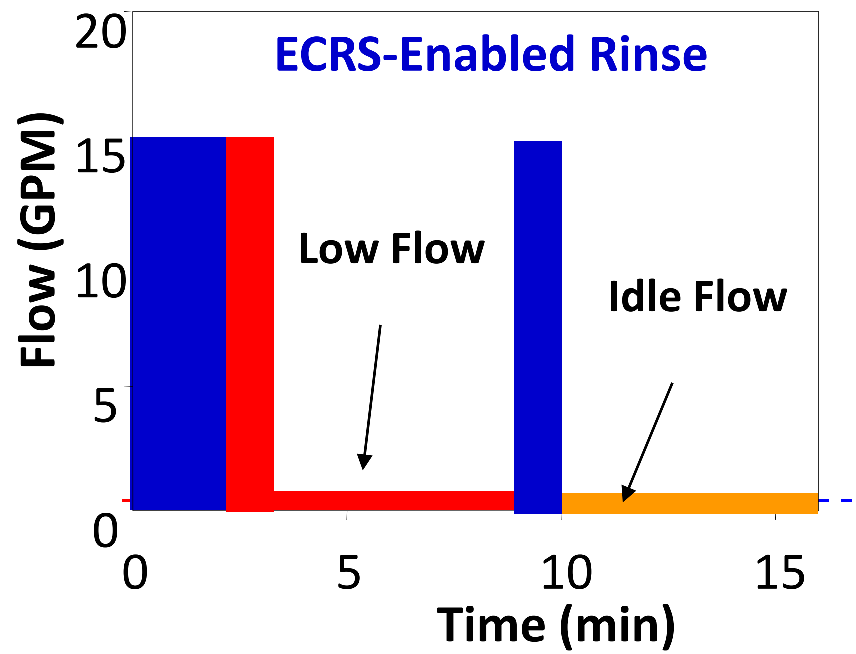
> 80% of graduates joined SC industry & suppliers (mostly ERC members)

13	Current member universities
37	Current PI/Co-PIs
39	Current graduate students

http://www.erc.arizona.edu/

Water & Energy Savings Enabled by Electro-Chemical Residue Sensor (ECRS)



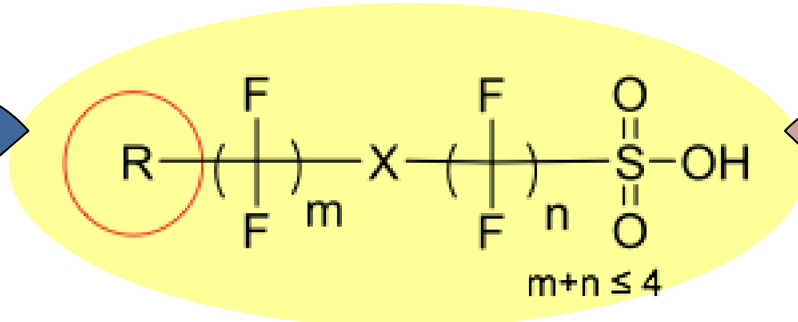


- Use initial cold rinse to flush tank
- Use hot water to finish flush and heat wafers
- Cycle time is not increased
- ***Savings: ~ 25% cold water and ~ 80% hot water***
- ★ Technology transferred to industry

Environmentally Friendly (PFOS-Free) Materials for Next Generation Photolithography

1^{st} & 2^{nd} Generation

3^{rd} Generation

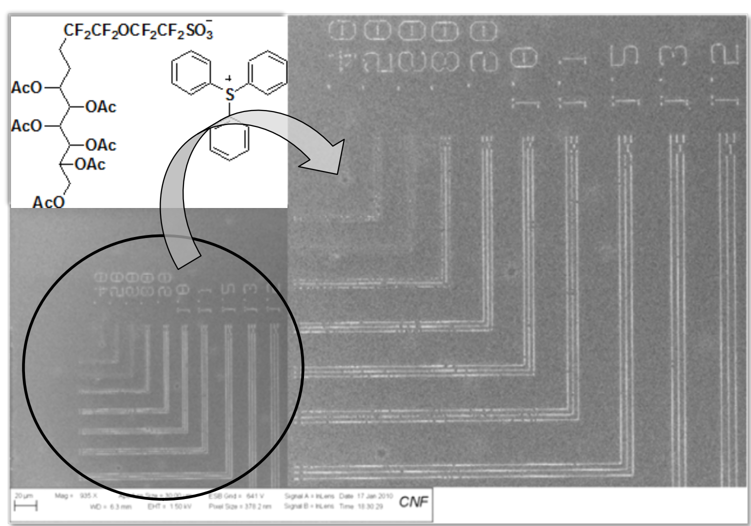


1st & 2nd Generation:

- Polar / Nonpolar
- Hydrophilic / Hydrophobic
- Aromatic / Aliphatic
- Linear / Branch / Ring

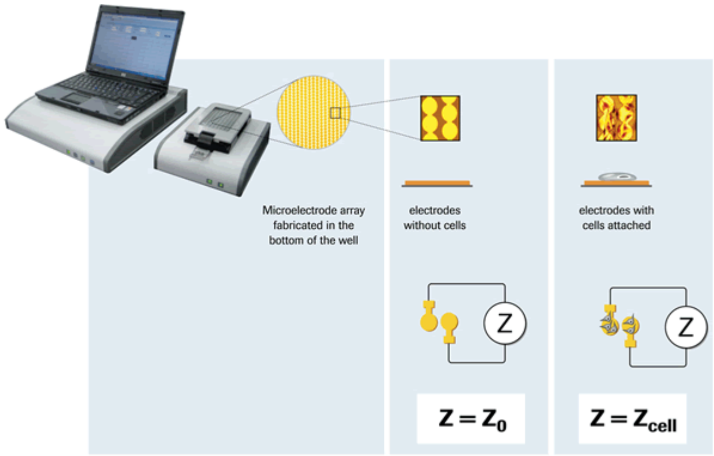
3rd Generation:

- Sugar based "Sweet" PAG
- Natural molecule-based Biocompatible/ Biodegradable PAG



New Techniques for Toxicity Assessment of Nanomaterials

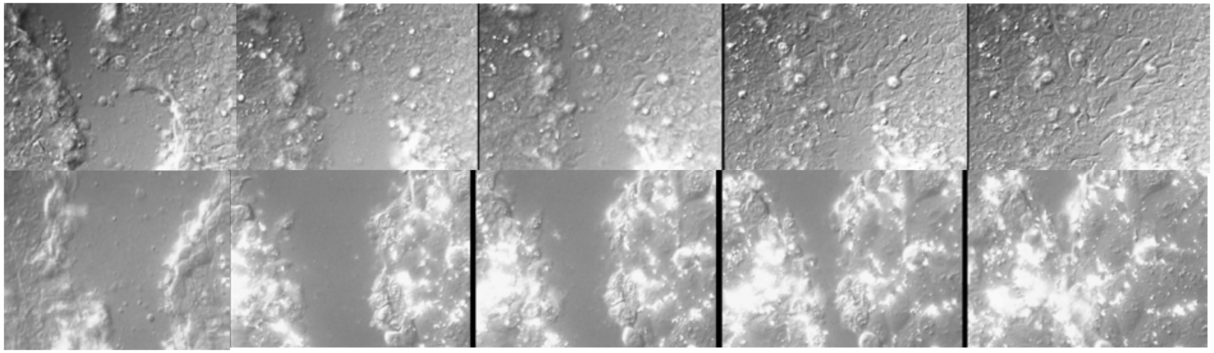
Impedance-based method



- ✓ HfO_2, ZrO_2 and CeO_2 NPs show mild to no toxicity.
- ✓ Higher toxicity correlated to chemical contamination
- ✓ Chemical reactive oxide species (ROS) production indicative of NP toxicity
- ✓ NPs producing ROS in water are most toxic.

Cell-based method (HBE lung cells)

Time:	0 h	0.5 h	1.0 h	1.5 h	2.0 h	HfO_2



0 ppm

250 ppm

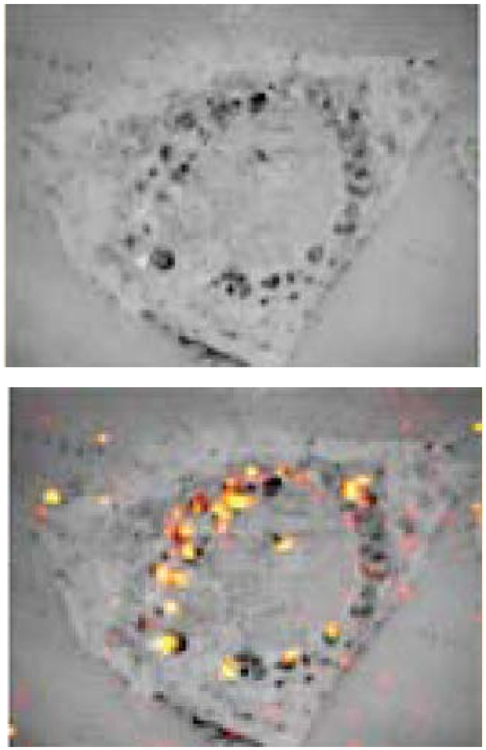
Predicting, Testing, and Neutralizing Nanoparticle Toxicity

Goal: Understand the factors that impact and reduce single-walled carbon nanotube (SWNT) toxicity.

Approach: Develop standard sonication and centrifugation processes to disperse SWNTs and assess their impact on the proliferative ability of a standard cell line.

Results:

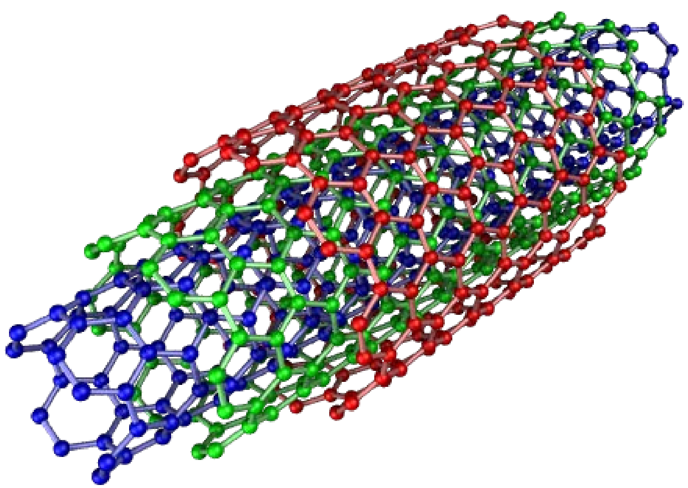
- SWCNT toxicity tends to correlate with contaminants, such as oxidized amorphous carbon species.
- Removal of these toxic contaminants appears to reduce the toxicity associated with carboxylated SWNTs.



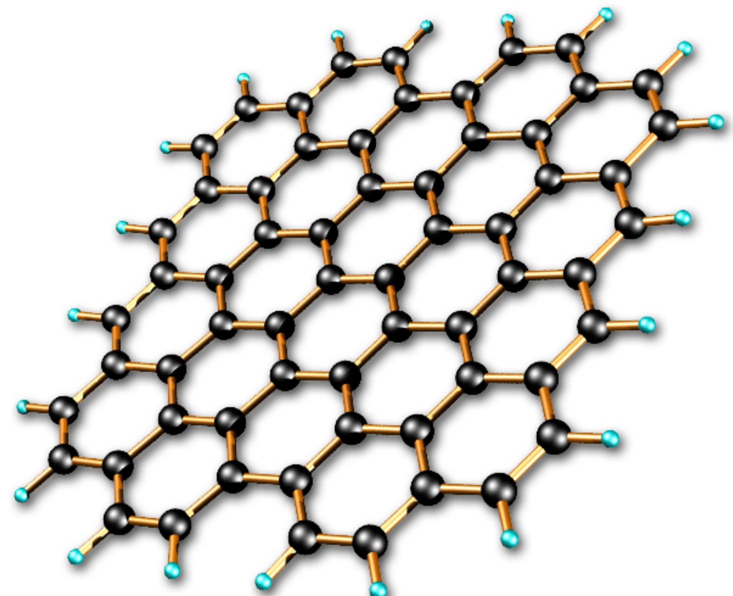
Sub-cellular location of SWCNTs using Raman microscopy.

Nanoelectronics:
Beyond Today's Technology

- Can we store and send 1's and 0's using something other than charge?
- Are there materials that offer advantages?



Carbon Nanotubes



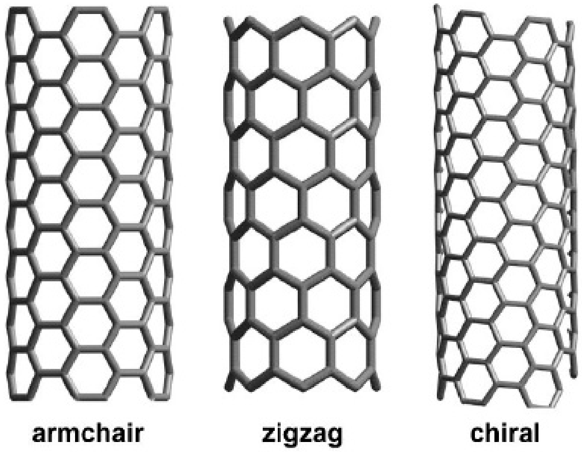
Graphene

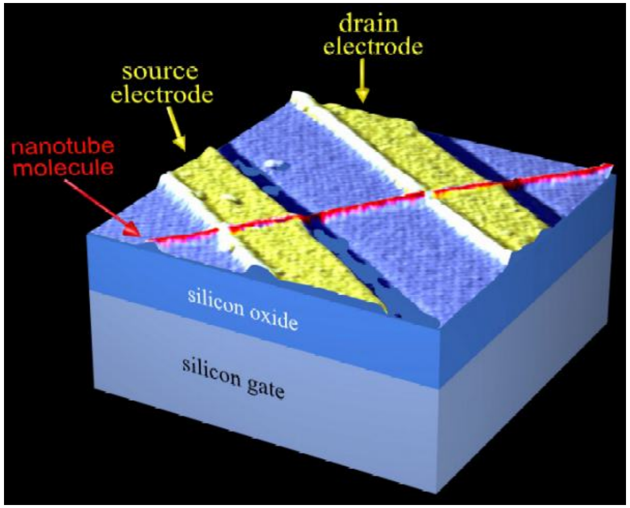
Carbon Nanotube Electronics

Carbon nanotube properties make them candidates to replace CMOS in transistor.

Challenges include:

- Making/sorting homogenous semiconducting material
- Precise placement of nanotubes
- Scalable process

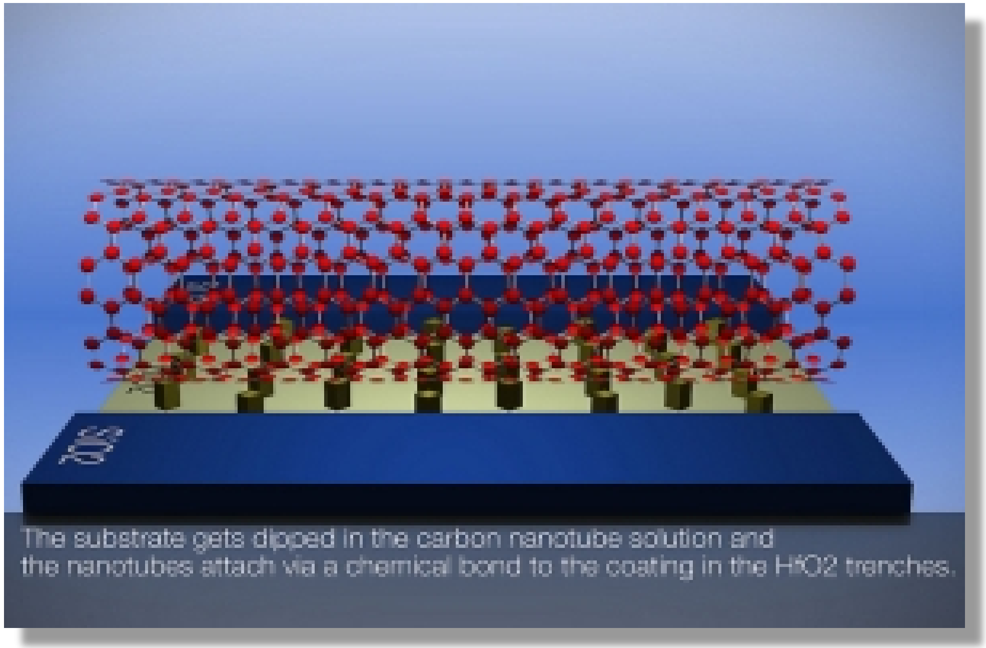




Carbon Nanotube Electronics

IBM researchers have discovered how to:

- precisely place carbon nanotubes on a computer chip,
- arrange the nanotubes 100 times more densely than earlier methods, and
- build a chip with more than 10,000 carbon nanotube-based elements



http://www-03.ibm.com/press/us/en/pressrelease/39250.wss

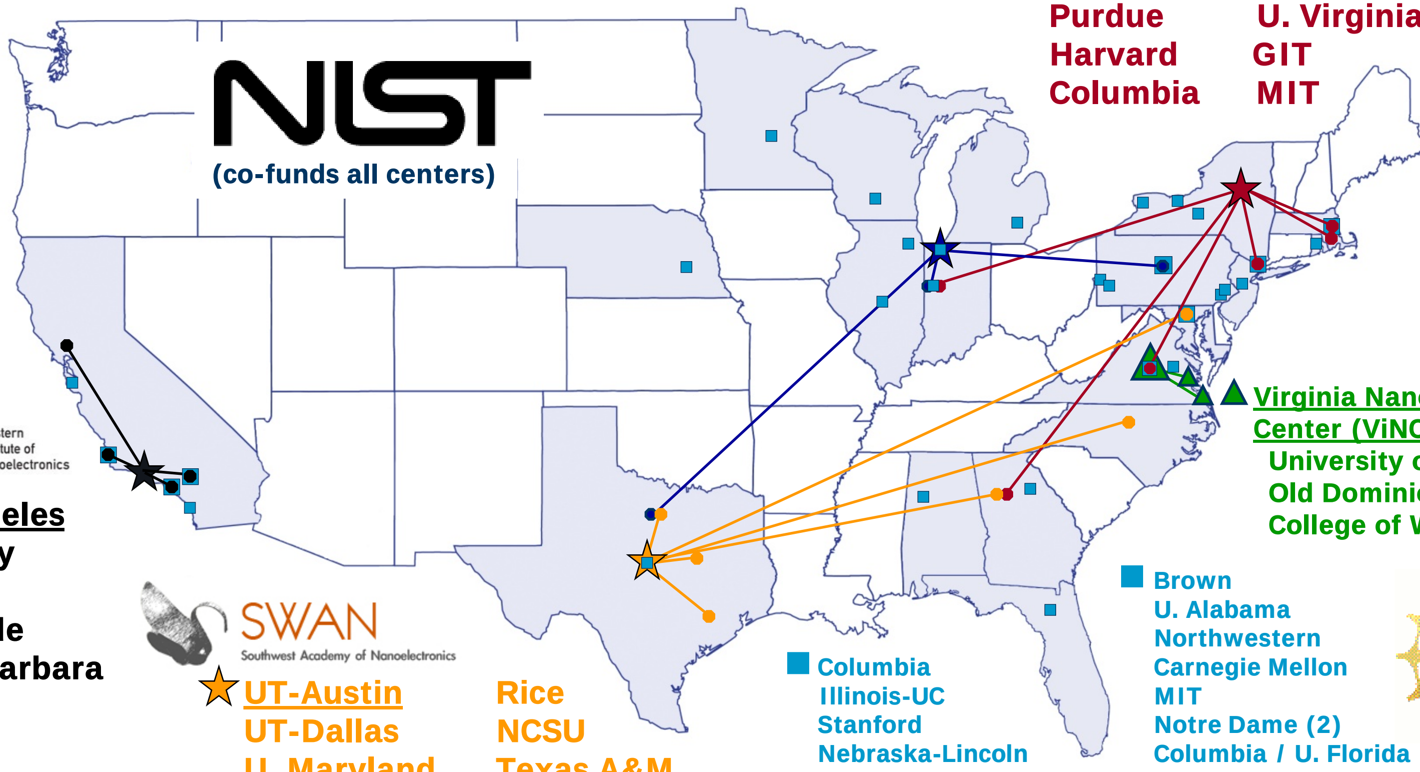
Nanoelectronics Research Initiative Industry-Govt Partnership

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



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

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

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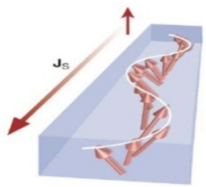
Northwestern
Carnegie Mellon
MIT
Notre Dame (2)
Columbia / U. Florida
U. of Minnesota
Cornell / Princeton
Drexel University / UI-UC / U. Penn

NSF

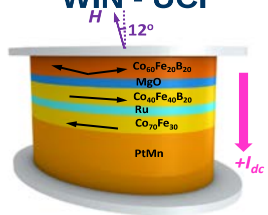
Over 40 Universities in 19 States

NRI: Research on Novel Materials and Devices for "Beyond Moore's Law"

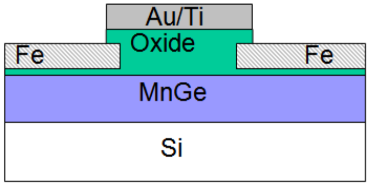
Spin-Wave Device
WIN - UCLA, UCSB



Spin-Torque Device
WIN - UCI

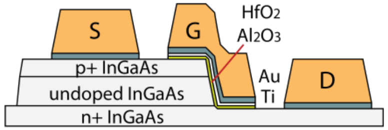


Spin-FET
WIN - UCLA



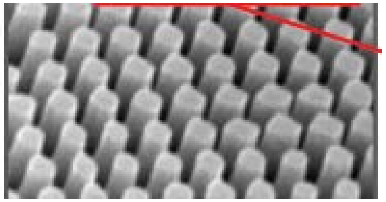
Tunnel Devices
MIND

Heterojunctions
Notre Dame, Penn State

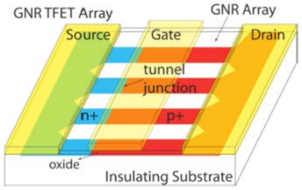


vertical TFET - side gated

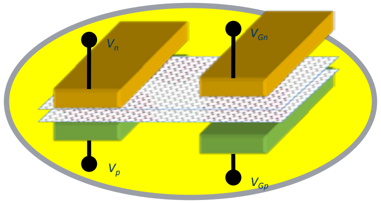
Nanowires
Penn State



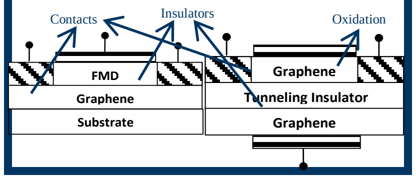
Graphene
Notre Dame



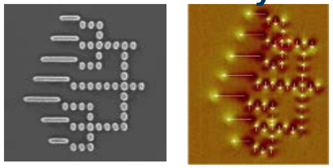
Bilayer pseudoSpin
SWAN - UT Austin



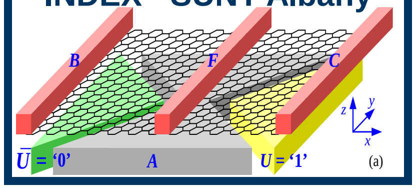
Graphene Processes
SWAN – UT Dallas



Nanomagnet Logic
MIND - Notre Dame
WIN - Berkeley

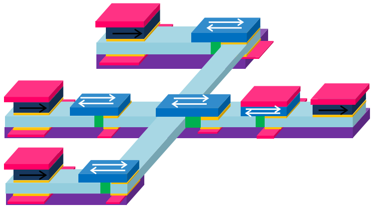


Graphene PN Junction Device
INDEX - SUNY Albany



Graphene Integration
INDEX – SUNY Albany

All-Spin Logic
INDEX - Purdue U.

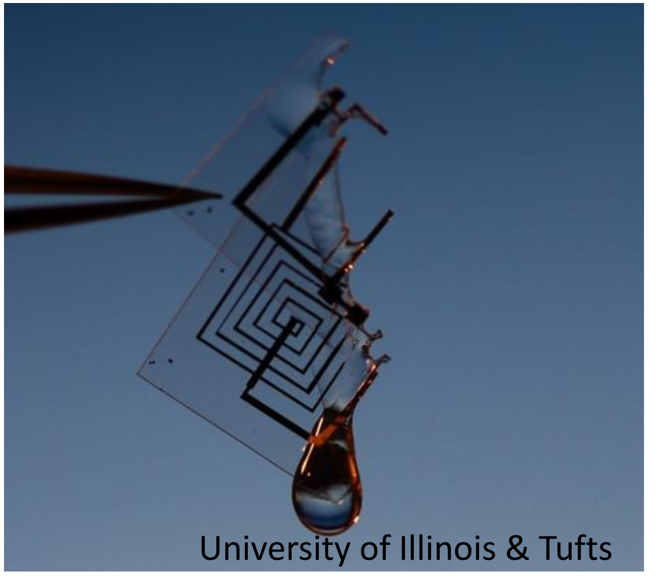


Looking Ahead

- Sustainable industry and sustainable nanotechnology go hand in hand
- Areas where work is needed:
  - Nano metrology/characterization
  - Nanomanufacturing
  - Nano sensors
  - Sustainability metrics

Take Away Messages

- Industries are keenly interested in sustainability from a business perspective
- Nanotechnology offers the potential to reduce use of resources and make new greener products
- Nanoelectronics (aka semiconductor industry) has potential to raise sustainability of many other industries


University of Illinois & Tufts