EE 218: Introduction to Nanotechnology and Nanoelectronics

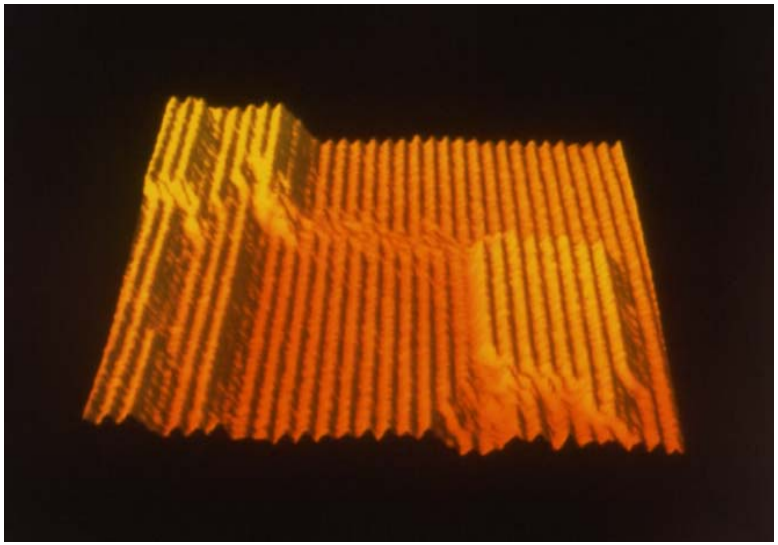
H.-S. Philip Wong
Professor of Electrical Engineering
Stanford University, Stanford, California, U.S.A.
hspwong@stanford.edu

http://www.stanford.edu/~hspwong

What is Nanotechnology?

Source: Apple Computer, Inc.

The Beginning of Nano



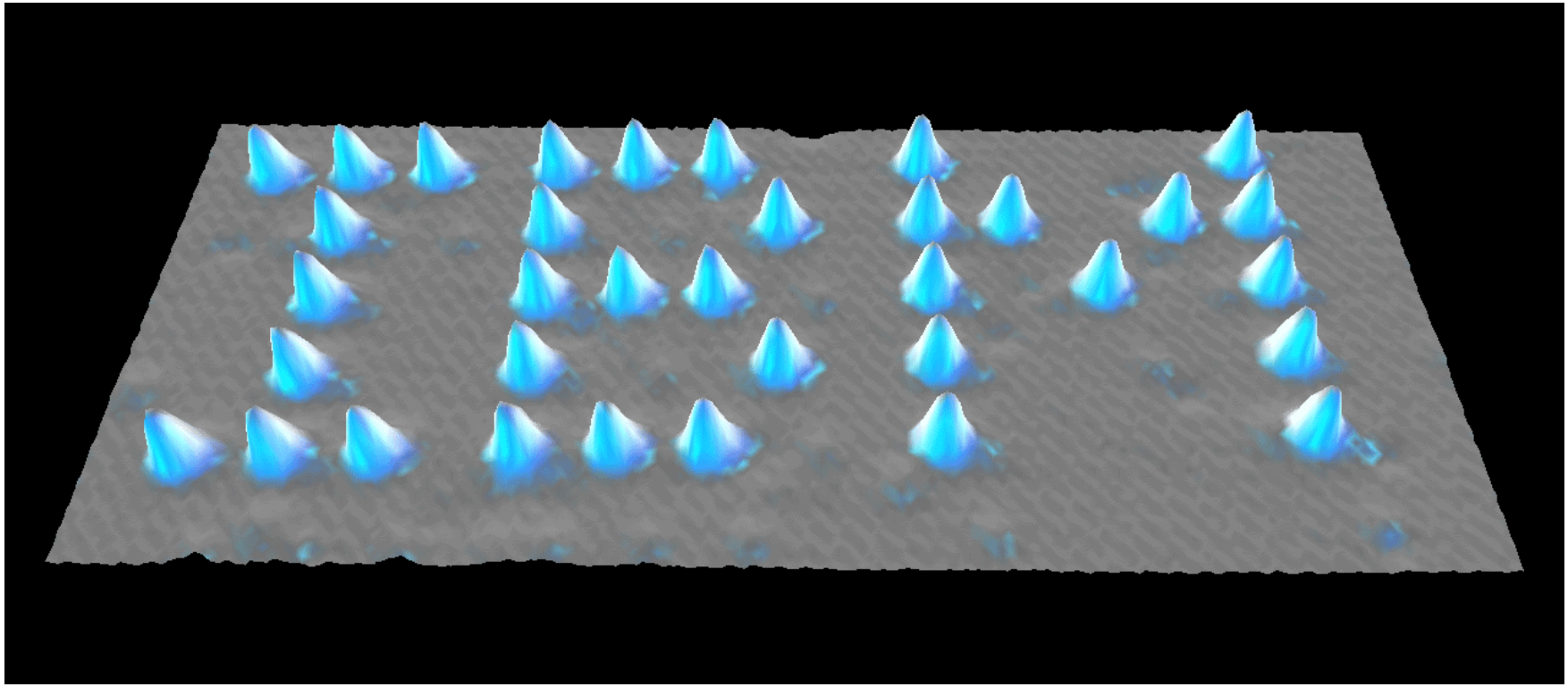
Source: IBM

Invention of the Scanning Tunneling Microscope (STM)

Source: IBM

Gerd Binnig, Heinrich Rohrer

Nobel Prize, 1986



Source: IBM

Sept. 2000

Defining Nanotechnology

Definition on www.nano.gov/omb_nifty50.htm (see report NS&T)

- Working at the atomic, molecular and supramolecular levels, in the length scale of approximately 1 – 100 nm range, in order to understand and create materials, devices and systems with fundamentally new properties and functions because of their small structure

- **NNI definition encourages new contributions that were not possible before.**

  - novel phenomena, properties and functions at nanoscale, which are nonscalable outside of the nm domain

  - the ability to measure / control / manipulate matter at the nanoscale in order to change those properties and functions

  - integration along length scales, and fields of application

Source: M. Roco (NNI), National Research Council, Washington, D.C., June 27, 2005.

MC. Roco, 6/27/05

The Scale of Things -- Nanometers and More

Source: NSF website

Things Natural

Dust mite

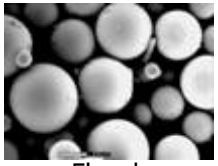
200 μm

Ant

~ 5 mm

Human hair

~ 10-50 μm wide

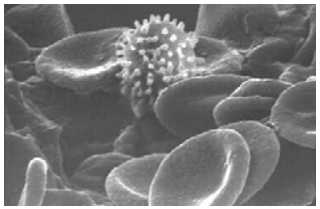


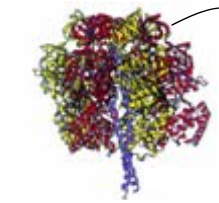
Fly ash

~ 10-20 μm

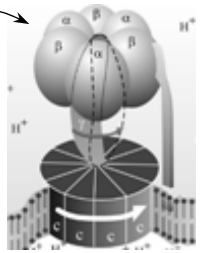
Red blood cells with white cell

~ 2-5 μm

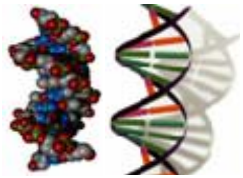




~10 nm diameter



ATP synthase

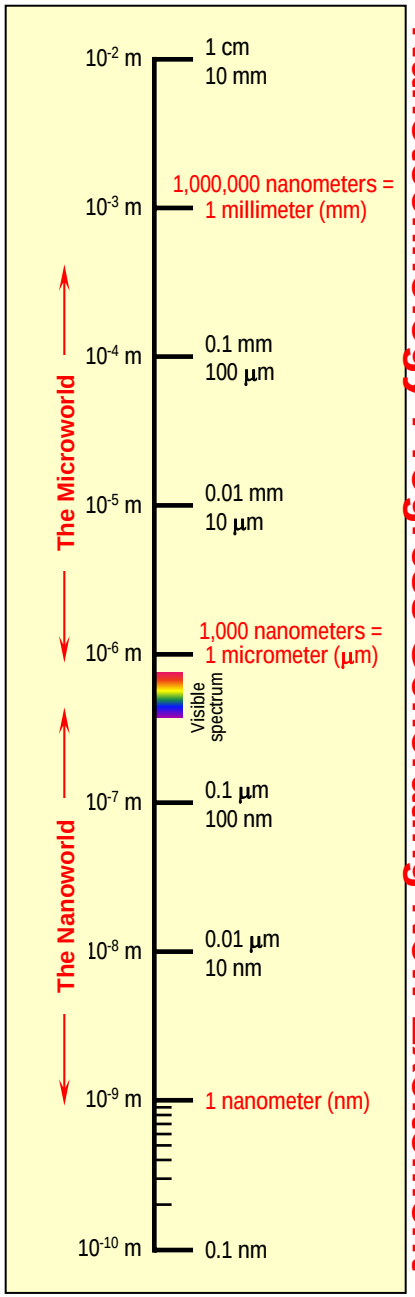


DNA

~2-1/2 nm diameter

Atoms of silicon

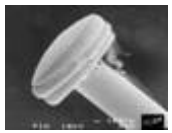
spacing ~tenths of nm



Nanotechnology Progress Generating New Excitement

Things Manmade

Source: J. Sphorer (IBM)

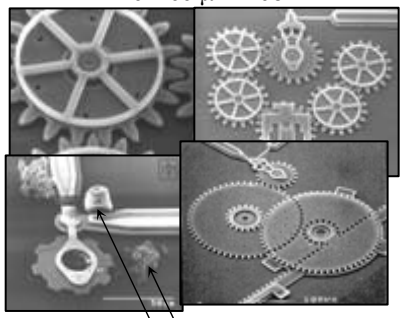


Head of a pin

1-2 mm

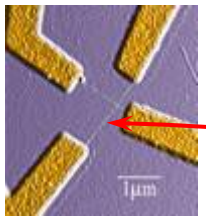
MicroElectroMechanical Devices

10 -100 μm wide

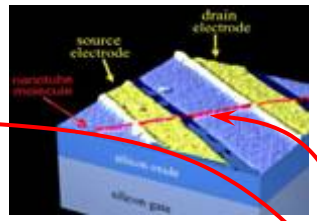


Red blood cells

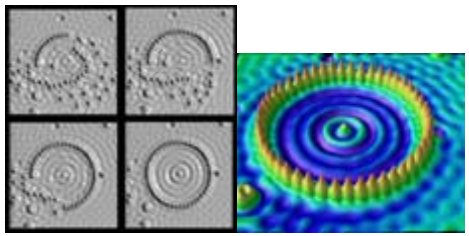
Pollen grain



Nanotube electrode



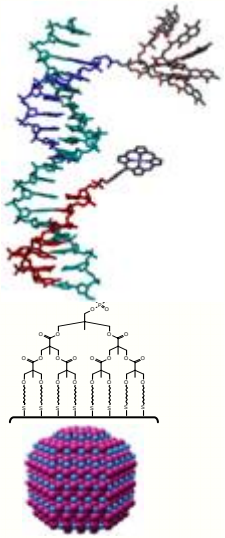
Nanotube transistor



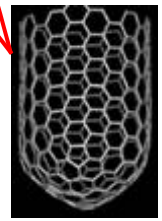
Quantum corral of 48 iron atoms on copper surface positioned one at a time with an STM tip

Corral diameter 14 nm

21st Century Challenge



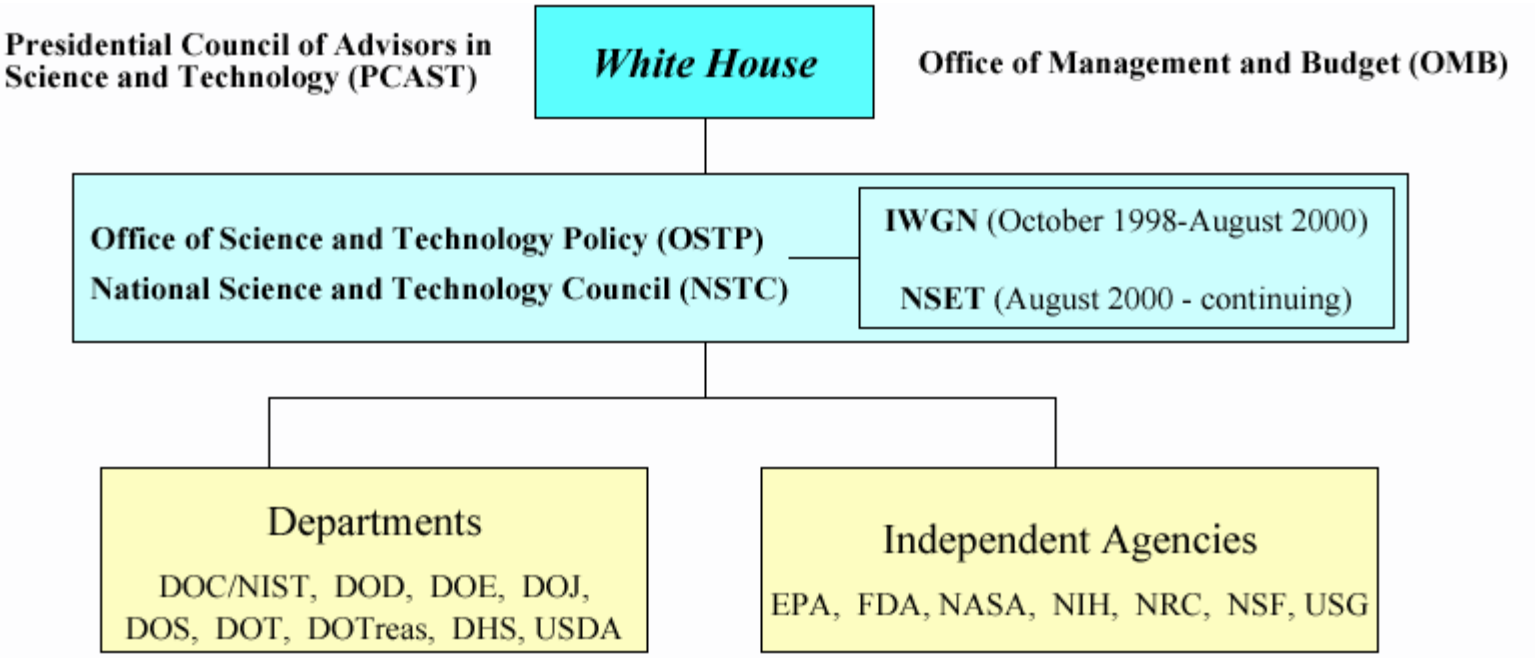
Combine nanoscale building blocks to make functional devices, e.g., a photosynthetic reaction center with integral semiconductor storage



Carbon nanotube

~2 nm diameter

US Nanotechnology Funding



Estimation: Federal Government R&D funding NNI (~$770M in 03)
Industry (private sectors) ~ NNI funding
20 state and local (universities, foundations) ~ 1/2 NNI funding

Source: M. Roco, NNI (10/29/2003).

NNI Funding by Agency

Fiscal year (all in million $)	*2000* Actual	*2001* Enact/Actual	*2002* Enact/Actual	*2003* Enact/Actual	2004 Req./Actual	2005 Req/Est.
National Science Foundation	97	150 /150	199 /204	221 /221	249 /256	305/338
Department of Defense	70	110 /125	180 /224	243 /322	222 /291	276/257
Department of Energy	58	93 /88	91.1 /89	133 /134	197 /202	211/210
Health and Human Services	32	39 /39.6	40.8 /59	65 /78	70 /106	89/145
NASA	5	20 /22	35 /35	33 /36	31 /47	35/45
NIST	8	10 /33.4	37.6 /77	66 /64	62 /77	53/75
EPA	-	/5.8	5 /6	5 /5	5 /5	5/5
Homeland Security (TSA)	-		2 /2	2 /1	2 /1	1/1
Department of Agriculture	-	/1.5	1.5 /0	1 /1	10 /2	5/3
Department of Justice	-	/1.4	1.4 /1	1.4 /1	1.4 /2	1/2
Congressionally-directed to DOD				80	103	150
TOTAL	270	422 /465	600 /697	770 /942	849 /1094	982/1231
		+72%	+50%	+35%	+16%	+ 13%

- NNI as part of U.S. Federal R&D ~ 0.25% (2000) to 1% (2004)
- Industry (x 1.7) + state and local organizations (x 0.4) = 1.1NNI budget in 2004

MC. Roco, 6/27/05

Source: M. Roco (NNI), National Research Council, Washington, D.C., June 27, 2005.

Global Nanotechnology Investment

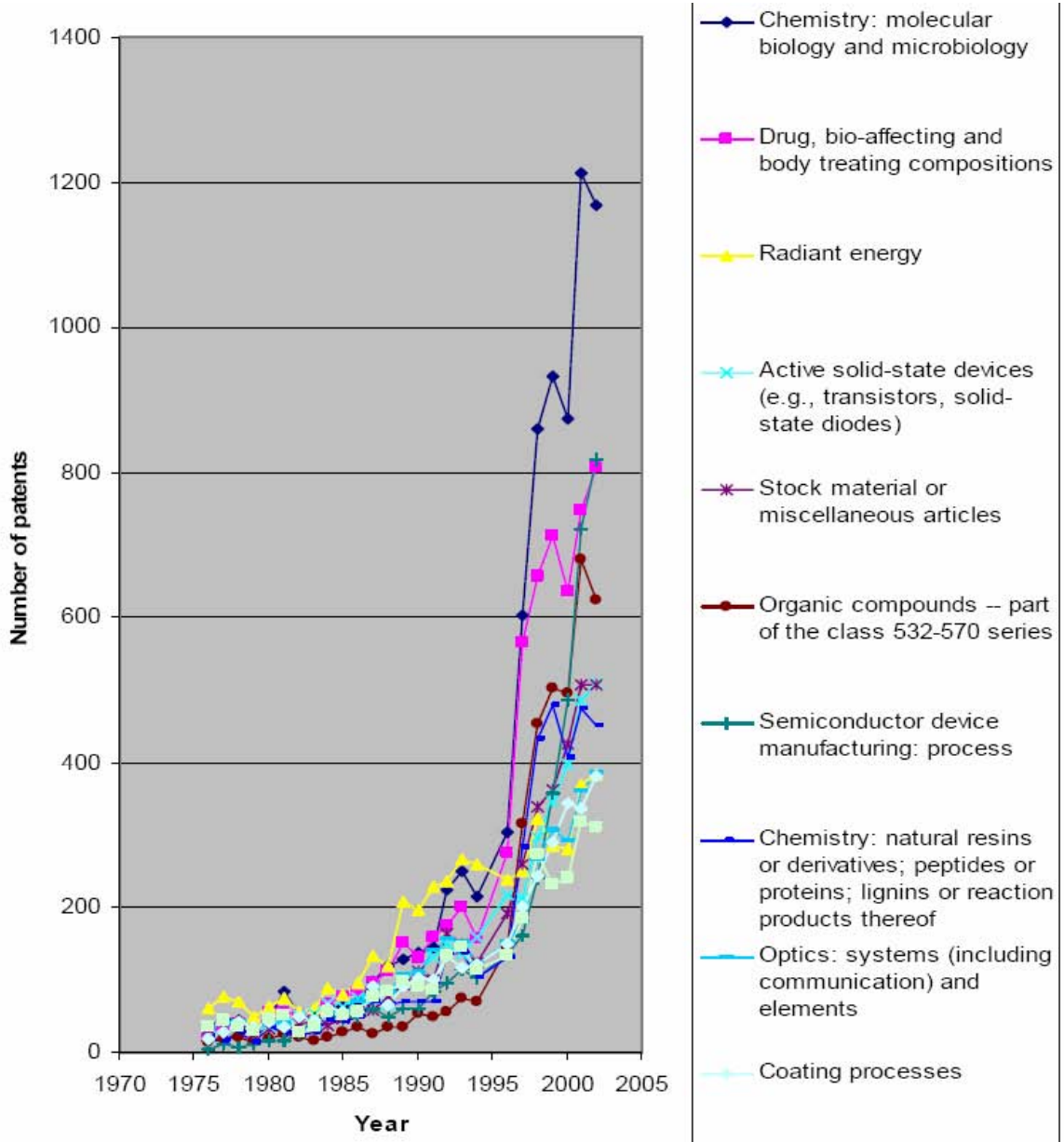
Source: M. Roco (NNI), National Research Council, Washington, D.C., June 27, 2005.

Areas of NNI investment
(Program Component Areas)

1. Fundamental Nanoscale Phenomena and Processes
2. Nanomaterials
3. Nanoscale Devices and Systems
4. Instrumentation Research, Metrology, and Standards for Nanotechnology
5. Nanomanufacturing
6. Major Research Facilities and Instrumentation Acquisition
7. Societal Dimensions (EHS, Education,ELSI)

Source: M. Roco (NNI), National Research Council, Washington, D.C., June 27, 2005.

MC Roco, 6/27/05



Technology field analysis by year

www.nsf.gov/nano
(Longitudinal Nanotechnology Patent Analysis, from J. of Nanoparticle Research, 2003)

Source: M. Roco, NNI (10/29/2003).

MC. Roco, 6/19/03

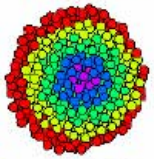
10-20 years vision

Timeline for beginning of industrial prototyping and commercialization

Increased integration, system approach

Converging science and engineering

- **1st Generation: Passive nanostructures ~ 2001**

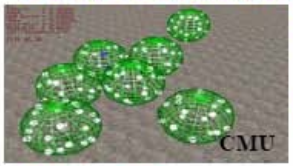


Ex: coatings, nanoparticles, nanostructured metals, polymers, ceramics

- **2nd Generation: Active nanostructures ~ 2005**

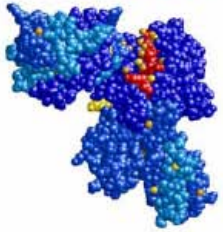
Ex: transistors, amplifiers, targeted drugs, actuators, adaptive structures

- **3rd Generation: Systems of nanosystems ~ 2010**



Ex: guided molecular assembling; 3D networking and new system architectures, robotics, supramolecular

- **4th Generation: Molecular nanosystems ~ 2020**



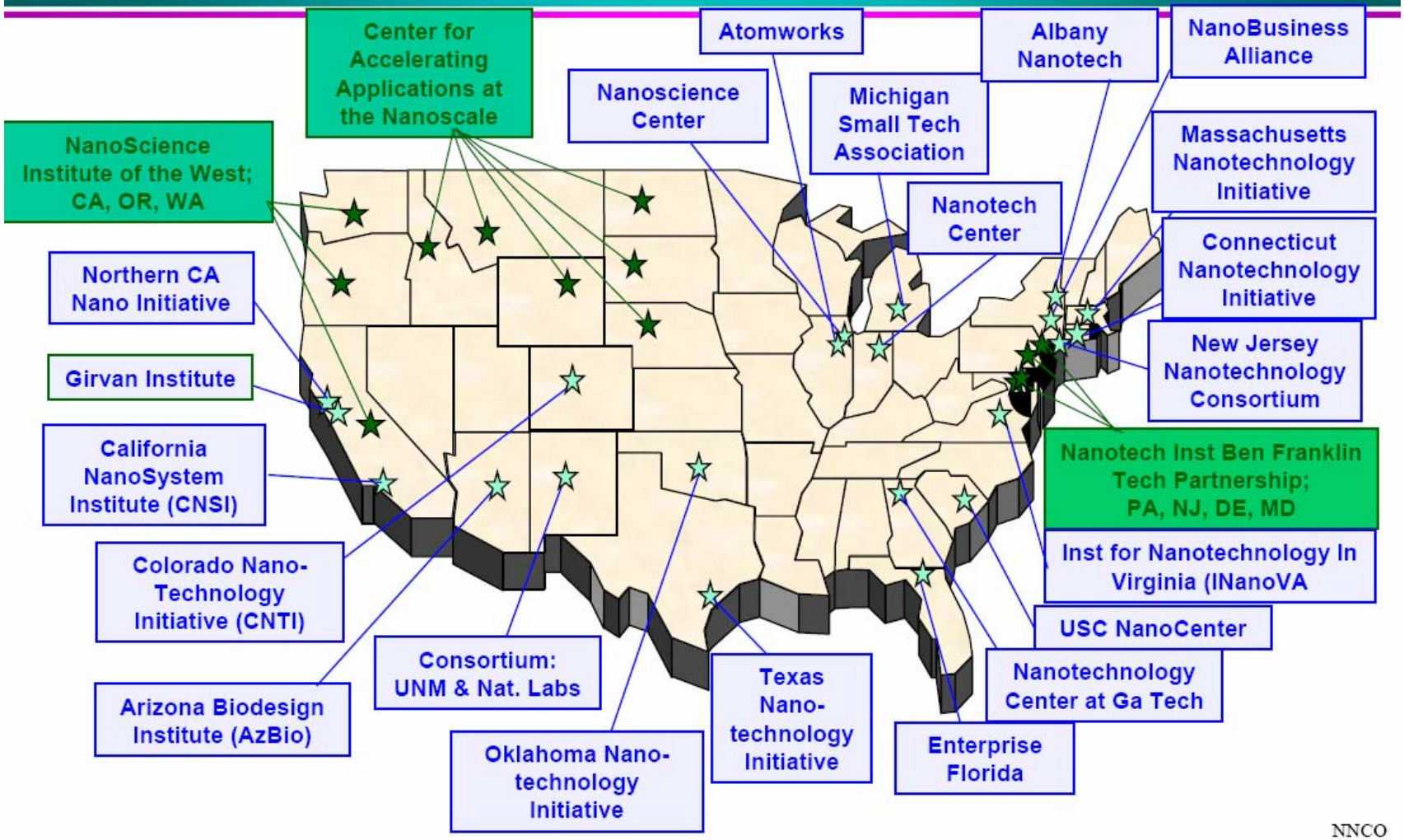
Ex: molecules as devices/components 'by design', based on atomic design, hierarchical emerging functions, evolutionary systems

Source: M. Roco (NNI), National Research Council, Washington, D.C., March 23, 2005

MC Roco, 9/08/04

NATIONAL NANOTECHNOLOGY INITIATIVE

Sampling of Current Regional, State, & Local Initiatives in Nanotechnology



Source: M. Roco (NNI), National Research Council, Washington, D.C., June 27, 2005.

IBM Research

http://www.research.ibm.com/pics/nanotech/

Nanotechnology

About IBM's Nanotech Research

IBM's nanotechnology research aims to devise new atomic- and molecular-scale structures and devices for enhancing information technologies, as well as discover and understand their scientific foundations.

Leading the development of nanotechnology, IBM's scientists have made numerous breakthroughs in the study of these nano-scale technologies.

In particular, carbon nanotubes and scanning probes derived from the atomic force microscope -- cousin of the scanning tunneling microscope -- show particular promise in enabling dramatically improved circuits and data storage devices. Research on nanoparticles leads to applications in biomedicine as well as hard disk drive storage. Photonic bandgap materials -- on-chip nanoscale structures the size of a wavelength of light -- will manipulate light as optical waveguides, splitters and routers. Research into nanomechanical information storage, such as IBM's Millipede project, continues to increase the possibilities for increased areal storage density.

IBM's research into nano-scale structures that self-assemble may one day obviate the need to "hand-position" atoms. Nanotechnology will allow the design and control of the structure of an object on all length scales, from the atomic to the macroscopic enabling more efficient and vastly less expensive manufacturing processes and providing the hardware foundation for future information technology.

What is Nanotechnology?

Top News

- IBM scientists demonstrate single-atom magnetic measurements
  September 9, 2004: First result by a promising new technique they developed to study the properties of nanometer-scale magnetic structures.
- IBM scientists make breakthrough in nanoscale imaging
  July 14, 2004: Directly detecting the faint magnetic signal from a single electron buried inside a solid sample is a breakthrough in nanoscale magnetic resonance imaging (MRI).
- IBM researchers develop low-cost method for making high-performance semiconductors
  March 17, 2004: A major scientific milestone toward new low cost electronics
- IBM DEMOS NEW NANOTECHNOLOGY METHOD TO BUILD CHIP COMPONENTS
  December 8, 2003: Creates nanocrystal memory devices using self assembly technique compatible with conventional semiconductor processing
- Scientists announce first 3-D assembly of magnetic and semiconducting nanoparticles
  June 25, 2003: A modular assembly method that will let us bring almost any materials together
- IBM Scientists Create World's Smallest Solid-state Light Emitter
  May 1, 2003: Pioneering New Applications for Carbon Nanotubes

More Nanotechnology News

Projects

Nanoelectronics
- Carbon Nanotubes
- Molecular Devices
- Nanomagnetics for ultra-dense storage
- Organic Transistors
- Photonic Crystals
- Silicon Transistors

Nanomaterials (self-assembly)
- Di-block copolymer templates
- Bottom-up Nanomachines
- Nanocrystal assemblies
- Quantum dots/wires
- UHV-TEM

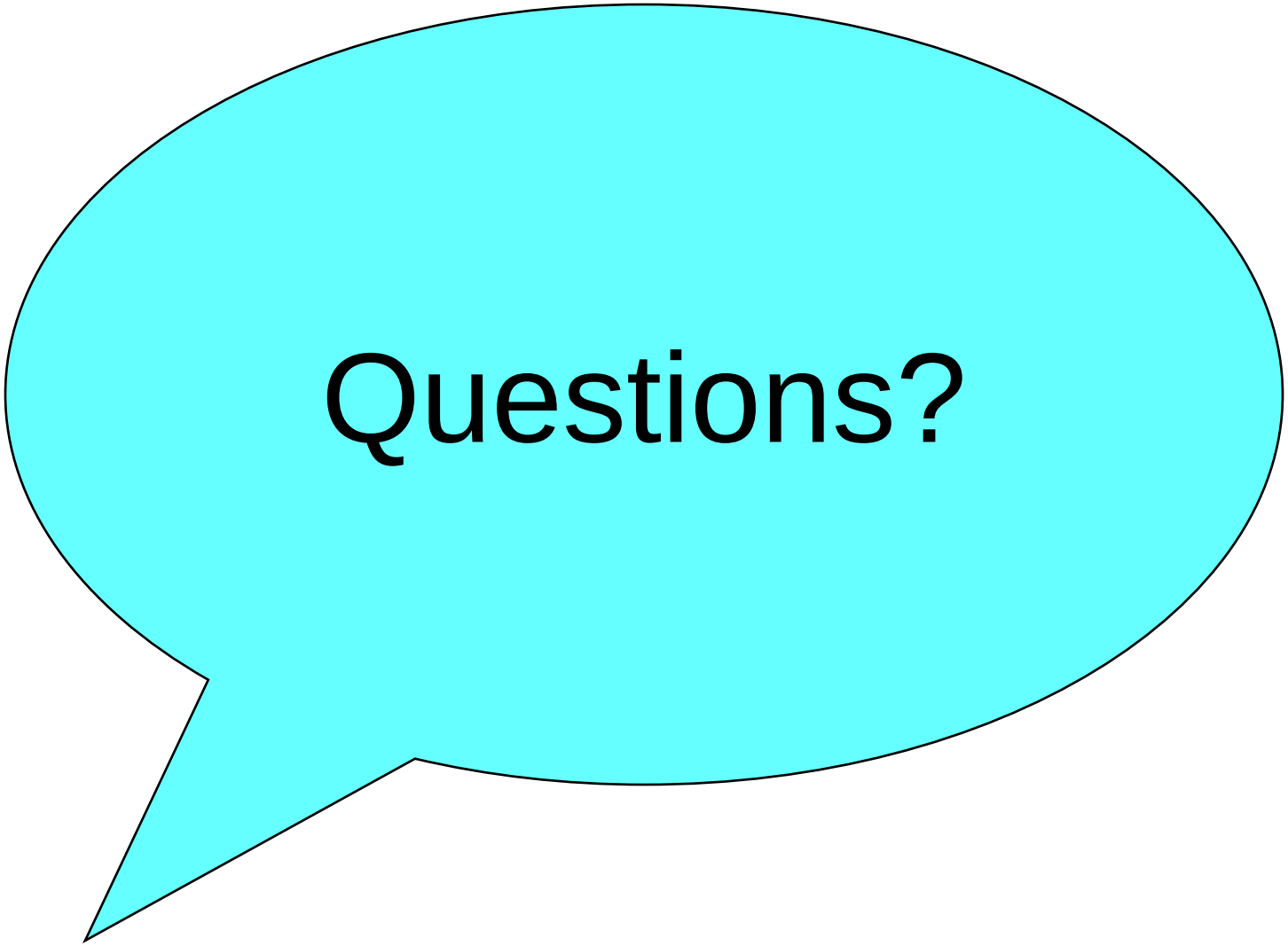
Nanomechanics
- AFM-based storage technology (Millipede)

Quantum Coherent Systems
- Quantum computing
- Quantum mirage
- Spintronics (nanomagnetics)

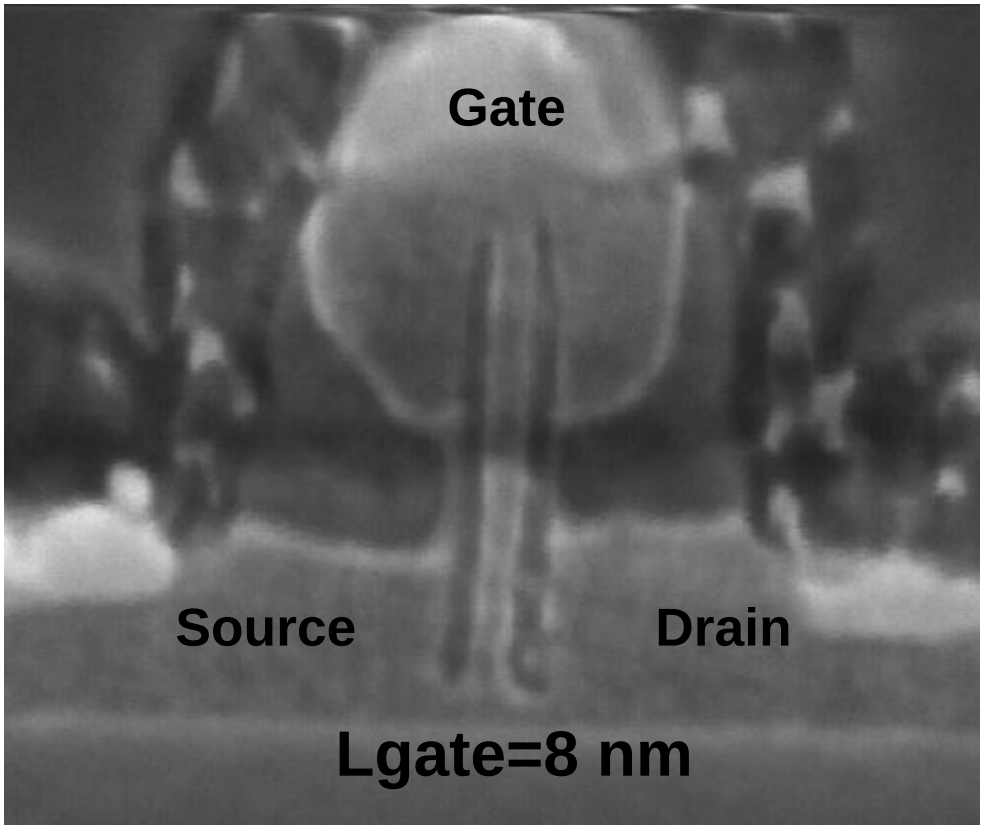
Bionanotechnology
- Biopatterning
- Cantilever Sensors

Material Characterization & Tools
- Assembly tool for molecular structures
- Electron Microscopy
- Magnetic Resonance Force Microscope
- Microcontact processing
- Nanoscale Materials Analysis

Nanotechnology in our Labs
- Almaden Research Center
- Watson Research Center
- Zurich Research Lab

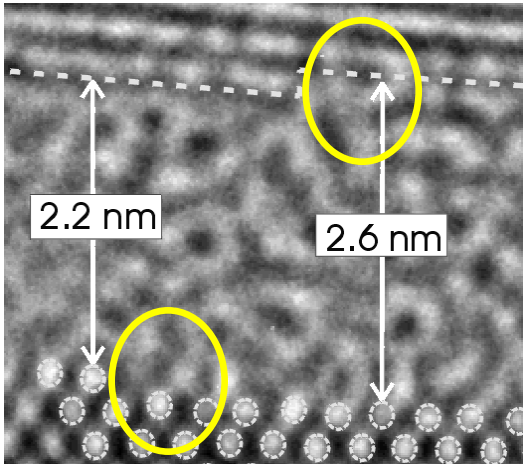

Questions?

An 8 nm Transistor Gate



Source: IBM

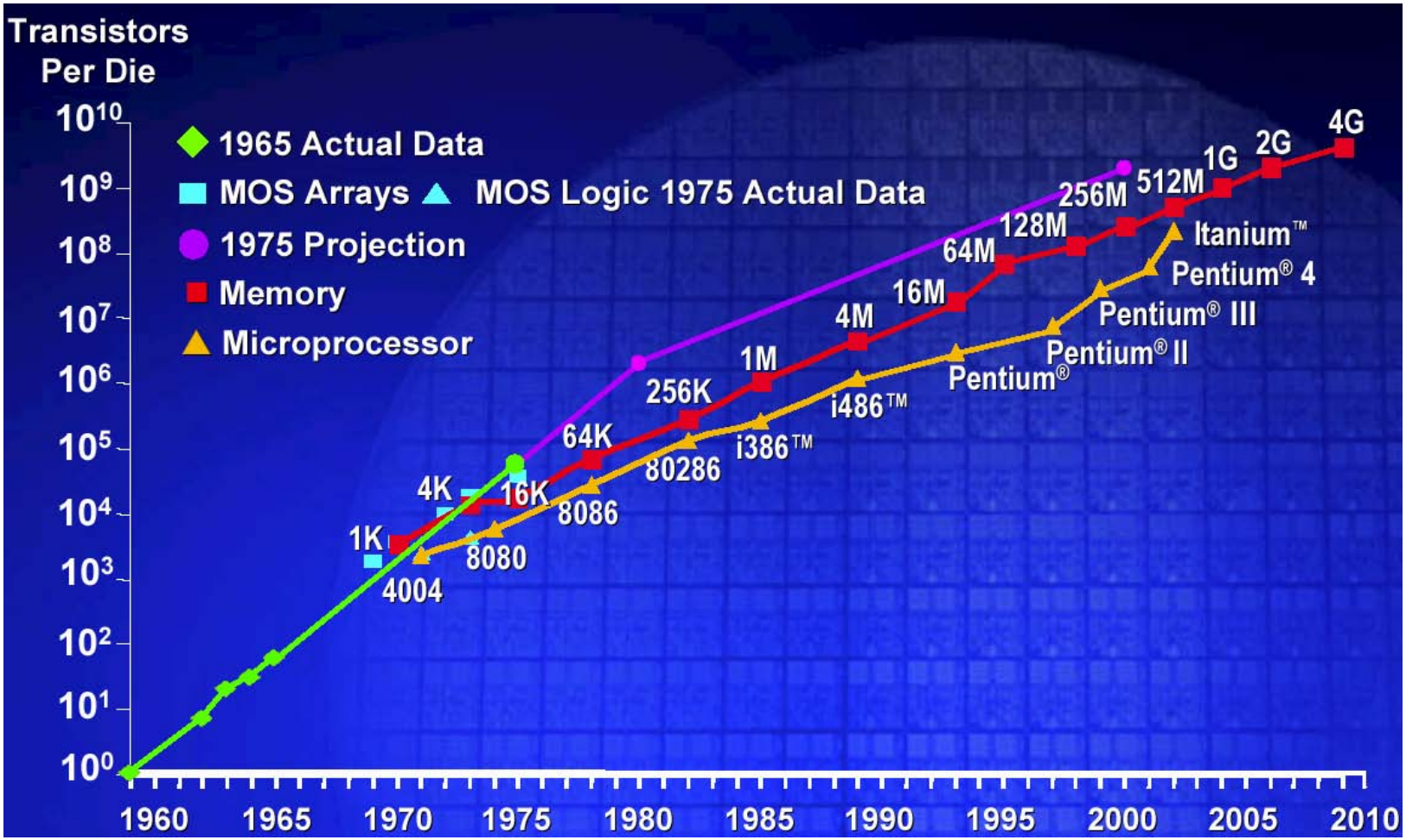
Atoms are starting to look big



Source: IBM

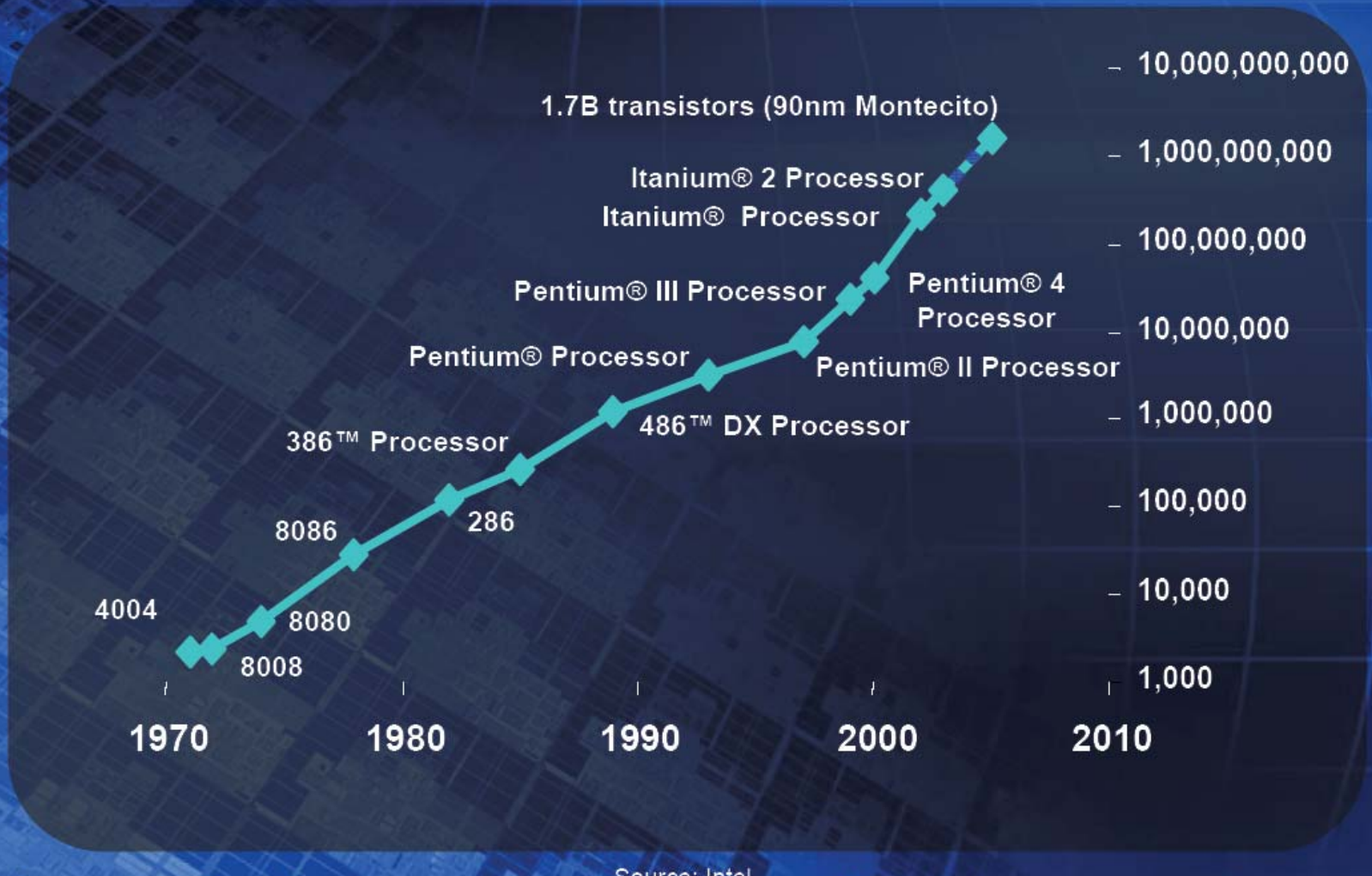
- **When one atom high "bumps" look significant in a photo of your transistors, both their manufacture and behavior are "exciting"**

Integrated Circuit Complexity



Source: G. Moore, Intel (2003)

Moore's Law Continues…



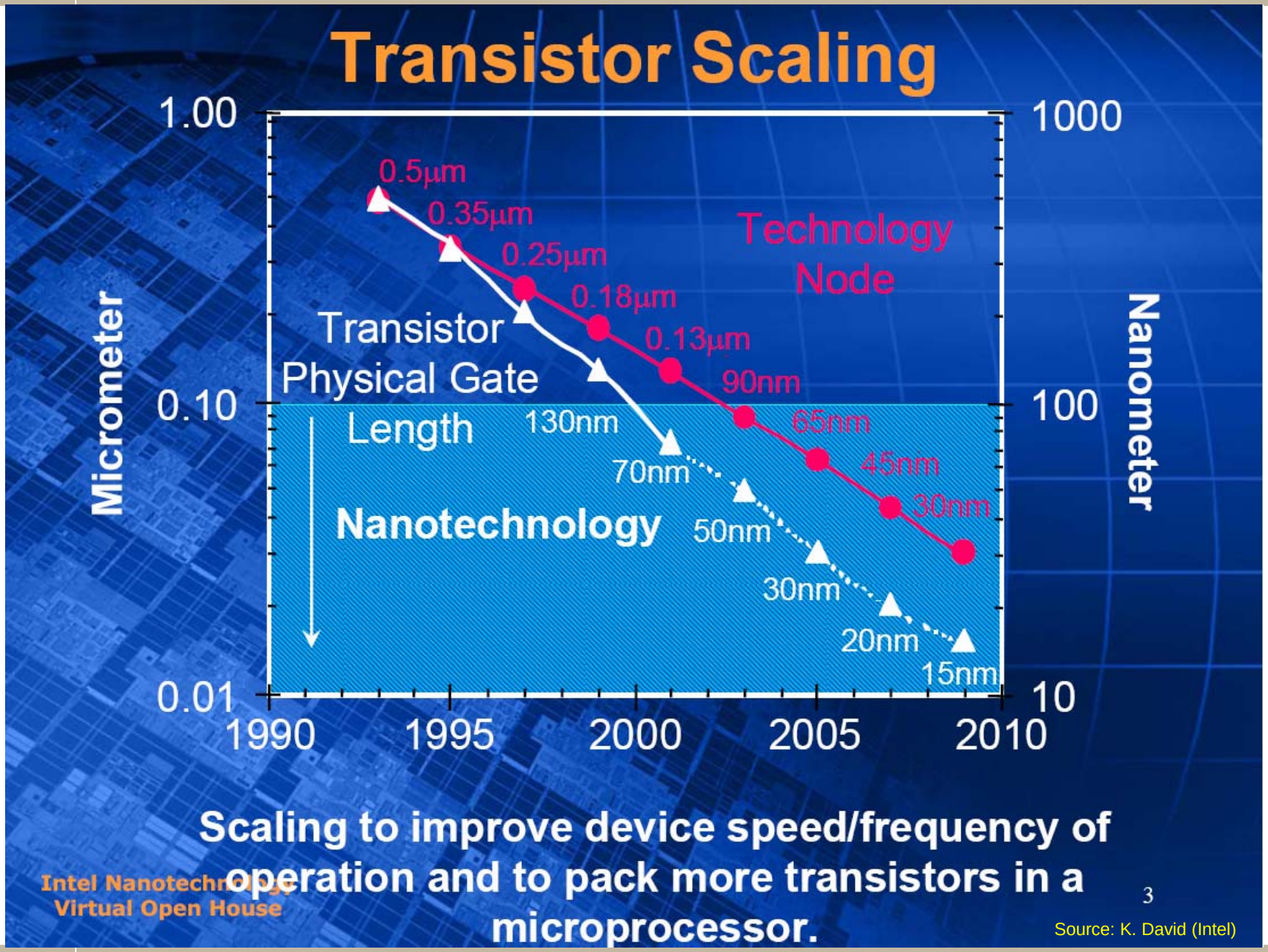
Source: Intel

Increase in microprocessor complexity owing to improvement in transistors, interconnect and packaging

Intel Nanotechnology Virtual Open House

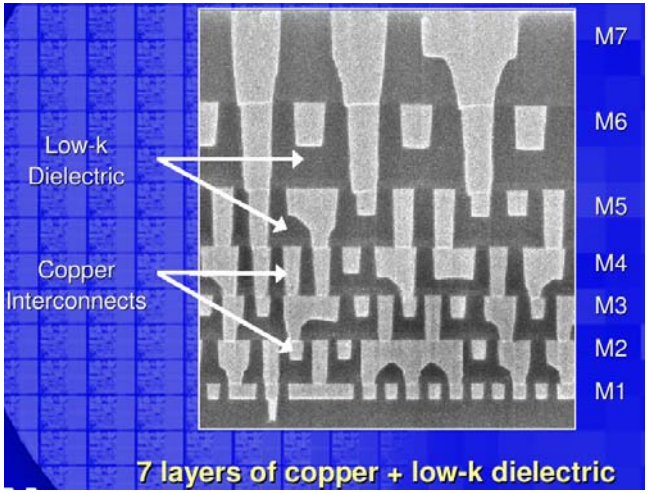
2

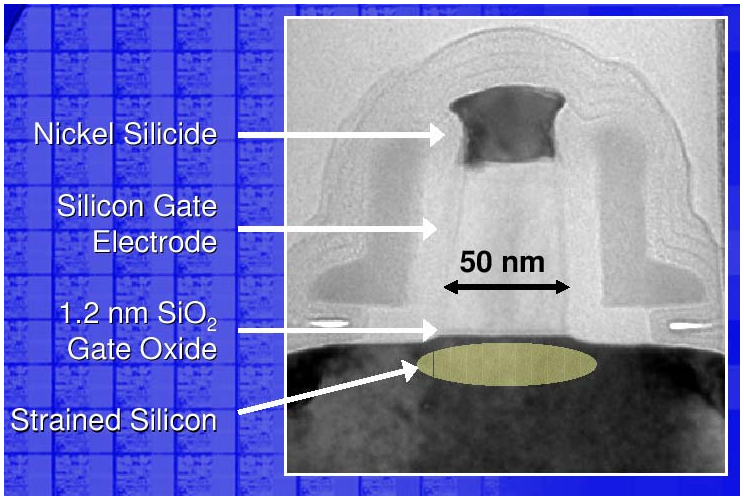
Source: K. David (Intel)


Transistor Scaling
1.00
0.10
0.01
Micrometer
1000
100
10
Nanometer
1990
1995
2000
2005
2010
0.5µm
0.35µm
0.25µm
0.18µm
0.13µm
90nm
65nm
45nm
30nm
Technology Node
Transistor Physical Gate Length
130nm
70nm
50nm
30nm
20nm
15nm
Nanotechnology
Scaling to improve device speed/frequency of operation and to pack more transistors in a microprocessor.
Intel Nanotechnology Virtual Open House
3
Source: K. David (Intel)

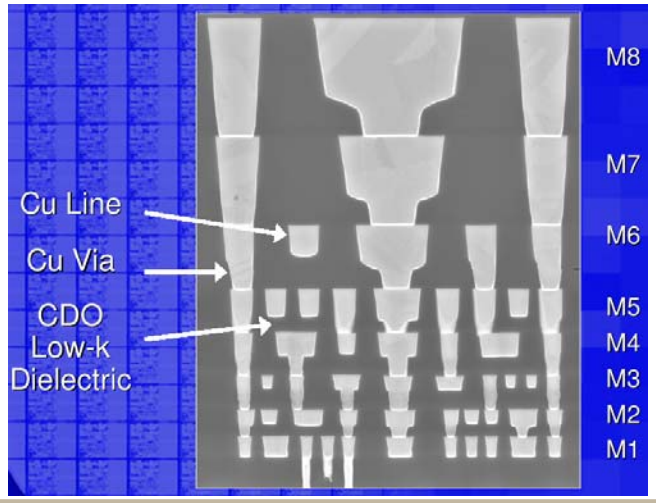
State-of-the-Art Technology

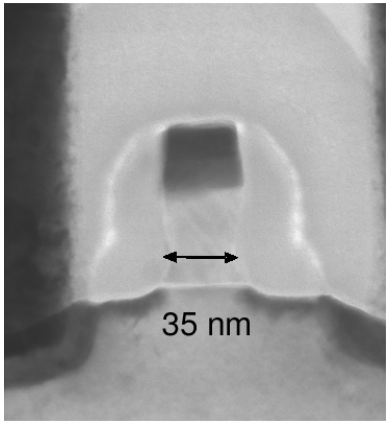
90 nm technology



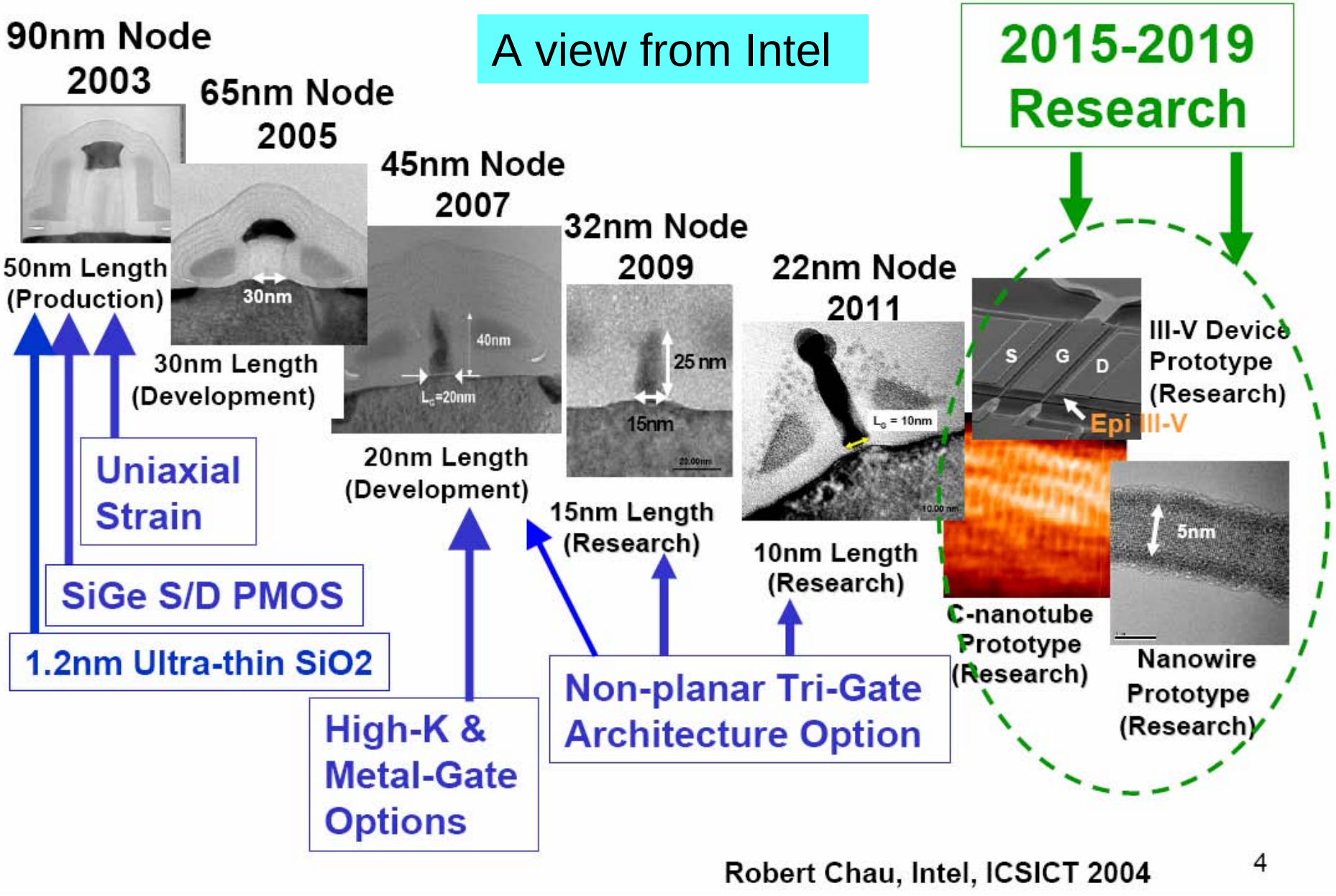


65 nm technology





Source: M. Bohr, Intel (2004)



Robert Chau, Intel, ICSICT 2004

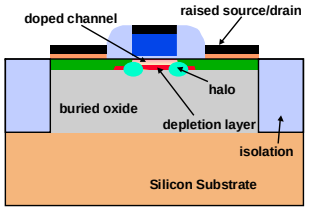
4

Time Horizon

Blue Sky

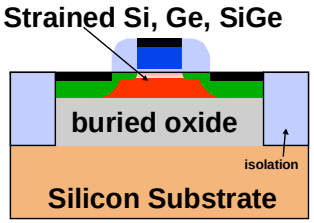
2004	2007	2010	2013	2016	2020
Physical Gate	37 nm	25 nm	18 nm	13 nm	9 nm	6 nm

Ultrathin SOI

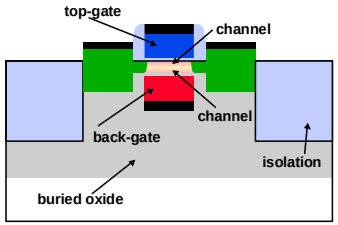


High *k* gate dielectric

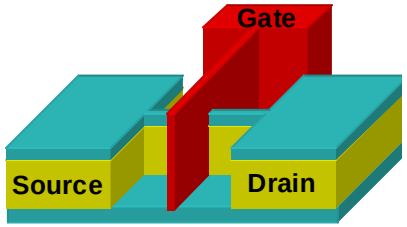
Strained Si, Ge, SiGe



Double-Gate CMOS

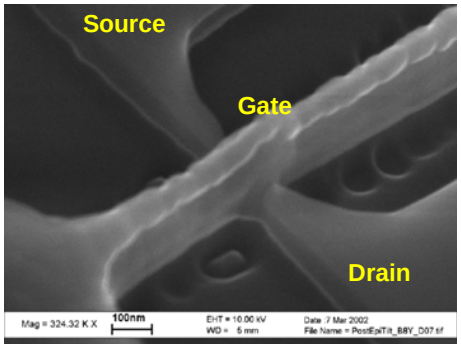


FinFET

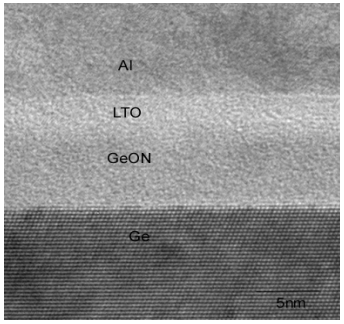


Evolutionary → Revolutionary

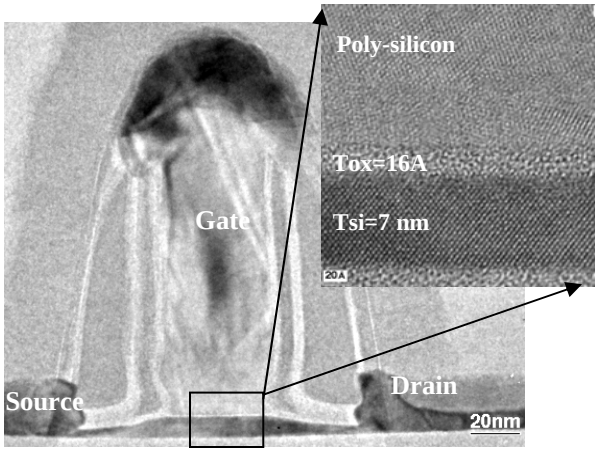
Future Si Devices



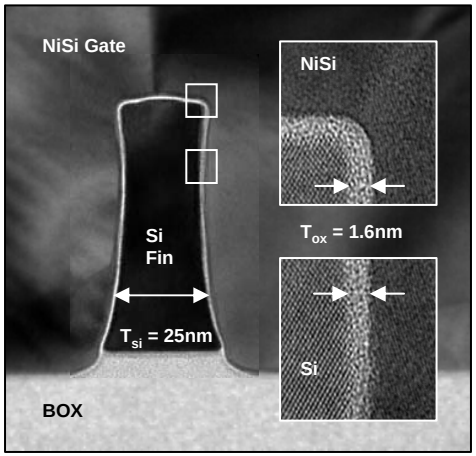
J. Kedzierski et al., *IEDM* 2001 , *IEDM* 2002

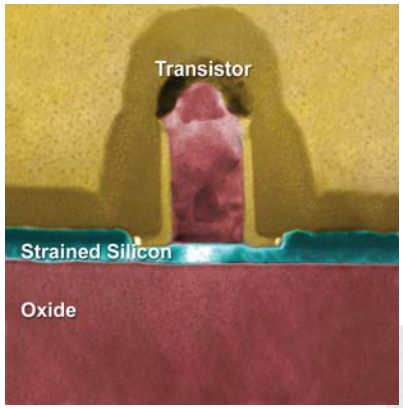


H. Shang et al., *IEDM* 2002

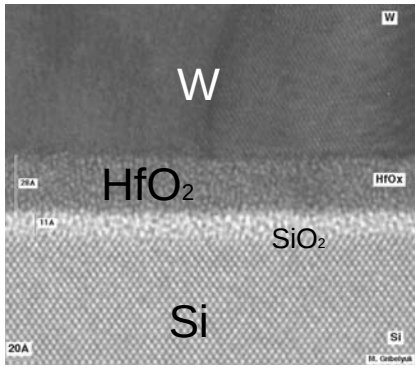


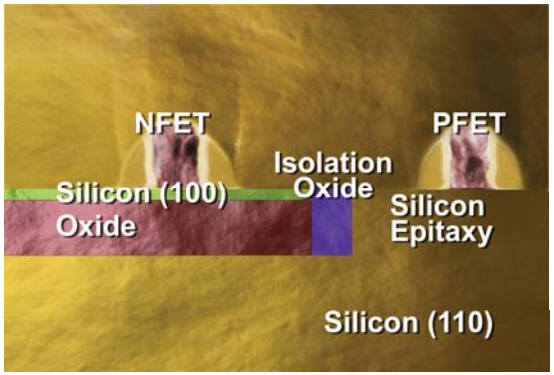
B. Doris et al., *IEDM* 2002



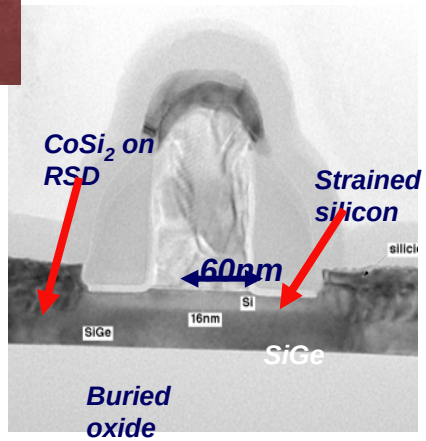


K. Rim et al., *IEDM* 2003





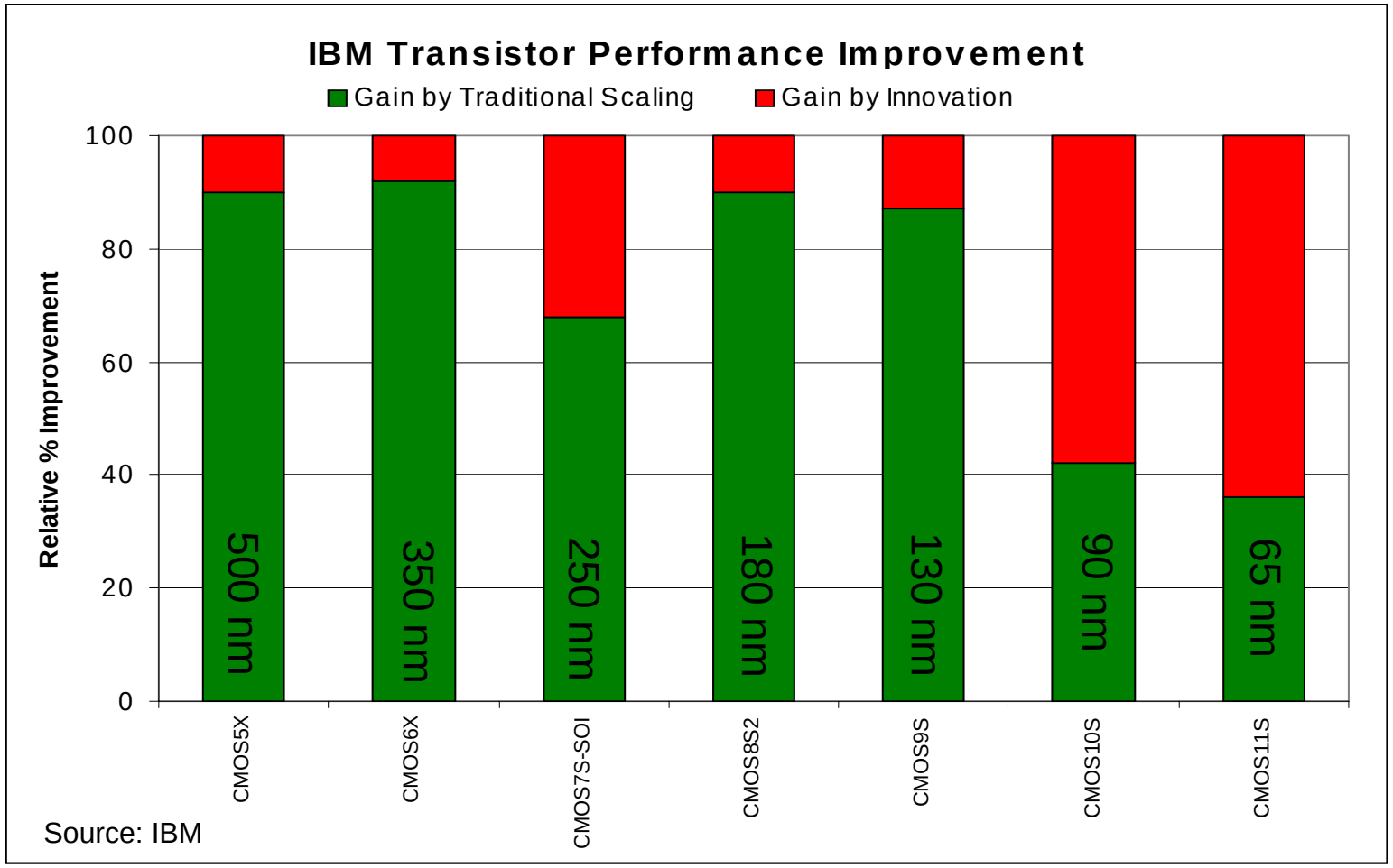
M. Yang et al., *IEDM* 2003



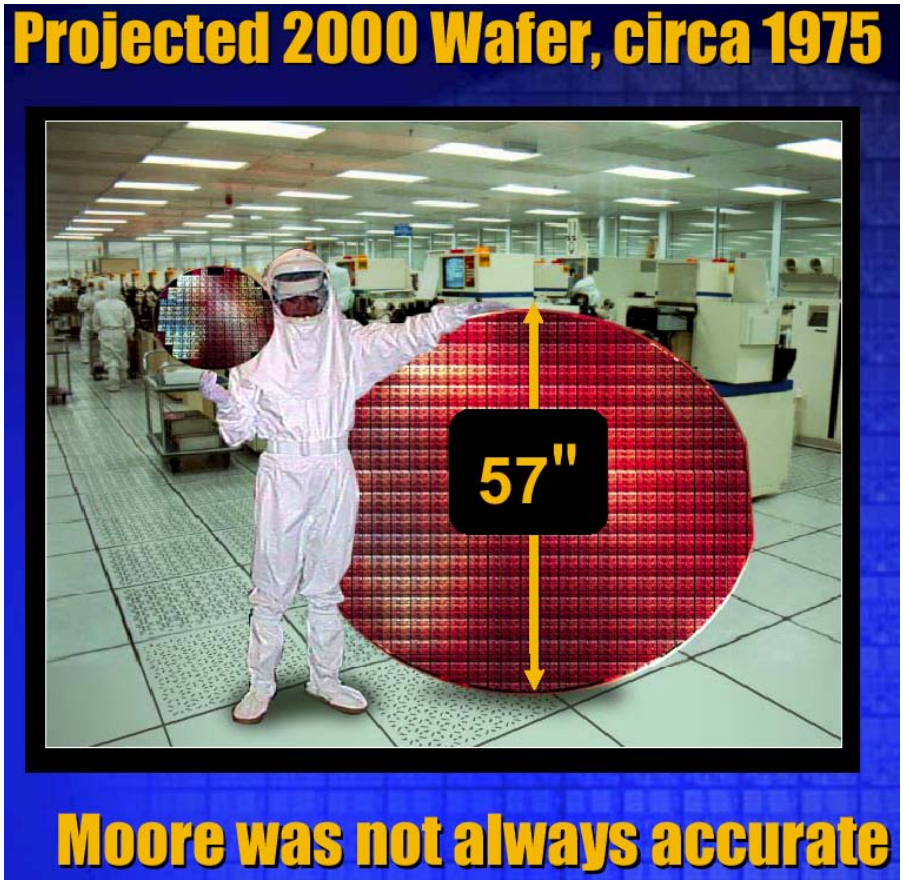
B. Lee et al., *IEDM* 2002

Innovation Overtakes Scaling in Driving Performance

- **Innovation (invention) will increasingly dominate performance gains**
  - Scheduled "invention" is now the majority component in all plans
    - Risk has increased significantly



Straight Line Projections Can Be Wrong…



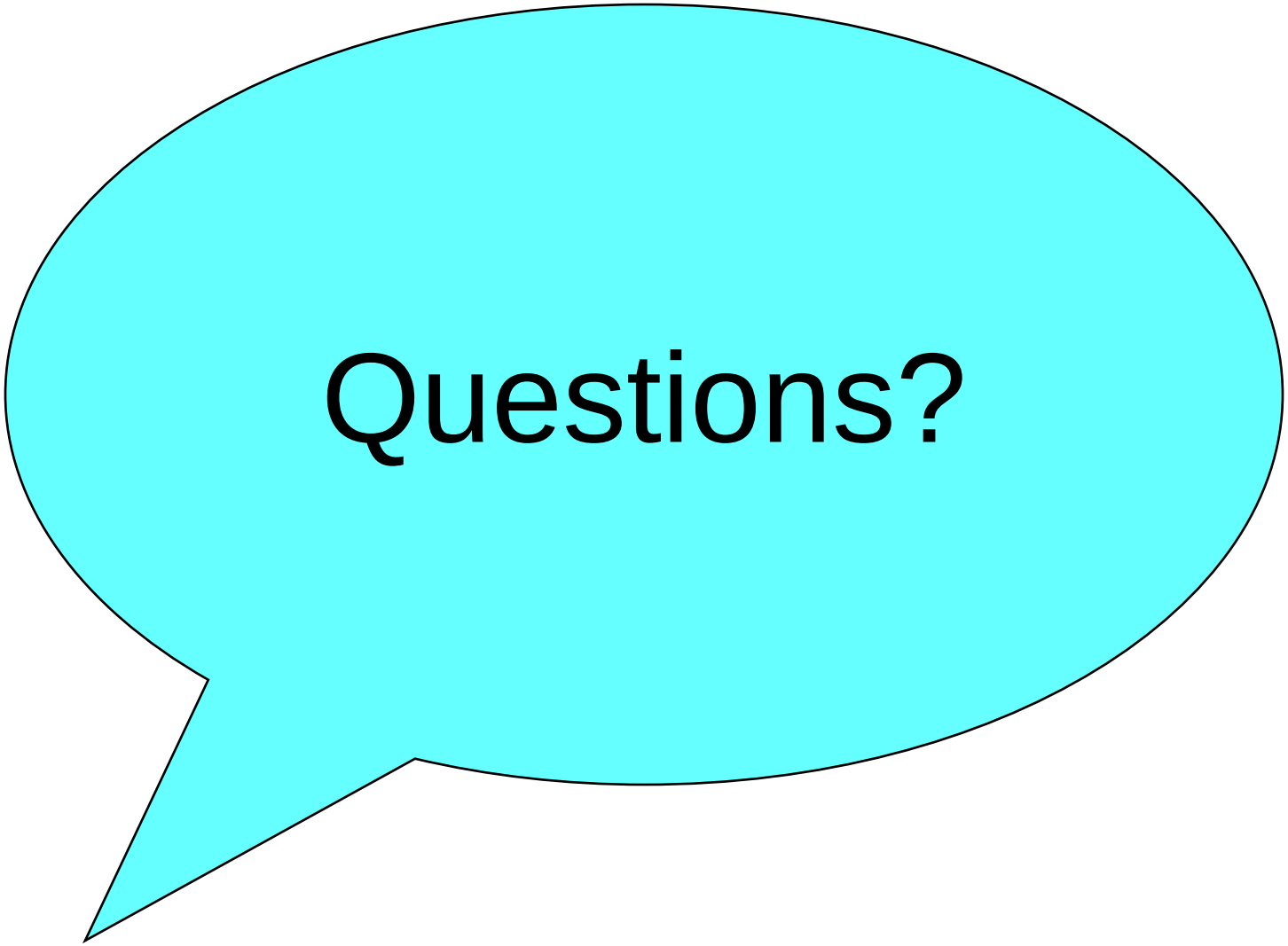
Source:

G. Moore, Intel (2003)

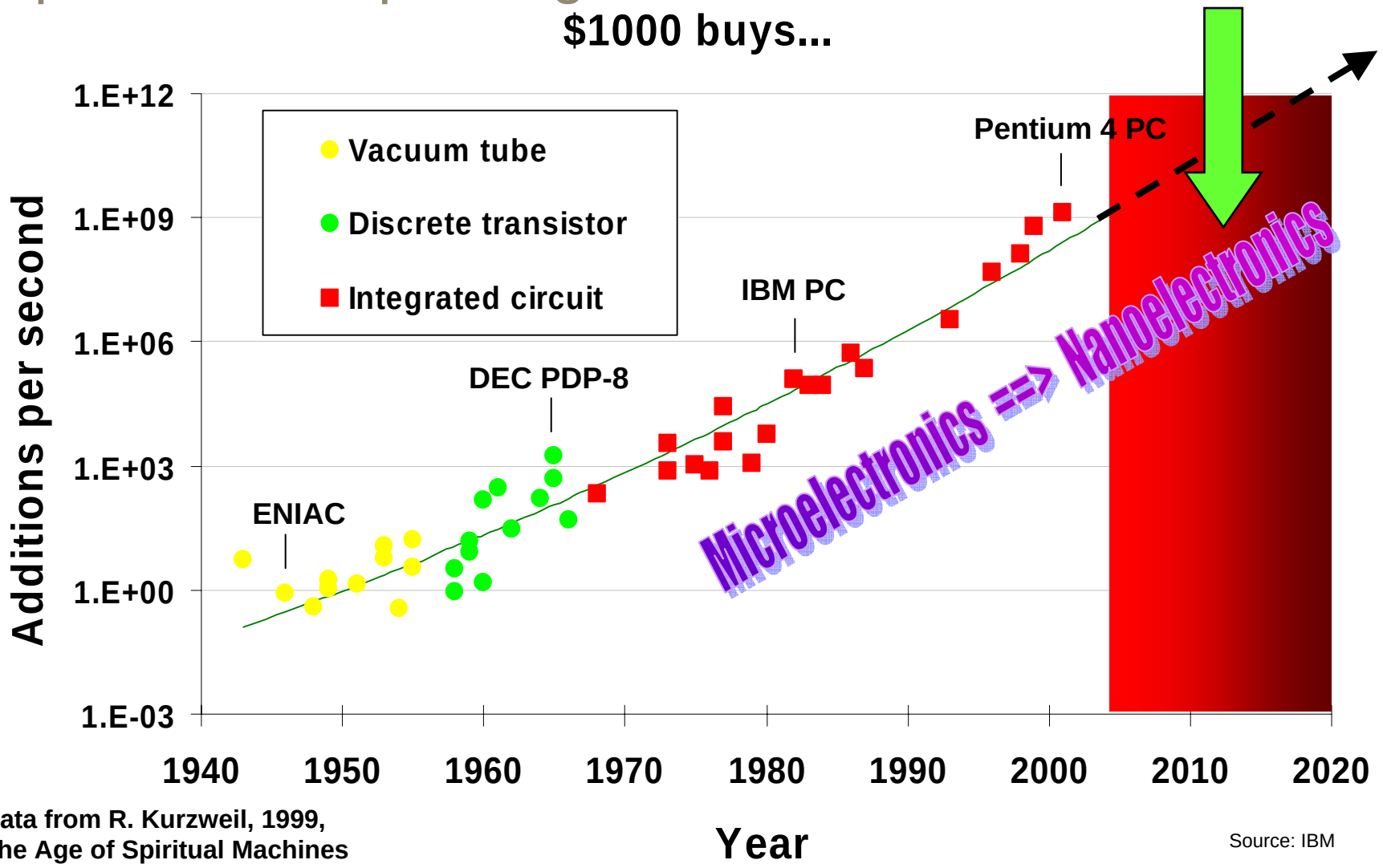
Therefore, we need to focus on the fundamentals

To Learn More About Si Technology…

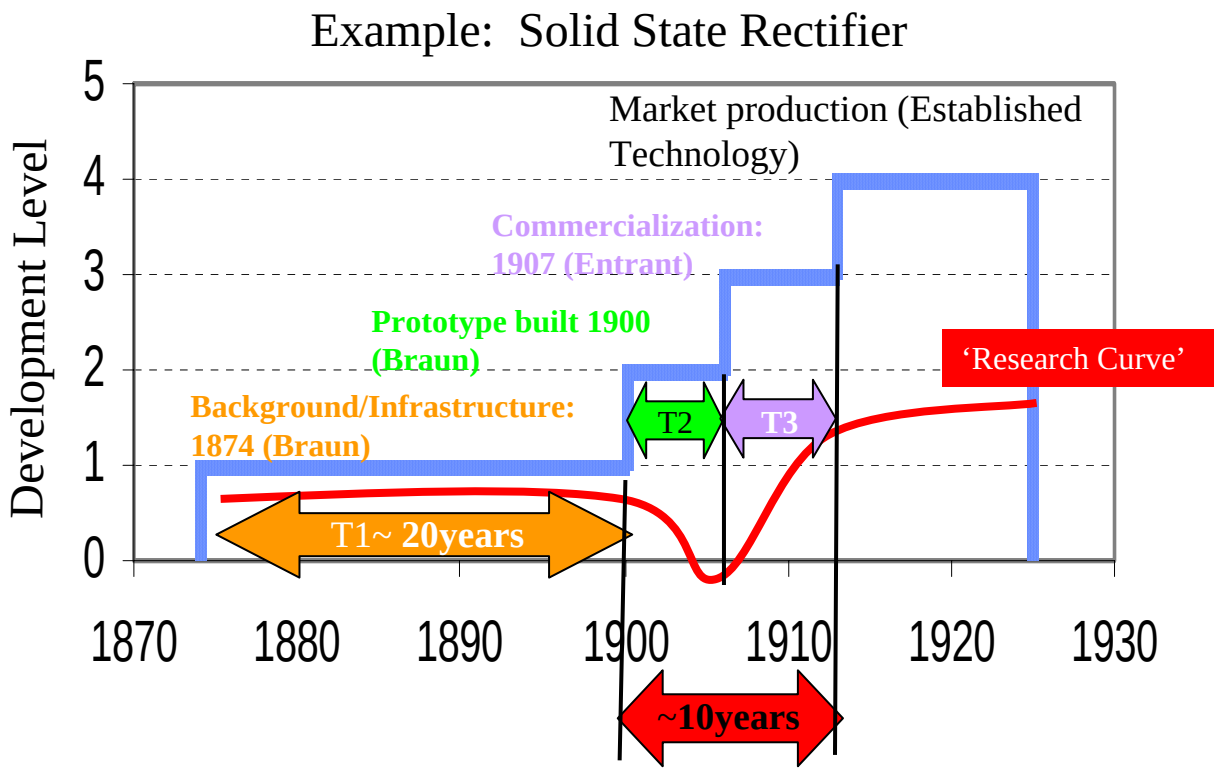
- **EE 212 – Fabrication technology (J. Plummer)**
- **EE 316 – Si CMOS device (H.-S. P. Wong)**
- **EE 311 – Device technology (K. Saraswat)**
- **EE 309 – Semiconductor memory (H.-S. P. Wong)**
- **EE 410 – Fabrication lab (K. Saraswat)**


Questions?

Several distinct technologies have been used to implement complex logic



Gestation for Technologies



- To be ready for 2016 - start now narrowing down options

After Ralph Cavin, SRC

Solid State Diode
T1 26 (1874-1900)
T2 7 (1900-1907)
T3 6 (1907-1913)
Learning Period 13 years

Vacuum Tube
T1 20 (1884-1904)
T2 9 (1904-1913)
T3 6 (1913-1919)
Learning Period 15 years

Transistor
T1 25 (1923-1948)
T2 6 (1948-1954)
T3 5 (1954-1959)
Learning period 11years

Integrated Circuit
T1 17 (1942-1959)
T2 3 (1959-1961)
T3 5(1961-1966)
Learning Period 8 years

International Technology Roadmap for Semiconductors

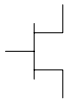
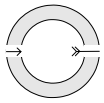
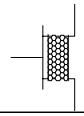
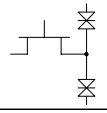
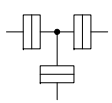
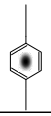
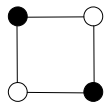
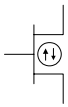
- **The International Technology Roadmap for Semiconductors (ITRS) is an assessment of the semiconductor technology requirements. The objective of the ITRS is to ensure advancements in the performance of integrated circuits. This assessment, called roadmapping, is a cooperative effort of the global industry manufacturers and suppliers, government organizations, consortia, and universities.**
- **The ITRS identifies the technological challenges and needs facing the semiconductor industry over the next 15 years. It is sponsored by the European Semiconductor Industry Association (ESIA), the Japan Electronics and Information Technology Industries Association (JEITA), the Korean Semiconductor Industry Association (KSIA), the Semiconductor Industry Association (SIA), and Taiwan Semiconductor Industry Association (TSIA). International SEMATECH is the global communication center for this activity. The ITRS team at International SEMATECH also coordinates the USA region events.**

International Technology Roadmap for Semiconductors ITRS

Emerging Research Logic Devices

2003 ITRS PIDS/ERD Chapter

Source: ITRS, J. Hutchby

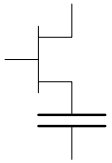
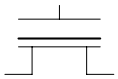
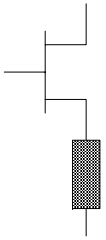
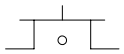
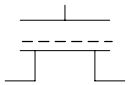
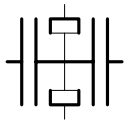
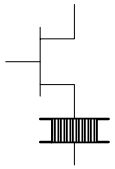
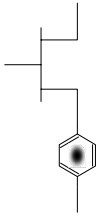
Device	 *FET*	 *RSFQ*	 *1D structures*	 *Resonant Tunneling Devices*	 *SET*	 *Molecular*	 *QCA*	 *Spin transistor*
Cell Size	100 nm	0.3 µm	100 nm	100 nm	40 nm	Not known	60 nm	100 nm
Density (cm^{-2})	3E9	1E6	3E9	3E9	6E10	1E12	3E10	3E9
Switch Speed	700 GHz	1.2 THz	Not known	1 THz	1 GHz	Not known	30 MHz	700 GHz
Circuit Speed	30 GHz	250–800 GHz	30 GHz	30 GHz	1 GHz	<1 MHz	1 MHz	30 GHz
Switching Energy, J	2×10^{-18}	$>1.4\times10^{-17}$	2×10^{-18}	$>2\times10^{-18}$	$>1.5\times10^{-17}$	1.3×10^{-16}	$>1\times10^{-18}$	2×10^{-18}
Binary Throughput, GBit/ns/cm^2	86	0.4	86	86	10	N/A	0.06	86

http://public.itrs.net

Emerging Research Memory Devices

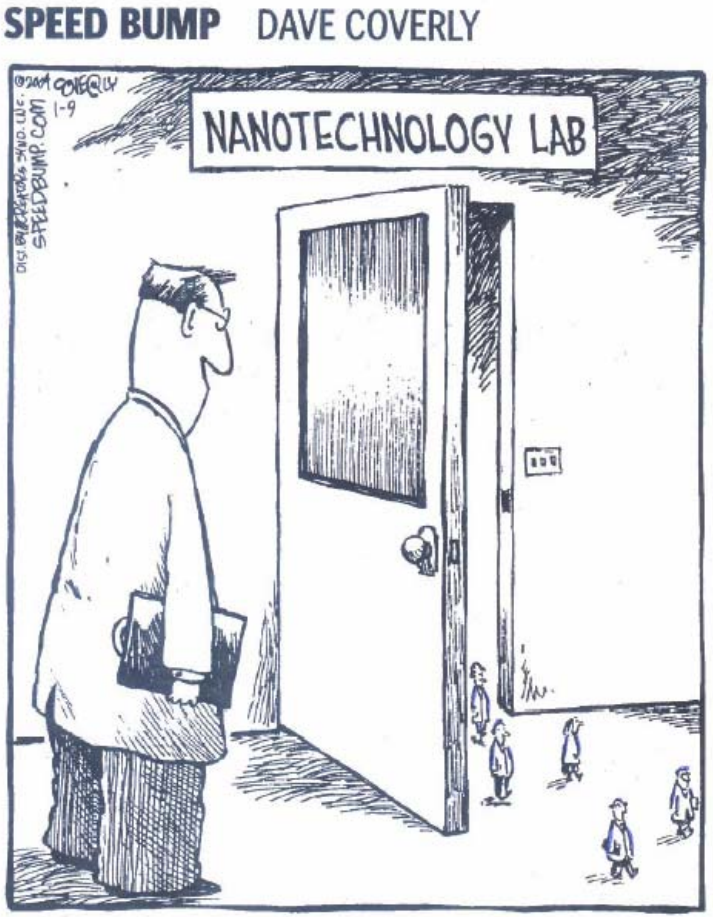
2003 ITRS PIDS/ERD Chapter

Source: ITRS, J. Hutchby

Storage Mechanism	*Present Day Baseline Technologies*		*Phase Change Memory**	*Floating Body DRAM*	*Nano-floating Gate Memory***	*Single/Few Electron Memories***	*Insulator Resistance Change Memory***	*Molecular Memories***
								
Device Types	DRAM	NOR Flash	OUM	1TDRAM eDRAM	Engineered tunnel barrier or nanocrystal	SET	MIM oxides	Bi-stable switch Molecular NEMS
Availability	2004	2004	~2006	~2006	~2006	>2007	~2010	>2010
Cell Elements	1T1C	1T	1T1R	1T	1T	1T	1T1R	1T1R

http://public.itrs.net

Nanotechnology development cannot be decided only by nanotechnologists



Nanotechnology will broadly affect society, from new products to art

MC. Roco, RD2, 9/08/04

Source: M. Roco (NNI), Nanotechnology Research Directions II, September 8, 2004.

Nano Pants

Lee Men's Flat Front Performance Khakis - Black

$ 38.00 >> $ 19.90
Buy at EssentialApparel / more info

"Nanocare revolutionizes fabric technology, making these pants totally carefree!

Product Features:
* Repels liquids
* Minimizes stains
* Wrinkle free
* Comfort waist with relaxed seat and thigh
* Contemporary plain styling
* 16 1/2 inch leg opening."

Nano Cosmetics

Select a Product:

LacVert Nano Hydrating Essence *by Debon*
Hydrating essence with nano technology energizes and smooths skin.
Cdn $46.00 ~ You save Cdn $8.00 15% off
Approx. US$38.87

ADD

LacVert Nano Brightening Eye Cream *by Debon*
Hydrating eye cream created with nano technology brightens eye area.
Cdn $39.00 ~ You save Cdn $10.00 20% off
Approx. US$32.96

ADD

LacVert Nano Hydrating Cream *by Debon*
Nourishing cream created with nano technology for fast absorption.
Cdn $39.00 ~ You save Cdn $16.00 29% off
Approx. US$32.96

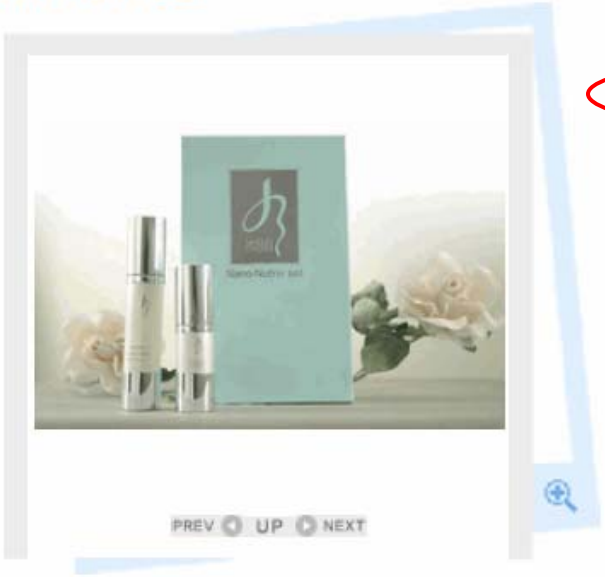
ADD

LacVert Magic Sun Block Cream SPF35 PA++ *by DeBon*
Waterproof high protection sunscreen for outdoor activities.
Cdn $25.00 ~ You save Cdn $9.00 26% off
Approx. US$21.12

ADD

Nano Skin Care Products

jenbjuti nano-nutriv set



Description | More Info | Specials | Reviews

Description

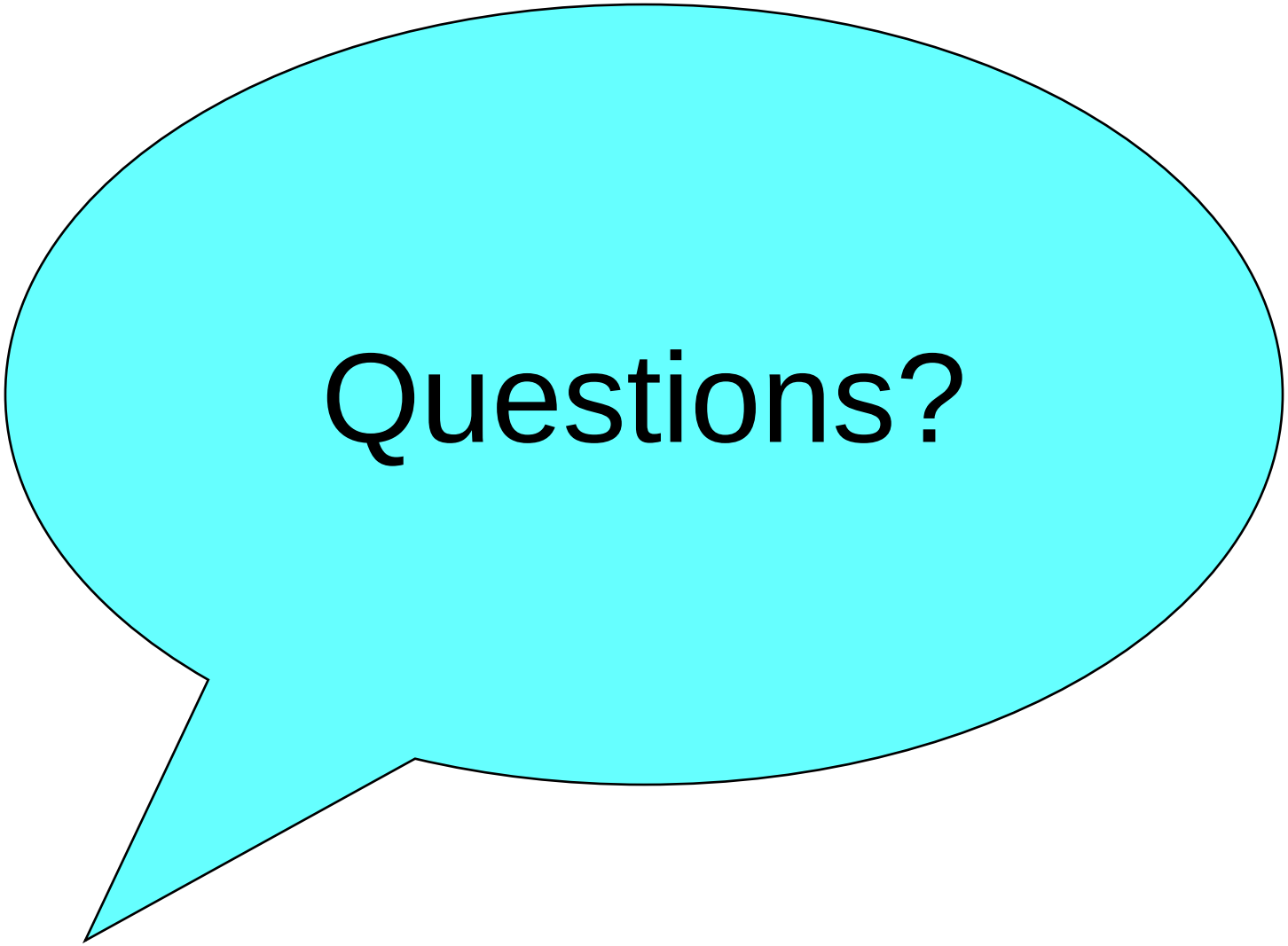
NANO NUTRIV SET is designed for normal and combination skin with acne breakouts, these products combine powerful and effective treatments into a simple daily regimen, clinically proven to help eliminate pimples, whiteheads, blackheads, and redness, leaving skin clear, smooth, and healthy.

NANO-PRIMORDIAL CONCENTRATE (JB9668-A) 15ml Delivers patented, scientifically proven formulas through advanced technology to treat problem skin. Help heal existing blemishes and prevent future breakouts, while restoring skin health, clarity and balance. Catechincompouncles, Flavonicls, Horse Chetsn, and Tannins work together to minimize the severity of active acne breakouts, soothe and reduces inflammation.

Simply apply to the skin twice a day on the face after cleansing, and pat lightly into the skin.

PURE-SKIN CALMING SERUM (JB9668-B) 30ml Strengthen your arsenal against acne. Hyaluronic Acid, complex, fennel and camomile work to aid healing, prevent clogged pores and reduce inflammation for clearer, healthier skin.

After using NANO-PRIMORDIAL CONCENTRATE (JB9668-A), apply moderate amount on particular area, which have acne and pimples.


Questions?