Thomas N. Theis
Director, Physical Sciences
IBM Research
Almaden - Yorktown - Zurich

Nanotechnology: A Look into the Future

Topics ...

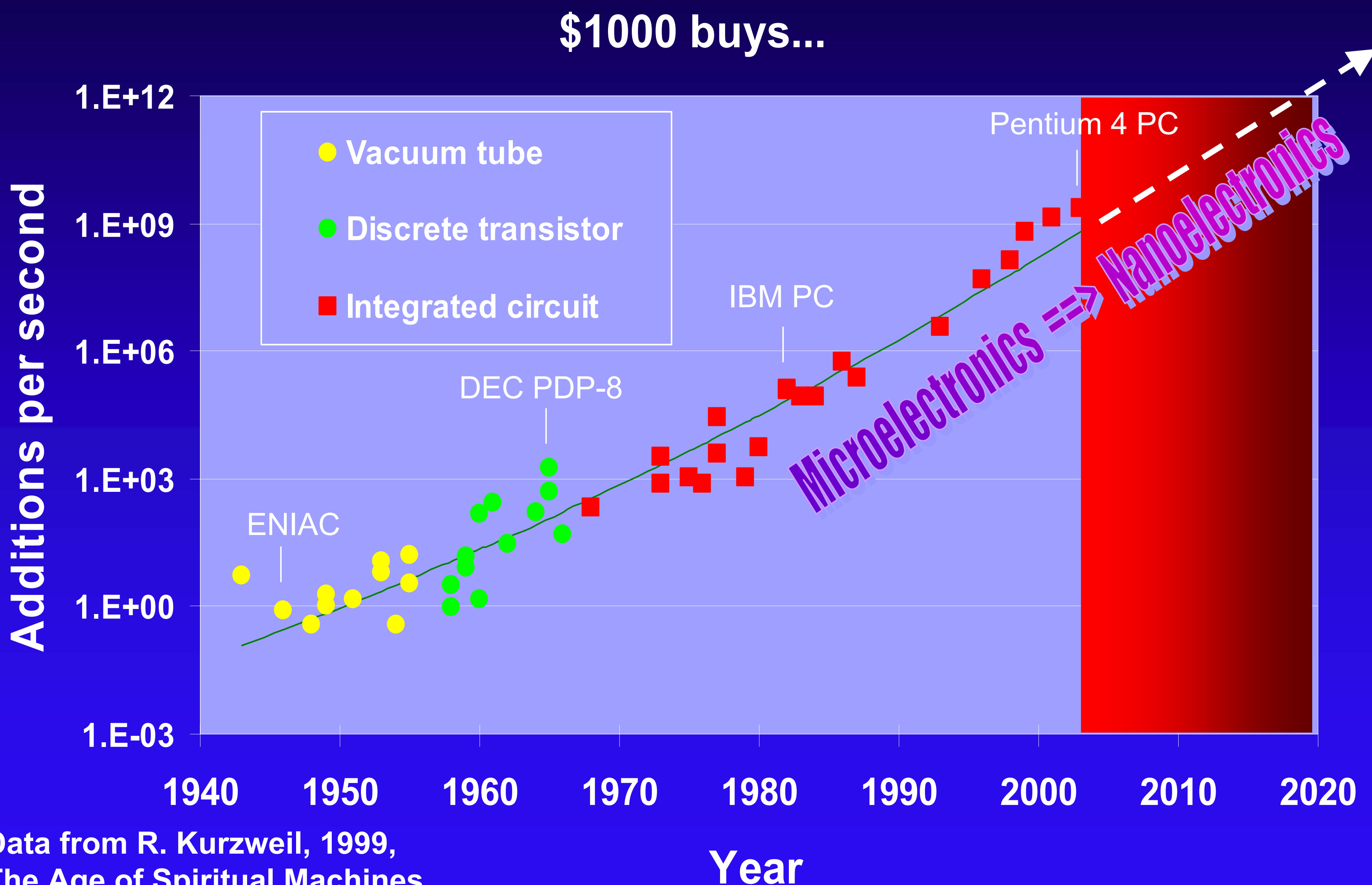
- Why is IBM pursuing research in nanoscale science and technology?
- Self-assembly - the challenge to do it better
- Outlook

Nanotechnology is…

"Research and technology development at the atomic, molecular or macromolecular levels, in the length scale of approximately 1 – 100 nm range…"

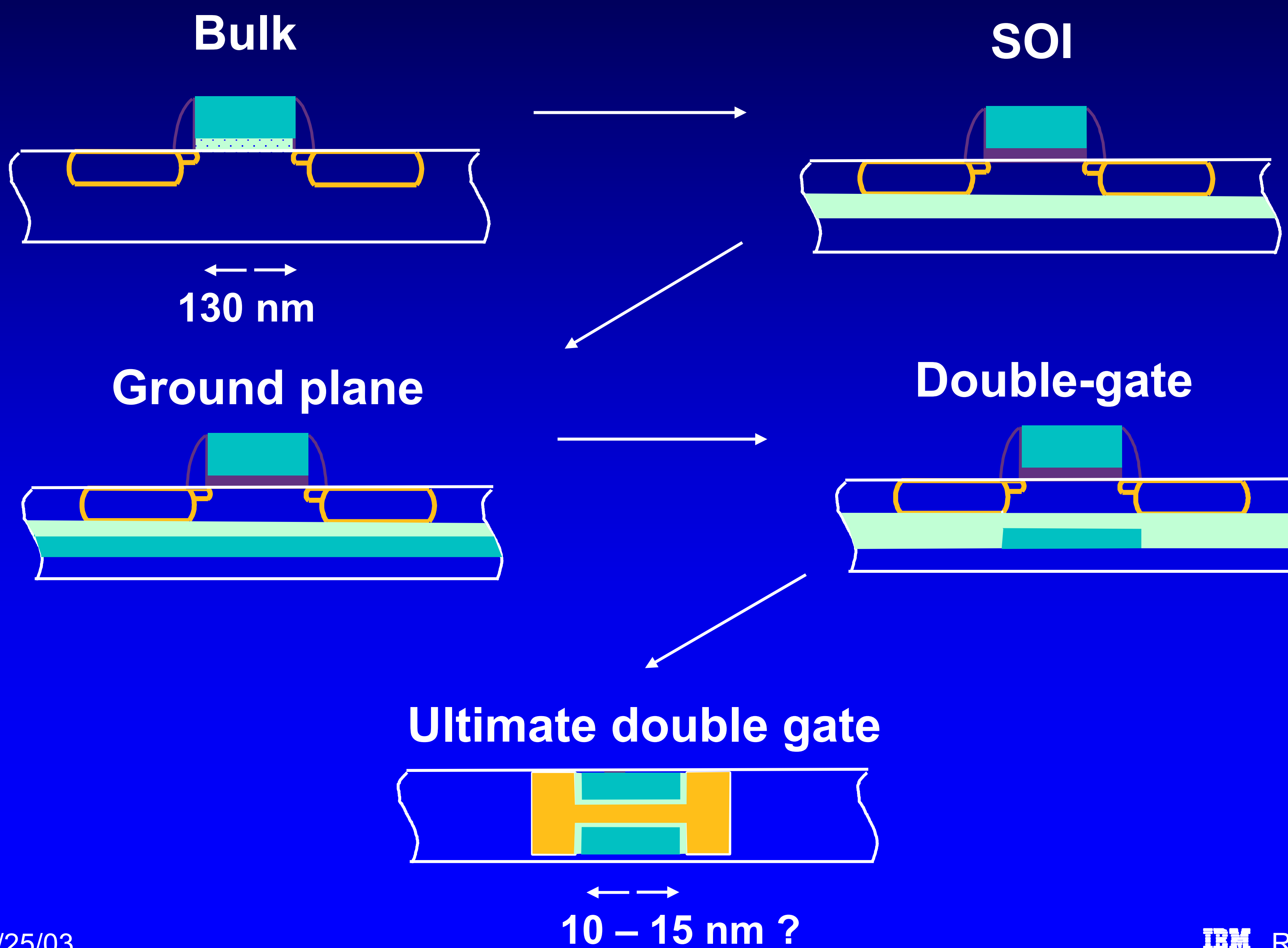
National Science Foundation
www.nsf.gov/home/crssprgm/nano/omb_nifty50.htm

By the NSF definition, silicon microelectronics is already a nanotechnology.

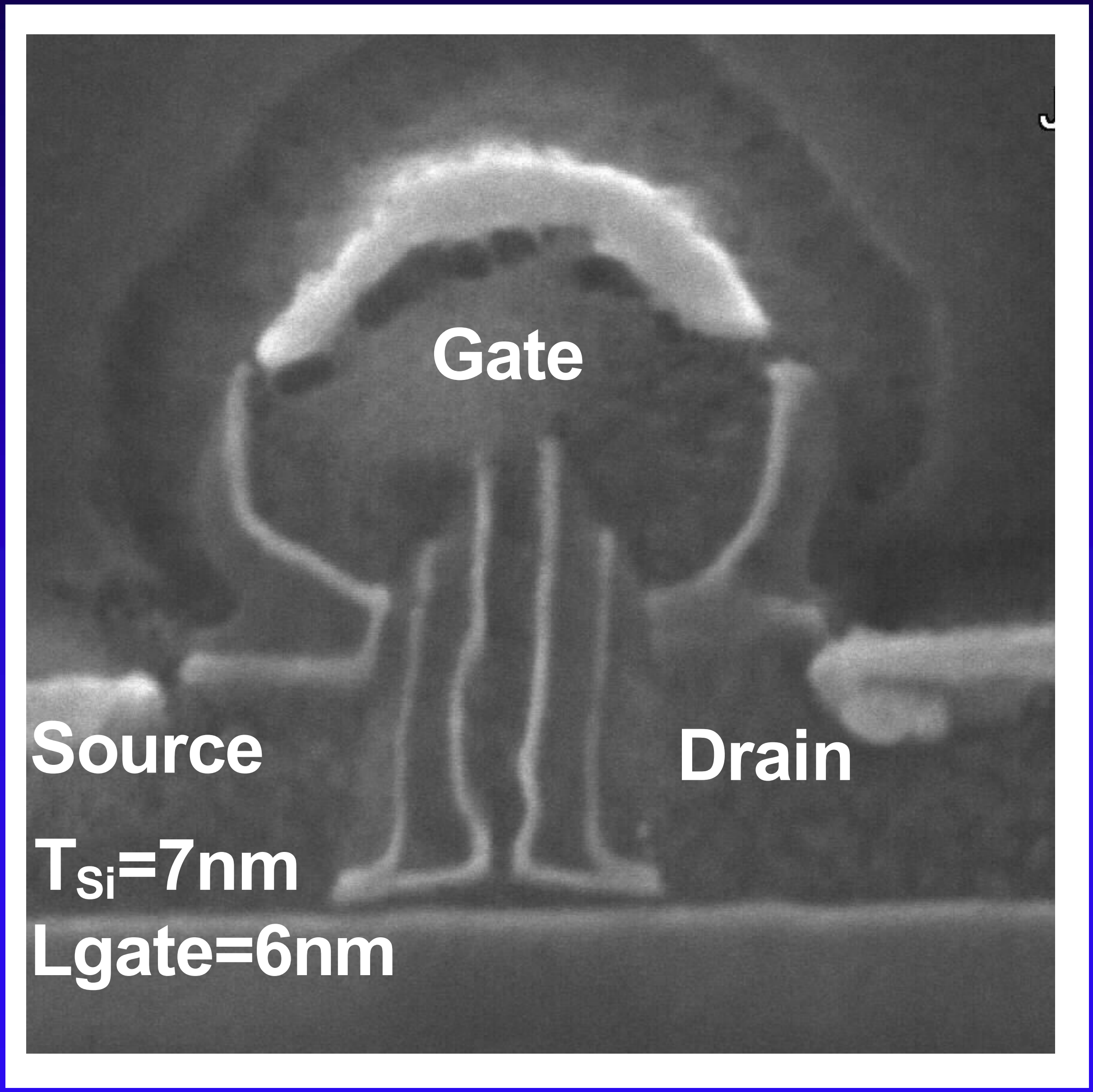


Data from R. Kurzweil, 1999,
The Age of Spiritual Machines

The silicon transistor has become a nanodevice.

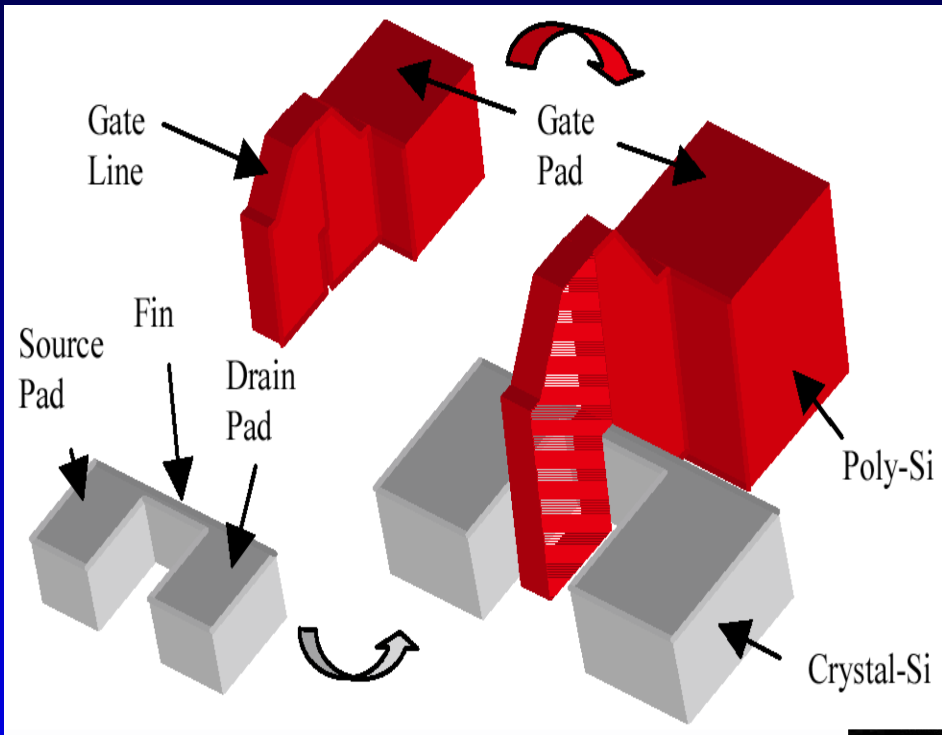


An Experimental Silicon Transistor

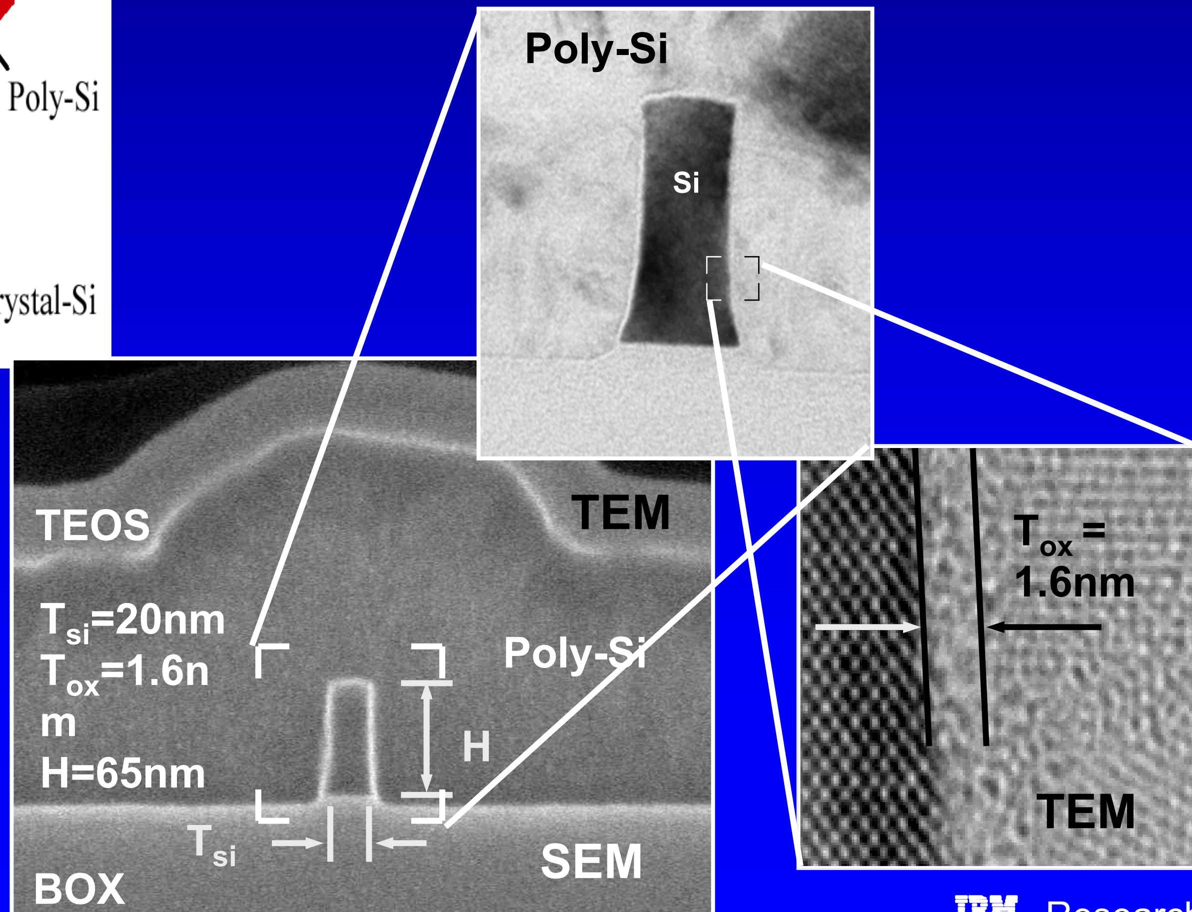


B. Doris et al., *IEDM* , 2002.

Approaching the ultimate silicon nanodevice (a double-gate Transistor or FinFET)

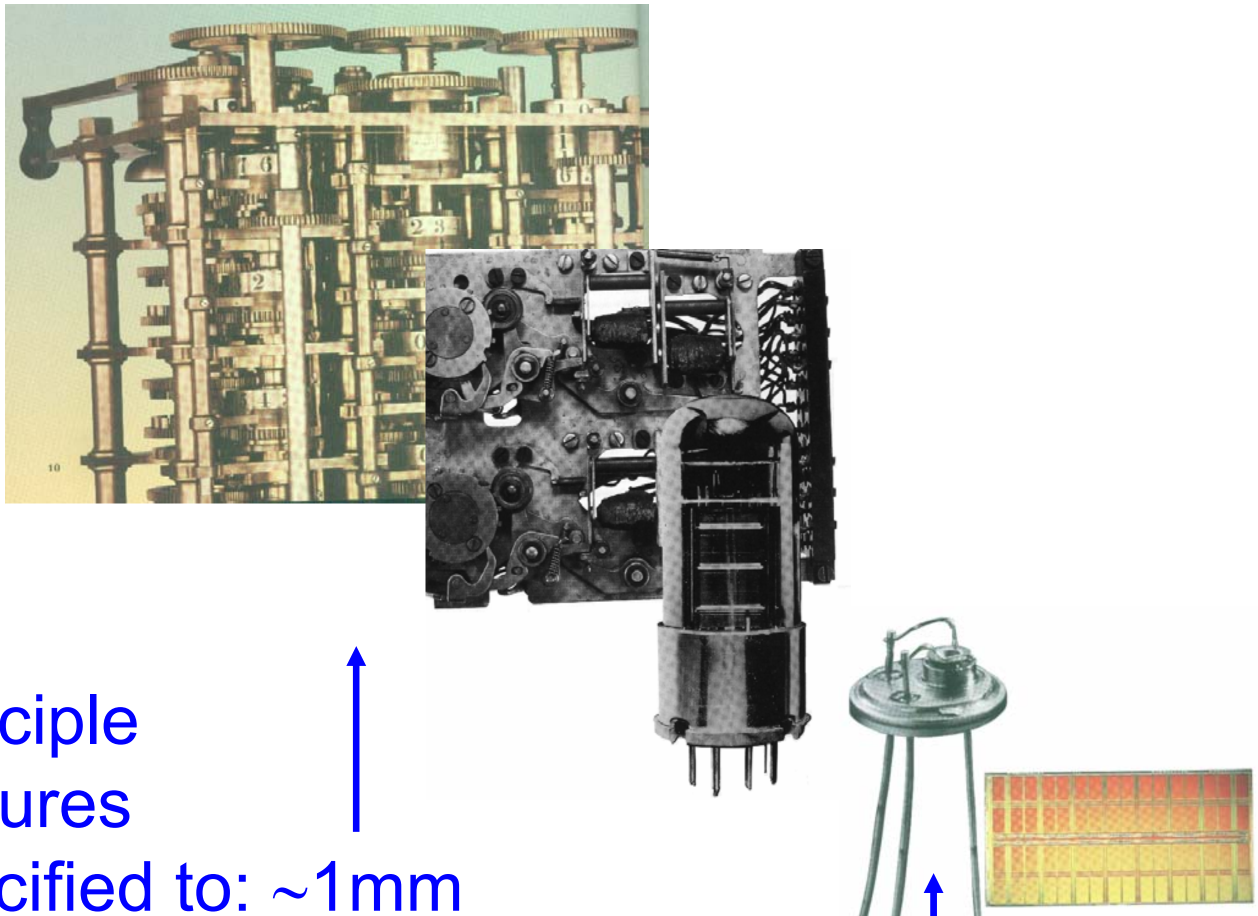


60 nm channel length FET



Cross-section

Is there a successor to silicon?



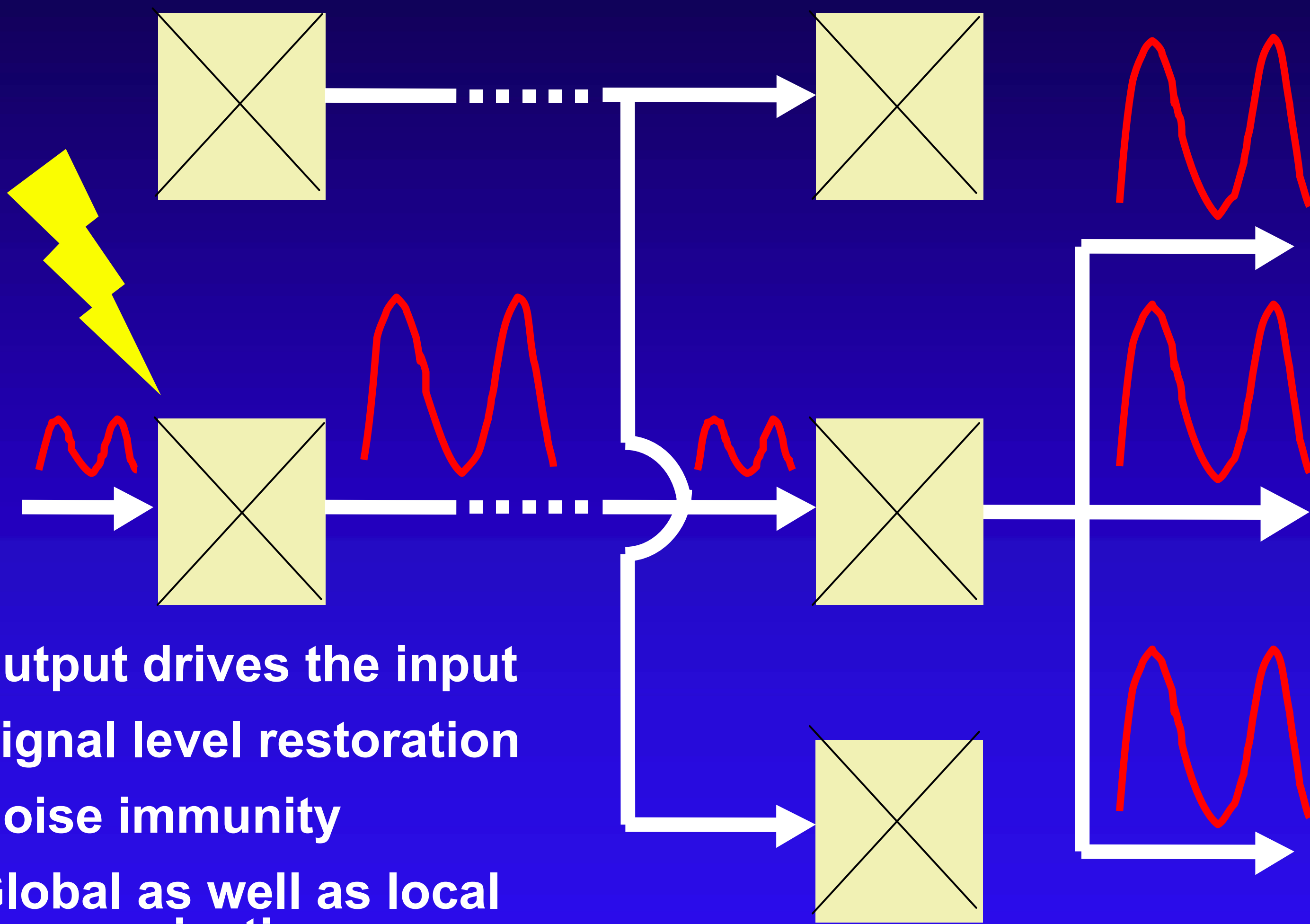
principle
features
specified to: ~1mm

~10 μm

~100 nm

Nanoscale Science and Technology

Attributes of Successful Digital Logic Devices



- Output drives the input
- Signal level restoration
- Noise immunity
- Global as well as local communications

After H.-S. P. Wong, "Novel Device Options" in Sub-100nm CMOS Short Course, *IEDM*, 1999

"Revolutionizing" a large, complex, stratified industry is not easy.

- Sphere of *successful* influence: +/- one layer

Application

Architecture

System

Circuit

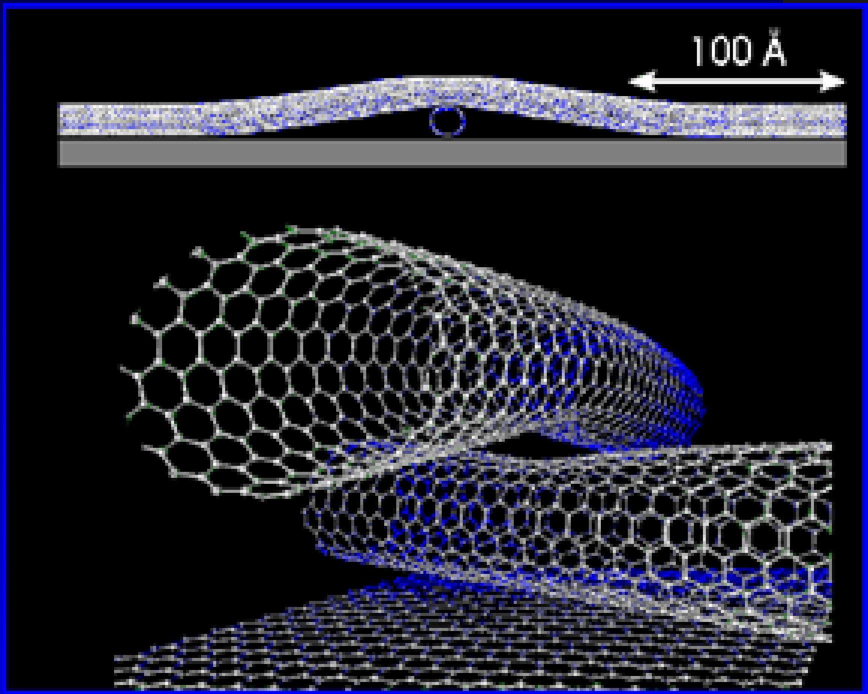
Device

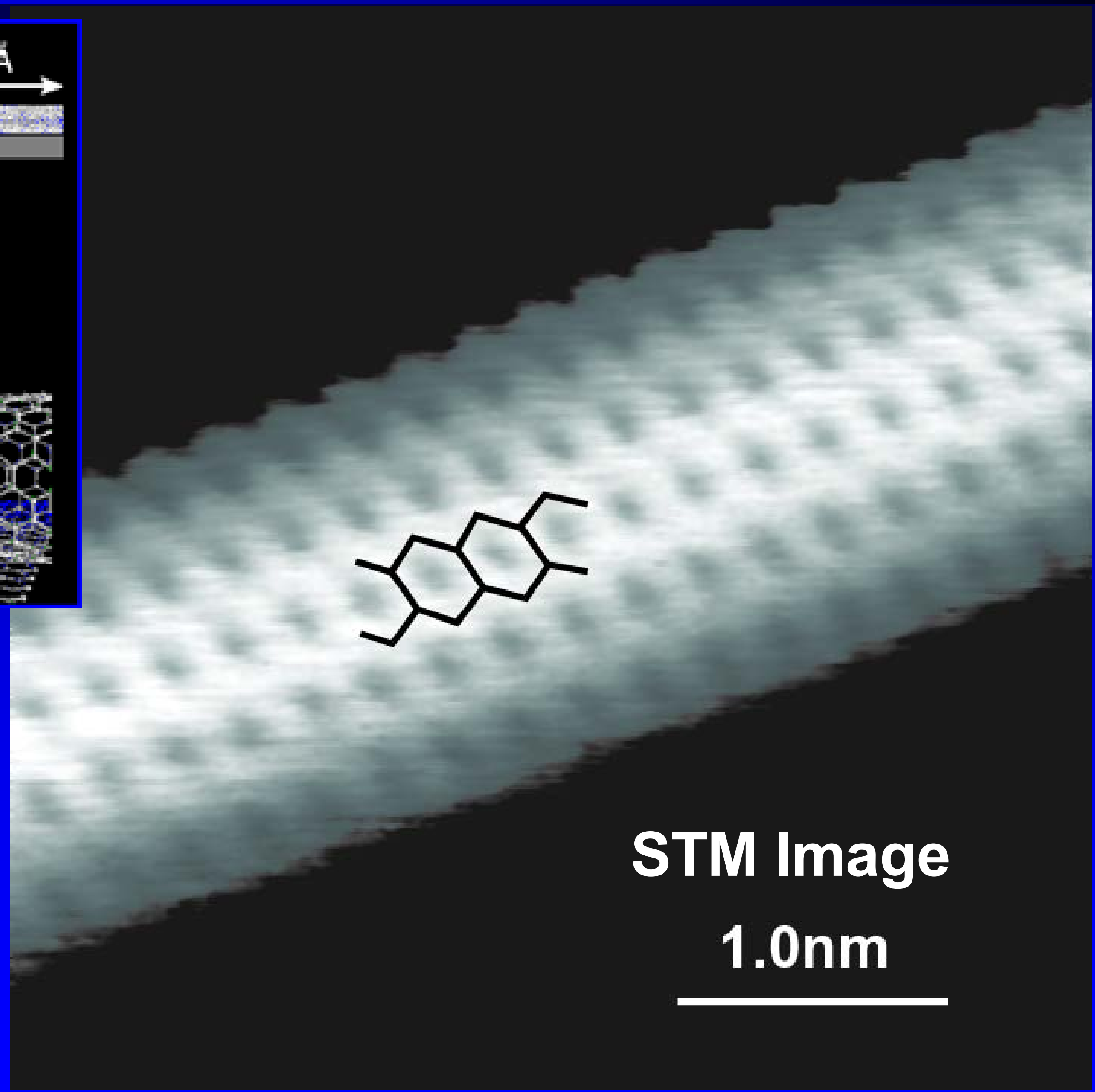
Materials

Physics/chemistry

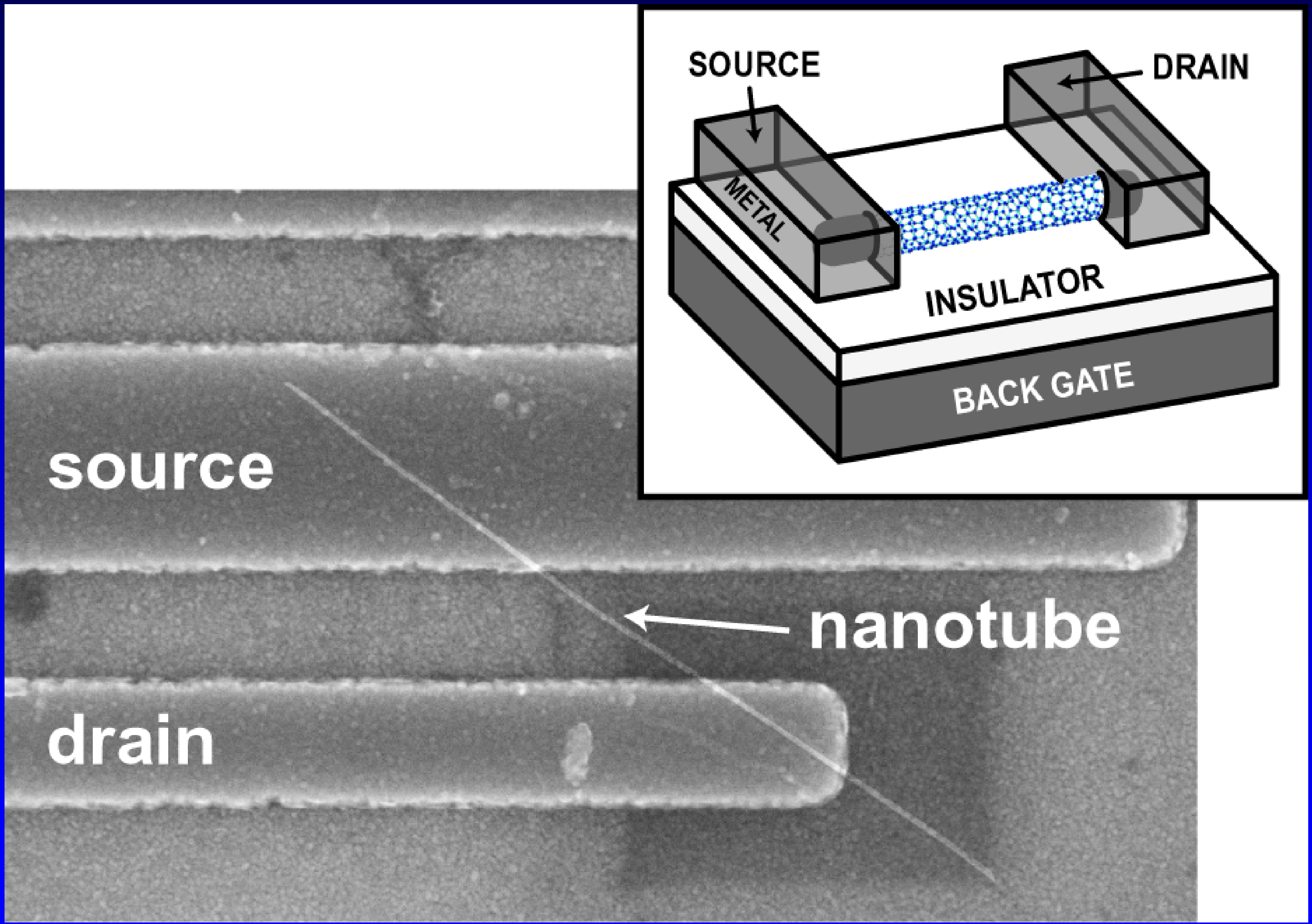
Adapted from M. Horowitz, in *Focus Center Research Program (MARCO) MSD-C2S2 Topical Workshop,* Nov. 12, 2001

Carbon Nanotubes

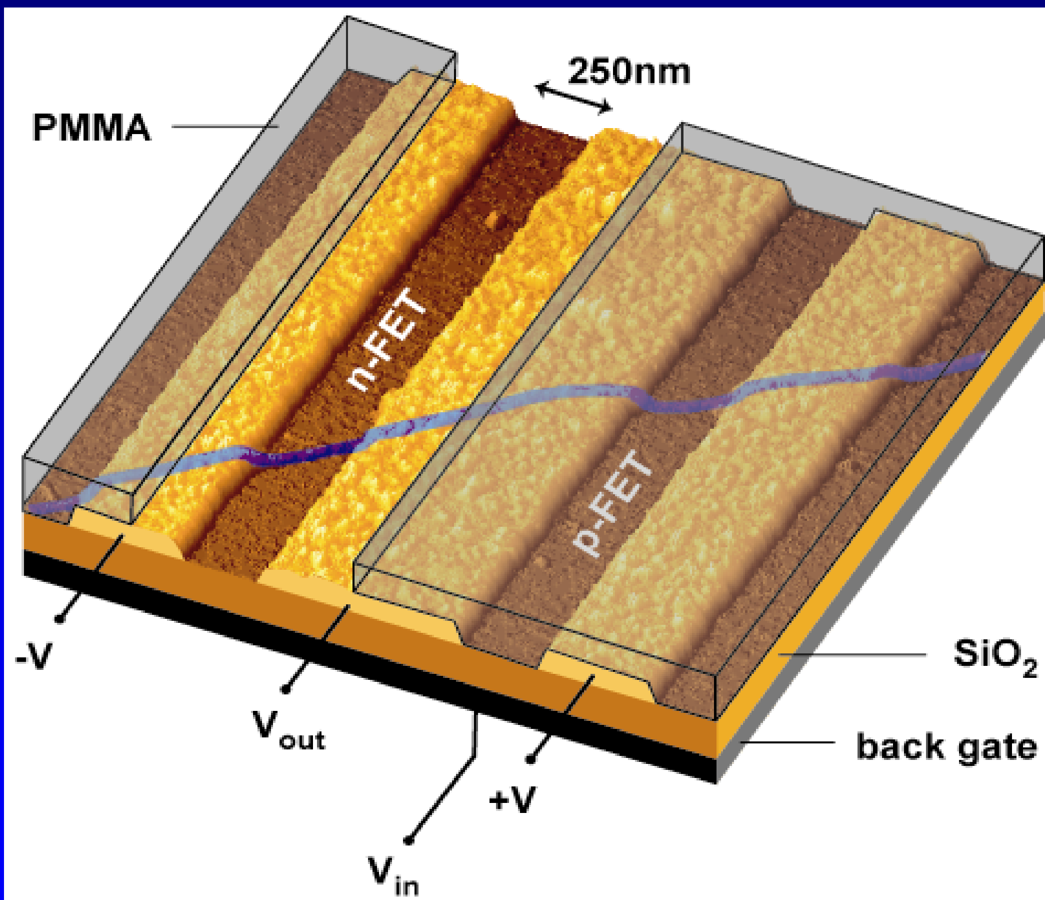


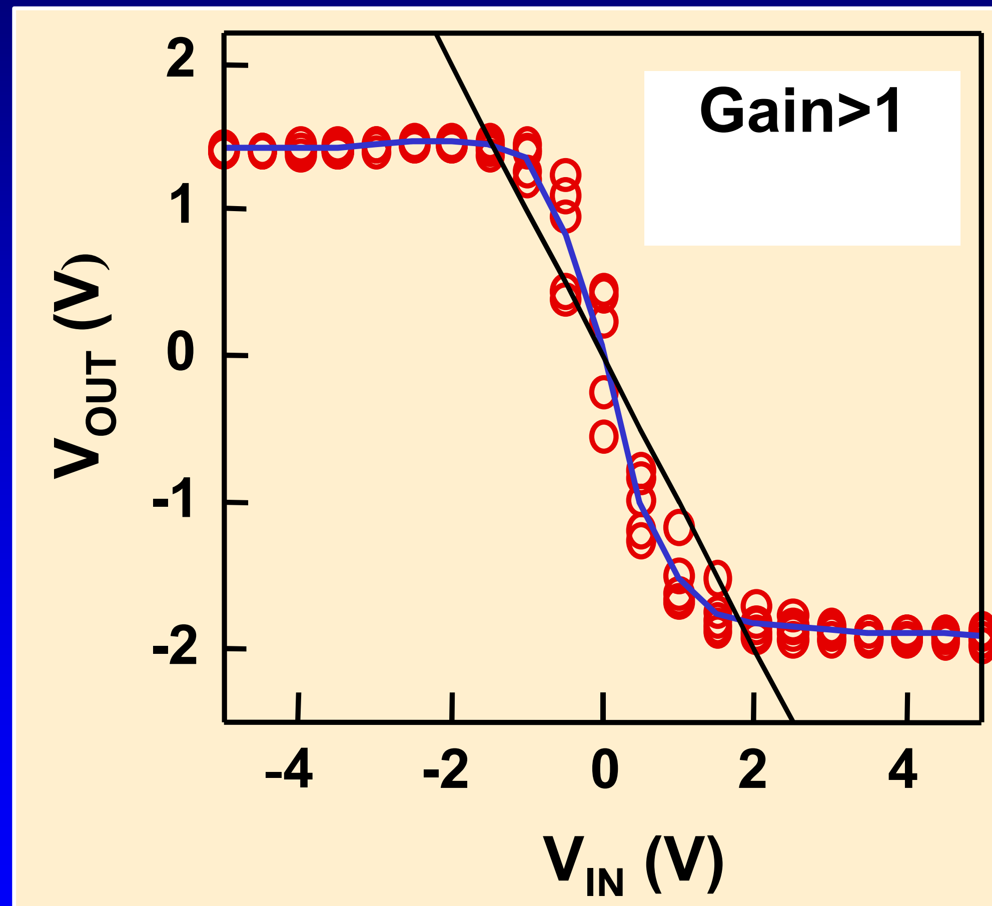


An alternative logic switch -- A simple Carbon Nanotube Transistor

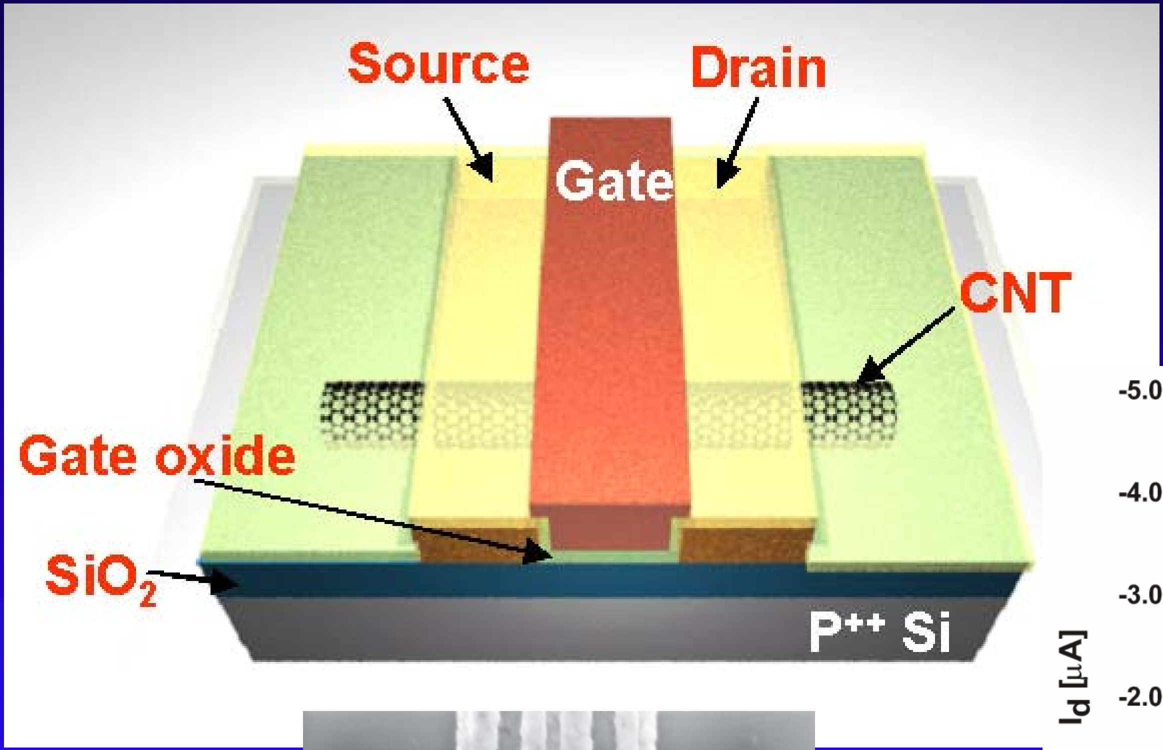


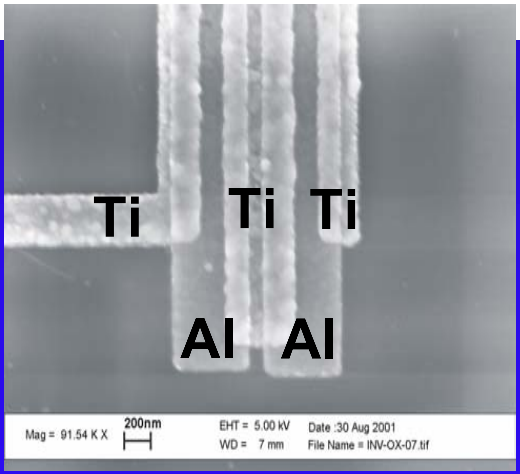
Carbon nanotube intra-molecular logic gate (NOT gate, voltage inverter)

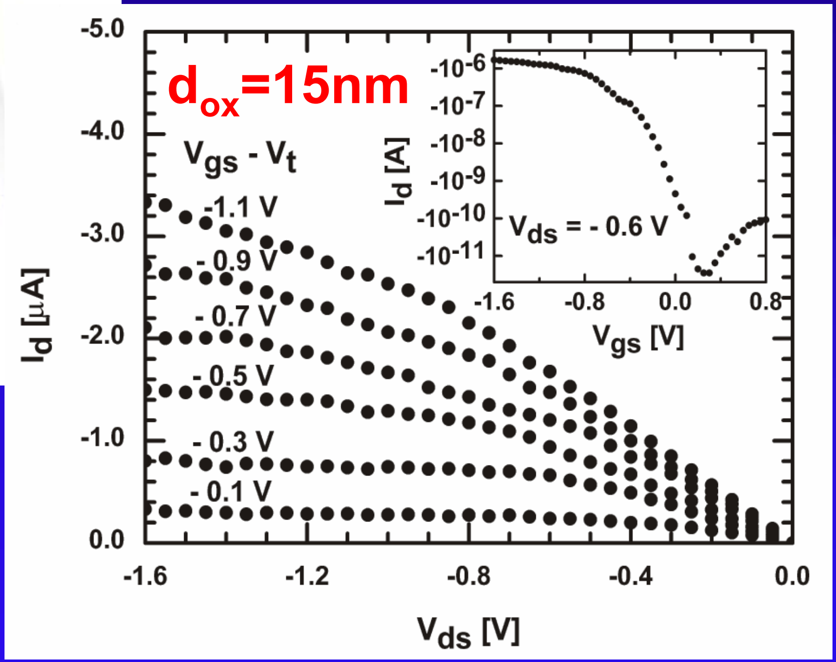




Top-gate carbon nanotube transistor







Appl. Phys. Lett. **80**, 3817 (2002)

Comparison with silicon

	p-MOSFET [a)]	p-CNFET
channel length	50nm	260nm
gate oxide thickness	1.5nm	~15nm
transconductance	650mS/mm	2300mS/mm
drive current $_{(Vg-Vt=-1.0V)}$	650mA/mm	2100mA/mm
threshold voltage	-0.2V	-0.5V
I_{On}/I_{Off}	10^6 - 10^7	~10^6
subthreshold slope	70mV/dec	130mV/dec

[a)] R. Chau et al. Proceedings of IEDM 2001, p.621

Carbon nanotube transistors have promise

because:

- Carrier transport is ballistic and ambipolar
- All bonds are satisfied, stable, and covalent
- Chemical synthesis controls a key dimension
- Device is not "wed" to a particular substrate

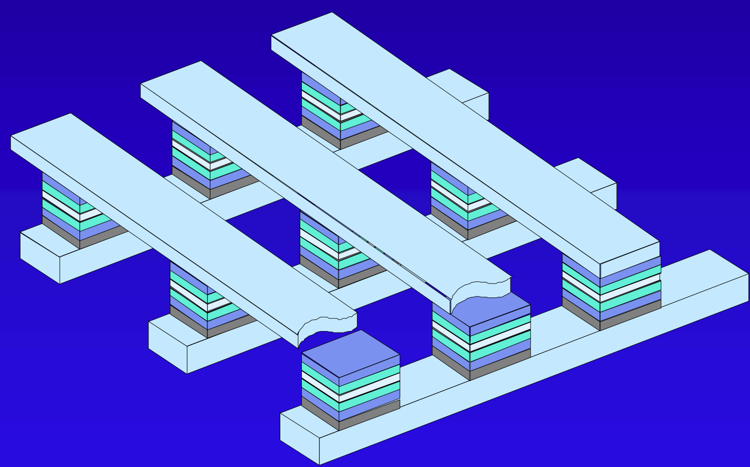
but <u>much</u> remains to be done:

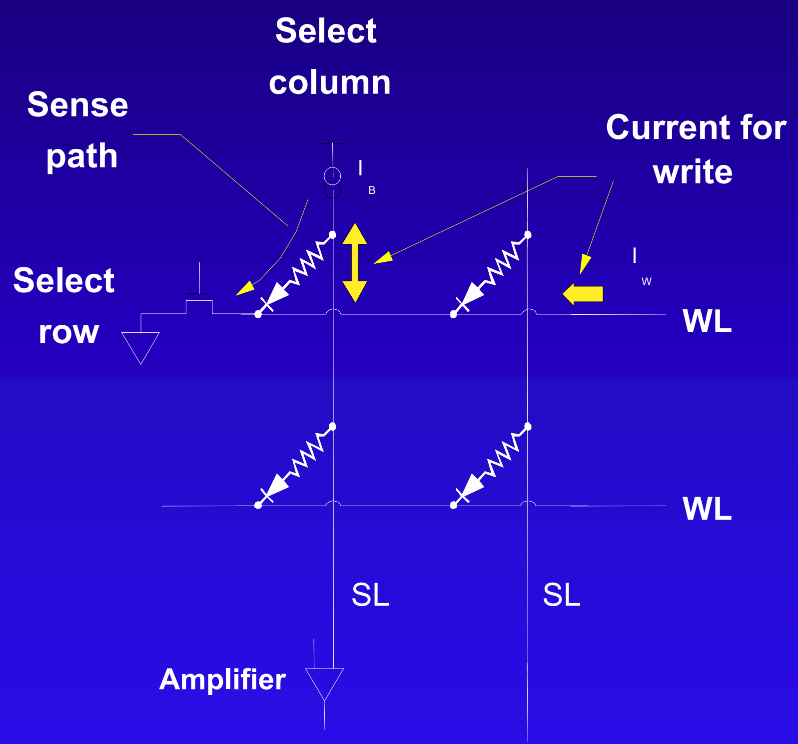
- Scalability
- Contacts
- Doping
- Device stability (charge trapping)
- High yield, selective growth of nanotubes (control of the diameter, length, chirality, position)

Memory

Everyone wants non-volatile, low-power memory.

Everyone wants a dense cross-point memory.





There is no conceptual problem with bistable hysteretic two-terminal devices as cross-point memory cells.

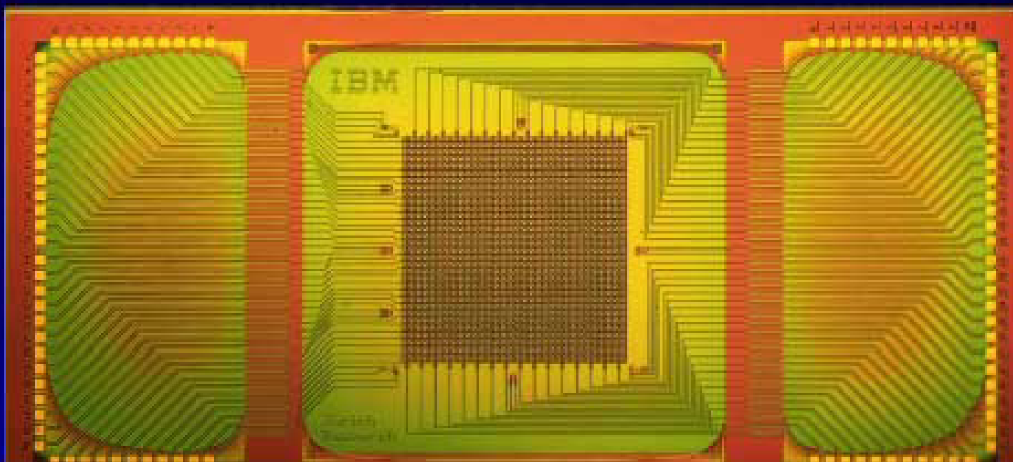
Memory Landscape

	volatile	non-volatile
1Transistor	1T-DRAM	▪ Floating-gate ▪ SONOS ▪ SET
Multiple Transistor	SRAM	
1T-1C	DRAM	FeRAM
1T-1R		▪ MRAM ▪ polymer RAM ▪ molecular memory ▪ phase-change RAM ▪ perovskite MIM RAM
1R (Cross-point)		▪ MRAM ▪ polymer RAM ▪ molecular memory ▪ perovskite MIM RAM

Memory (continued)

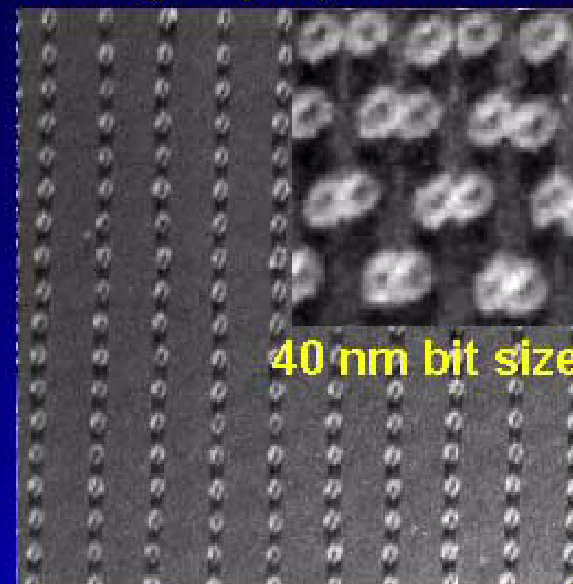
- **There is no shortage of two-terminal, bistable hysteretic memory devices and materials!**
  - **MTJ MRAM** (IBM/Infineon, Motorola, Toshiba, NEC, Sony, HP, Honeywell, Micromem, Motorola, NVE, Samsung, USTC, Toshiba)
  - **Chalcogenide glasses** (Intel/Ovonyx, Micron Technology/Axon Technologies, Samsung, ST Micro)
  - **Polymeric resistive memory** (Intel/Opticom, AMD/Coatue)
  - **Molecular memories** (Hewlett Packard, Molecular Electronics Corp., Zettacore, Nantero, …)
- **But ...**
  - All memories require logic devices for read/write. Candidate memory cells must be integrated with logic.
  - Replacing a transistor-based memory cell with a cross-point cell will typically reduce performance.

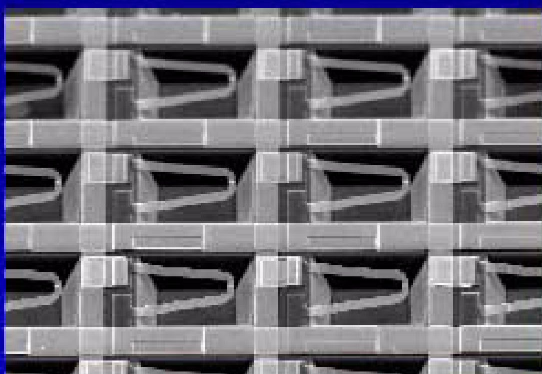
Millipede: A nanomechanical approach to storing information

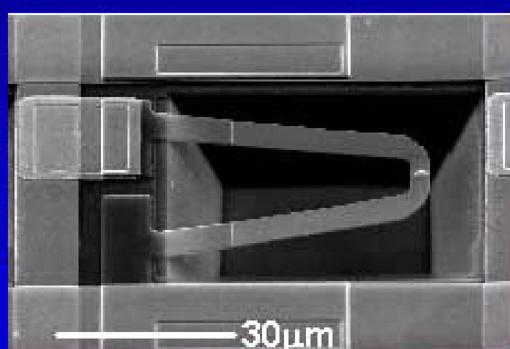


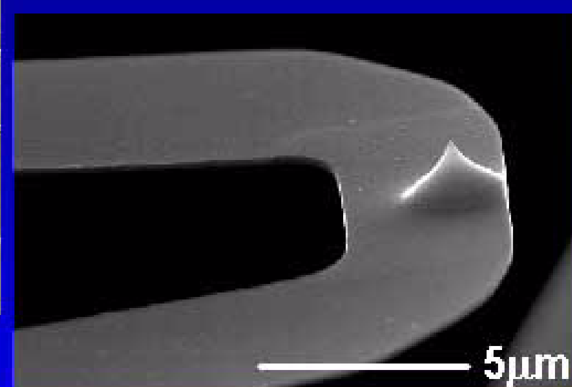
32 x 32 (1024) Cantilever Array

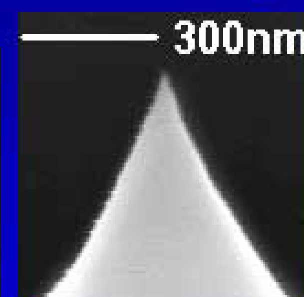
Thermomechanical writing in polymer media







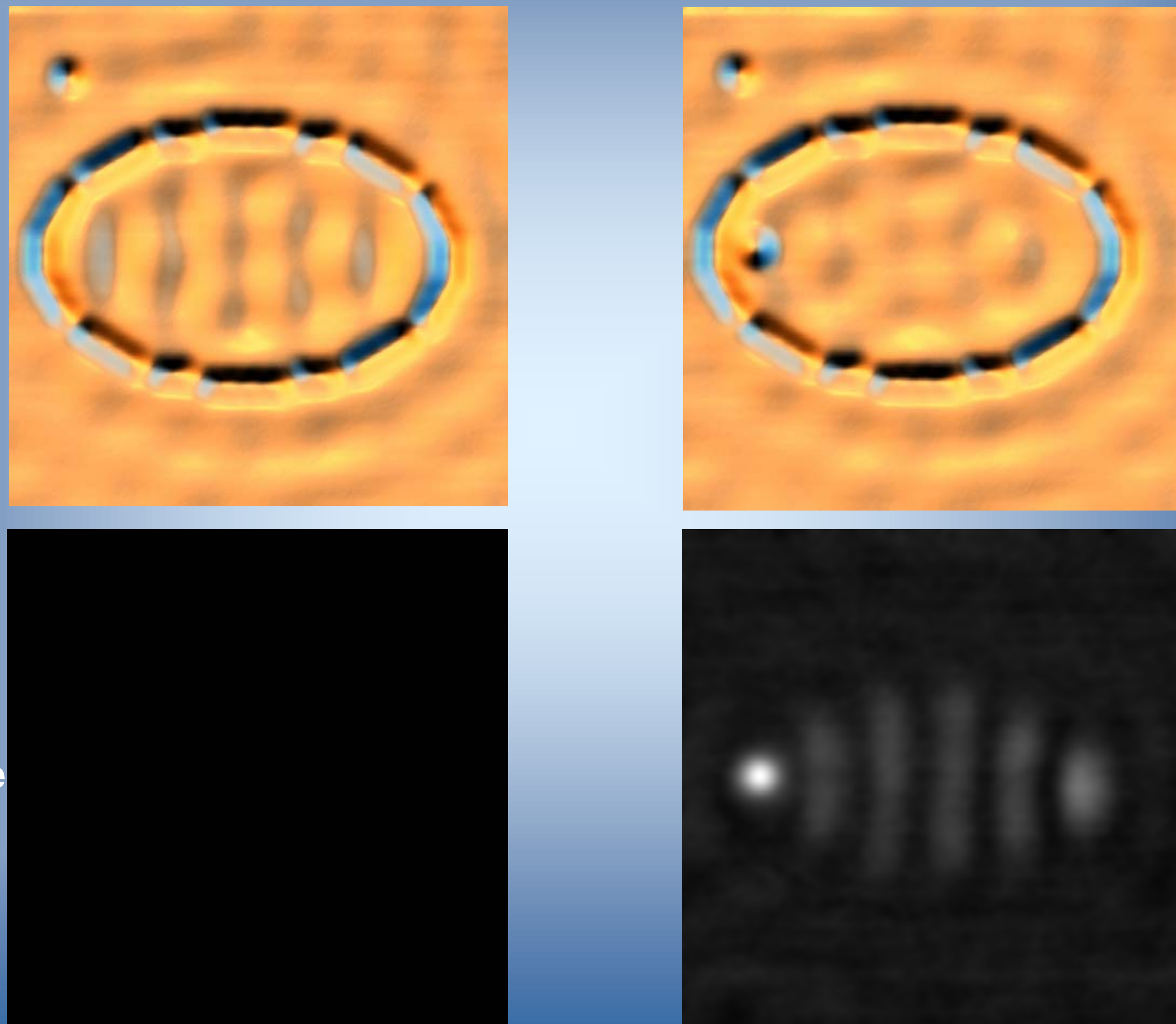




The Quantum Mirage:
Single Channel Information Transport

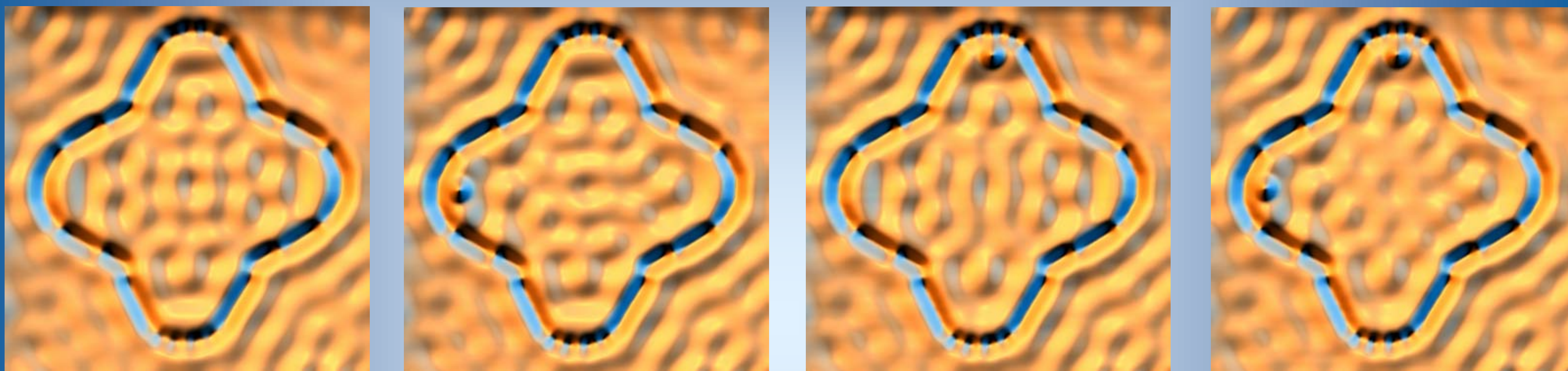
Topograph

dI/dV difference

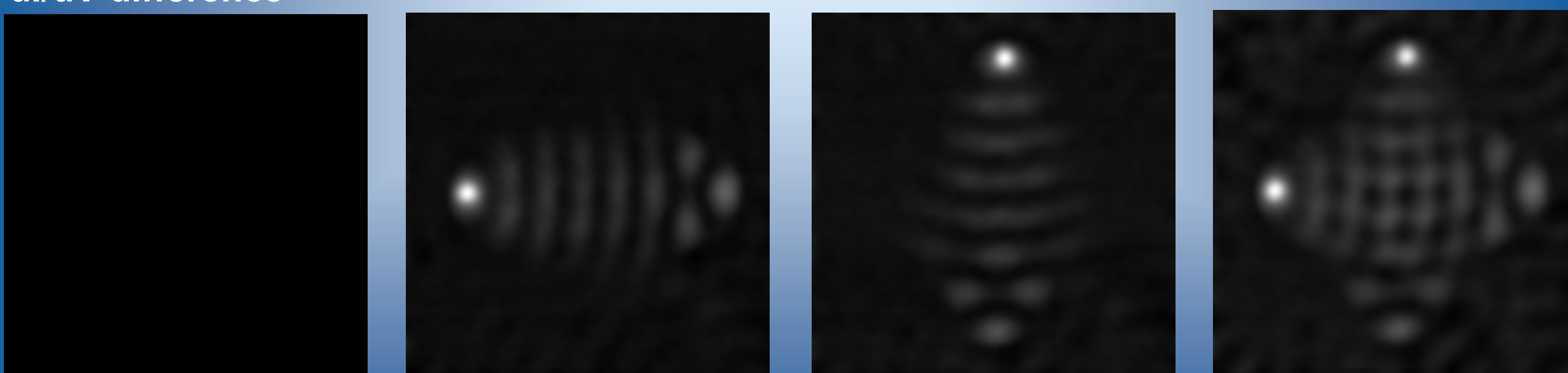


Multi Channel Information Transport

Topograph



dI/dV difference

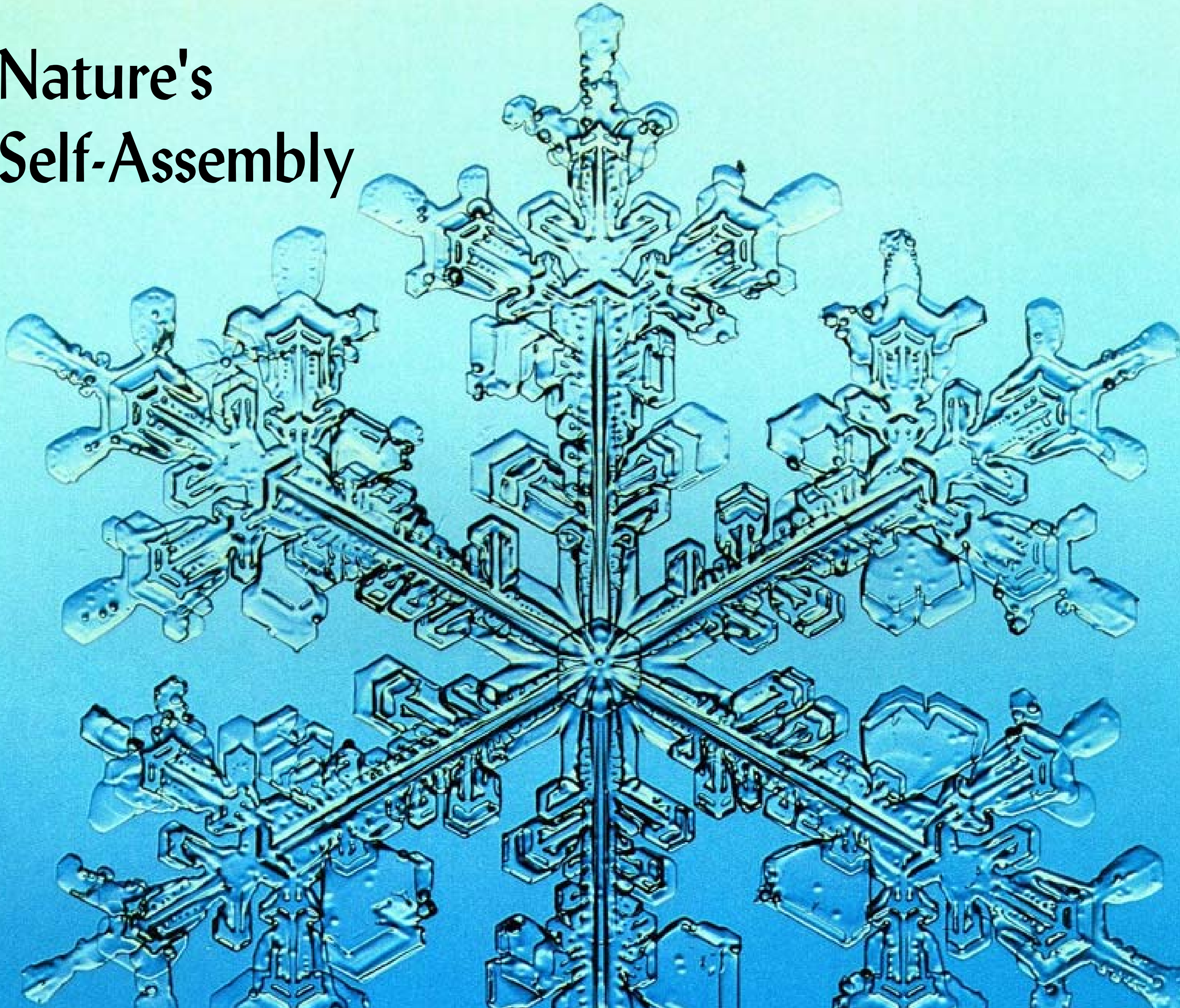


But how can we position atoms cheaply?

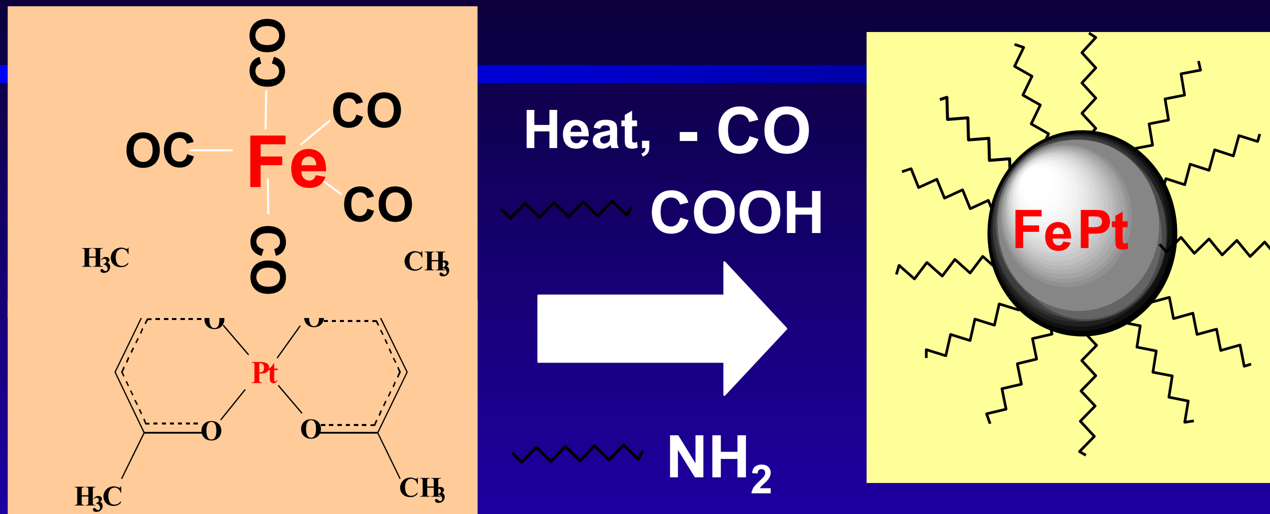
Persuade them to assemble themselves!

http://www.its.caltech.edu/~atomic/snowcrystals/photos/WWick/wwick.htm

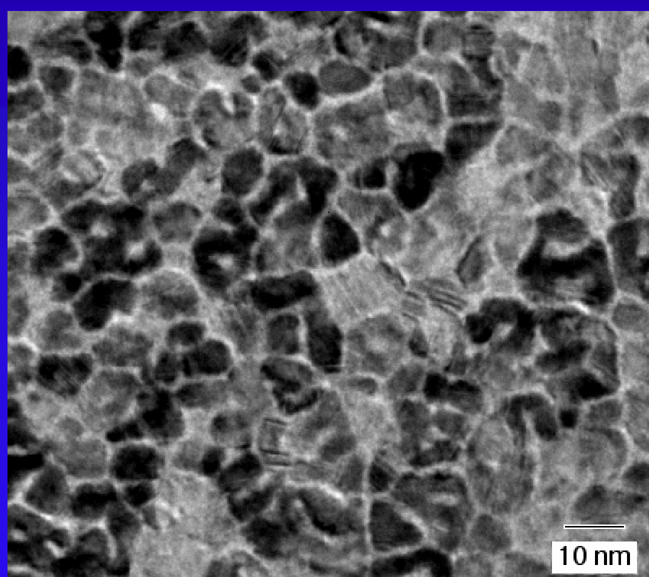
Nature's Self-Assembly



Self-assembled Magnetic Nanocrystals

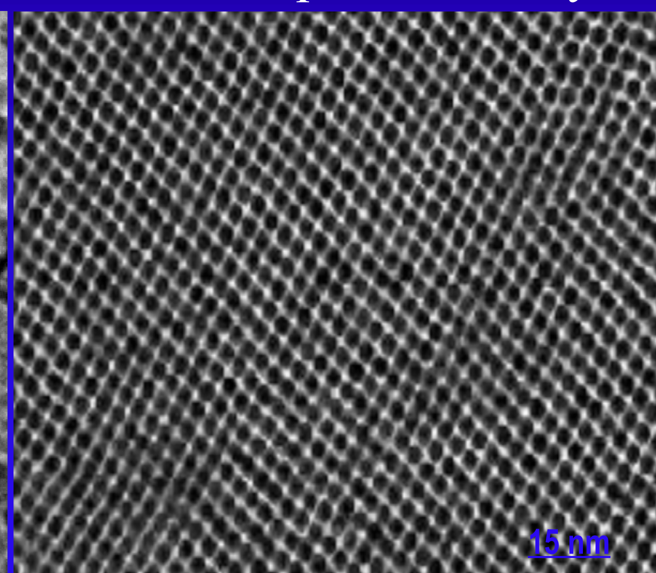


35 Gbit/in^2 media



8.5nm grains $\sigma_{area} \cong 0.5$

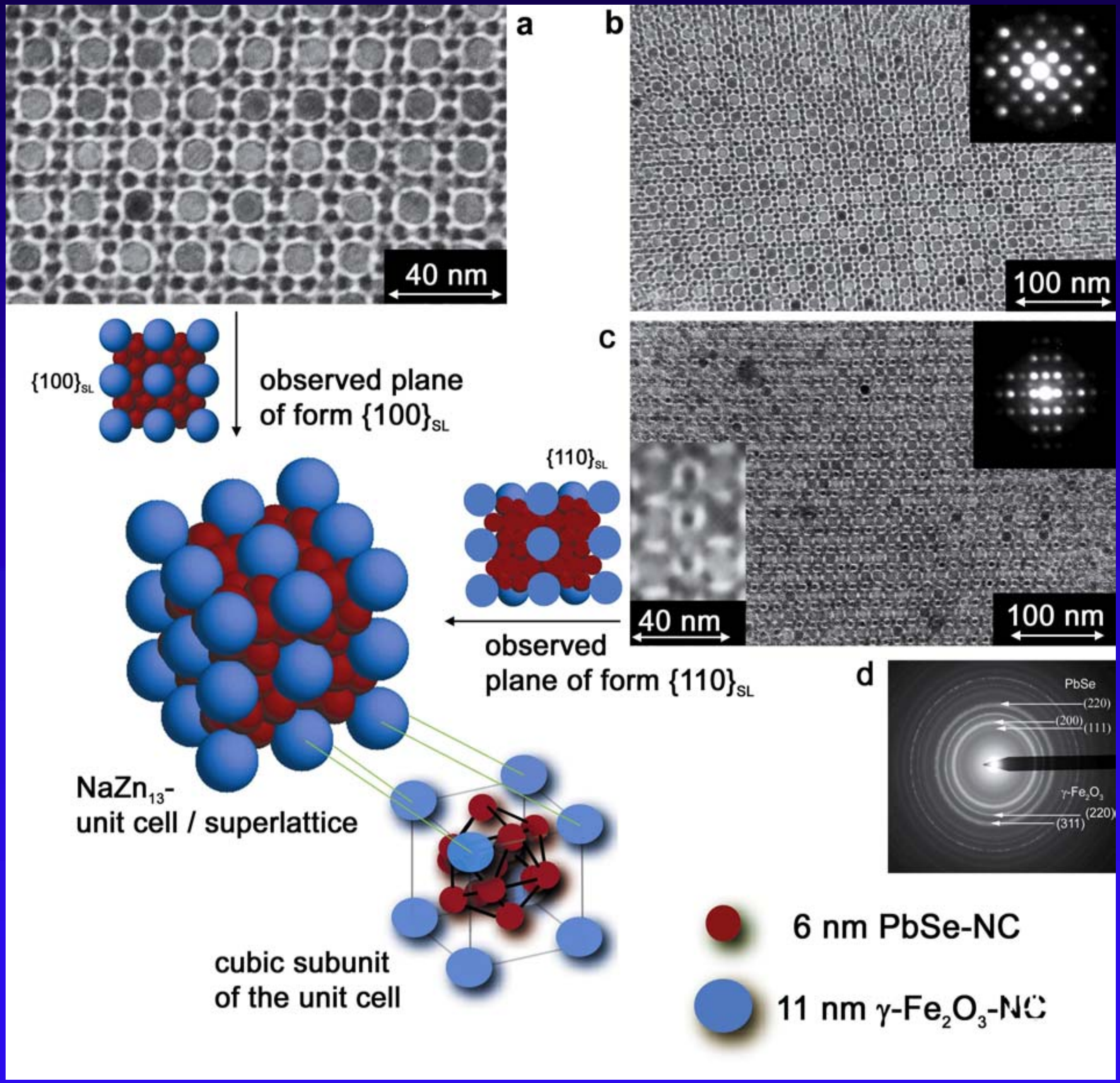
FePt Nanoparticle Arrays



4 nm FePt NPs $\sigma_{area} \cong 0.05$

S. Sun, C. B. Murray, D. Weller, L. Folks, A. Moser, Science, 287, 1989 2000

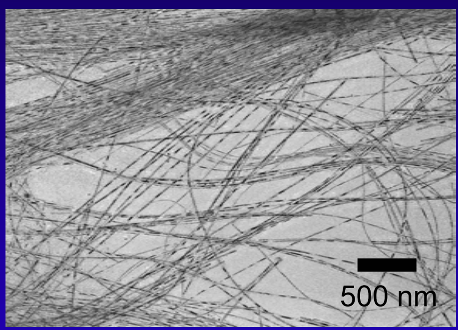
Multi-Component Nanocrystal Superlattices

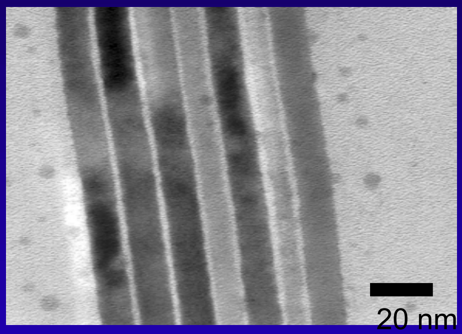


AB_{13} binary Nanocrystal Superlattice of PbSe and Fe_2O_3

F. X. Redl, K. S. Cho and C. B. Murray.

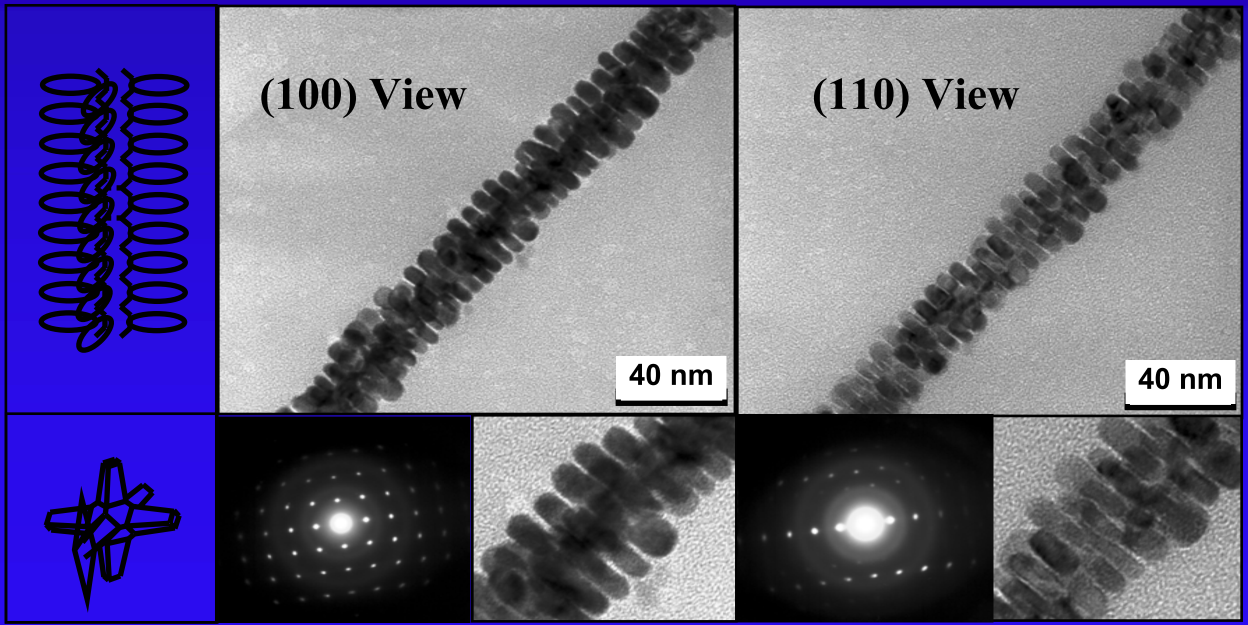
Semiconductor Nanowires



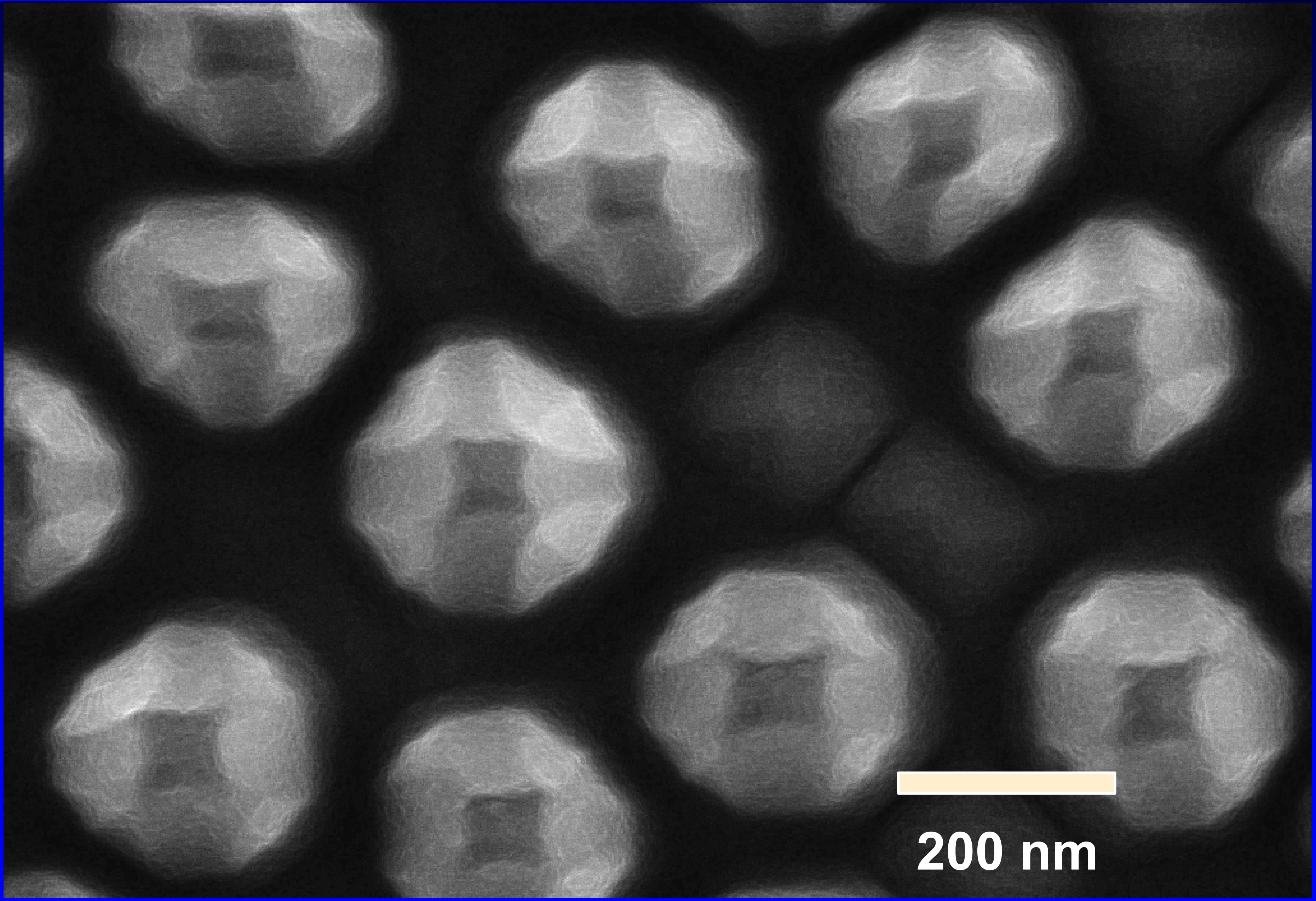


Straight PbSe Nanowires

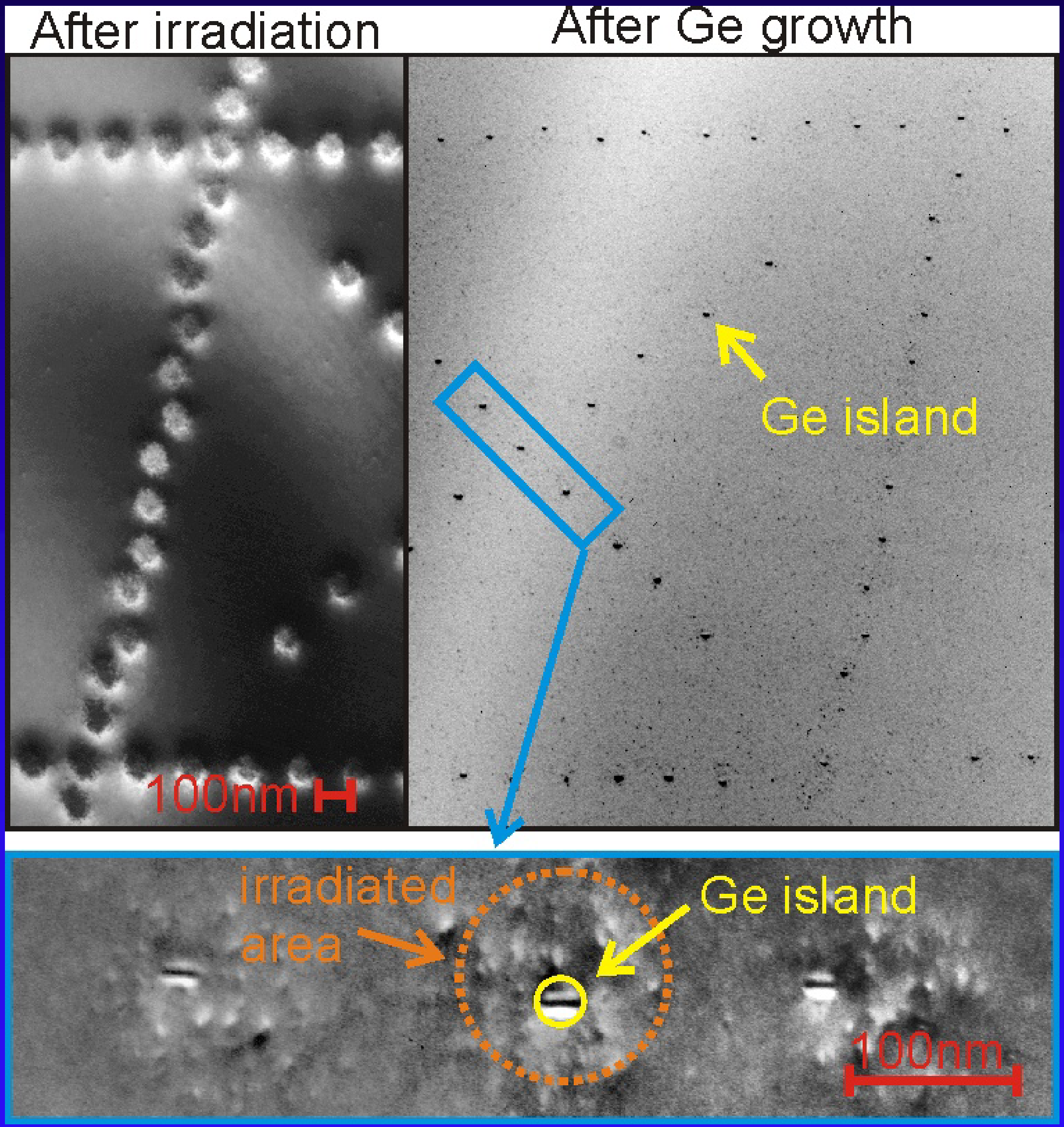
Branched PbSe Nanowires with High Surface Area



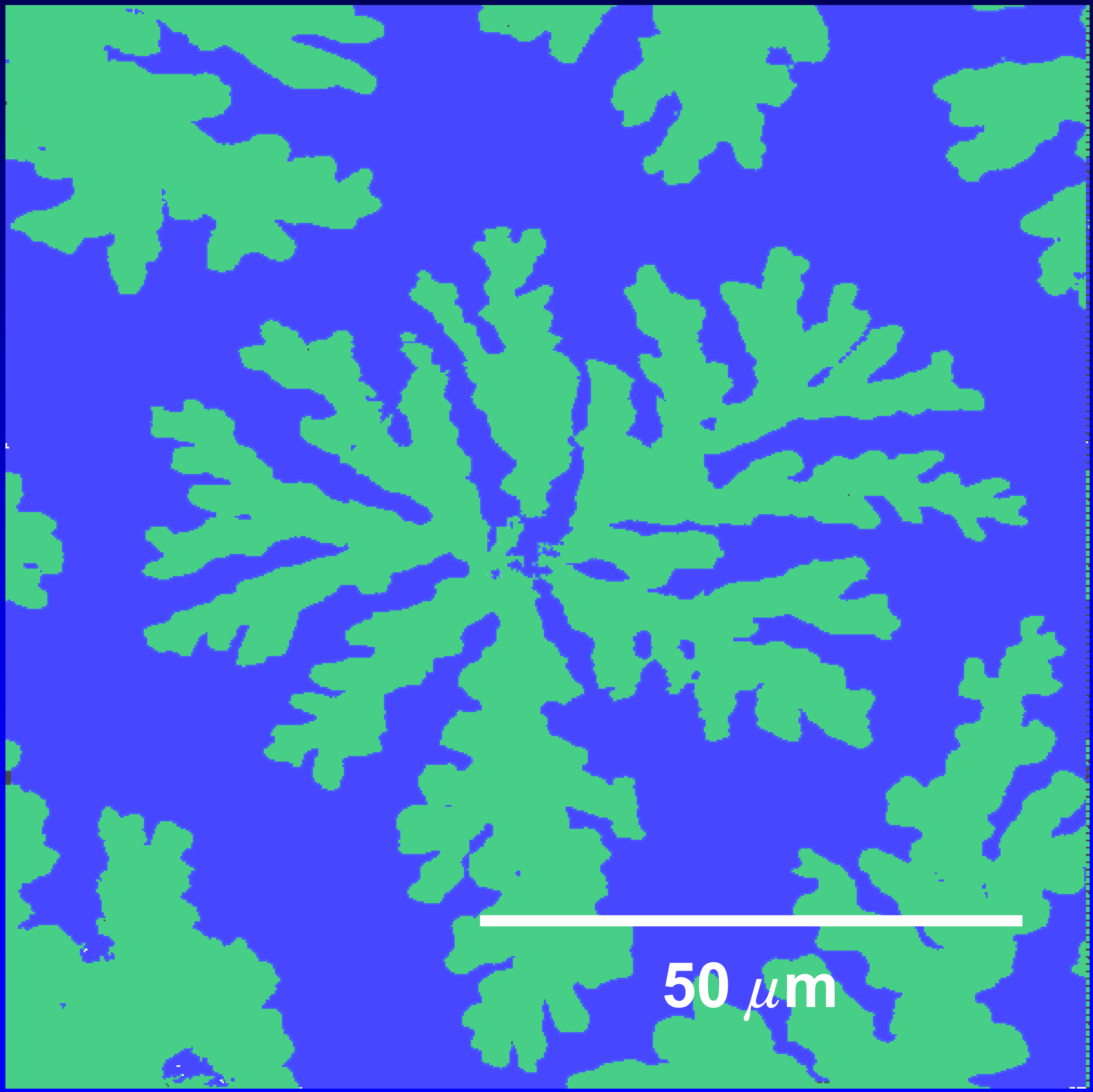
Self-assembly: SiGe Quantum Dots



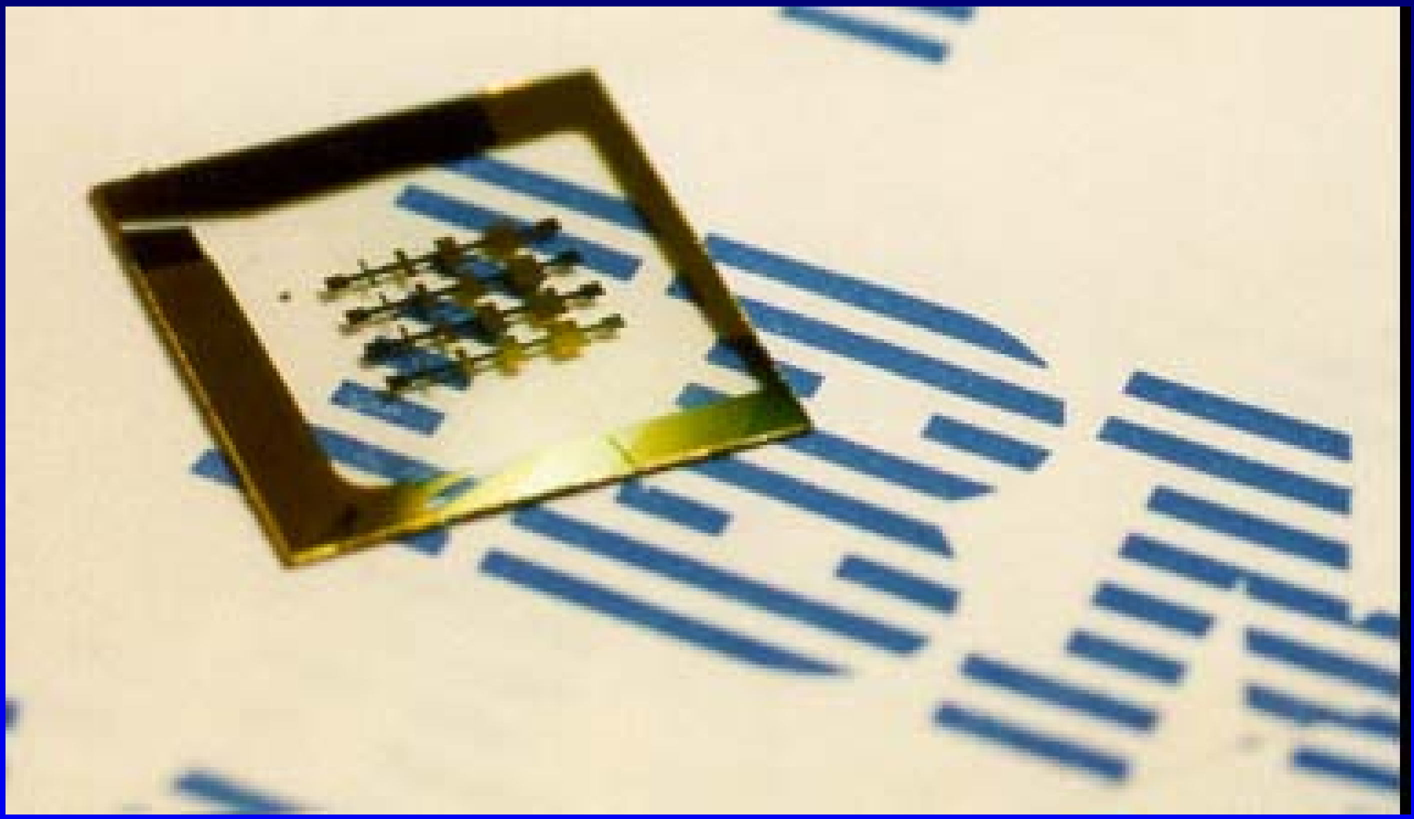
Precise Placement of Quantum Dots



Self Assembly:
A One-Monlayer-Thick Pentacene "Snowflake"

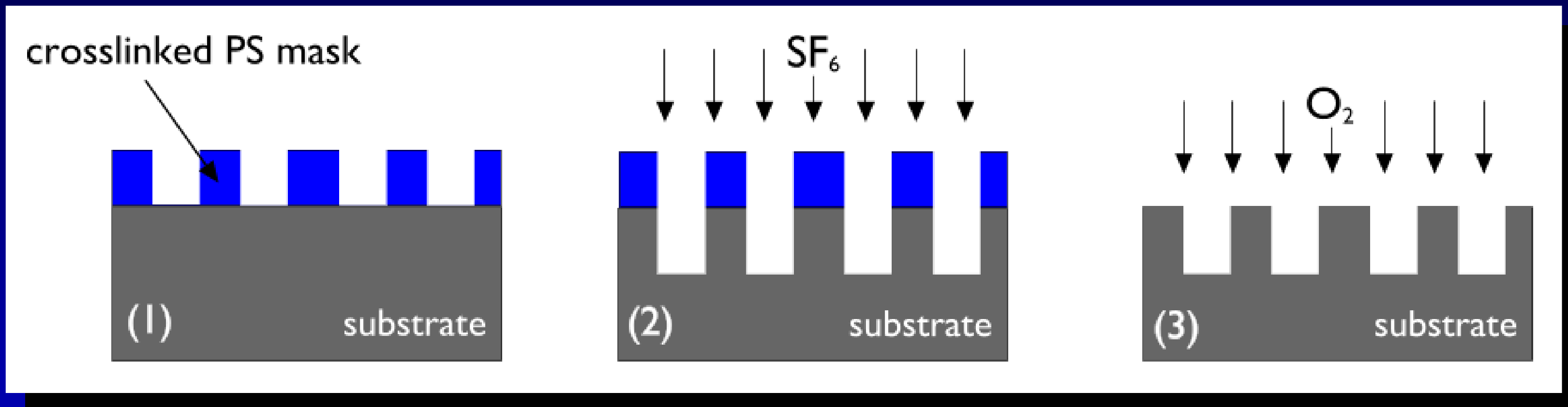


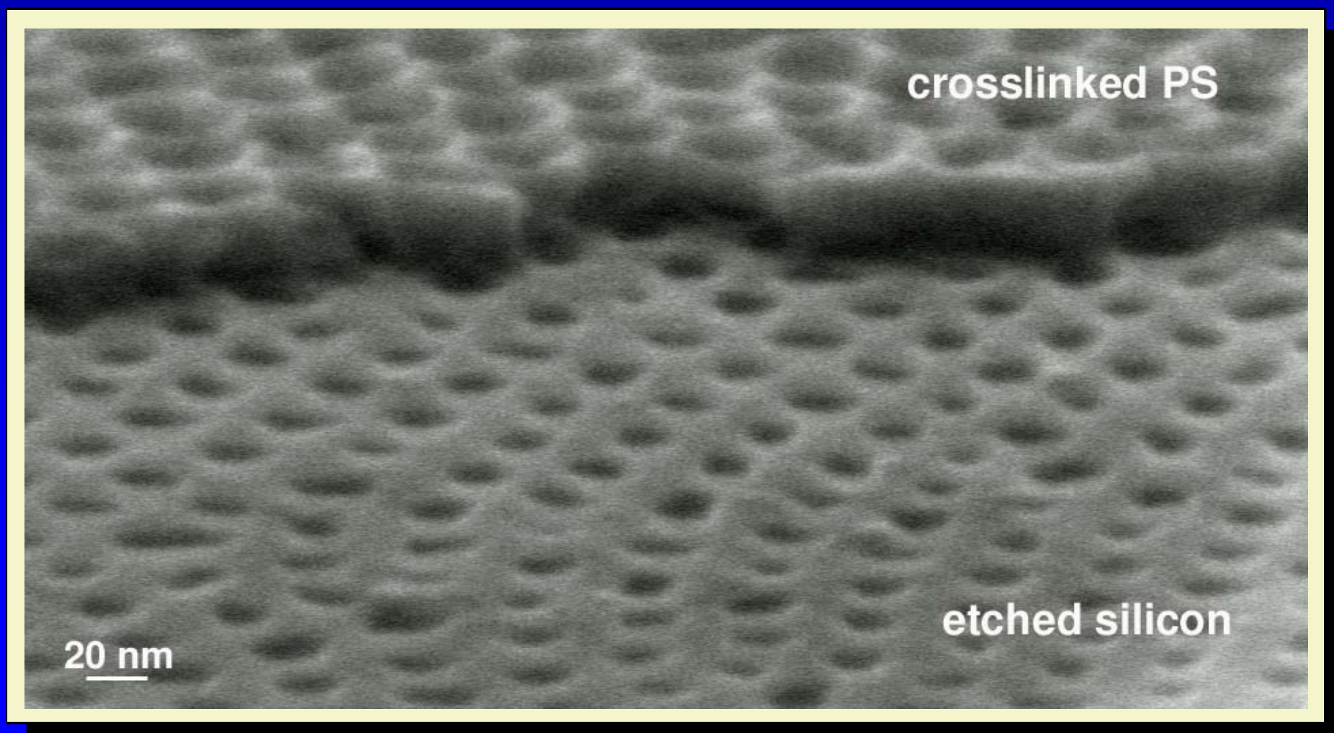
Thin Film Transistors on Transparent Plastic:



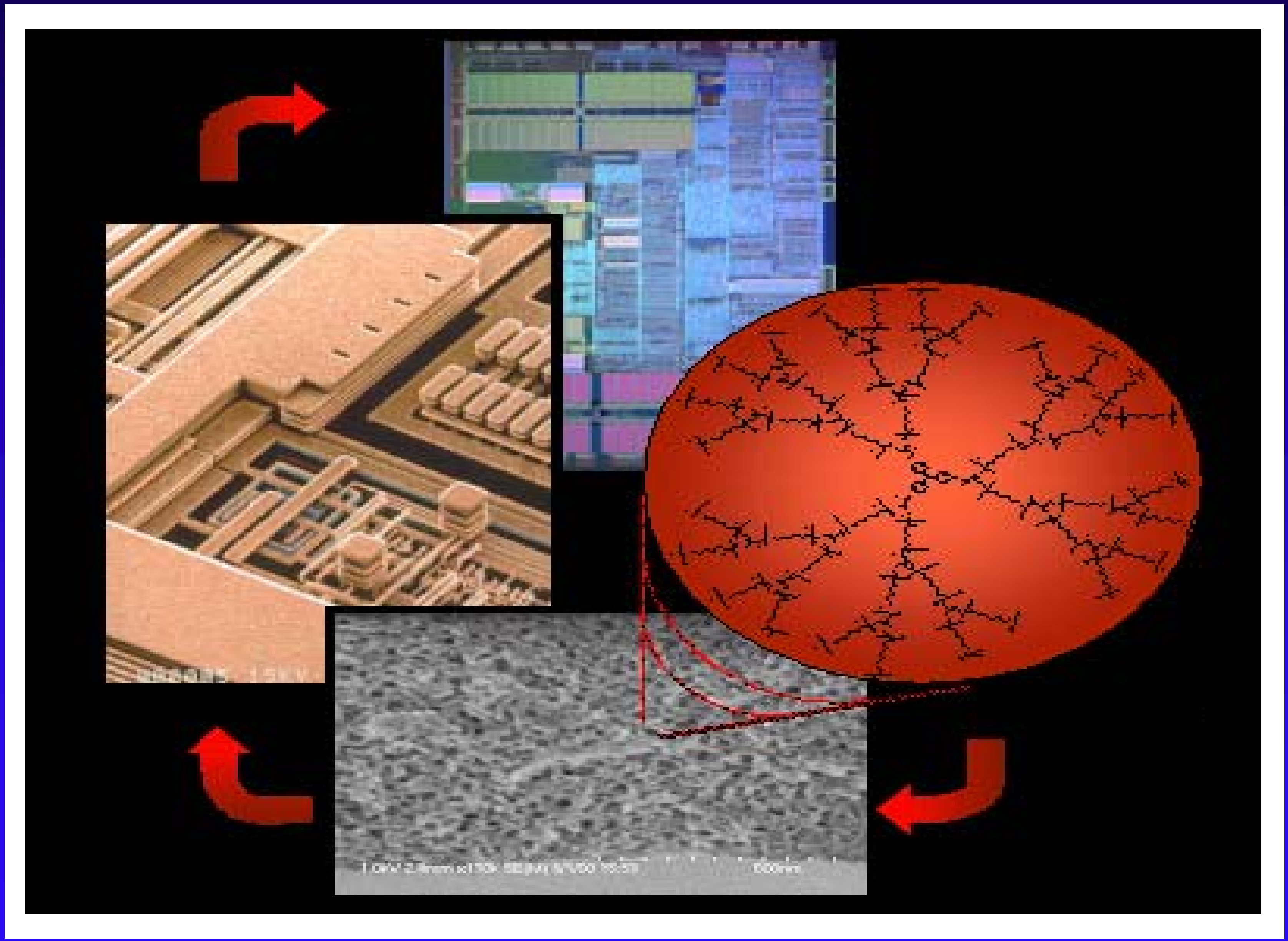
μ = 0.2 to 0.4 $cm^2 V^{-1}s^{-1}$, operating voltage 0 to 4 V.
All fabrication processes done at room temperature.

Patterning Silicon with Block Co-polymers

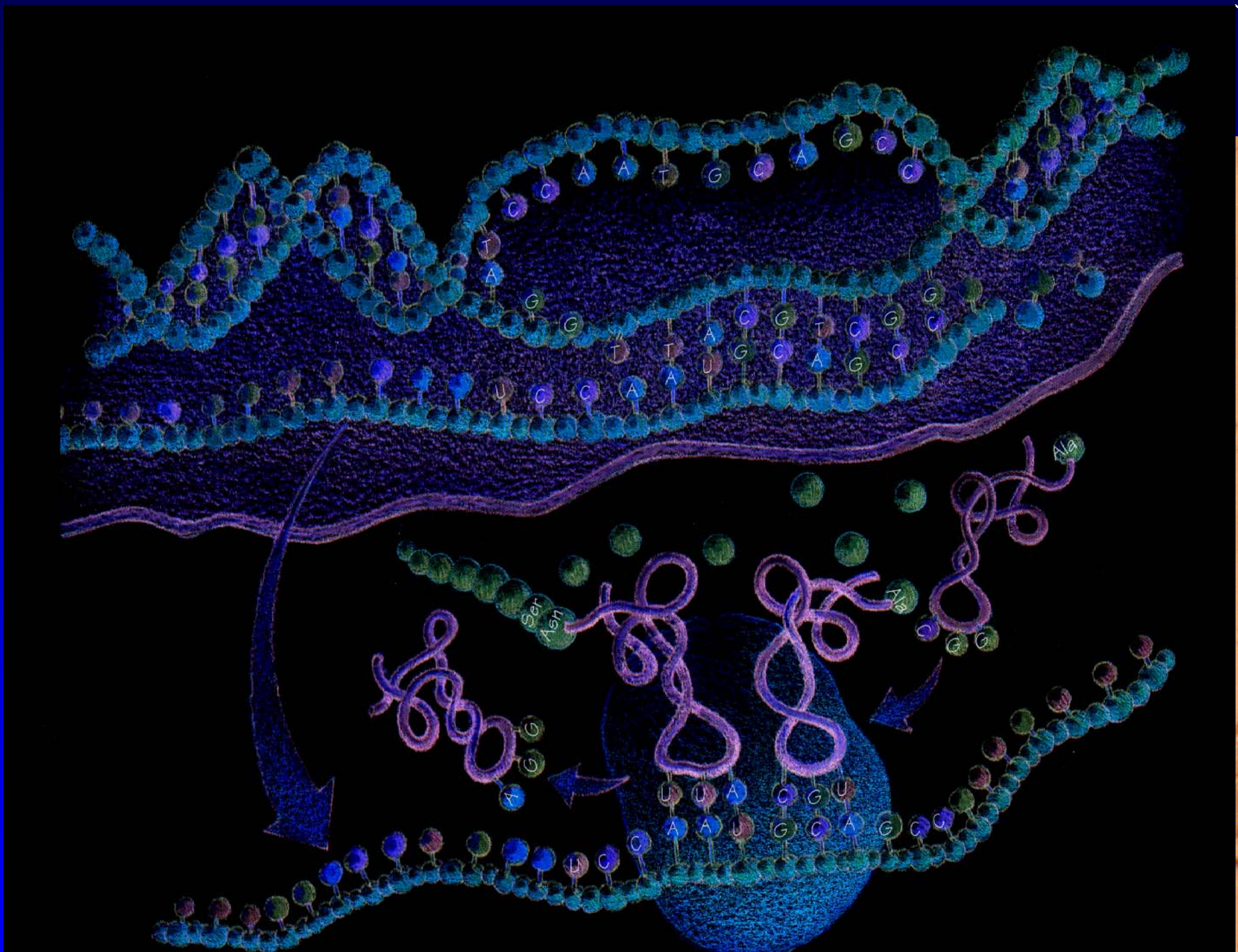




Pourous Dielectrics for On-Chip Wiring



How much digital information will specify the structure?



Drawing from: "To Know Ourselves," US Dept. of Energy and The Human Genome Project 1996.

A living thing
(Paramecium)

How much digital information is needed to BUILD the structure?

- Microprocessor – Gigabytes
- Living Thing – Megabytes!

Nanotechnology …

The ability to design and control the structure of an object on all length scales, from the atomic to the macroscopic.

Nanotechnology: We're just getting started.