Beyond the Wall: Technologies for the Future

SPIE 2001 Symposium on Microlithography

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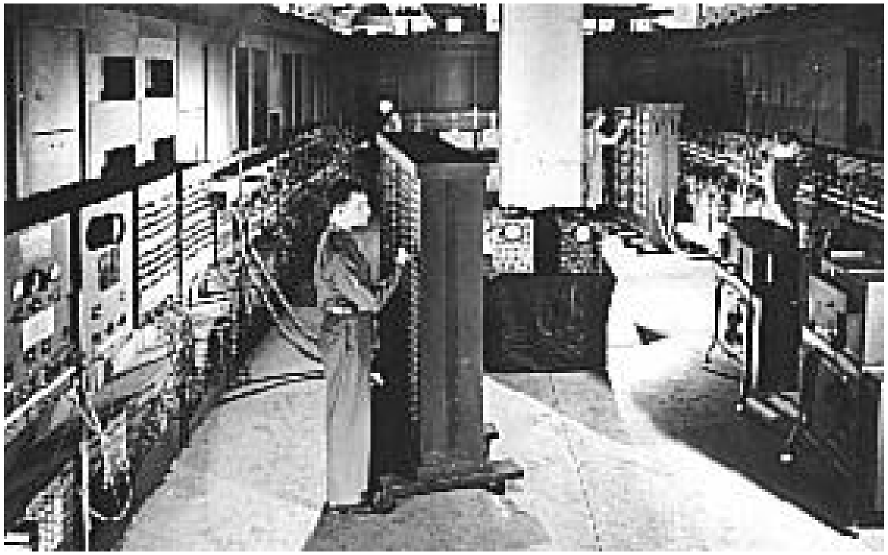
Outline

- Current status
- Near term future
  - The Wall is dead ahead!
- Future disruptive technologies?

Predicting the Future?

ENIAC - 1946

- First stored-program electronic computer
- 17,500 vacuum tubes
- 60,000 pounds
- 174 kilowatts
- 5000 operations/second



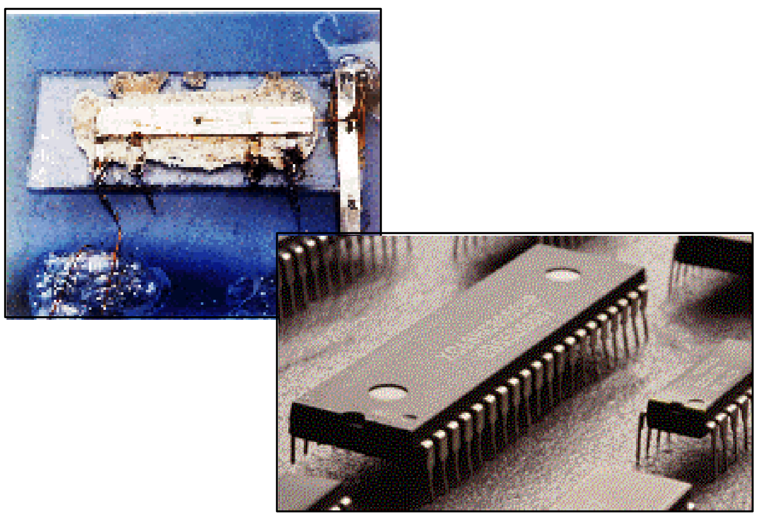
1949 Prediction: Some day a computer as powerful as ENIAC will contain only 1,500 vacuum tubes, weigh only 3,000 pounds, and consume only 10 kilowatts

Viewing the future through the old paradigm…

Disruptive Technologies Defy Predictions

Transistor

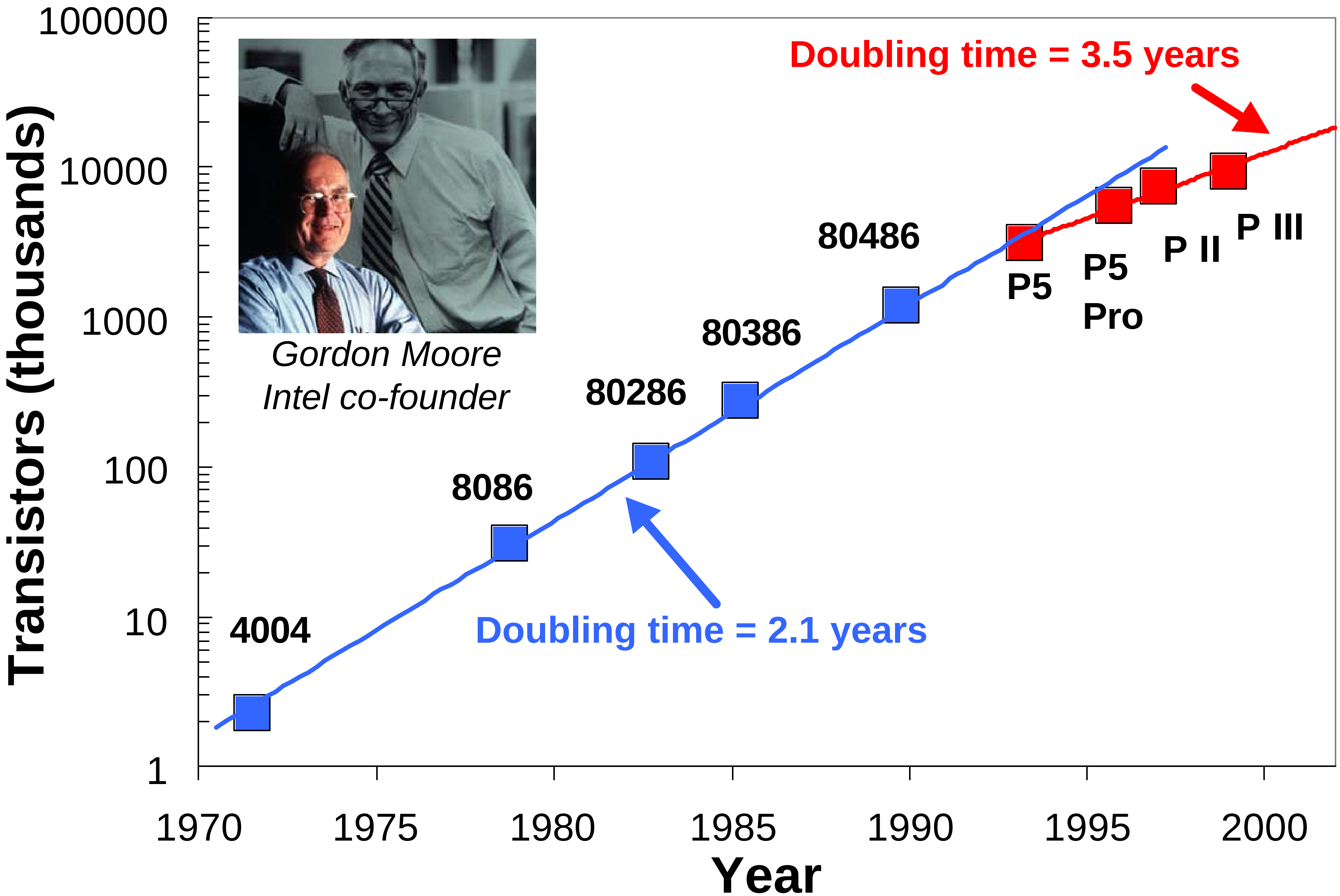
Invented *1947 (Bell Labs)*
Production *1952 (Western Electric)*
Bypass the limitations of the vacuum tube



Integrated Circuit

Invented *1959 (Texas Instruments and Fairchild)*
Production *1961 (Fairchild)*
Bypass the limitations of "tyranny of wiring"

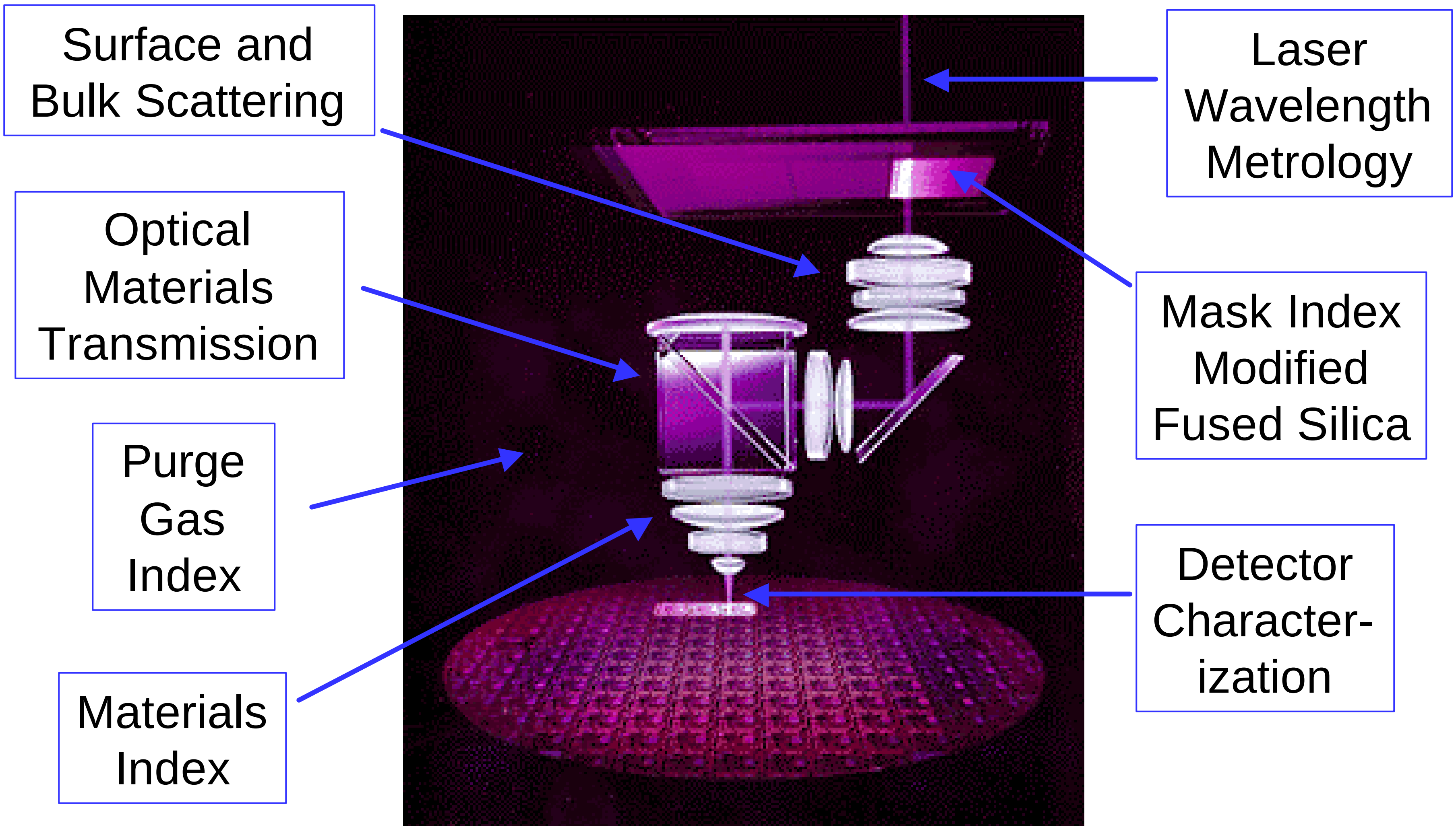
Moore's Law


100000
10000
1000
100
10
1
Transistors (thousands)
1970
1975
1980
1985
1990
1995
2000
Year
Gordon Moore
Intel co-founder
4004
8086
80286
80386
80486
P5
P5
Pro
P II
P III
Doubling time = 3.5 years
Doubling time = 2.1 years

Key Drivers of the Integrated Circuit Industry

- Computer aided design
- Manufacturing improvements
  - Yield improvement, scale-up
- Lithography
  - Visible ✍ Ultraviolet ✍ Deep UV ✍ ?

NIST Metrology for All Aspects of Lithography Process

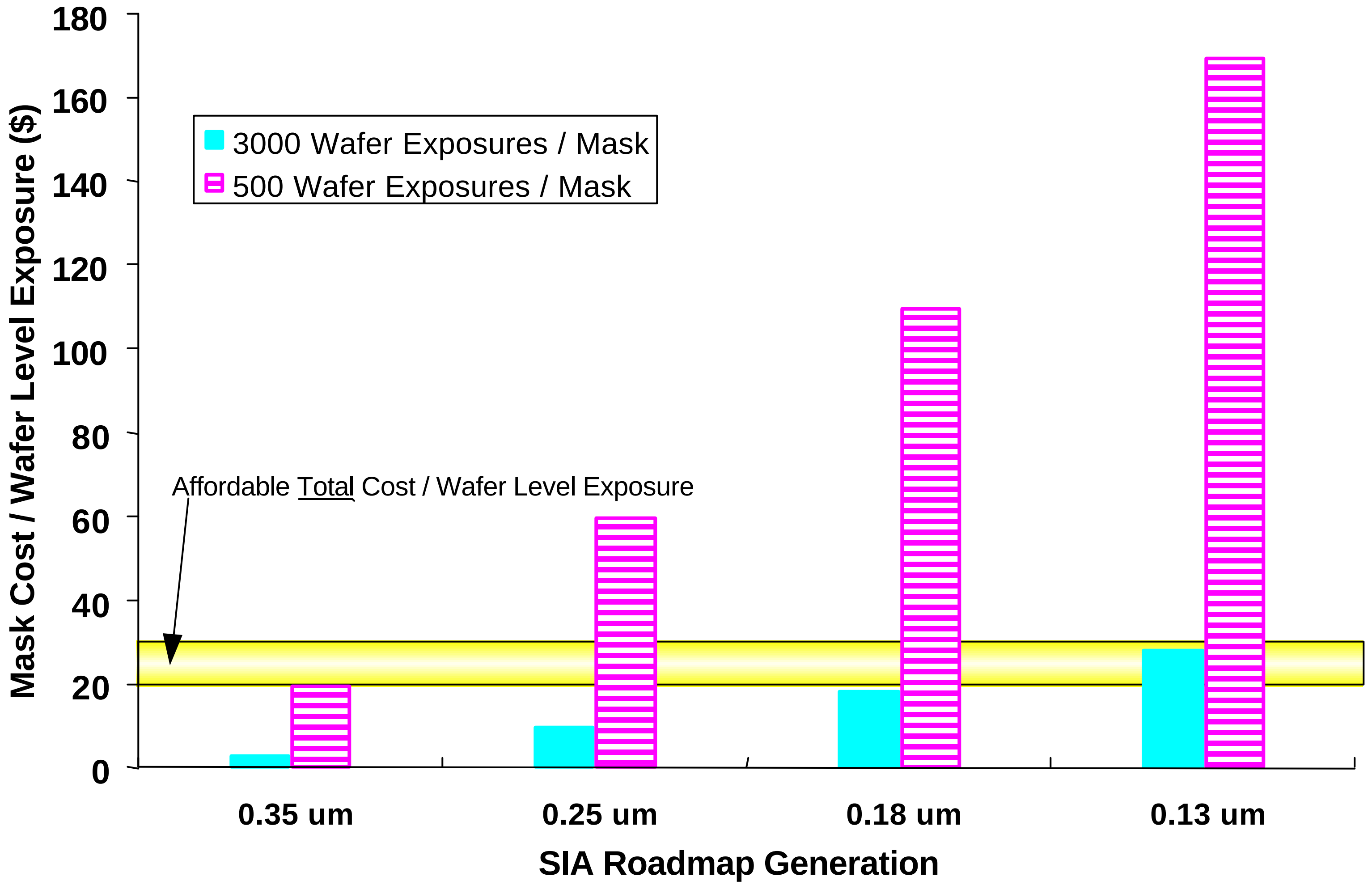


Lithography Costs

- Number of products increasing dramatically
- Wafers/mask exposure decreasing
- Tool costs/wafer exposed increasing
- Mask cost/level increasing

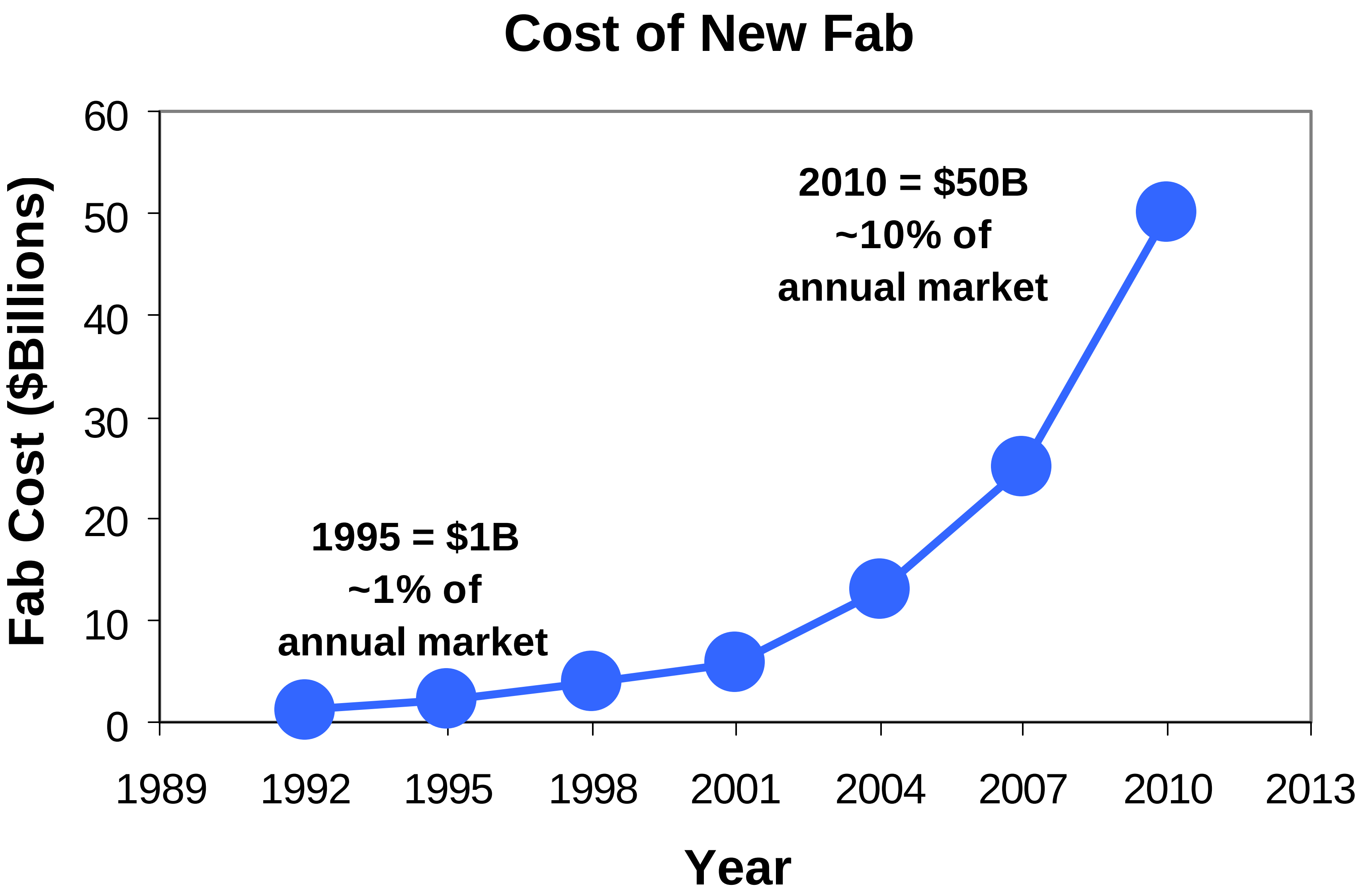
- *Net Result: Lithography costs per wafer at 100 nm may exceed total affordable process cost per wafer*

Mask Costs



180
160
140
120
100
80
60
40
20
0
Mask Cost / Wafer Level Exposure ($)
3000 Wafer Exposures / Mask
500 Wafer Exposures / Mask
Affordable Total Cost / Wafer Level Exposure
0.35 um
0.25 um
0.18 um
0.13 um
SIA Roadmap Generation

“Moore’s Second Law”



The Real Challenge

- **Manufacturable solutions for each technology element**
- **Cost effective solutions**

without both there will be a crisis

IS TIME RUNNING OUT?

NIST Investment in Longer-Term R&D

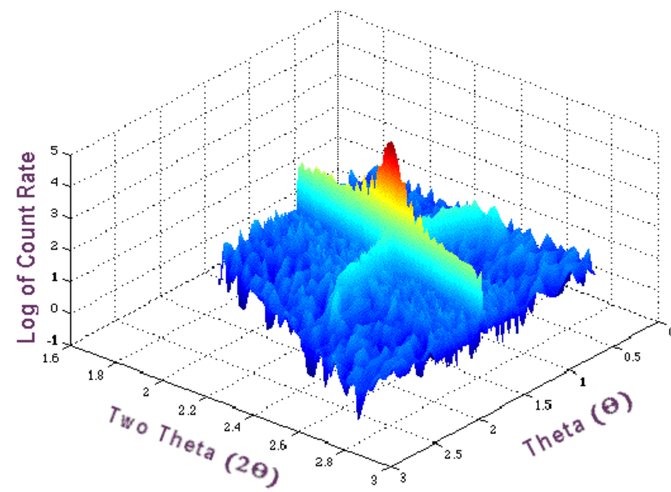
Optics Measurement Infrastructure

Metrology anticipating industrial need

- **Characterize commercial exposure meters for semiconductor UV photolithography: improved accuracy from ±20% to ±1%**

- **Measurement of quartz index of refraction at 193 nm for DUV photolithography shows discrepancies among suppliers at 10^{-5} level. 10^{-6} required by designers -- NIST developing new measurement techniques**

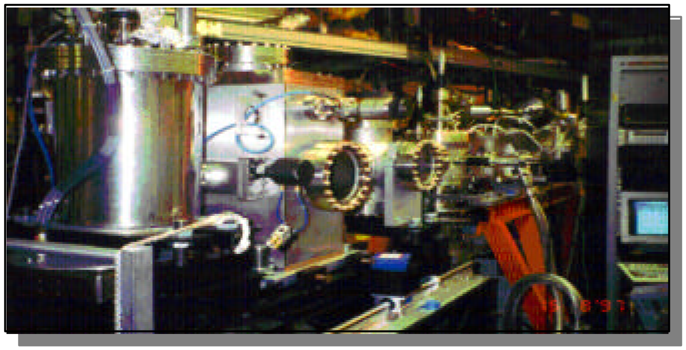
- **Measure thin films of new materials with x-ray diffraction: thickness, composition, structure unambiguously (service provided to SEMATECH)**



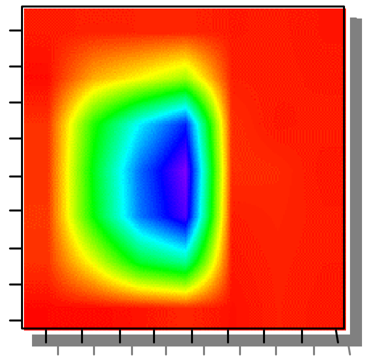
NIST Investment in Longer-Term R&D

SURF III Upgrade: New Standards and Science

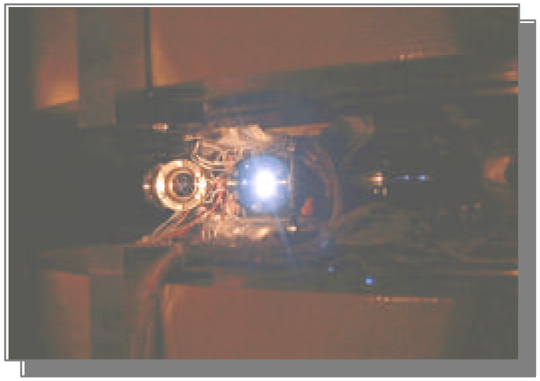
400 MeV storage ring optimized for radiometry



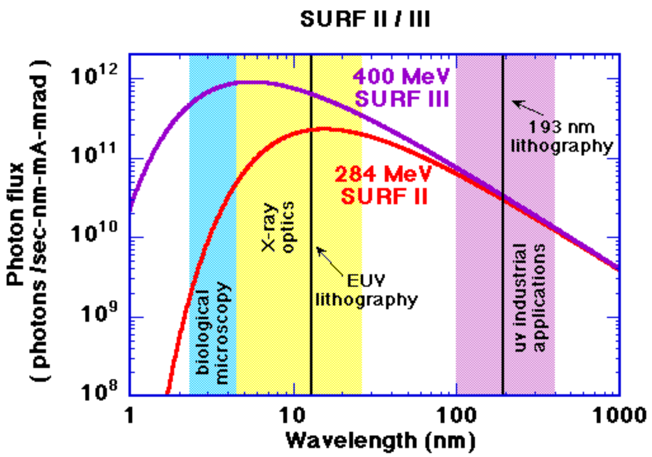
Cryogenic spectroradiometry at SURF II



VUV detector damage studies



First light from SURF III December 1998



SURF III applications:

- **Measurement of EUV multilayer optics**
- **EUV optical properties**
- **X-ray radiometry**
- **DUV radiometry**

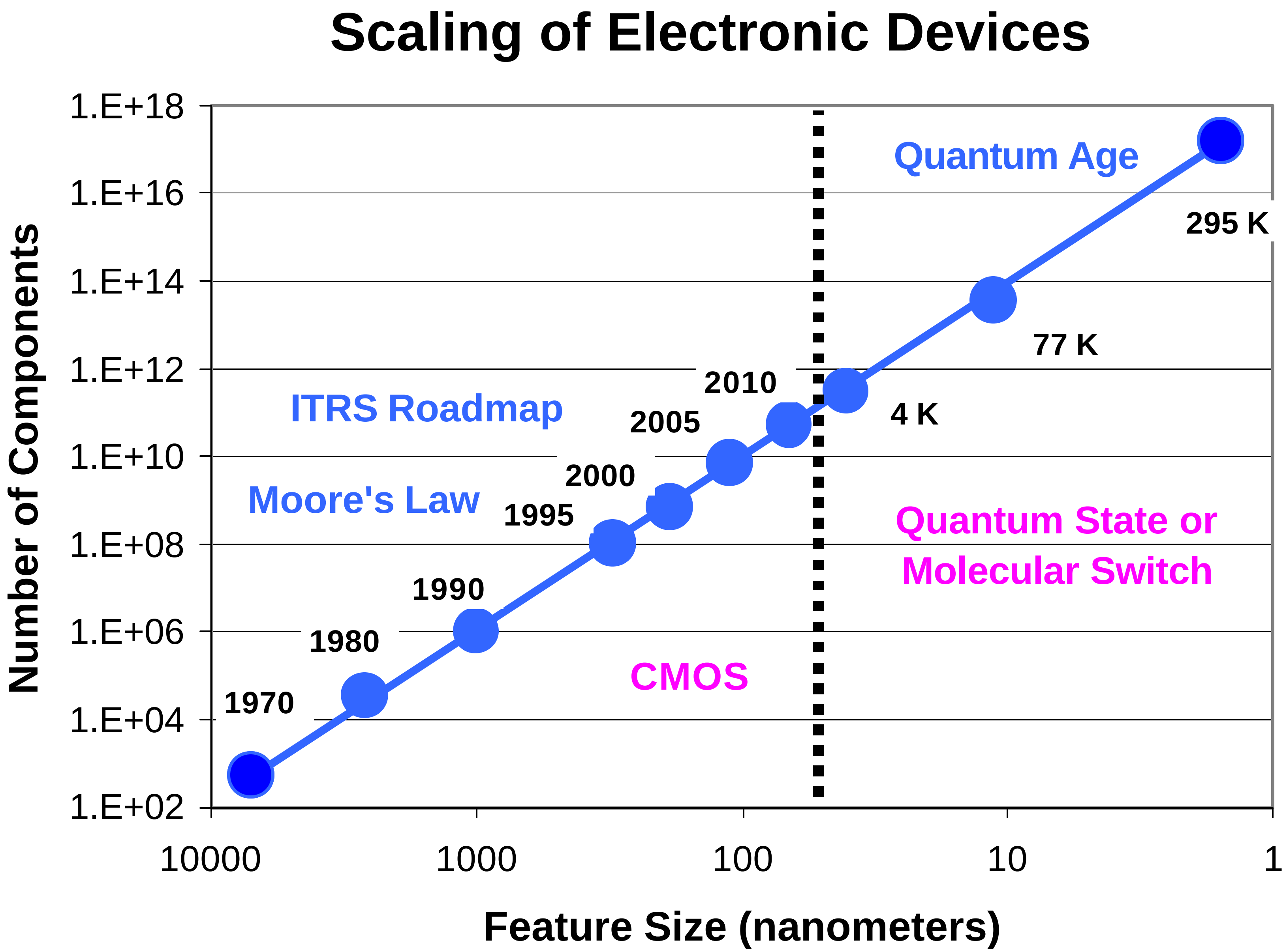
Barriers Ahead to Current Roadmap: Cost/Performance Slowdown

- **Roadmap goals have been driven by incremental improvements in lithography.**

- **This path is destined to end by about 2010.**
  - **Physical limits**
  - **Economic limits (cost/performance slowdown)**
  - **Combination of physics and economics**

- ***Need commitment and resources on longer-term solutions.***

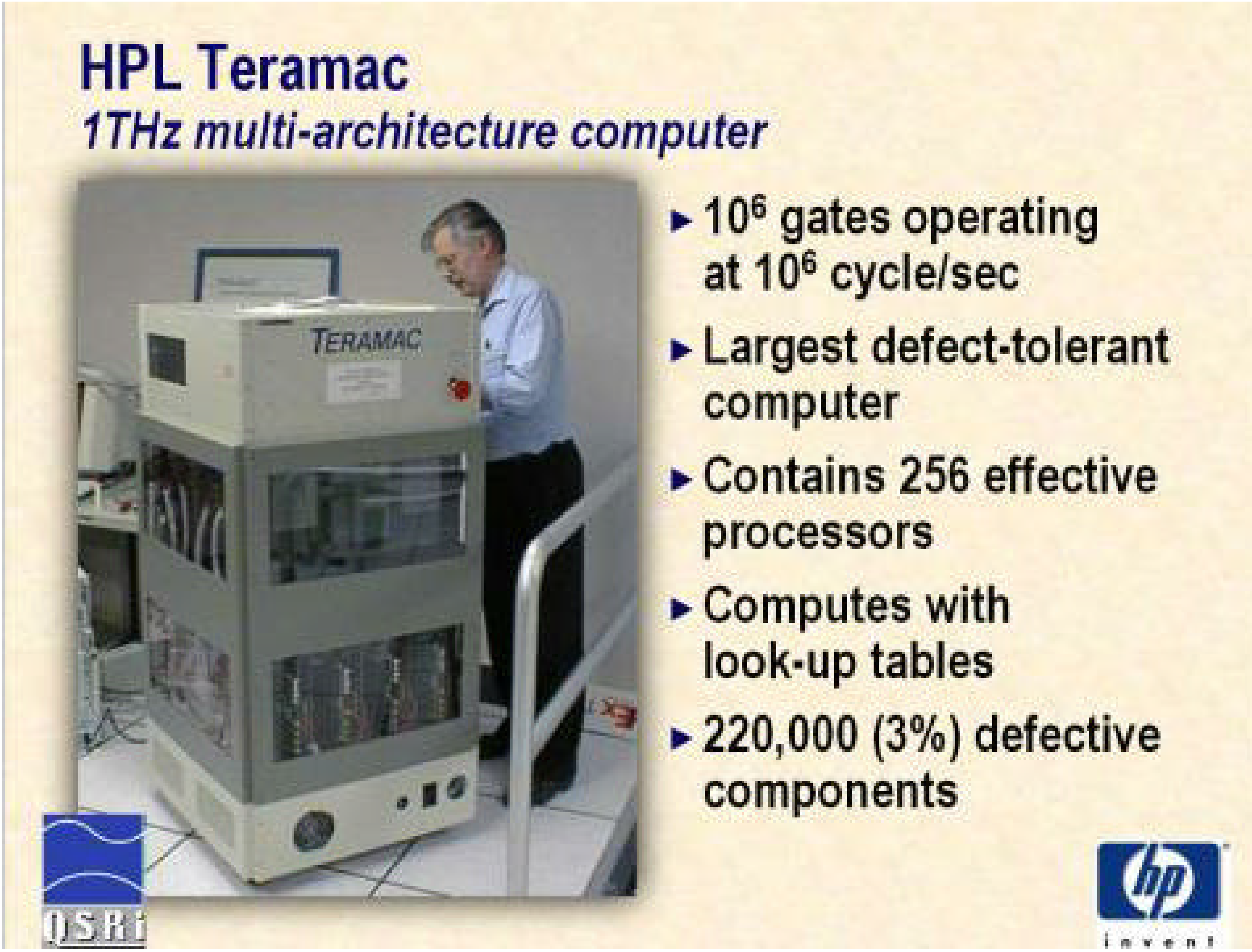
When Moore's Law Hits the Wall?



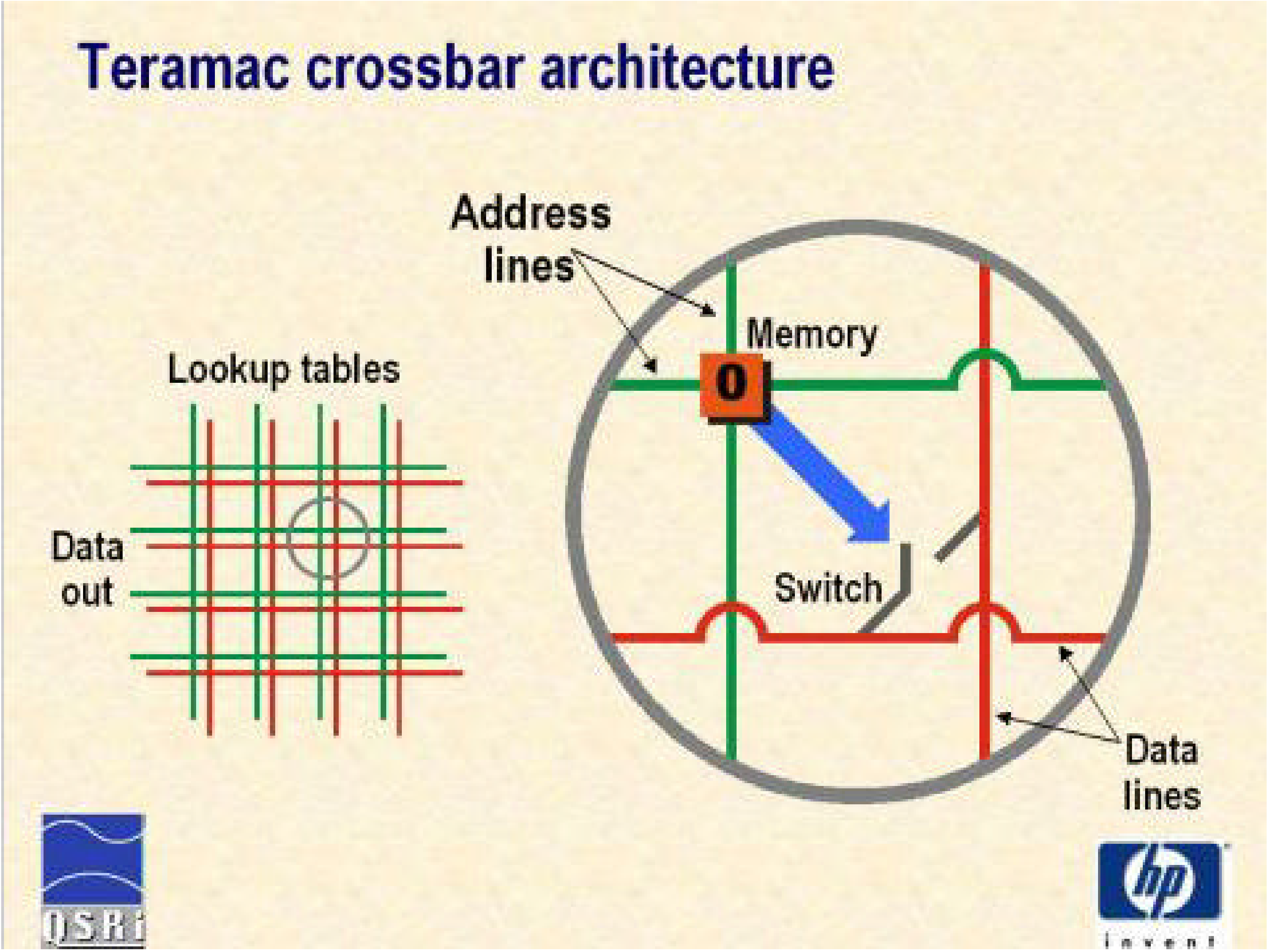
New Technology Solutions?

- Packaging/architecture advances with CMOS
- Molecular Electronics
- Quantum computing

Architecture Solutions?



Architecture Solutions?



New Technology Solutions?

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- Molecular Electronics
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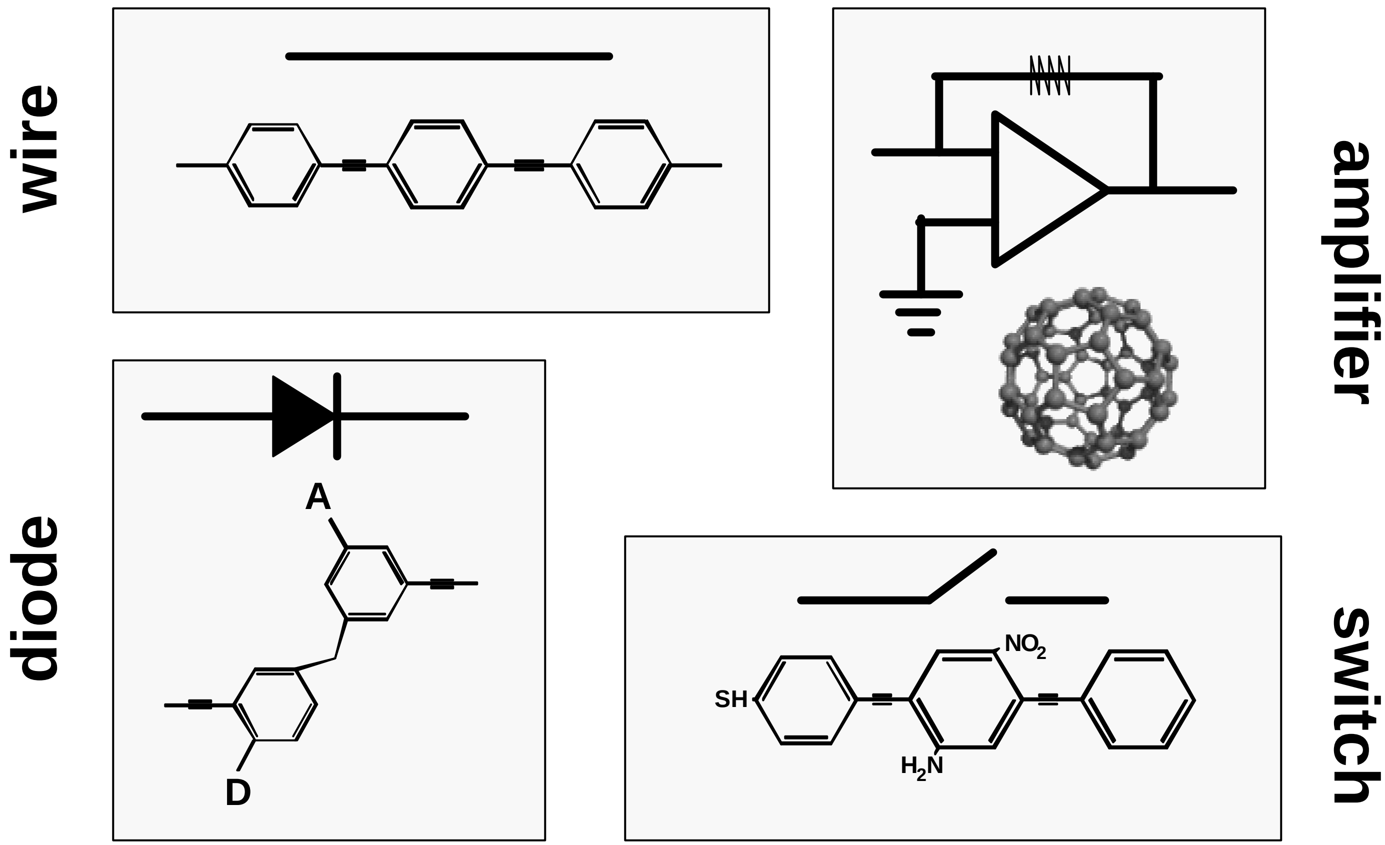
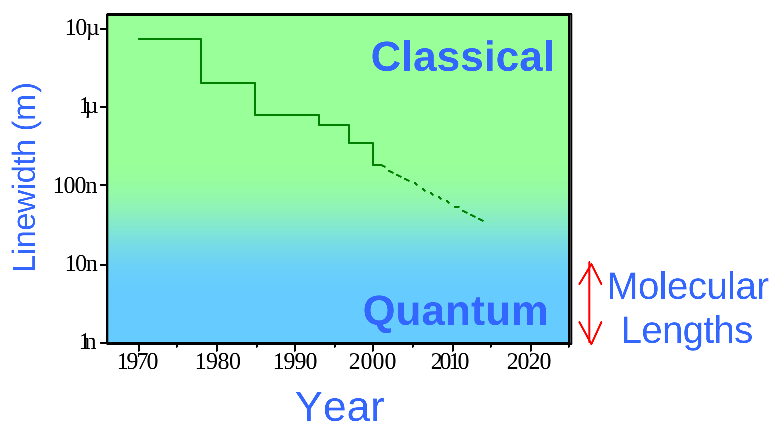
Molecular Electronics or Moletronics

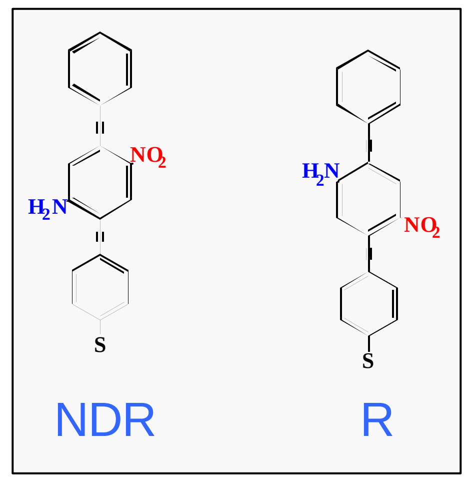
A new technology that uses molecules to perform the function of electronic components.

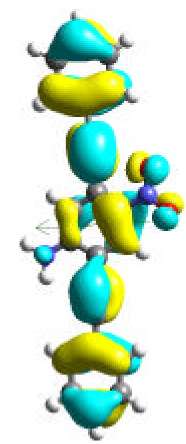


Why Use Molecules?

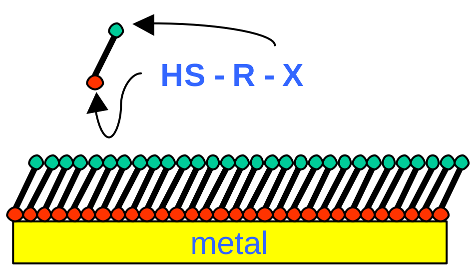
- Even big molecules are small
- Functional control through synthesis
- Self-assembling devices







NDR – Negative Differential Resistance
R – Resistor



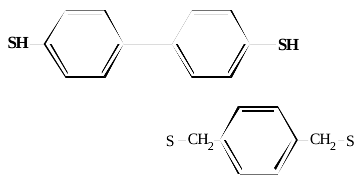
10 nm

Some Examples of Recent Advances

(not a comprehensive list)

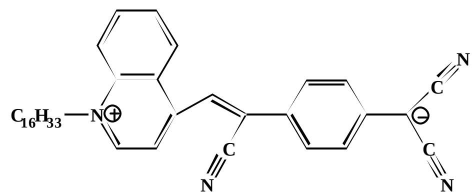
Conductance

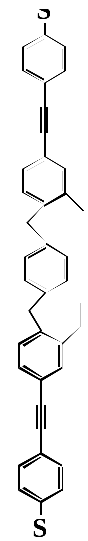
Rice , Yale, Penn State



Diodes

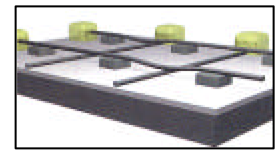
Yale, Univ. of Alabama, Rice





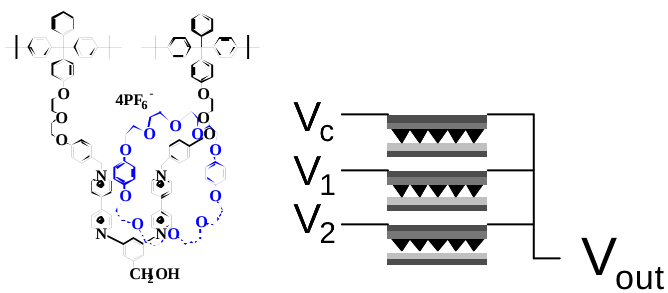
Memory

Harvard



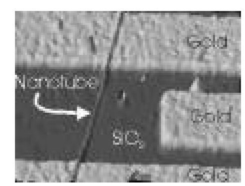
Logic Function

Hewlett-Packard, UCLA, Mitre Corp.



Nanotube FET

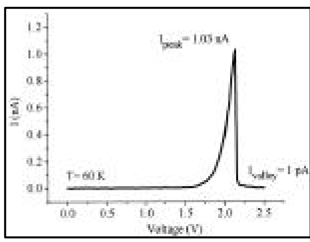
IBM

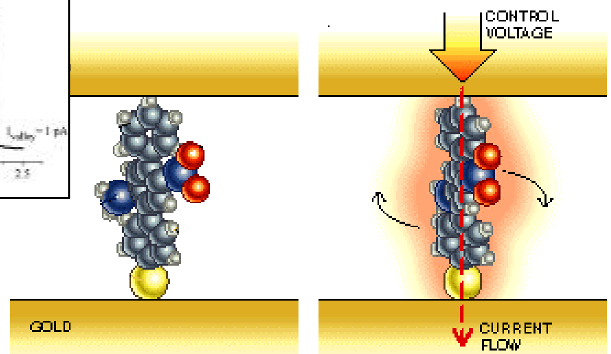


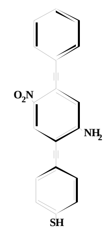
"I was one of the biggest skeptics. Now I believe that this is the inevitable wave of the future."
R. Stanley Williams, Hewlett-Packard

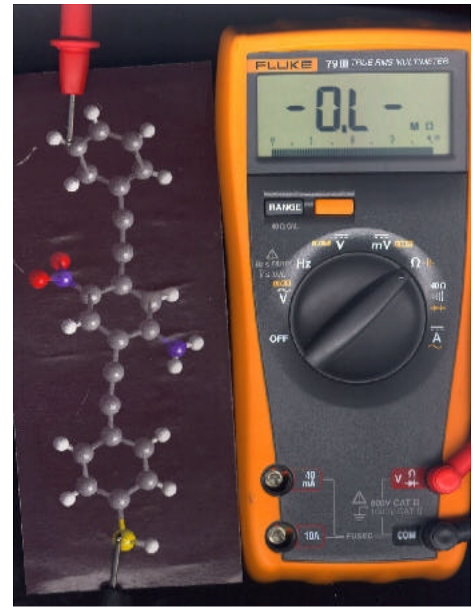
Grand Challenges for Moletronics

- Develop Moletronics Metrology
  - Test vehicle for molecular components
  - Validated models
  - Characterized prototype
- Correlate Structure and Function









“The field suffers from an excess of imagination and a deficiency of accomplishment.”
J. Hopfield, Princeton University

Science, vol. 286, p. 1551
Sci. Am. June 2000

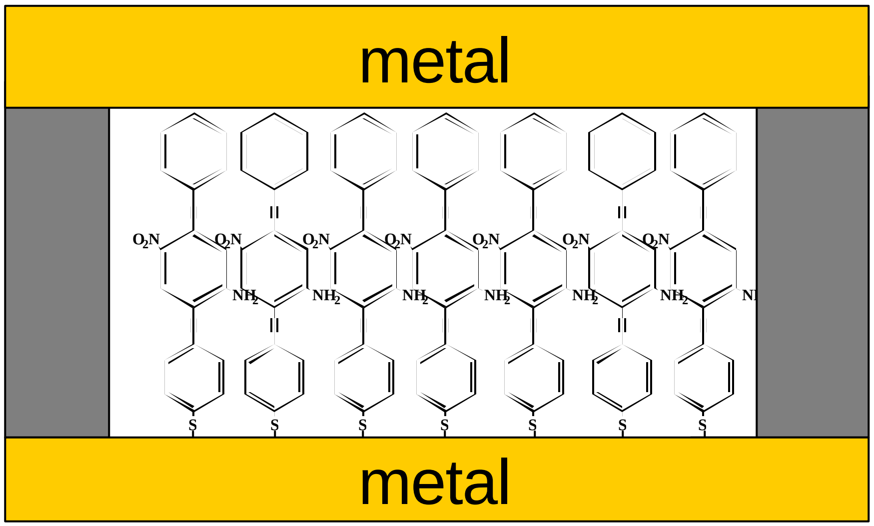
A Role for NIST in Molectronics

To develop the measurement tools and information infrastructure necessary to predict, measure, and control the flow of charge through molecules and ensembles of molecules.

> **“To knowledge by measurement.”**
> *Kammerlingh Onnes, Leiden Univ.*

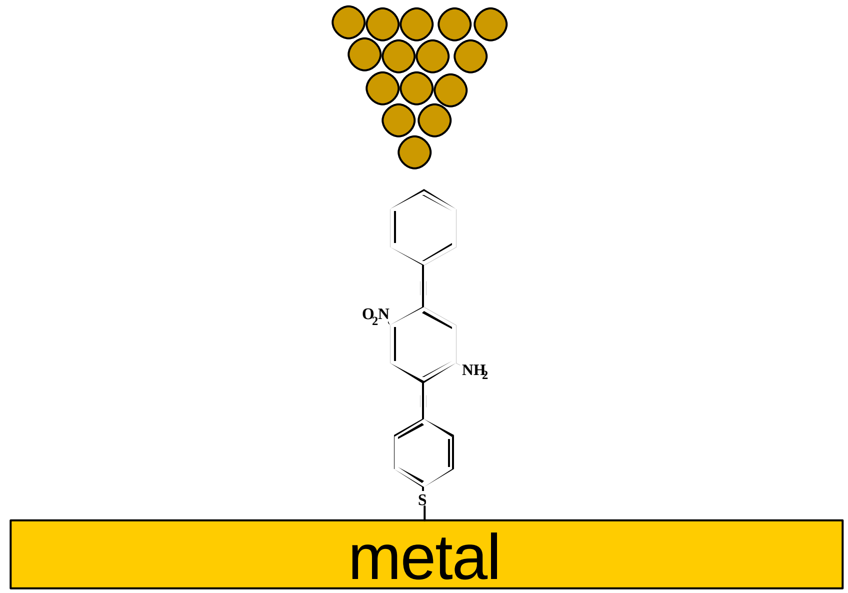
Wiring-Up Molecules

Ensembles of Molecules



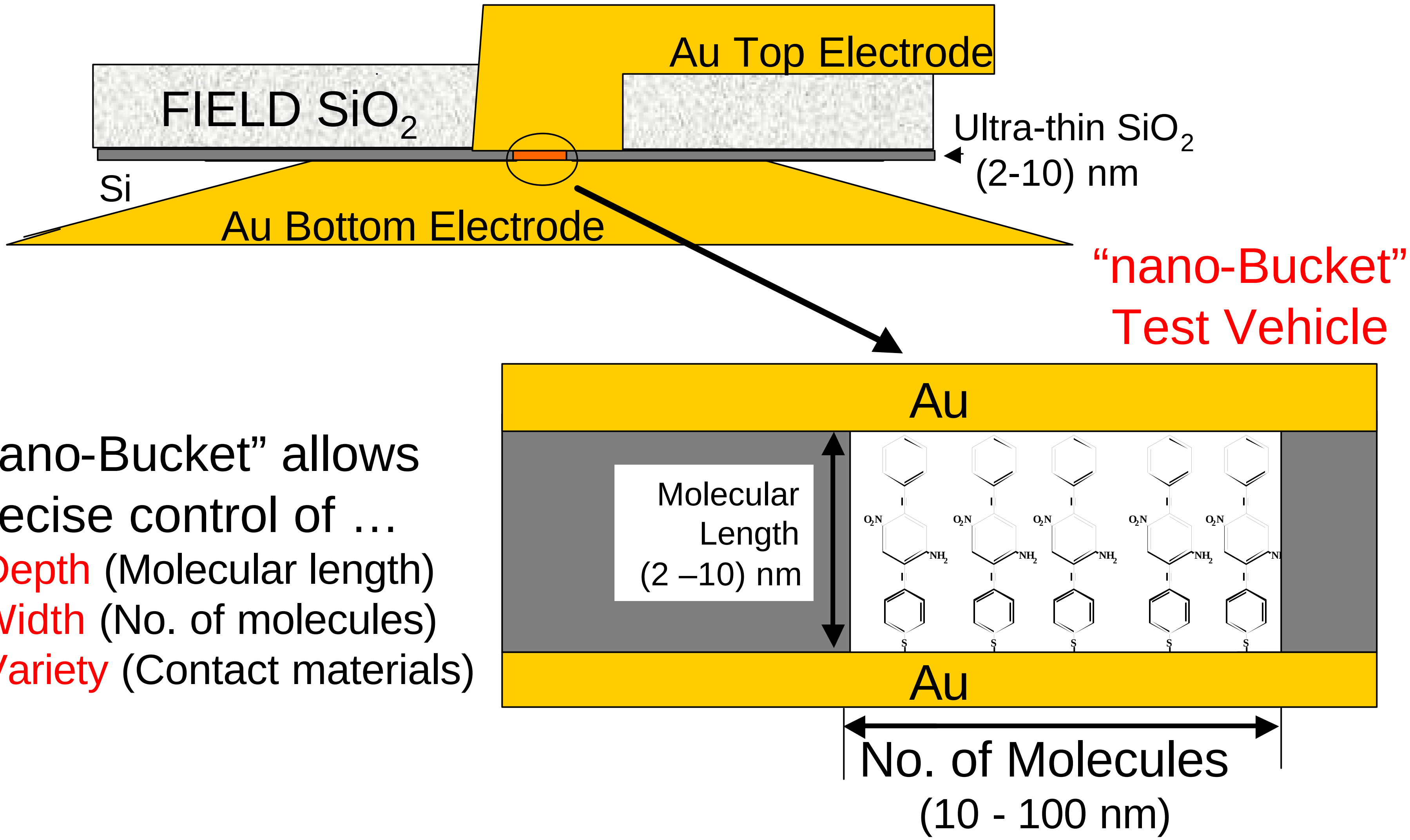
Nano-Fabrication

Single Molecules



Scanning Tunneling Microscopy (STM)

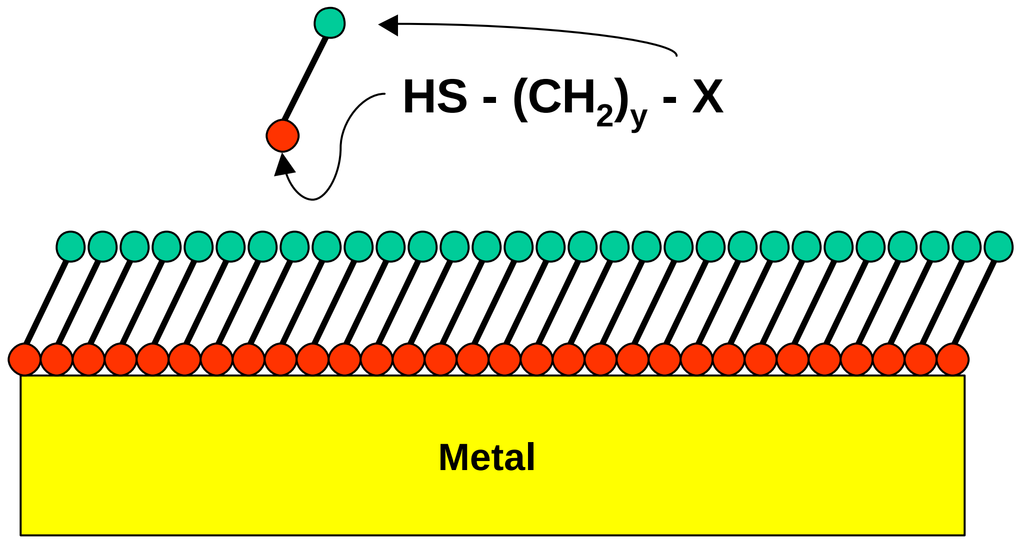
Wiring: Ensembles of Molecules



"nano-Bucket" allows precise control of …

- Depth (Molecular length)
- Width (No. of molecules)
- Variety (Contact materials)

Self-Assembled Monolayers (SAMs) for Moletronics



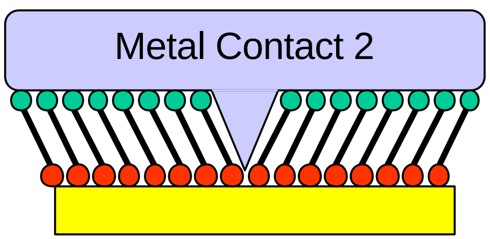
SAMs can solve electrical contact problem:

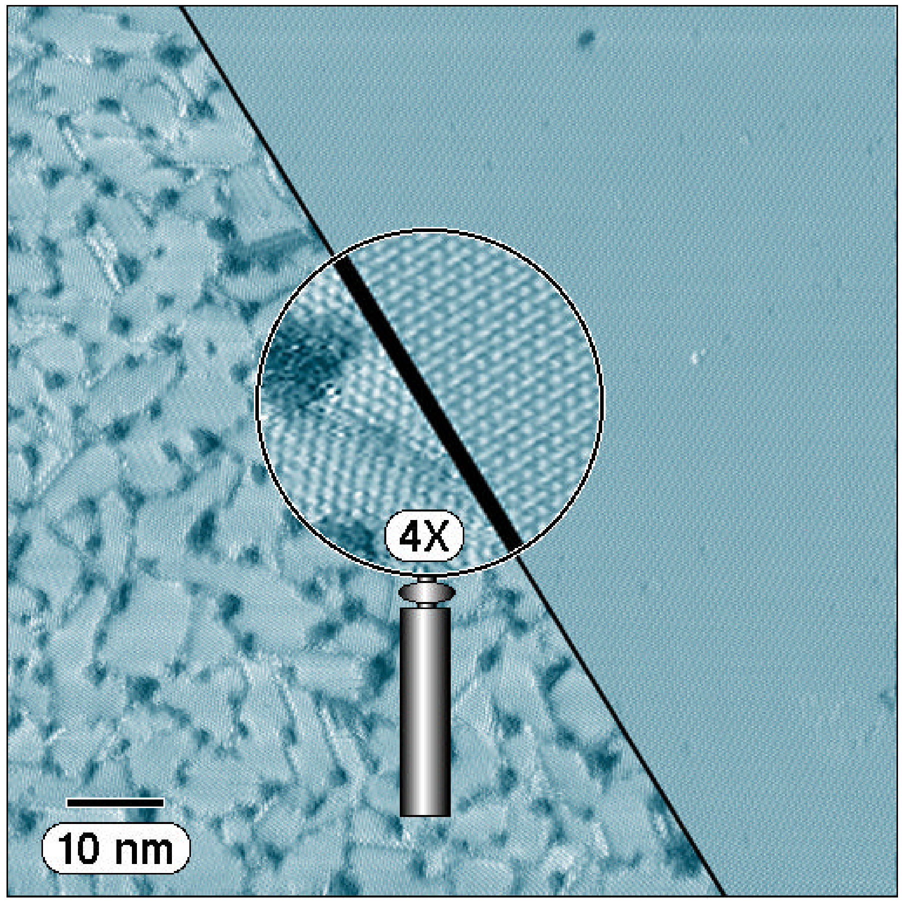
- **One contact spontaneously formed.**
- **Well-defined orientation and structure?**

Controlling SAM Defects Is Critical:

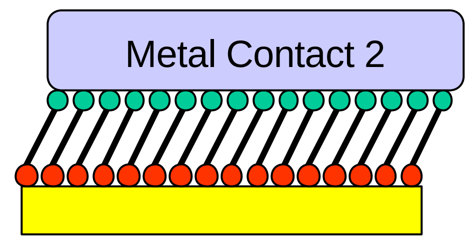
Understanding SAM Structure

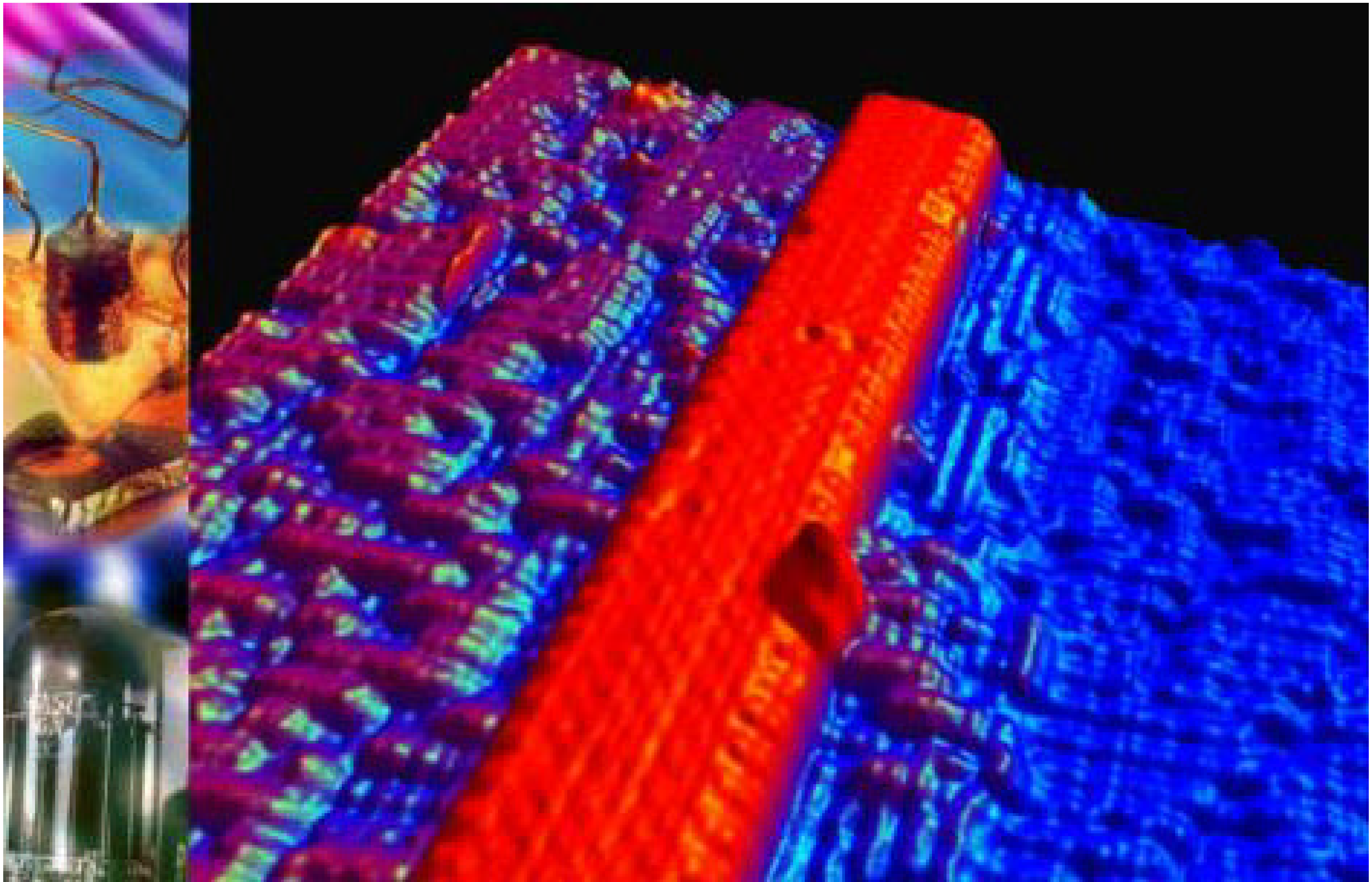
Defect-Laden SAM via Conventional Assembly





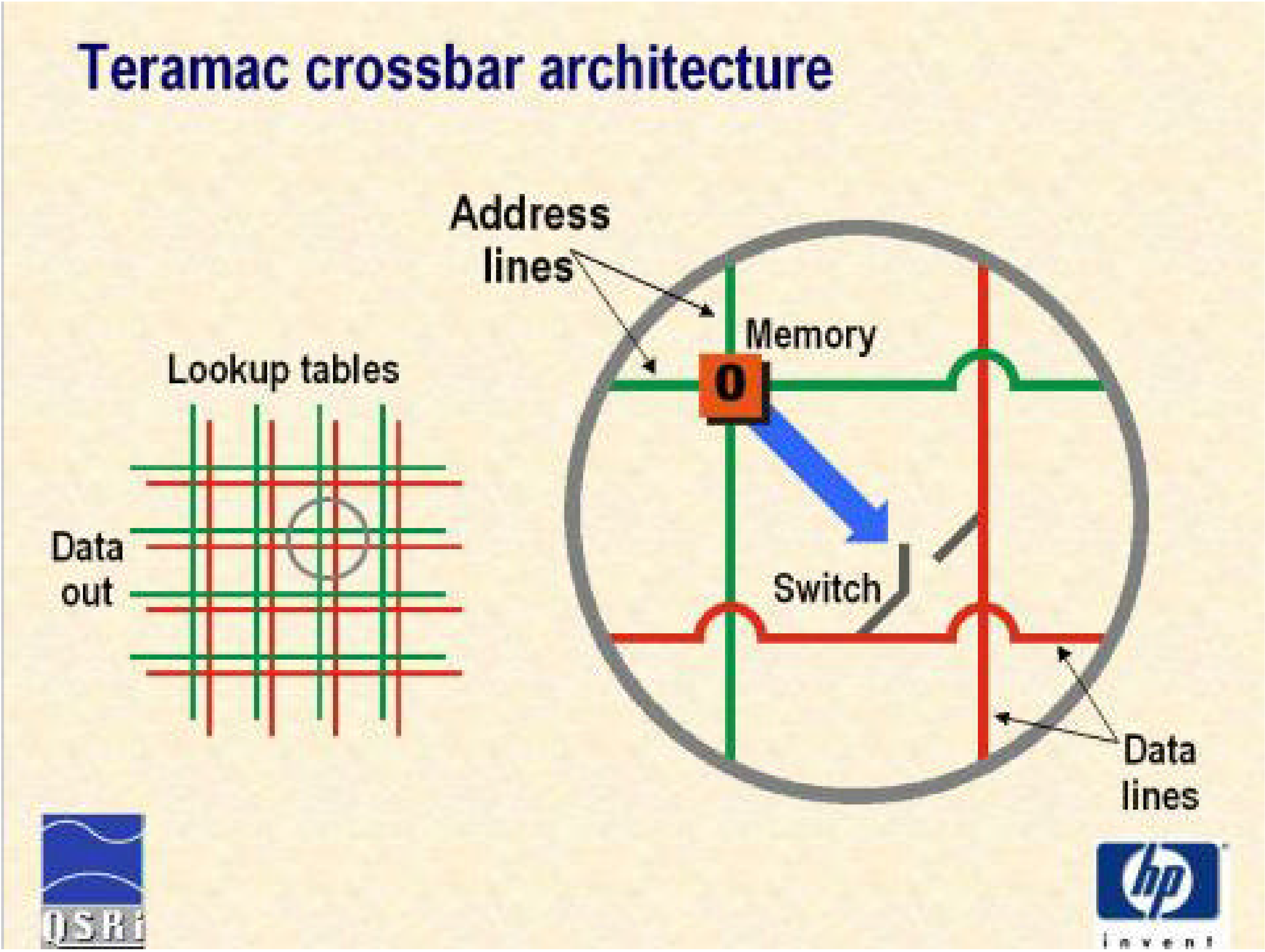
Defect-free SAM by NIST-Developed Method

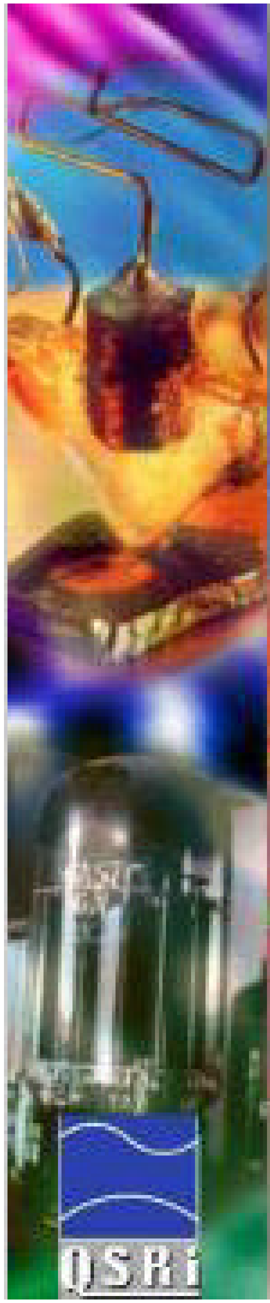


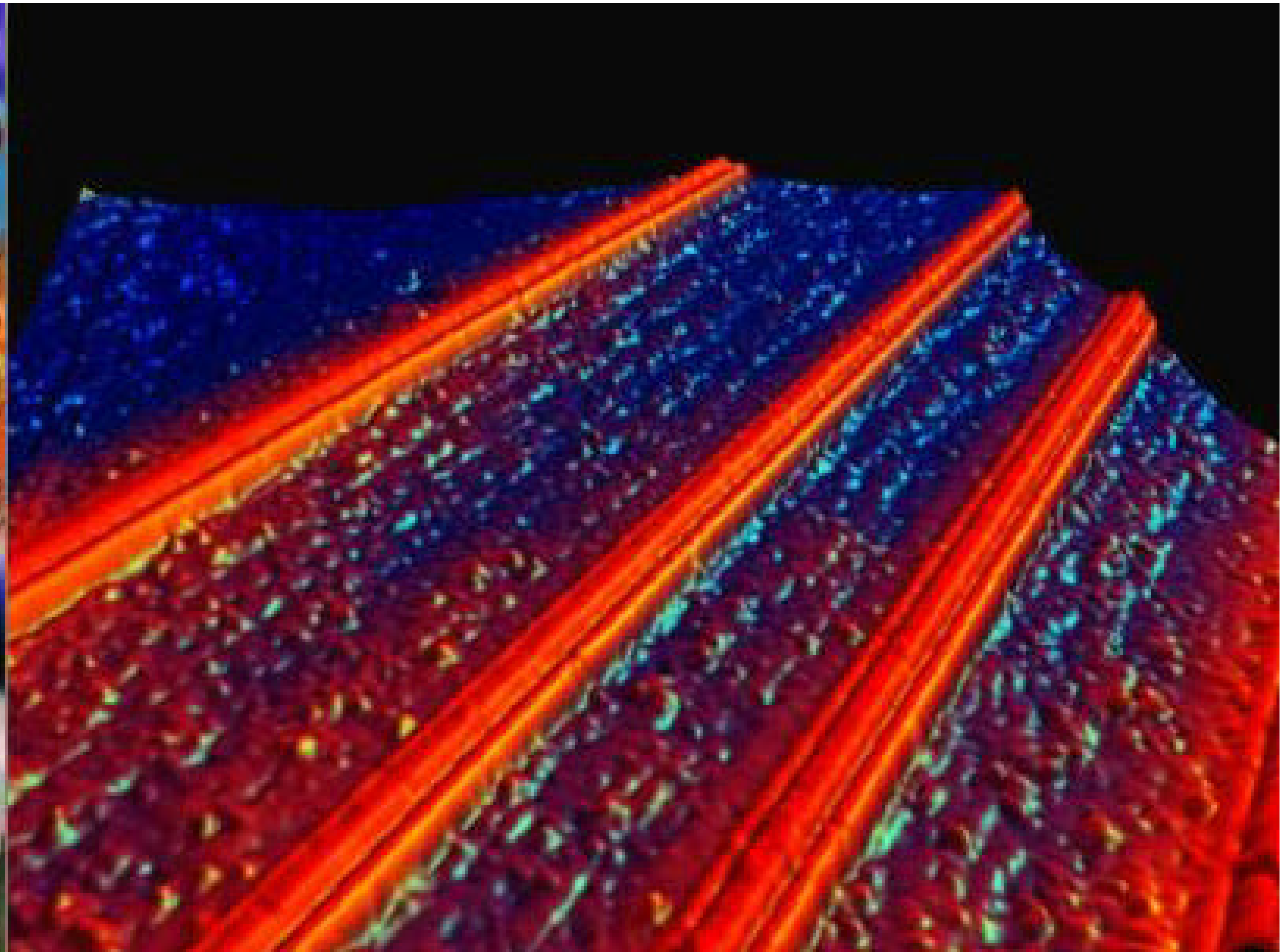


A 10 atom wide 'wire' on a silicon surface formed by 'self-assembly'

Architecture Solutions?







Self-assembled parallel wires -
precursor to a nanoscale crossbar

New Technology Solutions?

- Packaging/architecture advances with CMOS
- Molecular Electronics
- Quantum computing

What is Quantum Information?

Classical Bit: 0 **or** 1

Quantum Bit (Qubit): a quantum superposition of ? **and** ?

$$|?\rangle_1 \sim |?\rangle_1 \; ? \; |?\rangle_1$$

Scaling of Quantum Information

- **<u>Classically,</u>** a 3-bit register can store **<u>one</u>** number, from 0 to 7.

1	0	1

- **<u>Quantum mechanically,</u>** 3-qubit register can store **<u>all</u>** eight numbers simultaneously through entanglement:

a|000? + b|001? + c|010? + d|011? + e|100? + f|101? + g|110? + h|111?

- **<u>Result:</u>**
  - **Classical:** one N-bit number
  - **Quantum:** 2^N N-bit numbers simultaneously

A 300-qubit register has more storage capacity than a classical memory containing as many bits as the number of particles in the universe (~10^{80})

Interest in Quantum Information

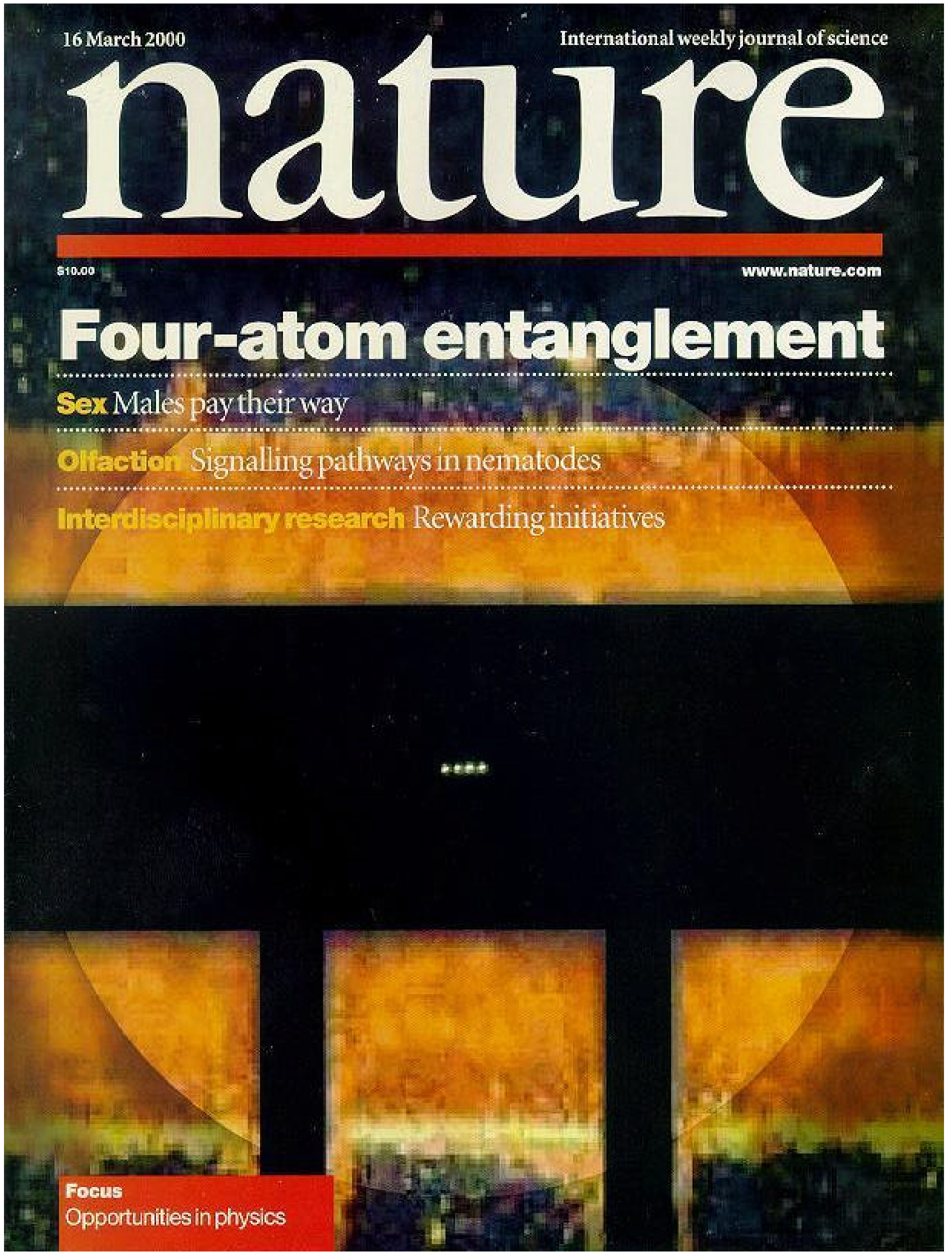
Leading active research programs include:

- IBM
- Hewlett-Packard
- Lucent
- AT&T
- Several universities world-wide
- Several US National Laboratories
  - NIST

Technical Approaches to Quantum Information Processing

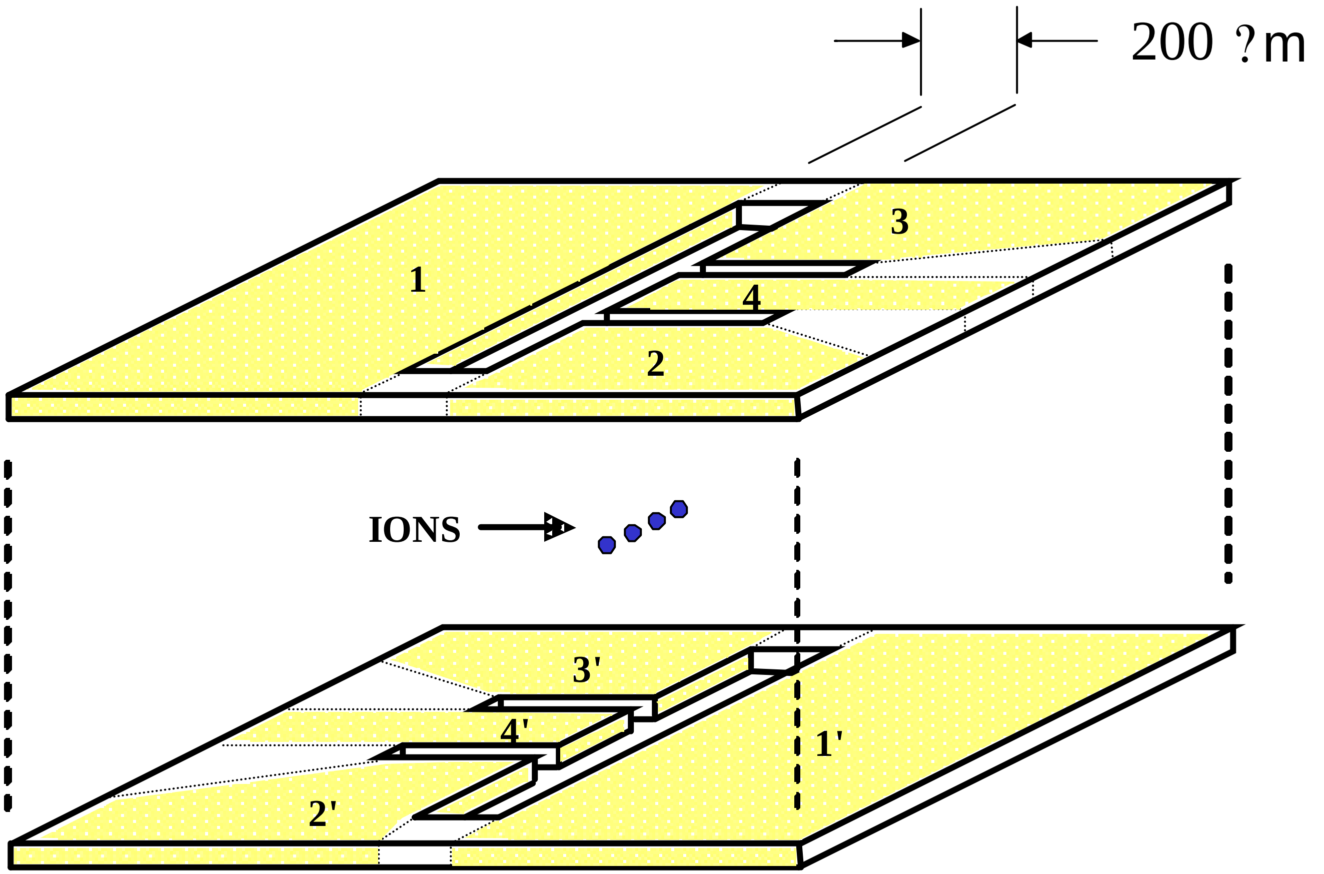
- **Nuclear magnetic resonance (NMR)**
  - IBM Almaden (Chuang) demonstrates 5 qubit NMR "quantum computer" August 2000
  - NMR probably not scalable beyond ~15 qubits
- **Solid-state implementations**
  - Isolated ion implantation, Josephson junctions, single electron transistors, quantum dots, etc.: severe decoherence problems
- **Atomic physics**
  - Ion traps
  - Trapped neutral atoms/Bose-Einstein condensates
  - NIST using both approaches

NIST demonstrated quantum entanglement of four Be^+ ions using lasers and electromagnetic traps. Approach is scalable in principle to very large number of ions.



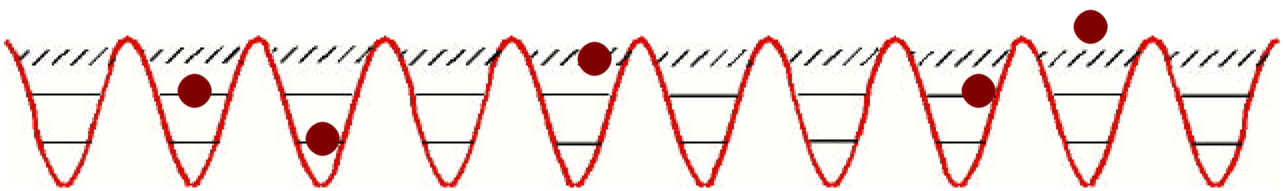
March 2000

NIST Lithographic Ion Trap for Studies of Quantum Entanglement



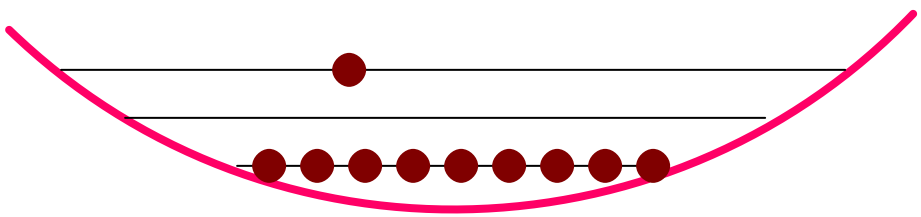
NIST Use of Neutral Atoms as Qubits

- **Optical Lattices**



Natural register for atomic qubits, but randomly filled, various states

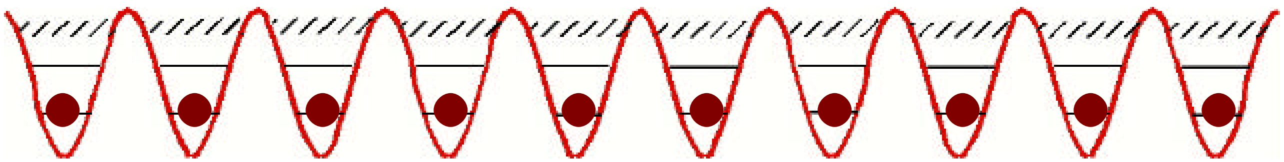
- **Bose-Einstein Condensation**



<u>Huge</u> number of atoms in <u>lowest</u> state

NIST Use of Neutral Atoms as Qubits

- Next:



<u>One</u> atom per lattice; <u>all</u> in lowest state (recently demonstrated at NIST)

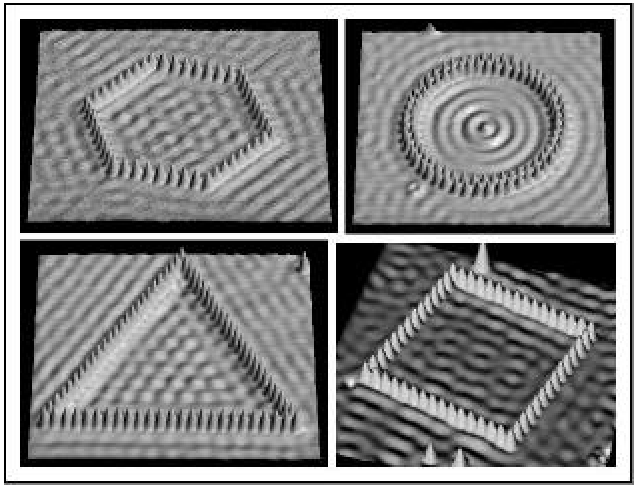
- Later: Microfabricated atom trap arrays

WHAT'S NEXT

- Short term: continue on the roadmap
  - Breakthroughs needed
  - Fix the cost equation
- Longer term (10 years ?)
  - A paradigm shift, new opportunities ....the future?

National Nanotechnology Initiative

- **$500 million multi-agency initiative for FY2001**
- **NSF, NIH, DoE, DoD, DoC/NIST, other agencies**
- **Government support of extramural and intramural R&D**



Fundamental shift: assemble devices from “bottom up” through manipulation of individual atoms and molecules

Applications in:

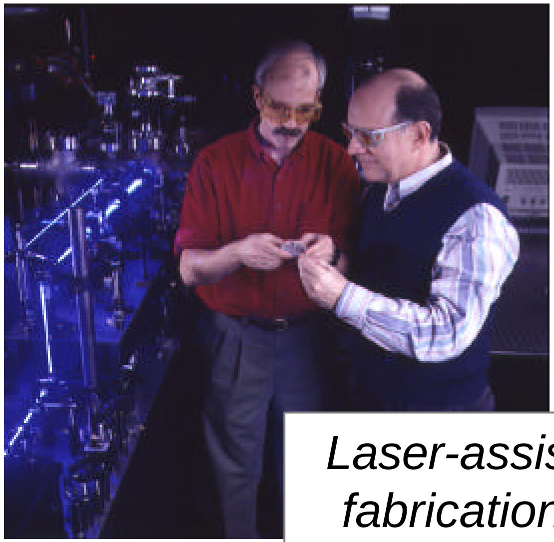
- Information Technology
- Health Care
- National Security
- Materials
- Energy

NIST Investment in Longer-Term R&D

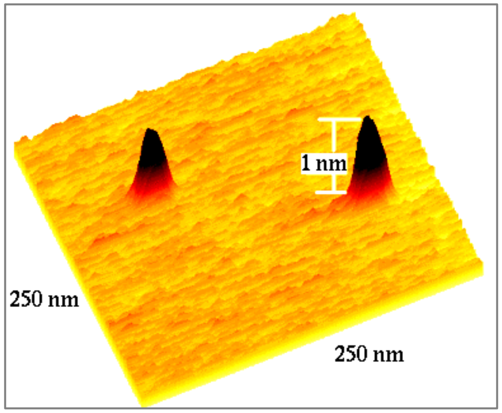
Nanotechnology Measurement Infrastructure

Metology anticipating industrial need

- **Provide measurement methods supporting the semiconductor, electronics, information, and telecommunications industries for device characterization and fabrication**



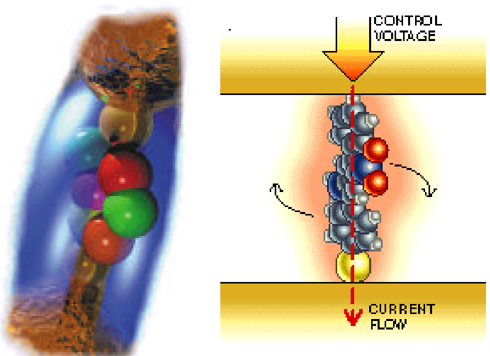
Laser-assisted fabrication of nanostructures



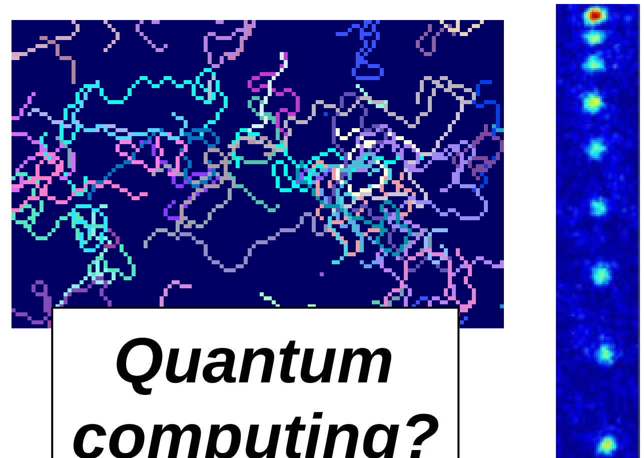
"Nanobumps" on mica from collisions with energetic ions

- **Develop methods to manipulate and characterize the quantum states of atoms, ions, and nanostructures for various applications**

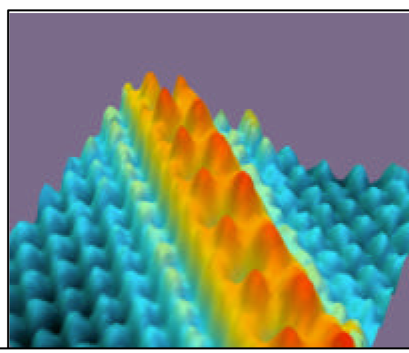
Where are we going?



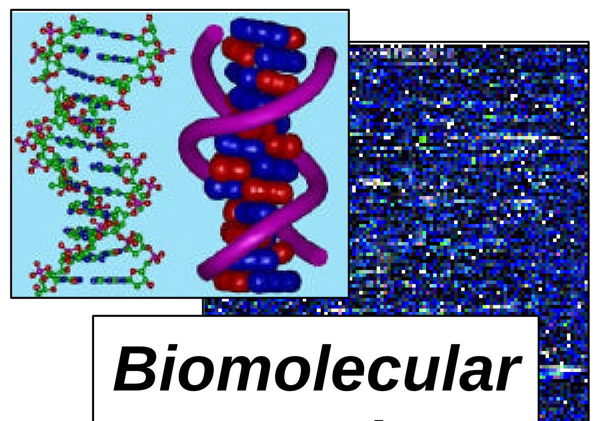
Moletronics?



Quantum computing?



Nanotechnology?



Biomolecular computing?

Summary

- Short term:
  - Continue on the roadmap
  - 193nm, 157nm, epl, euv, ?
- Longer term
  - New opportunities and challenges
    - » *just over the horizon*