Beyond the Wall:
Technologies for the Future

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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

Doubling time for transistors (thousands):

- Doubling time = 2.1 years
- Doubling time = 3.5 years

Intel co-founder

4004

8086

80286

80386

80486

P5

P II

P III

Year


Transistors (thousands)
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

- Surface and Bulk Scattering
- Optical Materials Transmission
- Purge Gas Index
- Materials Index
- Laser Wavelength Metrology
- Mask Index Modified Fused Silica
- Detector Characterization
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

SIA Roadmap Generation

Mask Cost / Wafer Level Exposure ($)

Affordable Total Cost / Wafer Level Exposure

3000 Wafer Exposures / Mask
500 Wafer Exposures / Mask
“Moore’s Second Law”

Cost of New Fab

Year


Fab Cost ($Billions)

1995 = $1B
~1% of annual market

2010 = $50B
~10% of annual market
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?

Scaling of Electronic Devices

- Moore's Law
- ITRS Roadmap
- Quantum Age
- Quantum State or Molecular Switch
- CMOS

Number of Components

Feature Size (nanometers)

- 1970
- 1980
- 1990
- 1995
- 2000
- 2005
- 2010

- 1.E+02
- 1.E+04
- 1.E+06
- 1.E+08
- 1.E+10
- 1.E+12
- 1.E+14
- 1.E+16
- 1.E+18

295 K
77 K
4 K
New Technology Solutions?

- Packaging/architecture advances with CMOS
- Molecular Electronics
- Quantum computing
Architecture Solutions?

HPL Teramac
1THz multi-architecture computer

- $10^6$ gates operating at $10^6$ cycle/sec
- Largest defect-tolerant computer
- Contains 256 effective processors
- Computes with look-up tables
- 220,000 (3%) defective components
New Technology Solutions?

• Packaging/architecture advances with CMOS

• Molecular Electronics

• Quantum computing
Molecular Electronics or Moletronics

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

- **Wire**: Diagram of a molecular structure connected by lines.
- **Amplifier**: Circuit diagram with a triangular symbol.
- **Diode**: Symbol with arrow indicating direction of current flow.
- **Switch**: Diagram with two lines crossing over a third line, containing chemical groups such as SH and NO₂.
Why Use Molecules?

- Even big molecules are small
- Functional control through synthesis
- Self-assembling devices
Some Examples of Recent Advances

(Not a comprehensive list)

**Conductance**
Rice, Yale, Penn State

**Diodes**
Yale, Univ. of Alabama, Rice

**Logic Function**
Hewlett-Packard, UCLA, Mitre Corp.

**Memory**
Harvard

**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
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

Single Molecules

Nano-Fabrication

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

Metal Contact 2

10 nm
A 10 atom wide ‘wire’ on a silicon surface formed by ‘self-assembly’
Teramac crossbar architecture

- Address lines
- Memory
- Switch
- Data lines
- Lookup tables
- Data out
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 $\psi_1$ and $\psi_2$

$$|\psi_1\rangle \sim |\psi_1\rangle \psi_1 |\psi_2\rangle_1$$
Scaling of Quantum Information

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

- **Quantum mechanically**, 3-qubit register can store **all** eight numbers simultaneously through entanglement:
  
  \[ a|000\rangle + b|001\rangle + c|010\rangle + d|011\rangle + e|100\rangle + f|101\rangle + g|110\rangle + h|111\rangle \]

- **Result:**
  - **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.
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**

  Huge number of atoms in lowest state
NIST Use of Neutral Atoms as Qubits

• **Next:**

 One atom per lattice; all 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

Metrology anticipating industrial need

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

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

“Nanobumps” on mica from collisions with energetic ions

Laser-assisted fabrication of nanostructures
Where are we going?

Moletronics?

Quantum computing?

Nanotechnology?

Biomolecular computing?
• Short term:
  – Continue on the roadmap
  – 193nm, 157nm, epl, euv, ?

• Longer term
  – New opportunities and challenges
    » just over the horizon