

# Nanosystems Modeling and Nanoelectronic Computers

James C. Ellenbogen, Ph.D.

703-983-5930 • [ellenbgn@mitre.org](mailto:ellenbgn@mitre.org)

MSR

The logo for the MITRE Technology Program, featuring a stylized graphic of stacked blocks in yellow, orange, and blue to the left of the text.

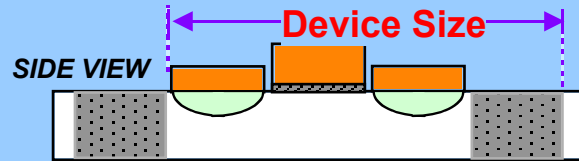
MITRE  
Technology  
Program

# Problem

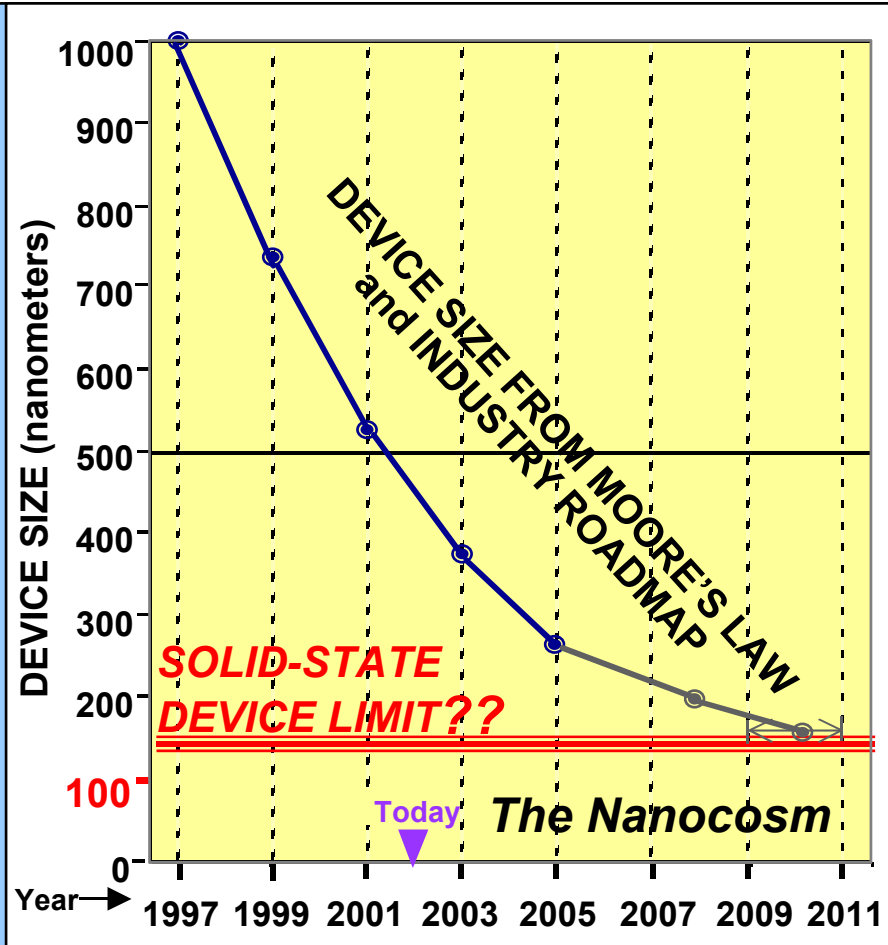
**What should a future, nanometer-scale electronic computer “look” like?**

# Background

- Exponential shrinkage of silicon-based transistors may end soon.



- Problems:
  - ◆ Fabrication & Costs:  
Light is too big
  - ◆ Operating principles:  
Quantum mechanics dominates in the nanocosm



# Objectives

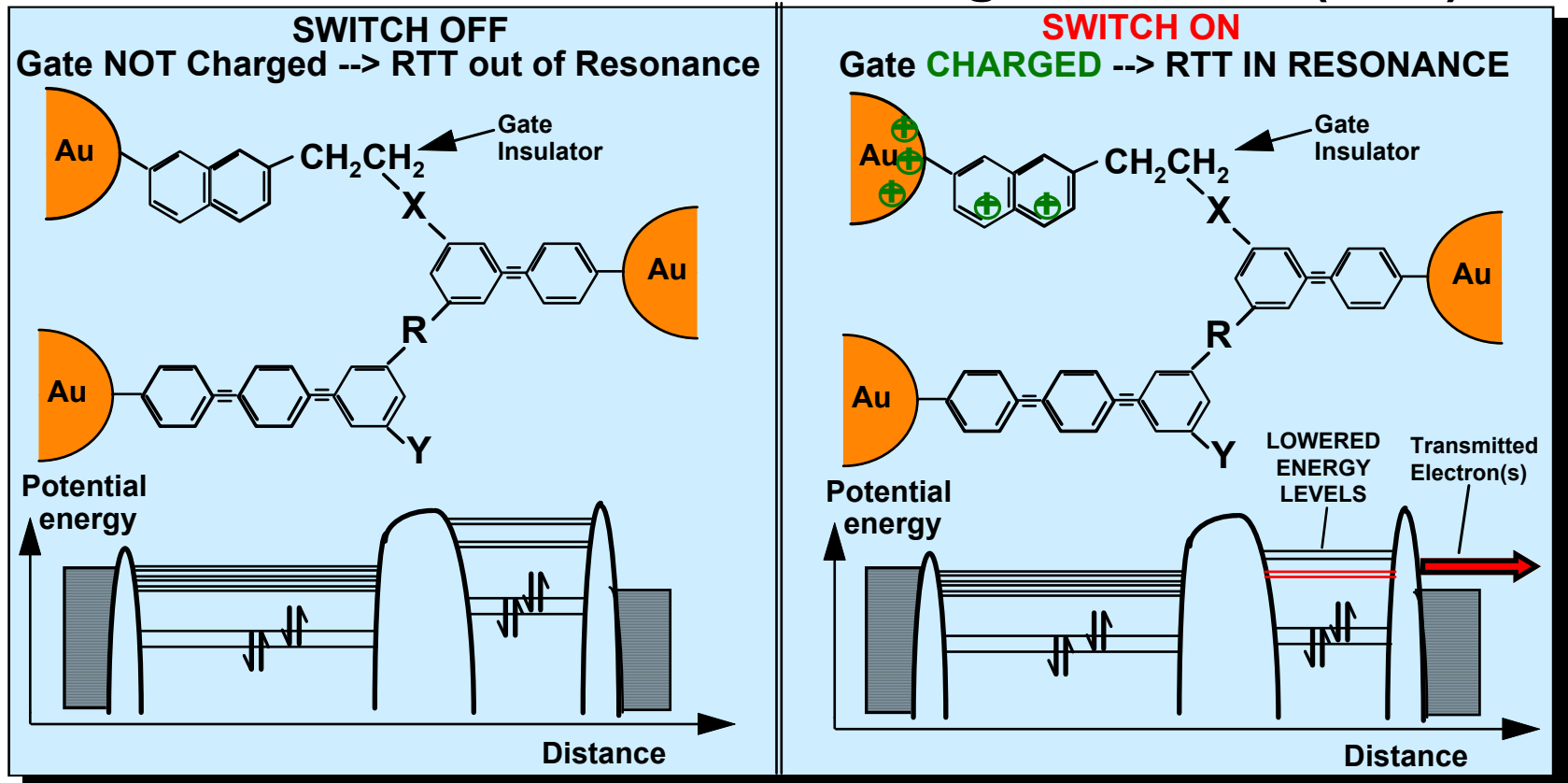
- **Assume technical leadership, worldwide, in developing, applying, and disseminating new design concepts for next-generation electronic computers integrated on the nanometer scale**
- **Develop techniques for more rapidly and accurately modeling such “nanosystems”**

# Activities

- **Developing and verifying new architectures for nanometer-scale electronic computers-- esp., molecular electronic computers**
- **Exploring fabrication concepts for such nanocomputers--e.g., directed self-assembly**
- **Exploring application concepts, as well-- esp., designing and building a micro-robot that will be controlled by nanocomputers**

# Highlight

MITRE has been issued four nanotechnology patents over the past year, including one for a molecular electronic resonant tunneling transistor (RTT)



# Further Highlight

- Last fall, published high-profile research article in journal Science
- Described recent dramatic advances in molecular-scale electronics, the demonstration of molecular transistors and molecular logic

PERSPECTIVES: NANOTECHNOLOGY

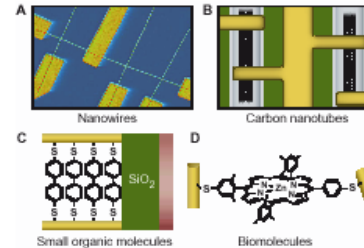
## Toward Nanocomputers

Greg Y. Tseng and James C. Ellenbogen

The rapid miniaturization of electronics to the micrometer scale has been a key force driving scientific and economic progress over the past 25 years. Nanometer-scale electronics (nanoelectronics) is the closely watched next frontier (1–5). Two reports in this issue describe dramatic steps toward the realization of electronic nanocomputers. Bachtold *et al.* (page 1317) demonstrate logic circuits constructed from individual carbon nanotube molecules (6). Huang *et al.* (page 1313) have assembled logic circuits from semiconductor nanowires (7).

In recent years, researchers have reported a variety of molecular-scale wires and switches (8–21), including molecular-scale transistors based on carbon nanotubes (8) and semiconductor nanowires (9). However, the two reports in this issue are the first to advance molecular-scale electronics fully from the single-device level to the circuit level. Both groups developed new methods to meet two key device requirements that previously prevented the realization of transistor circuits. First, the component transistors must produce signal amplification or “power gain” with an output to input ratio much greater than 1. Second, each transistor must be controlled by its own local “gate” contact.

Bachtold *et al.*'s study builds on the same group's earlier discovery that individual semiconducting nanotubes adsorbed between two metal contacts on a silicon substrate behave like the field-effect transistors in today's microcomputers (8). However, the controlling gate contact in that experiment consisted of the entire supporting silicon chip. In such a layout, multiple nan-



**Approaches to molecular-scale electronics.** (A) Diodes and transistors based on semiconductor nanowires are assembled with microfluidics to form logic AND, OR, NOR, and XOR circuits and logic functions such as a half adder (7). (B) Carbon nanotube transistors (8) are connected by gold interconnects to construct logic circuits such as a NOT circuit, NOR circuit, static random access memory (RAM) cell, and ring oscillator (6). (C) Field-effect transistors based on self-assembled monolayers of polyphenylene molecules are combined to create a NOT circuit (11, 12). (D) Porphyrin molecules store digital information as electrical charges like dynamic RAM cells (20).

otube devices placed on a chip all must be switched simultaneously. Furthermore, the power gain was less than 1 because the silicon oxide insulator between the gate contact and nanotube was relatively thick, preventing sufficient capacitive coupling between the gate contact and nanotube.

To construct nanotube circuits, the group has now used electron beam lithography to pattern local aluminum gate contacts and exposed them to air to form very thin insulating layers on the aluminum leads (6). Insulator thickness is reduced substantially, enabling the new nanotube transistors to operate independently with a gain ratio in excess of 10, a remarkable increase. By wiring nanotube transistors together with gold interconnects made by lithography, the authors have constructed a range of logic circuits.

Huang *et al.* also build on their earlier achievements in devices to achieve circuits. Earlier this year, the group demon-

strated diodes and bipolar transistors made from nanowires in a crossed geometry (9). In the present work, they assemble OR and AND logic circuits with only diodes, but to construct other circuits required the development of nanowire field-effect transistors. The new nanowire transistors are formed by placing two nanowires in a crossed geometry and using thermal heating to generate an insulating oxide between the nanowires. As with Bachtold *et al.*'s nanotube transistors, the nanowire transistors feature local gate contacts with thin insulators and are thus easily integrated into transistor circuits.

With the exception of the contacts, Huang *et al.*'s nanowire circuits are assembled without “top-down” methods such as lithography. Instead, “bottom-up” parallel assembly tools such as microfluidics are used. This feature enables them to build and test relatively large numbers of devices and demonstrate readily reproducible behavior in them. Furthermore, Huang *et al.*'s circuits incorporate at least one natural nanometer-scale metric—the constant, small dimension of the crossing points of the nanowires—suggesting that the entire circuits might be slunk in a straightforward way to the nanometer scale. This capability is important given that the circuits in both studies are still micrometer-scale systems.

The two reports use very different types of nanometer-scale structures and different techniques for assembly, thus pursuing different routes to building electronic nanocomputers. In the variety and complexity of the circuits they have demonstrated, both surpass two other important results in nanoelectronics announced very recently by Derycke *et al.* (10) and Schön *et al.* (11, 12). Derycke *et al.* demonstrated a NOT logic circuit or

G. Y. Tseng is in the Department of Physics, Stanford University, Stanford, CA 94305, USA, and the Nanosystems Group, The MITRE Corporation, McLean, VA 22102, USA. E-mail: gytseng@stanford.edu  
J. C. Ellenbogen is at the Nanosystems Group, The MITRE Corporation, McLean, VA 22102, USA. E-mail: ellenbn@mitre.org

www.sciencemag.org SCIENCE VOL 294 9 NOVEMBER 2001

1293

MITRE

© 2002, The MITRE Corporation

# Impacts

- **Invented new approaches for design, fabrication, and application of next-generation nanocomputers**
- **MITRE concepts and innovations have assisted DARPA in conducting world leading R&D program in molecular-scale electronics**
- **MITRE nanotech publications and presentations assisted in**
  - **Starting other govt. nanotech R&D programs**
  - **Starting U.S. nanotechnology companies**
  - **Educating next generation of U.S. scientists and engineers**
- **MITRE recognized world-wide as being among the leaders in nanotechnology R&D**

# Future Plans

