Grand Challenge Area

Nano-Electronics, -Photonics, and -Magnetics: The Next Generation of Information Technology Devices

Challenge

Further miniaturization of microelectronics – with more functionality and at lower cost – will require new approaches to fabrication and processing, and new methods for acquiring, storing, processing, transmitting, and displaying data.

Vision

Nano-electronic systems offer the potential to sustain the revolution in information technology devices provided by silicon-based micro electronics over the last 30 years. Nano-based systems will improve computer speed, expand mass storage, and reduce power consumption. Communication paradigms will change by increasing bandwidth for data transmission, and by developing flexible, flat displays that are many times brighter than conventional displays.

The physics of today's transistor devices does not scale to the length of a few nanometers. The properties of nanostructures need to be measured and incorporated into new device concepts, and the devices placed into new system architectures.

Without breakthroughs, the continued miniaturization of information technology devices may stall, due in part to economically unacceptable increases in manufacturing costs. The cost of a single fabrication plant for 65 nanometer electronic devices is now estimated at approximately $4 billion. Therefore, it is necessary to identify novel synthesis, processing, and manufacturing technologies such as (a) printing and stamping approaches to pattern transfer; (b) processing of devices in parallel via arrays of microelectromechanical systems (MEMS) technologies; (c) innovations in surface processing, controlled nucleation, directional growth, and directional etching innovations; and (d) batch formation of precursor nanostructures followed by directed self-assembly.

Agency Participation

(leads in bold)

DOD	Devices for communication, command, control, surveillance, and reconnaissance
DOE	MEMS, laboratory-on-a-chip
IA	Molecular electronics and advanced communication systems
NASA	Highly effective, miniaturized, low-power devices for spacecraft
NIST	Standards for measurement, manufacturing quality control
NSF	Novel phenomena, devices, and architectures

Research Example: Molecular Electronics—Nanowire interconnects (supported by DOD and NSF)

Researchers have been working on molecular-scale electronics devices for years. Advances in this field may extend the famous "Moore's Law" for an additional 10 to 20 years, or well beyond the fundamental limits of purely silicon-based technology. Moore's law describes the exponential growth of computational power over time, and has become a standard guide by which computational manufacturers judge their technological advancements.

One concept for molecular electronics comes from the work of researchers at Hewlett-Packard (HP), the California Institute of Technology and the University of California at Los Angeles (UCLA). They have placed a particular molecule, a rotaxane, into one of two electrically distinct states that correlate to a "0" or a "1." This approach preserves the digital nature of electronics and permits the current approach for memory and logic to be carried forward. The most complex elements of logic and memory can be extracted from such a molecular electronic "bit," which is formed by a few rotaxane molecules that are "sandwiched" between two crossed wires. Thus, the rotaxane or a similar molecule can be arranged to represent digital logic and memory. An array of such bits (similar to an expanded tic-tac-toe board) allows for error-free computation even in the presence of defective components, a critical characteristic for many nanotechnologies.

An early application of this technology is as highly efficient, random access memory. Today, random access memories are patterned at a density of about 3×10^8 bits/cm^2. Using rotaxane switches, the HP, Caltech, and UCLA research team has demonstrated working memory and logic prototypes that are up to 100 times more dense than conventional devices (see Figure 11). Although certain challenges, such as interconnection, must yet be met in order to demonstrate working circuitry at these densities, this molecular electronics technology is already exceeding traditional approaches by orders of magnitude in laboratory demonstrations.

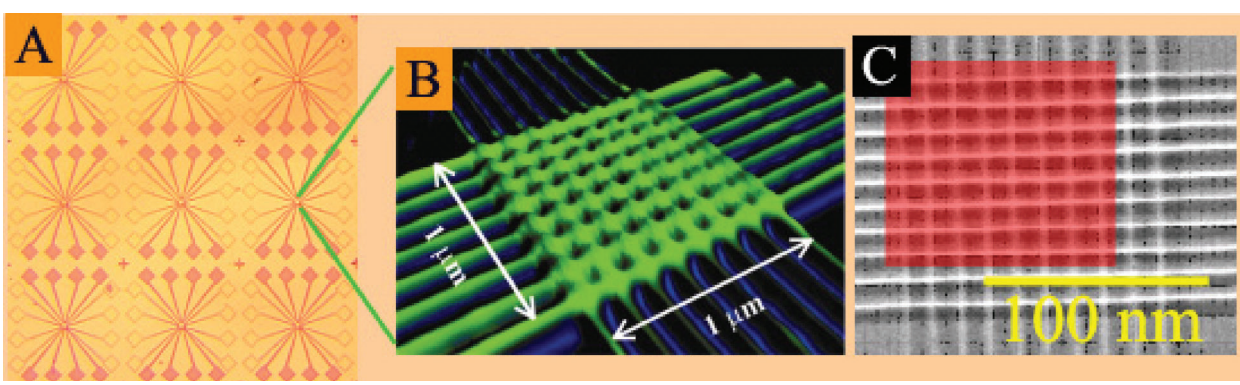

Figure 11. (A) Optical micrograph of an array of 64-bit molecular electronic circuits. (B) Atomic force micrograph revealing the detailed structure of one of the 64-bit circuits, patterned at a density of 7×10^9 bits/cm^2. This circuit has been utilized for simultaneous logic and memory operations. (C) The smallest circuit currently known (5×10^{11} bits/cm^2). As in (B), a bit is formed at each intersection of the lines. The highlighted 64 bits of this ultra-dense circuit fits inside a single bit of the circuit shown in (B) (courtesy J. Heath, Caltech).