

Making Molecular Switches

With the electronics industry facing physical limits in the next decade or so on how small it can shrink silicon-based transistors, many teams of researchers are looking for still smaller switching devices as the basis for

on top, thus forming a programmable switch.


When the switch was closed, a current flowed, rising to a few tenths of a nanoampere at a potential of -2 V. But when a potential of $+0.7$ V was applied, the molecules in the monolayer were oxidized, which changed their configuration and prevented current flow, thus opening the switch. Although some current leaked through the open switch, it was found to be 60 to 80 times less than the closed-switch current.

Once the switching behavior had been repeatably induced, the researchers configured linear arrays of the switches as AND/OR logic gates.

The initial work, reported in the July 16, 1999, issue of *Science*, was limited in two important ways. First, the opening of the switch was irreversible,

so repeated logic operations were impossible. Second, the wires themselves were fabricated by conventional lithography, thus limiting how small the devices could be made.

In subsequent developments, the UCLA team has overcome both of these limitations. "We've been able to make a reconfigurable switch that can switch back and forth at least several dozen times," explains team member James R. Heath of UCLA. "In addition, we've been able to use nanowires that are also chemically assembled—both those based on carbon such as nanotubes and those based on silicon." Details of this new research are being withheld while patents are applied for, but Heath expects early publication.

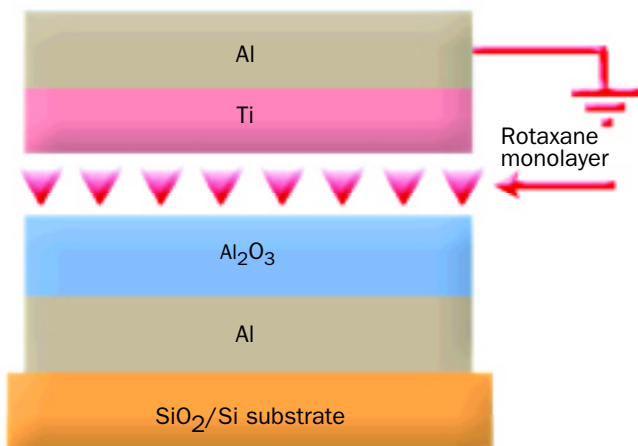
Despite the progress, more hurdles lie ahead. For example, the devices made so far have only two terminals. Integrated circuits have always needed three-terminal devices. 

Ion sputtering

With radical departures such as molecular switches still far from commercialization, the

semiconductor industry must continue its struggle to scale down the size of microcomponents below the current realm of 100 to 200 nm. Optical lithography, even with ultraviolet (uv) radiation, cannot reach below 100 nm, and the main alternatives—electron-beam and X-ray (or extreme-uv) lithography—face substantial technical challenges. But for some applications it may be possible to fabricate 15-nm-scale features by using the self-organization mechanism of ion sputtering of surfaces, according to recent work performed at the Institute of Semiconductor Electronics of the Rheinisch-Westfälische Technische Hochschule Aachen (Aachen, Germany). The research was reported in the Sept. 3 issue of *Science*.

When ions bombard a surface and sputter material from it, erosion rates can vary according to the curvature of the surface at the microscopic level. Under some conditions, erosion

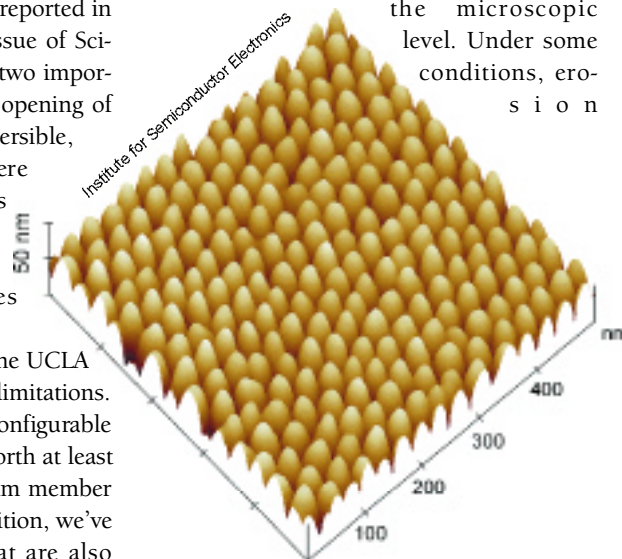


Side-view cross section of a device shows a single monolayer of rotaxane molecules sandwiched between two electrodes, functioning as a programmable switch.

future computers. A team at the University of California, Los Angeles (UCLA), department of chemistry and at Hewlett-Packard (Palo Alto, CA) has succeeded in demonstrating that molecules arranged in a monolayer between two electrodes can act as such switches.

The group, led by C. P. Collier and E. W. Wong of UCLA, initially aimed at developing the first step toward a chemically assembled electronic nanocomputer—one fabricated by chemical reactions, not by lithography, the photographic method used in silicon-based integrated circuits. The idea was to sandwich a molecular monolayer and a tunneling barrier between two electrodes, with the monolayer functioning as a programmable switch. They chose three types of rotaxane molecules for the switch and found that all three functioned similarly.


An array of lithographically patterned aluminum wires, each about $6 \mu\text{m}$ across, was first laid down on a silicon substrate. Next, the molecular monolayer was deposited, and then a second array of wires was laid down with titanium on the bottom and aluminum



When bombarded with ions, the surface of this GaSb semiconductor gets ordered to a regular hexagonal array of 35-nm dots.

rates increase in depressions, leading to an instability in which depressions deepen, leaving regularly spaced islands behind. The Aachen research team exploited this self-organizing instability by bombarding a gallium antimonide (GaSb) surface with 420-eV argon ions to produce extremely regular

hexagonal arrays of 50-nm-wide dots. The dots had a conelike cross section, and the hexagonal pattern was nearly perfect. Using the same process, researchers produced quantum dots, a widely used semiconductor device, by sputtering GaSb onto aluminum antimonide and etching the surface.

Although the technique produces features that are smaller than those achievable with optical lithography, some problems must be overcome before it can be widely applied. The most serious is the formation of ion-induced defects in the materials. Possible cures such as annealing or chemical etching are being pursued. If they work, the method could be extended to a wide range of semiconductor materials, including those most commonly used on silicon wafers. 

Rolf Landauer

The scientific mind is supposed to be a skeptical one, not accepting authority unless confirmed by observation and experiment. Yet fads and fashions are well known in science, and it often takes courage to doubt widely held, if ill-founded, beliefs. Rolf Landauer, who died in April at age 72 of brain cancer, had that sort of courage and used it to look skeptically at some long-established ideas in information theory. In the process, he put the once somewhat fuzzy concept of information on a firm physical foundation and was able to show new directions for the development of the theory of computation.

“Information is physical” became Landauer’s slogan, one he often repeated in papers and in conversations with colleagues at IBM’s Thomas J. Watson Research Center (Yorktown Heights, NY), where he worked for almost 50 years until his death. Although at times journalists, and even some computer scientists, have elevated information almost to a mystical plane, Landauer emphasized that all information is embodied by real physical systems such as transistors, electrons, photons, or DNA molecules. It is neither abstract nor ethereal.

Landauer’s most noted discovery came in 1961, when he questioned the doctrine, formulated by no less an authority than John



von Neumann, that the processing of a bit of information inevitably has a thermodynamically determined minimum energy cost comparable to kT , the thermal energy of an atom or molecule. Von Neumann's logic was that

processing information generates order and must be compensated by the consumption of energy, generating a corresponding amount of entropy or disorder. But Landauer proved that there was in fact no minimum energy consumption in processing information or in transmitting it. Instead, energy was only expended when information was destroyed—by erasure, for example.

The idea had profound implications for information theory, for it implied that there was no definite limit to the energy efficiency of computers. But it had equally important implications for thermodynamics. For example, physicists had long reasoned that Maxwell's demon—the hypothetical entity that could reduce entropy by segregating fast- from slow-moving molecules—could not function in practice because the calculations the demon required would use more energy and generate more entropy than could be gained. Yet Landauer's principle implied that the demon could continue to operate so long as it did not erase its results and had the memory to store them.

Landauer pursued both of these threads. He became a contributor to the study of non-equilibrium thermodynamics (which focuses on systems, such as the hypothetical demon and living organisms, which can maintain states far from equilibrium) in the early 1970s, a time when this field tended to be shunned as unfashionable. And he elaborated on his theme of the physical basis of information even though it took time for other scientists to accept his principle, which contradicted the prevalent idea that the production of information cost energy, not its erasure.

Charles Bennett, Landauer's younger colleague at IBM, was inspired by Landauer's

concept. He went on to show that the erasure of information was not, in principle, unavoidable and that all computation could be carried out reversibly, with the computer undoing its work and returning to its original state,

even after the results had been passed along. This result in turn led to, among other things, the development in the 1980s and 1990s of the field of quantum computation. This technology, although far short of practicality, relies on quantum systems to carry out information processing and potentially offers great advantages for some problems.

Landauer's skeptical mind did not spare the intellectual children and grandchildren of his own ideas, and he repeatedly challenged Bennett and other researchers to demonstrate that quantum computing could ever become a practical alternative. His critiques encouraged researchers to find new ways to overcome the problems that he pointed out, but in an interview shortly before his death he cautioned that "no one can be at all sure that quantum computing will, in the end, do better than transistors."

Wide-ranging clearly describes Landauer's interests, which included some fundamental theoretical problems that tie the transmission of information to the very structure of physical laws—such as the relativistic prohibition of transmitting information faster than the speed of light. He re-examined the long-known paradox that photons can in theory tunnel through barriers faster than the speed of light and concluded that the existing theoretical explanations of the apparent contradiction did not hold up.

It's possible that some of Landauer's willingness to question prevailing wisdom arose from his early experiences viewing his father's illusions as a Jew in Germany between the World Wars. Landauer recalled that his patriotic father, like many German Jews (and others) in the 1930s, was sure that the Nazi madness would blow over. "I'm

alive today because he died in 1935,” Landauer explained in a 1998 interview in *Scientific American*. “We would have never left Germany if he had continued to be head of the family.”

Landauer’s family settled in New York City, where he attended Stuyvesant High School. He went on to Harvard, pursuing both physics and electrical engineering. After a brief stint at the precursor to the National Aeronautics and Space Administration, working on nuclear propulsion, he joined IBM in 1952. In 1957, he developed a fundamentally new approach to the theory of conductance in metals, calculating conductance from the probability that a scattered electron would make it to the other end of a conductor rather than being deflected back to the entrance point. Landauer’s formulation became the basis for understanding many important phenomena in conduction and had great practical application.

After his path-breaking work in the thermodynamics of computation, Landauer became director of IBM Research’s solid-state science division, leading the laboratory toward an early emphasis on large-scale integration. He returned to full-time research in 1969, developing his ideas throughout the 1970s. It was only in 1981, after a conference at the Massachusetts Institute of Technology that he and others organized, that the physics of computation really began to become visible as an ongoing field of work. Landauer’s philosophy of science was evident in the organization of that conference, which included an intentionally diverse group. “That inevitably brought in some contributions that were recognizably flawed,” he recalled years later. “But we knew what was nonsense to some would be visionary to others.”

Throughout his long career, Landauer favored what he called a “low-brow intuitive style” that relied on clear physical pictures and avoided the heavy use of mathematics or unphysical abstractions such as infinitely precise computers. His work has done much to place the often-abstract world of computation and information theory on the secure foundation of physical process. 