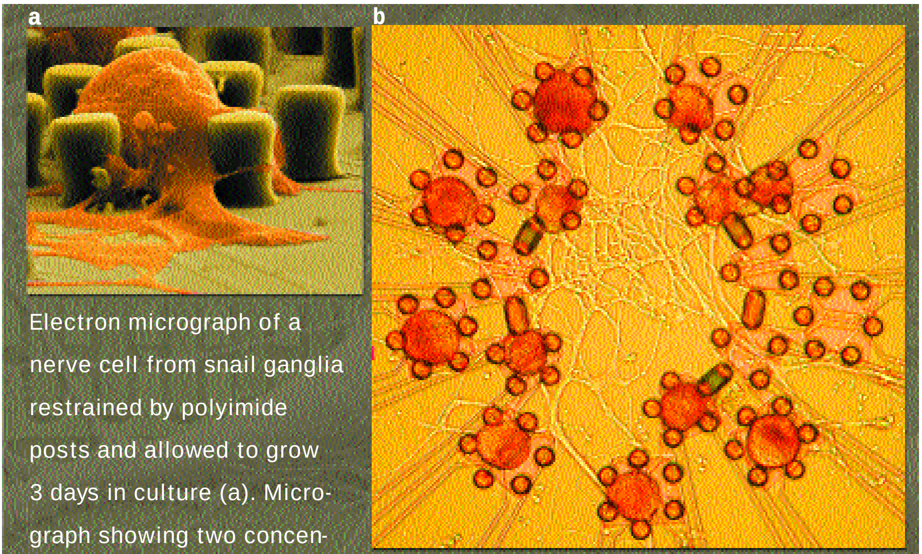
by Eric J. Lerner

Neurons on a chip

Brains and computers have very different strengths. Computers can perform extremely fast calculations, but brains are far better at complex tasks, such as associating one memory with another or rapidly recalling associated data. So researchers have long dreamed of directly linking neurons and transistors to benefit from the strengths of both. In August, two German researchers reported that they had succeeded in putting a small network of snail neurons on a chip and interfacing them with transistors. Günther Zeck and Peter Fromherz of the department of membrane and neurophysics at the Max Planck Institute for Biochemistry (Munich, Germany) demonstrated that they could send signals from a transistor on the chip through a neuron to another neuron and back to a second transistor (*Proc. Natl. Acad. Sci. U.S.A.* 2001, *98*, 10,457). The work could pave the way for the creation of operating devices that merge biological and silicon data processing.



Electron micrograph of a nerve cell from snail ganglia restrained by polyimide posts and allowed to grow 3 days in culture (a). Micrograph showing two concentric circles of cages of neurons connected by neurites (bright threads) after 2 days in culture (b).

Max Planck Institute for Biochemistry

In the German neuron chip, nerve cells from snail ganglia—used because they are larger than mammalian neurons—are placed atop a transistor flanked by two stimulators. A thin layer of silicon dioxide insulator covers each stimulator, which is a positively doped area in negatively doped silicon. When charge flows into the stimulator from an external circuit, a capacitive link is established to the neuron across a tiny gap, which stimulates it to fire. In turn, when the neuron fires, voltage changes link to a field-effect transistor below the neuron and complete an input–output junction between silicon and neuron. The researchers eliminated the danger of damaging biochemical reactions with metal electrodes by eliminating all neuron-to-metal contact, which they did by covering the whole chip surface with highly inert silicon dioxide.

Individual snail neurons were suctioned out from a dissected but still living snail ganglion and deposited, one on each of the stimulator–transistor sites. Each site was surrounded by a tiny picket fence to keep the neurons from moving about, but which allowed them to send out axons to make connections with other neurons. The whole chip was immersed in a nutrient bath, which was kept in contact with two intact snail brains to encourage neuron growth.

Within several days, the neurons had sent out a web of fibers and joined together into a connected network. This enabled the researchers to test pairs of neurons by stimulating one of a pair and then seeing it fire, set off the other neuron, and have that neuron's signal detected by the second transistor.

Fromherz sees this as just a first step in an ambitious program. "The aim is to study how associative memory functions in a real neural network and perhaps harness that functioning in an electronic circuit," he says. The team intends to create networks of snail neurons on a chip with defined connections and study learning in the neurons. The researchers also plan to use rat neurons, and eventually, they hope to develop massive interfaces with living slices of brain tissue containing tens of thousands or millions of neurons.

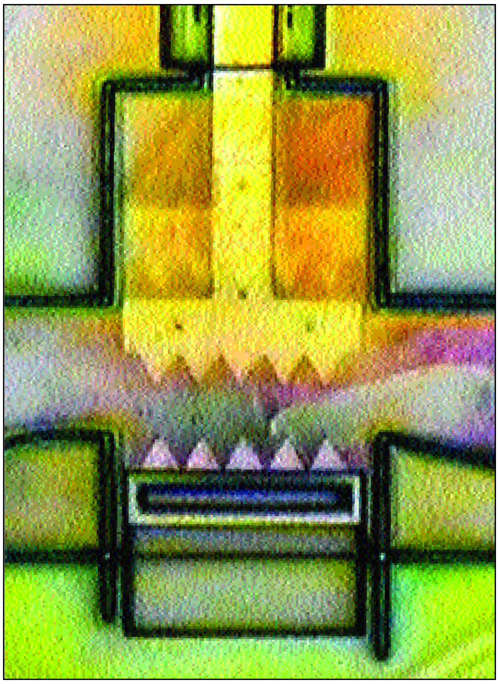
Cellular manipulator

Merging neural networks and transistors is one way to interface cells and silicon. Another way is to build silicon micromachines to manipulate and transform cells. In a rapidly advancing field, Sandia National Laboratories researchers have demonstrated a micromachine that temporarily distorts blood cells at a rate of 10/s. Such manipulation could enable the injection of thousands or even millions of cells with genetic material, creating a practical alternative to the current and potentially dangerous gene-therapy method of using viruses to insert genetic material into cells.

Like other micromachines, the cell manipulator is produced by photolithographic methods widely used in manufacturing silicon circuit chips. However, in this surface micromachining process, a layer of silicon dioxide is etched away from around and underneath moving parts, allowing them to move along prescribed paths. The innovation in the Sandia work is to make some of the parts—including the channels through which cells and fluids flow—out of silicon nitride, an insulator, rather than out of silicon, a conductor.

"This means that we can put insulated electrical devices, such as an electrostatic motor, right on the chip," explains Sandia researcher Murat Okandan. "In addition, silicon nitride is transparent, so we can directly view what is going on in the channels. With this material, we can integrate microfluidic, optical, electrical, and magnetic systems all on the same chip." The cell manipulator also benefits from Sandia's SUMMiT V fabrication process, which allows five separate polysilicon layers to form in any pattern.

In operation, fluid containing red blood cells is pumped through channels slightly larger than the cells themselves. An electrostatic motor actuates a piston via a lever as the red cells enter a chamber. The piston is designed to temporarily disrupt the cell membrane to allow chemicals to pass in that would otherwise be repelled. In future experiments, the Sandia team expects to use fluorescent materials to demonstrate the reversible membrane disruption.


Sandia National Laboratories

Silicon microteeth chomp down on red blood cells being pumped through a microchannel only 20 µm wide.

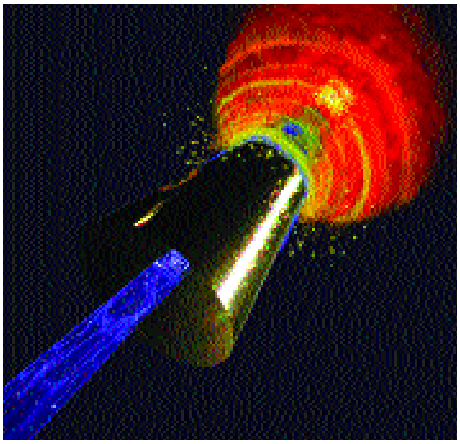
"Beyond that, we want to replace the piston with a silicon needle so we can inject DNA or other materials into the cells," says Okandan. A single micromanipulator measures 0.6 × 0.5 × 1.5 mm, and hundreds or thousands can work in parallel at low cost. Thus, millions of cells could be rapidly provided with new genetic material and reinjected into a patient in a future clinical application.

Fast-ignition laser fusion

The development of controlled thermonuclear-fusion power has proven exceedingly difficult over the past 50 years. So far, there is only one proven way to obtain the combinations of density, confinement time, and high particle energy or temperature needed to produce net energy from fusion: setting off a fission bomb. Yet progress has been made, and in August, a Japanese team demonstrated a promising new approach to heating fusion fuels with lasers that could considerably reduce the amount of energy needed for the task (*Nature* 2001, *412*, 798).

Laser fusion is a form of inertial-confinement fusion in which the heated fuel is allowed to expand freely, with only its inertia providing the needed time for fusion burn. The other main approach is magnetic confinement, in which magnetic fields trap the fusion plasma (see *The Industrial Physicist*, June 2000, pp. 14–17). Laser fusion, however, seeks to duplicate the process used to set off thermonuclear weapons, but it uses lasers as the driving force instead of radiation from a fission bomb, and of course, it uses far less fusion fuel.

In the conventional laser-fusion approach, pursued at facilities such as Nova at Lawrence Livermore National Laboratory (LLNL), symmetrically arranged nanosecond-long laser pulses are focused on a frozen pellet of deuterium and tritium, heavy isotopes of hydrogen. The intense X-rays generated in the outer layer of the pellet by the laser pulses compress the pellet to hundreds of times its original density. This, in turn, sets up a shock wave that converges on the pellet's center. When the shock wave reaches the center, the fuel ions are heated to energies above 10 keV (equivalent to a temperature of more than 10^8 °C). Fusion burning starts to generate energy, which heats the rest of the fuel to fusion temperatures and "ignites" it before it has time to blow apart.


Institute of Laser Engineering, Osaka University, Japan

Laser pulse enters a 60° gold cone whose tip is inserted to within 50 µm from the center of a spherical polymer target to create fusion.

The problem with this approach is that it requires an extremely symmetrical shock wave to converge exactly on the pellet center if the "spark" is to be lighted. "Even with perfect symmetry in the laser pulses, just hydrodynamic instabilities can ruin the symmetry," comments Michael H. Kay, director of fast ignition for LLNL. The fast-ignition concept demonstrated by the Japanese researchers at Osaka University (who worked in collaboration with physicists at three English facilities: Rutherford Appleton Laboratory in Chilton, Blackett Laboratory at Imperial College in London, and the University of York) separates the compression and the heating of the pellet. In contrast to the work at Livermore, which is applied to simulating weapons, the Japanese research is aimed purely at the development of a new energy source.

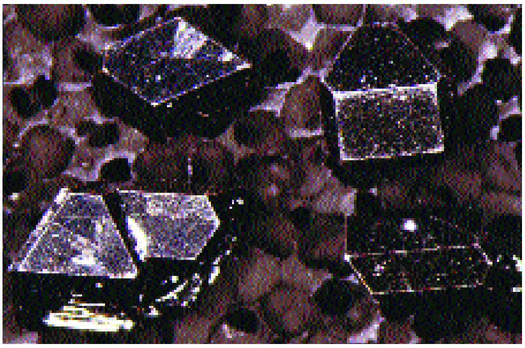
In the Japanese approach, the spark is provided by a second laser pulse that lasts only a picosecond. This laser pulse, focused on the outside of the pellet with an intensity of more than 10^{19} W/cm^2, generates huge electrical fields and accelerates a beam of electrons to relativistic energy. These electrons then penetrate the high-density core of the compressed pellet, heat it, and set off fusion reactions. Not only is the need for ultrahigh symmetry eliminated, because compression does not set off the spark, but the density required is 5 times less than in the conventional approach and the energy required is a factor of 20 less.

In the preliminary experiments done at Osaka, a 1.2-kJ nanosecond pulse was used for compression and a 60-J subpicosecond pulse for heating. The number of fusion reactions, indicated by the number of neutrons produced, was 20 times higher when the heating pulse was used than when it was not. This result in turn showed that the temperature had risen by 120 eV (about 1.3 × 10^6 °C) to several hundred electron-volts. To achieve similar results with compression alone needed twice as much energy, a proof that fast ignition really was more efficient.

These results are far from those required for net energy production, which needs a temperature and density 10 times higher. (Magnetic fusion experiments have already exceeded temperatures of 40 keV.) But theoretical studies indicate that fusion ignition by this method may be achievable with laser pulses a few hundred times larger than those in this experiment, which falls within the capacity, for example, of the National Ignition Facility now under construction at LLNL. Ω

Super buckyballs

In the search for better and higher temperature superconductors, many researchers have looked at the versatile buckyballs (C_{60}), which have been known for a decade to superconduct when metal atoms are packed between the spheres in a crystal array. Until now, however, it looked as if only modest critical temperatures of 40 K could be achieved. But a Lucent Technologies/Bell Laboratories team—Jan Hendrik Schön (also of the University of Konstanz, Germany), Christian Kloc, and Bertram Batlogg (now at ETH Zurich)—has found a way to push a C_{60}-based crystal's critical temperature, T_c, up to 117 K, close to that achieved by copper-containing ceramics (*Science* 2001, *293*, 2432). Moreover, the team has discovered a way of predicting T_c for related crystals, perhaps pointing the way to still higher temperature superconductors.


Lucent Technologies' Bell Labs

A crystal lattice of buckyballs moved further apart by using intervening molecules of tribromomethane and injected with holes becomes superconducting at 117 K.

The researchers first observed that injecting holes instead of electrons into C_{60}-based crystals resulted in much higher critical temperatures. "We're not sure of the reason that holes interact more strongly with phonons, but they do, and it's a strong effect, nearly tripling T_c," says Schön. The link between charge carriers and phonons—lattice vibrations—is the basis for superconductivity in the standard theory.

On theoretical grounds, the team also knew that the critical temperature rises exponentially with increasing density of energy states. (The density of states is how many energy states exist in a given energy interval.) They reasoned that if they could move the buckyballs farther apart in the lattice by using larger intervening molecules, their binding energy would be less and the energy bands would grow narrower, but the number of states would remain the same, thus increasing the density of states.

This is exactly what the scientists found experimentally. As they increased spacing from 14.15 to 14.45 Å, a change of just 2%, the critical temperature increased from 52 K to 117 K. To achieve this spacing, they used molecules of tribromomethane ($CHBr_3$). They found that the material went from an insulator to a high-T_c superconductor as they shifted more holes into it by applying an external electric field. "Because we need to inject the holes, this cannot be a bulk superconductor for cables," comments Schön. "But the ability to turn superconductivity on and off could be very useful for electronic applications and sensitive detectors." Also, in contrast to ceramic superconductors, the buckyball crystal is isotropic, which could be a benefit for some applications.

The next step is to push the interlattice spacing up by another 1%, increasing the critical temperature to 150 K, close to the best results obtained with ceramics. "Nearly 200 compounds have been incorporated into buckyball lattices, and lattice spacing and energy bands have been measured for most of them," Schön points out. "So we are now searching the literature to find those with the right lattice spacing." Selecting a material won't be easy because too distant a spacing weakens the bonds, causing the crystal to fall apart. Ω