

Brighter lights from photonic crystals

Incandescent light bulbs, whose technology has remained essentially unchanged since Edison invented them, waste about 95% of input energy. Five percent of the electricity goes to light and the rest to heat

4.2 μm from its neighbors. Alternating layers of rods are stacked at 90° and offset from the layer below that runs parallel to it. The array was fabricated by creating silicon dioxide molds, filling them with tungsten by chemical vapor

deposition, and then etching away the silicon dioxide to produce a freestanding stack of rods.

The array has remarkable optical properties in that it easily transmits

radiation in the visible range if shrunk by a factor of 10. Fleming comments. In addition, there may be significant practical problems in using tungsten rods as fine as 120 nm in a light-bulb filament. So Edison's invention may still have a few years left before it is radically modified. ■

Chopping up nanotubes

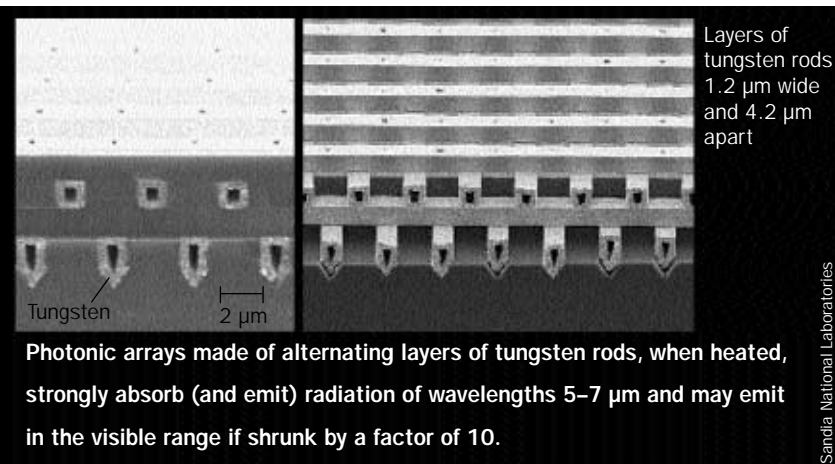
The most promising potential successors to silicon-based circuits seem to be carbon nanotubes, which researchers have already made into diodes and transistors. But nanotubes are inherently longer than their 5-nm widths. To create a useful density of circuit elements, they have to be divided in some way to form units with lengths closer to their widths.

A Korean-Japanese collaboration has found a way to do just that. The researchers, from Seoul National University, Soongsil University (Seoul), and Nagoya University in Japan have inserted regularly spaced fullerenes inside nanotubes and modified their electronic structures by, in effect, breaking them into separate electronic units only about 10 nm long (*Nature* 2002, 415, 1005). The team used an 82-carbon-atom fullerene with gadolinium atoms trapped inside that were a bit too big to fit easily within the nanotube. As a result, the fullerenes bulged the nanotube outward slightly every 10 nm, like peas inside a pod.

The deformation changed the electronic structure of the nanotube in a periodic manner. "We think that this change is caused by a combination of factors," says Young Kuk of the department of physics at Seoul National University, a leader of the team. "Part of the change is due to the elastic strain on the nanotube, part to charges transferred from the gadolinium atoms to the nanotubes."

The main change in the region around each fullerene is a shrinking of the nanotube's bandgap from 0.5 eV to 0.1 eV. This creates localized quantum dots, a well-known electronic structure that is, for example, used in some types of lasers. "We are now working on creating multiple quantum light-emission devices and a field-emission transistor," says Kuk.

The insertion of the fullerenes is a rela-



Photonic arrays made of alternating layers of tungsten rods, when heated, strongly absorb (and emit) radiation of wavelengths 5–7 μm and may emit in the visible range if shrunk by a factor of 10.

because the peak of the thermal-emission spectrum is far in the infrared at the temperature that a filament reaches (about 1,500 K). But experiments with metallic photonic crystals conducted at Sandia National Laboratories indicate that light-bulb efficiencies could potentially be increased 10-fold to around 50–60% (*Nature* 2002, 417, 52). In the process, the color of the light could be shifted closer to that of sunlight.

Photonic crystals are regular arrays of tiny objects that permit the transmission of only certain wavelengths of radiation. Because of interference effects, wavelengths in certain bands—comparable to the spacing between the objects—cannot propagate through the array. Much research has been devoted to photonic arrays made up of holes in silica glass, which have applications in optics and fiber communications.

Instead of holes, the Sandia team made metallic photonic crystals that consist of micrometer-wide rods of tungsten. Metallic photonic crystals are of interest because they can be heated to temperatures well above 1,500 K and used for applications that involve high rates of energy transfer, such as lighting or photovoltaics. The Sandia array is simple in structure, consisting of alternating layers of rods, each 1.2 μm wide and spaced

with wavelengths shorter than 5 μm and completely reflects radiation longer than 7 μm . Most important, radiation is strongly absorbed in the intermediate band from 5 to 7 μm . "We measured absorption of 22% at 6 μm ," says James Fleming, one of the researchers. "A sheet of tungsten would only absorb 1% at the same wavelength."

Because any material emits most strongly at the same wavelengths at which it absorbs most strongly, the Sandia photonic array emits in the 5- to 7- μm band when heated and almost not at all at longer wavelengths, where it is highly reflective.

"If we shrink the whole array down by a factor of 10, using 120-nm rods and 420-nm spacing, we will shift the emitting band down to around 600 nm, right in the middle of the visible spectrum," explains Fleming. The researchers calculate that such an array, heated to 1,500 K, would emit half its energy in the visible range, not just 5%. In addition, with the emission peaked in the green, the yellowish tinge of incandescent light would be eliminated.

Although mathematical models correctly predict the absorption peak, a qualitative explanation of exactly what is going on is not yet clear. "We certainly need to understand the absorption peak better theoreti-



Computer simulation shows large fullerenes trapped inside a nanotube and how a scanning tunneling microscope tip would reveal the subsequent periodic change in the tube's electronic bandgap.

tively easy process, although a slow one at present. The fullerenes and the nanotubes are simply kept together in a sealed tube at 500 °C for three days. It is easy to vary the spacing between the fullerenes or to introduce several different types of metallofullerenes, the team reports, which produces different electronic nanodevices.

A University of Illinois–University of Pennsylvania collaboration almost simultaneously announced similar work using the C-60 fullerenes, known as buckyballs. But the smaller fullerenes do not distort the structure of the nanotubes and so do not change the bandgap structure. Only the density of states is modified. “We found that without the distortion of the tube caused by the larger molecules, there was no bandgap change. So you can't make separate quantum devices this way,” comments Kuk. The larger metallofullerenes, however, seem to open a wide range of possible nanodevice structures. ■

Raman spectra

Raman spectroscopy is extremely useful to biochemists because with a single spectrum, it reveals the presence and relative concentrations of dozens of chemicals. Spectroscopy of individual cells would be particularly valuable because it would allow researchers to observe biochemical changes as they happen during growth and division or when cells become damaged or turn cancerous. But an individual cell in a nutrient solution, such as a yeast cell, moves around continuously, buf-

feted by Brownian motion. To obtain spectra, a researcher must pin down the cell without damaging it.

East Carolina University physicists Changan Xie, Mumtaz A. Dinno, and Yongqing Li have solved this problem by combining Raman spectroscopy with optical tweezers that can immobilize the cells (*Optics Lett.* **2002**, *27*, 249). Optical tweezers, which harness the gentle pressure of photons from a laser to move or fix tiny objects such as cells, have been used for years. They need only tiny amounts of power, around 2 mW, to trap cells without damaging them. However, Raman spectroscopy requires much higher powers, 20 to 100 mW, because the Raman scattering that couples photons with phonon vibrations is weak. Previous attempts to take Raman spectra of individual cells showed that the high level of radiation rapidly damaged the cells.

Li and his colleagues solved this problem in a conceptually simple manner. For most of the time that a cell is trapped, a diode laser operating at 785 nm produces the 2 mW needed for immobilization. Only for a short period, 2 s at a time, does the laser switch to the higher 20-mW power needed to take the Raman spectrum. The exposure is too short to damage the cell, and taking a few minutes between exposures avoids cumulative damage.

The ability to take spectroscopic “snap-

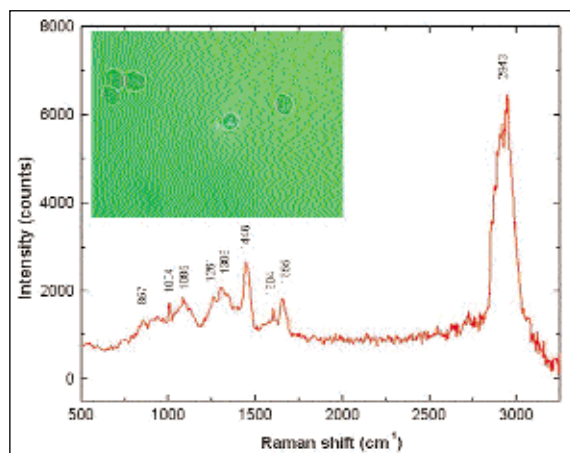
shots” of individual cells has opened a range of applications. The Raman tweezers allow instant differentiation between living and dead cells: dead cells lack some of the characteristic Raman bands because their complex molecules have already denatured. Beyond this elementary level, the research team is developing many other applications. “With Raman spectra, we can quickly differentiate between different types of bacteria without taking the time to culture them,” says Li. “We are looking at ways this process might be used to guard against bioterrorism, for example.” In addition, the ability to take repeated spectra from the same cell allows studies of biochemical changes during cell division. This is a hot area of study as scientists try to unravel the biochemical reactions that allow cells to differentiate (become specialized) and maintain their specialization generation after generation.

Another major application will be to study the response of individual cells to drugs. “We will be able to watch as the drug actually takes effect and changes the chemical mix within the cell,” says Li. Because the laser-tweezers/Raman-spectroscopy system consists of relatively inexpensive, off-the-shelf components, it may rapidly become a standard piece of equipment in biochemical laboratories. ■

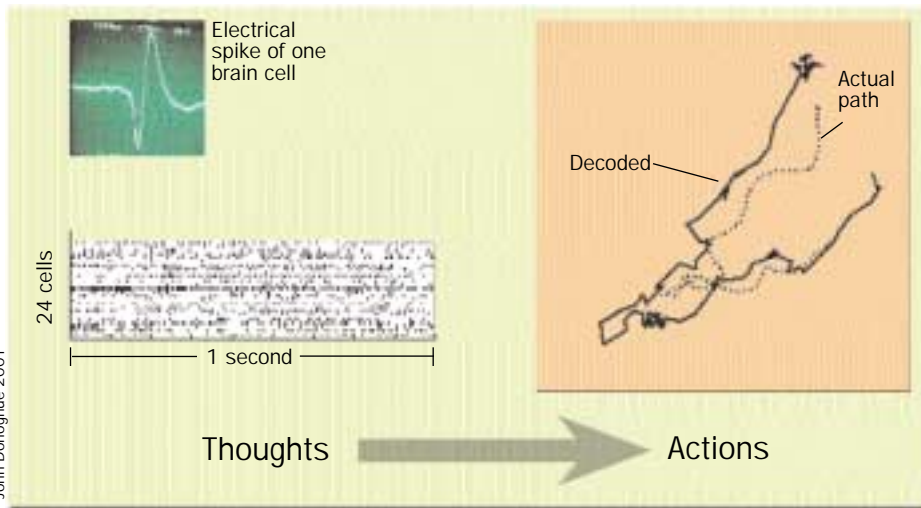
Thought control

The ability to control machines merely with a thought is a staple of science fiction. But for some severely paralyzed patients, such control may be the only route to any degree of independence. As a result, researchers have sought to find ways of using signals from the brain to control simple activities, such as directing a cursor on a screen. So far, however, the need for long training periods and the inability to produce accurate motions have hobbled these efforts.

Now a Brown University research group has shown that a monkey can be trained in minutes to control a cursor with its brain almost as accurately as the animal can with its hand (*Nature* **2002**, *416*, 141). Moreover, the researchers found that they were able to accomplish this feat with a simple mathematical algorithm using the output of as few as six neurons.



Raman spectrum (using 20 mW of power for 2 s) of a living yeast cell caught by optical tweezers (using 2 mW of power) reveals the presence and relative concentrations of different chemicals.



The spike pattern of 24 brain cells decoded into a hand path signal and compared with the actual path, which is probably based on signals from millions of cells.

The method, developed by John Donoghue, chair of the department of neuroscience, graduate student Mijail D. Serruya, and colleagues, uses a set of implanted electrodes to record the firing rates of from 6 to 30 neurons. The electrodes are placed in the motor cortex, which generates signals to control muscles. The first step is to record a minute of neuronal signals as the monkey moves the cursor with a manipulator. A linear regression equation then generates linear coefficients that relate the firing rate of each neuron to the cursor's motion in the up and down directions.

Using these linear coefficients, the Brown team sets up a program to control the cursor's motion with just the output from the neurons. That is, the speed with which the cursor moves in the up or down direction is determined by the sum of the firing rates of the neurons, each multiplied by a different linear factor (either positive or negative). A similar equation governs the left-right motion of the cursor.

Once they generate the program, the experimenters switch control of the cursor from the monkey's hand to its brain by running the output of the neurons through the program. The monkey then controls the cursor directly using the neural signals. "In some trials, the monkey stopped using the manipulator altogether," says Serruya. Based on the neural-control runs, a second, refined, set of linear coefficients is calculated. When the monkey uses this second linear filter to control the cursor, the control is nearly as good as with its hand. The monkey is able to move the cursor to an arbitrary target in almost exactly the same time

with neural control as with hand control.

"Our results demonstrate that a simple mathematical approach, combined with a subject's own learning abilities, can provide accurate goal-directed control," says Donoghue. If this system can be applied to paralyzed patients, a cursor would not only give them independent access to communications—from synthesized speech to the Internet—it could potentially be used to control a robotic arm. Eventually, more sophisticated models might use neural signals to control impulses to a patient's own muscle, thus partially restoring movement.

The research team has formed its own company, Cyberkinetics (Providence, RI), to transfer this technology to human patients. For this purpose, the training program will have to be changed because the initial hand-control data will be unavailable. ■

www.tipmagazine.com

On the TIP Web site, you get all of the current and previous issues, profiles of industrial physicists, collections of articles on buzz topics, search functions, indices, valuable links, contact with the staff, and information about jobs, employers, and hot new products.

