Materials Scientists Put The Squeeze on Electrons

Bits of semiconductor so small they can confine electrons may revolutionize communications and computing

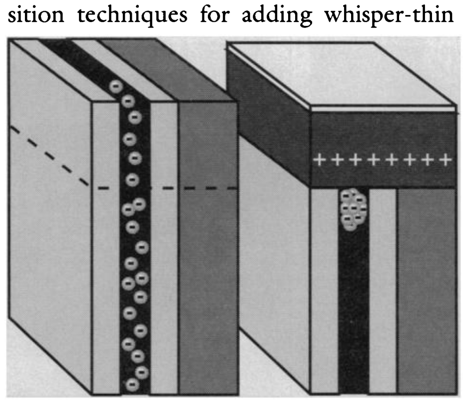
FOR DECADES, MICROELECTRONICS RESEARCHERS were happy to think of electrons as particles—miniature ping-pong balls that bounced around between energy bands and pelted through switches and wires. Now, by making ever more minute semiconductor structures, they're rediscovering the other side of electrons' quantum-mechanical duality: their wave nature. Materials scientists are now building devices so small that they cramp the electron waves, forcing them into specific wavelengths and energies.

As a result, these "quantum structures"—nanoscale layers, channels, and boxes known as quantum wells, quantum wires, and quantum dots—turn the broad energy bands of conventional semiconductors into more sharply defined energy levels. And that's a transformation that promises greater speed and efficiency for the resulting circuits and optical devices.

Coaxing light from present semiconductor lasers, for example, takes a big jolt of electrical power, because the broad energy bands of the material include only a few energy states that make efficient laser action possible. But a quantum structure responds to a gentle electrical nudge, because most or all of its energy states cluster at the right level. The result is the same amount of laser light for less power. And, as a bonus, the infinitesimal scale of quantum wires and dots, measured in tens of nanometers or hundreds of angstroms, means that the resulting circuits and lasers could be miniaturized to the nth degree.

All this is not confined entirely to the future. One kind of quantum structure, the quantum well, has already found its way into the transistors in satellite microwave receivers and the lasers in some fiber-optics communications systems—and in run-of-the-mill compact disc players. "What excites me about these devices is to see quantum mechanics enter our living rooms," says Arthur C. Gossard, a materials scientist at the University of California, Santa Barbara, who is doing basic research on quantum structures (see article on page 1326).

But the minuscule dimensions involved in quantum electronics—equivalent to just hundreds of atom-widths—present a huge barrier to building more complex quantum structures. "Fabrication of these systems is a real challenge," says Gossard. That's actually a triumph of understatement. The effort is straining to the limit the traditional tools of semiconductor processing—lithography for laying out circuit patterns, etching processes for sculpting the materials, and deposition techniques for adding whisper-thin layers of new material. It's also spurring investigators to invent some new ones, such as strategies for synthesizing tiny structures chemically—building them up molecule-by-molecule instead of carving them out of larger pieces of material.



Wiring a well. *Cleaving a quantum well* (left) *and depositing electron-donating material on its edge draws electrons into a quantum-wire-like region* (right).

But even their best efforts don't always yield quantum structures that are small enough, sharp enough, or uniform enough to behave the way theory says they should. And once researchers have mastered individual quantum structures, they'll still face the formidable challenge of interconnecting them into superdense computer chips or the elements of high-capacity communications systems. Making such assemblages is theoretically possible, says Mark Reed, an electrical engineer at Yale University, "but it's going to take a heck of a lot longer than most people want to admit."

The basic principle behind quantum wells, wires, and dots, is the same: Confine electrons in a restricted region of semiconductor by hemming it in with another semiconductor that has a higher "bandgap," a measure of the amount of energy that has to be pumped into the material to get electrons flowing. Like water seeking a low point, electrons will naturally tend to flow in the confined region, where the bandgap is lower. In quantum wells, that region is often a 100- to 200-angstrom-thick slice of the semiconductor gallium arsenide, built up by vapor deposition on a base of the higher-bandgap material aluminum gallium arsenide. A second layer of aluminum gallium arsenide closes off the top. Confined in the slice, the electrons have so little headroom that their energy states are forced to cluster around specific peaks.

Quantum wires confine the electrons on four sides rather than two, squeezing them into a linear channel and thus achieving an even sharper clustering of energy states. One obvious way to make quantum wires is to slice a quantum well into narrow strips. The trouble is that on this minuscule scale, the electron or ion beams that act as the knives are blunt intruments. They usually damage the intended structures (though many groups are looking for ways to repair such processing damage), and they can't cut strips any narrower than about 300 angstroms. The resulting slivers can behave as quantum wires only at very low temperatures, where background electronic noise subsides, allowing the feeble quantum effects in these relatively large structures to stand out.

To cut their creations down to the needed size—about 200 angstroms or less—quantum-wire makers are resorting to ingenious sleights-of-hand. Loren Pfeiffer of AT&T Bell Laboratories, for example, tries to trick electrons into treating one edge of a quantum well as a quantum wire. His approach: Cleave a quantum well, then, on the new edge, grow a very thin layer of electron-donating silicon atoms sandwiched between insulating coatings of aluminum gallium arsenide. The lower bandgap material in the quantum well edge lures electrons away from the deposited silicon atoms, converting a very thin region along the edge (about 100 angstroms deep) into a sort of quantum wire. Right now, however, these structures look more promising as vehicles for studying the physics of confined electrons than as the basis of future technologies because they are complex and expensive to make. "I don't know whether anyone could make a billion dollars off them using present fabrication methods," says Pfeiffer—though he hastens to add that the same is true of other experimental quantum structures.

One way to simplify the wiremaking is to bypass quantum wells and make quantum

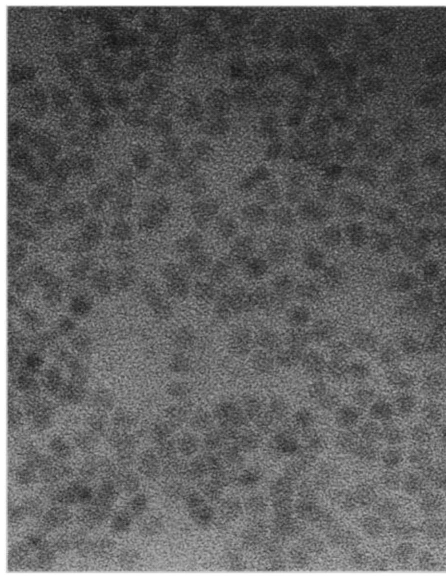
SOURCE: LOREN PFEIFFER; ILLUSTRATION: D. DEFRANCESCO wires directly. At Bellcore, Eli Kapon, director of quantum structure research, chemically etches V-shaped grooves into the surface of a semiconductor substrate, then blankets the surface with aluminum gallium arsenide, narrowing the grooves to quantum dimensions. Then comes a layer of gallium arsenide and a top coating of aluminum gallium arsenide. Ideally, the gallium arsenide flows to the bottom of the grooves, forming low bandgap regions that trap electrons in channels less than 100 angstroms wide. Kapon says he has already fashioned arrays of the resulting wires into lasers as efficient as the best quantum well lasers. And because his technique is still in its infancy, he sees a good chance of bettering that performance in the future.

But some researchers, seeking to simplify things further, are skirting such intermediate steps as quantum wells or etched grooves. The strategy of Gossard and his colleagues at Santa Barbara, for example, is to cut a semiconductor across the crystal grain, resulting in a series of steps, each just an atom or two high, then deposit alternating partial layers of high- and low-bandgap materials on the steps. That might sound like a recipe for a stack of quantum wells, but by varying the thickness of the layers as they are laid down, the Santa Barbara group is able to break them into an array of quantum wires (see illustration on page 1329). But unlike Kapon, Gossard and his co-workers have not yet proved their wares in a working laser or other device.

There's an outside chance, though, that none of these heroic measures may be needed in the future. That hope was raised last April, when researchers at Britain's Royal Signals and Radar Establishment and the University of Grenoble in France reported that pure silicon sculpted into a forest of very thin pillars by a simple chemical etching process gave dramatic evidence of an altered electronic behavior: It emitted an intense glow when stimulated with a laser (*Science*, 17 May, p. 922). That's a phenomenon never seen in bulk silicon, and it has convinced some researchers that the silicon pillars, about 30 angstroms thick, "are true quantum wires," says Louis E. Brus of Bell Labs.

But researchers are a long way from building this "porous silicon" into working devices, in part because they still aren't sure just how its electronic structure has been transformed. And that kind of uncertainty is commonplace in this arena of quantum structures. Researchers don't always know exactly what they've got their hands on when they build a new nanoscale structure—with the result that rival research groups often dispute each other's claims to having produced a true quantum structure. In theory, the diagnosis should be simple: A quantum structure should emit and absorb light at unusual frequencies, corresponding to the spacing of the quantized energy levels, and it should allow current to pass only at specific energies. But so far, few quantum structures have had a signature clear enough to go unchallenged.

The difficulty of making quantum wires—



LOUIS BRUS AND MICHAEL STEIGERWALD

Dots of potential. *A Bell Labs process precipitates clusters of cadmium selenide tens of angstroms across.*

and convincing the rest of the community that you've succeeded—might seem enough to discourage researchers from pushing further, to quantum dots: devices in which electrons are caged at a single point rather than in a line or a plane. But though the obstacles are greater, so are the rewards. Quantum dots should achieve virtually perfect quantum confinement, forcing all the electrons into the same set of quantized energy states. The result: efficiencies that are predicted to be orders of magnitude better than those of quantum wires when the dots are wired into switches and lasers. And because of the infinitesimal spacing that might be possible between quantum-dot devices, they might lend themselves to computer chips 10,000 times more powerful than today's best silicon devices and to massively parallel computer architectures, paving the way for computers that think more like people than machines.

As with quantum wires, the obvious way to make dots is to start with an ordinary quantum well, pattern it lithographically with a beam of electrons, and carve it up with a beam of ions. Reed, who until last year worked at Texas Instruments, starts with a quantum-well device known as a resonant tunneling diode, which has electrical contacts on the top and bottom of the semiconductor stack. Using a very sharp and narrow ion beam, Reed slices away at the diode layers until only little pillar-like remnants are left standing, like buttes on the floor of Monument Valley. The structures—at 1000 angstroms across—might seem too big to act as quantum dots, but "dead" regions left by the beam restrict the low bandgap area in each one to about 100 angstroms across. That's small enough to qualify, Reed contends, based on measurements of how current flows through the structures as the voltage is increased. The tests show a group of five or six "sharp peaks," Reed says—just what would be expected from quantum dots.

But instead of painstakingly carving out quantum dots, why not build them up molecule-by-molecule, letting chemistry do the work? That's the approach taken by several groups, including Brus and his colleague Michael L. Steigerwald at Bell Labs. They grow their dots in tiny reaction vessels called "inverse micelles"—tiny droplets of cadmium solution wrapped in soap-like compounds. The droplets are suspended in a bath of a selenium-containing solution. As selenium ions migrate into the droplets, molecules of the semiconducting compound cadmium selenide gradually precipitate, forming clusters tens of angstroms across, which are then encapsulated in an organometallic reagent to stabilize them. A change in the color of the semiconductor from the black of the bulk material to red and yellow in the particles betrays a change in its electronic structure, says Brus, which convinces him that he has made genuine quantum dots (*Science*, 26 April, p. 511).

If chemistry can make quantum dots, perhaps chemistry can connect them up into the palm-sized supercomputers of researchers' dreams. Some groups are now investigating that possibility, toying with notions such as wiring the dots together with the long-chain molecules of certain conductive polymers. To some other researchers that sounds just one step removed from fantasy. But others are more sanguine. "About 5 or 10 years ago people were saying that you couldn't make devices out of quantum wells," says Gossard. "It can really startle you to see how fast things in this field can develop." He, for one, is not ruling out quantum leaps in quantum devices. ■ GORDON GRAFF

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