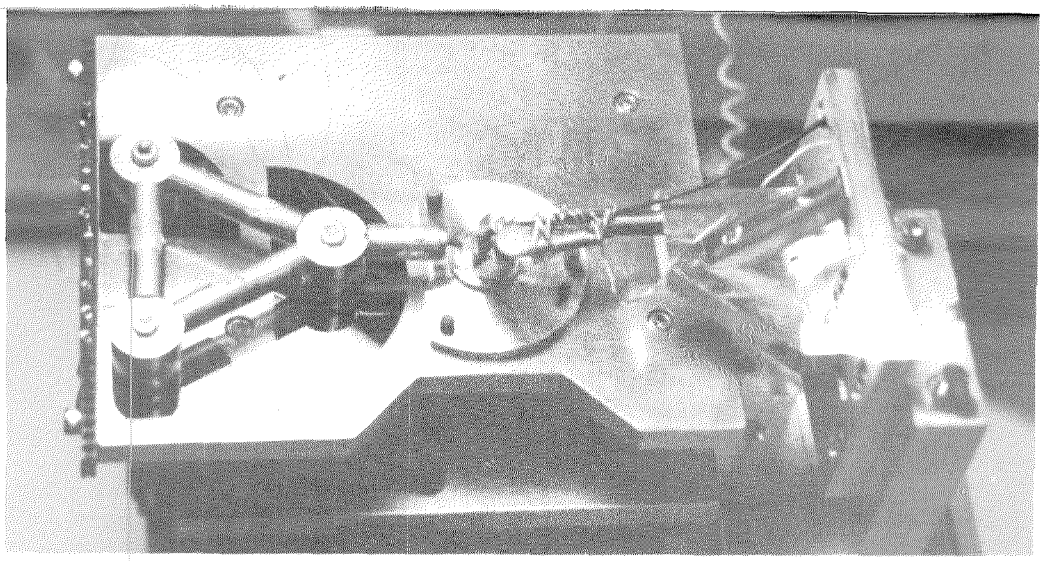
Lab Notes



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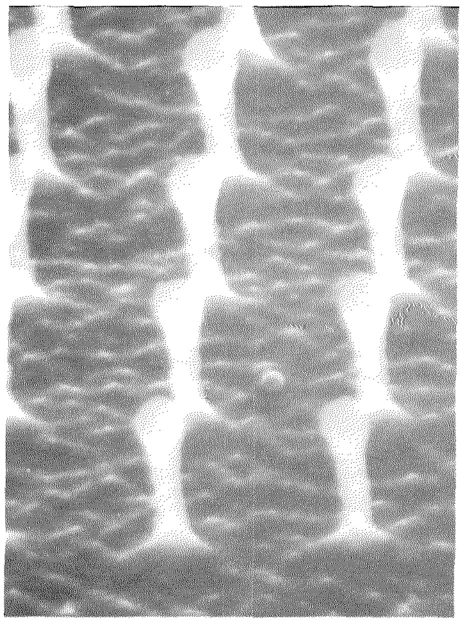


Above: An orchard of quantum dots. The bulbous dots, 0.05 microns in diameter, sit on gallium arsenide stalks spaced 0.38 microns apart. Right: The piezoelectric walker. Each leg of the triangle is 1.5 inches long. The rod on the right apex carries the needle; the chip bearing the quantum dots is the tiny black square in the mounting to the walker's right. The optical fiber goes off to the right.

Eyeing the Dots

Electronic devices, even things as small as computer chips, use electrons in bulk to make things happen. Millions of electrons surge through any given circuit, as faceless as lemmings or commuters at rush hour. But as individual components get smaller and smaller, strange things begin to happen. An electron, looked at by itself, *does* have a personality—a property called a quantum state. And when there are few enough electrons in each component, the effects of these personalities begin to emerge.

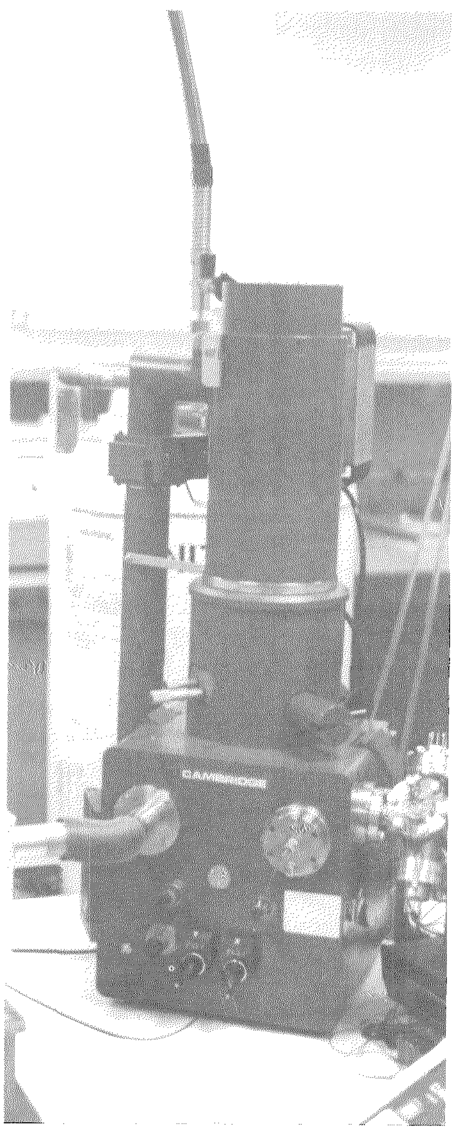
According to quantum physics, an electron can behave like either a particle or a wave, depending on its circumstances. Quantum effects occur when the size of the component approaches the wavelength of an electron. In gallium arsenide crystals, this happens at slightly less than 0.1 microns—roughly 500 atomic widths. (A micron is one-millionth of a meter.) When it happens, the electron is no longer free to do as it pleases, but is confined to specific motions dictated by its quantum state. This behavior would give quantum devices very different properties from bigger components.

Physicists have been sneaking up on quantum devices in stages. The first step was the quantum well, where electrons can move in only two dimensions: length and width. A group led by Amnon Yariv, the Thomas G. Myers Professor of Electrical Engineering and Professor of Applied Physics, recently made a quantum-well laser 300 microns long by 1 micron wide by 0.005 microns—a mere 20 atoms—thick. The laser runs on 0.5 milliamps of power, a record low and close to the theoretical minimum threshold current for a quantum-well device. These lasers should become widely available in 4 to 5 years.

But that's only one step toward making ultimately small devices. Next comes the quantum wire, so small that electrons can only move lengthwise, and ultimately the quantum dot, where electrons essentially can't move at all. Quantum-wire lasers should have a threshold current 10 to 20 times lower than quantum wells, and the properties of quantum dots are a hot topic for theorists. Assistant Professor of Applied Physics Kerry J. Vahala's group is beginning to build and test these devices.

Building these devices is a formidable task, and there is no favorite technique yet. Vahala's group is experimenting with well-established chip-

The electron microscope sits on a tabletop in the lab. The sample chamber is behind the word "Cambridge."



manufacturing technology and other more esoteric approaches. In any case, the process usually begins with a crystal of alternating gallium arsenide and aluminum gallium arsenide layers on a gallium arsenide base. The upper layers are etched by various methods, leaving behind layered islands, each of which is a device. The finished crystal looks like a set of parallel lines or rows of dots.

Testing the completed devices is more daunting. Each line or dot must be tested individually. Standard chip components must also be tested, but they are much larger, and have leads running off to the chip's edges, where wires can be attached. But a dot, obviously, has no leads—if it did, it wouldn't be a dot.

The first challenge is simply *finding* the devices. The researchers can use electron microscopy to look at the crystal as a whole, but probing a specific dot isn't like a biologist chasing an amoeba around a microscope slide with a micropipet. For one thing, electron microscopy only works in a vacuum, so the sample chamber is sealed. Furthermore, much of the work must be done at liquid-nitrogen (77K or −196°C) or liquid-helium (4K or −269°C) temperatures.

"Our ability to see these effects is temperature-dependent," Vahala explains. "The effects are always there, but other phenomena tend to obscure them. If you make things cold enough, however, the quantum effects become noticeable."

The device is located by "cathodoluminescence." The crystal emits light when struck by an electron beam. Quantum dots (and wires) emit characteristic sets of frequencies that depend on their sizes—a quantum effect. By collecting and analyzing the emitted light, the researchers generate an image that locates the devices precisely. Graduate student Michael Hoenk has built a fiber-optic light-collection system that fits inside the electron microscope's sample chamber. As the microscope sweeps its beam across the crystal, the optical fiber hunts for patches of dots and wires. The team is currently using this system to study structures between 0.05 and 0.1 microns in size.

The next step is to combine the optical fiber with an electrical probe. The probe uses an 0.2-micron-diameter needle from a scanning tunneling electron microscope as the world's tiniest jumper cable. The needle pumps electricity to the dot, and the same fiber that found the dot collects any light it emits when zapped.

Graduate student Peter Sercel and Research Fellow John Lebens have built a triangular walker to guide the needle to the dot. Each side of the triangle is a piezoelectric rod that contracts in a very precise way in response to electricity. Each apex of the triangle has an electrostatic foot. Switching on two of the feet anchors them to a silicon plate. The free foot is moved left or right by applying current to the appropriate rod. Then that foot is switched on and another foot freed to move the walker in any direction.

The walker has not jump-started any dots yet, but Vahala expects to begin very shortly. "In a sense, these dots are large man-made atoms," Vahala says. "This system will allow us to probe the electrical and optical properties of these 'atoms' with an eye toward their potential application in new devices."□—*DS*