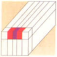
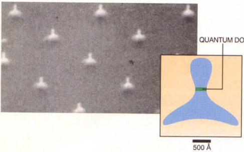
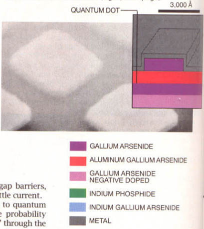


ZERO DIMENSION: QUANTUM DOT

AT&T investigators are building dots in an in situ vacuum process (*left, this page*). Lithographically defined dots built at IBM may be used as capacitors. In these devices, electrons are confined at the interface between the layers of aluminum gallium arsenide and gallium arsenide (*right, this page*). Texas Instruments' array of dots (*left, next page*) may be used as transistors. Chemists fabricate dots by capturing clusters of atoms (such as cadmium, in orange, and sulfur, in yellow) in zeolite cages as shown in this computer simulation by Galen D. Stucky at the University of California at Santa Barbara (*right, next page*).





dall, a researcher at Texas Instruments in Dallas, spends most of his time carving through layers of quantum wells. A principal difference: Randall wants to make transistors.

So far integrated-circuit makers have thrived by forcing chip designs ever smaller and by building ever tinier transistors, or switches. But when circuit dimensions approach the size of an electron wavelength, electrons begin leaking through the device, preventing transistors from truly switching off. "We anticipate the first real problems in the latter part of the decade," when chip makers try to push circuit designs tighter than .25 micron, or 2,500 angstroms, says Robert T. Bate, who is Randall's boss and manager of TI's quantum work.

Randall and his colleagues hope to skirt that pitfall by exploiting quantum effects to build transistors far smaller than the troublesome 2,500 angstroms [see "The Quantum-Effect Device: Tomorrow's Transistor?" by Robert T. Bate; SCIENTIFIC AMERICAN, March, 1988]. To do so, they are developing sophisticated descendants of the early resonant tunneling diodes. One notable success: the BiQuaRTT, or bipolar quantum resonant tunneling transistor.

All varieties of resonant tunneling diodes and transistors play by the same basic rules, explains Reed, one of the key BiQuaRTT designers, who recently left TI for Yale University. Start with a thin quantum well layer sandwiched between two equally thin but higher band-gap layers. Apply a voltage. At many voltages, electrons are prevented from flowing through the layers of the device by the high band-gap barriers, and the device conducts little current.

Nevertheless, according to quantum mechanics, there is some probability that electrons can "tunnel" through the barriers. The odds of tunneling can be improved by applying just the right voltage to the device. At these specific voltages, the energy of the incoming electrons matches the energy levels of the quantum well. Electrons then tunnel through the barriers, and current flows. "It's like playing a flute," Reed says. "You only get out those notes that you want."

Of course, one transistor does not an integrated circuit make. (Some integrated circuits have far more than a million transistors.) Researchers at Fujitsu have connected as many as five or six resonant tunneling transistors in series with high-speed switches. Several U.S. government agencies are funding a few research teams to develop more complex circuits and devices.

Texas Instruments is among them; sometime within the next 30 months, workers there hope the BiQuaRTT will prove able to handle complex logic and so become the stuff of circuits that are orders of magnitude smaller than today's devices. In addition, "we want to take advantage of the strange characteristics of these devices," Randall explains. Because tunneling readily occurs at two different voltages, "we've got a device that goes 'off-on, off-on'" at two different voltages, he says. Now he hopes to show that such a switch can replace a few conventional transistors and that multiple BiQuaRTTs will work together.

If two dimensions are promising, then one or zero dimensions look even better. Electrons scatter less when traveling through quantum wires, attaining higher mobilities—and so make for faster switches. Quantum wire lasers could be powered by far less current and thus radiate less heat than their two-dimensional cousins.

Wiry Semiconductors

So much for theory. To make quantum wires, workers must wall up four sides of a low band-gap material with higher band-gap barriers thin enough to let electrons tunnel through on command—about an electron wavelength thick. Exercising the precise control needed to make such vertical walls is tricky; it has pushed some researchers to restudy how layered semiconductors are created in the first place.

At the four-year-old Optoelectronics Technology Research Laboratory, located about an hour northeast of Tokyo in Tsukuba Science City, Toshiro Isu is watching his scratchy, black-and-white videotape once again. Since January, Isu, a researcher at the laboratory, has recorded moving pictures of layers of gallium and arsenic growing inside an MBE vacuum chamber. In the images, clumps of millions of gallium atoms form in several seconds, then seem to melt into the existing arsenic layers.