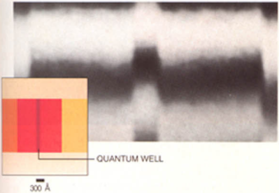
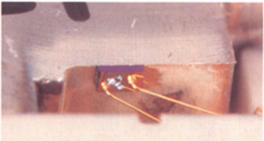
TWO DIMENSIONS: QUANTUM WELL

Incorporating a single quantum well (*left*) into this laser diode (*right*), built at Spectra Diode Laboratories, improves the efficiency of the laser. The outer doped layers inject electrons (negative charges) and holes (positive charges) into the quantum well, which then recombine and emit photons, or light. Because the quantum well contains less aluminum than the surrounding layers, it is a lower band-gap material.





ergy electrons between two slices of materials with higher-energy electrons.

The energy of electrons is described by band theory. The valence, or outermost, electrons of every atom fall into specific energy bands. Metal atoms have only a few valence electrons at low energy. Because they readily swap these electrons with one another, metals make good conductors.

Semiconductors and insulators, on the other hand, have more valence electrons and are not inclined to conduct current. Adding a small amount of energy to a semiconductor boosts some valence electrons to a higher-energy level, the so-called conduction band, and enables the material to carry current. The energy needed to propel an electron from one band to another is the band-gap energy—the difference between the valence and conduction band energy levels. Because every semiconductor demands a slightly different amount of added energy to trigger conduction, some semiconductors have higher or lower band-gap energies than others. Insulators, which require tremendous energy to push their valence electrons to the higher-energy bands, have the largest band gaps.

With these ideas in mind, researchers at both IBM and AT&T tried proving they could confine electrons. Esaki, Tsu and Chang began by alternating multiple layers of gallium arsenide with layers of aluminum gallium arsenide, a higher band-gap compound. AT&T workers had a simpler aim: to sandwich one thin, low band-gap material between two higher band-gap materials, thus producing a quantum well.

The efforts of both groups were plagued by swarms of fabrication problems. For one, how do you lay down an even layer of material only a few atoms deep? "We had to build a vacuum system ourselves" to deposit thin layers, Chang recalls sighing. Equally troublesome was controlling substrate contamination and the alignment of the crystal lattices of the materials.

In 1974, however, the researchers triumphed. The IBM workers demonstrated materials that had the predicted, steplike energy levels indicative of quantum confinement. Raymond Dingle and his colleagues at Bell Laboratories in Murray Hill, N.J., built a single quantum well, shone laser light on it and found that the novel material absorbed different, but predicted, frequencies of light—an alternative indication of quantum confinement. Soon thereafter, Esaki and Chang built the first real quantum well device—a resonant tunneling diode.

Ballistic Transistors

Many others jumped on a dimensionally related bandwagon: two-dimensional electron gases (2DEGs), in which electrons are trapped at the horizontal interface between a low band-gap layer of material and a layer that is doped with extra charges. With these materials, researchers explored complex phenomena, namely, the quantized and fractional Hall effects [see "The Quantized Hall Effect," SCIENTIFIC AMERICAN, April, 1986]. In carefully constructed 2DEGs, electrons can travel for relatively long distances before colliding with an atom or a defect, thus enabling engineers to build "ballistic" or "high electron mobility" transistors.

Such 2DEGs are the bedrock for the fastest transistors. (They only achieve the highest speeds at temperatures of a few kelvins.) Unlike quantum wells, in which electrons push through several, vertically arranged layers, electrons in 2DEGs must stay within the horizontal plane. That construction restricts the kinds of devices that can be built.

Researchers returned to quantum wells and superlattices, which are specially constructed multiple quantum wells, in the early 1980s, this time armed with highly precise fabrication tools. Among the biggest guns: molecular-beam epitaxy (MBE) machines.

At the heart of a state-of-the-art MBE is an ultrahigh vacuum chamber, which allows workers to deposit layers of atoms as thin as two angstroms on a semiconductor substrate. Attached to the vacuum chamber, like spokes on a hub, are three or four passages that lead to effusion cells. Elements such as gallium or aluminum are vaporized in these cells, then shot down the passages toward the substrate. By programming the shutters between the passages and the vacuum chamber, scientists can dictate the thickness of the deposited layers. All told, a full day must be spent to grow about eight microns of semiconductor layers on a single gallium arsenide wafer.

Compared with the next step, how-