2000 A/cm^2 entered the target chamber. The normal fluorescent linewidth is about 160 Å. When the device lased, the line narrowed to about 18 Å and the intensity of emission increased by three orders of magnitude, Kolb told us. The line narrowing was accompanied by mode-pattern damage to the mirrors and is further evidence of laser action, he said. In more recent results using hole-coupled mirrors, over 10 MW of output power has been observed from a 10-cm^3 sample of the electron-beam excited xenon. —GBL

IBM tries for a semiconductor superlattice

Leo Esaki, Raphael Tsu, Leroy Chang and their collaborators at IBM Research Center are trying to build a manmade superlattice, which consists of alternating layers of monocrystalline semiconductors; the arrangement results in a one-dimensional periodic potential function for the conduction electrons with a period much greater than the natural period. With such a superlattice, Esaki says, it should be possible to build amplifiers and oscillators that operate at 1 terahertz, a much higher frequency than presently available.

Esaki, who is known for inventing (in 1958) the tunnel diode that bears his name and is a negative-resistance high-speed device, chatted with us in his lab at IBM, where an elaborate computer-controlled array is being used to fabricate superlattices. He explained that unlike the ordinary periodic potential in a crystal whose period is 2–3 Å, his group is building layered structures with periods of 50–100 Å. There are naturally occurring superlattices too, such as copper-gold alloys and silicon carbide.

By varying the alloy composition or impurity density during epitaxial growth, one can vary arbitrarily the amplitude and periodicity of the superlattice potential over a range of values. If the superlattice period is shorter than the electron mean free path, Esaki and Tsu have argued,[1] one could expect to observe strong energy dispersion effects in the structure. These effects would allow one to observe quantum-mechanical properties in a new domain of physical scale, they say, because of very narrow allowed and forbidden energy bands associated with a series of minizones in the Brillouin zone, not seen in the host crystal. The electrons behave very much like light in a Fabry-Perot interferometer, bouncing back and forth between the plates and producing interference. In the case of electrons, they go to the mini-Brillouin zone and cause interference. If the electron mean free path is less than the period, one does not have the minizones.

If one measures the *I–V* characteristic of such a superlattice structure, one observes negative differential conductivity, that is, in some region, increasing the voltage causes the current to drop. Tsu explained that when the electron is accelerated to the Brillouin zone, it returns as a hole and then oscillates back and forth in configuration space and momentum space. Such a so-called "Bloch oscillator" was discussed by Brian Pippard many years ago; in ordinary metals, Tsu said, the mean free path would be impracticably long.

The IBM experimenters are trying to make a Bloch oscillator and an amplifier. Devices made from superlattices, they believe, would have virtually no frequency limitation except when the energy quantum for the frequency involved is a significant fraction of the width of the narrow energy band. Because the potentials they envision are small compared with band-gap energies of the host semiconductors, and because the properties depend on a sustained periodic variation, they say one should view the structure as a perturbed bulk crystal rather than as a series of junctions. Junction devices are slowed down because of their inherent capacitance, Tsu points out. For computers and other sophisticated devices, in which high speed is important, a bulk device is more desirable than a junction device. One can think of using the superlattice in flip-flop circuits or other bistable devices, he went on, and can even consider such far-out ideas as a wristwatch radar.

In a recent paper, Tsu and Esaki have computed[2] the transport properties of a finite superlattice from the tunneling point of view. In an ordinary multitunneling calculation, the electron tunnels through, loses its coherency and tunnels through again. For the superlattice, on the other hand, each time the electron tunnels, the phase relationship is maintained. The technique resembles the ray-tracing approach, in which one starts with a photon; each time it goes through a layer, there is a change in index of refraction, some part going forward and some part going back; then one sums up everything. Similarly, for the electrons, Tsu and Esaki keep track of the phase and amplitude of the electron each time it goes through a barrier. They calculate the transmission coefficient, use statistics and then integrate over the whole Fermi surface to find the total current. The calculations are in agreement with the IBM observations of negative-resistance behavior. So far they are only able to make samples with about five periods that are coherent.

Esaki enthusiastically explained that the superlattice is in two different ways an ultimate device. First, it operates as a 1-THz (10^{12} Hz) source (0.3 mm), a frequency very difficult to obtain by any other method. Second, the technology of making such a structure requires very precise control of crystals.

The technique used is molecular-beam epitaxial vapor deposition. The group has made[3] superlattice structures that typically have 100 periods with each period consisting of a gallium-arsenide layer about 60 Å thick and a $Ga_{0.5}Al_{0.5}As$ layer about 20 Å thick. They then measured the transport properties. Part of the output from the molecular-beam sources is channeled into a mass spectrum analyzer, which ionizes the beam and then counts the ions; this count allows one to determine the density of the beams. By knowing the arrival rate the computer then calculates how many molecules are deposited. The computer monitors the gallium, aluminum, arsenic and any dopants, such as phosphorus. The computer acts as a master clock, opening and closing the proper shutters and controlling the temperature of the ovens. To make a 100-layer sample takes about 10 hours. The apparatus operates initially at 10^{-10} torr.

Chang told us they are trying to improve the materials to make the mean free path longer and to find a process to make the layering more reproducible. The lifetime of the electrons is limited by the mobility, which is decreased by scattering from defects, crystal distortions, strains and inhomogeneities. In principle, Esaki says, one can make the superlattice periodicity with 1 or 2% accuracy. Although most crystal growth is still black magic, Esaki remarks, the IBM group is trying to eliminate as much of the witchcraft as possible. Although many device physicists do not believe that superlattice devices can be made, Tsu counters that you should only believe in an experimenter when he says something *can* be made, not when he says it is impossible to make. —GBL

References

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