to intervene, if possible, and prevent the disease's progression. Enter the next controversial procedure—cryotherapy. The idea is that since the developing blood vessels are growing wildly toward the edge of the retina, perhaps their growth might cease if the edge of the retina were destroyed by cold. It is an idea born of desperation. "We would only try it in those with active disease that is getting worse and for whom we forsee disaster. Except for cryotherapy, the only thing to do is to hunker down and wait until the retina detaches," says Avery. Yet cryotherapy also has its risks. It can result in hemorrhage, optic atrophy, or the inadvertent freezing of the optic nerve or the macula, which is essential for clear vision.

But this time, an answer to whether cryotherapy works is forthcoming. The National Eye Institute is beginning a multicenter randomized controlled clinical trial of the treatment. It will involve about 300 babies at 24 centers. As a side benefit, it should result in some incidence data for ROP.

Once a baby's retina has detached, the only treatment left is to try and attach it again. But this is a difficult and controversial surgery—"*the* most difficult retinal attachment in ophthalmology," says Gary Abrams of the Medical College of Wisconsin in Milwaukee.

Surgeons disagree on when to do the surgery and, even in the best of hands, the success rate is none too high. If the surgery is done early, the ROP might progress anyway and undo the surgeon's work. If it is done later, when the proliferative process in the child's retina has ceased, it may be too late for success. "We have not settled the question of timing," says Steve Charles of the University of Tennessee. "ROP is an active proliferative process. With early surgery, you're damned if you do and damned if you don't." Even if a surgeon does manage to attach a child's retina, there is no guarantee the child will see. In many cases, there is other damage to the eye. "What we need is a very careful evaluation of pre- and postoperative functioning of the eye," says Flynn. "The most pressing question is, Are these babies benefiting from the surgery? Nobody has the answer."

Yet perhaps the recent meeting was a start. Everyone acknowledged the gaps in the data and the need to be more systematic and scientific in gathering evidence in the future. The national cryotherapy study is a step in the right direction. Solutions to the problem of preventing and treating ROP most likely will not be immediately forthcoming, but at least there should be some information on the incidence of the disease and on whether current experimental treatments are worth continuing at all. ■

GINA KOLATA

Ballistic Electron Transport Seen in GaAs

Ballistic electrons are not slowed by collisions; but an ultrahigh-speed transistor using them is conjectural

THE first published evidence for the proposition that electrons can travel through a semiconductor without being slowed by collisions—that is, ballistically—is now in. Last November, two groups of researchers, one a joint AT&T Bell Laboratories/Bell Communications Research collaboration and the other from IBM's Yorktown Heights Laboratory, reported experimental data showing a ballistic peak in the electron energy spectra of gallium arsenide test devices.

With competitive groups shooting for the same goal, it is not surprising that each would strongly press its claim. Moreover, a year ago, Japanese researchers from Fujitsu Limited in Atsugi, Japan, had also reported energy spectra showing a peak for fast-moving electrons in gallium arsenide, but at the time they could not attribute it to ballistic transport. The Bell Labs/Bellcore collaboration has the distinction of presenting the first spectroscopic evidence for ballistic transport, beginning with a presentation of its findings at a physics meeting last March. However, for reasons related to the somewhat different device structures adopted by the American groups, physicists contacted by *Science* tended to credit IBM's with being the more conclusive experiment.

In theory, the faster the electrons zip through a transistor, the faster the device can switch on and off. Accordingly, overblown accounts of ballistic electrons traveling at nearly the speed of light and providing the makings for transistors that can switch trillions of times per second have appeared in the popular press. Actually, however, no one has shown how to take advantage of ballistic transport in a practical transistor.

As they stand, the test devices are just that. IBM's, for example, exhibits ballistic behavior only when cooled to 140 K or below, and a key transistor parameter, the gain, is still small. Moreover, the results of static spectroscopic measurements do not translate directly into such dynamic properties as switching time, so how fast a ballistic transistor might be is a matter of conjecture. "We were trying to prove ballistic transport is possible, not make a transistor. There is no final device concept yet," says Mordehai Heiblum, speaking for the IBM group, which also includes Marshall Nathan, David Thomas, and Christina Knoedler.

Nonetheless, the estimated electron velocity achieved, about 10^8 centimeters per second (cm/sec), is about five times faster than the maximum in gallium arsenide under ordinary conditions and ten times faster than in silicon, which provides considerable incentive to search for transistor designs that can exploit such speeds. Moreover, the increased understanding of the physics of ballistic electron transport that the test devices provide could yield clues as to how to proceed. "With this knowledge, we would know how to make a real ballistic device," says John Hayes of Bellcore who collaborated with Anthony Levi, Philip Platzman, and William Wiegmann of Bell Labs.

Finally, ballistic transport is of substantial interest apart from any electronic device applications to solid state physicists, who want to understand the behavior of nonequilibrium or hot electrons. Even the existence of ballistic behavior has been questioned. "Until the [IBM and Bell] reports, the only conclusion reachable was that there is no ballistic transport," comments David Ferry of Arizona State University, who has specialized in the properties of electrons under highly nonequilibrium conditions.

If electron transport were ballistic, electrons would accelerate without interruption to the velocity compatible with a kinetic energy gain of eV, when a voltage V is applied. Ordinarily, collisions prevent ballistic behavior. Elastic collisions scatter the electrons in all directions in a characteristic pattern, in effect randomizing the electron velocity. Inelastic collisions do the same but also cause a loss of energy. The net effect of it all is that the electrons assume a thermal equilibrium or Maxwellian distribution of velocities whose average with no applied voltage is zero.

When a voltage is applied, the electrons begin to pick up speed, but the various collision processes quickly intervene to slow the acceleration until a steady state is reached wherein the rate at which the electrons gain energy from the applied voltage equals the rate at which it is lost by way of collisions. In the end, the Maxwellian velocity distribution simply shifts en masse to one with an average velocity that remains well below the ballistic value. It is thought that the dominant processes for slowing fast-moving electrons in gallium arsenide arise from the interaction of these electrons with lattice vibrations and with slower moving electrons.

In 1979, Michael Shur of the University of Minnesota and Lester Eastman of Cornell University proposed that ballistic transport might be possible despite the ever present collisions. Collisions occur in a statistical way that is characterized by a scattering time. Each kind of collision has its own scattering time, which depends on the electron energy and the temperature. During time intervals much shorter than the scattering time, an electron suffers few if any collisions. Alternatively, an electron suffers few or no collisions while traveling a distance less than the mean free path, given by the product of the average velocity and the scattering time.

Shur and Eastman noted that modern microfabrication technology made it possible to construct a transistor whose active region (the channel or gate length in a field effect transistor, for example) was shorter than their estimated value of the mean free path in gallium arsenide. Hence, they concluded, with a very short channel, it should be possible to generate very high velocity ballistic electrons without a large applied voltage and thereby make a very rapidly switching field effect transistor that does not consume a lot of power.

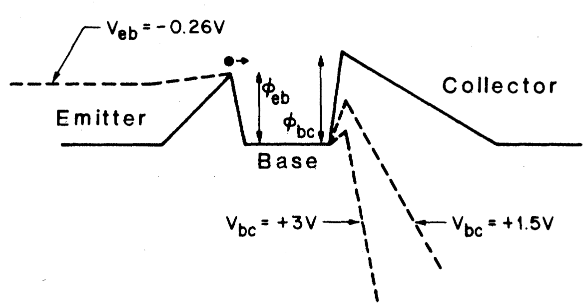
The proposal was controversial and clouded by loose use of such terms as ballistic. For example, most physicists appreciated quite quickly that pure ballistic transport was impossible, even in principle, in semiconductors. Part of the idea is that, since scattering is statistical, there is no time interval so short as to rule out any collision whatsoever. An alternative view is that the statistical nature of collisions means that, from a large number of electrons, at least a few will suffer collisions in any time interval. According to the purists, for short time intervals during which electrons suffer few or no collisions the transport is quasi- or near-ballistic. Although usage of ballistic continues, physicists now generally understand it to mean quasi-ballistic.

To get ballistic transport of high-velocity electrons, it is necessary to inject energetic electrons into the semiconductor from an external source. In this way, the electrons enter at high velocity and travel ballistically until collisions slow them down in the usual way. The IBM and Bell Labs ballistic devices work this way and fall under the heading of hot electron transistors because the electrons are injected into their active regions at energies well above the thermal equilibrium value of those already present. Moreover, only hot electrons that retain a substantial fraction of their excess energy even after many collisions contribute to the transistor action.

Hot electron devices date back to at least 1960 but never lived up to the hoped-for high-speed performance. In 1979, John Shannon of Phillips Research Laboratories in Redhill, United Kingdom, devised what he called the camel transistor, a silicon structure designed to overcome some of the deficiencies of earlier hot electron devices, which were made of dissimilar materials. Later, Roger Malik of the Army Electronics Technology and Device Laboratory, Fort Monmouth, New Jersey, Eastman at Cornell, and several collaborators reported a similar structure in gallium arsenide, which they named the planar-doped barrier transistor.

In either case, the transistor comprises three sections dubbed the emitter, the base, and the collector that are separated by two energy barriers whose heights have an approximately triangular profile. The energy barriers prevent the flow of thermal equilibrium electrons between the emitter and the base and between the base and the collector. When a negative voltage is applied to the emitter relative to the base (which is usually grounded), the energy of the emitter electrons increases, lowering the barrier for electron flow from the emitter to the base. When the barrier is low enough, electrons are thermally excited (thermionic emission) into the base.

If the barrier is very thin, the injected electrons suddenly find themselves with a large excess energy relative to the electrons already in the base (that is, they are hot), and they rush across the base toward the collector. Whether the hot electrons reach the collector depends on how much energy they lose by way of collisions and on how high the barrier between the base and collector is; that is, they must retain enough energy to surmount this barrier. One measure of the transistor gain is the fraction of the injected electrons that reach the collector.



Electron spectrometer

The solid line shows the equilibrium electron energy (conduction band edge) in the different parts of the planar-doped barrier transistor, while the dotted lines indicate the energy shift with applied voltage. [*From* Phys. Rev. Lett. *54*, *1570* (*1984*)]

Triangular barriers are produced by changing the concentration of impurities (dopants) that are the source of the electrons in silicon and gallium arsenide, which in their pure state have very few at room temperature. Those who have mastered the art of molecular beam epitaxy can control the composition of a growing epitaxial film almost atomic layer by layer, so in principle this growth technique allows the tailoring of barriers of any shape and size when fabricating vertically oriented transistors.

Having made a device, how does one look for ballistic transport? It turns out that the usual measures of transistor behavior, such as current-voltage curves, are not sufficiently sensitive to the presence or absence of ballistic electrons to provide conclusive evidence. Last year, Hayes of Bellcore and Levi and Wiegmann at Bell Labs adopted a different approach called hot electron spectroscopy. Spectroscopy of hot electrons is not a new idea, but the investigators were the first to apply it successfully to gallium arsenide planar-doped barrier transistors.

Consider what happens when the height of the base-collector barrier is varied by means of the collector-base voltage while holding the emitter-base voltage fixed. As the barrier is lowered, by applying a positive voltage to the collector relative to the base, it will let more and more hot electrons into the collector. It is not the smooth variation of the collector current with barrier height but the derivative of this curve that gives the spectroscopic information. The Bell researchers showed that, at a particular barrier height, the derivative is proportional to the number of electrons whose kinetic energy in the direction perpendicular to the barrier is just sufficient for them to surmount it. In this way, it is possible to map out the number of hot electrons per unit energy reaching the barrier; that is, an energy spectrum or distribution.

The signature for ballistic electrons would be a spectral peak having the same narrow distribution and the same high average energy as the injected electrons had. In their initial experiments, which were done at liquid helium temperature (4.2 K), the Bell researchers measured hot electron energy spectra for two planar-doped barrier transistors with base lengths of 1700 and 1200 angstroms. They found distinctly hot electrons, with a narrower and higher energy peak in the device with the shorter base, but no ballistic electrons.

Newer results were reported last spring at the March Meeting of the American Physical Society in Baltimore and just recently published. In these experiments, the investigators noted the onset of a second higher energy peak as the base length decreased below 850 angstroms. With a 650-angstrom-long base and an injection energy of 0.25 electron volt, the peak became quite distinct. Although a figure was not published, according to Hayes, the peak was quite narrow, about 0.07 electron volt. In addition, the researchers calculated the electron mean free path expected under the experimental conditions to be about 400 angstroms.

From these findings, the Bell group concluded that the higher energy peak was due to quasi-ballistic electrons suffering few, if any, collisions. The lower energy peak was attributed not to injected electrons that had lost energy by way of collisions, but to electrons in the base region to start with that had gained energy as a result of collisions with the energetic injected electrons.

Hearing of these results, Tahuy Wang and Karl Hess of the University of Illinois, together with Gerald Iafrate of the Army electronics laboratory have made computer (Monte Carlo) simulations of the behavior of the planar-doped barrier transistor. The simulations of a device with a base length of 600 angstroms and an injection energy of 0.26 electron volt dramatically show ballistic behavior with a narrow peak at the injection energy in the electron distribution at the barrier between the base and the collector.

However, the width of the peak in the simulations was much narrower than the experimentally measured one. Both the Bell experimenters and the Illinois theorists postulated that fluctuations in the barrier height due to the random positions of the dopants in the gallium arsenide could be the cause of the broadening. For example, there are about 10^{18} dopant atoms per cubic centimeter in the base (100 parts per million). While this is a typical concentration for semiconductors, because of the short length of the base, the number of atoms is small. Statistically, fluctuations are larger for small numbers of "events" (in this case, the positions of the atoms) than for large. Hess told *Science* that the estimated barrier height fluctuation under these conditions was 0.1 electron volt, comparable to the observed width of the electron distribution.


Source: IBM

IBM hot electron transistor

Electrons travel vertically downward. The dark finger projecting from the right is the emitter and emitter-base tunneling barrier. The large dark area is the base. The collector is out of sight below. Light areas are metal electrodes.

Tunneling barriers provide an alternative to triangular barriers and provide some advantages, including reduced barrier height fluctuations. In a lengthy 1981 review of hot electron devices, for example, IBM's Heiblum discussed a gallium arsenide hot electron transistor whose barriers were made of the related semiconductor aluminum gallium arsenide. The barrier between the emitter and the base was to be thin enough that electrons could quantum mechanically tunnel through when a negative voltage was applied to the emitter. The barrier between the collector and base was to be thick, so that no tunneling occurred, and it operated similarly to the triangular barrier.

The first group to report on a hot electron transistor of this type comprised Naoki Yokoyama, Kenichi Imamura, Toshio Ohshima, Hidetoshi Nishi, Shunichi Muto, Kazuhiro Kondo, and Satoshi Hiyamizu of Fujitsu. In transistors with a base length of 1000 angstroms, the Japanese investigators found well-defined hot electron peaks for a range of injection energies. In each case, the spectroscopic peak was about 0.2 electron volt below the injection energy. From Monte Carlo simulations, the group concluded that the energy loss probably occurred during the tunneling process itself, implying the transport across the 1000-angstrom-thick base was ballistic. Direct evidence for this conclusion is still lacking, however.

Now the IBM group has reported results on devices with base lengths of 1100 angstroms and 300 angstroms. The barrier between the emitter and base was only 120 angstroms thick, while the base-collector barrier was almost 1100 angstroms thick. With the longer base, the researchers found hot electron peaks, but the energy of the peaks and the broad energy distributions were independent of the injection energy, indicating the behavior was not ballistic. With the thinner base, they found narrow peaks of width 0.06 electron volt at the injected energies, which ranged from 0.28 to 0.33 electron volt, in measurements at 4.2 K. The calculated width of the injected electron distribution was 0.04 to 0.06 electron volt. Similar behavior was seen at temperatures up to 140 K. At higher temperature, thermal excitation of electrons over the barriers overwhelms the ballistic behavior.

A puzzling aspect of the IBM results is that only about one-half of the injected electrons made it to the base. No explanation for this behavior is in hand. Whatever the cause, the IBM's ballistic electron energy spectra are in better agreement with the Monte Carlo simulations of Wang, Hess, and Iafrate than are those of the Bell collaboration. The theorists attributed this to the absence of barrier height fluctuations.

As for taking advantage of ballistic transport in practical devices, everyone agrees that is some time off. The important thing is that the phenomenon has been demonstrated. "We have been searching for six years for experiments than can show over what time scale we can avoid collisions," says Harold Grubin of Scientific Research Associates in Glastonbury, Connecticut, who has long insisted on a careful definition of what ballistic transport means. "So, it is a very important step to show that we can be in the nearly collisionless regime." ■

Arthur L. Robinson

ADDITIONAL READING

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