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Solid State Physics as a Source of Modern Electronics

Solid state physics leads to device effects from which electronic technology provides new tools for science.

Rolf Landauer and John J. Hall

In discussing the useful technology that has come out of solid state physics, we must first recognize that both the source field and the range of applications are broad and cannot easily be delineated. As far as the origin of useful ideas is concerned, there are no strictly valid boundaries between solid state physics on the one hand and physical chemistry, electrochemistry, physical metallurgy, and quantum electronics on the other. We are dealing with a continuous spectrum of activities concerned with the behavior of matter in condensed aggregates. The range of applications is also broad: photography and other image-formation techniques, the development of adhesives, the generation and storage of electrical power, even the manufacture of costume jewelry. Of the older applications, the development of new structural materials has offered the greatest source of ideas for the physicist. In this field we have seen many advances; for example, we now understand a great deal about stress corrosion mechanisms (*1*); we know how to imbed thin fibers of nonplastic materials into a plastic matrix to obtain strength comparable to that in ideal substances (*2*); we have learned how to use single crystals to prevent the fracture of turbine blades (*3*). These are only a few of the many examples of fundamental progress in the field of structural materials.

However, it is difficult in the older fields to separate the impact of today's physics from the natural ultrarefinement of yesterday's technology. Consider, for example, the central concept in the field of structural materials: the dislocation. The dislocation is a defect in the crystalline pattern of atomic arrangements; it explains how plastic deformation can occur in real crystals under forces much smaller than the smallest which would be expected to produce deformation in ideal crystals. The notion of dislocation requires only that a crystalline arrangement of atoms is normally present; beyond that, dislocation theory relies upon classical elasticity theory, with little need for the more recent advances of solid state physics. Indeed, the word *dislocation* has simply enabled us to replace the older notions of the metal physicists about "locked-in microstress" with a more detailed, suggestive, and precise concept. This is in no sense an adverse reflection on the importance of the idea of dislocations; the point is made here to emphasize the fact that crisp illustrations of the relevance of fundamental physics to technology can be drawn only from new fields of application. We therefore concentrate, in this discussion, on the impact of solid state physics on the largest of the new fields: electronics. And even here we select a main track and ignore many important developments—for example, light-emitting semiconductor diodes and nonreciprocal ferrite devices.

Through technology we learn to transcend the limitations of our biological endowment. The early development of tools represented man's ability to handle matter more effectively than the strength of his skin and the shape of his fingers permitted when he used only his bare hands. The use of fire, the wheel, the use of ladders—all are links in a chain which, in the 19th century, brought us into a period in which we became independent of human and animal sources of energy. Now, in the 20th century, we are learning how to handle information in ways which far transcend our ability to shout down the hallway or figure sums with pencil and paper. Our accelerating capabilities in handling information can, however, be expected to go far beyond automated bookkeeping and long-distance telephony. For example, we have started to use the computer in the schools, not only as a means of relieving the immense administrative burden but as an instructional tool which promises eventual tailoring of courses to the individual student's speed of response. Today we spend much of our energy constructing highways and airports, classrooms and office buildings, when our real aim is to transmit, exchange, and control information. We will eventually learn to eliminate the unnecessary overhead and to deal with the information. We thus foresee

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a partial solution to many of our most pressing problems: shortages of classrooms and offices, traffic congestion, even air pollution.

While the information-handling revolution has its sources in the 19th century, with Morse, Bell, and Babbage, it is the past 20 years that have seen its tremendous acceleration, with the development of modern solid state electronics. By *electronics* we mean the handling of complicated electrical wave forms for communicating information (that is, passing it from one place to another); for probing, as with a radar signal or in a paramagnetic resonance experiment; or for causing one complex stream of information to interact with another, as in the case of data processing. We have chosen solids as the vehicle for electronics because of their permanent structure and their potential for handling large quantities of information at high speeds in relatively small volumes. Of course, modern solid state technology is far from approaching the packaging density achieved in biological systems, but the disadvantage of lower packaging density is in part offset by the much greater speeds of solid state devices. Whereas biological devices work at a low kilohertz rate, the speed of solid state circuits has been increased by almost two orders of magnitude in the past decade, so that, in modern computers, logical operations are performed at a rate approaching 1 gigahertz. And this great increase in speed has, of necessity, been accomplished through a reduction in component size; such reduction, if it is continued, may yet bring us within the size range of biological systems. Figure 1 shows an example of modern integrated circuitry: two chips, each containing 55 circuits and more than 200 transistors in an area less than 0.03 square centimeter. This is not a device representing the extreme limit of our skills, but an example of what many laboratories are producing today.

Electrons in Solids

The phenomena in solids that have proved most generally useful in information handling are those capable of high speed: speed to manipulate large volumes of information in short times; speed to make increased bandwidth available for transmission of information. Since we cannot move the atoms in a solid very fast, we must work with the electrons, or with excitations such as sound waves or spin waves. However, we do not want merely to pass information from place to place, we want streams of information to interact with other streams. This requires nonlinear behavior, which, in spin-wave or sound-wave phenomena, tends to occur at relatively high energies—a tendency which limits the usefulness of such phenomena. It is much easier to cause one charge, through its Coulomb field, to interact with and control other charges; thus, much of our remaining discussion deals with the flow of electrons in solids.

The electron has several degrees of freedom, all of which the solid state physicist—and, on his heels, the technologist—has learned to use. First, the electron has a spin, which has given rise to the great body of science and advanced technology of magnetism. However, while acknowledging the central importance of ferrite devices, for example, in communications and data processing, we will not discuss magnetism further, even though it could easily have furnished alternative "case histories" for most of the discussion that follows.

The position of electrons in a solid plays a central role in all polarization phenomena, such as ferroelectricity—the spontaneous ordering of charge positions. Ferroelectricity currently has a great deal of research vitality; whereas a few decades ago only one or two classes of ferroelectric materials were recognized, today we realize that there is an almost infinite variety of such materials (*4*). They are of particular importance whenever a material of high dielectric constant is needed. The lead zirconate-titanate ceramic capacitor, smaller by an order of magnitude than its paper or mica counterpart, played a role in reducing the bulk of electronic packages. But ferroelectrics are of greatest current interest as electrooptic materials whose index of refraction is controlled by an electric field, and as nonlinear materials for obtaining parametric effects in the optical regime (*5*).

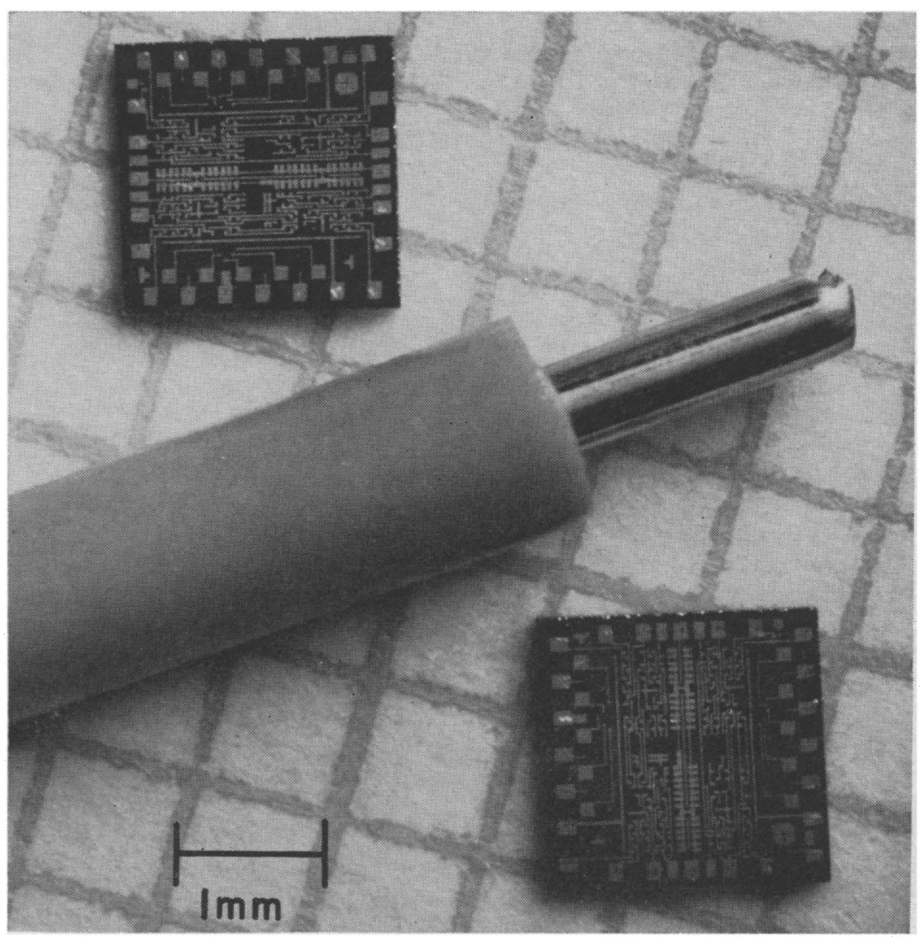


Fig. 1. Two modern integrated circuitry chips, compared with a length of 22-gauge insulated wire, a size commonly used for wiring computers today. Each chip is 1.8 millimeters on an edge, contains 55 circuits and 213 transistors, and functions as a complete four-bit adder-accumulator.

Superconducting Electrons

In some situations we may use more than one degree of freedom of the electron. The modern theory of superconductivity teaches us that both the spin and the velocity of the electron contribute to the ordering which gives rise to superconductivity. Superconductivity as a dissipationless transport mechanism is a remarkable phenomenon, and it is surprising that it has not found more widespread application. Perhaps this may be attributed to some conservatism on the part of the technologist in developing techniques permitting safe and convenient use of the low temperatures required for this effect. However, there are signs that this reluctance is being overcome: superconducting magnets of niobium-tin alloys, capable of producing a 100,000-oersted field, are now commonplace; systems for transmitting large amounts of direct-current power over long distances through superconducting transmission lines are now being seriously considered (*6*), as is the use of lossless microwave cavities in the construction of linear accelerators (*7*). We believe that we are only beginning to appreciate some of the intriguing possibilities offered by superconductivity, as demonstrated by the relatively recent discovery of Josephson tunneling.

Josephson tunneling is interesting both as an example of the conceptual surprises which still await us in solid state physics and as an indication of the speed with which some of these effects can be taken up by the technologists. It was first predicted by Brian Josephson at Cambridge in 1962 (*8*); within a year it had been observed experimentally (and unequivocally) by Anderson and Rowell at Bell Telephone Laboratories (*9*). The geometry involved is illustrated in Fig. 2, which shows schematically two superconductors separated by an insulating barrier approximately 15 angstroms thick and connected externally through an electrical circuit. The insulator is thin enough to allow superconducting electron pairs to tunnel through the barrier while maintaining their superconducting interaction; thus the junction exhibits ordinary superconductor behavior, and can maintain direct-current flow in the absence of an applied field. However, upon application of a direct-current voltage to the junction, an alternating current is produced whose frequency is proportional to the applied

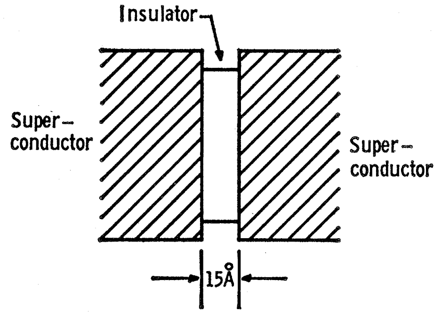


Fig. 2. Schematic diagram of a Josephson junction. The two superconductors need not be of the same metal.

voltage; the magnitude of this current does not depend upon the direct-current voltage but depends only on the characteristics of the junction. This highly nonlinear behavior seems somewhat surprising at first; however, let us consider a much simpler system which exhibits equivalent characteristics.

Consider a particle of charge q moving in a double potential well, as represented in Fig. 3A. This particle will have a symmetrical ground state, with a wave function ψ_s, and a first excited state with a very similar but antisymmetric was function ψ_a, as shown in Figs. 3B and 3C, respectively. The energy separation between the ground state and the first excited state is proportional to the strength of the coupling between the two wells, which we will

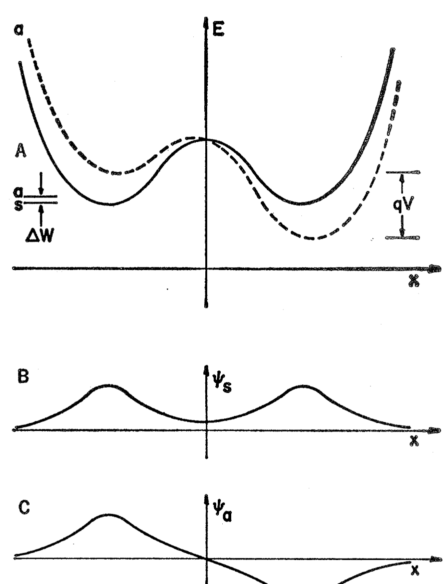


Fig. 3. (A) A double potential well (solid line), and the same well subjected to an electric field (dashed line). The energy separation ΔW is that between the symmetric ground state, *s*, and the antisymmetric first excited state, *a*. (B) The symmetric ground state wave function ψ_s. (C) The first excited state wave function ψ_a.

assume to be small; the energy separations between the ground state and higher-lying excited states are considerably larger.

Now let a direct-current voltage V be applied, between the wells, to the system in the ground state, as shown by the dashed line of Fig. 3A, and let the polarization energy qV be large compared to the energy difference, ΔW, between the ground state and the first excited state. Since the two wells are only very loosely coupled, we may follow the wave functions in each for some time without considering the coupling. The rate of phase change for each well is governed by the wave equation

$$\frac{h}{2\pi i}\ \frac{\partial\psi}{\partial t} = H\psi,$$

in which h is Planck's constant, i is $(-1)^{1/2}$, t is the time, and H is the energy function. The value of H will differ for the two wells, in view of the energy difference produced by the applied voltage. Thus a departure from the symmetric ground state, in which the wave function is in phase in the two wells, will develop. As the phase difference between the two wells grows, eventually the antisymmetric state is reached, in which the phase of the wave function in one well differs from the phase of that in the other by π. While both the symmetric and the antisymmetric states are currentless, the intermediate states are superpositions of the two, and make a nonvanishing contribution to the probability-current density.

Thus, as the phase difference between the two wells grows, a current develops which reaches a maximum when the phase difference reaches $\pi/2$; then the current decreases, becomes zero when the phase difference passes through π, then reverses sign and repeats this pattern. This is just the fundamental Josephson behavior: an oscillating current resulting from an applied direct-current voltage. The analog of the Josephson direct current is obtained when a field is applied temporarily and then turned off abruptly. This procedure establishes a fixed phase difference between the wells, and a steady current. Since in the model of Fig. 3 the particle is not replenished through external circuitry if it tunnels out of one well, we cannot, of course, maintain a steady direct current indefinitely.

The nonlinearity in our model results from the polarization energy's being larger than the energy separation

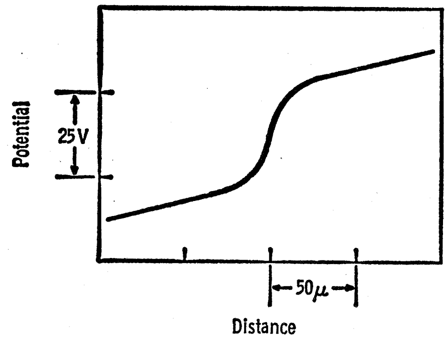


Fig. 4. The potential distribution in a piece of gallium arsenide subjected to a large field, at a given instant.

between the symmetric and antisymmetric states; because of this difference the time development of the wave function in each of the wells is more strongly affected by the field than by the tunneling process. For development of the oscillations, it is essential that the phase be unaffected by random external disturbances. If the phases can relax rapidly relative to the rate at which the phase difference between the wells develops, then of course the phenomenon disappears. On a macroscopic scale, this "phase memory" is provided by the mechanism of superconductivity, which enables us to observe the oscillatory current in a large-scale geometry, and over long periods.

Now, aside from their general conceptual appeal, the Josephson effects have potential technological applications. First, as we have seen, a Josephson junction is an oscillator, from which small but measurable amounts of power have been obtained in the range of wavelengths from several millimeters down to a fraction of a millimeter, a most refractory frequency range. However, it appears that, initially, the junction will be more useful as a sensitive detector of radiation in this wavelength region. In this inverse mode of operation, changes in the voltage drop across a junction carrying constant current are observed when the junction is exposed to radiation. Sensitivity to less than 10^{-12} watt of far-infrared radiation and a response time of better than 10 nanoseconds have been reported for these devices (*10*).

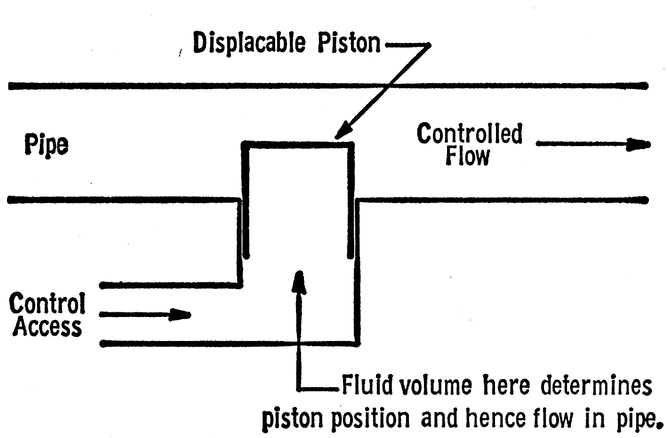
Furthermore, the Josephson junction acts like a superconducting device in its own right, and, as with other superconductors, the supercurrent may be quenched by application of a magnetic field, so the device may be used as a switch. Indeed, the Josephson tunnel junction turns out to be an extremely high-speed switch which can be actuated in much less than 1 nanosecond and is a promising candidate for applications in the areas of logic and memory (*11*).

Normal Electrons

It is the electron's velocity which, of all its degrees of freedom, has proved of most importance to modern electronics. Its velocity, rather than its spin or position, is the main basis for the high-speed operation of the transistor and other current-flow devices. In discussing these, we do not want just to celebrate the 20th birthday of the transistor; rather we want to point out that this is a family of devices, capable of a great deal of further evolution. Some of this development will result from the technologist's efforts, but much of it will have to come from solid state physics. Of course, the transistor is not the only current-flow solid state device. The Esaki diode—just 10 years old—not only is a useful device but was the first clear-cut example of solid state tunneling.

Another device, of still more recent vintage, is the Gunn oscillator. Most semiconductor devices are characterized by spatial inhomogeneity: different parts of the device have different compositions. The Gunn effect, however, occurs in spatially homogenous crystals. We are used to thinking of a uniform crystal, subjected to a uniform excitation, as responding in a homogenous manner. That this is not necessarily the case was discovered by J. B. Gunn in 1962 (*12*). While studying the behavior of hot electrons—that is, electrons subjected to very high electric fields—in gallium arsenide, he found that the pieces of gallium arsenide broke into oscillation when subjected to fields greater than some critical value. This most unusual behavior has subsequently been the subject of a great deal of study, concerned both with the macroscopic kinetics of the effect and with the particular features of the electron band structure in gallium arsenide which permit these kinetics.

The mode of operation of a Gunn oscillator is illustrated schematically in Fig. 4, which shows the instantaneous potential distribution, plotted against distance, in a piece of gallium arsenide subjected to a very high electric field—over 3000 volts per centimeter. Rather than support the field uniformly throughout its length, the gallium arsenide develops a negative differential resistance—an instability in the material now understood in terms of its particular band structure. The field tends to avoid those values at which the negative differential resistance occurs, assuming either higher or lower values; this leads to the nonuniform potential gradient shown in Fig. 4. A region of nonuniform field must be accompanied by an internal charge distribution; these charges, and the field distribution with them, move across the sample with approximately the velocity of the current-carriers. When they emerge from the sample, a new disturbance of the same kind is generated at the opposite end, and this in turn is swept through the



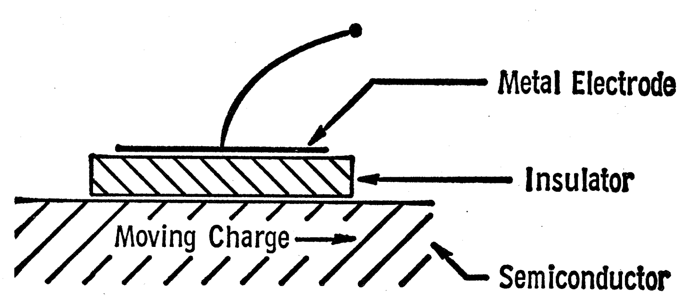


Fig. 5 (left). A simple hydraulic system whose operation may be compared to that of a transistor. Fig. 6 (above). Schematic diagram of the insulated gate field effect transistor (IGFET).

sample by the field. It is the repetition of this process which constitutes the Gunn oscillations.

Of course the Gunn effect has important technological applications. Today Gunn-effect devices operated in the mode described above are capable of delivering 250 milliwatts of continuous power at a frequency of 10 gigahertz, and more than 10 kilowatts under pulsed conditions. A related device, operating in the so-called LSA (limited space-charge accumulation) mode, in which the instability is not allowed to fully nucleate and propagate through the sample, is capable of producing power in milliwatt amounts at a frequency of 150 gigahertz (*13*). Perhaps more important has been the impetus which Gunn's discovery has given solid state research in this area; very recently oscillations have been found in bulk germanium, under high-electric-field conditions, which are phenomenologically very similar to the Gunn effect, but which may be based on very different physical principles (*14*).

As we have seen, the Gunn oscillator and the Josephson oscillator both have potential as sources of power in the microwave and infrared regions. However, while the former operates at the milliwatt level, the latter is at present capable of power output only in the subnanowatt range. This is the sort of historical accident which has often impeded the technological development of superconducting and other low-temperature devices, for in almost every case the development of a significant cryogenic device has been followed almost immediately by development of a semiconductor or ferrite device which provides better or more convenient performance. Nevertheless, cryogenic-device operation offers a number of intrinsic advantages which, we are sure, technology will eventually exploit: quiet operation, relatively little dissipation of power, and relatively longer potential lifetime of the device.

Now let us go on to the most interesting, or at least the most important, of the semiconductor devices, the transistor itself. To explain the operation of the transistor—and to provide the reader with a simple home recipe for the invention of new transistor types in his basement shop—we will use the concept of charge control (*15*). Transistors are basically devices in which two kinds of charge are used. One kind, Q_m, is the charge that is caused to move through the device by an applied electric field or a concentration gradient. The second kind, Q_c, controls the motion of Q_m. Charges Q_c and Q_m are typically in the same piece of matter, or at least spatially very close together, so an approximate neutrality condition must be satisfied:

$$Q_m + Q_c = \text{constant.}$$

The region through which Q_m moves is connected to a readily available reservoir of electrons of the same type; after moving through a control region, these electrons are trapped in a final collecting region, from which they cannot readily be reemitted.

The control region is analogous to the simple hydraulic system shown in Fig. 5, in which the flow of an incompressible fluid through a pipe is controlled by the motion of a fluid-actuated piston. This system is subject, also, to a law of conservation: conservation of fluid. The analogy between the pipe and the transistor may be carried farther. If the piston does not leak (a situation equivalent to one in which Q_m and Q_c cannot intermingle), then bringing in more control fluid (or control charge) requires energy, but keeping the piston in place does not. Therefore the direct-current gain of the structure is infinite. If there is a leak, then a continuous small flow of controlling fluid must be supplied to keep the piston in position.

Conceivably, the many different ways of separating electrons into the two classes Q_m and Q_c all lead to new transistor types. Of course, the two classes of electrons must be relatively well defined, so that, in the period in which the class Q_m electrons are in the control region, there are no appreciable interclass transitions (a situation analogous to the pipe's not being leaky). However, as we learn to make smaller and smaller devices, the electrons spend less and less time in the device, hence this restriction becomes less and less severe. The most familiar separation of electrons into classes is that for the junction, or bipolar, transistor, in which Q_c represents the majority carriers—that is, the electrons in one band—in a semiconductor and Q_m represents the minority carriers in the same space—that is, the electrons in the other band. The recombination process that permits electrons to jump from band to band represents the piston leakage in our analogy.

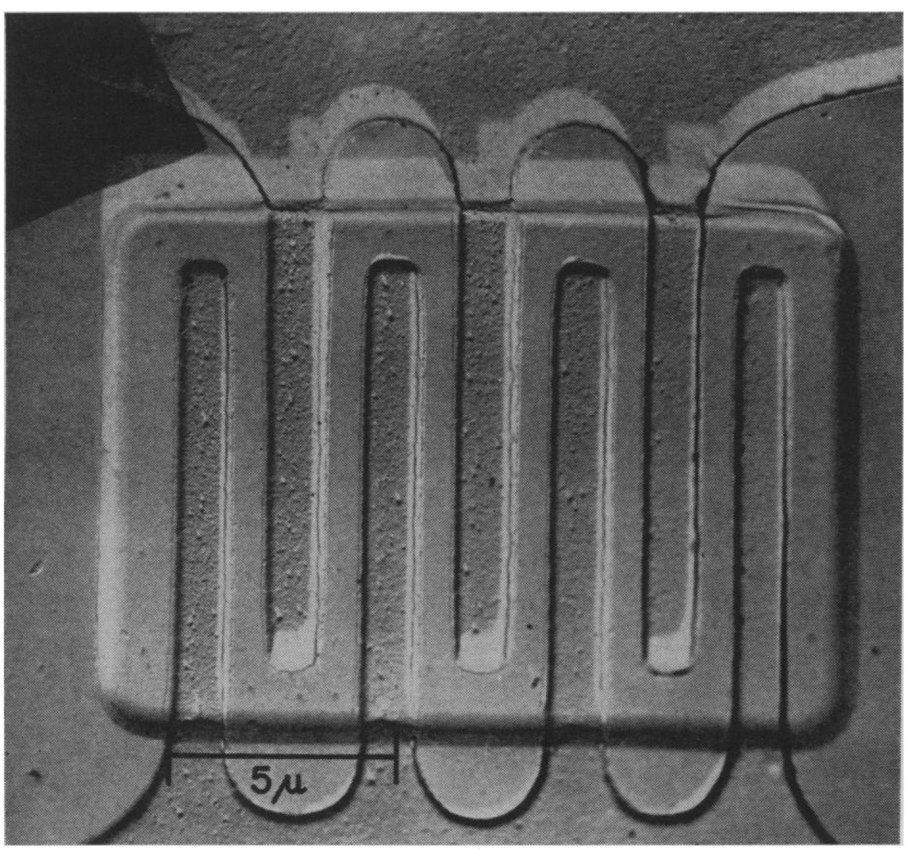


Fig. 7. An electron micrograph of an experimental transistor structure. The three stripes extending from the top are the base contacts, while the four extending from the bottom are the emitter contacts. These stripes are deposited aluminum films and each is 1 micron wide; the structure was produced by the Electron Beam Technology Group at the IBM T. J. Watson Research Center.

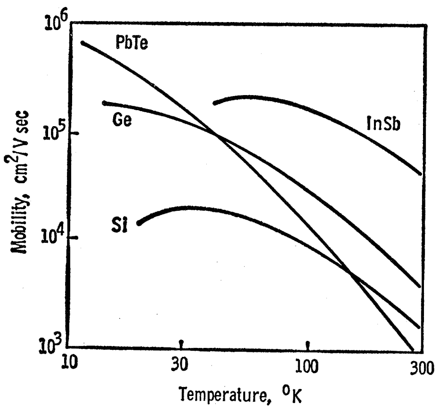


Fig. 8. Mobilities of electrons in several relatively pure semiconductors as a function of temperature.

A form of transistor which has been the object of considerable developmental work in recent years is the insulated gate field effect transistor (IGFET), shown in Fig. 6. The device is essentially a sandwich, made up of a thin insulator placed between a piece of semiconductor and a metal electrode. The control charge is brought in on the metal electrode and produces an image charge in the semiconductor surface, which is the moving charge. The integrated circuitry of Fig. 1 is typical of one variety of IGFET. These devices are particularly well suited for uses requiring a high degree of integration, and their manufacture involves fewer steps than that of the junction transistor. Another possible mechanism of separation of the electrons into classes Q_m and Q_c suggests the hot-electron transistor (*16*), a device much investigated but never made fully operational. In this structure, the control charges are low-energy or thermal electrons, while the moving charges are high-energy or hot electrons, brought in at an energy appreciably above the Fermi level (or kT) in the control region. Other bases for separation might be electron spin (up or down) or, in a superconducting material, the distinction between the paired, superconducting electrons and the unpaired, normal electrons.

Conclusion

The future evolution of the transistor, and with it that of our information and data-handling capabilities, can move in directions other than the invention of new transistor types. Within a given device structure, significant progress may be made in controlling or reducing dimensions, and these dimensions are an important factor in the speed of operation. Here there is room for progress through science, as well as through technology. In our present methods of manufacturing ultrasmall transistor structures, optical schemes borrowed from the photolithography industry are used. A mock-up of the desired structure is reduced in size optically and used to expose, and thus selectively polymerize, a photoresist material on the semiconductor wafer. These techniques are limited to optical resolutions. An important advance now under development is the use of high-resolution electron-beam techniques for exposing the photoresist material. Figure 7 is a scanning electron micrograph of an experimental transistor produced with the aid of electron beams; the entire structure is 15 microns across, and each stripe has a controlled width of only 1 micron. As part of a more fundamental attack, we may look for the development of genuinely useful ultraviolet or x-ray optics, and then use these shorter wavelengths in the manufacturing processes. A still more fundamental advance would be the use of electron beams to catalyze direct deposition or etching processes—an area about which very little seems to be known.

Evolution of the transistor could also move in the direction of use of improved or novel materials. A transistor's speed of operation is intimately related to the mobilities of its moving and control charges—that is, to the velocities which the electrons acquire from the driving fields. Figure 8 shows the electron mobility for a number of materials as a function of the temperature. We see that silicon and germanium, which are the workhorses of the transistor industry, are far surpassed in electron mobility by other materials (among "other materials" may be included silicon and germanium themselves at temperatures below room temperature). We certainly believe that we shall learn how to use some of these other materials in practical structures.

Much of our discussion has emphasized the role of science in guiding the technologist. It would be inappropriate to end on this note. The technology of solid state electronics has, in turn, given the solid state physicist new and important tools for investigating solids. For example, the IGFET structure shown in Fig. 6 suggested and made possible investigation of the two-dimensional surface gas of electrons induced by the control charge (*17*). This two-dimensional gas differs fundamentally from electrons in the bulk semiconductor; determination of its properties would have been impossible without the modern IGFET device. Technology has given science new materials and new structures; today the tools and materials of the factory are becoming more and more the techniques and samples of the laboratory.

An even more important role of technology has been that of raising questions for the scientist to answer. The field in the insulator of an IGFET reaches 10^6 volts per centimeter; do we really know what an insulator is in fields such as these? Do the textbook theorems which state that nice, well-ordered materials with filled conduction bands make the best insulators really apply? (After all, one of our best insulators, porcelain, doesn't answer this description.) Does nature impose an upper limit on electron mobility? Are the materials we know now—indium antimonide or lead telluride—about the best we can develop, or can we find materials with electron mobilities ten or 100 times higher? What are the transport properties of electrons confined to structures whose dimensions are of the order of an electron wavelength in a solid? In asking questions such as these, modern electronics is, in fact, serving as a continuing source of solid state physics.

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18. We thank the many members of this laboratory who have contributed to this article through discussion and suggestion.