tages of GaAs, but its technology is still in a more primitive stage.

The technology that makes GaAs microwave transistors possible is now being extended to the fabrication of integrated microwave circuits. One wonders when the application of the proved high-speed microwave capabilities of GaAs to digital circuits will begin. Exploratory attempts have already been made (*21*). A realistic view suggests, however, that the invasion of large-scale digital applications by GaAs will be much more difficult than the conquest of the microwave field. The reason is that one or a few microwave devices with superior frequency response can extend the bandwidth of a system and have great economic value. On the other hand, digital systems use thousands to millions of devices, and low-cost fabrication is essential. Fast devices are less important because the speed of a system is also limited by the delays in the package. The highly developed and versatile silicon technology, optimized by many years of experience, will not be displaced easily.

Summary

Although the limitations of the methods of lithography in use at a particular time are easily recognized and attract substantial attention, experience shows that technological ingenuity keeps pushing them to ever-smaller dimensions. There seems to be no fundamental reason to expect that lithographic limits will not continue to recede. The limits to the advance of miniaturization are to be found in the ability of materials to withstand high electric fields and in the ability of packaging technology to remove heat from active components and provide for power distribution, signal interconnection, and flexible mechanical assembly.

References and Notes

1. G. E. Moore, in *Technical Digest 1975 International Electron Devices Meeting* (IEEE, New York, 1975), pp. 11–13.
2. J. L. Buie, in *1976 WESCON Technical Papers* (Western Electric Show and Convention, El Segundo, Calif., 1976) paper 23/2.
3. G. Pircher, in *Solid State Devices, 1975* (Société Française de Physique, Paris, 1975), pp. 31–72; J. T. Wallmark, in *Solid State Devices, 1974* (Institute of Physics, London, 1975), pp. 133–167.
4. G. R. Brewer, *IEEE Spectrum* **8** (No. 1), 23 (1971).
5. A. V. Crewe, J. Wall, J. Langmore, *Science* **168**, 1338 (1970).
6. T. E. Everhart, in preparation.
7. N. W. Parker, S. D. Golladay, A. V. Crewe, in *Scanning Electron Microscopy/1976*, O. Johari, Ed. (IIT Research Institute, Chicago, 1976), part 1, pp. 37–44.
8. H. I. Smith and S. E. Bernacki, *J. Vac. Sci. Technol.* **12**, 1321 (1975); R. Feder, E. Spiller, J. Topalian, *ibid.*, p. 1332.
9. A. N. Broers, W. W. Molyen, J. J. Cuomo, N. D. Wittels, *Appl. Phys. Lett.* **29**, 596 (1976).
10. A. W. Lo, *IRE Trans. Electron Comput.* **EC-10**, 416 (1961).
11. B. Hoeneisen and C. A. Mead, *Solid State Electron.* **15**, 819 (1972); *ibid.*, p. 981.
12. S. A. Abbas and R. C. Dockerty, *Appl. Phys. Lett.* **27**, 147 (1975).
13. D. R. Collins, *ibid.* **13**, 264 (1968).
14. C. H. Bennett, *IBM J. Res. Dev.* **17**, 525 (1973).
15. R. Landauer, *ibid.* **5**, 183 (1961); *Ber. Bunsenges. Phys. Chem.* **80**, 1048 (1976).
16. R. W. Keyes, *Proc. IEEE* **63**, 740 (1975); *IEEE J. Solid State Circuits* **SC-10**, 181 (1975).
17. For a detailed description of the packaging of a modern computer see R. J. Beall, in *1974 INTERCON Technical Papers* (IEEE, New York, 1974), paper 18/3.
18. F. H. Gaensslen, V. L. Rideout, E. J. Walker, in *Technical Digest 1975 International Electron Devices Meeting* (IEEE, New York, 1975), pp. 43–46; F. H. Gaensslen, V. L. Rideout, E. J. Walker, J. J. Walker, *IEEE Trans. Electron Devices*, in press.
19. D. A. Jenny, *Proc. IRE* **46**, 959 (1958).
20. C. A. Liechti, *IEEE Trans. Microwave Theory Tech.* **MTT-24**, 279 (1976).
21. R. L. Van Tuyl and C. A. Liechti, in *1974 IEEE International Solid State Circuits Conference Digest of Technical Papers* (Winner, New York, 1974), pp. 114–115.

Solid-State Electronics: Scientific Basis for Future Advances

J. A. Giordmaine

The leaps forward in conceptual understanding, the new device principles, the advances in analytical technique, and the achievements in materials preparation that make up the scientific basis for the electronics revolution described in this issue can be readily identified, in retrospect. A list of such contributions would certainly include crystal structure analysis based on x-ray and electron diffraction, the explanation of conductivity in terms of the quantum theory of solids, the growth of ultrapure single crystals of electronic materials with controlled doping, the concept of a semiconductor amplifier, the invention of high-frequency oscillators based on stimulated emission, and the demonstration of quantum tunneling devices.

As Niels Bohr remarked, however, it is very difficult to predict, especially the future. Any attempt to identify a scientific basis for future advances is limited by a number of constraints. The lead time between scientific discovery and utilization in solid-state technology is at least 5 years, frequently more than enough time for the economic factors determining utility to have changed beyond recognition. The important scientific advances rarely emerge in a completely scheduled or planned pattern and not always in response to a perceived need. Progress often occurs in stages of abrupt change in the conceptual basis of the field, following a steady if undramatic accumulation of essential background understanding. Today the challenges of large-scale integration and the pace of change of the technology are making heavy demands on resources previously dedicated to longer-term research. Fundamental research of all kinds is carried on in a climate of increasingly critical scrutiny and diminishing real support.

In spite of the maturing of semiconductor technology and the uncertainties and vulnerability of the research enterprise, I believe that there is considerable ground for optimism about the prospects for continuing innovation in solid-state electronics. From a fundamental point of view, our present degree of control over electrons and their motion in solids may be compared with our ability to manipulate light at the beginning of the 19th century. We are now able to exploit behavior dependent on electron density and current flow, analogous to quantity of optical radiation and radiant intensity. The device utilization of the wave nature of electrons—making specific use of amplitude, phase, and coherence as in the case of light in diffraction, interference, holography, and the laser—has barely begun with the discovery of the Josephson effect.

From a nearer-term point of view, the exponential growth of the scale of in-

The author is director of the Solid State Electronics Research Laboratory, Bell Laboratories, Murray Hill, New Jersey 07974.

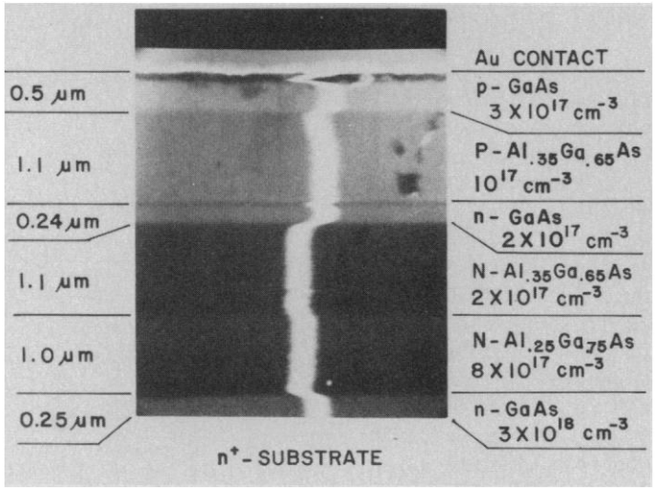

Fig. 1. Scanning electron micrograph of an MBE double-heterostructure laser. The active *n* region has a thickness of 0.24 μm; the superimposed line scan is a secondary emission signal to help delineate the layers. [Photograph courtesy of A. Y. Cho, R. W. Dixon, H. C. Casey, Jr., and R. L. Hartman]

tegration provides new openings for the invention of functional substitutions—ways of using properties of matter to achieve results otherwise obtained by brute force multiplication of devices. Examples of such functional substitutions are optoisolators, quartz-crystal filters, and optical fiber interconnection of computers—economical solutions that drastically reduce the number of components required to perform a given function. Closely related examples are magnetic bubbles and charge-coupled devices, which combine multiple-device functions in a single monolithic structure. The spread of integrated circuit applications has led to a proliferation of specialized "custom" circuits, on a scale much larger than the variety of earlier discrete transistors. More economical, mass produced, general-purpose circuits, programmable by electrical or other means after manufacture, may become increasingly important. Such circuits and their processing or programming represent a merging of hardware and software functions in circuit architecture that will make new types of demands on semiconductor technology.

A substantial increase in the speed of logic and memory access into the subnanosecond region would have a fundamental impact on digital data and signal processing in computers and communication. Extrapolations based on scaling arguments, however, suggest that current silicon technology can yield only modest potential increases in device speed. Moreover, basic limits on heat removal by liquid cooling rule out the utilization of silicon technology in high-density circuits at much higher speeds than are presently available. The need for increases in digital processing speed offers a natural occasion for technological innovation. The recently introduced small-scale optical integrated circuits containing injection lasers coupled to modulators and other components by optical waveguides, as well as medium-scale superconducting integrated circuits based on Josephson tunneling devices, are examples of radically new directions for which the scientific basis is undoubtedly still emerging.

In this article I will cite a few examples of areas of research that can reasonably be expected to contribute to future advances in solid-state electronics.

Surfaces, Thin Films, and Epitaxy

The early contributions of surface science to solid-state electronics are perhaps epitomized by the essential role played by the understanding of surface states in the work on metal-semiconductor interfaces that immediately preceded the transistor (*1*). The theory (*2*) of the influence of surface states on rectification characteristics provided the working basis needed to deal with the unexpected results of preliminary experiments on field-effect amplification, and in fact opened the way to the discovery of point contact transistor action in 1947. As part of the expansion of surface physics work during the subsequent two decades, a detailed understanding of the electronic properties of a few well-characterized surfaces in high vacuum, including silicon, emerged from the measurements of band bending, work function, and photoemission spectra (*3*). Metal oxide semiconductor (MOS) technology, which arose during the mid-1960's and early 1970's, depended in a fundamental way on the control of silicon–silicon oxide interface phenomena, including surface states, surface charges, and space charges in the oxide. It should be noted that the success of this technology to date, which required detailed characterization of the interfaces and solution of difficult instability problems due in part to ion mobility in the oxide, was achieved in the absence of a basic understanding of the atomic arrangement or the electronic structure of the interface.

Prospects for providing such a fundamental picture have increased in recent years as a powerful combination of improved experimental and theoretical tools has been brought to bear on the study of clean surfaces. On the experimental side, combinations of different electron spectroscopies (*4*) applied to clean, well-characterized surfaces in ultrahigh vacuum have allowed accurate determination of surface state energy levels both near and within the band gap. For example, observations of the same silicon surface by ultraviolet or x-ray photoelectron spectroscopy, two-electron ion-neutralization spectroscopy, electron loss spectroscopy, Auger electron spectroscopy, and low-energy electron diffraction provide independent information on states both in the vicinity of the surface and directly at the surface, on the chemical composition of the surface, and on the symmetry of the surface lattice arrangement.

On the theoretical side, new computational methods are available for calculating detailed maps of the electron distribution at a surface, taking the atomic arrangement into explicit account self-consistently (*5*). The surface geometry is either a relaxed version of the bulk structure or a reconstructed arrangement with symmetry wholly different from the bulk. A comparison of the electron spectroscopy results with theoretical predictions of surface state energy spectra based on a particular surface model allows confirmation of the assumed atomic arrangement. Together, the theoretical and experimental approaches have provided the first complete description of surfaces, including identification of the atomic species present, their atomic arrangement, and the distribution of valence electrons in space and energy. The recent extension of the calculations to GaAs-Ge junctions (*6*) suggests that these methods will be applicable to semiconductor and metal-semiconductor interfaces as well, and should yield an atomically detailed picture of the interface structure, electron states, charges, reconstruction, and the related junction electronic properties. An arsenal of recently introduced experimental tools, including angle-resolved photoelectron spectroscopy, synchrotron far-ultraviolet and x-ray spectroscopies, and backscattering and channeling of energetic ions, suggests a substantial rate of progress.

A beginning has also been made in the investigation of polycrystalline semicon-

ductor thin films (*7*). An understanding of the behavior of grain boundaries in such films, for example, is not now available, and will be essential in exploring their potential for low-cost solar cells.

A particularly promising example of an outgrowth of basic surface science research is molecular beam epitaxy (MBE) formation of compound semiconductor films (*8*). In this technique separate atomic and molecular beams from multiple thermal sources in high vacuum irradiate a substrate at intensities chosen to grow films with a desired composition and doping. The slow growth rate together with the independent control of the separate beam sources allows fabrication of semiconductor junction profiles, both in doping and in composition, to a precision approaching the level of a single atomic layer. The MBE process originated in fundamental studies of the adhesion of gallium and arsenic atoms to GaAs surfaces; early characterization of MBE surfaces was aided by the unique opportunity for electron diffraction diagnostic probing of the surface in situ during film growth in vacuum. Molecular beam epitaxy has already been used to prepare films and layer structures for a variety of GaAs and $Ga_xAl_{1-x}As$ devices. These include varactor diodes having highly controlled hyperabrupt capacitance-voltage characteristics, IMPATT diodes, microwave mixer diodes, Schottky barrier field-effect transistors (FET's), injection lasers (Fig. 1), optical waveguides, and integrated optical structures. The potential of MBE for future solid-state electronics is greatest for microwave and optical solid-state devices and circuits where submicrometer layer structures are essential, and where the inherent adaptability of the process to planar technology and integration will offer a number of opportunities. A measure of the potential of the technique for millimeter wave electronics is a recently demonstrated MBE GaAs Schottky barrier diode cryogenic mixer with noise temperature of 315 K at 102 gigahertz (*9*).

Possible longer-term implications of MBE for solid-state electronics are related to the capability of growing extended layer sequences with alternating composition such as GaAs and AlAs (Fig. 2). Such superlattice structures with periodicities of 50 to 100 angstroms show negative resistance characteristics attributed to resonant tunneling into the quantized energy states associated with the narrow potential wells formed by the layers (*10*). Detailed optical spectra and electron microscope studies of MBE superlattices establish that the potential well distributions can be controlled and positioned to a precision of a few atomic layers.

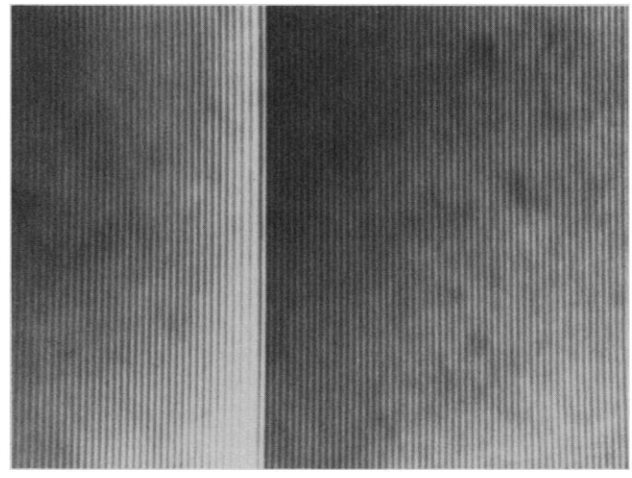

Fig. 2. Bright-field transmission electron micrograph of MBE alternating layers of GaAs and AlAs; the periodicity of the pattern is 56 Å; at the right of the interface the structure is seven layers of GaAs and three layers of AlAs; at the left of the interface the structure is nine layers of GaAs and one of AlAs. [Photograph courtesy of P. M. Petroff]

Electron diffraction and optical studies have been made of MBE multilayers prepared by exposing a GaAs substrate sequentially to beams of gallium, arsenic, and aluminum in brief pulses carefully timed to deposit the equivalent of a single atomic layer (*11*). For a narrow range of substrate temperatures around 850 K, a monolayer crystalline compound forms with regular periodicity extending over domains of at least 100 Å in size, having the planar structure GaAsAlAsGaAs . . . and an equivalent formula $AlGaAs_2$. The new material differs from the parent crystals GaAs and AlAs and from the solid solution in its optical and electronic properties as well as its short-range and long-range order. The stability of such synthetic new materials, grown at temperatures considerably below the melting point of the solid solution, may, in fact, be determined by kinetic rather than thermodynamic considerations. The technique may make available a new class of electronic materials similar in composition to naturally occurring compounds but distinct in structure and properties.

Defects, Recombination, and Reliability

As silicon technology has reached its present state of maturity, the reliability of integrated circuits has become largely determined by residual defects distributed randomly over the chip area. The number of components per chip has

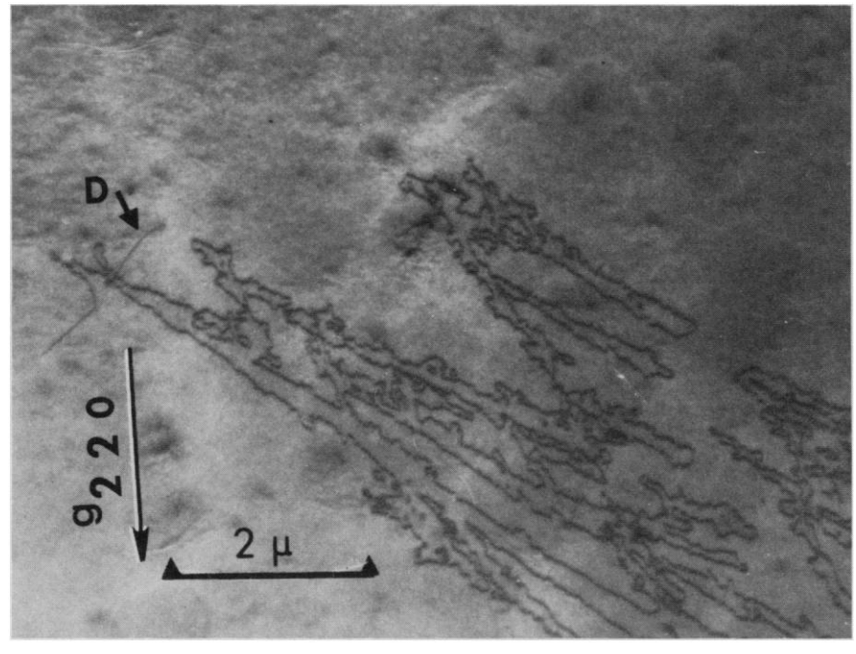

Fig. 3. Transmission electron micrograph showing a dislocation (*D*) at the origin of a dark line defect network (g_{220} is a lattice direction). [Photograph courtesy of P. M. Petroff and R. L. Hartman]

meanwhile been increasing by a factor of about 2 each year. The result of the reduction in device size has so far been an improvement in reliability per individual component or per circuit function. With further miniaturization expected from submicrometer electron beam and x-ray lithography, however, this picture can be expected to change. Practical limits on size set by reliability problems, as well as the limits on size, packing, and circuit configuration set by power dissipation, will be felt long before fundamental limits set by thermodynamic or quantum considerations become important (*12*). The reliability limits arise in large part from the mobility of atoms, vacancies, dislocations, and other defects driven by electric fields and gradients of temperature or chemical potential. The problems include electromigration, electrochemical corrosion, and surface and bulk diffusion of metallization; they already appear in present devices and integrated circuits under special conditions. There is still very little fundamental understanding of these processes. A broader picture of the physics of solid-state diffusion will be essential to take full advantage of future advances in lithography.

In technologies other than silicon, the reliability constraints are quite different. In the case (discussed below) of Josephson junction circuits operating at liquid helium temperature, for example, not only have heat dissipation problems disappeared, but there are as yet no known mechanisms for circuit degradation. That favorable situation is balanced, however, by reliability problems in thermal cycling due to severe mismatch in thermal expansion of the substrates and metallization films.

An example of a technology in which defect motion already appears to have important consequences for reliability is optoelectronics. In GaAs and other light emitting diodes (LED's) and injection lasers made with compounds of group III and group V elements, light is emitted by radiative recombination of electrons and holes in the vicinity of a junction or heterojunction. Whenever a nonradiative recombination event takes place, however, the available band-gap energy is released to the lattice in a burst equivalent to an instantaneous local temperature of $\sim 10^4$ K. When this process occurs at a vacancy or interstitial defect, the available energy is often enough to activate motion of the defect (*13*). The mobile defects are trapped at any nearby dislocation and can cause the dislocation to grow (*14*). In injection lasers and LED's such recombination-induced motion may give rise to growth of the dense, opaque networks of dislocations termed dark line defects which ultimately cause premature failure (*15*) (Fig. 3). Improved lifetimes of present communication lasers and LED's are the result of careful growth conditions, control of defect concentration, and avoidance of dislocations on which mobile point defects can collect (*16*). A more complete characterization of defects, their motion, and their interactions with dislocations will provide a basis for future, more permanent solid-state optical devices.

A new spectroscopic technique, deep level transient spectroscopy (DLTS) (*17*), allows direct measurement of energy levels and concentration of the electrically active defects in the neighborhood of a junction. DLTS observations also measure the cross section of the defect for stimulation of nonradiative recombination. Such results have led to useful models of the coupling of the defect to the lattice, and new information on how the energy released in a nonradiative process is transferred to phonons and finally appears as heat in the crystal (*18*). Only a few of the defects characterized by DLTS have so far been identified. The identification of larger numbers of such defects will be essential for full control of luminescent devices.

Defects also play a well-known but poorly understood role in the parasitic high-frequency oscillations sometimes observed in aged injection lasers, in the stability and noise figure of microwave FET amplifiers, and in other solid-state electronics applications. Present studies of defects are providing an understanding of a variety of mechanisms of device degradation. The future manufacture of more reliable optoelectronic and microwave devices will rest on such an understanding.

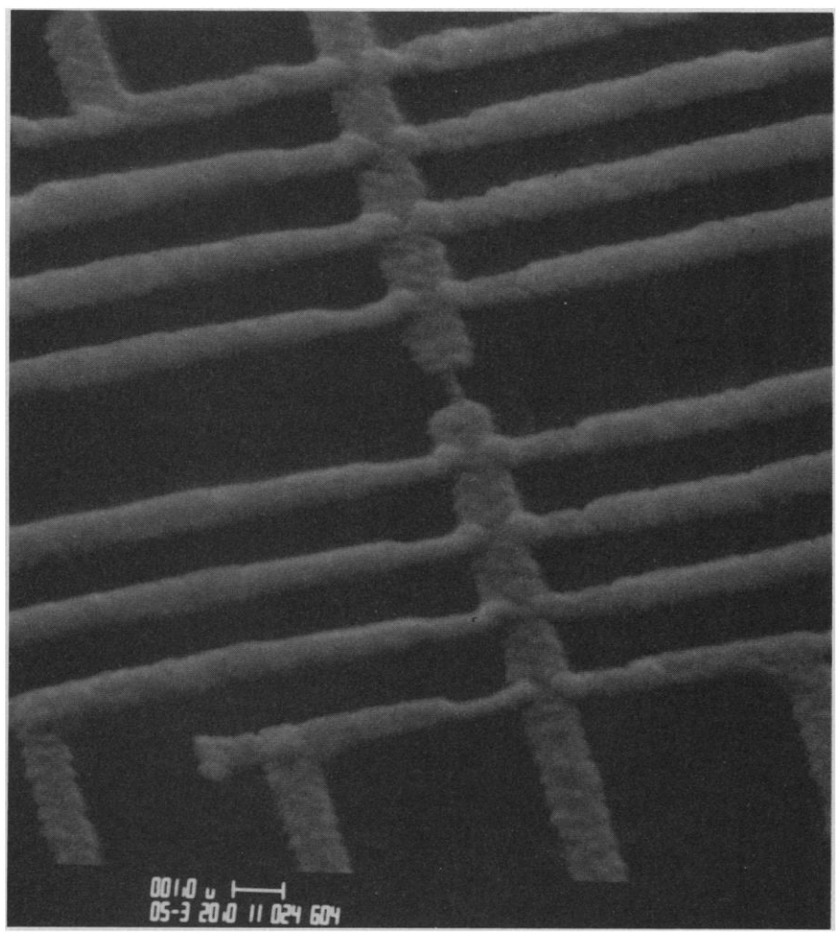

Fig. 4. Probe measurement of phase-dependent normal and pair potentials along a superconducting strip near a constriction. Scale bar, 1 μm. [Photograph courtesy of G. J. Dolan and L. D. Jackal]

Superconductivity and Speed

Early attempts to utilize the phenomenon of superconductivity for solid-state logic and memory devices made use of its most striking property: the abrupt loss of electrical resistance at the phase transition from normal to super-

conductivity. The best known of these devices, the cryotron (*19*), consists of a metallic gate film kept superconducting at a temperature slightly below its transition temperature, and an adjoining control film. The gate film can be converted to its normal state by a magnetic field due to current in the control film. The two stable conduction states of the gate film and the switching action of the control film provide memory and logic functions. The switching time of this device was expected to be about 10^{-9} second, determined by eddy current damping in the normal phase during propagation of the phase boundary down through the submicrometer film thickness. In practice, however, the switching time turns out to be 10^{-8} to 10^{-7} second, determined either by a lateral propagation time due to nonuniform phase nucleation or by a thermal time constant associated with transfer of a residual latent heat of transition. This device is no longer competitive in performance with room-temperature devices and the cryotron has not had widespread application.

The conceptual leap forward that has led to a fresh look at the possibility of a superconducting electronics technology originated in fundamental solid-state physics research, rather than a direct attempt to make superconducting devices. This idea was, of course, the recognition that superconducting electron pairs, as well as normal electrons (*20*), could tunnel from one superconductor to another across a thin-film insulator (Fig. 4).

The predicted behavior, soon discovered in the laboratory (*21*), gives rise to two states of conduction across an insulating tunnel junction, one a normal dissipative current driven by finite voltage across the junction, the other an electron pair or Josephson supercurrent occurring at zero voltage. Switching between the two voltage states by magnetic field or current injection from adjoining control lines (*22, 23*) provides the basis for memory and logic. Unlike the cryotron, the Josephson junction is switched entirely in the superconducting phase and avoids delays of phase boundary propagation. The inherent delay of the Josephson switching action is determined primarily by the superconducting energy gap, a value corresponding to a time of $\sim 10^{-12}$ second (1 psec). Indirect experimental measurements show a delay time of $\lesssim 5$ psec. The high speed (10- to 100-psec logic delay compared to ~ 1 nanosecond for high-speed transistors) and low switching power (10 microwatts compared to 10 to 100 milliwatts for high-speed transistors) make Josephson technology an attractive candidate for high-performance computing and data processing.

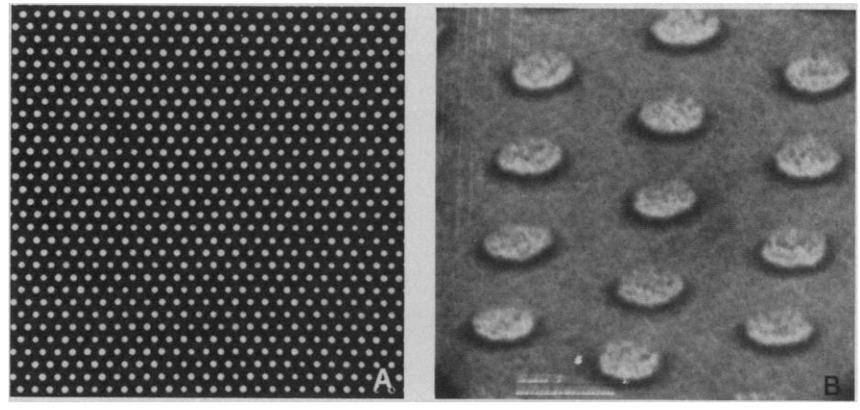

Fig. 5. Electron micrograph (B) showing a two-dimensional triangular lattice pattern of 1-μm holes in superconducting aluminum film. When the magnetic flux density is adjusted to match the flux vortex lattice with the hole lattice, strong "resonant" vortex pinning is observed. (A) Structure in (B) shown at lower magnification. [Photograph courtesy of A. F. Hebard, A. T. Fiory, and S. Somekh]

One of the main problems requiring further attention before this technology can find any wide application is the thermal cycling damage. While Josephson junctions may well have an indefinite operating life at liquid helium temperature, cycling of the structures to room temperature introduces severe stress as a result of the different thermal expansion of the metallization layers, the insulating oxide layer, and the substrate. Stress relaxation tends to occur by hillock growth on the films, short-circuiting the 40- to 50-Å-thick oxide insulating layer on repeated cycling. Fundamental research on the metallurgy, oxidation, tunneling, deposition, and growth of superconducting materials could determine the future of this promising technology (Fig. 5).

Materials and Quantum Electronics

Research on materials, crystal growth, and solid-state optics is becoming an increasingly visible segment of quantum electronics. Research on solid-state laser sources, largely confined in the past to GaAs and the GaAs-Al,Ga,As heterostructure system, has been extended to a wide range of binary, ternary, and quaternary III-V and IV-VI compounds (*24*). The potential importance of the 1- to 1.1-μm region has stimulated work on junction lasers based on ternary-ternary, ternary-quaternary, and other heterostructures such as Ga,As,Sb-Al,Ga,As,Sb; InP-Ga,In,As,P; and In,GaAs-In,Ga,P. The binary and ternary IV-VI compounds have become increasingly important as sources for the 3- to 30-μm region (*25*). The Pb,Sn (Te,Se) systems are unusual in that the energy gap passes through zero within the ternary composition range and makes possible a continuous range of infrared laser sources.

The complex materials requirements for a double-heterostructure injection laser arise from the need for both carrier and optical confinement, to avoid dislocation-prone lattice mismatch at the heterostructure interface, and for low levels of nonradiative centers. Although a large body of information on phase diagrams, dependence of band gap on composition, and certain other properties of these complex systems is becoming available (*24*), an enormous amount of further data and understanding will be needed before reproducible, low-cost production of reliable devices becomes feasible, especially outside the GaAs-Al,Ga,As system.

The materials science effort in this field has made possible improvements in and new combinations of liquid phase epitaxy and MBE growth, and in turn a wide range of new injection laser techniques. Recent advances include distributed feedback lasers, with a periodic index variation adjoining the active region to provide sharp frequency selectivity; Bragg reflector lasers, with the usual cleaved end mirrors replaced by coupled passive optical waveguides containing etched Bragg reflection sections; and many different types of stripe lasers. Virtually all continuously operating lasers are now constructed in a narrow stripe geometry to provide sharper transverse mode selection and better coupling of the laser light output to an optical fiber.

As the position of optics in communications and solid-state electronics becomes more established, there will be a developing need for combinations of opti-

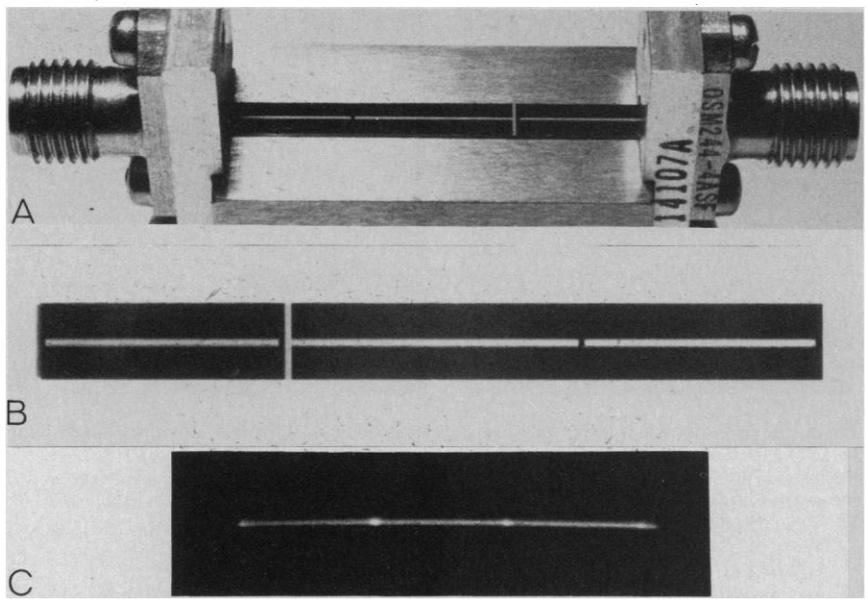

Fig. 6. (A) Picosecond-speed solid-state switch formed from a 1-inch metallic stripline on a 10-mil silicon substrate. The right terminal of the strip is charged. A 10-psec optical pulse (2×10^{-9} joule) illuminates the 8-mil gap at the right to generate a pulse moving toward the left; the crossbar shorting stubs act to form a rectangular pulse. The gap at the left is irradiated by a second optical pulse for correlation measurement of the electrical pulse length. (B) Enlargement of stripline, reversed. (C) Two-photon fluorescence photograph of a picosecond pulse train. [Photographs (A) and (B) courtesy of D. H. Auston, C. Shank, and E. Ippen]

cal functions, as in multiple sources and modulators, multiplexed optical sources, and perhaps optical sources with nonlinear devices to generate new or tunable frequencies. It is likely that there will be advantages of function, stability, and cost in fabricating these combinations on a single substrate, as is the case for silicon integrated circuits. In progress toward such integrated optical structures in recent years (*26*), surface waveguides have been demonstrated in many materials, on many substrates, and by many different techniques, including sputtering, evaporation, ion implantation, and diffusion. Lenses, couplers, and gratings, as well as active devices such as injection lasers and waveguide modulators, have been adapted to couple to optical waveguides and fit the integrated optics format. Simple small-scale integrated optical circuits have been demonstrated using both monolithic and hybrid techniques. Monolithic circuits, so far fabricated only in the GaAs-Al,Ga,As system, have included laser, waveguide, modulator, coupler, and Bragg grating elements. Hybrid circuits have been demonstrated with a wide variety of magneto-, acousto-, and electro-optical techniques and materials. A substantial amount of materials science and device research is being directed toward improved growth techniques and exploration of the possible original functions such circuits may perform.

Future advances in solid-state electronics can also be expected on the basis of the scientific and technical developments in ultrashort light pulse generation and nonlinear optics over the past 15 years. As an example, consider the recent use of ultrashort light pulses, generated by mode-locked solid-state and dye lasers, as the basis of a picosecond solid-state switch (*27*). Ultrashort visible light pulses, with energy in the nanojoule range, produce substantial surface conductivity at a silicon surface as a result of the creation of high-density plasma. The picosecond time scale of the onset of surface conductivity has been applied to ultrahigh-speed electrical switching and gating circuits. In the example of Fig. 6, the silicon photoconductor forms the dielectric substrate of a microstrip transmission line. A gap in the line can be closed at 10-psec rate by a visible light pulse; the line can be shorted by a subsequent infrared pulse, producing bulk photoconductivity. The use of standard transmission line reflection techniques allows generation of a sharply terminated pulse. Research in this field is closely coupled with materials studies of electron-hole diffusion and recombination under high-density plasma conditions.

Nonlinear optical techniques, such as optical harmonic generation, optical parametric oscillation, and stimulated Raman scattering, have so far had an impact primarily on research instrumentation. Widespread application of nonlinear optics in solid-state electronics—for example, its routine use in integrated optical circuits for frequency conversion—will probably require specialized materials with strongly nonlinear behavior. While there now appears to be a good working knowledge of the nonlinear properties of inorganic crystals, organic nonlinear susceptibilities are still only partially understood (*28*). Research on the mechanisms of the nonlinear optical properties of organic materials may well lead to materials with nonlinear optical properties superior to those of presently known inorganic crystals.

The examples cited above are perhaps a few of the plausible research directions likely to have an impact on the *evolution* of solid-state electronics during the coming years. A comparison of the variety and richness of the physics and materials science at hand today with that, say, of 1945 would seem to argue for at least as favorable prospects for an electronics *revolution* during the coming 32 years.

References

1. W. Shockley, *Electrons and Holes in Semiconductors* (Van Nostrand, New York, 1950), pp. 31–34.
2. J. Bardeen, *Phys. Rev.* **71**, 717 (1947).
3. F. G. Allen and G. W. Gobeli, *ibid.* **127**, 1500 (1962).
4. J. E. Rowe and H. Ibach, *Phys. Rev. Lett.* **32**, 421 (1974); J. E. Rowe, *Phys. Lett. A.* **46**, 400 (1974); H. Hagstrum, *Science* **178**, 275 (1972).
5. J. A. Appelbaum and D. R. Hamann, *Phys. Rev. B* **6**, 2166 (1972); *Phys. Rev. Lett.* **31**, 106 (1973); *ibid.* **32**, 225 (1974); K. C. Pandey and J. C. Phillips, *ibid.*, p. 1433.
6. G. A. Baraff, J. A. Appelbaum, D. R. Hamann, *Phys. Rev. Lett.* **38**, 237 (1977).
7. K. J. Bachmann, E. Buehler, J. L. Shay, S. Wagner, *Appl. Phys. Lett.* **29**, 121 (1976).
8. A. Y. Cho and J. R. Arthur, *Prog. Solid State Chem.* **10**, 157 (1975).
9. A. Y. Cho, R. A. Linke, M. V. Schneider, in preparation.
10. L. L. Chang, L. Esaki, R. Tsu, *Appl. Phys. Lett.* **24**, 593 (1974).
11. A. C. Gossard, P. M. Petroff, W. Weigmann, R. Dingle, A. Savage, *ibid.* **29**, 323 (1975).
12. R. W. Keyes, *Proc. IEEE* **63**, 740 (1975).
13. D. V. Lang and L. C. Kimerling, *Phys. Rev. Lett.* **33**, 489 (1974).
14. L. C. Kimerling and P. M. Petroff, *Appl. Phys. Lett.* **29**, 461 (1976).
15. R. L. Hartman and P. M. Petroff, *ibid.* **23**, 469 (1973).
16. B. C. DeLoach, *Bell Lab. Rec.* **53**, 203 (1975).
17. D. V. Lang, *J. Appl. Phys.* **45**, 3023 (1974).
18. ——— and C. H. Henry, *Phys. Rev. Lett.* **35**, 1525 (1975).
19. D. A. Buck, *Proc. IRE* **44**, 482 (1956).
20. B. D. Josephson, *Phys. Lett.* **1**, 251 (1962); I. Giaever, *Phys. Rev. Lett.* **5**, 147 (1960); *ibid.*, p. 464.
21. P. W. Anderson and J. M. Rowell, *Phys. Rev. Lett.* **10**, 230 (1963); J. M. Rowell, *ibid.* **11**, 200 (1963).
22. J. Matisoo, *Proc. IEEE* **55**, 172 (1967).
23. T. A. Fulton, J. H. Magerlein, L. N. Dunkleberger, in "Proceedings of the 1976 Applied Superconductivity Conference," *IEEE Trans. Magn.* **MAG-13**, 56 (1977).
24. M. B. Panish, *Proc. IEEE* **64**, 1512 (1976).
25. T. C. Harman and I. Melngailis, *Appl. Solid State Sci.* **4**, 1 (1974).
26. P. K. Tien, *Rev. Mod. Phys.*, in press.
27. D. H. Auston, *Appl. Phys. Lett.* **26**, 101 (1975).
28. B. F. Levine, in *Dielectric and Related Molecular Processes*, M. Davies, Ed. (Chemical Society, London, in press), vol. 3.