References and Notes

1. J. D. Meindl, K. N. Ratnakumar, L. Gerzberg, K. C. Saraswat, in *Digest of Technical Papers, IEEE International Solid-State Circuits Conference, 1981* (IEEE, New York, 1981), pp. 36–37.
2. P. H. Abelson and A. L. Hammond, *Science* **195**, 1087 (1977).
3. R. B. Friedman and D. H. Gustafson, *Comput. Biomed. Res.* **10**, 199 (1977).
4. S. A. Glantz, *IEEE Comput. Mag.* **11**, 68 (1978).
5. C. J. McDonald, *Ann. Intern. Med.* **84**, 162 (1976).
6. W. V. Slack and L. J. Van Cura, *Comput. Biomed. Res.* **1**, 527 (1968).
7. T. L. Lincoln and R. A. Korpman, *Science* **210**, 257 (1980).
8. W. O. Baker, W. S. Brown, M. V. Mathews, S. P. Morgan, H. O. Pollak, R. C. Prim, S. Sternberg, *ibid.* **195**, 1134 (1977).
9. J. D. Meindl, *ibid.* **210**, 263 (1980).
10. R. L. White and J. D. Meindl, *ibid.* **195**, 1119 (1977).
11. J. A. Berkman and J. W. L. Prak, in *Digest of Technical Papers, IEEE International Solid-State Circuits Conference, 1981* (IEEE, New York, 1981), pp. 168–169.
12. W. J. Spencer, *IEEE Trans. Biomed. Eng.* **BME-28**, 237 (1981).
13. A. L. Komaroff, *Proc. IEEE* **67**, 1196 (1979).
14. S. R. Garfield, *Sci. Am.* **222**, 15 (April 1970).
15. B. J. Blum, R. Lenhard, Jr., H. Braine, A. Kammer, in *Proceedings of the First Annual Symposium on Computer Application in Medical Care* (IEEE, New York, 1977), pp. 131–138.
16. E. Osserman, L. Katz, W. Sherman, F. Putney, *J. Am. Med. Assoc.* **239**, 1772 (1978).
17. R. A. Seltzer, G. W. Reimer, L. R. Cooperman, S. B. Rossiter, *Am. J. Roentgenol.* **128**, 825 (1977).
18. M. J. Meldman, D. Harris, R. J. Pellicore, E. L. Johnson, *Am. J. Psychiatry* **134**, 38 (1977).
19. E. H. Shortliffe, B. G. Buchanan, E. A. Feigenbaum, *Proc. IEEE* **67**, 1207 (1979).
20. C. Bordage, A. Elstein, J. Vinsonhaler, C. Wagner, in *Proceedings of the First Annual Symposium on Computer Application in Medical Care* (IEEE, New York, 1977), pp. 204–210.
21. P. Szolovits and S. G. Pauker, *Proc. IEEE* **67**, 1224 (1979).
22. G. L. Irvin and R. Zeppa, *Ann. Surg.* **183**, 594 (1976).
23. D. H. Gustafson, J. H. Greist, F. F. Strauss, H. Erdman, T. Laughren, *Comput. Biomed. Res.* **10**, 83 (1977).
24. J. Conklin, J. Munzenrider, P. W. Neurath, W. M. Ross, *Radiology* **123**, 441 (1977).
25. H. L. Abrams and B. J. McNeil, *N. Engl. J. Med.* **298**, 255 (1978).
26. C. H. Marshall, *Postgrad. Med.* **60**, 105 (1976).
27. R. S. Ledley, G. Di Chiro, A. J. Luessenhop, H. L. Twigg, *Science* **186**, 207 (1974).
28. H. K. Huang, M. Cerroni, J. C. Mazziotta, in *Proceedings of the First Annual Symposium on Computer Application in Medical Care* (IEEE, New York, 1977), pp. 356–363.
29. L. E. Cloe, *Am. J. Roentgenol.* **127**, 187 (1976).
30. A. C. Kak, *Proc. IEEE* **67**, 1245 (1979).
31. E. L. Ritman, J. H. Kinsey, R. A. Robb, B. K. Gilbert, L. D. Harris, E. H. Wood, *Science* **210**, 273 (1980).
32. R. D. Melen, A. Macovski, J. D. Meindl, *Proc. IEEE* **67**, 1274 (1979).
33. R. L. Popp and A. Macovski, *Science* **210**, 268 (1980).
34. V. Sondak, H. Schwartz, N. Sondak, Eds., *Computers and Medicine* (Artech, Dedham, Mass., 1979), p. 205.
35. B. Nussbaum, T. Minckler, R. Roby, E. Ackerman, *Am. J. Clin. Pathol.* **67**, 149 (1977).
36. D. A. Wycoff and J. R. Wagner, *ibid.* **70**, 390 (1978).
37. B. Drewinko, B. Wallace, R. W. Crawford, J. M. Trujillo, *ibid.* **67**, 64 (1977).
38. J. P. Horwitz, E. B. Hills, D. Andrzejewski, J. Penkala, S. Albert, *J. Am. Med. Assoc.* **235**, 1708 (1976).
39. K. Biemann, *Proc. IEEE* **67**, 1287 (1979).
40. R. J. Elin, *Science* **210**, 286 (1980).
41. M. Ariet and L. Crevasse, *J. Am. Med. Assoc.* **239**, 1201 (1978).
42. W. Chu, P. A. N. Chandraraina, D. E. Raeside, R. E. Brown, H. Poehlman, *Radiology* **123**, 795 (1977).
43. T. W. Sykes, R. L. Haynes, E. R. McFadden, *Am. Rev. Respir. Dis.* **115**, 581 (1977).
44. L. J. Thomas, Jr., K. W. Clark, C. N. Mead, K. L. Ripley, B. F. Spenner, G. C. Oliver, Jr., *Proc. IEEE* **67**, 1322 (1979).
45. L. C. Sheppard and N. T. Kouchoukos, *Anesthesiology* **45**, 250 (1978).
46. M. Hilberman, B. Kamm, M. Tarter, J. J. Osborn, *Comput. Biomed. Res.* **8**, 447 (1975).
47. M. E. Wade, P. J. Coleman, S. C. White, *Obstet. Gynecol.* **48**, 287 (1976).
48. J. J. Almasi and L. J. Heitlinger, in *Proceedings of the First Annual Symposium on Computer Application in Medical Care* (IEEE, New York, 1977), pp. 290–296.
49. L. C. Sheppard, *Proc. IEEE* **67**, 1300 (1979).
50. M. J. Giannini, *Computer* **14** (No. 1), 12 (1981).
51. W. Schneider and W. Seamone, *ibid.*, p. 41.
52. R. J. Leneway and B. R. Montgomery, *ibid.*, p. 49.
53. G. C. Vanderheiden, *ibid.*, p. 54.
54. M. A. Rahimi, *ibid.*, p. 19.
55. A. Thomas, *ibid.*, p. 25.
56. J. H. Aylor, B. W. Johnson, R. L. Ramey, *ibid.*, p. 35.

Ultrafast Phenomena in Semiconductor Devices

C. V. Shank and D. H. Auston

Summary. Evolving high-speed semiconductor technology requires a more complete understanding of semiconductors on a picosecond time scale. This article discusses ultrafast phenomena that may influence device performance and describes new experimental methods utilizing short optical pulses to investigate materials and device structures.

The building blocks of future ultrahigh-speed computers will be products of rapid advances now taking place in device technology. During the last 30 years there has been remarkable progress in the evolution of new high-speed devices. Semiconductor circuits have been increasing in speed by approximately a factor of 10 each decade. A number of new high-speed device technologies are being developed. In this article we will limit the scope of our discussion primarily to the fundamental aspects of emerging high-speed semiconductor technologies.

As semiconductor electronic devices become smaller and faster, we must extend our understanding of ultrafast processes in semiconductors, which will ultimately determine performance. New experimental methods are being developed to explore semiconductors on ever finer time scales. We will discuss the basic concepts that will influence semiconductor device performance and present recent experimental results.

In Fig. 1 we compare the time scales of existing high-speed technologies. The solid lines indicate achieved performance and the dashed lines projected performance. Clearly, the speed of optics exceeds that of all other high-speed technologies. Although they are not electronic, techniques involving short optical pulses have pushed our ability to resolve events in time to a fraction of a picosecond (*1*) and are valuable tools for fundamental investigations of high-speed electronic devices. Optoelectronics combines the fields of optics and electronics and shows considerable promise for the development of high-speed devices that can join some of the high-speed capabilities of optics with electronics. Superconducting electronics, based on Josephson junction logic devices (*2*), has advanced to the point where cryogenic computer systems are being constructed (*3*). The intrinsic speed of response of a Josephson junction is limited by the superconducting energy gap (that is, $\tau = \hbar/\Delta E$, where $\hbar$ is Planck's constant divided by 2π). In typical Josephson junctions this time is a fraction of a picosecond; in practice, device capacitances limit per-

C. V. Shank is head of the Quantum Physics and Electronics Department, Bell Laboratories, Holmdel, New Jersey 07733, and D. H. Auston is a member of the technical staff at Bell Laboratories, Murray Hill, New Jersey 07674.

0036-8075/82/0212-0797$01.00/0

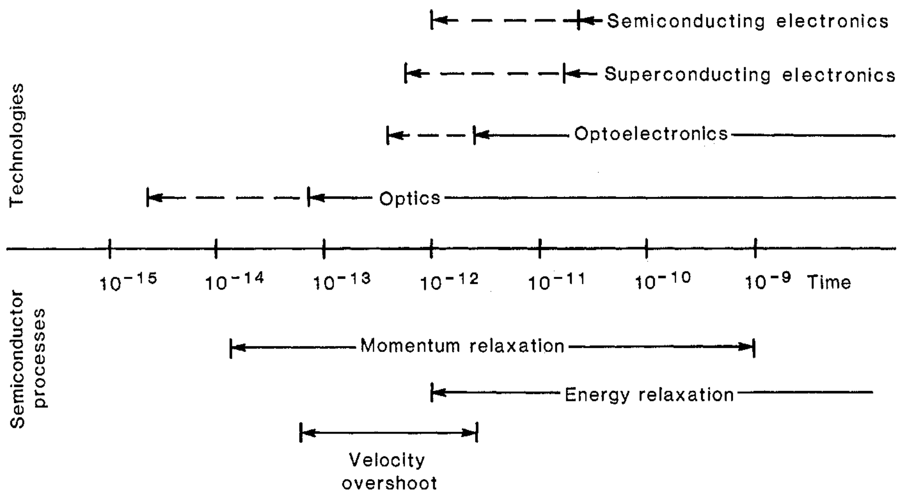

Fig. 1. Time line of technologies and fast physical processes in semiconductors. Solid lines represent achieved speed and dashed lines projected speed.

formance. A recent review by Keyes (*4*) examines some of the fundamental limits of digital information processing and their importance for semiconductor and superconducting electronic technologies.

Ultrafast Processes in Semiconductors

We can gain some insight into the speed of a semiconductor device by examining the performance of an idealized circuit containing only a block of semiconductor and a load capacitor, C. From elementary circuit analysis we can calculate the time, t, to switch the voltage from an initial voltage, V_0, to a voltage V:

$$t = \int_{V_0}^{V} \frac{C\,dV}{I(V)} \tag{1}$$

The current, $I(V)$, is the transferred current-voltage relationship of the device. We see immediately from Eq. 1 that an important factor in determining the speed of the circuit is the capacitance, C, that must be charged by the device current. This capacitance is minimized by reducing the physical size of the device and other parasitic capacitances. A second and very fundamental factor governing switching speed is the current-voltage relationship that is determined by the dynamics of the drift of electrons across the active region of the device (for instance, the channel for a field effect transistor). Such transit time effects can be minimized by reducing the drift length. Further reductions may be possible by carefully considering the physics of nonequilibrium carrier transport in the semiconductor.

The motion of carriers through a semiconductor under the influence of an electric field ultimately determines the basic limits of device performance. We can describe this motion by using the classical dynamical equations (*5*) for the average momentum $m\mathbf{v}$ and energy ε of a distribution of carriers.

$$\frac{d m\mathbf{v}}{dt} + \frac{m\mathbf{v}}{\tau_m(\varepsilon)} = e\mathbf{E} \tag{2}$$

$$\frac{d\varepsilon}{dt} + \frac{\varepsilon - \varepsilon_L}{\tau_\epsilon(\varepsilon)} = e(\mathbf{E}\cdot\mathbf{v}) \tag{3}$$

where e is the electron charge, ε_L the equilibrium energy, $\mathbf{E}$ the electric field, and $\tau_m(\varepsilon)$ and $\tau_\epsilon(\varepsilon)$ the momentum and energy relaxation times. In general, τ_m and τ_ϵ are a function of carrier energy and represent an average of electron interactions with the lattice, ionized impurities, and other carriers. From Eq. 2 we see that in the steady state the carrier velocity is given by

$$v = \mu E \tag{4}$$

where $\mu = e\tau_m(\varepsilon)/m^*$ is the mobility (m^* is the effective mass). In the region where the mobility is constant, current flow is governed by Ohm's law. Significant deviations from this simple ohmic behavior are seen at high electric fields and on time scales short compared to $\tau_m(\varepsilon)$ and $\tau_\epsilon(\varepsilon)$. The relaxation times τ_m and τ_ϵ are both functions of energy, and usually τ_ϵ is longer than τ_m because an electron usually requires several phonon interactions to dissipate energy, while it is possible for electron-phonon collisions to take place which randomize momentum with a small energy exchange. Typical values (*5*) are in the range of 10^{-13} to 10^{-11} second for τ_m and 10^{-12} to 10^{-10} second for τ_ϵ (*6*).

Let us consider electrons under the influence of a field that is rapidly turned on. If $\tau_m << \tau_\epsilon$ the electrons accelerate to a velocity given by Eq. 4. As the electrons are heated by the field they gain energy and $\tau_m(\varepsilon)$ drops to a lower value. Correspondingly, we see from Eq. 4 that the velocity decreases from its "overshoot" value. The amount of overshoot, if any, depends on the size of the accelerating field, the disparity in relaxation times, and their energy dependence. Monte Carlo calculations (*7*) have been performed which demonstrate this effect. A typical plot of velocity against time is shown in Fig. 2. Whether or not velocity overshoot effects can be used to speed up semiconductor devices depends on the active device length and the time scale of the overshoot. According to calculations by Rusch (*7*), velocity transients are completed in a fraction of a picosecond in silicon.

The mechanism (*8*) for velocity overshoot in a material like GaAs differs from that just described for nonpolar materials. Let us consider the transport of electrons in the central conduction valley in GaAs. When an electric field is rapidly applied, the carriers are heated and can be scattered to a satellite valley. The effective mass in the satellite valley is larger than that in the central valley. During the first few picoseconds, while the electrons are in the central valley, the average electron velocity can exceed or overshoot its quasi-equilibrium value as the carriers move from the central valley (small effective mass) to the satellite valleys (large effective mass). Monte Carlo calculations have established that these transients are important in GaAs (*7, 9*) during the first few picoseconds after the field is switched on. Electron carriers travel less than 1 micrometer in this time period.

In Fig. 1 we have illustrated the relative time scales of interest for velocity transients. The time scale for present-day semiconductor technologies is pushing into the time regime where nonequilibrium transport considerations begin to be important. The time resolution of high-speed optics (*10*) extends well past the limits of present-day electronic technologies and, as we will see, optics is becoming an important tool for investigating ultrafast phenomena in semiconductors.

Velocity Overshoot Measurement

Methods for investigating ultrafast processes in semiconductors by microwave and other techniques extend back several decades. Recently, rapid advances in optical pulse generation and optoelectronic switching techniques have opened up a new range of measurement possibilities. As shown in Fig. 1, picosecond or even subpicosecond time resolution is necessary to investigate nonequilibrium transport processes such as velocity overshoot.

Direct electrical measurements of carrier velocity transients with subpicosecond precision are not possible at this time. However, short pulse optical techniques (*6*) have been recently devised which provide time resolution on this scale. An all-optical approach for measuring carrier velocities (*11*) with subpicosecond time resolution is shown in Fig. 3. A GaAs layer approximately 2 μm thick was grown between two heavily doped $Ga_{0.3}Al_{0.7}As$ layers. A voltage applied across this sandwich structure creates an electric field **E** in the GaAs layer. The electric field modifies the optical absorption in a manner first described by Franz (*12*) and Keldysh (*13*). The field-induced absorption change appears as a displacement of the exponential band tail and exhibits an oscillatory behavior for photons with energies in excess of the band gap.

The basic concept of the measurement technique is to optically inject carriers near the band edge and use the Franz-Keldysh effect to monitor the evolution of the electric field as the holes and electrons drift to opposite ends of the region of applied field. As the carriers drift, a small space-charge field opposite in sign to the applied field grows in time until the carriers reach their respective contacts. The screening field **ΔE** must be kept small compared to the applied field **E**. The small space-charge field induced by the carriers perturbs the optical absorption through the Franz-Keldysh effect. By measuring the induced change in optical absorption as a function of time, we can determine the carrier velocity.

The experiment is performed by exciting the GaAs layer with a short pulse from a passively model-locked dye laser. A second optical pulse, which is spectrally broadened, is used to probe the absorption spectrum at delayed times. The optical absorption spectrum is measured as a function of time delay after excitation by the pump pulse.

The carrier velocity is determined by plotting the change in the optical absorption as a function of time following excitation. Near $t = 0$ the velocity can be determined approximately by the slope function

$$\frac{\partial}{\partial t}\frac{\Delta\alpha(t)}{\Delta\alpha(\infty)} \cong \frac{v_e + v_h}{d} \qquad (5)$$

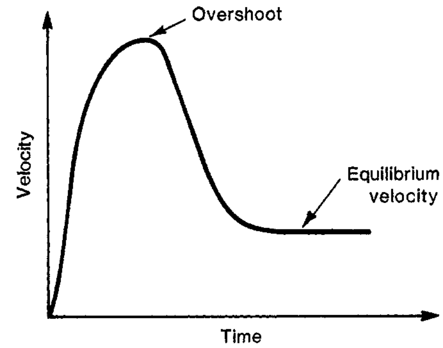

Fig. 2. Plot of velocity against time illustrating velocity overshoot. In this example the electrons are accelerated to an overshoot velocity and then slow to an equilibrium velocity. The time scale is picoseconds or fractions of a picosecond, depending on the semiconductor material.

where $\Delta\alpha$ is the absorbance change, v_e and v_h are the electron and hole velocities, and d is the length. After $t = 0$ a computer fit to the data is required.

The data for an applied electric field of 22 kilovolts per centimeter are plotted in Fig. 3. The points are experimentally measured transmittance changes. The dashed curve is a continuation of a single-velocity computer fit to the data near $t = 0$ for $v_e = 4.4 \times 10^7$ cm/sec. Clearly, this single-velocity curve diverges dramatically from the data for times greater than 2 psec. The data points fall below the dashed curve, indicating that the electrons are slowing down. The solid curve, which more closely fits the experimental data, is two-velocity fit with $v_e = 4.4 \times 10^7$ cm/sec for $t < 1.1$ psec and 1.2×10^7 cm/sec for $t > 1.1$ psec.

A short channel GaAs device could, in principle, take advantage of the experimentally observed factor of 4 transient increase in carrier velocity due to velocity overshoot. An electron moves a fraction of a micrometer in GaAs before slowing down to its equilibrium saturation velocity. In addition to increased speed, velocity overshoot will influence space-charge effects that determine the current-voltage characteristic of short channel devices.

High-Speed Semiconductor Technology

There is considerable controversy over which technology will be most important in high-speed electronic applications. The progress made in silicon integrated circuits over the last 20 years has been extremely impressive and has led to great optimism about the future of this technology. Enormous expenditures of capital on silicon processing have created a highly sophisticated industry. For any new technology based on a semiconductor material other than silicon to be seriously considered, the material must provide significant advantages over silicon. The semiconductors GaAs, InP, and InGaAs, made up of elements from groups III and V of the periodic table, all have significantly higher mobilities and saturation velocities than silicon. The availability of convenient semi-insulating substrate material for the III-V compounds provides an advantage in fabricating arrays of high-speed devices by reducing parasitic capacitances. These materials also have optical properties that are useful for generating and detecting light.

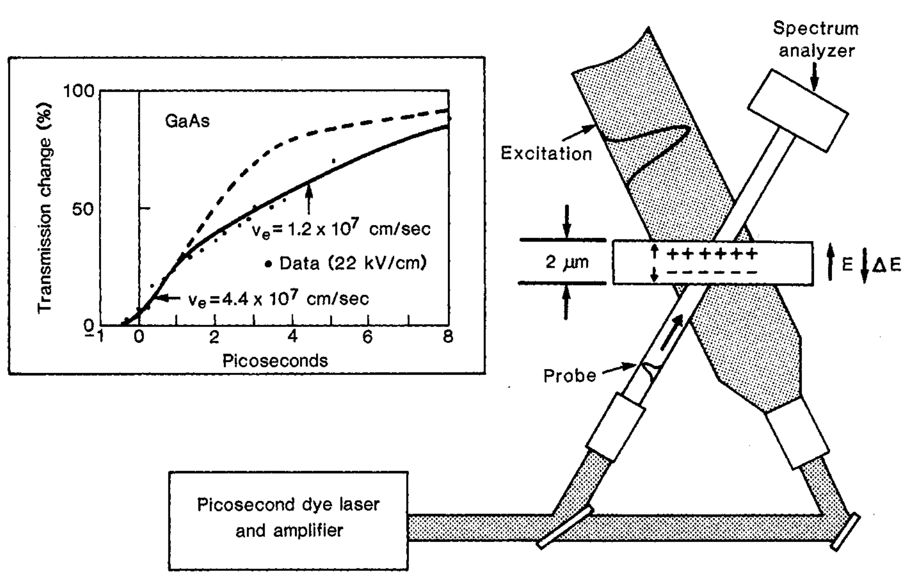

Fig. 3. Diagram of apparatus for making a time-resolved measurement of velocity overshoot in GaAs. (Inset) Plot of measured transmission change against time. The dashed line is a single-velocity fit of 4.4×10^7 cm/sec and the solid line a computer-generated two-velocity fit.

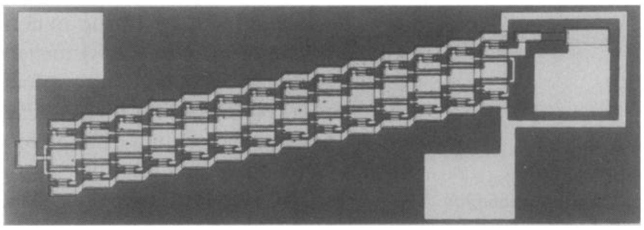

Fig. 4. A 27-stage, high-electron mobility, transistor ring oscillator with output buffer and probe resistor fabricated by Mimura *et al.* (*17*) of Fujitsu Laboratories.

since, in principle, one requires a test instrument whose response is faster than the device under test. When the goal is to make faster devices, this approach clearly fails, and one usually resorts to bootstrap techniques whereby the device measures itself—or, more accurately, an identical device. Examples of this approach are the ring oscillator technique used to estimate the speed of response of the modulation-doped field effect transistor discussed previously. Since the time resolution of this type of measurement is no better than that of the devices themselves, only estimates of speed can be made, and it is not possible to learn any of the details of the response.

In addition to the choice of materials, new concepts in materials fabrication have emerged. Molecular beam epitaxy and other thin-film techniques such as metal–organic chemical vapor deposition (*14*) have opened up new possibilities for materials and devices. One of the most interesting phenomena taking advantage of molecular beam technology is the mobility enhancement first reported by Dingle *et al.* (*15*) in modulation-doped GaAs-$Al_xGa_{1-x}As$ superlattices. These structures consist of alternate layers of undoped GaAs and silicon-doped $Al_xGa_{1-x}As$. Because of the higher electron affinity of GaAs, free electrons in the $Al_xGa_{1-x}As$ layers are transferred to the undoped GaAs layers, where they form a quasi-two-dimensional electron gas.

The measured mobility in the GaAs layers increased from 5,000 to more than 200,000 square centimers per volt per second. The mobility enhancement is attributed to the spatial separation between the electrons and the parent donor impurities. In conventionally doped GaAs the low-temperature mobility (~ 77 K) is limited by impurity scattering. Since the ionized donors and electrons are spatially separated in the modulation-doped structures, the impurity scattering is reduced and the mobility enhanced. Additional mobility enhancement comes about from screening of the impurity interaction by the carriers (*16*).

Mimura *et al.* (*17*) reported a new field effect transistor structure in which modulation doping mobility enhancement is used. In Fig. 4 we show a photograph of a ring oscillator made with a modulation-doped structure. The ring consists of 27 transistors. From the ring oscillation frequency, an average switching delay of 17.1 psec per stage was measured with a power dissipation of 0.96 milliwatt at the temperature of liquid nitrogen. This is the shortest switching delay reported so far for a semiconductor logic technology and is comparable with the shortest delay time reported for Josephson junction logic (13 psec) (*2*). On the basis of these results, Mimura and co-workers expect to achieve switching delays below 10 psec with a power dissipation of about 100 μW per stage.

Picosecond Optical Electronics

Another area where optics shows promise of providing a unique interface with electronics is that of very high speed test instrumentation. One of the difficulties faced by developers of new high-speed electronic components is the lack of accurate techniques for evaluating and characterizing device performance. The problem is a fundamental one

An alternative approach is to draw on a related, but higher speed, technology to provide the necessary time precision. Since optical pulse techniques are almost three orders of magnitude faster than electronics, they have the potential for making electronic measurements with greatly enhanced speed. To achieve this, it is essential to have very high speed transducers that can couple the two technologies. Recently, it was demonstrated that photoconductors made of semiconductors with high defect densities can act as optical-electronic transducers with response times of 8 psec or less (*18*). When illuminated by picosecond optical pulses, these photoconductors function as picosecond electrical pulse generators and sampling gates. Materials such as amorphous and radiation-damaged semiconductors are ideal for this purpose, since they have carrier lifetimes as short as 4 psec (*18*). When introduced into high-speed electronic circuits, they provide a capability for generating and measuring electronic events with greatly improved time precision. The timing is controlled by introducing variable path

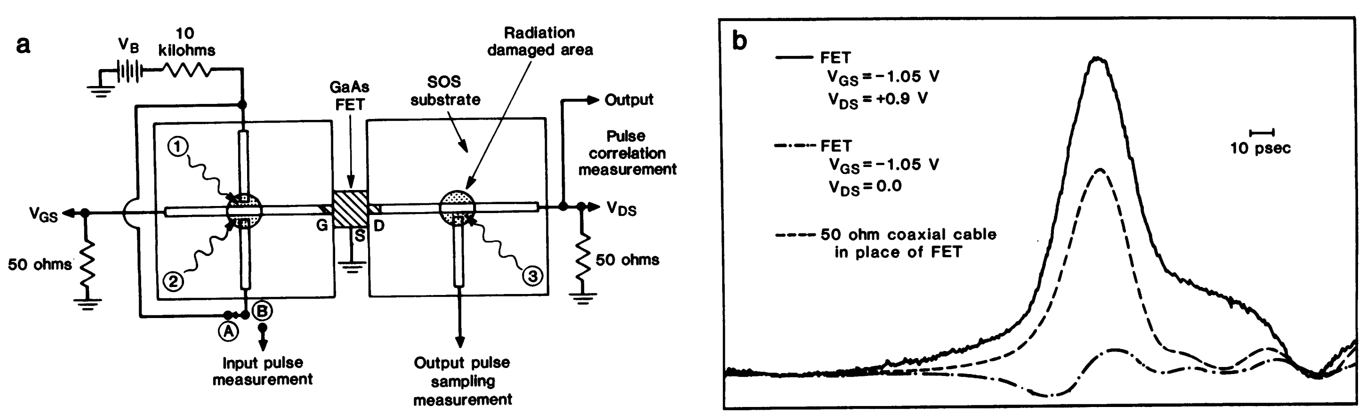

Fig. 5. (a) Schematic of picosecond optical electronic circuit used to measure the electronic response of a GaAs field effect transistor. Picosecond optical pulses, indicated by wavy lines 1, 2, and 3, are focused on gaps in the microstrip transmission lines where very high speed photoconductors have been made by damaging the silicon-on-sapphire wafers with radiation. (b) Electronic response of an FET with the circuit shown in (a). (Solid line) Impulse response when photoconductor 1 is used as the pulse generator and 3 as the sampling gate under bias conditions for optimum gain (+3.7 decibels). (Dashed curve) Impulse response with the FET replaced by a 50-ohm transmission line. (Dash-dot curve) Impulse response of the FET with no drain bias.

lengths into the optical pulses used to illuminate the photoconductors, and the measurement is essentially free of jitter.

An example (*19*) of this approach is illustrated in Fig. 5a. In this case, high-speed photoconducting pulse generators and sampling gates were used to measure the electronic impulse response of a GaAs field effect transistor (FET). Argon ion bombardment at 2 million electron volts was used to increase the speed of a 1-μm silicon-on-sapphire epitaxial film. The photoconducting regions were located at gaps in microstrip transmission lines, so that when they were illuminated by optical pulses a short burst of electrical charge could be transferred from one microstrip line to another. In this way, short electrical pulses produced by optical pulses 1 and 2 could be used to activate the gate (G) of the FET. The current response of the FET emanating from the drain (D) was then sampled by a third optical pulse, which transferred a fraction of the signal to the sampling line. The complete temporal response was measured by continuously varying the relative timing between optical pulses 1 or 2 and 3 and averaging the sampled signal at a high repetition rate (80 megahertz). Having two photoconductors at the input side provided added flexibility, making it possible to sample the input electrical pulse for calibration.

Some typical results are illustrated in Fig. 5b. Three curves are shown. The dashed line is the system response when the FET is replaced by a continuous transmission line. When the FET is inserted, but without a d-c drain-source bias, the capacitively coupled response indicated by the dash-dot curve was obtained. When the drain-source bias was turned on (solid curve) a net gain was observed, and the signal revealed two components: one almost as fast as the system response, and a slower tail extending out to 75 psec. This example illustrates the potential for using optical pulses to make precision electronic measurements. Although a dye laser was used in this case, pulsed semiconductor lasers could also be used to make a compact integrated device. A wide variety of high-speed devices, including photodetectors and diodes, as well as transistors and thin-film and bulk electronic materials can be measured by this method. It is anticipated that further improvements in the photoconducting materials and circuits will result in an electronic measurement system with a resolution of 1 psec.

Future

Advances in microfabrication techniques should make possible the construction of high-speed semiconductor devices with submicrometer channel lengths which take advantage of the velocity transients described in this article. New materials and device geometries are likely to produce a new generation of high-speed logic devices.

As high-speed very large scale integrated circuits are constructed, the coupling between devices will become of paramount importance. Fan-out ratios (that is, the need to drive several outputs) and load capacitances will place demands on the current levels available from high-speed devices. Transmission line dispersion will be a severe problem for sending picosecond electrical pulses (*20*) more than 100 μm. Low-dispersion superconducting interconnections could alleviate this problem. It is possible that semiconducting and superconducting technologies could be combined to take advantage of the high drive current levels of semiconductors and the low dispersion of superconducting interconnections.

Single-mode optical fiber waveguides promise to transmit data at rates as high as 1 terabit per second over kilometer distances. Optical fibers would be particularly useful as high-speed data links between electronic processors. The prospect of optically interconnecting small electronic circuits is an intriguing one. At present, the inefficiency of converting electrical to optical signals limits the feasibility of this approach.

The optoelectronic devices that we have described may be the precursors of a high-speed interface between optics and semiconducting electronic devices. The optical properties of III-V compounds make them particularly suited to this application.

As new high-speed semiconductor technologies are developed, a more detailed understanding of time-dependent processes will be required. Short optical pulse techniques will play an important role in this process.

References and Notes

1. C. V. Shank and E. P. Ippen, *App. Phys. Lett.* **24**, 373 (1974).
2. D. G. McDonald, R. L. Peterson, C. A. Hamilton, R. E. Harris, R. Kautz, *IEEE Trans. Electron Devices* **ED-27**, 2945 (1980).
3. W. Anacker, *IBM J. Res. Dev.* **24**, 107 (1980).
4. R. W. Keyes, *Proc. IEEE* **69**, 267 (1981).
5. See, for example, K. Seeger, *Semiconducting Physics* (Springer-Verlag, New York, 1973), p. 52.
6. C. V. Shank, R. L. Fork, R. F. Leheny, J. Shah, *Phys. Rev. Lett.* **42**, 112 (1979).
7. J. G. Rusch, *IEEE Trans. Electron Devices* **ED-19**, 652 (1971).
8. H. Kroemer, *Solid State Electron.* **21**, 61 (1978).
9. T. J. Maloney and J. Frey, *J. Appl. Phys.* **48**, 781 (1977).
10. R. L. Fork, B. I. Greene, C. V. Shank, *Appl. Phys. Lett.* **39**, 671 (1981).
11. C. V. Shank, R. L. Fork, B. I, Greene, *ibid.* **38**, 104 (1981).
12. W. Franz, *Z. Naturforsch.* **13**, 484 (1958).
13. L. V. Keldysh, *Sov. Phys. JETP* **7**, 788 (1958).
14. H. M. Manasevit, *J. Cryst. Growth* **55**, 1 (1981).
15. R. Dingle, H. L. Störmer, A. C. Gossard, W. Wiegmann, *Appl. Phys. Lett.* **33**, 665 (1978).
16. K. Hess, *ibid.* **35**, 484 (1979).
17. T. Mimura, K. Joshin, S. Hiyamizu, K. Hikosaka, M. Abe, *Jpn. J. Appl. Phys.* **20**, 598 (1981).
18. D. H. Auston, A. M. Johnson, P. R. Smith, J. C. Bean, *Appl. Phys. Lett.* **37**, 371 (1980); P. R. Smith, D. H. Austin, A. M. Johnson, W. M. Augustyniak, *ibid.* **38**, 47 (1981).
19. P. R. Smith, D. H. Auston, A. M. Augustyniak, *ibid.* **39**, 739 (1981).
20. R. L. Kautz, *J. Res. Natl. Bur. Stand.* **84**, 247 (1979).