Multiple Quantum Wells for Optical Logic

Structures comprising alternating layers of gallium arsenide–based semiconductors are candidates for the optical analog of transistors

Artificially structured materials and quantum mechanical engineering are terms that reflect the increasingly sophisticated ability of materials scientists to fabricate materials with structures and properties unknown in nature. At the 1984 Conference on Lasers and Electro-Optics (held in Anaheim, California, 19 to 23 June), researchers heard about two new ways to use one type of artificial structure called multiple quantum wells as optical devices that perform logic operations the way transistor circuits do.

With the tremendous civilian and military interest in ultrahigh-speed digital computers and signal processors and in wide-bandwidth digital communications systems, it is no surprise that engineers would consider operating on streams of photons rather than electrons. After all, what goes faster than light? However, the properties of photons and electrons are somewhat complementary. So an optical computer, to take one example, is not very likely to have the same organization as today's electronic machines, with the only difference being that optical transistors switch beams of light in miniaturized waveguides on a chip.

Even the speed of light is misleading. Electrical signals in waveguides travel nearly that fast. The big speed advantage of optics comes in highly parallel systems. Today's electronic computers are mostly serial machines. They carry out instructions sequentially, one after the other. Computer scientists well recognize that carrying out parts of a computation in parallel in separate processor units dramatically increases the speed. Unsolved to date are the problems of how to subdivide the computation and arrange the connections between processors for general rather than special-purpose machines.

Because optical devices can be put into two-dimensional arrays with the input and output signals traveling perpendicular to the array, optical systems are inherently parallel. Peter Smith of AT&T Bell Laboratories, in an invited laser conference talk on optical switching and logic, cited a telecommunications example. To transmit a high-resolution digital television image requires devices in a serial processor to operate at 10^9 bits per second; that is, each transistor would have to have a response time of less than 1 nanosecond.

On the other hand, an optical device of area 1 square centimeter could accept 10^6 light beams, each of 10-micrometer diameter from a miniature solid-state laser. Each irradiated area would only have to respond in 1 millisecond to handle the TV image. Moreover, experimental multiple quantum well (MQW) switches have reacted in 30 nanoseconds, giving a theoretical capability of 30,000 simultaneous TV transmissions.

How might an optical logic device work? One alternative derives from the nonlinear optical effect called optical bistability. Bistable optical devices switch from being relatively opaque to being transparent (or vice versa) when the intensity of the light passes a critical level. Abraham Szöke and his colleagues at the Massachusetts Institute of Technology predicted the existence of the phenomenon in 1969. In 1976, Hyatt Gibbs (now at the University of Arizona), Samuel McCall, and Thirumalai Venkatesan of Bell Labs reported seeing the effect in a Fabry-Perot optical cavity filled with sodium vapor.

An optical computer is not very likely to have the same organization as an electronic machine.

A Fabry-Perot cavity (also called an interferometer, etalon, or resonator) comprises two partially reflecting mirrors. Sodium vapor is a nonlinear optical medium, which is to say that its optical properties depend on the intensity of the light. The relevant nonlinearity for optical bistability is that of the index of refraction, which grows when the light intensity increases.

Semiconductors provide a more practical bistable optical device than sodium vapor. In 1979, David Miller (now at Bell Labs), S. Desmond Smith, and Arthur Johnston of Heriot-Watt University in Edinburgh and the Bell Labs group nearly simultaneously published accounts of optical bistability in semiconductors. The Scottish team worked with indium antimonide, initially at a temperature of 5 K and later 77 K. The Americans studied gallium arsenide at temperatures below 120 K.

One example of the subsequent development of the field is the work of Miller, Eitan Abraham, Colin Seaton, Smith, and several co-workers at Heriot-Watt, who demonstrated a way to use optical bistability to get transistor-like behavior and perform logic operations. Transistors, for example, exhibit gain; that is, the output signal can be higher than the input. The Heriot-Watt group used two lasers. One continuously irradiated the indium antimonide with intensity just below the critical switching point. The second, weaker, laser provided the input signal. A pulse from this source was just intense enough to switch the device from the low to the high transmitting state. However, the output pulse is as intense as the continuous holding light, thereby illustrating gain.

Getting to room temperature is the next step, and this is where MQW's first arrived on the optical logic scene. The MQW's come about when periodic structures comprising alternating ultrathin layers are constructed of two semiconductors with different electrical and optical properties but with crystal structures having nearly identical lattice spacings. The matching lattices ensure a continuous crystal with few defects.

Multiple quantum wells are made by the technique of molecular beam epitaxy (*Science*, 23 May 1980, p. 916), which is capable of depositing layers only one atom thick, but 100 angstroms or more is a more typical thickness for each layer of a bistable optical device. For this application, the semiconductors are gallium arsenide and the pseudobinary alloy aluminum gallium arsenide, where the relative proportions of aluminum and gallium are variable over a wide range.

The minimum energy for free electrons is lower in gallium arsenide than in aluminum gallium arsenide. Electrons therefore tend to congregate in the lower energy material, whose layers comprise the wells. Moreover, because the layers are so thin, the energy levels available to electrons moving perpendicular to the boundary between layers no longer make one nearly continuous band but split into a few discrete bands. This is the quantum nature of the well and gives the MQW structure electrical and optical properties that are qualitatively different from those of either of the base semiconductors.

Most of the MQW's that find their way into bistable optical devices have come from the laboratory of Arthur Gossard and William Wiegmann of Bell Labs. In 1982, two groups used their material in research that demonstrated room temperature effects: Gibbs and several collaborators at Arizona and Bell Labs and Miller and several Bell Labs colleagues.

Entities called excitons play a crucial role. The fundamental optical absorption in semiconductors occurs when bonding or valence electrons are excited to the lowest energy states for free electrons. At low enough temperatures, the electrostatic attraction between such an electron and the positively charged electron vacancy or "hole" that is left behind is sufficient to bind them together, forming an exciton. Excitons give rise to sharp absorption lines at wavelengths slightly longer than that at which the broad fundamental absorption begins.

As it turns out, the nonlinear refraction index in gallium arsenide traces to exciton effects. At very high laser intensities, the exciton absorption saturates (the absorption coefficient decreases), and this translates into a change in the index of refraction. The mechanism in indium antimonide is different.

Excitons tend to be thermally ionized at room temperature in both ordinary gallium arsenide and MQW material. However, in MQW's the exciton binding energy is substantially increased because of the quasi–two-dimensional nature of the thin gallium arsenide layers. Because the excitons are more stable, researchers thought that MQW's would be more likely to exhibit optical bistability at room temperature. An additional benefit that seemed to be just as important is that the magnitude of the nonlinear effect is also increased, so less energy would have to be absorbed to bring about the switching effect. Recent experiments at Arizona suggest, however, that ordinary gallium arsenide works just as well at room temperature.

In any case, at Anaheim, Jack Jewell (now at Bell Labs), Michael Rushford, Yong Lee, Mial Warner, and Gibbs reported the achievement with MQW's of logic operations that they had earlier tested with dye-filled Fabry-Perot cavities. Their method, like the one at Heriot-Watt, makes use of two lasers, which they call the input and the probe. But the similarities end there. Unlike the earlier work, logical operations do not follow from using an intense enough laser to induce a transition between low and high transmitting states. Instead, the idea is to use the input laser to set the wavelength at which the device is transmitting. The wavelength of the probe laser determines the type of logical operation.

Because of constructive interference of the light reflecting back and forth within a Fabry-Perot cavity, coherent light (such as that from a laser) entering the cavity from one end emerges from the other end with nearly full intensity, provided that the length of the cavity is a half-integral number of wavelengths, the resonance condition. Off resonance, almost all the light is reflected back toward the source with little or no light transmitted.

The resonance condition depends on the index of refraction because the wavelength of light in a medium other than vacuum is shortened by $1/n$, where n is the index of refraction. It is therefore possible for researchers to shift the resonance in MQW's or other nonlinear optical materials by increasing or decreasing the laser intensity. In the logic demonstrations, the input laser wavelength and intensity are adjusted so that a pulse of irradiation temporarily shifts the resonance wavelength one full width half maximum. Two simultaneous pulses shift the resonance two such distances. The wavelength of the probe laser is set at the initial resonance, at one of the two shifted resonances, or halfway between shifted neighboring resonances.

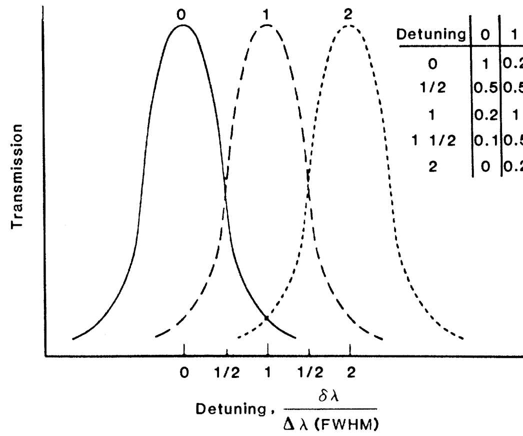
In digital logic, circuits called gates perform the logical operations. For example, an AND gate has two inputs and one output. The inputs can be high (binary 1) or low (binary 0). The output is high only if both input 1 and input 2 are high. To make an optical AND gate, the probe wavelength is set at two full width half maxima from the initial resonance. The device will transmit the probe pulse only if it receives two input pulses (two highs). Other logic operations are shown in the figure.

The logic device consists of a central MQW section of total thickness 1.0 micrometer. The gallium arsenide and aluminum gallium arsenide layers are 76 and 81 angstroms thick, respectively. Buffer layers of aluminum gallium arsenide give a total thickness of 1.25 micrometers to the cavity. Although the logic operations themselves take only a few picoseconds, the device relaxes to the initial resonance condition in about 5 nanoseconds after the pulses pass, which sets the response time. Devices have operated with pulses coming at rates up to 82 megahertz.

To speed up operation, it is necessary to increase the rate at which free electrons and holes created by absorption of the laser light recombine. Jewell told *Science* that there are ways to do this that could decrease the response time to 100 picoseconds or less.

The energy in the input laser pulse is less than 8 picojoules. One method of reducing the energy further would be to narrow the width of the resonance, as this would decrease the distance the input pulse would have to shift the resonance. Accomplishing this requires a very high quality optical cavity, which places tighter tolerances on fabrication. However, mirrors that are sufficiently flat and parallel are readily available.

Switching energy is a major problem in both electronic and optical devices because the energy must be dissipated as heat. If the switches are packed closely together and operate rapidly, the heat load is too high and the devices fail. Two years ago, Peter Smith at Bell Labs published a lengthy review of optical devices that many took to be quite pessimistic. Smith argued that fundamental considerations dictated that heat dissipation limitations would preclude simply plugging optical transistors into systems



Detuning	0	1	2	T	R
0	1	0.2	0	NOR	OR
1/2	0.5	0.5	0	NAND	(AND)
1	0.2	1	.2	XOR	$\overline{\text{XOR}}$
1 1/2	0.1	0.5	0.5	OR	(NOR)
2	0	0.2	1	AND	NAND

Optical logic

The curves show the transmission of the Fabry-Perot cavity as a function of laser wavelength for 0, 1, and 2 input pulses. The wavelength of the probe laser is set at one of the five detuning values indicated. The table gives the transmission of the probe laser for all combinations of number of input pulses and probe pulse wavelength. Logic operations listed under T are those obtained by observing the transmitted light, while operations under R are those from reflected light. [Redrawn from Appl. Phys. Lett. **44**, *172 (1984)]* designed like existing electronic digital computers or signal processors.

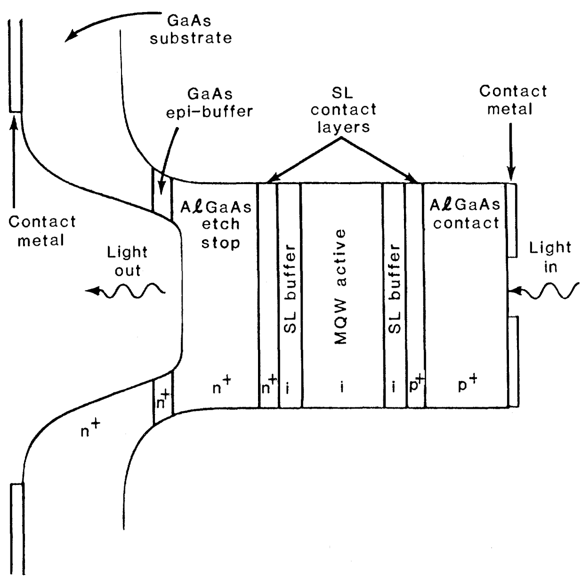
In his laser conference talk, Smith did not exactly recant. But, to a questioner who asked, "Wasn't your article a kiss of death for optical logic?" he responded that it was a matter of finding optically nonlinear transparent materials that did not absorb energy or of developing systems designs that did not require large numbers of rapidly switching devices to be in close proximity. In addition to the already cited example of massively parallel systems, one could envision extremely fast (less than a picosecond) devices that only had to switch intermittently, for example.

With the laser focused to a 10-micrometer-diameter spot, the 8 picojoules in the Arizona experiments translate to about 100 femtojoules per square micrometer. At the laser conference, Miller discussed work by him and several colleagues at Bell Labs on a quite new type of bistability in MQW's with a total switching energy density of less than 18 femtojoules per square micrometer. Moreover, there is no Fabry-Perot cavity, so device construction is simplified. It even has an acronym—SEED, for self electrooptic effect device.

An electrooptic effect is one in which an electric field modifies the optical properties of a material. In the SEED, the field shifts the exciton and fundamental absorptions to longer wavelengths by amounts proportional to the field strength. This effect was reported this year at Bell Labs by Tom Wood, Charlie Burras, Miller, Daniel Chemla, Ted Damen, Gossard, and Wiegmann, who found that fields of the order of 10^4 to 10^5 volts per centimeter could induce shifts in the room-temperature positions of MQW exciton absorption lines of about 1 percent. The large shift is due to the quantum wells, which confine the excitons so that the intense electric field cannot dissociate them. Keeping the laser wavelength fixed, they observed that the absorption changed by a factor of 2 as they applied the field.

SEED structure

The structure is built up by molecular beam epitaxy on a heavily n-type (n$^+$) *gallium arsenide substrate. Superlattice (SL) buffer and contact layers are MQW material that is transparent to the laser light, as are the aluminum gallium arsenide contact layers. A hole is etched through the opaque gallium arsenide substrate. Light enters the device from the top and exits through the hole in the substrate. The top metal contact is negative with respect to the substrate contact, thereby reverse-biasing the* p-i-n *diode. [Redrawn from* Appl. Phys. Lett. **44,** *16 (1984);* ibid. **45,** *13 (1984)*]



In the meantime, Miller, Gossard, and Wiegmann were exploring the consequences on optical bistability of an absorption that increased with laser intensity rather than decreased, as in earlier MQW work. Gallium arsenide–aluminum gallium arsenide MQW's can exhibit such behavior because the wavelength of the exciton and fundamental absorptions increase as the sample temperature rises. Absorption of laser light can heat up the small MQW's significantly, but usually they are mounted on heat sinks to avoid this.

Miller, Chemla, Damen, Gossard, Wiegmann, Wood, and Burns put these two effects together in the SEED, which makes use of an electric field rather than temperature to cause increasing absorption. The device comprises 50 layers of 95-angstrom-thick gallium arsenide separated by 98-angstrom aluminum gallium arsenide layers, together with thicker buffer and electrical contact layers (see figure). One contact layer is *n*-type (conducts by way of free electrons), the other *p*-type (conducts by way of holes). The MQW and buffer layers are nonconducting. The entire structure is a diode; that is, it conducts electricity if the *p*-type contact layer is positive (forward bias) but not if it is negative (reverse bias).

A voltage source, a resistor, and the SEED form a series electrical circuit. With the SEED reverse biased, the voltage is mainly across the MQW part of the device. The resulting electric field shifts the MQW exciton lines to longer wavelengths, so that laser light whose wavelength is near the zero-field exciton line is only weakly absorbed. As the laser intensity increases, the free electrons and holes from dissociating excitons lower the resistance of the SEED, so that less of the voltage is across it and more is across the resistor. The lower voltage releases the exciton line back toward its normal position, resulting in increasing absorption, in a positive feedback scenario, until the exciton line and the laser wavelength match. Then the SEED switches from high transmitting to low transmitting because of the greatly increased absorption.

As for optical logic, Miller says that the SEED could in principle be used in previously proposed schemes. Right now, the important point is the demonstration of a low switching energy. There are two energies relevant to the SEED, optical and electrical. With a large, by optical standards, device of 600 micrometers diameter, the energy in the laser pulse causing switching was 1 nanojoule, and somewhat more than 4 nanojoules was dissipated in the electrical circuit.

However, the switching energies per unit area were 4 and 14 femtojoules per square micrometer, respectively, giving the total previously cited. Taking advantage of these low figures will require smaller devices and the concomitant adoption of microfabrication techniques of the type common in integrated circuit manufacture, which may be a fair tradeoff for not having to build a high-quality Fabry-Perot cavity.

Two other items are also on the agenda. One is increasing the contrast in the transmission between the high and low transmitting states, which is about 2:1 as compared to 6:1 in the MQW devices that Jewell and his colleagues are working with. The other is speeding up the response time, which is limited by the *RC* time constant of the circuit rather than any intrinsic properties of the SEED. Miller says he is very confident that 10 nanoseconds is reachable and perhaps 1 nanosecond as well.

None of this means that optical logic is poised for taking over of the computing and signal processing industries. A good perspective on optical logic of any type came from S. Desmond Smith of Heriot-Watt, who closed his own invited talk at the laser conference on nonlinear optics with the observation that no one is claiming the emergence of a new technology. For the moment, there are lots of interesting results and a lot of work to do.

—Arthur L. Robinson