

Optoelectronic applications of quantum wells

By D.A.B. Miller

The successful applications of optics in communications and in consumer electronic products give us great confidence in, and renewed expectations for, optics and optoelectronics. We hope to continue making new and better systems by combining the complementary abilities of these two fields. Optics excels in some areas where electronics is weaker, such as in communication of information. The challenge—and the opportunity—is to get the best out of both. However, this creates a demand for new optoelectronic devices.

One key technology here is layered semiconductor growth. We already use this technology to make many of our optoelectronic devices, such as laser diodes. Layered semiconductors are also well suited for integrating both electronics and optics in one structure. With the additional possibility of very thin layers (e.g., 100 Å), they allow us to use quantum mechanics as an engineering tool. This new freedom may enable us to make the devices that we lacked in the crucial area of overlap between optics and electronics.

The devices discussed here are the start of the realization of these ideas. We find new physical mechanisms in such thin-layered structures, and we can make real devices with very attractive performance characteristics and impressive yields. Some of these devices are quite unlike anything we were able to make before. They are applicable both in small numbers in waveguide systems and in very large numbers in two-dimensional optical device arrays.

This article will introduce some of the concepts of very thin layers and describe a few of the resulting novel kinds of devices.¹ These “quantum well” and “superlattice” structures permit new optical modulators and switches, including some very large arrays of devices that allow us

seriously to contemplate two-dimensional optical logic systems. (They also, incidentally, give us various novel electronic devices.) The discussion will also show how these optoelectronic devices may be incorporated with electronics, perhaps ultimately to attain that goal of having the best of both electronic and optical worlds.

Quantum wells and superlattices

Figure 1 shows schematically a typical multiple layered structure consisting of alternate layers of two different

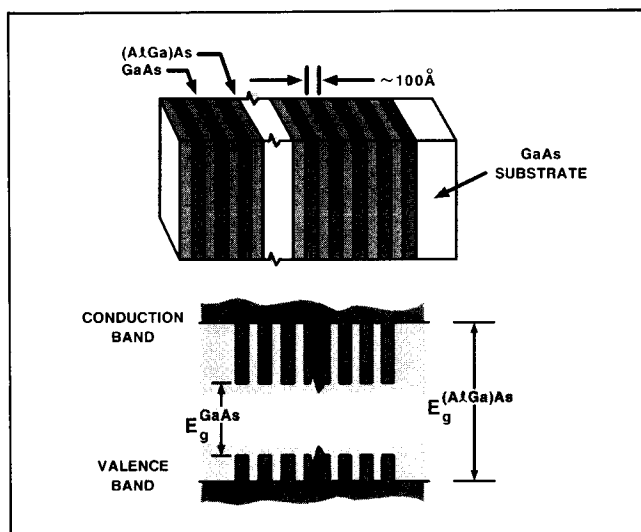


FIGURE 1. Schematic illustration of a multiple quantum well structure. The top figure shows the actual layer structure of alternating GaAs and AlGaAs layers on a GaAs substrate. The bottom figure shows the band structure. E_g is the bandgap of the material. The energy of a hole in the valence band should be viewed “upside down.” The hole also sees lower energy in the GaAs layer.

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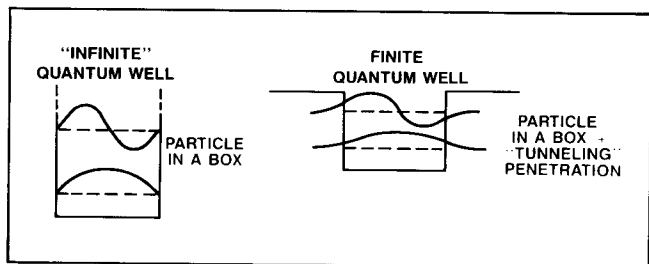


FIGURE 2. Wavefunctions in an idealized "infinite" quantum well and in a realistic "finite" well.

semiconductor materials. Such a structure with layer thicknesses of ~ 100 Å (about 40 atoms) can be grown using modern techniques such as molecular beam epitaxy (MBE) or metal-organic chemical vapor deposition (MOCVD), otherwise known as organo-metallic vapor phase epitaxy (OMVPE).

A typical multiple quantum well structure might consist of about 100 such layers altogether, giving a total thickness of about $1\text{ }\mu\text{m}$. Such a structure would take about one hour to grow in an MBE machine. We can grow almost arbitrary structures down to the level of individual atomic layers in micron thick structures using such techniques. We can control the compositions of AlGaAs alloys and can dope layers either p-type or n-type or leave them undoped. In addition, we can use the same growth techniques to make refractive index structures such as waveguides or even multi-layer dielectric mirrors. These latter structures are, of course, on slightly larger length scales, such as 1000 Å to a few microns.

The special properties of very thin layers (*e.g.*, 100 Å) come from the relatively simple quantum mechanical problem of confining particles in boxes. The electron wave sees itself as being in a box or "well" in a GaAs layer, surrounded by AlGaAs walls or "barriers." For illustration, we could presume the walls are infinitely high—a so-called "infinite well" (see Fig. 2). Quantum mechanics then says that there can be no wave amplitude inside the walls because there is no chance of finding the electron there. Hence, we have zero wave amplitude at both sides, giving standing wave patterns, sine waves with zeros at the walls. There are, therefore, only certain allowed wavelengths or "states" for the electron. The electron motion is quantized, with discrete energies corresponding to the different allowed wavelengths.

In GaAs and AlGaAs, both the electron and its positively charged equivalent in the valence band—the hole—see minimum energy within the GaAs layer. This is a so-called "type 1" material system; these systems are the most used for devices so far.

In a normal "bulk" semiconductor, we get an absorp-

tion spectrum starting at the bandgap energy and rising smoothly with higher photon energy. For GaAs, this bandgap energy is about 1.42 eV, corresponding to a wavelength of about 870 nm. In the quantum well, because of the quantization of both electron and hole energies, we get a spectrum with a series of steps corresponding to absorption between these discrete states (see Fig. 3).

The widths of the steps are typically of the order of 50 to 200 meV, and hence are very easily seen even at room temperature. At the edge of each of these steps we can also see sharp and clear peaks called exciton peaks. In bulk materials, such peaks can only be seen at low temperatures. When we absorb at these exciton peaks, we are really creating not separate electrons and holes, but pairs of an electron and a hole orbiting round about one another like a very large hydrogen atom.

In bulk GaAs, such excitons would be about 300 Å in diameter. In quantum wells, however, they are squeezed much closer, typically of the order of 100 Å. This makes the exciton a much more tightly bound and stable state, which helps us see it at room temperature. These excitons greatly improve the operation of some of the devices discussed below by making the absorption stronger and more abrupt in the important spectral region near the bandgap where these devices work.

Putting several quantum wells together, as in Fig. 1, gives a multiple quantum well (MQW) structure. Provided

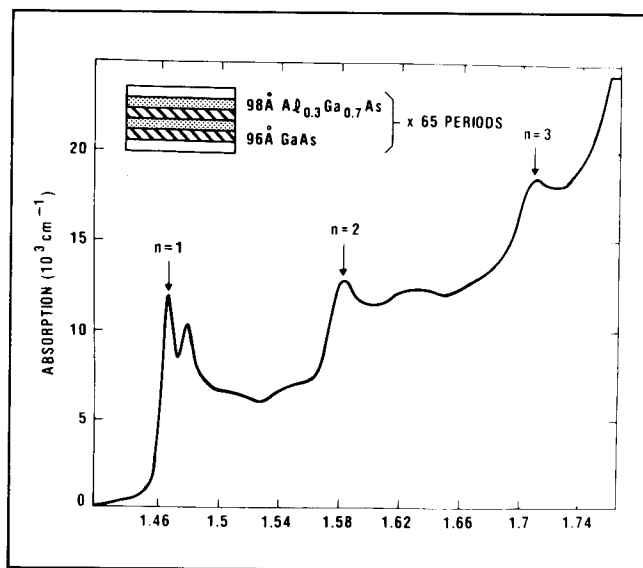


FIGURE 3. Room temperature optical absorption spectrum of a typical quantum well material. $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ is an AlGaAs alloy with 30% Al. $n=1,2,3$ refers to the electron and hole levels involved in the transitions. There are two sets of peaks corresponding to the two different kinds of holes ("heavy" and "light") in the valence band.

the barriers are thick enough, this behaves like many separate wells. In reality, we must also remember that the AlGaAs barriers are not infinitely high walls. In fact, both electrons and holes quantum-mechanically "tunnel" some way into the walls, as shown for the "finite well" in Fig. 2. If we make the walls too thin, then we may actually couple the electrons or holes in adjacent wells. This can be useful to us in devices, for example in coupled wells, as noted briefly below.

If we make many such wells with only thin barriers between them, then we obtain what is best described as a "superlattice," a structure where all of the electron levels are coupled together to form a new kind of material—a "lattice of lattices." Now the electrons and holes are not really confined within any one layer. Superlattices are also interesting for devices. They show some different mechanisms from those of quantum wells, although there is a close relation between the mechanisms.

We can make both quantum wells and superlattices in many different kinds of materials. GaAs and AlGaAs have almost identical lattice constants (spacing between atoms), so arbitrary epitaxial structures can be grown. InGaAs wells with InP or InAlAs barriers, grown on InP substrates, also work well, and are compatible with 1.5 μm wavelengths for optical fibers. Use of InGaAsP can make quantum wells for 1.3 μm wavelengths. Quantum wells can also be made using many other III-V and II-VI materials. Many of the possible systems are under active research at the moment. There are possibilities for quantum wells extending all the way from the visible spectrum into the mid-infrared region near 10 μm . It is also possible to grow layered semiconductor structures that are not perfectly lattice-matched. In this "strained" case, there are some limits on useful layer thicknesses, but many interesting structures are possible.

Quantum wells can make different kinds of devices. They have been very successful in improving the performance of semiconductor laser diodes² and can also make novel long-wavelength (e.g., 10 μm) photodetector modulators using the transitions between the electron levels in the conduction band.³ Quantum wells can also be used to make many novel kinds of electronic devices, including high-speed field effect transistors and resonant tunneling structures.⁴ The same growth technology can also be used for high-speed heterojunction bipolar transistors. All of these different kinds of devices can, in principle, be integrated with quantum wells or superlattices to make them into optoelectronic devices. It is also likely that we will be able to come up with new kinds of devices that are neither truly optical nor electronic, but are optoelectronic from their basic physics; the simplest self-electro-optic-effect devices are primitive examples of this.

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Quantum well modulators

Quantum wells let us make various new kinds of modulators. In an optical modulator, we change a voltage or current to change the transmission of a light beam. We can change the amplitude with absorption changes or the phase through refractive index. By interfering the beam with another beam, we may make an amplitude modulator using refractive effects as well.

The first new major mechanism to be investigated in quantum wells for optical modulation is the quantum-confined Stark effect (QCSE). In bulk semiconductors, when we apply fields we generally see a broadening of the optical absorption edge. Such an effect can be used to make modulators, although it usually requires waveguide structures. Applying electric fields perpendicular to the quantum well layers gives an actual shift of the absorption edge. The sharp absorption features, such as the exciton peaks, are retained. This electroabsorption phenomenon is the QCSE.

When we apply an electric field perpendicular to a quantum well, the electron and hole tend to move toward opposite sides of the well. This polarization reduces the energy of the electron and hole, because each can be viewed as having run "downhill" toward the appropriate electrode. The energy required to create an electron and a hole is reduced, so the exciton absorption peak moves to lower energy. Importantly, as we do this, the walls of the well stop the electron and hole from going too far. The electron and hole can still orbit about one another, even though they are displaced. If the walls were not there, the electron and hole could be totally ripped apart, "field-ionizing" the exciton. (It is the rapid field-ionization that prevents us from seeing this effect in bulk materials, because then the Heisenberg uncertainty principle prevents us from seeing a sharp absorption line for a short-lived particle.) The effect is called a Stark effect by analogy with the slight "Stark" shift in atomic absorption lines in a hydrogen atom in the presence of a strong electric field. To see this particular effect with an actual hydrogen atom would

require confining it within about 0.5 Å and applying a field of 10^{10} – 10^{11} V/cm.

The classic structure for a QCSE modulator is a p-i-n diode is shown in Fig. 4. (The "i" region is "intrinsic," *i.e.*, undoped.) As we reverse bias this diode, we apply an electric field perpendicular to the quantum well layers. We can make a modulator by passing a light beam either perpendicular to the layers (as shown) or in the plane of the layers in a waveguide configuration. One qualitatively new aspect of such modulators is that the QCSE absorption changes are so large that we get useful modulation (*e.g.*, a factor of 2 or 3) even in a single pass through only one micron of material. Hence we can make two-dimensional arrays of devices for arrays of light beams propagating perpendicular to the surface.

One reason for interest in these modulators is their very low operating energy. In contrast to many optical devices, the energy density required for quantum well modulators is quite comparable to that at which electronic devices normally run. Therefore, we may hope to integrate them usefully with electronics, for example. The basic operating energy is the energy required to charge the device capacitance. For a hypothetical $10 \times 10 \mu\text{m}$ modulator that is $1 \mu\text{m}$ thick, the capacitance is ~ 12 fF. With a typical drive voltage of 5 V, the energy is $(1/2) C V^2 = 140$ fJ. Although this energy is larger than the logic energy of a low energy electronic device, it is much smaller than the energy required to drive a bonding pad on an electronic chip. Also, although such a device is larger than the smallest electronic logic gate, it is much smaller than a bonding pad. Devices approaching these dimensions are now being made in large numbers integrated within self-electro-optic-effect devices (see below). In operation, there is also the power dissipation from any photocurrent generated in the diode by the absorbed power. Waveguide devices can also be

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made with fewer quantum wells and hence lower voltage drive (*e.g.*, 1V).

QCSE modulators have many other attractive features. They can be very fast, with their speed essentially limited by the time taken to apply the electric field to them. The microscopic physics suggests fundamental limits < 1 ps. The best high speed performance is in the range of 20 GHz in a real device.⁵

They have great potential for integration with both electronic and optical devices, such as lasers. They may also be successfully integrated with multi-layer dielectric stack mirrors grown in the same MBE machine. This allows us to make surface reflection modulators.⁶ Here the light propagates through the quantum well, off the mirror, and back through the quantum well again. These two passes through the quantum well improve the modulation contrast. For GaAs devices, where the substrate is opaque, we also avoid having to remove the substrate. Working in reflection makes mounting of devices easier, and this is the way that large arrays of devices are currently being made. It is also possible to make interesting quantum well modulators inside Fabry-Perot cavities formed with epitaxial mirrors both above and below the quantum wells.⁷

Although most QCSE modulators so far have used simple quantum wells, we can also use more complex structures, such as pairs of closely coupled wells.⁸ In this case, applying the field pulls the electron into one well and the hole into the other. This can be called "localization" of the particle, in this case in one well rather than being spread over two. This means there is little "overlap" between the electron and hole. As a result, the absorption is greatly reduced. Another recent development, related to the coupled wells, is Wannier-Stark localization in superlattices.⁹ In a superlattice without field, the optical absorption does not have a very abrupt absorption edge because the electron wavefunctions extend throughout the structure and hence must have different energies by the Pauli exclusion principle. However, as we apply an electric field, we localize the electrons within individual wells, recovering a sharp absorption edge again. This effect can be used to

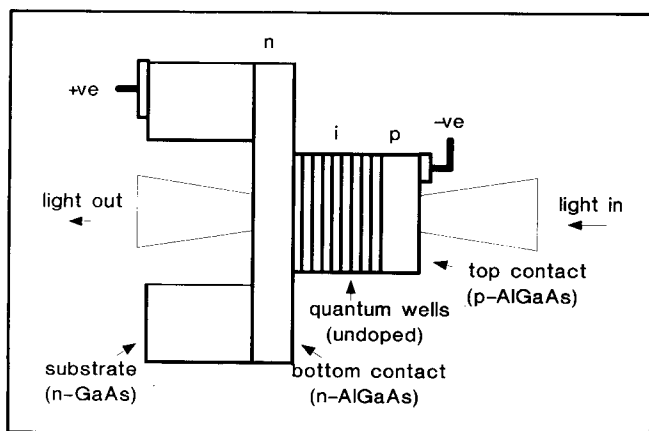


FIGURE 4. Quantum-confined Stark effect quantum well modulator structure (not to scale).

make modulators. Many other structures have also been proposed (see Ref.1). The best structure will probably depend on the precise application, since each structure has its strengths and weaknesses. We will become true "quantum mechanics" in engineering such devices.

Another way to make absorption modulators with quantum wells is known as "phase-space absorption quenching" (PAQ).¹⁰ Here, we electrically control the number of electrons in the quantum well, using for example a quantum well field effect transistor structure. The reason for this change in absorption spectrum goes back to the Pauli exclusion principle. When we fill the quantum well with carriers, we can no longer absorb into those states, and hence the optical absorption associated with those states simply disappears from the spectrum. Consequently, the absorption edge moves to higher photon energies as the lower energy states are filled with electrons. These are particularly well suited for waveguides, where we could make useful modulators with only one quantum well.

It is possible to fill and empty several wells, although this requires some ingenuity. Both the QCSE and PAQ can also be used to make changes in refractive index resulting from the absorption changes. Working at photon energies just below the absorption edge will give useful refractive index changes for both of these effects. These changes are large enough to make devices like waveguide directional couplers only 100s of microns long, much shorter than most other techniques.¹¹ The PAQ is particularly attractive because it essentially removes "area" from the absorption spectrum, an effect that gives larger refractive changes than mere shifts of absorption.¹² These effects are not yet large enough to make useful refractive modulators for light perpendicular to the layers, except possibly with resonators.⁷

Compared to other modulators, quantum well devices have different strengths and weaknesses. The strengths obviously lie in their small size, their low energies, and the ease with which they can be integrated with other optical, opto-electronic, and electronic devices. The absorptive devices are outstanding also in their ability to work for light beams propagating perpendicular to the layers. The disadvantages of these absorption modulators include relatively high insertion loss, relatively narrow operating wavelength region (a few nanometers for the highest performance devices, a few 10s of nanometers in less efficient designs), some saturation problems at high intensities, and potential temperature sensitivity. It may be possible to avoid the saturation problems by redesigning the quantum well barriers, and there has been some recent success in this.¹³ The temperature sensitivity comes from the temperature dependence of the band gap energy (~ 0.4 meV/

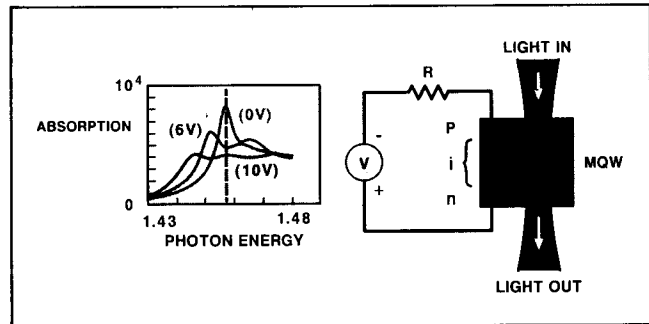


FIGURE 5. Schematic of a resistor-biased SEED (right), together with absorption spectra (in cm^{-1}) of the quantum well diode at different voltages (left). These spectra show the shift of the exciton peaks from the quantum-confined Stark effect at different voltages across the diode. At the operating wavelength or photon energy shown by the dashed line, there is a positive feedback with increasing incident light power.

$K = 0.24$ nm/K at 850 nm), a phenomenon that also affects all semiconductor laser diodes. It is not too drastic and is seldom even noticed in laboratory demonstrations of devices.

Self-electro-optic-effect devices

Devices discussed so far are electrically controlled with optical outputs. Can we make devices that are also optically controlled? If so, we could use optics for all the external communication of information. The idea, for example, of optical logic devices is not new. However, such devices have had many problems. They typically require too much energy and also do not have many of the requirements for devices that are usable in real digital systems.

The basic idea of the self-electro-optic-effect device (SEED) is simple. Combine quantum well modulators with photodetectors, and possibly some other circuitry, to give devices with both optical inputs and outputs. The use of the quantum well modulators gives optical information outputs that can use very little energy. The use of optoelectronics lets us avoid many of the systems problems.

The simplest SEED to understand is the resistor-biased optically bistable circuit shown in Fig. 5. In this case, the same diode functions simultaneously as photodetector and modulator. When operating at the photon energy shown by the dashed line, as we reduce the voltage across the diode, we will increase its optical absorption. Suppose that initially there is no light shining on the diode. Then all of the (reverse bias) supply voltage will appear across the diode because there is no current flowing in the circuit. As we start to shine light, we start to get absorption and pho-

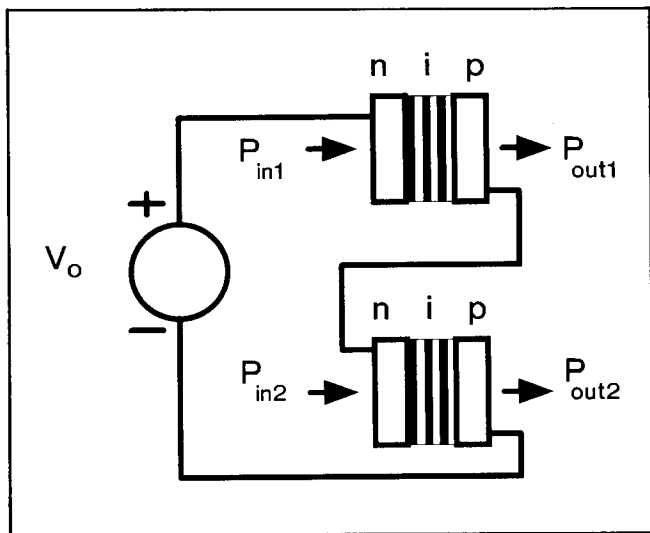


FIGURE 6. Schematic of a symmetric SEED. Two incident light beams P_{in1} and P_{in2} shine on the two series-connected quantum well diodes. The device is bistable in the ratio of the two input powers. With equal input beams, one stable state is P_{out1} high and P_{out2} low, corresponding to all the supply voltage across diode 1. The other stable state is the opposite.

tocurrent (one electron for every absorbed photon). This current gives a voltage drop across the resistor, reducing the voltage across the diode. The voltage reduction gives an increase in absorption, and hence a further increase in photocurrent. Past a certain critical "switch-down" input power, this positive feedback process will run away, switching the diode into a low voltage, high absorption state. At a lower "switch-up" power, the positive feedback operates in reverse and the device switches back to a low absorption (high voltage) state. Between these two powers, the device is actually bistable; it can have either high or low transmission.

However, simple bistability is difficult to use in large logic systems.¹⁴ All logic systems require some gain. Most proposals for use of bistability get the necessary signal gain by biasing the device very close to switching with a power beam, so a small additional beam can switch it. The problem is that the bias beam power must be very precisely set. Such critical setting is not feasible in any large system because of device variations. Furthermore, any small reflections, such as a slight reflection of the output beam back into the device, can also switch the device. This gives very poor input/output isolation.

The symmetric SEED (S-SEED)¹⁵ is also a bistable device, but it is bistable in the ratio of two light beam powers. Instead of having a resistor as the "load" for the quan-

tum well diode, it uses another quantum well diode, as shown in Fig. 6. Imagine for the moment that a constant power shines on one diode. A simplified way of looking at this diode is that it behaves like a resistor whose value is set by the power of the light beam. Then we can see that we will obtain bistability in the transmission of the other beam through the other diode, just as before. Of course, we can reverse the roles of the two diodes and obtain bistability in the transmission of the first diode.

Suppose now that we shine essentially equal powers on the two diodes, perhaps derived from one laser with a beam splitter. The device will be in one or other bistable state, with one diode transmitting and the other diode absorbing. However, as we turn down the power in both beams together (e.g., by reducing the laser power), the device will not switch. The voltage on the diodes only changes when the photocurrent in one diode starts to exceed the photocurrent in the other. Provided we reduce both beams together, there will be no change in the ratio of the photocurrents. This allows us to get signal gain in an unusual way. We may turn down the power in both beams simultaneously, then switch the device with additional low power input beams. Then we may turn up the power and read the device at high power. Thus, with low power input beams we have caused a large change in output power, giving gain. Here, the input and output occur at different times, and this is called "time-sequential gain." In contrast to usual bistability, we have gain without biasing close to a switching threshold. It also has some input/output isolation, because small reflections of the output back into the device will not switch it.

Another unusual aspect of the S-SEED is that it uses pairs of beams. The output of one device is a pair of beams, one with high power, the other with low power. A logic "1" is one beam more powerful than the other, a logic "0" is the reverse. Incidentally, this makes the logic level essentially independent of attenuation, as long as both beams are attenuated equally. The input of the next device is also such a pair of beams. At its input, S-SEED is actually sensitive to the ratio of these two beams. This is important since it avoids the need for high contrast in the modulators.

The S-SEED can also perform logic operations. For example, by presetting the device in a "1" state, it can operate as a NAND gate; only if both pairs of input beams represent a logic "1" will the device switch to the "0" state. Inversion occurs because the diode with larger input power becomes more absorbing after switching.

The first S-SEED laboratory demonstration was in 1987. At the time of writing, 64×32 arrays of devices are starting to become commercially available for experimental applications (see Fig. 7).¹⁶ Devices such as these have

respectable performance. Switching energies are a few picjoules in current devices, low enough to start to make them interesting. Switching speeds < 1 ns have been demonstrated (with higher energies). There are good prospects for further improvements in energy (with reduced device size and operating voltage) and speed (with improved quantum well designs).¹³⁾

The first systems experiments are now in progress with such devices. Because the S-SEED is a complete logic device, such systems do actually work without critical setting of parameters. There has been remarkable progress in optical systems for such devices, such as spot array generators to deliver equal light beams to all the devices in an array at once.¹⁷ One particularly convenient feature of the S-SEED for systems experiments is that it can be run slowly at low power, removing the need for high power light sources for initial experiments.

It is difficult to judge the ultimate importance of devices such as S-SEED arrays at this time. They are only just becoming generally available, and they are so different from previous devices that they will require different systems approaches to take full advantage of them. At the very least, they offer us opportunities that simply were not there before. The 64×32 array corresponds to a chip with 6,144 logical "pin-outs," two inputs and one output for each gate, a number unthinkable with current electron-

ic technology. (The chip actually has 16,384 physical "pinouts" because each gate has a separate pair of power supply beams, and each logical connection is differential, using two beams).

The device also has various potential functions. In addition to logic, it can also operate as a dynamic memory. Reducing the optical power does not change the state of the device, so it can hold its state with very low average powers (200 nW per device for the current S-SEED arrays and as low as 40 pW per device in other related devices). It may also have analog applications. For example, related devices have operated as optically addressed spatial light modulators, linear light-by-light modulators, and as "loser-takes-all" analog decision circuits that may have applications in optical neural networks.¹⁸

Many other SEED configurations have been proposed. The concept can also be used in waveguides. A SEED oscillator circuit has been used to perform optical clock recovery from a bit stream, for example.¹⁹ Such devices could have interesting performance when integrated. SEEDs incorporating transistors have also been suggested. The distinction between SEEDs and integration of detectors, modulators, and electronics then starts to break down. In one sense, all such devices are SEEDs.

Integration with electronics

As mentioned above, the integration of optics with electronics may help us get the best out of both. Optics has obvious potential in routing in fibers and also in the ability to make very large numbers of interconnections using free-space optics. Optics does not suffer from frequency-dependent crosstalk and avoids ground loop problems entirely. It also reduces the energy required for communication of information for some rather fundamental reasons.²⁰ One main problem has been the lack of suitable devices that give optical outputs from electronics. To be most useful, such devices must be integrable in large numbers into electronic systems, they must be small, and they must be energy efficient. Quantum well modulators potentially can satisfy all these requirements, provided we have an actual integration technology.

This integration is starting now. At least two schemes are being investigated. One scheme—the so-called field-effect transistor SEED (F-SEED)—integrates field effect transistors (FETs) with quantum well modulators by making the FETs directly in the top layer of the modulator diode.²¹ In this case, a relatively standard FET design and processing technology can still be used while allowing optical modulators beside every FET in the circuit if desired. The same diode layers can also be used as photodetectors to give optical inputs as well. In principle, such a concept

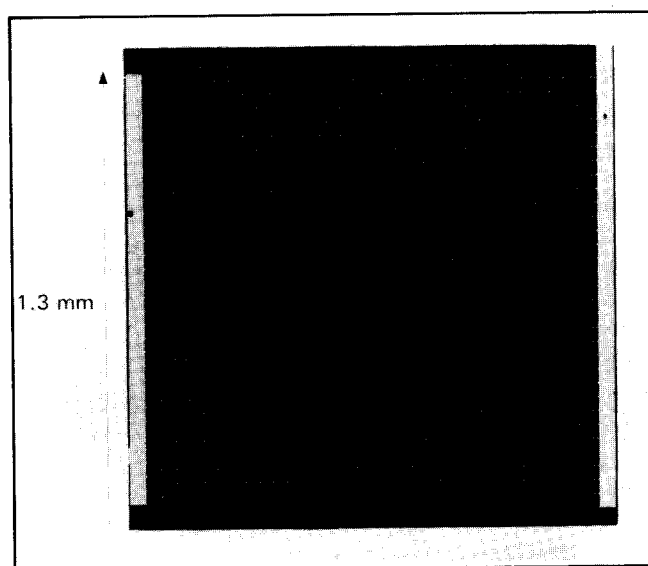


FIGURE 7. A 64×32 array of symmetric SEEDs. The array is 1.3 mm square. It is designed to work in reflection with 16,384 light beams in arrays. Each SEED consists of two mesa diodes connected in series. Each mesa is $10 \times 10 \mu\text{m}$. There is one pair of electrical connections for the bias supply.

can be extended to give arbitrary logical functionality between inputs and outputs by using FET logic. This is therefore suitable for "smart pixels" or functional blocks, small blocks of electronic logic with optical inputs and outputs. Such a concept uses electronics for logic and local complex interconnections, both of which electronics is good at, and uses optics for other longer and more global interconnection where it excels. As with any new integration concept, this still needs technology development, but prospects are good.

Another scheme is to try to integrate quantum well modulators with silicon electronics. One major problem with getting optical information out of silicon is that it has proven very difficult to integrate optical output devices onto silicon. Laser diodes and light-emitting diodes typically have short lifetimes in this case. There have, however, been successful attempts in making quantum well modulators on silicon substrates.²² In preliminary tests, these have performance comparable to those on GaAs substrates and have operated for 1000 hours without apparent degradation. Much work remains to be done here also. Actual integration with silicon integrated circuits raises many other technical issues that remain to be resolved. This area, too, is very promising.

Looking ahead

This article has only touched on the field of quantum well optical and optoelectronic physics and devices. The physics of quantum-confined semiconductor structures is a major fraction of semiconductor physics research today. There are many novel physical mechanisms in these thin-layered structures, both optical and electronic. Real devices can be made. Prospects for integration of large numbers of devices, possibly with other optical or electronic devices are good. The devices are usually different kinds of devices from those we are used to and will probably have new applications. It is difficult to predict where this technology will lead, but it seems certain to change the nature of optoelectronics in the future.

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GLOSSARY

Absorption edge: The spectral region for photon energies near the bandgap energy where the semiconductor changes from being transparent, at energies below the bandgap energy, to being strongly absorbing at higher photon energies (shorter wavelengths).

Bandgap: The bandgap energy is the energy separation between the valence band and the conduction band in the semiconductor.

Band offset: When two semiconductors of different bandgaps are joined, the band offset ratio is the ratio of the difference in conduction band energies to the difference in valence band energies. It is not easy to calculate from first principles, and usually must be measured.

Bulk semiconductor: A normal semiconductor, *i.e.*, not a thin layer.

Direct gap: A direct gap semiconductor has an abrupt strong optical absorption edge, which is required for devices such as lasers. Silicon is not a direct gap semiconductor, but most III-V and II-VI materials are.

Doping: The addition of small controlled amounts of impurities to affect the number of electrons (n-doping) or holes (p-doping) in the semiconductor.

Epitaxial: Grown crystalline with the same lattice constant as the material on which it is grown.

Exciton: An electron-hole pair, usually created optically, especially the lowest energy bound state of the pair. This state is like a large hydrogen atom but with a hole instead of a proton.

Hole: A hole is the absence of an electron in the valence band. For practical purposes, it behaves like an electron but has a positive charge.

II-VI: A compound using elements from group II (*e.g.*, Zn, Hg, Cd) and group VI (*e.g.* S, Se, Te) of the periodic table.

III-V: A compound using elements from group III (*e.g.*, Al, Ga, In) and group V (*e.g.*, As, P, Sb) of the periodic table.

Intrinsic: Undoped, or at least with no intentional doping.

MBE: (molecular beam epitaxy) A high vacuum growth technique using beams of atoms and molecules from ovens.

MOCVD: (metal-organic chemical vapor deposition) A growth technique using gases in a reactor.

MQW: (multiple quantum well) A structure containing many quantum wells. It is usually crystallographically a

superlattice, but the barriers are thick enough to prevent strong tunneling through them.

OMVPE: (organo-metallic vapor phase epitaxy) Same as MOCVD.

Photon energy: Photon energy $h\nu = hc/\lambda$, where λ is the wavelength of the light, c is the velocity of light, and ν is the frequency. The photon energy (expressed in electronvolts) is particularly useful in optoelectronics because it corresponds directly to separations of electron energy levels in the material. $h\nu$ (eV) = $1.24/\lambda$ (μm).

Quantum well: A thin semiconductor layer of low electron (or hole) potential energy between two other semiconductor layers with higher potential energy.

Superlattice: Strictly, a lattice of lattices. In practice, periodic alternating thin layers of two semiconductors where the particles tunnel strongly through the barrier layers.

Tunneling: The quantum-mechanical process that allows particles to penetrate into or through barriers, even though they classically do not have enough energy.