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QUANTUM WELL OPTOELECTRONIC SWITCHING DEVICES

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Quantum well semiconductor structures allow small, fast, efficient optoelectronic devices such as optical modulators and switches. These are capable of logic themselves and have good potential for integration with electronic integrated circuits for parallel high speed interconnections. Devices can be made both in waveguides and two-dimensional parallel arrays. Working arrays of optical logic and memory devices have been demonstrated, to sizes as large as 2 048 elements, all externally accessible in parallel with free-space optics. This article gives an overview of the physics underlying the operation of such devices, and describes the principles of several of the device types, including self-electrooptic effect devices (SEEDs).

1. Introduction

Optical communications using optical fibers and semiconductor lasers have made dramatic advances in the last ten to fifteen years. In this area and other areas such as information storage, optics is playing an increasing role in information movement and processing. The potential capabilities of optics are largely complementary to those of electronics. Optics is very good at communicating information. Electronics is very good at logic and complex functionality. If we can manage to devise technologies that allow us to take best advantage of both, perhaps in a hybrid optical/electronic fashion, we may be able to make systems that perform much better. One problem, however, is that we have very few choices of optical or optoelectronic devices. This article deals with one important development in such devices. With modern layered semiconductor growth techniques such as molecular beam epitaxy, we can make "quantum wells", very thin layers of semiconductors with new properties. These quantum wells give new physical mechanisms that we can engineer at the atomic level to give new devices. In optics and optoelectronics, quantum wells allow us to make low-energy, high-speed optical modulators and switches. A very important aspect of these devices is that they are compatible with existing optical devices (such as diode lasers) and existing electronics. Prospects for integration with other such devices are good.

In this short review article, I will briefly introduce quantum wells and some of the important physical mechanisms. Then I will describe some of the new optoelectronic devices. I will also attempt to put this body of work in context with its ultimate potential for benefiting systems. I will not try to give a comprehensive review of all the work in this area. The body of work is now too large to allow this in a short article. Instead, I will try to explain the basic ideas and illustrate these with examples. Some other reviews cover specific subjects in greater detail.[1-8]

It is important to emphasize at the outset that these devices, although based on new physics in apparently exotic structures, actually work under practical conditions. They can also be made with good yields. At the very least, we are able to make classes of devices that were simply impossible before. For example, at the time of writing, we can make 64 × 32 arrays of optoelectronic logic gates that can all be accessed in parallel with optical beam arrays.[9] This corresponds to a chip with at least 6 144 logical "pin-outs" in a 1.3 × 1.3 mm area (two inputs and one output per gate). These and other quantum well optoelectronic devices might have a major impact on applications of optics and optoelectronics in switching and processing systems. For example, such devices might ultimately allow us to interconnect complex systems optically, either in optical or hybrid optoelectronic systems, thereby avoiding many of the communications problems that limit purely electronic systems.

2. Quantum Wells

2.1. *Growth*

One important benefit of growth techniques such as molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD, otherwise also known as organo-metallic vapor phase epitaxy (OMVPE)) is that they allow us to grow one semiconductor controllably on another. This control extends almost to individual atomic layers. This technology has been particularly successful in the III-V semiconductors. Here there is a large choice of well-behaved binary materials such as GaAs and InP, and high quality alloys, such as the ternary alloys AlGaAs and InGaAs. A large fraction of the various possible binaries, ternary alloys and quaternary alloys (e.g. InGaAsP) can be grown successfully. This gives us the freedom to adjust the bandgap energy from layer to layer by choosing different materials for the different layers. This freedom, when applied to very thin layers (e.g. 100 Å), is what allows us to make quantum wells.

We can do this while still retaining high quality material because the growth is epitaxial; the crystalline structure is retained throughout all the layers. We must also make sure that the lattice constants of the different materials are the same or similar. Epitaxial growth will break down if the difference in lattice constants is too great. The large choice of available materials allows us to choose both the bandgap energy and the lattice constant independently in many cases with III-V materials systems. We can also deliberately introduce controlled amounts of lattice constant mismatch between adjacent layers. If this mismatch is small enough and the layer is sufficiently thin, the growth is still epitaxial. In this case, however, the layers are strained. The strains introduced can be very large by absolute standards, and this strain can be used as a tool to change the band structure of the materials, thus giving us another degree of freedom.

The most investigated III-V's are the GaAs/AlGaAs system, usually grown on GaAs, and various systems out of the InGaAlAsP family, usually grown on InP substrates. A particularly fortunate coincidence is that GaAs and AlAs have very nearly the same lattice constant, so that any combination of GaAs, AlGaAs and AlAs layers can be grown without any significant limitations from strain. These III-V systems are interesting for electronics because of various high speed transistor applications. They are also important for optics because they make good laser diodes and detectors, and because, with the InP substrate systems, devices can be made that match the best wavelengths for using optical fibers (1.3 μm and 1.55 μm). A principle reason for the use of such III-V materials for optical applications is of course that many of them are direct bandgap materials. This gives them a much sharper and stronger optical absorption edge, a feature that is important for all the devices that I will discuss here. It also allows efficient light emitting devices, such as lasers and light emitting diodes. At the present time, we might view III-V materials as being an option for electronic applications, but they are almost essential for any practical semiconductor optoelectronic application, especially if we want to emit or modulate light beams.

Other material systems, such as II-VI's, have similar features to those found in III-V's. The growth technology is, however, less advanced at this time. There has been considerable work on group IV materials, such as Ge and Si and GeSi alloys, that may have long term potential, although useful direct gap materials have so far been elusive. One very important technology is growth of very different materials on one another. A classic example is GaAs on Si. If one could grow good enough GaAs materials on Si substrates, one could certainly reduce substrate costs. More importantly, however, one could perhaps mix high-performance III-V electronics with high complexity Si circuits. Perhaps the most important qualitative advantage would be that one could add optical devices to Si circuits. This is the kind of technology that would enable us to get the best of both the electronic and optical worlds. Such growth is, however, hard. The resulting material is not of such high crystal quality, with large dislocation densities. Partly as a result of this, attempts to grow laser structures on Si have been disappointing, usually with short lifetimes for the lasers. One hope, which I will discuss below, is that some of these quantum wells optoelectronic devices, such as optical modulators, will be less demanding than lasers. They might therefore allow useful optical input and output devices on Si integrated circuits. This remains to be demonstrated, although first results are encouraging.[10]

2.2. *Basic physics*

The basic concept of a quantum well is illustrated in Fig. 1. If we take, for example, a thin layer of GaAs between two layers of AlGaAs, we will find that an electron in the conduction band will see lowest potential energy if it is in the GaAs material. Hence the GaAs layer is a "potential well" for the electrons. For this particular material system, we find that holes in the valence band have lowest potential energy also in the GaAs layer. (Hole energy should be viewed "upside down" compared to electron energy). This kind of material system is called "Type I". It is not always the case that both electron and hole have minimum potential energy in the same material. For example, InAs/GaSb heterostructures confine electrons and holes in different material layers, give a so-called "Type II" system. All of the devices that I will discuss here use Type I materials.

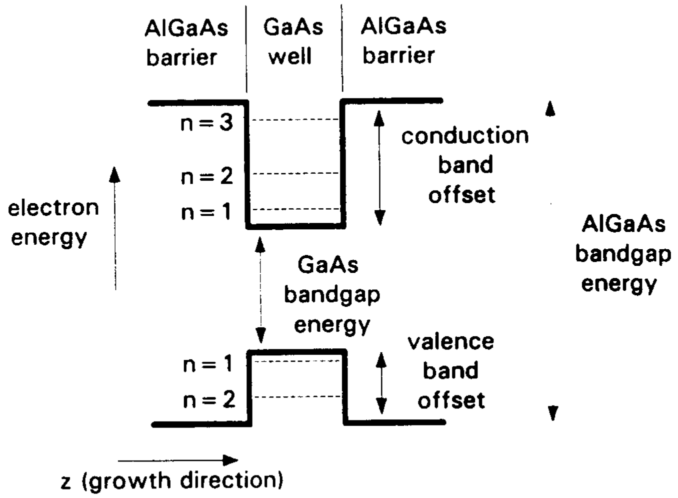

Fig. 1. Schematic of a quantum well.

The key point that gives us "quantum wells" is that the layers can be made so thin that we cannot neglect the fact that electrons (and holes) can be viewed as waves. We therefore get a classic "particle in a box", at least in one direction. Fortunately, this is a very easy problem to solve quantum-mechanically. We get discrete states for the motion in the direction perpendicular to the layers. These discrete states correspond to the allowed standing wave pattern in the box. The walls of box (i.e. the AlGaAs layers) reflect the waves back into the box (i.e. into the GaAs layer). The resulting modes are essentially the same as the allowed standing waves of a skipping rope held at both ends. For the particularly simple case where the "walls" are very high, the boundary condition is simply that the wavefunction must be zero at the walls. The "high wall" case is often called an "infinite" well. (The well is infinitely deep.) The allowed wavefunctions are then simply sine waves.

We can formally evaluate this by solving Schrödinger's equation

$$\left[-\frac{\hbar^2}{2m^*}\frac{\partial^2}{\partial z^2} + V(z)\right]\phi(z) = E\phi(z) \qquad (1)$$

where z is the direction perpendicular to the layers, $V(z)$ is the potential energy (i.e. the "quantum well" potential), E is the energy and ϕ is the wavefunction, m^* is the effective mass of the electron (or hole). The solutions of Eq. 1 for the case of very high walls, are, for the wavefunction,

$$\phi(z) = A\sin(n\pi z/L_z) \qquad (2)$$

where A is a normalization constant, L_z is the thickness of the well, and $n = 1, 2, 3, \ldots$ is a quantum number. (The position of the origin is chosen at the left of the well for convenience.) For the associated energies, we have

$$E_n = \frac{\hbar^2}{2m^*}\left[\frac{n\pi}{L_z}\right]^2 \quad . \tag{3}$$

The allowed energy levels are spaced quadratically with increasing n. Also, note that this spacing is inversely proportional to the effective mass, m^*. Electrons and holes in semiconductors behave as if they have a mass different from the free electron mass. This different mass is a consequence of the electron wave propagating through the periodic crystal lattice. For electrons in most III-V materials, the electron mass is quite light. For GaAs the electron effective mass is ~ 0.067 m_o, where m_o is the free electron mass. Consequently, even a layer as thick as 100 Å shows the effects of quantization very strongly even at room temperature. For such a well, with very high walls, the energy of the first allowed electron state is 56 meV above the bottom of the conduction band.

There are actually two kinds of holes, the light hole and the heavy hole. In GaAs, these have masses of ~ 0.094 m_o and ~ 0.34 m_o respectively. There are therefore two "ladders" of confined hole states. In general for most III-V semiconductors, the electron and light hole masses are always similar to each other, and are both approximately proportional to the bandgap energy from material to material. The heavy hole masses are usually a substantial fraction of the free electron mass, and are generally similar in all of the III-V's.

In an actual quantum well, the walls are not infinitely high. For example, for $Al_xGa_{1-x}As$ with fractional aluminum content of $x = 0.3$, the bottom of the AlGaAs conduction band is approximately 250 meV above the bottom of the GaAs conduction band (i.e. the conduction band "offset" is ~ 250 meV). For the same conditions, the top of the AlGaAs valence band is approximately 125 meV below the top of the GaAs valence band. Incidentally, although the overall difference of the bandgap energies of GaAs and AlGaAs is well known and easy to measure experimentally, the precise way in which that bandgap energy difference divides between the conduction and valence bands (the "offset ratio") is not well known. It is difficult to measure the offset ratio experimentally, and first principles calculations do not give sufficiently accurate answers for useful predictions.

The fact that the walls or "barriers" are only of finite height means that the wavefunction does not go to zero at the walls. In fact, the wavefunction penetrates into the barriers. In the barriers, the wavefunction is a decaying exponential. This is easily checked by solving Schrödinger's equation for the case where E is less than the barrier height. The case of a well with finite barriers can also be solved analytically, although not in closed form. The resulting energies are lower than for the infinite well case. This is because the particles are not so tightly confined. For a 100 Å GaAs well with $Al_{0.3}Ga_{0.7}As$ barriers, the energy of the first electron state is ~ 30 meV.

In practice, we often make many quantum wells one after the other in a multiple layered structure. We can still think of the physics in the same way provided the walls between the adjacent wells are sufficiently thick. If the thickness of the walls is comparable to or smaller than the penetration depth of the wavefunctions into the walls, then the physics starts to change. The adjacent wells can no longer be considered separately. They start to couple with one another, and we then need to think of such a multiple well system as a superlattice. A superlattice is strictly a lattice of lattices. It has similar properties to any lattice, although on a different scale. The discrete states of the isolated quantum wells couple to give "minibands" just as atomic states couple to give bands in a crystalline solid. The wall thickness at which such effects become important will vary depending on the materials. As a guide, for barrier thicknesses > 100 Å, such coupling is typically weak, and for thicknesses < 10 Å it is strong.

2.3. *Optical properties and excitons*

The quantization of the electron and hole motion is easily seen in an optical absorption spectrum as in Fig. 2. We can clearly see a series of steps rather than the relatively smooth absorption spectrum usual for normal bulk semiconductors. The steps correspond to allowed transitions between quantized electron and hole states. Only certain of these transitions are allowed. For a transition to be allowed, there must be a strong overlap integral between the relevant hole and electron states. For the simple case of infinite well, the selection rule is $\Delta n = 0$, where Δn is the difference between the electron and hole quantum numbers. This rule is because all the sine waves are orthogonal to one another. Only the overlap integral between identical sine waves is non-zero. This is still a good first approximation for the finite well.

One might expect that the spectrum would be a series of lines corresponding to the discrete allowed electron and hole states. We must remember however that the electron and hole are free to move in the other two directions (in the plane of the layers), and can have any (positive) kinetic energy from this in-plane motion. Hence, we

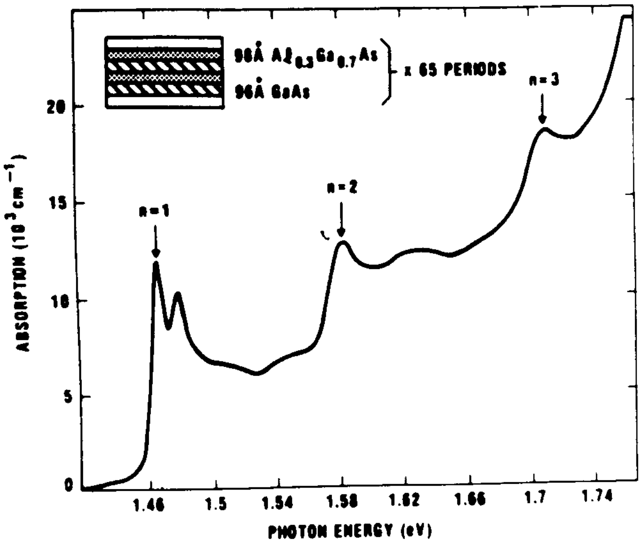

Fig. 2. Optical absorption spectrum of quantum well material.

really have not a discrete state, but a "subband" corresponding to discrete motion perpendicular to the layers and arbitrary motion within the layers. The allowed absorption between the subbands in the valence and conduction bands causes the steps.

It is also clear that there are sharp peaks at the edges of the steps in the spectrum. These peaks are called exciton absorption peaks. Such peaks are well known in bulk semiconductors, but are usually only strong at low temperatures. In quantum wells, these absorption peaks are relatively strong, and are clear even at room temperature. This gives a particularly strong and abrupt absorption edge, which helps the performance of some of the devices.

When we absorb a photon near the absorption edge in a semiconductor, the simplest picture is that we raise an electron from the valence to the conduction band. In fact we also leave behind a hole in the valence band. A more complete and useful picture is to say that we create an electron-hole pair. An important additional effect is that the electron and hole are attracted to one another because of their opposite electrostatic charges. (The electron is negative and the hole is positive.) One important consequence is that the electron and hole can form states in which they are bound to one another, just as the electron and proton are bound in a hydrogen atom. These states are called excitons.

The lowest energy exciton state (and usually the most important one) is the 1 S exciton. This exciton is sometimes loosely called "the" exciton. This state is analogous to the hydrogen atom ground state. For III-V semiconductors and most other semiconductors, as long as the bandgap energy is not too high, the excitons can be described with exactly the same theory as the hydrogen atom. The only differences are the use of the electron and hole effective masses, which are small, and the large dielectric constant of the semiconductor. Both of these effects combine to make the exciton binding energy much smaller than that of the hydrogen atom. For bulk GaAs, for example, the exciton binding energy is ~ 4.2 meV, and the corresponding diameter is ~ 300 Å. Exciton absorption peaks correspond to the direct creation of such excitons by optical absorption. The peaks are found at energies just below the bandgap energy of the material by the amount of their binding energy. The peaks can be relatively strong because the overlap between electron and hole is large in such states. The particles are confined relative to one another within the exciton diameter.

The exciton is a relatively fragile particle in bulk materials, especially at room temperature. In fact, such excitons are usually destroyed at room temperature by colliding with an optical phonon before they have even completed a fraction of a classical orbit. These phonons are unavoidable since they are simply a result of the thermal vibrations of the material. Such rapid destruction leads to an uncertainty-principle broadening of the absorption peak. When the particle is destroyed in much less than the classical orbit time, the lifetime broadening is comparable to the binding energy. As a result, the peak is often barely resolvable at room temperature.

In quantum wells, it is clear that the excitons must be squeezed, at least in one direction, if the well thickness is substantially less than the bulk exciton size. What is less obvious, and apparently counterintuitive, is that as we squeeze the exciton in one direction it actually also gets smaller in the other directions. That is, it becomes smaller in its orbit in the plane of the layers as well. This is easily proved by calculations. It can also be rationalized by arguing that nature prefers being more nearly spherical rather than pancake-shaped. Anyway, there are two consequences of this smaller overall size. First, the classical orbit is faster and the binding energy is larger. Even though the lifetime of the exciton is similar to that in the bulk (e.g. ~ 300 fs), the line is clearly resolved from the bandgap energy. Second, in this smaller particle the overlap between electron and hole is even larger; consequently, the absorption peak is even stronger. Note incidentally that we do not need to have any excitons in the quantum wells in order to have the exciton absorption peaks. Absorption at the peaks corresponds to the creation of an exciton, not raising an existing exciton to an excited state. In atomic physics, this process is more nearly analogous to the creation of a positronium atom (an electron and a positron orbiting round one another) by absorbing gamma-ray photons in the vacuum.

Exciton absorption peaks are important in all the devices I will discuss below when there is little or no density of carriers or excitons in the wells. This is normally the case for the electroabsorption modulators. If one creates free carriers or excitons at densities approaching or exceeding one per exciton volume (e.g. 10^{17} cm^{-3}) then the exciton peaks tend to disappear. The simplest way to view this is that there is no more space left to put excitons. This is approximately correct, although there are many processes that contribute to this effect, including screening and exchange. Such processes are difficult to calculate exactly, requiring many-body physics. This disappearance of the exciton peaks can be induced by optically creating high carrier or exciton densities, by doping the structure to give built-in carrier densities, or by electrically injecting carriers (as for example in a diode laser). Even though the peaks corresponding to bound electron-hole states can be destroyed this way, the resulting absorption spectrum is still strongly influenced by the Coulomb attraction of electron and hole. The fact that the electron and hole are still attracted means that on the average they are still closer than they would otherwise be, resulting in increased absorption, even above the nominal absorption edge.

2.4. *Other devices and mechanisms*

The main subject of this paper will be electrically controlled quantum well optical modulators and optically controlled devices based on these. There are, however, many other kinds of devices that can be made using quantum wells and several other important physical mechanisms. Many of these devices can be potentially integrated with the optical modulators and switches. Some of these mechanisms are also relevant to the devices I will discuss later, sometimes as parasitic or limiting effects. In this section I will summarize some of these other devices and effects.

2.4.1. *Electronic devices*

On electronic device that uses a quantum well is the modulation-doped field effect transistor (MODFET).[11] This device takes advantage of modulation doping, where the dopant material is placed in the barrier. The charge carriers fall into the quantum well, where they form the conducting channel of the transistor. Now, however, they no longer collide with the charged dopants. As a result, the mobility of the carriers can be higher. These structures are themselves also one of the ways of making phase-space absorption quenching optical modulators that I will discuss below.

Another class of electronic devices being investigated for possible applications are those based on resonant tunneling.[12] Many different device structures are possible. The simplest resonant tunneling device uses a single quantum well with two relatively thin barriers on either side. When an electron is incident on a barrier at an energy near to one of the confined levels of the quantum well, it can tunnel strongly through the structure. As the voltage is changed across the whole structure, the current first increases as the energy of the incident electrons approaches this resonance. Then for higher voltages, the current can decrease because the incident electron energy is now too high. This gives a negative differential conductivity, which can be used for example to make high frequency oscillators. The physics of these various tunneling processes is also important for some of the optical devices. Tunneling is one of the processes that sets how fast the optically created carriers can leave the quantum well.[13] Carriers must leave the wells rapidly otherwise they build up and can saturate the optical absorption.[14]

2.4.2. *Optical devices based on absorption saturation*

Some of the first work on quantum well optical switching devices concentrated on the use of absorption saturation as a nonlinear mechanism (see Ref. 1). In any direct bandgap semiconductor, if we create a large density of carriers by absorbing intense light (usually from a laser), we can saturate the optical absorption near to the bandgap. This is true even neglecting excitonic effects. The simplest machanism is called phase space filling or dynamic Burstein-Moss shifting. As we create larger carrier densities, they tend to collect in "pools" near the centre of the bands, because this is where the energy is lowest. Therefore, the states near the band centre tend to become filled. By the Pauli exclusion principle, there can however only be one particle per state. Consequently, we cannot absorb again into these states because they are full. So, the absorption in the region just above the bandgap energy is essentially removed from the optical absorption spectrum, up to the level of the top of the "pools".

This is a simplistic explanation. There are other important contributory mechanisms, such as the shrinkage of the bandgap with increasing carrier density, known as bandgap renormalization. This effect requires many-body theory to calculate it properly. The basic reason for the shrinkage is however that when we create a new carrier, the existing carriers move to screen the resulting field from the carrier. This screening results in a reduction of the energy of the system as a whole, thereby reducing the energy required to add the carrier. As we saturate the absorption, we change the refractive index in the semiconductor, especially in the region just below the bandgap energy. This is because of the fundamental relation between refractive index and absorption, usually expressed through the Kramers-Krönig relations.

The most investigated use of these effects is to make nonlinear refractive devices operating at photon energies just below the bandgap energy. Here, there is a small residual absorption. This absorption creates carriers that saturate the absorption above the bandgap energy. This saturation changes the refractive index seen below the bandgap energy. There are many ways of making switching devices out of such an effect. The most common is to make a Fabry-Perot resonator filled with such a nonlinear refractive material. Such a device shows optical bistability.[15] The basic positive feedback mechanism of this bistability is that increasing intensity tends to pull the resonator towards resonance, which in turn increases the intensity inside the cavity, thus pulling the resonator further towards resonance, and so on. This can result in a switching into a resonant state, which has high optical transmission.

Many such semiconductor devices were demonstrated. However, they all tended to require too much switching energy to be very practical. Excitonic saturation effects are an interesting possibility to try to improve performance. The excitonic saturation mechanisms were also briefly discussed above. These are closely related to the non-excitonic effects discussed in this section. In saturating an excitonic peak there is however the additional advantage that a relatively large absorption is concentrated within a small spectral width. This can enhance both absorption saturation and the associated nonlinear refraction.

Hence, quantum wells, with their strong exciton peaks at room temperature, are particularly attractive. The practical problem is that, to get enough refractive index change to make a switching device, we usually require to saturate much more than the exciton peak. This means that we must rely on less efficient processes, such as the interband saturation discussed in this section, to complete the process. Consequently, the potential advantage of the quantum wells may be lost for these refractive devices. A typical carrier density required for strong saturation and switching might be 10^{18} cm^{-3}. Exciton saturation effects are strong for densities in the region of 10^{17} cm^{-3}. Given approximately 1.5 eV per photon, for example, we see the required energy density for 10^{18} cm^{-3} carriers is $\sim$ 250 fJμm^{-3}. This may not seem large, but will be an important number for comparison below. Incidentally, this is also a typical carrier density for laser diodes, which therefore also have similar energy densities.

Although such nonlinear refractive devices have thus far been disappointing, the excitonic absorption saturation itself may still be useful. Laser diodes have been successfully mode-locked to produce trains of picosecond pulses using quantum wells as saturable absorbers.[16]

There are other nonlinear optical mechanisms that may ultimately prove to be of practical interest in quantum wells. One such mechanism is the a.c. Stark effect (see Ref. 1), a mechanism that also exists for bulk materials. With this mechanism, intense optical pulses at photon energies just below the band gap energy cause changes in the absorption and refractive index of the quantum wells. Importantly, such changes only last as long as the optical pulse. There is no "memory" effect from the finite lifetime of photoexcited carriers. The reason for this is that the carriers are only "virtually" excited. In virtual excitation, the quantum mechanical phase of the excitation remains coherent with the light field. As a result the excitation can be coherently re-emitted into the light field. Essentially, the excitation is re-emitted before it has time to scatter; it is really the scattering that makes a transition "real" rather than "virtual". We could rather crudely regard the a.c. Stark effect as saturation by virtual carriers. It is an ultrafast mechanism, although it still requires significant energy densities to operate, and has not yet been used for a practical device.

2.4.3. *Other optical devices*

There are many other optical devices that can be made using quantum wells. Certainly the major practical use of quantum wells to date is in improved laser diodes. There are a number of reasons for this improvement. These are discussed in other review articles[17] and I will not discuss this further here. Another recent area of interest is in the use of intersubband transitions for long wavelength (e.g. 8-12 μm) infrared detectors.[18] In such devices, *n*-doped quantum wells are used. Electrons can be excited from their lowest state in the conduction band to higher states or to the continuum above the top of the quantum well by such long wavelength radiation. One main advantage of such devices is that they can be made using a well controlled materials system such as GaAs/AlGaAs.

3. Quantum Well Modulators

3.1. *Quantum-confined Stark effect modulators*

The effect that has been used most for optical switching devices with quantum wells is the quantum-confined Stark effect (QCSE). This is an electroabsorptive effect. Electroabsorption is a change in optical absorption with applied electric field. QCSE electroabsorption is seen when electric fields are applied perpendicular to the quantum well layers. One effective way of applying such a field to quantum wells is to grow a diode as shown in Fig. 3. As this diode is reverse biased, field is applied perpendicular to the layers as required. Note that there need be no steady current flowing in the modulator. This helps reduce operating power.

The change in absorption spectrum with field perpendicular to the layers is shown in Fig. 4 for a simple quantum well. One remarkable feature that is clear from these

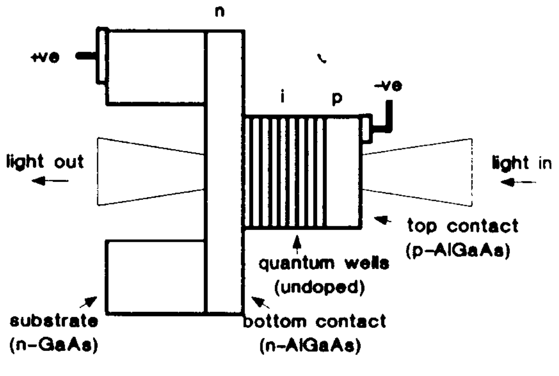

Fig. 3. Quantum well modulator structure.

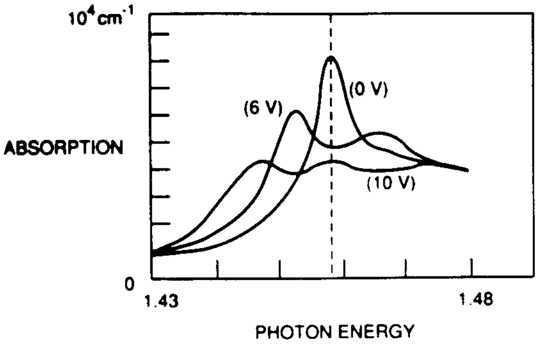

Fig. 4. Absorption spectra for different perpendicular fields for a simple quantum well. The shift of the peaks to lower photon energies, accompanied by a reduction of the peak area, is caused by the quantum-confined Stark effect. The dashed line shows a typical operating photon energy for a self-electrooptic effect bistable device.

spectra is that the exciton peaks are not destroyed by the field. Instead, they are shifted to lower photon energies, with some reduction in strength. This is very unusual for semiconductors. In conventional semiconductors, if we are able to see exciton peaks, the peaks are very easily destroyed by applied electric fields, and do not show strong shifts. Electroabsorption in bulk materials therefore looks very different.

The reason why conventional semiconductors show a broadening of their exciton resonances with applied field is simply that the exciton is field-ionized. The fields at which significant electroabsorption effects are normally seen, ~ 10^4 V/cm – 10^5 V/cm, correspond to very large potential drops over the size of the exciton. A field of ~ 10^4 V/cm corresponds to one binding energy over one exciton diameter for a 100 Å diameter exciton with a binding energy of 10 meV. Such a field is large enough to tear the exciton apart in a time short compared to its classical orbit time. Consequently, there is a large lifetime broadening of the exciton line because of the Heisenberg uncertainty principle. In principle, there is a small Stark shift, just as the transitions of a hydrogen atom can be shifted slightly in energy by applying an electric field. This shift, which actually corresponds to polarizing the exciton with the field, is however small (e.g. < 1 meV) before the exciton peak disappears from the spectrum completely.

In the quantum well, the crucial difference is that the walls of the well prevent the field ionization. As the field is applied perpendicular to the layers, the electron is pulled in one direction and the hole is pulled in the opposite direction. As they get to the walls of the well, they are prevented from going any further, at least on the subpicosecond timescale that is important for exciton linewidths. The electron and hole are therefore very strongly polarized, but can still complete several classical orbits before being destroyed by some other process as usual. The orbits are somewhat displaced, but the important point is that there is no lifetime broadening.

Because of the strong polarization of the electron and hole, there is a relatively large change in the exciton energy. The dominant part of this energy comes from polarization P in a field E, an energy of (1/2) $P.E$. This is a reduction in energy, because the electron and hole can each be seen to have "run downhill" towards the appropriate electrode. It is essentially quadratic with applied field E because to lowest order the polarization P is proportional to E. Slightly compensating this reduction is the increased kinetic energy of the electron and hole as they are squeezed into smaller and smaller thickness against the appropriate wall of the well. There is also a small correction because of the reduced Coulomb attraction of electron and hole to each other since they are now further apart. This latter correction can be seen as a reduction in exciton binding energy.

The reduction in the area under a given exciton peak with increasing electric field is also easy to understand. As the electron and hole are pulled apart, their overlap is reduced, leading to a proportionate reduction in optical absorption. The calculation of QCSE shifts and overlaps is relatively straightforward. There are many different ways of performing these calculations, and I will not detail any of these here. One interesting point about overlaps is that, as the lowest transitions lose absorption strength, this overlap is picked up by other transitions, specifically those that were forbidden at zero field. With applied field, the wavefunctions in the quantum well are no longer simple sine waves. In fact they become Airy functions. The simple selection rule that applies for sine waves no longer applies, and all possible transitions between levels become allowed to at least some degree.

Devices based on the QCSE and related effects have some unique characteristics. One particularly important qualitative aspect is that they can modulate light strongly (e.g. by a factor of 2) even with only about 1 μm of material. This effect is strong enough to make devices that operate for light propagating perpendicular to the surface, even for epitaxial structures. This allows us to make two-dimensional arrays of devices. Nearly all other methods of making optical modulators with semiconductors cannot do this.

One very important quantitative aspect is that the operating energy is low. This energy is straightforward to calculate. At its most elementary, the operating energy is the energy required to charge the volume of the modulator to the operating field. This is the same as (1/2) CV^2, where C is the modulator capacitance and V is the operating voltage. For a 1 μm thick modulator, with a dielectric constant of $\sim$ 13, the capacitance is $\sim$ 115 aF/μm^2 (1.15×10^{-16} F/μm^2). For such a device, operating at 5×10^4 V/cm, corresponding to an operating voltage of $\sim$ 5 V, this means an energy of $\sim$ 1.4 fJ/μm^2. This energy density is therefore about 2 orders of magnitude less than that required for similar changes in optical properties by absorption saturation. It is also significantly less than the energy densities required to run laser diodes (per unit optical area). Perhaps most importantly, it is comparable to the operating energy densities of electronic devices. This is because the same physical process is required to operate the electronic device itself. The operating volume of the electronic device must be charged and discharged to run it. The best electronic devices run with somewhat lower energy densities, because the operating voltage can be somewhat less than the 5 V discussed here. Nonetheless, we now have an optical output device that can run at similar energy densities to good electronics devices. This is a new opportunity in optoelectronics. This energy can also be much smaller than the energy required to drive a bonding pad on an electronic chip. For example, for our hypothetical 1 μm thick, 5 V modulator with a $10 \times 10\ \mu m^2$ area, the capacitance is $\sim$ 12 fF, and the electrical drive energy is $(1/2)\ CV^2 = 140$ 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 and the associated off-chip lines. 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-electrooptic effect devices (see below).[9] In operation, there is also the power dissipation from any photocurrent generated in the diode by the absorbed power. Waveguide devices can be made with fewer quantum wells and hence lower voltage drive (e.g. 1V).[19]

Another important point about the QCSE and related effects is that they are fast. As far as we understand the basic physics, there is no speed problem with the QCSE itself until we get to the subpicosecond timescale. Device speed will only be limited by the speed with which we can change the field across the quantum wells, which is simply the speed with which we can charge the capacitance. Modulators have been demonstrated to speeds of $\sim$ 20 GHz,[20] apparently limited only by external circuit considerations.

Quantum well modulators have great potential for integration with both electronic and optical devices, such as lasers.[21] Techniques have been demonstrated that enable the operating wavelength of the quantum wells to be adjusted locally by selective diffusion while still allowing the QCSE modulators to work.[22] This is an important degree of design freedom; it means for example that we might be able to make a laser diode on one part of the wafer, make transparent waveguide material on other parts, and waveguide quantum well modulators (with their bandgap set for optimum modulation of the laser wavelength) on yet other parts, all using the same grown layer structure. The modulators 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.[23, 24] 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.[25, 26] These Fabry-Perot devices can have much greater contrast ratios because of the multiple reflections of the light through the material and the coherent cancellation of reflections inherent in the resonator structure.

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.[27] 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.[28, 29] 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 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.

Another way to make absorption modulators with quantum wells is known as "phase-space absorption quenching" (PAQ).[30] 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.[31]

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 100's of microns long, much shorter than most other techniques.[32] 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.[31] These effects are not yet large enough to make useful refractive modulators for light perpendicular to the layers, except possibly with resonators.[33]

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, optoelectronic 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 10's of nanometers in less efficient designs), some saturation problems at high intensities, and potential temperature sensitivity. The insertion loss depends upon the design, and to some extent is traded off against other parameters such as contrast ratio or device size. For example, if we choose to work in the spectral region for wavelengths somewhat longer than the zero field bandgap energy, the insertion loss can be very low because there is little absorption here. This should be balanced by the fact that the resulting absorption with field will probably be somewhat less than could be achieved by working at somewhat shorter wavelengths. For a waveguide modulator, however, this is not a major drawback, since we can make it sufficiently long to compensate for the lower absorption. It may be possible to avoid the saturation problems by redesigning the quantum well barriers, and there has been some recent success in this;[14] although some modulators show saturation effects at intensities as low as a few kW/cm^2, this work suggests that, by lowering and thinning the barriers, saturation intensities $>$ 100 kW/cm^2 can be achieved. The saturation is thought to result from the build-up of carriers in the quantum wells, and can therefore be reduced by arranging for the carriers to be emitted faster from the wells, as in this work.[14] The temperature sensitivity comes from the temperature dependence of the band gap energy ($\sim$ 0.4 meV/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.

4. Self-Electrooptic-Effect Devices

It is clear from the above discussion of modulators that it is possible to make some very small (e.g. of micron dimensions) and highly efficient devices that can operate with very low energies. If, however, we were to insist on using these only as discrete devices with external electrical drive, it would be very hard to take full advantage of such small size. We would for example typically end up with bonding pads much larger (e.g. 100 μm) than the devices themselves, probably also with larger capacitance. Certainly the capacitance of the electrical line would be likely to exceed that of the devices. The dissipation would most likely be dominated by the line terminating resistor rather than the device itself in high speed applications. These arguments point towards integration of modulators. If we could also combine optical inputs into the same concept, we would be able to make devices with optical inputs and outputs that use the many communication advantages of optics.

The concept of the self-electrooptic effect device (SEED) is to combine a photodetector (or photodetectors) with one or more quantum well modulators, possibly with some intervening circuitry, to give a device with optical inputs and outputs.[4] This becomes an attractive concept when all of these functions can be integrated. Then we may scale to small devices with proportionate improvement in performance. Long electrical lines, parasitic capacitances and line termination become irrelevant and unnecessary. Because of the low energy of the quantum well mechanisms, we may at last be able to defeat one argument against optoelectronics in processing. That argument states that it is inefficient to convert from electronics to optics and back again. This has historically been true with most of the devices that we have had available to us. It need not be true with integrated quantum well devices.

One important development with SEEDs has been that detectors and modulators can be combined in very simple circuits to perform usable functions. It is ultimately desirable to be able to incorporate more complex circuits so that we can perform more complex functions. Incorporation of more electronics is technologically harder, though possible. This is the subject of the next section. Here, we will concentrate on the simpler SEEDs with no active electronic components. Because of their relative simplicity, it has been possible to make large arrays of devices.[9]

The simplest SEED is a resistor-biased optically bistable device (R-SEED).[34] The circuit for this device is shown in Fig. 5. If we choose to operate this device at a photon energy near to the position of the heavy hole exciton peak at zero field, as shown by the dashed line in Fig. 4, we can take advantage of a positive feedback mechanism. At this photon energy, as we reduce the voltage from some high reverse bias, the optical absorption increases. The diode structure shown is actually a good photodetector also. In practice, we can typically get one electron of current for every absorbed photon. Therefore, as we start to shine light on the photodiode/modulator, we start to generate some photocurrent, which gives a voltage drop across the resistor. Consequently, the voltage across the diode drops, increasing the optical absorption, and therefore further increasing the photocurrent. This positive feedback mechanism can become so strong that, at some critical upper switching power, the device switches into a high absorbing state, with essentially no voltage then across the diode. Decreasing the optical power again eventually results in a switching back to a low absorption state at some lower power. Between these two power levels, the device is actually bistable, being stable in either a high absorbing or a low absorbing state. A representative input/output characteristic for a bistable SEED (actually an S-SEED discussed below) is shown in Fig. 6.

The basic dynamics of the R-SEED can be understood by viewing the diode as a capacitor.[35] For a reverse biased p-i-n diode, this is a good approximation. The capacitance, C, of such a structure is approximately that of a plane-parallel capacitor with plates separated by the intrinsic region. The photocurrent acts to discharge the capacitance, and the resistor and power supply tend to charge it up. From this we can deduce directly that the dominant time constant for the operation of the device is the resistor-capacitor time constant, RC.

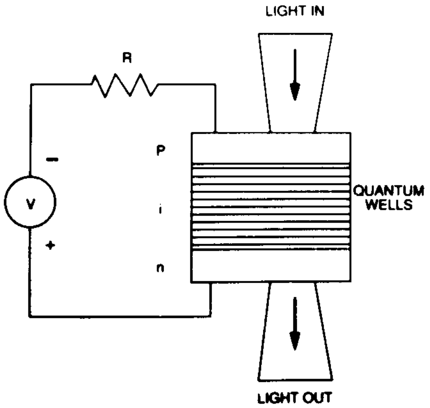

Fig. 5. Schematic of simple resistor-biased optically bistable self-electrooptic effect device (SEED).

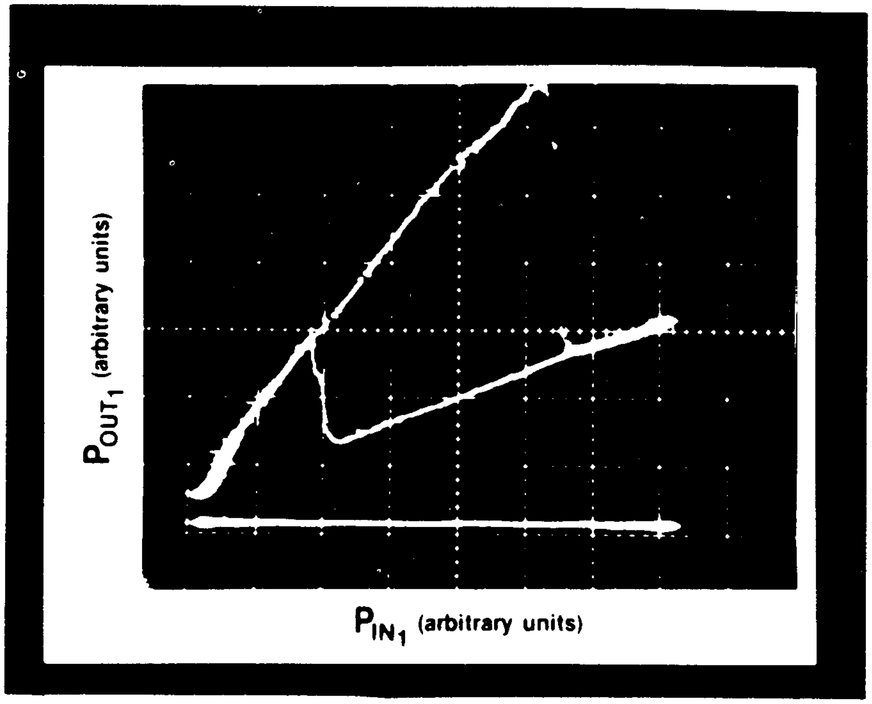

Fig. 6. SEED optical input/output characteristics showing optical bistability (this particular characteristic is taken with a symmetric SEED).

We could switch this device from the high into the low voltage state by suddenly optically creating a charge $Q = CV_0$ in the diode, thereby totally discharging the diode. This requires an absorbed optical energy

$$E_a = \frac{\hbar\omega}{e} CV, \tag{4}$$

where e is the electronic charge; one electron of charge is created for each absorbed photon. In an actual device the absorbed energy will be some large fraction of the incident energy (e.g. 50%), so this energy sets the overall scale of optical switching energies. In switching with slowly varying powers, the switching energy can be defined as the product of the incident power and the switching time. The resulting optical energy is still generally ~ E_a, although it can be several times larger depending on the precise conditions. E_a is therefore a useful characteristic optical energy for the device. In general, E_a is comparable to or smaller than the stored electrostatic energy $(1/2)\ CV^2$.

In practice, R-SEEDs usually show switching times ~ RC and switching energies close to E_a. One important point is that by varying the resistor we can choose either high speed, high power operation with a low resistor value, or low speed, low power operation with a large resistor. In this case the switching energy remains constant, independent of speed over many decades. The limit to the lowest usable power is set by the leakage current of the diode. This may be in the pA range for a very good diode, allowing operation with pW's of power. Speeds from 2 ms to 30 ns have been reported for discrete R-SEEDs.[35] The energies are essentially independent of speed over this range as expected. Other phenomena, such as the finite emission time of carriers from quantum wells and saturation of optical absorption, will probably set ultimate speed limits for SEEDs.

As discussed above, when operating at an appropriate wavelength, the photocurrent can decrease as we increase the reverse bias voltage. This corresponds to negative differential conductance. The value of this conductance is simply the slope of the diode current/voltage curve at a given voltage and power. Increasing the optical power increases the conductance proportionately. Therefore, the quantum well diode, with light shining on it at an appropriate wavelength, has an electrical characteristic rather like a tunnel diode. Consequently, we can make many circuits similar to those made with tunnel diodes and other negative resistance devices. One simple circuit would be the same as in Fig. 5, and would show electrical bistability;[35] ramping the power supply voltage up and down at constant optical power gives bistable switching of the voltage across the quantum well diode. We can if we wish view all of the bistabilities seen with this circuit as a consequence of the negative resistance.

Another classic negative resistance circuit is an oscillator. If we replace the resistor in Fig. 5 with an inductor, the circuit will oscillate once the magnitude of the negative differential conductance is large enough to overcome the losses of the rest of the circuit, and it oscillates at the resonant frequency of the inductive/capacitive circuit. Hence simply shining a light beam on a quantum well diode in series with an inductor and a voltage supply can cause it to oscillate.[35] The oscillation is seen not only on the voltage across the diode, but also in the power of the transmitted light beam. This beam can be quite deeply modulated this way (e.g. a factor of 2), generating an optical clock. Simple discrete bulk inductors readily give frequencies in the MHz region. This concept has not been tested in an integrated configuration, and much higher frequencies may be possible.

One extension of this concept is to make a locked oscillator that can extract the clock from a random optical bit stream.[36] If, in addition to a continuous power beam, we also inject a weak bit stream whose underlying clock frequency is close to the natural oscillation frequency of the oscillator, the frequency of the oscillator can be locked onto this clock. This is the same kind of locking that can take place with any oscillator. This has been tested experimentally with a SEED oscillator.[36] The net result is that we generate a powerful optical clock beam locked in frequency and phase to the clock of a weak optical bit stream. This optical clock can then be used with another SEED gate to re-time and amplify the signal. The whole system therefore performs all the functions of a digital regenerator. Such a system might become of serious practical interest if it were integrated.

As a substitute for a resistor in Fig. 5, we could use another reverse-biased photodiode, giving a diode-based SEED (D-SEED)[35] as shown in the circuit schematic in Fig. 7. As a very rough approximation, we could imagine that the photodiode behaved as a resistor whose value depends on the amount of light shining on it (this light would come from another light beam). Then we can see that we would get bistability as before. This approach has one interesting feature; the effective value of the "resistor" is not fixed in advance, and hence we can set the operating power and speed of the device with the amount of light on the second photodiode. More light will give faster, higher power operation. Note that in this D-SEED we can view switching as taking place when the photocurrent from one photodiode starts to exceed that from the other. It therefore has the unusual property that the state of the device will not change if both light beams (i.e. the light beam on the quantum well diode and the beam on the load photodiode) are changed together so that their ratio is unchanged.[37] This property is used extensively in the symmetric SEED discussed below.

Another interesting SEED variation that has been demonstrated, and works well with a D-SEED, is a self-biased SEED.[19] This is a SEED without any power supply. This also works, to a lesser extent, with the R-SEED. If we take the circuit as in Fig. 5 and simply set the supply voltage to zero (i.e. replace it by a short circuit), the SEED can in principle still work because of its own built-in field. This self-biased SEED works best if the built-in field is large. The self-biased SEED demonstrated used a waveguide p-i-n diode with a thin intrinsic region and only two quantum wells.[19] The resulting built-in field was $\sim 10^{5}$-V/cm. This field is sufficient to shift the exciton substantially to lower photon energies without any applied bias.

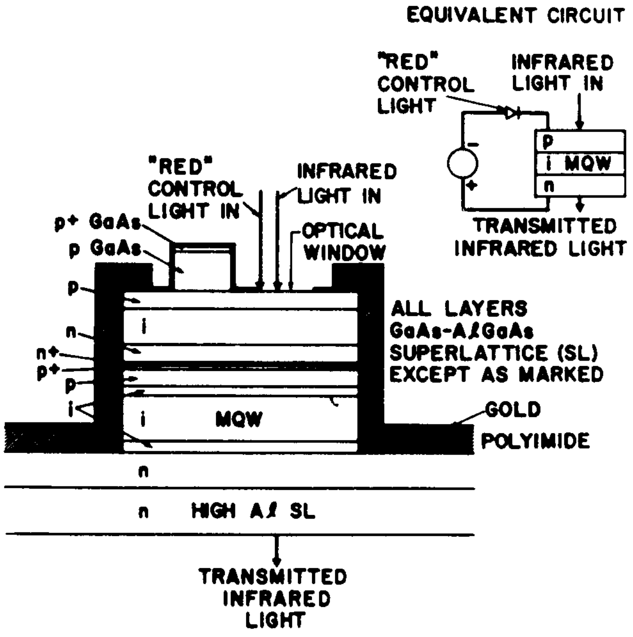

Fig. 7. Layer structure and circuit schematic for a diode-based SEED (D-SEED). (The structure used a fine period superlattice instead of AlGaAs for material quality reasons. The active layers are the quantum wells.) The whole structure is ~ 6 μm thick.

The D-SEED was the first SEED to be integrated.[37, 38] The layer structure for doing this is shown in Fig. 7. Here, the load photodiode is an AlGaAs p-i-n diode grown vertically on top of the quantum well diode. In operation, a short wavelength beam (e.g. a red light beam) is shone on the top of the structure, so that it is absorbed entirely in the AlGaAs diode. An infrared beam, at the appropriate wavelength for the quantum well exciton peak, is also shone on the top (or on the bottom). It passes through the AlGaAs diode without absorption. We then see bistability in the transmitted infrared beam as we would expect, with the switching power and speed set by the red beam power.

With this vertical structure, it is relatively straightforward in principle to make arrays of devices. These consist of mesas with insulators deposited on the sides, with a common top contact taken off the top of all the mesas, and the bottom *n* layer in the structure used as the other power supply contact. There is therefore only one pair of electrical connections for the entire array. All the devices in the array are reverse-biased in parallel. An important point to note about this device is that the only capacitance that charges and discharges in normal device operation is the internal capacitance of the device. Although the device is internally partly electronic, there is no external electrical communication of information, and hence no lines to charge. All the information is communicated optically. This fact means that we can scale the device to smaller dimensions and proportionately improve its performance.

Integrated D-SEEDs have been demonstrated in 2 × 2 arrays of 200 × 200 μm^2 mesas,[37] and in 6 × 6 arrays of smaller (60 × 60 μm^2) devices.[38] The devices were very uniform in their performance across the arrays. Performance also scaled well with area.[38] Operating speed could be varied from ~ 1 μs to 10 s with a reciprocal speed/power trade-off. For example, for the smaller devices, a switching power of 180 μW was required for switching at 1 μs. Switching with as little as 40 pW was observed. The slowest switching time in the device was limited only by the leakage current in the diodes, which was in the range of picoamps. As mentioned above, we may turn down both beam powers together, and the device will hold its state. Hence we may hold memory with little power, only turning up the beams when we want to read out or rapidly change state, as in a dynamic memory. In fact we may also turn off the beams completely for a limited period of time. The device will start to change state by discharging its internal capacitance through the difference in the leakage currents in the two diodes. If we do not let this go too far, then we may turn both light beams on again and the device will latch back into its previous state. Hence we have a dynamic memory without the sense amplifiers normally required in electronic implementations. Zero power holding times as long as 30 s have been demonstrated.[38] The steady-state holding power for such a memory is only ~ 250 nW/cm^2.

Most of the work on SEEDs has concentrated on devices for digital applications. The devices also have analog modes. Such modes may be useful in spatial light modulator applications or in optical neural networks. One interesting mode of the D-SEED is the self-linearized modulator or optical level shifter.[35, 38] Suppose that we change the operating wavelength or photon energy such that it is at lower photon energies, below the zero-field exciton peak position (i.e. to the left of the dashed line in Fig. 4). Then instead of a positive feedback (giving bistability), we get a negative feedback. This negative feedback adjusts the voltage across the diode so that the photocurrent equals the current in the rest of the circuit. Since the photocurrent is usually linearly proportional to absorbed power, we have a modulator that is linear when driven from a current source, i.e. a self-linearized modulator.

One particularly easy and interesting way to make a constant current source is, of course, a reverse-biased photodiode, which is exactly the circuit of the D-SEED. This self-linearized operation has been demonstrated with both discrete[35] and integrated[38] D-SEEDs. Since the current from the conventional reverse biased photodiode can be linearly proportional to the light incident on it, we can have a self-linearized light-by-light modulator. Note that this is an inverting device, since more light on the conventional diode gives more absorption in the quantum well diode. Since the incident light need not be coherent or narrow band, we can also have a linear (inverting) incoherent-to-coherent converter. In fact, the incident light could be a visible, incoherent image on an array of D-SEEDs, in which case we could form a linear, inverted replica of it in a coherent infrared image.[38] It is also of course possible to use a similar visible image onto a D-SEED array operating in the bistable mode, in which case we can form a thresholded version of the image.[38] These various modes have all been demonstrated with a 6 × 6 D-SEED array.

It is of obvious interest to see whether devices such as the optically bistable R-SEED or D-SEED can be used for practical digital logic applications. Simple bistability is however difficult to use in large logic systems. 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)[39] 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 quantum well diode, it uses another quantum well diode, as shown in Fig. 8. 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 another bistable state, with one diode transmitting and the other diode absorbing. As we turn down the power in both beams together (e.g. by reducing the laser power), however, 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

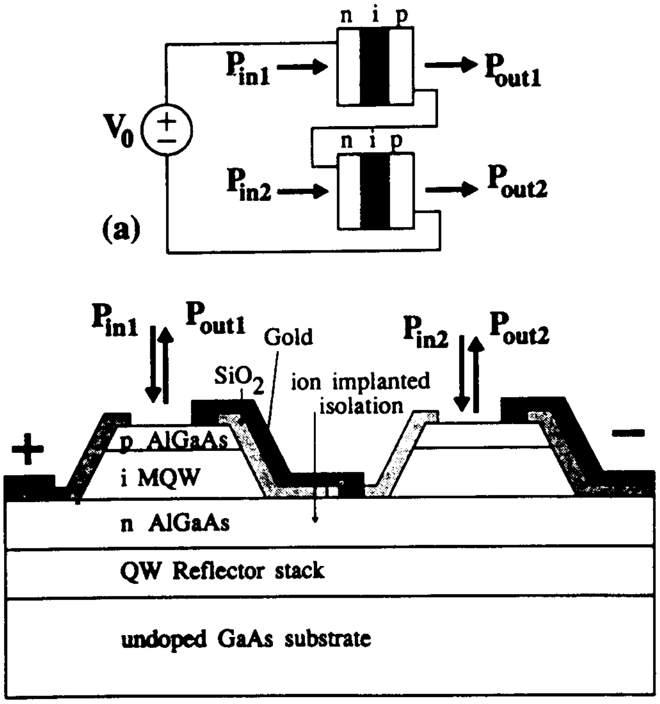

Fig. 8. Layer structure and schematics for symmetric SEED (S-SEED).

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, the 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.

Figure 9 shows a 64 × 32 array of S-SEEDs. Devices in this array consist of two mesas, each 10 × 10 μm^2. Switching energies are a few picojoules in current devices. 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[14]). 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 large arrays of devices.[8] 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.

These devices are very different from other kinds of devices, and taking full advantage of the abilities of optics with such devices will require some ingenuity itself. At the very least, they offer us opportunities that simply were not there before. As mentioned above, 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 electronic 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).

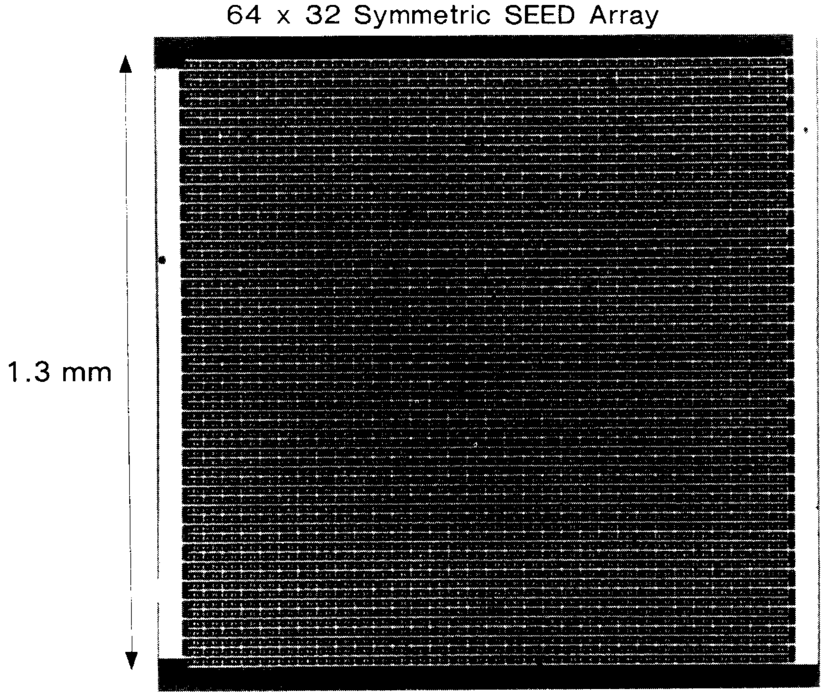

Fig. 9. A 64 × 32 array of symmetric SEEDs. Each device uses two mesas, each of which is 10 × 10 μm^2.

5. 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. Such free-space connections are qualitatively different from those possible in electronics. Free-space optics is particularly useful in making regular but global interconnections. A simple example is an imaging interconnect; one simple lens can image every output on one chip onto a corresponding input on another. Even this simple interconnect is difficult electrically as it involves inversion; top goes to bottom and left goes to right, an operation that would involve crossing every wire. Such an interconnect may be too simple to be of great topological benefit, but other global regular interconnects, such as perfect shuffles, are certainly of interest in switching and fast Fourier transforms for example.

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.[40] 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.[41] An integration scheme is shown in Fig. 10. 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.

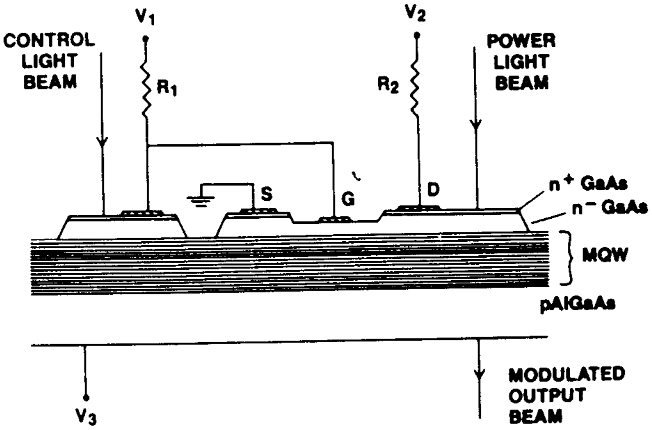

Fig. 10. Schematics for a field-effect transistor SEED (F-SEED). The particular circuit shown gives an optical signal amplifier.

The particular circuit illustrated in Fig. 10 performs as an optical signal amplifier. In principle, such a concept can be extended to give arbitrary logical functionality between inputs and outputs by using FET logic. This concept 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.[10] In preliminary tests, these have performance comparable to those on GaAs substrates, and have operated for 1 000 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. At the present time, this area too is very promising.

6. Conclusions

At the time of writing this article, the first quantum well switching devices are starting to become commercially available. New device concepts are being demonstrated and proposed at a growing rate. The first serious attempts at optoelectronic integration with quantum well devices are under way now, with promising initial results. As these ideas and technologies advance, it will become clearer to us what the real impact on systems will be. Already the availability of two-dimensional arrays of quantum well optical switching devices (symmetric SEEDs) has stimulated serious systems experiments in the use of two-dimensional "free-space" optics. The resulting advances in optical systems have made free-space optical interconnects much less bizarre than they would have seemed only a few years ago. The ultimate importance of these devices will depend on their impact on improving system performance. This may happen evolutionarily, through the gradual introduction of optics into electronic systems to solve particular communications problems within processors. This is already happening using existing devices such as laser diodes, fibers and photodetectors. The quantum well devices may help this process with improved performance and better integration. More speculatively, we might see revolutionary change because the quantum well devices offer qualitatively new opportunities, such as allowing us to use free-space optics. This is not something that we can condense into some simple number, such as device speed or size or power, although all of these are important. Such possibilities suggest new system architectures that previously would have been hard for us to contemplate. In this article, I hope that I have given some feel for the possibilities with quantum well optoelectronic devices. More profoundly, I hope that the article may stimulate new concepts in devices and systems.

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