"Optical Computing" eds. B.S. Wherrett and F.A.P. Tooley, Proceedings of the 34th Scottish Universities Summer School in Physics, Edinburgh, August 1988 (Adam Hilger, Bristol, 1989) pp 71 - 94

QUANTUM WELL ELECTROABSORPTIVE DEVICES: PHYSICS AND APPLICATIONS

D. A. B. Miller

AT&T Bell Laboratories, Holmdel, NJ 07733, USA

1.

INTRODUCTION

Quantum wells are one of the more promising developments of recent years for applications in optical devices. They offer low-energy optical mechanisms compatible with laser diode light sources and semiconductor electronic devices, and are particularly well suited to integration with electronics and for fabrication of two-dimensionally parallel arrays compatible with the opportunities of free-space optics.

In this short set of lecture notes, I will give a brief summary of quantum wells, their electroabsorptive properties, and their possible applications in optical switching and computing. Comprehensive reviews of nearly all of this material already exist in the literature [1-4]. For the most part, I will not make specific references to the literature except when the work is too new to be included in these reviews.

I will start by introducing layered semiconductor structures and quantum wells (section 2), and proceed to summarize electroabsorption in semiconductors in general and in quantum wells, introducing in particular the quantum-confined Stark effect (QCSE), which is the mechanism on which all the devices discussed here are based (section 3). In section 4, I will discuss optical modulators, and in section 5 I will summarize the self-electro optic-effect devices (SEEDs), which are the ones most interesting for optical switching (in the sense of light switching light).

2.

LAYERED SEMICONDUCTOR STRUCTURES

The modern techniques of layered semiconductor growth, such as molecular beam epitaxy (MBE) or organo-metallic vapor phase epitaxy (OMVPE, also called metal-organic chemical vapor deposition (MOCVD)), allow us to grow crystalline semiconductor layers with thickness control down to single atomic layers. Within limits related to the mismatch of the lattice constants of the bulk materials, we can grow layers of different semiconductors one on top of the other. We can choose to dope different layers as we wish, and can obtain very abrupt interfaces between materials and between doping levels.

Such growth techniques can be applied to make many different kinds of devices (e.g. sophisticated transistors, laser diodes, optical detectors, optical waveguides, and quantum well devices as discussed here), and have the potential for integrating several different types of these devices together. They also allow the study of various novel physical effects seen only in "low-dimensional" systems. Perhaps the most studied material system is GaAs/AlGaAs. These materials have almost identical lattice constants, and essentially arbitrary layered structures can be grown. Most other III-V materials can also be grown, and InGaAs/InAlAs and InGaAs/InP have received particular attention for long-wavelength optical devices. II-VI materials and group IV materials (e.g. Ge/Si) are the subject of active research. Structures involving controlled amounts of strain resulting from lattice mismatch can be grown, giving new properties.

We will discuss here only the optical properties of one particular class of such structures, namely quantum wells. Quantum wells consist of alternating layers of two different semiconductors. The electrons and holes see lower energy in one semiconductor layer than in the other (a potential "well"). If both electrons and holes have lower energy in the same layer, this is called a "Type I" structure, and this is the only one we consider here. (For electrons seeing lower energy in one semiconductor layer and holes in the other, the structure is "Type II"). The layers can be so thin that the electrons and/or holes are "quantum-confined", i.e., they behave like particles in a box in one direction, hence the term "quantum well". In the case of GaAs/AlGaAs, the electrons and holes both see lower potential energies in the GaAs material, which has a lower bandgap energy, with the AlGaAs layers (having a larger bandgap energy) forming the "walls" or barriers. Quantum wells are further restricted in that the barriers have to be sufficiently thick that tunneling between adjacent well layers is weak; the basic physics of quantum wells is essentially that of one well between two barriers, although we often use many such wells, especially to obtain enough optical absorption.

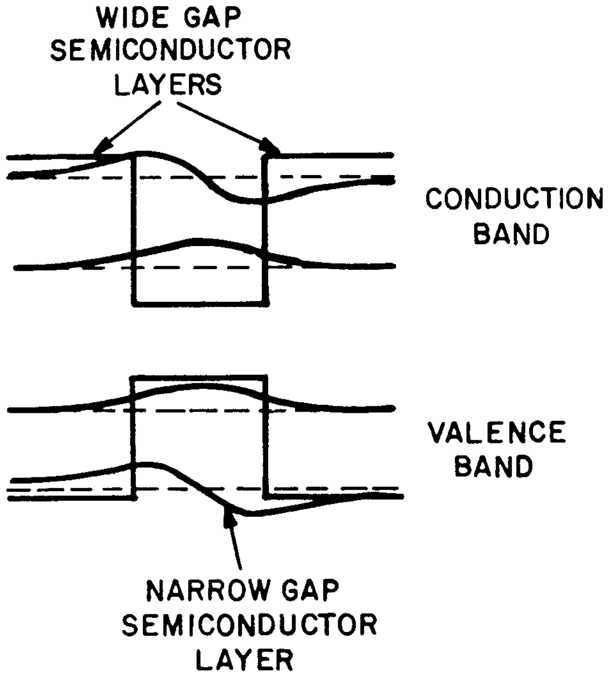

Fig. 1 Wavefunction and potential structure for a simple quantum well, showing two confined states in the conduction and valence bands (not to scale).

Fig. 1 shows some typical wavefunction solutions in a typical potential structure for a quantum well. Strictly, these are so-called "envelope functions" that are a relatively slow modulation in space over the unit cell wavefunctions. In practice, we can usually factor out the effect of the unit cell wavefunctions, which can be viewed as giving the particle an effective mass different from the free electron mass, m_o (effective mass approximation). Then the envelope functions can be calculated by solving Schroedinger's equation treating the particles as having the appropriate effective masses. For the case of simple rectangular structures, this is particularly straightforward, giving sinusiodal solutions within the wells and exponential tails into the barriers for the "bound" states. This is essentially the well-known "particle in a box" solution of the wave equation. In the majority of semiconductors of interest here, the electrons are relatively "light" (e.g. effective mass $m_e \sim 0.07\ m_o$ for GaAs), and there are two kinds of holes, namely "heavy" holes and "light" holes, with effective masses $m_{hh} \sim 0.4\ m_o$ and $m_{lh} \sim 0.09$ respectively in GaAs.

3.

ELECTRO-ABSORPTION IN QUANTUM WELLS

Fig. 2 shows a typical absorption spectrum of a GaAs quantum well sample at room temperature. Unlike a normal bulk semiconductor, it shows a series of "steps" in the absorption. These steps result directly from the "particle in a box" quantization discussed above. Without field, only transitions between the same kind of sinusoidal wavefunction in the valence and conduction bands are possible, simply because of the overlap integrals between sinusoidal waves. There is one step corresponding to each such allowed transition. (The actual spectrum is the sum of two such sets of steps because of the two different kinds of holes). It is also clear that there are strong peaks at the edges of the steps. These peaks are exciton absorption peaks. When we absorb a photon to make an interband transition in a semiconductor, we take an electron from the valence band and raise it to the conduction band, but we also leave behind a hole in the valence band, and we must take account of this hole. In fact, a more useful picture is to say we are creating an electron-hole pair. The lowest energy state of such a pair is what is loosely referred to as "the" exciton, which corresponds to the electron and hole orbiting round one another like a hydrogen atom, although with a much larger radius (e.g. ~ 140 Å in bulk GaAs) because of the larger dielectric constant and lower effective masses in the semiconductor. In such a state, the electron and hole have very strong overlap because they are held close together, and, as a result, the optical absorption for the creation of the electron and hole in this state is strong, hence the strong peaks in the absorption. In the case of the quantum well, there is one such exciton peak for every step. Strictly, there are many possible exciton states corresponding to the various excited states of the hydrogen atom, and these have to be included in any complete description of the absorption, although the lowest state is usually the only one to show a strong feature.

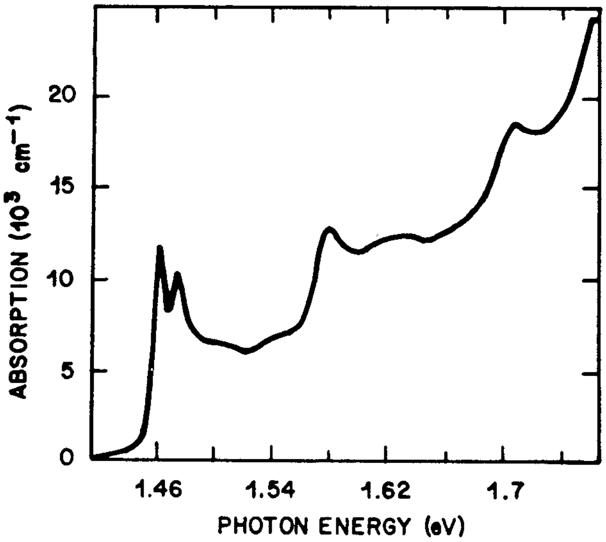

Fig. 2 Absorption spectrum of a GaAs quantum well sample at room temperature for ~ 100Å *quantum wells.*

The exciton peaks in quantum wells are particularly strong because the excitons are squeezed by the walls of the wells to be even smaller, making the electron and hole even closer, hence giving even stronger absorption. This smaller exciton also orbits faster in the classical sense. In the case of a typical bulk exciton at room temperature, it cannot normally complete a classical orbit before being destroyed by collision with an optical phonon, and hence the exciton line becomes very broad by the uncertainty principle and the exciton cannot really be considered as a stable particle. The faster orbit of the quantum well exciton allows several orbits before such destruction, hence giving still a well-defined peak.

The simplest and best-known electroabsorption mechanism in bulk semiconductors is the Franz-Keldysh effect, which is calculated neglecting any excitonic effects. The effect of applying an electric field can be viewed as tilting the conduction and valence bands. Thus, loosely speaking, an electron can be lifted by a photon with energy less than the bandgap energy to a point below the conduction band from which it may tunnel laterally into the conduction band. This gives a weak absorption tail extending below the band gap energy.

When we include excitons in bulk semiconductors, we must also note that these excitons are very readily ionized by applied electric fields. This gives a broadening of the exciton line even for quite modest fields that is a consequence of the uncertainty principle since the lifetime is reduced by the field ionization of the exciton. When excitonic absorption lines are clearly present, this behavior actually dominates the electroabsorption at least for low fields. Consequently therefore in bulk semiconductors the dominant effect of applying electric field is to broaden the band edge, including any excitonic feature, and generate an absorption tail extending below the bandgap energy.

In quantum wells, for electric fields applied in the plane of the quantum well layers, exactly the same phenomena occur as occur in the bulk semiconductors, in that the exciton absorption peak is strongly broadened with the field and a weak absorption tail appears below the bandgap energy. If, however, we apply the field in the direction perpendicular to the quantum well layers, we see quite different behavior. As we apply the electric field, the exciton absorption resonances remain clear and well resolved, and can be shifted substantially to lower energies with increasing field. The reason for this is that the field ionization of the exciton is essentially prevented because the electron and hole are pulled only to opposite sides of the same well and cannot go any further. In this situation, they are still capable of executing orbits round about one another even though these orbits are somewhat displaced, and hence we still have a well-defined particle that may live for many classical orbits. The energy of this particle has however been substantially changed because the electron and hole are pulled apart by field. The dominant contribution to the energy is simply a term of the order of (1/2)**P.E**, **P** being the polarization of the electron and hole in the presence of the field **E**. In general terms this is nothing other than a Stark shift, but in this case the shift may be several times the binding energy of the particle. This is in strong contrast to Stark shifts of unconfined hydrogen atoms or excitons in which the shift of the resonance with field never exceeds about 10% of the binding energy. The mechanism that applies in quantum wells is therefore described as a Stark effect that is dominated by the special properties that result from the quantum confinement of the electron and hole within the quantum well, and hence can be called the quantum-confined Stark effect. To see this same effect with an actual hydrogen atom would require that we confined it between two walls only ~ 1/2 Å apart and that we applied electric fields of the order 10^{10} V/cm. It is of course important in the quantum well case that the quantum well is significantly smaller then the bulk exciton. Otherwise the exciton could be effectively field ionized just by pulling the exciton and the hole far apart to opposite sides of such a wide well. The actual shifts of the exciton absorption lines are relatively easy to calculate because they tend to be dominated by the shifts of the single particle electron and hole states, and hence all we need to solve is the problem of an electron or a hole in a skewed quantum well corresponding to the quantum well potential plus an electric field potential. There is only a small correction from the change in the Coulomb attraction between the electron and hole themselves. The experimental agreement with such theory for the shifts of the exciton absorption peaks is in general very good.

I show a set of spectra in Fig. 3 for the optical absorption edge of the quantum well as electric field is applied. For quantum wells of the order of 100Å in thickness, fields $\sim 10^4$-10^5 V/cm show substantial shifts of the exciton absorption peaks while still retaining their essential sharpness. The small amount of broadening that is seen in the spectra is not due to field ionization, but rather to practical effects associated with minor imperfections in the quantum wells. The slight loss of area under the exciton peaks as they shift is essentially because the electron and hole overlap has been reduced by pulling them apart.

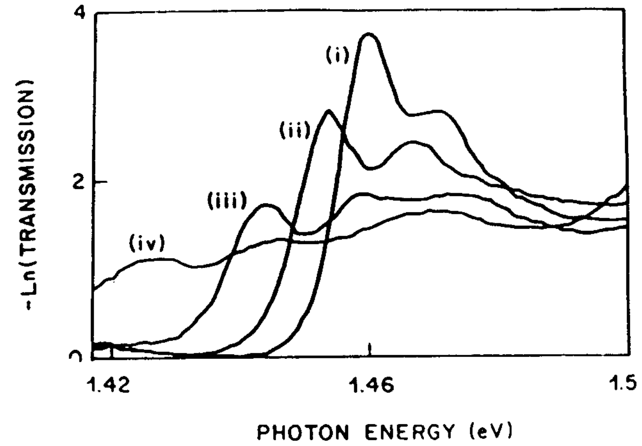

Fig. 3 Absorption spectra for a 94Å *quantum well sample as electric field is applied perpendicular to the layers.* (*i*) *0 V/cm;* (*ii*) 6×10^4 *V/cm;* (*iii*) 1.0×10^5 *V/cm;* (*iv*) 1.5×10^5 *V/cm.*

The changes in absorption coefficients that are induced in these quantum wells in this spectral region are many 1000's cm^{-1} in absorption coefficient. Thus, with structures only of the order of a micron in thickness we can make significant changes in optical transmission. This change in transmission forms the basis for most of the devices that I will discuss here. There are also associated changes in refractive index, which always occur whenever there is a change in absorption spectra, and these may also be of some interest for optical devices.

4.

OPTICAL MODULATORS

The necessary fields to make optical modulators (and the other devices that we will discuss below) can most conveniently be applied by putting the quantum wells within the intrinsic region of a reverse biased p-i-n diode. For an intrinsic region of thickness 1μm, for example, consisting perhaps of 50 or more quantum wells, applying a reverse bias of, say, 10 volts will apply a field of 10^5 V/cm, exactly the magnitude required for large optical modulation. With these systems such a structure can be grown, for example, on a GaAs substrate in a MBE machine, and will typically utilize transparent AlGaAs p and n layers. In using such a device, in this simple structure at least, it is necessary to remove the GaAs substrate, which is opaque at the operating wavelength.

It is worth emphasizing here one of the major physical features of this electro-optical effect that makes it particularly attractive from a physical point of view for optical devices. This is that operating energy per unit optical area can be extremely low. The energy required to change the optical properties of a one micron thick layer of this material is of the order of a few $fJ/\mu m^2$, since this energy is essentially CV^2 where C is the capacitance of diode structure and V is the operating voltage. This energy density is comparable to that of a good electronic device, although it is not quite as low as the very best electronic devices because the operating voltage here is somewhat higher.

Such quantum confined Stark effect devices have various other attributes that are also important for practical devices. They will probably operate very fast; to date, this effect has operated as fast as we have been able to apply electric field to it, and the physical limit is expected to be somewhere below a picosecond. This effect is also extremely well suited for the fabrication of two-dimensional, parallel arrays of devices, since we can obtain sufficient change in transmission with only microns of thickness of material. Other semiconductor electro-optical effects do not in general enable us to do this. These devices are also compatible with laser diodes and electronics in fabrication, in operating wavelengths, in optical powers, in electric powers and voltages, and in materials, and are therefore very promising for integrated optical and opto-electronic systems.

Many different optical modulators have been proposed and demonstrated based on the quantum-confined Stark effect. In the GaAs/GaAlAs system in particular many different structures have been tried. These modulators can also operate quite effectively in the waveguide mode with the light propagating in the plane of the quantum wells; this configuration is particularly interesting for the possibilities of integrating laser diodes and modulators within a chip. Other variations on the basic modulator structure include modulators in which there is a dielectric stack mirror, made of GaAlAs and AlAs quarter wave layers, grown directly on the substrate before the growth of the quantum well diode itself. This enables us to avoid removing the GaAs substate; the light incident from the top of the structure passes through the quantum wells, reflects off the mirror, and passes back through the quantum wells to re-emerge, modulated, from the top surface. This has the additional advantage of offering two passes through the quantum well material, hence improving the contrast ratio of the modulator further. Another variation in modulator design is to change the actual shape of the quantum wells themselves. Although the majority of devices have used simple (rectangular) quantum wells it is possible to use much more complex shapes if we wish. The theory is readily extended to such structures. One example structure is where we replace the simple quantum well with a pair of well layers separated with a very thin barrier - a coupled-well system. This has different behavior from the simple rectangular well but can show a larger reduction in the overlap integral of electrons and holes with applied field, and hence can give enhanced change in absorption from that particular mechanism. In general such different quantum well shapes offer us a way of making engineering improvements to quantum well modulators, although they probably do not offer order of magnitude advantages, at least as so far as we understand them at the moment. The usefulness of such sophisticated structures depends on the particular application in which we are interested. The quantum-confined Stark effect in such diodes can also be used to make tunable photodetectors; the p-i-n structure is of course ideally suited for photodetection since essentially all electron-hole pairs generated in the intrinsic region will result in photocurrent being collected in the reverse-biased device.

Although the majority of the work in such modulators has been performed in GaAs/GaAlAs structures, other material systems have been investigated with, overall, considerable success and promise for devices operating at other wavelength regions. Most investigated have been those materials which have the potential to operate in the longer wavelength regions, such as 1.3 μm and 1.5 μm, that are of most interest for very long distance optical fiber communications. Examples of such systems are InGaAs/InAlAs, GaSb/AlGaSb, and InGaAs/InP. All of these show sufficient electroabsorption with particularly clear shifts being seen in the GaSb/AlGaSb and InGaAs/InP systems. Electroabsorption has also been clearly seen in the InGaAs/GaAs system, which is particularly interesting as it is a strained-layer system. There is therefore considerable promise for extending these effects into many materials systems and hence many operating wavelengths.

Quantum-confined Stark effect absorption modulators have various features in their favor compared to other modulators. First of all they can operate at low voltage, particularly in the waveguide devices where operation with a volt or less is possible. They can also have very low total volume (for example, cubic microns in principle) which is therefore promising for highly integrated devices. I have already mentioned their low energy density capability. They also have the potential to be very-low-chirp modulators (i.e. there is very little frequency sweep as the amplitude is changed), and high speed operation has been demonstrated, at this time up to about 5.5 GHz. Other attractive features include the absence of any need for velocity matching; this is a common problem in modulators in which the overall structure is large and account has to be taken of the different propagation velocities of light through the structure and of the electric field pulse which is to modulate the light. Finally it must be emphasized again that such structures relying on the quantum-confined Stark effect have an almost unique ability to make light modulation for propagation perpendicular to the surface of arrays of devices.

Among the drawbacks of such modulators is the difficulty of taking full advantage of their small size because of stray capacitances introduced in mounting non-integrated devices. They also have a relatively narrow wavelength region of operation (e.g. of the order of a few nanometers for optimum performance). It is also clear that some temperature stabilization will be required to maintain optimum performance. Such stabilization would need to be within, say 5K, (corresponding to the approximately 2Å/K shift of the band edge). This is clearly an engineering constraint but it is by no means a major technical problem. Modulators may also saturate at high intensities (for example $\sim 10\text{kW/cm}^2$) depending to some degree on the time taken to sweep carriers out of the structure). Another obvious constraint is that these are absorption modulators, and there will always be a tradeoff between the contrast ratio of modulation and the amount of background absorption or loss that will be involved with the modulator. For devices in which the light is propagating perpendicular to the layers, it is not easy to make very high contrast modulators, although of the order of

8:1 contrast has been demonstrated for a reflection devices with the built in-mirrors. For the case of waveguide modulators very high contrast can be made (e.g. 30:1) although again there is some tradeoff involving background absorption and the ultimate performance of the device.

As to refractive-index-based modulators, these devices are under active research at the moment. It is possible to make large changes of refractive index in the quantum wells resulting from the quantum confined Stark effect. The largest index changes occur in those regions of strong absorption (e.g. near the exciton absorption peaks), and hence cannot be utilized efficiently for a device. To achieve the necessary criterion of obtaining half a wavelength path length change in less than one absorption length, it is necessary to operate at wavelengths reasonable longer than the band edge, and hence some tradeoff in performance is again necessary in order to make the background absorption low enough. It does appear, however, that such quantum well refractive modulators may offer significant performance advantages over some other systems.

5.

SELF ELECTRO-OPTIC EFFECT DEVICES

The devices discussed so far have been devices in which the optical transmission is controlled by applying an electrical voltage. Clearly to be able to use this same physical effect (the quantum-confined Stark effect) for devices in which light switches or controls light, we must somehow make the system sensitive to light inputs. The way of doing this is simply to combine the quantum well modulator with some form of light detection, so that light shining on the detector causes a change in voltage across the modulator and hence creates a device with both an optical control input and an optical output. This is the principle of the self electro-optic effect device (SEED). I have already mentioned above that the optical modulators themselves offer very low energies of operation. To take advantage of this to make optically-controlled optical devices with similarly low energies, it is very important to integrate the detector and the modulator so that we do not incur large stray capacitances or other parasitics in the system. If and only if we manage to achieve such an efficient integration will we be able to make devices that can take full advantage of the low operating energy of the quantum-confined Stark effect in optical switching applications in which light controls light. If we are able to achieve such integration however, we will be able to make optical switching devices with extremely low operating energies. These energies are so low that we will be able to achieve interesting devices even without having to use resonant cavities.

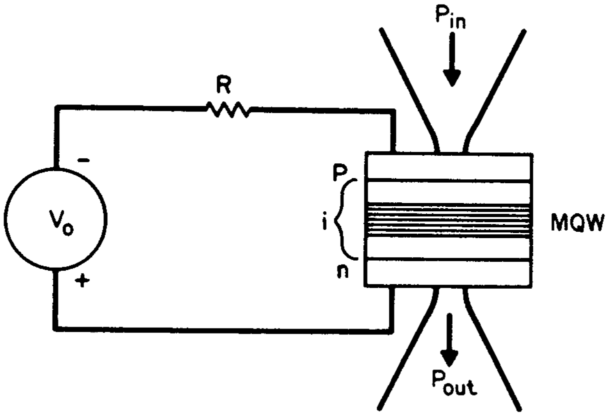

Fig. 4 Resistor-biased bistable SEED circuit.

A large number of such self electro-optic effect devices have been proposed, either in integrated or nonintegrated form, and several have been demonstrated. The simplest of all of these devices is the resistor-biased bistable SEED. This is shown schematically in Fig. 4. In this device the same quantum well diode is used both as the detector and the modulator. For bistable operation we operate at a wavelength approximately coincident with the position of the exciton peak at 0 V bias. In operation, before we shine any light into the device, all of the supply voltage in the circuit shown in Fig. 4 appears across the quantum well diode as a reverse bias. Hence the optical absorption of the diode is relatively low. As we start to shine light into the diode we start to generate a photocurrent, which gives us some voltage drop across the resistor R. This voltage drop means that there is less bias voltage across the quantum well diode, and hence we have a larger absorption within the diode. Consequently, the photocurrent increases somewhat more, giving a yet larger voltage drop across the resistor, and hence yet smaller voltage across the quantum wells, resulting in yet larger absorption in the quantum well diode, and so on. Hence we have a positive feedback mechanism, and this mechanism can become so strong that the device switches into a state of high absorption. This is at the basis of the bistability of this simple system, which is an example of optical bistability from increasing absorption. Such devices are easy to demonstrate, in discrete configurations at least, and the switching power and speed can be chosen over a wide range by choice of the resistor in the circuit. For example, for large discrete devices of dimensions on the order of 100μm, switching speeds of a few 10's of nanoseconds would be typical with switching powers of the order of mW's. This can be scaled reciprocally to much lower switching powers, for example much less than a nW, with a proportional increase in the switching time. In such a simple system, the switching time is essentially the resistive-capacitive time constant of the device in the circuit. Devices with smaller area will switch faster for a given power because their capacitance is lower, hence the critical importance of integrating such devices so that they can be made small without being dominated by parasitic capacitances.

Many other variations on simple devices like this are possible. If instead of choosing to work at the peak of the exciton absorption of zero field, we chose instead to work at a somewhat longer wavelength where the optical absorption will increase as we increase the reverse bias, then instead of getting positive feedback (which gave rise to the bistability) we will obtain negative feedback. If instead of using a resistor and a voltage supply as the external circuit, we use a current source, then this negative feedback mechanism works in such a way that the device adjusts its own voltage so that it absorbs an amount of power proportional to the current being supplied by the current source; Hence we can obtain what is called a self-linearized modulator, in which the optical power substracted from the beam varies exactly linearly with the control current through the device. Such a device can also be used with a constant current input, in which case over a given range of input powers it substracts a constant power from the output, hence performing the function of optical "level-shifting".

The bistability in very simple circuits can be viewed also as being a consequence of negative differential resistance. When we have chosen to operate at the wavelength near the zero field exciton absorption peak as we shine light onto the diode, the photocurrent generated with a constant light power shining on the device can actually decrease as we increase the reverse bias voltage because the absorption of the diode is decreasing. Therefore we have a situation of decreasing current for increasing voltage, hence the negative differential resistance. As a consequence it is possible to make electrically bistable devices out of these systems as well with constant light being shone on the devices. Another consequence, however, is that we make an oscillator. It is well known that negative differential devices operated in conjunction for example with a "tank" circuit, i.e. an inductor-capacitor resonator, can make simple oscillator systems. In the present case, therefore, if we make a circuit with a reverse bias supply and a series inductor (utilizing for example also the intrinsic capacitance of the diode itself), with a constant light power shining on the device we can obtain optoelectronic oscillation, that is, the electrical voltage across the diode oscillates essentially sinusidally in time and also the transmitted optical power shows an oscillation at the same frequency.

Some of these simple systems have recently been combined to make a proof-of-principle demonstration of an all-optical repeater[5]. In this system an incoming bit stream on an optical beam is partly injected together with a power beam from a cw laser diode into a SEED structure operating as an oscillator, with the natural frequency of the oscillator chosen to be near that of the incoming bit stream's clock frequency. Even although the fraction of the incoming bit stream that is injected optically into the oscillator is small and its absolute power is low, it is found that this bit stream can lock the local oscillator to the clock frequency of the bit stream. Thus in such a system we have performed "optical clock recovery". This optical clock signal is now injected together with another portion of the power of the incoming optical bit stream into a decision element, which may be either a SEED optically bistable device or a SEED level shifter, functioning as an AND gate. The output of this latter decision device becomes the retimed, regenerated and amplified version of the incoming bit stream, hence performing in principle the function of optical regeneration. The actual performance of the particular system demonstrated so far is still modest because highly non-optimized and non-integrated devices were used, but with integrated systems and better designed devices, respectable performance may be achievable.

The bistable SEEDs described so far have involved resistive loads. We can however replace the resistor with a current source and achieve improved bistability. Furthermore, this kind of source is particularly well suited for integration. One simple way of making a current source is to reverse-bias another photodiode. The current through such a photodiode will, over a large range of the reverse bias voltages, be essentially independent of voltage and depend instead only on the amount of light shining on the photodiode. The first integrated SEED devices were made using this principle. First a quantum well p-i-n diode was grown on the substrate. Then, after an internal contact, a conventional AlGaAs p-i-n photodiode was grown. This gives two photodiodes electrically in series so that the conventional photodiode can serve as a load for a quantum well diode. When this series structure is connected to a constant external electrical bias supply we can obtain optical bistability seen in an infrared beam, which passes unaffected through the AlGaAs photodiode and is modulated by the quantum well photodiode, with the threshold for switching controlled by a red light beam that is shone on (and totally absorbed in) the AlGaAs photodiode. In this integrated SEED we can make very small structures with essentially no stray capacitance. The only point at which this stray capacitance is important is at the point in the structure where the voltage changes, which is at the junction between these two photodiodes. That junction however is internal to that device and has no other electrical connection to it. Hence there is essentially no stray capacitance. This device therefore can be scaled in size with proportionate improvements in performance. This particular integrated SEED was successful demonstrated and did display the required scaling behavior both in time and in overall operating energy, although this particular structure was not successfully operated faster than a microsecond because of the limitations on the current density in the internal ohmic contact. However 6 × 6 arrays of small devices were successfully demonstrated[6]. An encouraging aspect of this device's operation was the high uniformity that could be obtained over the various devices.

This integrated SEED device could also be used with constant infrared beams but modulated red beams so that a visible image could be transferred into a transmitted infrared image, either bistably or by self-linearized modulation, depending upon the operating wavelength. Thus a spatial light modulator was successfully demonstrated[6]. Another interesting operating mode of this particular device is what can be referred to as "optical dynamic memory"[6]. If we suppose, with particular red power and particular infrared power shining on the device, that we have bistable operation and the device is in one or other of its bistable states, then we may abruptly interrupt both light beams and the device will retain its state for a comparatively long time (e.g. up to 30 seconds). On turning the light beams back on again the device returns to its former state. The reason for this is that the state is essentially stored as the internal voltage over the quantum well diode. When the lights are both removed, there is nothing to change this voltage other than the leakage currents in the diodes, which are intrinsically low and are also relatively well balanced between the two diodes. When the lights are turned back on again the device latches itself back into its former state provided that voltage has not drifted too far. Hence it performs a function that in electronics is known as "dynamic memory", with the particular feature that there is no need for sense amplifiers because the device is intrinsically bistable. Thus we have a memory that can operate at very low average powers while still being able to switch fast when required by operating at high power.

Another SEED configuration that can be viewed as an extension of the above diode biased integrated SEED, is the so-called "symmetric" SEED.[7] In this case instead of using an AlGaAs photodiode as the load for the quantum well diode, we use another, identical quantum well diode. Hence we have two quantum well diodes in series with each other and with a voltage supply (Fig. 5). As before, the sense of the voltage supply is to reverse bias the quantum well diodes. In this case, we generally operate this device with two infrared beams. One beam shines through one quantum well diode and the other shines through the other quantum well diode. We can explain the operation of this device in a similar way to that used to explain the diode-

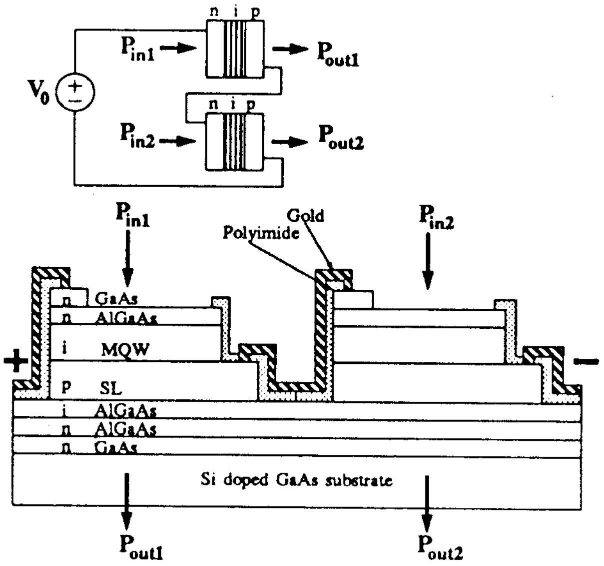

Fig. 5 Symmetric SEED circuit and structure schematic. SL is a short period superlattice used to obtain a high quality structure, and MQW is the multiple quantum well material.

biased SEED device. For example if we shine a constant infrared light beam power into the first diode we will see bistability in the transmission in the second diode as we vary the power incident upon it. We may reverse these roles using the second quantum well diode with a constant light beam power shining on it as the load of the first quantum well diode hence obtaining bistability seen in the other light beam. In fact this device is bistable in the ratio of the two incident infrared light beam powers. To understand why it is the ratio, note that the switching from one state to the other starts when one photocurrent attempts to exceed the other photocurrent. Hence changing both light beam powers by an equal factor does not change the state of the device. Of course, this device has two outputs which are complementary. When one quantum well diode is highly transmitting the other is highly absorbing and *vice versa.* Input/output characteristics as one light beam is varied are shown in Fig. 6.

The operation with the ratio of two light beams has some important and non-trivial consequences. One immediate consequence is that, if we derive both light beams from the same light source, then fluctations in that light source power do not cause the device to switch. Another consequence is that we may turn down the power of the light source to both devices to a low level, and then switch the device from one state to the other with a small additional power on one of the diodes. Then we may increase

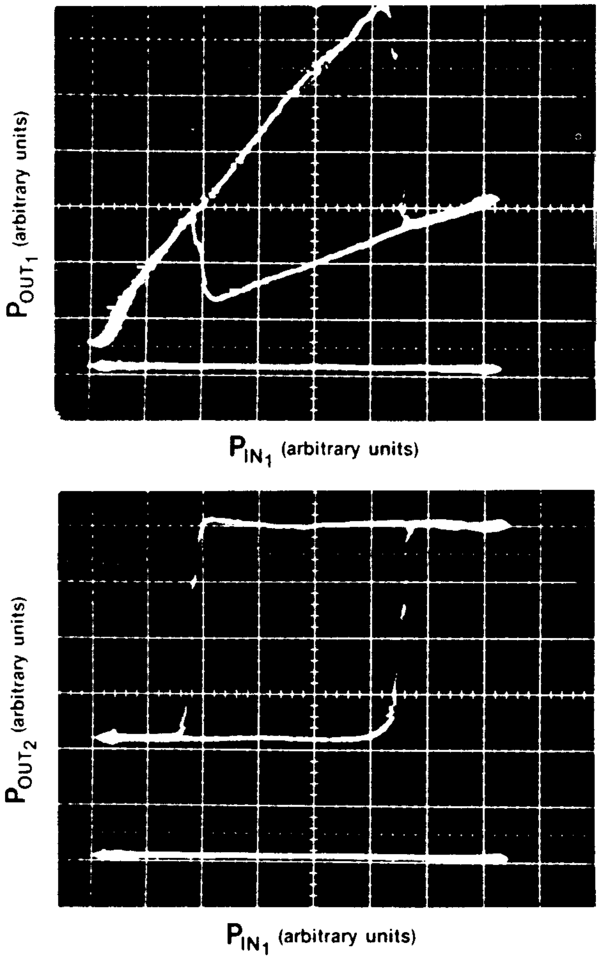

Fig. 6 Input/output characteristics of a symmetric SEED as one input power is varied.

the power from the light source to a much larger level, the state of the device will be retained, and hence we may read out the new state of the device at a high power level. Consequently we can achieve power gain; we only used a small power to change the state of the device but we have caused a large change in the transmitted power when we read the state out at high power. This phenomenon can be called time-sequential gain. This gain can be very large if we wish; in fact with low leakage SEED devices we could obtain gain of many thousands or even millions, although the gain-bandwidth product would remain constant since high gains mean that the device is being switched at very low powers and hence will take a longer time to switch. Another important attribute of this device is that it also has relatively good input/output oscillation. When the device is sensitive to inputs (i.e., when it is being operated at low power), there is relatively little output from the device. However, when it is being operated at high power, so that it has a large output, it is relatively insensitive to inputs. Hence the gain of the device does not amplify small fluctations fed back into the output of the device from the output beams themselves. Thus this device is, in effect, a three-terminal device; it shows gain without critical biasing, it is insensitive to power supply fluctations, and shows relatively good input/output isolation. It is interesting to note that in this device the inputs and the outputs are applied or can be applied at the same physical points of the device. One might ask how then it can be a three-terminal device. The answer is that input and the output are essentially orthogonal in *time*, and so in the most general sense of the definition of a three-terminal device this device is indeed such a device. Although it operates in a slightly unusual fashion for a three-terminal device, this three terminal nature does indeed make it much easier to contemplate making systems with such a device. The unusual requirement of varying the power supply in order to obtain the gain is quite compatible with clocking schemes that would be required in use of such devices in systems. The use of a pair of light beams to carry the information from one device to another also has several attractive aspects. In this case the state of the beams is conveyed by whether or not one beam is larger than the other, and not by the absolute power in either beam. Thus the logic state is not affected by slight attenuations of both light beams together.

Quantum well SEED devices can also be extended to include more sophisticated circuits between detector and modulator. An obvious example is to attempt to include electronic transistors to provide gain or increased functionality in the device. Various schemes involving the bipolar transistors and modulators have been proposed although these have not yet successfully been integrated. One system involving field effect transistors and modulators has been demonstrated in a partially integrated form.[8] This field-effect transistor SEED (F-SEED) consists of field-effect transistors fabricated in the top layer of the modulator structure itself. The fabrication of the field effect transistors is essentially identical to standard metal-semiconductor field effect transistor (MESFET) fabrication techniques. However with this integration we find that there is a modulator available underneath each and every transistor if we choose to use it, since the drain of the transistor is automatically connected to the top layer of the modulator. Hence, as the drain voltage alters in the normal operation of the field-effect transistor circuit, this voltage can be used to modulate a light beam passing beside the drain of the field effect transistor. We can also use other portions of the modulator structure as photodetectors, and hence we can envisage circuits with optical inputs connected to some transistor circuitry to provide enhanced functionality while at the same time being able to extract optical outputs from the same system. Hence we have a way of making intelligent, functional blocks of electronics with optical interconnections. The simplest of such circuits has been demonstrated, with the field-effect transistor, modulator and detector integrated (only the other circuit components, such as resistors, were not integrated in this demonstration).[8] This circuit involved only a single field effect transistor with a single photodiode and modulator, but could be operated as an optical amplifier showing a differential gain of 25 between the variations in input power to the photodiode and the variations in transmitted output power from the modulator. When looked at from the point of view of electronics, this method offers a potentially low energy technique for extracting optical information from electronic circuits, since the optical output "pads" in this system need only be of micron dimensions as far as the optics are concerned, hence comparing very favorably with typically hundred micron dimensions of electronic output pads.

There are limits to the performance of SEED devices. I have already discussed above the basic electrical energy limitations; in devices without electrical gain, the optical energy requirements are that the optically created charge be able to charge or discharge the device capacitance. The resulting optical energy requirements are rather similar to the electrical energy requirements, i.e., in a range of 1 to 20 $\mathrm{fJ}/\mu\mathrm{m}^2$ micron depending on the voltage and device type. Speed limitations on SEED devices will most likely be due to limits in the photodetection process. The quantum-confined Stark effect itself can probably operate faster than 1 ps although at present measurements of the speed have been limited by external circuit capacitances to of the order of 100 ps. Photodetection on the other hand will be intrinsically limited by carrier emission times from the wells; transport data show, in preliminary experiments, times of 30 to 100 ps for this process. SEEDs have been successfully tested down to switching times of the order of 1 ns. There will also be limits in both modulators and SEEDs to the maximum power that can be passed through the modulator parts of these devices. One limiting mechanism is that, if the optically-created carrier density becomes too high, the exciton absorption may be saturated. This process is much less severe in quantum wells with field applied because the fields sweep the carriers out. Saturation intensities in the range of 3 to 10 kW/cm^2 have been observed in GaAs devices. InGaAs/InP devices seem to have more of a problem probably because of another mechanism, namely that it is difficult to extract the holes from the rather deep wells encountered in this material, hence leading to space charge effects that quench the electroabsorption.[9]

6.

CONCLUSIONS

It can be seen that now layered semiconductor growth technology is in a very advanced state, and that we are able to reuse this technology to make novel electronic and optoelectronic devices, of which the quantum well modulators and SEEDs are an important example. The low operating energy of these devices and their compatibility with semiconductor materials and devices and also laser diodes makes them particularly attractive for optical switching applications and integrated optoelectronics in general. A very important aspect of this capability for optoelectronic integration is that we are able with these devices to tailor the functionality of the device to suit the system. At this point we are just starting to see the fruits of this ability. For example the symmetric SEEDs and the field effect transistor SEEDs discussed above are showing that we can use the integration abilities to make devices more suited to practical systems. In general we might hope that this kind of integration will enable us to choose what we want to do in electronics and what we want to do in optics, with a relatively easy interchange between one and the other that does not incur gross inefficiences either in power or in cost at the transition between the two technologies. If this can be achieved it will greatly enhance the abilities of electronics and the usefulness of optics for processing and switching applications.

1. For an introductory tutorial review on quantum well electroabsorption and devices, see D.A.B. Miller, "Electric Field Dependence of Optical Properties of Quantum Well Structures" in "Electro-optic and Photorefractive Materials", ed. P. Günter, (Springer-Verlag, Berlin, 1987), p. 35.
2. For a review of quantum well linear optics and nonlinear effects related to absorption saturation, see D. S. Chemla, D. A. B. Miller and S. Schmitt-Rink, "Nonlinear Optical Properties of Semiconductor Quantum Wells", in "Optical Nonlinearities and Instabilities in Semiconductors", ed. H. Haug, (Academic, New York, 1988).
3. For a review of electroabsorption physics and devices in quantum wells, see D. A. B. Miller, D. S. Chemla and S. Schmitt-Rink, "Electric Field Dependence of Optical Properties of Semiconductor Quantum Wells" in "Optical Nonlinearities and Instabilities in Semiconductors", ed. H. Haug, (Academic, New York, 1988).
4. For a short review of some recent device work, see D. A. B. Miller, Opt. Eng. **26**, 368-372 (1987)
5. C. R. Giles, T. Li, T. H. Wood, C. A. Burrus, and D. A. B. Miller, Electron. Lett. **24**, 848-850 (1988)
6. G. Livescu, D. A. B. Miller, J. E. Henry, A. C. Gossard, and J. H. English, Optics Lett. **13**, 297-299 (1988)
7. A. L. Lentine, H. S. Hinton, D. A. B. Miller, J. E. Henry, J. E. Cunningham, and L. M. F. Chirovsky, Appl. Phys. Lett. 2, 1419-1421 (1988)
8. D. A. B. Miller, M. D. Feuer, T. Y. Chang, S. C. Shunk, J. E. Henry, D. J. Burrows, and D. S. Chemla, Paper TUE1, Conference on Lasers and Electro-optics, Anaheim, April 1988
9. I. Bar-Joseph, G. Sucha, D. A. B. Miller, D. S. Chemla, B. I. Miller, and U. Koren, Appl. Phys. Lett. **52**, 51-53 (1988)