Quantum wells for optical information processing

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Abstract. Quantum wells, alternate thin layers of two different semiconductor materials, show an exceptional electric field dependence of the optical absorption, called the quantum-confined Stark effect (QCSE), for electric fields perpendicular to the layers. This enables electrically controlled optical modulators and optically controlled self-electro-optic-effect devices that can operate at high speed and low energy density. Recent developments in these QCSE devices are summarized, including new device materials and novel device structures. The variety of sophisticated devices now demonstrated is promising for applications to information processing.

Subject terms: optical information processing; quantum wells; electroabsorption.

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CONTENTS

1. INTRODUCTION

Over the past few years, quantum wells (QWs) have emerged as a new and exciting class of materials for optical devices. QWs consist of alternating ultrathin layers (e.g., 100 Å thick) of two different semiconductors and can take advantage of impressive layered semiconductor growth technologies, such as molecular beam epitaxy or metal-organic chemical vapor deposition, that are already well developed. Consequently, even though some of the unusual new physical mechanisms in QWs were discovered only recently, it already has been possible to demonstrate a variety of sophisticated devices with practical potential.

This is currently a rapidly evolving field. The purpose of this paper is to provide a short review of some of the recent work in QW electroabsorptive devices. Section 2 introduces QWs, the types of devices, and the physical mechanisms involved. This discussion, included for completeness only, is brief. Except for some recent work extending the understanding of the physical mechanisms, much of this material has been reviewed elsewhere.[1] Work on materials other than GaAs/GaAlAs is summarized in Sec. 3, and in Sec. 4 some of the more sophisticated recent devices are discussed.

2. QUANTUM WELLS AND ELECTROABSORPTIVE DEVICES

The basic optical properties of QWs of interest for devices were recently summarized in another paper in this journal,[1] and only a brief summary of some of the key points is given here.

Normal semiconductors show an absorption spectrum near their band gap energy that is relatively smooth and featureless at room temperature. QWs, on the other hand, show a clear series of steps. These steps result from the fact that electrons and holes are confined like particles in a box (in one direction) and transitions are allowed only between similar confined states for electrons and holes. In the system most often studied, which consists of alternating layers of GaAs and AlGaAs, the particles are confined within the GaAs "well" by the AlGaAs "barriers," with typical thicknesses of these layers being ~ 100 Å. The steps are further enhanced by strong exciton absorption peaks at the edges of the steps. For each confined state of electron and hole, the lowest-energy electron/hole pair state is the exciton, in which the electron and hole orbit around one another like a hydrogen atom. The strength of an optical transition is generally proportional to the "overlap" of electron and hole, and in the case of the exciton, this is large because they are in a tight orbit around one another, hence the strong absorption peak. The smaller the exciton, the larger is this peak. Excitonic effects in QWs are particularly large because the exciton is made smaller by being confined inside the QW. This effect is so large that the exciton peak can be seen even at room temperature. (See Ref. 2 for a longer discussion of confined states and QW excitons.)

Many interesting nonlinear optical effects are associated with these exciton peaks,[1,2] but we will not consider these further here. The effect that interests us most is the so-called

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quantum-confined Stark effect (QCSE),[3,4] which describes the changes in optical properties of QWs when electric fields are applied perpendicular to the QW layers. One of the most interesting consequences of this effect is that the sharp optical absorption edge near the band gap energy can be shifted to lower energies by this field *without destroying the sharp exciton absorption peaks.* This contrasts strongly with the behavior of bulk materials, in which the exciton peaks are destroyed with moderate fields and the remaining absorption changes correspond to a broadening of the absorption edge, often referred to as the Franz-Keldysh effect.

The physics of the SCSE is relatively well understood.[3-5] The reason for the persistence of the exciton peaks is that the walls of the QW prevent the electron and hole from being totally torn apart from each other by the field. This prevents lifetime broadening of the exciton resonance. The shift of the exciton resonance with field is simply equivalent to the Stark shift that would occur in a strongly confined hydrogen atom, hence the title QCSE. The relationship between the QCSE and the Franz-Keldysh effect is now understood.[6] The absorption does become somewhat weaker as it shifts to lower energies because the electron/hole overlap is reduced by the electron and hole being pulled to opposite sides of the well[5]; the absorption lost in this way is picked up by the growth of forbidden transitions that appear at higher photon energies, resulting in sum rules for this electroabsorption.[5] Work on the physics of the QCSE is summarized in Ref. 5.

The practical result of the QCSE is that we obtain a new and strong electroabsorption mechanism in semiconductors. The changes in absorption are so large that it is possible to make optical modulators that are only micrometers thick and whose transmission can be changed by more than a factor of 2 with voltages ~5 to 10 V. We can therefore contemplate two-dimensional arrays of optical devices based on this effect in which the light beams propagate perpendicular to the surface, a class of devices that has always been difficult with semiconductors.

Because only micrometers of material thickness are required for substantial modulation, it is possible to obtain the necessary field by including the QWs within the depletion region of a diode and reverse-biasing the diode.[7] This results in an energy-efficient device, with no static dissipation except that from the photocurrent generated by absorption of the beam being modulated. The energy required to change the transmission of the device is also small, being simply $\frac{1}{2}CV^2$, where C is the device capacitance and V is the voltage applied; this results in operating energies in the range of a number of fJ/μm^2. This energy density is very low by the standards of optical devices and is comparable to the energy densities required to run good electronic devices. The modulation is also fast, with speeds of ~100 ps demonstrated (see Ref. 1 for a discussion), and the fundamental limit is probably less than a picosecond.

With such low energies and relatively convenient devices, it is attractive to consider whether devices can be made that can operate under optical control rather than only electrical control. One way of achieving this is to make devices that incorporate both an optical detector and a QW modulator. This is the most general definition[8] of the self-electro-optic-effect device (SEED).[5,8-13] The simplest form of SEED is that in which the QW diode is itself the only photodetector.[9,10] When the diode is incorporated in an external circuit, an optoelectronic feedback results because the photocurrent changes the voltage across the diode, which in turn changes the absorption of the diode, which in turn changes the photocurrent, and so on. The absorption can either increase or decrease with voltage, depending on the wavelength chosen, so either positive or negative feedback can be achieved. With positive feedback, the device is optically bistable.[9] With negative feedback and a current drive, a self-linearized modulator results[10] in which the power absorbed by the modulator is proportional to the drive current; this same configuration also can be used as an optical level shifter in which a constant power is subtracted from the transmitted light. One extension of the self-linearized modulator is to use another reverse-biased "load" photodiode as the current source. Then, the power transmitted by the QW diode decreases linearly with increased power on the "load" photodiode. The basic principles of all of these SEEDs are treated in detail in Ref. 11, and all are reviewed in Ref. 1.

3. NEW MATERIALS

There are several motivations for investigating materials systems other than GaAs/GaAlAs for QW optical devices. Apart from the obvious desire to extend our knowledge, there are specific shortcomings of the GaAs system for some applications. First, the GaAs/GaAlAs QWs are grown on GaAs substrates, and these substrates are therefore opaque at the wavelengths at which the QWs show their most interesting electroabsorptive effects. This can be overcome by selective chemical etching to remove the substrate or by growth of an integral mirror,[14] as discussed in the next section, but it is obviously desirable to have the option of avoiding this problem. Second, the GaAs QWs do not operate at the wavelengths of greatest interest for long-distance optical fiber communications (e.g., ~1.3 and 1.5 μm). Of the many possible materials for QWs, those based on InGaAlAs and InP materials systems have received most attention, with significant work also in the GaAlSb system. In all of these cases, the growth technology already has been advanced because of the interest in these materials for long-wavelength optoelectronic devices.

The first of these other materials systems to be investigated was the combination of InGaAs wells with InGaAlAs barriers, grown on InP substrates.[15] This was followed by studies of InGaAs wells with InAlAs barriers.[16,17] These materials do show excitonic peaks at room temperature that are influenced by electric field, with some shift of the peaks. These shifts are accompanied by significant broadening of the absorption edge, and the QCSE behavior is not as clear as in GaAs/GaAlAs QWs. However, these materials are suitable for long-wavelength operation, and the InP substrates used are transparent at the operating wavelength. Recently, InGaAs QWs with InP barriers (also on InP substrates) have shown very clear QCSE,[18] as shown in Fig. 1. These data agree well with theory, testing the QCSE quantitatively for a system other than GaAs/GaAlAs. The photocurrent response of this material is also good, suggesting possible extensions to SEEDs. One possible reason for the differences in these different materials systems is that higher impurity concentrations in the nominally intrinsic region may result in broadening of the spectra.[18] GaSb wells with GaAlSb barriers also have shown clear QCSE.[19] This materials system is suitable for

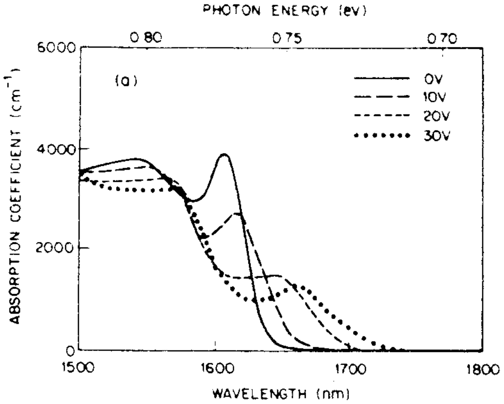

Fig. 1. Absorption spectra taken at room temperature with a diode containing 100 periods of alternating 100 Å InGaAs and InP layers for different reverse-bias voltages applied to the diode.[18]

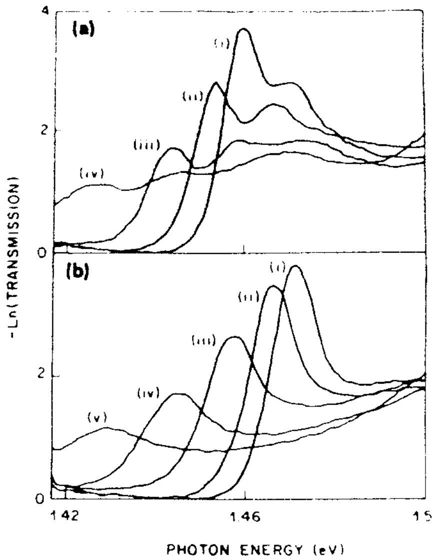

Fig. 2. Absorption spectra of a quantum well waveguide as a function of electric field applied perpendicular to the quantum well layers. (a) Incident polarization parallel to the plane of the layers for fields of (i) 1.6 × 10^4 V/cm, (ii) 10^5 V/cm, (iii) 1.3 × 10^5 V/cm, and (iv) 1.8 × 10^5 V/cm. (b) Incident polarization perpendicular to the plane of the layers for fields of (i) 1.6 × 10^4 V/cm, (ii) 10^5 V/cm, (iii) 1.4 × 10^5 V/cm, (iv) 1.8 × 10^5 V/cm, and (v) 2.2 × 10^5 V/cm.[5,21]

One final system that has shown clear QCSE behavior is InGaAs wells with GaAs barriers, grown on GaAs substrates.[20] This system is exceptional in that the materials are not lattice matched. However, the resulting material is of high quality, but the layers are under strain (i.e., a strained-layer superlattice). The GaAs substrate is transparent to the operating wavelength. In general, strained-layer growth does impose some limits on the thicknesses that can be grown. It is encouraging, however, that these strained-layer systems can show the QCSE because this greatly increases the materials systems possible for future development.

4. NEW DEVICES

Although initial interest centered on devices with light propagating perpendicular to the layers, the QCSE also makes interesting waveguide devices in which the light propagates in the plane of the layers.[13,21-27] There are several reasons for interest in such a configuration. First, the thickness of materials that can be depleted by reverse-biasing a diode is practically limited to a few micrometers by the finite impurity concentrations. If light propagates through such a thickness only once, the depth of modulation is limited. In a waveguide, however, the light can propagate along the layers for a much longer distance, giving higher modulation depth. In fact, the total thickness of QW material can be quite thin, resulting in modulators with very low drive voltage (< 1 V).[13] A second reason is that the opacity of the substrate is irrelevant; hence, the substrate need not be removed. The fact that the QW region is thin also means that the electric field is more nearly identical in all of the wells. The spectra in Fig. 2 were taken in a GaAs/GaAlAs waveguide ~ 150 μm long and containing only two QWs.[5,22] Because of the uniform field, the spectra remain sharp even at very high fields, whereas in samples with many wells the spectra are sometimes less distinct at large fields because the peaks in some wells are shifted more than those in other wells in lower field regions of the diode.

Figure 2 also illustrates another aspect of the waveguide geometry; this modulator is highly polarization dependent. The polarization dependence results from microscopic selection rules in layered structures and is not caused by the applied static field. In the polarization with the optical electric vector perpendicular to the layers (the polarization accessible only in the waveguide), the lowest ("heavy-hole") exciton peak is absent, and all of the absorption strength appears on the higher ("light-hole") exciton (see, e.g., Ref. 2).

A final reason for making such waveguide structures is to integrate the modulator with a laser diode made from the same structure.[24,25] This has been achieved and is an attractive laser/modulator system.

Although most QCSE devices have used simple QWs, it has also proved possible to observe the QCSE in coupled wells consisting of pairs of thin wells separated by a thin barrier,[27] also in a waveguide structure. In terms of practical performance, it is comparable with other waveguide modulators. It ultimately may be possible to make higher-contrast modulators by this technique because the reduction in electron/hole overlap with field can be larger.

Another solution to the problem of opaque substrates is to grow underneath the modulator a dielectric mirror composed of the same materials as the QW structure so that the whole structure can be operated in reflection, with the light making a double pass through the QWs.[14] The structure and the zero-voltage spectrum of such a modulator are shown in Fig. 3. The mirror is a quarter-wave stack. The double pass can improve the contrast ratio; 8:1 contrast has been achieved with this structure.

An example of the sophisticated optoelectronic integration that ultimately may be possible with QWs is the demonstration that charge-coupled devices and QW modulators can be made in the same structure.[28] This has considerable promise as a possible structure for an electrically addressed spatial light modulator.

In addition to being modulators, the p-i-n QW diodes are good detectors,[4,9,29-31] with one electronic charge collected for each photon absorbed in the QWs under reverse-bias operation. One unusual feature of these detectors is that

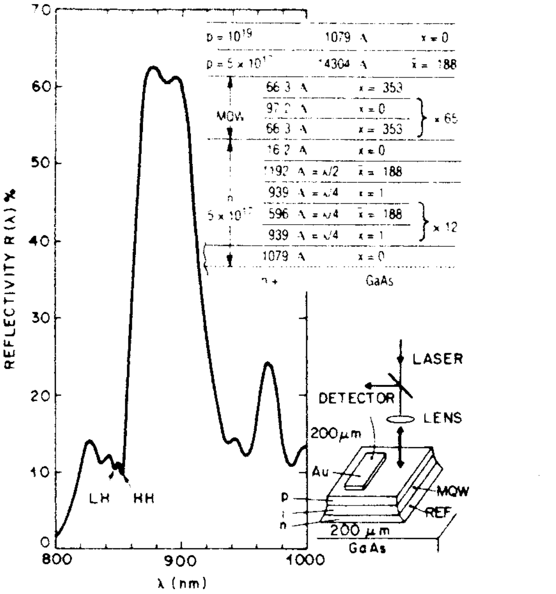

Fig. 3. Reflection spectrum at zero bias of a GaAs/Ga$_{1-x}$Al$_x$As modulator grown on a quarter-wave stack mirror. The sample structure and the optical apparatus for operating the modulator are shown in the insets. The regions with an average x of 0.188 are very fine period superlattices.[14]

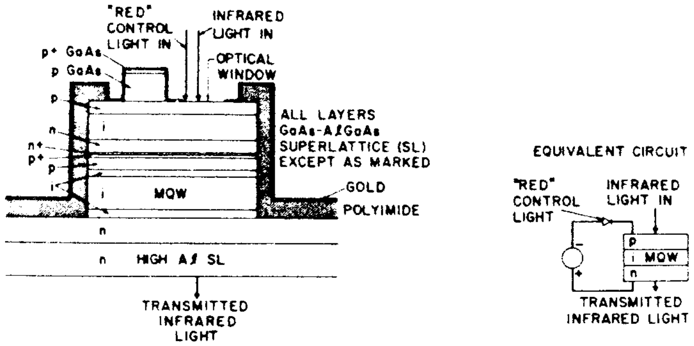

Fig. 4. Schematic diagram of the integrated SEED structure for a single device in an array, showing also the equivalent electrical circuit.[12]

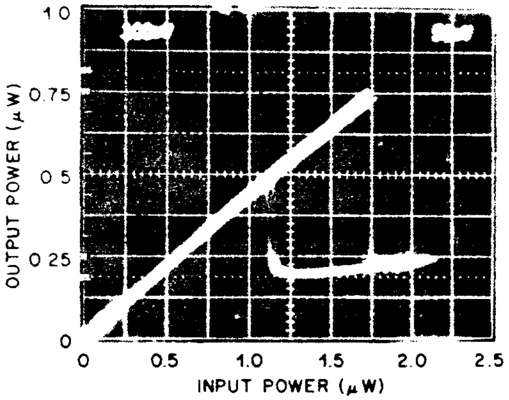

Fig. 5. Input/output characteristics for the four devices in an integrated SEED array superimposed.[12]

they can be tuned by applied voltage,[29] and this feature can be used for sensitive wavelength measurement. The detectors are also quite fast and also can be used for multiple wavelength detection.[30,31]

The SEED also relies on the ability to perform detection and modulation in one device. Additional configurations of the simplest SEEDs, in which the QW diode itself is the only photodetector, have been demonstrated.[11] The QW diode, under constant optical illumination, can show negative differential resistance; increasing voltage can give decreasing absorption and hence decreasing (photo)current. This negative resistance results in electrical bistability and also a negative resistance optoelectronic oscillator in which the load resistor is replaced by an inductor. For constant optical and electrical input, an oscillating voltage and oscillating optical output are obtained from this device. Frequencies above 1 MHz have been demonstrated.

The basic SEED operation is also obtained with waveguide modulator diodes.[5,13,22] These have the advantage of higher contrast ratios. It is also possible to make a self-biased SEED[13] out of a low voltage drive modulator with no external electrical power supply. The built-in field of the diode is sufficient to shift the exciton to longer wavelengths, and no other power supply is required, With a photodiode load, this configuration shows bistability.

One of the most sophisticated structures made so far with QWs is the integrated diode-biased SEED.[12,*] In this device, the function of a load resistor in the bistable SEED is performed by a second, "load" photodiode that is grown on top of the QW modulator diode. The structure is shown in Fig. 4; it consists of some 2500 layers altogether and is ~6 μm thick. The load diode is transparent to the infrared light used for the QW modulator but absorbs red light. For the purposes of bistability, the load diode can be considered most simply as a resistor whose value is set by the red light. This light therefore sets the threshold for bistability, and bistability has been observed over the range from 1 μs switching time with 1 mW of power all the way to 10 s switching time with 40 pW of power with 200 μm mesas, with the switching power controlled by (and approximately equal to) the red power. One advantage of the integrated load is that it enables two-dimensional arrays to be made with only one pair of electrical connections to the whole array. The uniformity of these arrays is encouraging; the optical input/output characteristics of all four devices in a 2×2 array are shown in Fig. 5. Another advantage of the integrated load is that it eliminates many of the stray capacitances that would otherwise degrade performance. Recently, fully functional 6×6 arrays of ~60 μm devices have been demonstrated with switching powers that scale down with area for a given speed, as expected.*

Other SEED configurations have also been proposed,[8] including an optically addressed spatial light modulator. This would use a structure similar to the integrated diode-biased SEED,[12] only this time the image could be input on the array of "red" beams. This information would then be transferred to the infrared beams, either nonlinearly by operating the devices in their positive-feedback mode or in a linear, inverting fashion by operating in the negative-feedback mode (self-linearized modulator). The SEED concept also is not long-wavelength operation, but the GaSb substrate is opaque at the operating wavelength.

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*D. A. B. Miller, J. E. Henry, A. C. Gossard, J. H. English, unpublished.

restricted to the use of diodes, whether QW or not, as the photodetectors. Various configurations employing phototransistors also have been proposed.[8]

5. CONCLUSIONS

It is clear that in the past few years there have been encouraging developments in QW QCSE devices. These are devices that operate at room temperature, at wavelengths and powers compatible with semiconductor diode lasers, with voltages compatible with semiconductor electronics, and in materials compatible with a wide range of optoelectronic devices. We now can see that these effects are not restricted to one materials system. Furthermore, some very complex, intimately integrated structures can be made that really work and that have yields large enough to be made in large arrays. The devices that have been demonstrated to date are only the first of many that can be made. It is to be hoped that over the next few years new QW devices will address some of the key device problems in optical information processing. At present it appears that this hope is limited as much by our imagination as by the QW technology.

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