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Optimization of reflection electro-absorption modulators

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Stanford University, 1991
OPTIMIZATION OF REFLECTION ELECTRO-ABSORPTION MODULATORS

A DISSERTATION
SUBMITTED TO THE DEPARTMENT OF ELECTRICAL ENGINEERING
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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

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June 1991
I certify that I have read this dissertation and that in my opinion it is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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ABSTRACT

In recent years, advances in quantum well physics and fabrication have dramatically increased the performance of opto-electronic modulators. These devices show great promise for optical interconnects, optical computing, and switching applications. Structurally, these modulators consist of semiconductor quantum wells grown in a Fabry-Perot cavity configured as a p-i-n diode. A reverse bias on the device causes electrically induced absorption changes in the quantum wells which then translate to modulation in the device reflectivity. These devices are low power and display very high contrast and large reflectivity changes.

In this thesis, the basic physics of quantum well optics will be discussed and an optimization procedure will be outlined for these Fabry-Perot modulators. In this way, large modulation can be achieved for both normally-on devices useful for optical interconnects and for normally-off modulators that can be configured as SEEDs (Self Electro-optic Effect Devices) for optical computing. Optimizing both the Fabry-Perot cavity and the absorption changes in the quantum wells resulted in the largest measured reflectivity changes and very high high contrast ratios.

As well as individual switching elements, these devices can also be used in a novel structure that employs diffraction effects to perform laser-beam steering, useful for optical switches and scanning applications. Both theoretical performance and experimental results that demonstrate the high resolution scanning capability of this device are explored.
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1. Introduction

1.1 Optical Interconnects

The most widely accepted reason for the importance of quantum well optical modulators is their possible application in the area of optical interconnects. In recent years advances in electronics technology have greatly increased the speed and density of electronic circuits and systems. Many systems today are limited more by interconnects than by the intrinsic speed of the devices themselves. Optics, already proven in the long distance communications field, promises to solve many of these limitations if practical optical interconnects for circuit boards and integrated circuits (ICs) can be developed.

1.1.1 Energy Considerations

The problem of electrical interconnects may be understood in terms of speed and power limitations. To obtain high density integration, metal lines on a circuit board must remain as narrow as possible, which increases their resistive loss. The width also influences their capacitance, which along with the parasitic resistance constitutes an RC time constant lowering the bandwidth and causing delays along the line. Because most digital circuits require synchronization with a master clock, increasing integration and higher clock speeds have made these delays more problematic. Taking high speed signals off the chip and across the circuit board is even more difficult. In this case the resistance of the lines is less important as the copper traces on the circuit board are relatively thick. However, the capacitance of such lines requires the chips to have a very high current driving capacity. This requirement necessarily translates to the need for large area transistors to act as output buffers that consume a large amount of power and are necessarily slower due to their size.

Using transmission line techniques, very fast electrical lines can be made. However, such transmission lines are low impedance and consequently draw high currents. The impedance of a transmission line usually varies as the inverse of the square root of the
dielectric constant and logarithmically with the geometric factors. Since available materials do not have a large range of dielectric constants and only small advantages can be gained by varying the geometry, one is never able to obtain transmission line characteristic impedances much larger than the typical 50 Ω value. An interesting analogy made by Miller is that the problem of electrical interconnects is really one of impedance mismatch. Switching voltages in logic circuits are typically kept above a volt to minimize the influence of thermal fluctuations and non-uniformities in thresholds. Since the switching transistors draw little current, their high impedance conflicts with the low impedance of electrical interconnects.

Thus, electrical interconnect lines tend to consume a great deal of power. In an electrical interconnect the electrical energy required to transmit a pulse is equal to CV^2, where C is the capacitance of the line and V is the voltage of the pulse. One half of this energy is dissipated in the driving impedance and the other half is stored in charging the line. For a transmission line, the power required is the same, but is divided equally between the magnetic and electrical wave energies. For a 1 nS pulse of 1 V in a 50 Ω line, this translates to an energy of 20 pJ, 100 times larger than the typical 200 fJ switching energy of a logic device.

These energy considerations, as well as other limitations of electrical interconnects, have prompted many researchers to suggest that optics can provide a better solution for interconnects. Numerous studies have been performed on the relative merits of optical versus electrical interconnect schemes. Optics, in effect, solves the impedance mismatch through a quantum mechanical solution. A laser with a low threshold current can act as a high impedance load and a detector biased through a high value resistor presents the circuit with an impedance roughly equal to the value of the resistor (FIG. 1.1). The conversion of electrons to photons and back to electrons again has changed the nature of the problem.
Such optical schemes may reduce the power needed for the connection. In an optical link, the parameters are much more technology dependent and functions of factors such as detector capacitance and laser threshold. The general consensus is that optics becomes more favorable as the length of the links becomes larger. With present day technology, power gains can be made on a circuit board and systems level by switching to optical interconnects but the advantages are much weaker for intra-chip connections. The power tradeoff, however, becomes more favorable if the light source is taken off the chip and optical modulators are used in the place of the laser. Quantum well modulators, being reverse-biased diodes, consume very little power and are much more efficient in modulating external light than are lasers in generating light. Since the drive power needed depends on the capacitance of the modulator, smaller devices are more efficient. Thus, using smaller modulators expands the range where optical interconnects are more efficient, moving the break-even point to smaller interconnect lengths. For example, simple calculations by Miller predict that interconnects using modulators with an area of $100 \mu m^2$...
will be beneficial once the connection length is above a fraction of a millimeter, and therefore useful for connections inside a chip.

1.1.2 Other Advantages

In addition to power efficiency, optics is thought to possess several other advantages. The most significant of these is probably its near infinite bandwidth. Unlike electrical lines that become highly attenuating at high frequencies due to the skin effect, losses in optical links are not frequency dependent and the bandwidth is limited by the laser linewidth and the laser modulation characteristics. Optics also offers higher connectivity. Electrical lines for interconnects are usually limited to the two-dimensional plane above the circuit, while in free-space optical links, the signals can be taken vertically off the chip allowing much higher connectivity between devices. Such structures have begun to be studied for possible applications in novel systems, such as neural networks that require a large number of connections. In addition, electrical lines suffer from problems of cross-talk, a limitation often more serious than the power-speed tradeoff. In this case, transmission lines crossing over uneven surfaces act as efficient antenna, radiating RF signals to other near-by lines. The only solutions are to increase the spacing between lines or to shield the sensitive areas. Both methods tend to lower the integration and performance while increasing complexity and cost. Other advantages that are frequently cited for optical interconnects are immunity to electromagnetic interference (EMI), immunity from short circuits or ground loops, and wavelength multiplexing capability.

1.1.3 Technological Issues

To reap the benefits of optical interconnects, there are certain technological issues that need to be overcome. Clearly, in free-space optical links, proper optical alignment is crucial. Experiments with bulk optics and large modulator arrays to construct free-space switching systems at AT&T Bell Labs show that very high uniformity and precise
alignment are required\textsuperscript{8-10}. Using arrays as large as 2000 elements, they found that special spherically corrected lenses were required as well as sub-micron control of the position and tilt of the wafers. Besides bulk optics, lithographically generated lenses and microlens arrays have been investigated for incorporation in semiconductor optical interconnect schemes\textsuperscript{11-12}. To illuminate an array of modulators from an external laser, or to route reflected signals from one modulator to another, Damman phase gratings\textsuperscript{13}, holographic gratings\textsuperscript{14}, and photorefractives\textsuperscript{15} are all under study.

1.1.4 Applications to Silicon VLSI

The ICs most limited by interconnects are the VLSI microprocessors and memories fabricated in silicon. Circuits made in other material systems, such as GaAs, have not yet reached that limit of integration where optics would be immensely useful. Unfortunately, unlike GaAs, silicon is an indirect bandgap semiconductor which, practically speaking, is incapable of light generation and whose absorption coefficient is too small to allow very fast photodetectors. Consequently, methods of achieving optical interconnects for use in silicon VLSI are more limited. Attempts to grow GaAs lasers directly on silicon have been rather unsuccessful, as the performance of the lasers was seriously degraded by the dislocations caused by the lattice mismatch\textsuperscript{16}. Though work on improving the growth of GaAs on silicon has been continuing for many years, it seems unlikely that lasers grown on silicon will reach the levels of reliability required for interconnects in the near future.

The hybrid approach, growing the lasers on GaAs and then wire bonding the GaAs chip and silicon chip together in one package, may be the only viable way. Such traditional hybrid techniques tend to be costly and the device speed tends to be limited by the macroscopic wire bond. A new pseudo-hybrid technique that seems to show promise is epitaxial lift-off. Pioneered by researchers at Bellcore\textsuperscript{17}, this technique consists of chemically lifting off the active layers grown lattice-matched on a GaAs wafer and
subsequently placing the very thin layers on the silicon. Though the material quality is excellent, there are questions of alignment and cost that need to be solved.

 Fortunately for modulators, the absorption properties of GaAs are much less sensitive to the material quality than are the recombination lifetimes, and a number of groups have reported GaAs modulators grown directly on silicon substrates\textsuperscript{18-19}. The evidence so far would therefore tend to indicate that modulators may be a more effective solution to the near future implementation of optical interconnects.

1.2 Other Applications

In addition to the need for compact optical switches for optical interconnects, modulators are useful in a variety of areas from optical fiber applications to mode locking and Q-switching of laser cavities.

1.2.1 Optical Fiber Applications

Due to the advantages of high bandwidth and low loss, optical fibers are currently replacing electrical lines for long distance communications. With the advent of erbium-doped fiber amplifiers the problem of loss in the fibers is no longer the limiting factor in fiber networks. More crucial is the chirp of the laser diode and its interaction with the dispersion in the fiber. As the intensity of a laser diode is modulated with current, there are accompanying changes in wavelength (chirp). In a dispersive media, different wavelengths travel at different speeds and therefore a pulse broadens with propagation distance. An optical modulator used with a fixed intensity laser source can therefore improve the performance of a fiber network. Since optical modulators change the intensity of the light without influencing the wavelength, they practically remove the limitation imposed by the chirp and fiber dispersion. Most of the work on electro-optic modulators for fiber applications has so far centered on lithium niobate waveguide devices\textsuperscript{20}, such as Mach-Zehnder interferometers and directional couplers\textsuperscript{21}. Quantum well modulators\textsuperscript{22},
however, may have advantages in these applications. Since they are fabricated in the same material as the laser light source and fast GaAs electronics, the integration of these elements on the same wafer could dramatically reduce cost. These modulators also act as photodiodes allowing current feedback to control linearity and modulation.

At short distances, where the chirp is not a problem, the bandwidth of an optical network is set by the maximum modulation frequency of the laser diodes. This figure is usually about 20 GHz, set by the gain in the material, the spontaneous emission rate, and the photon lifetime. Modulators, on the other hand, when driven without photocurrent feedback are free from recombination lifetime limitations and are only limited in speed by their RC time constant. Consequently, a 10 μm diameter device in GaAs with a 0.5 μm cavity length in a 50 Ω system would be predicted to have an intrinsic 3 dB bandwidth of nearly 200 GHz. The integration of such modulators with high frequency electronics, such as HEMTs could have enormous potential in terms of interconnect bandwidth.

1.2.2 Optical Computing and Laser Applications

There are numerous other fields where optical modulators could have a large impact. Using positive feedback from the photocurrent generated in a modulator, it is simple to make a bistable device, such as a SEED (self electro-optic effect device). This bistability can be used to fabricate a logic device or a simple latch. Besides the work at AT&T Bell Labs that centers around using SEEDs in an optical processor, the SEED devices are also attractive for other purposes, such as optical analog to digital converters. There has also been work on using quantum well modulators in laser cavities to produce mode locking and Q-switching.

These are a few of the areas where quantum well electro-optic modulators may be useful. However, their capability to act as a reliable interface between electronics and optics and the ease of integration with electronics may make them useful for many other
applications. In chapter 7, for example, we outline a new application of modulators to perform laser beam steering, an area that could be useful from laser printers to laser rangefinders to optical spectrum analyzers. Clearly, characterization and optimization of these devices is important for their future applicability.
2. Materials and Growth

2.1 GaAs / AlGaAs Material System

![Band diagram of GaAs around the Γ point.](image)

Figure 2.1. Band diagram of GaAs around the Γ point.

All our work on optical modulators has been performed on GaAs substrates using molecular beam epitaxy (MBE). Gallium Arsenide is the second most commonly used semiconductor after silicon. Though electronic integration is not as well advanced in GaAs as in silicon, due to particular processing problems such as the lack of a native oxide and a higher material defect density, the material does possess some unique advantages. The higher electron mobility results in faster electronic devices while the existence of an insulating substrate reduces parasitic capacitances. Unlike silicon, which has an indirect bandgap and is therefore extremely inefficient in light generation and absorption, GaAs has a direct bandgap and is optically efficient. FIG. 2.1, taken from Shur, shows the band
diagram of GaAs about the $\Gamma$ point where the crystal momentum is zero. From the figure it is clear that the minimum in the conduction band corresponds with the maximum in the valence band. In optical transitions, momentum conservation can only lead to vertical transitions in such a diagram. Since the valence band maximum is directly below the conduction band minimum, GaAs lends itself to fabrication of solid state lasers and detectors. Thus the strengths of GaAs lie in high speed electronics and optoelectronics.

The ability to make heterostructures with GaAs using the Al$_x$Ga$_{1-x}$As alloy enhances its usefulness tremendously. Consequently, there are numerous works that describe the mechanical, electronic, and optical properties of the GaAs/AlGaAs material system in great depth$^{29-33}$. Since the lattice constant of AlAs is very close to that of GaAs, high quality interfaces can be produced. The bandgap of the AlGaAs alloy increases with aluminum concentration. At room temperature the bandgap of GaAs is 1.424 eV, while that of the alloy is

$$E_g (\text{Al}_x\text{Ga}_{1-x}\text{As}) = 1.424 + 1.247x \ eV, \quad \text{for } x < 0.45$$

$$E_g (\text{Al}_x\text{Ga}_{1-x}\text{As}) = 1.900 + 0.125x + 0.143x^2 \ eV, \quad \text{for } x > 0.45$$

The reason for the split in the range is that the material becomes indirect above the 0.45 composition. For the direct gap region ($x < 0.45$), the discontinuity in the bandgap is split between the conduction band and the valence band in a 65% and 35% ratio, respectively.

In addition to the bandgap, almost physical properties of the alloy are a function of the aluminum fraction. Of these, the one most relevant to this work is the refractive index. Since materials of different alloy composition possess different indices, the fabrication of multi-layer optical structures is possible. At energies slightly below the bandgap, where the material is transparent but electro-optic effects are strong, the refractive index ranges from about 3 in AlAs to 3.5 in GaAs with a close to linear variation in the alloy composition.
2.2 Strained InGaAs/GaAs

Besides lattice matched materials, one is also able to grow dislocation-free materials with different natural lattice constants if the thickness of these mismatched layers is kept sufficiently thin\textsuperscript{34-35}. In this case, the material is pseudomorphic, which means that the horizontal lattice constant of the thin layer changes from its natural value to match that of the substrate. Since the lattice constant of InAs is 7\% larger than that of GaAs, thin layers of InGaAs can be easily incorporated into devices on GaAs substrates. The smaller bandgap of the InGaAs alloy yields devices with longer operating wavelengths as well as larger band discontinuities to the AlGaAs alloy. The bulk bandgap of InGaAs at room temperature is

\[ E_g(\text{In}_x\text{Ga}_{1-x}\text{As} - \text{bulk}) = 1.425 - 1.614 x + 0.54 x^2 \text{ eV}. \] (3)

However, since the InGaAs layer is under compression when grown on a GaAs substrate, the valence band structure is modified drastically. The degeneracy between the light hole and the heavy hole bands at the top of the valence band is broken (see FIG. 2.1), and both bands shift down to lower energies to increase the bandgap. The dispersion relations parallel to the wafer surface is also changed with the light hole assuming a heavy mass and the heavy hole a lighter mass. Since the heavy hole band is shifted less than the light hole, transitions to the heavy hole band occur at the absorption edge with an apparent bandgap of

\[ E_g(\text{In}_x\text{Ga}_{1-x}\text{As} - \text{strained}) = 1.425 - 1.166 x + 0.183 x^2 \text{ eV}. \] (4)

Although there is no clear agreement on the values of the band offsets in InGaAs/GaAs, published results\textsuperscript{36-38} suggest that an offset ratio similar to the direct gap GaAs/AlGaAs
value of 65% - 35% is likely. To calculate the actual discontinuities, this ratio is modified to take into account strain induced shifts in the valence band.

The InGaAs remains strained if the thickness of the grown layer is kept below a certain critical thickness\(^{34}\). Once this limit has been exceeded, many studies have noticed that dislocations appear and the material quality is dramatically degraded\(^{39-40}\). These dislocations can be viewed either by TEM cross sections, or as a characteristic cross hatch pattern on the wafer surface. Such defects in the crystal act as non radiative recombination centers, and cause carrier scattering. As a result the photo-luminescence peak shrinks in size and the mobility is reduced. Since the material relaxes through these defects, the effective bandgap becomes smaller, approaching the bulk value. Though this critical thickness is a function of the growth temperature and growth procedure, it is known fairly accurately for single strained layers\(^{39}\). For multi-layer structures, however, the critical values are less well understood, since calculating the degree of strain coupled from one layer to another is very complicated.

2.3 Quantum Well Material

Advanced growth techniques, such as MBE or metal-organic chemical vapour deposition (MOCVD), have made possible growth of thin single crystal semiconductor layers with atomic layer precision. If a thin semiconductor layer with a small bandgap is sandwiched between material of larger bandgap, quantum confinement results. Due to the small effective mass of the carriers in semiconductors, envelope wavefunctions with energies on the order of meVs have long wavelengths. Consequently, if the thickness of the thin material is below about 500 Å, quantum effects result\(^ {41}\). The physics of such structures in the envelope approximation is surprisingly similar to basic quantum mechanics problems in introductory text books. The band diagram for a distinct quantum well is as shown in FIG. 2.2.
The wavefunction is sinusoidal in layers where the energy of the particle is larger than the band minimum and exponentially decaying in layers where the energy is lower. The envelope wavefunctions for both electrons and holes can be calculated with the Schrodinger equation using an effective mass for the particle and assuming that the potential is a combination of the effect of the band discontinuity as well as the Coulomb effects.

The true wavefunction is, of course, a product of the periodic Bloch wavefunction taken at the appropriate band edge, and the slowly varying envelope function. If the energy of the particle is close to one of the band edges, we need only take into account the Bloch wavefunction at that edge rather than summing over all the bands. If we further assume that the Bloch wavefunction is the same in both materials at the interface, we can arrive at simple boundary conditions for the envelope function: it must be continuous across the interface and that the spatial derivatives divided by the effective mass at each side must be equal. With this effective mass approximation we can treat the situation almost like an elementary "particle in a box" problem.

Thus we have reduced the problem of heterostructure energies to the simple single particle problem governed by the Schrodinger equation. The complexities of the bands and the effects of the rapidly varying Bloch waves are all taken into account through effective
parameters such as the effective mass and the band offsets $\Delta E_c$ and $\Delta E_v$. If our assumptions are valid, that is we stay close to the band edges and the materials are similar, then this simple envelope approximation yields reasonable agreement with experiment.

2.3.1 Electronic States

There are two types of quantum wells. In type I structures, pictured in FIG. 2.2, the band discontinuities are such that both the electrons and holes are confined in the same layer, while in type II structures they are confined in alternate layers\(^{42}\). Since both the GaAs/AlGaAs and InGaAs/(Al)GaAs material systems are of the first type, we shall be exclusively concerned in this work with type I wells. In this case, the confinement in the growth direction causes the electronic states to become quantized and discrete. The quantization in the conduction band leads to a confinement energy for the electron that is simple to calculate using the 1D envelope approximation. Due to the light effective mass, this confinement energy is on the order of 40 meV in 100Å wide wells. Since the band discontinuities are not infinite, the wavefunction leaks somewhat into the barriers. In addition to the lowest energy $n=1$ state, there are other higher quantized states. The spacing between these levels changes as the top of the well is approached and the wavefunctions turn to plane waves above the barrier band energy.

Although the electron states in the conduction band can be well represented by a single mass, the valence bands are more complex. In the bulk GaAs, the valence band is doubly degenerate with a light hole and a heavy hole band with approximate masses of $0.074m_0$ and $0.62m_0$ respectively (see FIG. 2.1). There is also a hole band at higher energies that is shifted about 340 meV due to the spin orbit coupling. This band is usually neglected in optical calculations of quantum structures except for its coupling effect in changing effective masses. The quantum confinement in the valence band splits the degeneracy between the light and heavy hole bands since the confinement energy depends on the mass (FIG. 2.2). Consequently, absorption and luminescence in GaAs quantum wells normally
exhibit two distinct peaks due to the interaction of the electrons with the different types of holes.

The band structure and therefore the optical properties are somewhat different in the strained InGaAs/AlGaAs materials system compared to the GaAs/AlGaAs. As we mentioned earlier, one of the effects of compressive strain is to shift the light hole to larger energies. At times, the energy of the light hole is raised so much that it becomes larger than the barrier height in GaAs. In this case the light hole becomes confined in the GaAs and the light hole resonance becomes much weaker and exhibits some type II properties. Since modulators depend on absorption changes at the band edge, we will be more concerned with the type I heavy hole resonance at the absorption edge.

Quantum well material properties reflect the two dimensional nature of the structure. The carrier wavefunctions in the wells are confined in the growth direction (usually defined as z axis) and plane waves in the x-y plane. If we count the number of modes to obtain density of states, we see abrupt steps associated with the different confined modes\(^42\). This step-like behaviour is in contrast to the density of states in bulk material that depends smoothly on the square root of the energy. The sharp discontinuity in the density of states in the quantum well is best observed in quantum well lasers where it leads to large differential optical gains that lower the threshold current for lasing\(^23\). The confinement energy also increases the band edge absorption to higher energies, and similarly increases the photon energy of quantum well lasers.

Although the absorption versus energy curves of quantum wells roughly follow the step-like density of states, there are large resonances at the step edges. These resonances are due to the presence of excitons. The dynamics of exciton formation and properties have been the subject of intensive study by many groups in the past few years\(^43-46\). The exciton is simply an electron and a hole in a hydrogen like state whose motions are correlated together due to the Coulombic attraction. The large overlap caused by this attraction makes optical transitions more likely and causes a strong resonance in the optical absorption.
curves. In luminescence the same enhancement is observed as the high barriers in quantum well material make the formation of an exciton more likely at room temperature. We will study the exciton quantum mechanics in greater depth in chapter 5, where we examine the excitonic absorption in InGaAs/AlGaAs material as a function of barrier height.

2.3.2 Quantum Wells in an Electric Field

![Diagram of quantum wells in an electric field](image)

Figure 2.3. Quantum confined Stark effect. The applied electric field tilts the bands. Since both the electron and hole move to lower energies, the optical transition energy, represented by the length of the arrow, decreases, and a red-shift in absorption results.

Since we use quantum wells to modulate the absorption in the Fabry-Perot modulators, the field dependent absorption properties are of most interest. Not long after the discovery of quantum phenomena in these materials\(^\text{41}\), the field dependent absorption properties were studied by Miller et al.\(^\text{45}\). For isolated wells, where the barrier region is thick enough to prevent coupling between wells, a red shift of absorption with field was observed. The origins of this effect, named by Miller as the quantum-confined Stark effect (QCSE) may be understood with the aid of FIG. 2.3. The applied electric field simply tilts all the
bands. The electron wavefunction moves towards one side of the well and the hole wavefunction towards the opposite side. Since both particles minimize their energy by going in the direction of lower potential, the energy separation between the two levels decreases with field, moving the optical transition to lower energies or longer wavelengths. Unfortunately, as the electron and hole move to opposite sides, their spatial overlap also decreases, thus reducing or weakening their resonance at high fields. Although there are similar excitons in the bulk, without the confining barriers they are very quickly ionized by an electric field. In quantum wells, however, the barriers prevent the exciton ionization and maintain a resonance to very high fields. Thus the QCSE is much stronger than the effect in the bulk material.

![Graph showing Absorption vs Wavelength for different fields](image)

**Figure 2.4:** Quantum confined Stark effect in In$_{0.2}$Ga$_{0.8}$As / Al$_{0.33}$Ga$_{0.67}$As. See chapter 4 for details. One can either raise or lower the absorption with field depending on the wavelength of operation.

Although there are many other ways to change the optical absorption properties in quantum wells, the QCSE has so far proved itself to be the most powerful. FIG. 2.4 is our own experimental data for the QCSE in strained InGaAs/AlGaAs quantum wells. The
experimental details in obtaining the data are given in chapter 5. Since the material is strained, the light hole is shifted to higher energies and only one peak is observed. With an applied bias, this peak shifts to longer wavelengths and decreases in size. Note that there are two regions of operation. If one picks the wavelength of peak absorption for the exciton at zero field (A), one obtains a large decrease in absorption with applied voltage. At wavelengths lower than the zero bias exciton wavelength (B), one obtains an increase in absorption with applied voltage. Though the two methods yield about an equal change in absorption, the latter region of operation has a much lower minimum absorption and thus a much larger absorption ratio. This will become a significant design factor for the modulators described in chapter 6.

2.4 Growth

All the material in this work has been grown using a commercial Varian Gen II MBE system. MBE is an ultra-high vacuum technique where epitaxial material is grown using evaporation of solid sources. The growth chamber is kept at ultra-high vacuum, typically about $10^{-10}$ Torr base pressure. This low pressure is necessary to decrease the incorporation of unintended impurities and to increase the mean free path of the particles such that molecular beams form. The elemental sources are heated electrically in inert pyrolytic boron nitride crucibles and a mechanical shutter in front of each furnace switches the beam on and off. The growth rate of the material is determined by the flux of the constituent atoms. Since the flux is a function of the furnace temperature, by varying the furnace power, different growth rates and alloy compositions can be achieved.

Substrate temperature is an important consideration in MBE growth. Typical growth temperatures are between 500 °C to 750 °C. Although GaAs material quality is quite good over the whole range, the AlGaAs material is best above 650 °C, while the InGaAs must be grown below 550 °C. The material is usually grown with an arsenic overpressure of about 10. An arsenic cracker is used to supply As$_2$. To determine growth
rates, reflection high energy electron diffraction (RHEED) is employed. This in-situ method uses reflected electrons to examine the growth dynamics. As the surface of the wafer changes from arsenic rich to gallium rich, the intensity of the reflected beam oscillates with a period corresponding to one monolayer of growth. So by simply measuring the frequency of these oscillations, an accurate value for the growth rate can be determined\(^47\).

The optical modulator structures are very sensitive to errors in the growth rate. Although RHEED gave reproducible results for the growth rate, the values did not exactly match those measured by growing and etching thick layers of material. Neither result correlated with growth rates measured from reflectivity tests. Although all three methods agreed to within a few percent, the high accuracy needed for the modulator structures (\(<1\%\)), made them unreliable. There could be a number of reasons for the disagreement between the methods. One source of error could be transients due to the opening and closing of the shutter. This had been a serious problem in the early days of MBE technology and led to erroneous measurements of band offsets. These transients were substantially improved by repositioning the shutter relative to the furnace. However, experiments with our machine still indicate a 5% overshoot once the shutter is opened with a time constant of about 15 seconds. Since RHEED is performed immediately after opening the shutter, it seems reasonable to expect higher measured values for the growth rate using this technique. Another source of error could be the temperature fluctuations in the furnace itself. Once the shutter is opened, the sources cool somewhat and it takes the furnace control circuitry some time to compensate for the cooling thus modifying the flux and the growth rate. Other sources of error such as those caused by the depletion of material in the furnace over time could also be significant. In my experience, I found the most reliable method to accurately grow the cavity was to use the initial calibration curves to relate the beam flux to the growth rate. I would use this value for the growth of the test wafer, and be off only by about a few percent. The corrections obtained with the test
wafer would then be used immediately in the growth of the actual wafer. If the two
growths were consecutive, keeping the furnaces hot between growths, accuracies better
than a fraction of a percent could be obtained.
3. Modulator Structure

![Diagram of modulator structure](image)

Figure 3.1. Typical electro-absorption modulator structure.

3.1 Overview

The typical quantum well modulator is fairly simple in structure. FIG. 3.1 is a schematic of the entire device. Optically, it is a Fabry-Perot cavity with two mirrors and a spacer layer. The mirrors are made of quarter wave layers of material with different refractive indices. In the GaAs based systems grown with MBE, this is easy to achieve using material with different amounts of aluminum. Since the entire structure is single crystal, there is very little scattering from the interfaces, and very high reflectivities are obtainable (over 99.9%). Of course, to achieve these high reflectivities, many pairs must be used to form the mirror. For example, in surface emitting laser structures where high reflectivities are crucial, 25 or 30 pairs of AlGaAs / AlAs is not unusual for a single mirror. Between the two mirrors is the spacer or the cavity region containing the quantum wells.
For the purpose of this device we are most interested in how the optical absorption changes in this cavity region. The length of the cavity should be an integral number of half wavelengths for the optical field to resonantly build up. The maximum interaction between the optical field and the cavity material occurs at this Fabry-Perot wavelength where small absorption changes lead to large reflectivity modulation.

Electrically, the structure is a p-i-n diode. The mirrors are both fairly heavily doped with the cavity left nominally undoped. Thus, when a reverse bias is applied to the device, the electric field is dropped almost entirely in the intrinsic region. Since the doping levels in the mirrors are quite high, there is no substantial enlargement of the depletion width with reverse bias voltage, and one can assume with minimal error that the electric field is uniform in the cavity and given simply by the applied bias plus the built-in voltage of the diode divided by the width of the cavity.

Since the mirrors are not simply bulk material and contain heterojunctions, they are somewhat resistive. This is a serious problem in vertical cavity surface emitting lasers where large current densities are required to achieve population inversion. It is far less of a problem with modulators. As modulators are reverse biased, the current passing through the mirrors is simply equal to the reverse leakage current plus the photocurrent. At these small currents, the resistance of the mirrors only gives a small correction to the voltage dropped across the cavity. This resistance, however, may be important for the high frequency properties of the device. Though we did not perform any high frequency experiments on the modulators, one expects the frequency response to be RC limited.

From experiments by Geels et al.\textsuperscript{48} 10 period mirrors doped at $3 \times 10^{18}$ cm$^{-3}$ with an area of 100 $\mu$m$^2$ had a resistance of 313 K$\Omega$ and a peak reflectivity of 95.7%. This resistance was reduced to 12$\Omega$ by grading the interfaces in the mirrors. This caused only a 2% drop in the peak reflectivity. The areas of our measured devices are far larger than the value of their test mirror, usually about 250,000 $\mu$m$^2$, and have only about 2 to 4 periods on the top mirror. Consequently, even with no grading in the interfaces, we would expect resistance
values of only about 60Ω. This value is negligible in our experiment since our operating
currents are less than a microamp.

In determining the doping levels in the mirrors, one should also be aware that heavily
p-type material can be optically quite lossy due to free carrier absorption. In our case we
minimized this effect by doping the mirror moderately at 5 \times 10^{18} /\text{cm}^3 level, with a small
500 Å thick highly doped layer ( \textgreater 10^{19} /\text{cm}^3 ) at the very top to minimize contact resistance.
In any device, one should make sure that the free carrier loss in the mirrors is much lower
than the residual absorption in the cavity, or the device will be limited by the doping loss
rather than the absorption modulation present in the quantum wells. Simple calculations
using literature data are usually sufficient for this purpose.

To isolate the devices, several different techniques can be used. In our case, a simple
wet etch past the cavity to the bottom mirror provides adequate isolation. Other techniques,
such as proton implantation, may be more convenient and allow planar device fabrication.
Electrical contact is typically made using an annular gold contact to the top of the device to
avoid optical obscuration and applying an ohmic metal contact to the entire lower surface of
the substrate. If a semi-insulating substrate is used, perhaps to reduce parasitics to achieve
improved high frequency characteristics, then the n-type contact could be made from the
top after etching down to the bottom mirror.

3.2 Fabry-Perot Cavity

There are two elements to the reflection modulator, the optical cavity and the quantum
well optical absorption region. The purpose of the cavity is to translate the absorption
changes in the quantum wells to a reflection change from the device. Ideally, we desire
quantum wells that can change their absorption from totally transparent to completely
opaque with a very small applied electric field and over a large range of wavelengths.
Practically, however, the achievable values of absorption change and the wavelength range
are limited and we must therefore optimize the Fabry-Perot (F-P) cavity to yield the maximum performance for a given absorption change.

3.2.1 Reflection Properties

In our first analysis, we will take a simplified view of the quantum well absorption properties. Looking at only one wavelength, let us assume that we can change the absorption in the quantum wells from a minimum value of \( \alpha_{\text{min}} \) to a maximum value of \( \alpha_{\text{max}} \). How do we then design the cavity to translate this to the largest possible reflectivity or transmission modulation?

The optics equations for the Fabry-Perot cavity are simple to derive. We can represent a wave propagating in the z direction as a complex exponential where the magnitude squared represents the intensity, and the exponential term represents the phase.

\[
E = a_1 e^{i(\omega x + \beta z)} + b_1 e^{i(\omega x - \beta z)} \tag{3-1}
\]

where the \(+ \beta\) term represents the wave moving to the left and the \(-\beta\) term the wave moving to the right. The index \( i \) represents the material. In the general case of an optical interface, we have incident waves and reflected waves on both sides of the interface.

![Figure 3.2. Incidence and reflection at a general interface](image-url)
If we call the incident waves $a_1$ and $a_2$ and the reflected waves $b_1$ and $b_2$, (see FIG. 3.2), then we can write:

\[ b_1 = r \ a_1 + t \ a_2 \]
\[ b_2 = t \ a_1 - r \ a_2 \]

(3-2)

For a simple dielectric interface, the well known formulas for reflection and transmission apply:

\[ r = \frac{n_1 - n_2}{n_1 + n_2} \quad \text{and} \quad t = \frac{2 \sqrt{n_1 \ n_2}}{n_1 + n_2} \]

(3-3)

Note that the reflected wave changes phase by $180^\circ$ on reflection from a higher refractive index material.

We can apply this same formalism to more complex cases, where instead of a simple dielectric interface there may be a multi-layer stack. In this case the numbers $r$ and $t$ will no longer be real, but will have associated phase changes. Of course the phase terms will depend on where we choose to take the reference plane. Given this degree of freedom, it can be shown that we can always find reference planes where $r$ and $t$ are real if we associate a $90^\circ$ phase change with the transmission. We will adhere to this method in analyzing the cavity. Alternatively, we could have taken the transmission to be real and assume a $+r$ in one direction and a $-r$ in the other direction. Our approach makes no difference to any physically observable property of the system and merely simplifies the analysis. It is important to note that $r$ and $t$ are the electric field reflectivity and transmission coefficient. The more commonly quoted values are the intensity reflectivity and transmission, denoted by $R$ and $T$. Since the intensity is proportional to the square of the electric field the intensity values are equal to the magnitude of the electric field values squared, or $R = r^* \ r$ and $T = t^* \ t$. 

Figure 3.3. Optical rays in a Fabry-Perot cavity

Given the three variables in the figure above, we can immediately write two simultaneous equations:

\[ E_{\text{refl}} = r_f E_{\text{inc}} + j t_f n_b e^{(2j \beta L - 2 \alpha_e L)} E_{\text{circ}} \]  \hspace{1cm} (3-4)

\[ E_{\text{circ}} = j t_f E_{\text{inc}} + r_f n_b e^{(2j \beta L - 2 \alpha_e L)} E_{\text{circ}} \]  \hspace{1cm} (3-5)

where \( r \) and \( t \) represent the electric field reflectivity and transmissivity of the mirrors. The back mirror is represented by the subscript \( b \) and the front mirror by the subscript \( f \) and \( \alpha_e \) is the electric field absorption coefficient (one half of the more familiar intensity absorption coefficient \( \alpha \)). The \( j \)'s associated with the transmission coefficients arise because of our convention to associate a \( 90^\circ \) phase shift with the transmission. If we now eliminate \( E_{\text{circ}} \) and substitute \( n_b' = n_b e^{-2 \alpha_e L} \) ( \( R_{b'} = R_b e^{-2 \alpha L} \)), then we can get:

\[ \frac{E_{\text{refl}}}{E_{\text{inc}}} = \frac{r_f - n_b' e^{2j\beta L}}{1 - r_f n_b' e^{2j\beta L}} \]  \hspace{1cm} (3-6)
Since we are interested in intensity values, we can simply find the magnitude squared of the above equation to obtain the familiar Fabry-Perot reflectivity equation. Often, the half-angle formula is used to express the $\cos(x)$ in terms of $\sin^2(x/2)$.

\[
\frac{I_{\text{refl.}}}{I_{\text{inc}}} = \frac{r_F^2 + r_B^2 - 2 r_F r_B \cos (2\beta L)}{1 + r_F^2 r_B^2 - 2 r_F r_B \cos (2\beta L)} \tag{3-7}
\]

At the Fabry-Perot modes, where an integral number of half-wavelengths fit in the cavity, the reflectivity drops quite sharply to reach a minimum value. Between these wavelengths, the reflectivity increases to a gentle maximum value. These are given by:

\[
R_{\text{min}} = \left[ \frac{r_B - r_F}{1 - r_B r_F} \right]^2 \tag{3-8}
\]

and

\[
R_{\text{max}} = \left[ \frac{r_B + r_F}{1 + r_B r_F} \right]^2 \tag{3-9}
\]

### 3.2.2 High Contrast Capability

As mentioned earlier, the optical field builds up in the cavity at the Fabry-Perot wavelength where the reflectivity is a minimum. Due to the increased intensity and hence interaction of the light with the medium in the cavity at this wavelength, we would expect the maximum reflectivity modulation to occur at this point. If we define the contrast to be the ratio of the reflectivity from the on state to the off state, $R_{\text{on}} / R_{\text{off}}$, we can immediately see from the expression for $R_{\text{min}}$ (eq. 3-8) that reflective devices can have very high contrast. If at some point we change the absorption in the cavity so that $r_B = r_F$, the numerator goes to zero and we should be able to achieve zero total reflectivity from the device, thus obtaining infinite contrast ratio. This is impossible to achieve with transmission modulators, since, as we shall see in section 3.2.4, an infinite contrast in transmission mode requires an
infinite cavity length and therefore infinite loss. The ability to obtain high contrasts is expressed in FIG. 3.4, where we plot the total reflectivity at the Fabry-Perot mode, as defined in eq. 3-8, as a function of cavity loss, $R_{b'}$, for various values of front mirror reflectivity, $R_f$. Note that for each curve the total reflectivity drops as the absorption increases (moving to the left on the graph). The total reflectivity goes through zero at the matching condition ($R_f = R_{b'}$), and then increases again to a maximum value equal to $R_f$. This makes intuitive sense. With no absorption anywhere, we would expect the total reflectivity to be unity from energy conservation principles. With infinite absorption between the mirrors, we would not be able to see the rear mirror, and we would expect $R_{on}$ to be just $R_f$. There are two ways of operating a modulator to obtain high contrast ratios. One can either match $R_f$ to the maximum absorption in the cavity and then decrease the absorption to raise the reflectivity, operating to the right of the matching condition in FIG. 3.4, or do the matching at the minimum absorption to operate to the left of the matching condition.

Figure 3.4. Plot of total reflectivity as a function of cavity loss for various front mirror reflectivities. Note that zero absorption corresponds to $R_{b'} = 1$ and infinite absorption to $R_{b'} = 0$. 
To compute the reflectivities, we can, in the simplest approximation, neglect dispersion in the material and assume that only the optical absorption $\alpha$ changes with voltage. We denote the minimum absorption coefficient in the cavity as $\alpha_{\text{min}}$, and assume that we can increase this value $X$ times to get $\alpha_{\text{max}} = X \alpha_{\text{min}}$. From the form of the equations, it is obvious that we desire the back mirror reflectivity, $R_b$, to be close to unity. Any losses through the back mirror lower the value of $X$, and are mathematically identical to uncontrollable absorption losses. Practically, we should always design the back mirror such that this loss is small compared to the minimum loss in the cavity.

To reduce the number of variables, let us first assume that $R_b = 1$ (the device is dominated by loss in the cavity) and that we have fulfilled the matching condition at the maximum absorption, such that

$$R_f = R_b \ e^{-2 \alpha_{\text{max}} L}$$

(3-10)

The maximum front reflectivity ($R_{on}$) that we can achieve for a given absorption change is simply given by:

$$R_{on} = \left[ \frac{r_f - r_f^{1/X}}{1 - r_f^{1 + 1/X}} \right]^2$$

(3-11)

We plot the results of the above equation as the solid lines in FIG. 3.5. On the other hand, if we match the front mirror reflectivity to the effective back mirror reflectivity at the minimum absorption,

$$R_f = R_b \ e^{-2 \alpha_{\text{min}} L}$$

(3-12)

then the on state reflectivity will be

$$R_{on} = \left[ \frac{r_f - r_f^X}{1 - r_f^{1 + X}} \right]^2$$

(3-13)

This is plotted as the dashed lines in FIG. 3.5. Note that the device matched at maximum reflectivity performs better, as it is less sensitive to the front mirror reflectivity. This also
makes intuitive sense. One would expect it to be easier to increase the reflectivity by lowering the loss rather than raising the loss. If instead of expressing $R_{on}$ in terms of $R_f$, as we do in eqs. 3-11 and 3-13, we expressed the dependence of $R_{on}$ on the cavity length for given values of $\alpha_{\text{max}}$ and $\alpha_{\text{min}}$, we would in fact find that the two matching conditions yield the same performance. However, matching at the minimum absorption would require a larger front mirror reflectivity, which agrees with our previous analysis.

![Graph showing insertion loss vs. front mirror reflectivity for different absorption ratios X](image)

Figure 3.5. Plot of insertion loss ($-10 \log (R_{on})\), as a function of front mirror reflectivity $R_f$ for various absorption ratios $X$. The dashed lines are for modulators matched at $\alpha_{\text{min}}$ while the solid lines are for those matched at $\alpha_{\text{max}}$.

### 3.2.3 Modulation Ratio - Insertion Loss tradeoff

So far we have only dealt with the high contrast ratio case where the matching condition ($R_f = R_0 e^{-2\alpha L}$) is satisfied either at $\alpha_{\text{max}}$ or $\alpha_{\text{min}}$. It is important to investigate the tradeoffs when this is not the case. In this case we either work to the left or the right of the matching condition. As we change the absorption in the cavity, we change the total reflectivity as given by eq. 3-8. This is diagrammatically shown in the figure below.
Figure 3-6: Modulating the total reflectivity without achieving the matching condition

We define the modulation ratio (MR) as the ratio of $R_{on}/R_{off}$, and the insertion loss (IL) by $-10\log(R_{on})$. To find the dependence of MR on $X$ and $R_f$ we use eq. 3-8 at the two extreme points and calculate the ratio to get:

$$
MR = \left[ \frac{r_{on} - r_{on} r_f \left( \frac{r_{on} + r_f}{1 + r_{on} r_f} \right)^X}{\left( \frac{r_{on} + r_f}{1 + r_{on} r_f} \right)^X - r_f} \right]^2
$$

(3-14)

Though the equation is quite complicated, by graphing it for various values of $X$, we see that the MR improves as the front reflectivity increases. This dependence, however, is quite weak, in qualitative agreement with our results for the matching condition shown in FIG. 3-5. Since it is fairly easy to change the front mirror reflectivity and we are interested in what performance we can achieve in an optimized device, we can simplify the equation by taking the limit of $R_f = 1$. The result is a very general equation showing the best performance that one can achieve in an absorptive reflective modulator.
\[
MR = \left[ \frac{r \left( 1 + X \frac{1 - r_{on}}{1 + r_{on}} \right)}{1 - X \frac{1 - r_{on}}{1 + r_{on}}} \right]^2
\]

(3-15)

This equation is plotted as the solid lines in FIG. 3.7 for various values of \(X\). Although we solved the problem by examining two points on the right of the matching condition (see FIG. 3.6), a similar analysis to the left of the matching condition yields the same limit. As one might expect, this limit is harder to achieve on the left side of the matching condition as the performance is more dependent on the front mirror reflectivity.

One may at first suppose that by using more complex structures we can obtain a better tradeoff between insertion loss and modulation ratio. For instance using two Fabry-Perot cavities coupled together end to end, we might obtain a different set of equations. The previous analysis is simple to apply to these more complex structures. Since we can replace \(R_b\) of the front cavity by the total reflectivity of the rear one, we mathematically reduce the number of cavities by one. If we use this procedure in the double cavity outlined, we obtain a fairly complex equation involving the three mirrors and two absorptions. Again, seeing the dependence of the tradeoff on these values we can take limits and obtain an equation for the maximum performance tradeoff. Interestingly enough, the tradeoff equations turn out to be identical, offering no benefits for the more complex cavity. The case for the double cavity can of course be generalized to \(n\)-coupled cavities. Consequently we see that eq. (3-15) represents a very powerful limiting criterion.

3.2.4 Tradeoff in Transmission Modulators

The analysis for transmission devices is similar to the reflective case. The Fabry-Perot transmission equation becomes more complicated as we can not make a simple substitution for \(R_b\). The relative transmitted intensity becomes:
\[ I_{\text{trans}} = \frac{T_f T_b e^{-\alpha L}}{1 + R_f R_b e^{-2\alpha L} - 2 r_b r_f e^{-\alpha L} \cos (2\beta L)} \tag{3-16} \]

At the Fabry-Perot wavelength, where the optical build-up occurs, this reaches a maximum value of:

\[ \frac{I_{\text{trans}}}{I_{\text{inc}}} = \frac{T_f T_b e^{-\alpha L}}{(1 - r_b r_f e^{-\alpha L})^2} \tag{3-17} \]

The equations are symmetric in terms of the front and back mirror properties which hints that there will be no advantage to a non-symmetric cavity, as there was in the reflective case. A little further analysis, again taking limits, shows that the tradeoff between modulation ratio and insertion loss is in fact maximized with both \( R_f \) and \( R_b \) equal to zero, that is with the device anti-reflection coated. This is not to say that there are no advantages in using a Fabry-Perot cavity. Incorporation of mirrors will lead to many optical passes through the cavity, decrease the length of cavity needed, and lower the operating voltage. For a given cavity length, the mirrors will effectively increase cavity size, giving larger modulation ratio at the expense of higher loss. However, for a constant modulation ratio, a longer cavity with no mirrors will lead to lower loss than a short cavity with mirrors. In the optimized case of both facets anti-reflection coated, the equation for the tradeoff is simple to derive and is given by:

\[ \text{MR}_{\text{trans}} = T_{\text{on}}^{1 - X} \tag{3-18} \]

where \( T_{\text{on}} \) is the maximum transmission occurring at the lower absorption. The insertion loss is then converted to dB and the equation is plotted as the dashed lines in FIG. 3.7. This simple tradeoff in transmission modulators is in contrast to the tradeoff in reflective devices that can easily produce very high contrasts. We can see that for a given loss, the reflective device is always capable of higher contrast. Of course, transmission devices do have some advantages. They may be simpler to implement in some architectures. Also,
the absence of high reflection mirrors makes them easier to fabricate and does not limit their operation to the sharp wavelength resonance of the Fabry-Perot mode.

![Graph](image)

**Figure 3.7.** Plot of maximum achievable modulation ratio versus insertion loss for different absorption ratios, X. The solid lines are for reflection and the dashed lines for transmission modulators. For each curve only the areas to the lower right are physically achievable.

### 3.2.5 Optical Bandwidth

From FIG. 3.5 we saw that the lowest insertion loss is obtained with high front mirror reflectivity, though this dependence is weak for devices that operate to the right of the matching point (increasing absorption decreases reflectivity). A high $R_f$ is not only hard to implement, but lowers the optical bandwidth (OB). This reduces the range of operating wavelengths for a given device, decreasing the manufacturing tolerance and allowing less error in matching the F-P mode to the exciton wavelength. This also makes the device more temperature sensitive. Different workers have analyzed the optical bandwidth in different ways. Some define OB as the range where the modulation ratio is greater than a specified value, while others look at reflectivity change. In the formalism that we have
developed, it is simplest to analyze the OB in terms of the HWHM of the F-P resonance at the matching condition. From eq. (3-7) we can compute the wavelength difference from the resonance point where the reflectivity is zero to the point where the reflectivity reaches half of its maximum value. Analyzing the device in this simple way neglects the influence of the quarter-wave mirrors that are generally used in the cavity. Frequently, the total thickness of the mirrors is many times the length of the cavity. Consequently, the optical field penetrates deep into the mirrors and the effective width of the cavity is increased. Another way to analyze the situation is to assume the cavity width is as given and instead take into account the wavelength dependent phase change from the quarter-wave stack. Macleod 50, quoting earlier work, asserts that this phase change can be taken account in a simple first order approximation merely by multiplying the optical bandwidth by a term that depends on the indices of the layers used in the mirrors. If we put these two terms together, we get an approximate value for the optical bandwidth given by:

\[ \Delta \lambda = \text{HWHM} = \frac{\lambda_0}{2 \pi m} \cos^{-1}\left(\frac{2R_f}{1 + R_f^2}\right) \cdot \left(\frac{n_h - n_l}{n_h - n_l + \frac{n_l}{m}}\right) \]  

(3-19)

where \( \lambda_0 \) is the free space wavelength of the resonance, \( m \) is the order of the cavity or the number of half-wavelengths that fit in the cavity, and \( n_h \) and \( n_l \) are the high and low refractive indices used in the mirror stacks. The first part of the equation is from a simple analysis of the cavity and the second part is the approximate multiplier that takes into account the phase changes from the mirrors. Plugging in typical values, we see that this correction term is quite important. Using a quarter-wave stack of GaAs and AlAs with refractive indices of 3.5 and 3 respectively in a second order cavity decreases the optical bandwidth by a factor of four.

Accurate values for the optical bandwidth are practically quite difficult to calculate. This is not simply because of the mirror effects, but because of dispersion in the material.
The refractive index profile at wavelengths around the quantum well resonance are very complicated and not yet accurately measured. Consequently, there is usually significant disagreement between models and experiment. Frequently, in the design process, simple equations that roughly predict the magnitude and direction of varying parameters are much more useful than complex programs that attempt exact prediction. Eq. (3-19), though not exact, is simple and accurate enough to be useful in designing modulator structures.

3.2.6 Design example

We have so far developed some simple equations that can help in the design of modulator structures. As a numerical example, it might by useful to calculate typical modulator properties using common quantum well parameters. We shall deal only with the optical cavity at this point, optimization with respect to the quantum well material will be discussed in chapter 4. Let us assume we are to use 100 Å GaAs quantum wells with 50 Å Al_{0.33}Ga_{0.67}As barriers. The barriers must be wide enough to provide adequate quantum mechanical isolation between the wells. Electro-absorption experiments by Jelley et al.\textsuperscript{51} indicate that with these quantum well structures, an electric field of 65kV/cm is required to change the absorption from 2,500/cm to 10,000/cm at a wavelength of 850 nm. We assume $n=3.5$ for GaAs, $n=3.4$ for the QW material, and $n=3$ for AlAs.

In the first step, we consider the case where the back mirror loss is low compared to the minimum loss in the cavity. Once we have decided upon the cavity size, we can go back and calculate what reflectivity and how many layers we need in the back mirror. If we keep the cavity size as the main dependent variable and aim for a high contrast case where the matching condition is satisfied, we can use the previous equations to calculate various properties, such as operating voltage, insertion loss, and optical bandwidth. The optical bandwidth and $R_{on}$ are displayed in FIG. 3.8. The operating voltage will be a simple linear function of $m$, the number of half wavelengths that fit in the cavity. For the first order cavity, $m=1$, the operating voltage is 0.8 V and for $m=20$, it increases to 16.25V.
As a practical note, one should avoid both very small and very large cavity lengths for a number of reasons. At very small cavity lengths (m=1 or m=2) the operating voltage will be low and the finite built-in voltage of the diode will be very significant. One can always forward bias the diode to partially reduce this field, but charge injection will become a problem. The problem with large cavity lengths is that one needs very low front mirror reflectivities, and anti-reflection coatings are needed. This is hard to do with AlAs/AlGaAs quarter-wave stacks and is best avoided.

![Graph](image)

Figure 3.8. Calculated values for the optical bandwidth and on state reflectivity for the design example of a modulator with 100Å GaAs / Al₀.₃₃Ga₀.₆₇As QWs.

In this section, we derived some simple rules that roughly predict the properties of electro-absorption devices. These simplifications, looking only at the Fabry-Perot wavelength and neglecting dispersion and index changes, make the equations simple to use and give general design criteria. However, these assumptions do place limits on the validity of the equations. For instance, we have completely neglected the excitonic lineshape and index dispersion, thus we are not able to fully predict the shape of the Fabry-
Perot resonance. Shifting the absorption characteristics with voltage also affects the refractive index through the Kramers-Kronig relations, thus shifting the position of the cavity to different wavelengths. In our calculations, we have completely neglected this effect which usually increases the performance of the device. For modulators with a wide optical bandwidth, this effect is small, as the Fabry-Perot dip is quite wide. But index changes may become more important for lower bandwidth cavities.

3.2.7 Thin Film Calculations

The formulas that we have derived to this point serve as design guidelines, showing how varying different design parameters can influence the performance. More accurate calculations on specific designs can be performed using standard matrix method thin film calculations. In this way detailed absorption characteristics of the exciton may be included, increasing the predictive power of the calculations. For our experiments we wrote programs in Pascal to calculate reflectivities of multi-layer devices at different biases. Although we took into account dispersion relations in the mirrors and the bulk, we did not include the excitonic absorption lineshape. We felt that the current limitations in the actual growth of the device make more accurate models irrelevant. More accurate models, however, have been attempted by other groups \(^{52-53}\). As we mentioned earlier, even these more accurate models fail to take into account the intricate dispersion relations in the quantum wells, making exact predictions difficult.

Our model is a computer implementation of a general thin film algorithm outlined in many optics texts, such as Macleod\(^{50}\). Briefly, each layer is represented by a characteristic matrix that multiplies an admittance vector at its back surface to give the admittance vector at its incident surface. Thus for an n-layer structure, we multiply n complex matrices to get the admittance vector at the surface of the structure. We then use the admittance vector at the surface to obtain the reflection coefficient. This may be expressed as:
\[
\begin{bmatrix}
B \\
C
\end{bmatrix} = \prod_{j=1}^{n} \begin{bmatrix}
\cos(\delta_j) & i \sin(\delta_j) / \eta_j \\
i \eta_j \sin(\delta_j) & \cos(\delta_j)
\end{bmatrix} \begin{bmatrix}
1 \\
\eta_s
\end{bmatrix}
\]

(3-20)

where
\[
\delta_j = \frac{2 \pi n \, d \cos(\theta)}{\lambda}, \quad Y = \frac{C}{B}, \quad \text{and} \quad R = \left| \frac{\eta_{\text{inc}} - Y}{\eta_{\text{inc}} + Y} \right|^2
\]

(3-21)

\(Y\) is the complex admittance of the material and reduces to the refractive index when only one layer is present. Non perpendicular geometries can be studied since \(\eta = n / \cos(\theta)\), where \(\theta\) is the angle between the propagating light and the normal. \(\eta_s\) relates to the refractive index of the substrate which may be complex if the substrate is absorbing, \(\eta_{\text{inc}}\) to the index of the incident medium (usually air), and \(\eta_j\) to the index for the jth layer of thickness \(d\). For each wavelength of interest, the complex refractive indices must be known and once the \(Y\) vector for the entire structure has been calculated, the reflectivity \(R\) can be obtained.

There are, of course, simpler formulas for periodic structures. For a quarter-wave stack in air with \(p\) periods, with high and low refractive indices \(n_h\) and \(n_l\), and a substrate of index \(n_s\), the reflectivity in will be

\[
R = \left[ \frac{1 - (n_h/n_l)^{2p} (n_h^2/n_s)}{1 + (n_h/n_l)^{2p} (n_h^2/n_s)} \right]^2
\]

(3-22)

Thus, roughly, every period improves the reflectivity by lowering the transmission through the layers by a factor of \((n_l/n_h)^2\). Similarly, a quarter-wave reflector stack is only reflective at the wavelengths where the layer thicknesses are roughly correct. The width of this band depends on the refractive index difference between the two materials:

\[
\delta_w = \frac{4 \lambda_0}{\pi} \sin^{-1} \left( \frac{n_h - n_l}{n_h + n_l} \right)
\]

(3-23)
In our experiments, the design was first carried out using the equations in the first section of the chapter. Having arrived at a basic design, a more complex model would be analyzed using the thin film calculation techniques using the matrix method. In attempting to realize the device, the errors in the fabrication frequently dominated the comparison with the theoretical model. However, with a certain amount of luck with the MBE, we were often rewarded with a device whose characteristics were quite similar to our models.
4. GaAs/AlGaAs and InGaAs/GaAs Modulators

4.1 Background

Quantum well electro-absorption modulators are fairly new devices with a short history. Their development can be traced through a large number of papers, each of which typically describes one device. In retrospect, one can examine the various devices and discuss their performance characteristics.

After the discovery of the QCSE at Bell Labs\textsuperscript{45}, the first quantum well modulators were transmission devices. The fabrication of a transmission GaAs/AlGaAs device is quite difficult because the substrate is not transparent at the wavelengths of interest. Consequently, the substrate must be carefully removed, leaving behind only the very thin epitaxial layers.

Reflection modulators that incorporated a back mirror composed of a multi-layer quarter-wave stack were later demonstrated by the same group. Although the contrast ratio was considered an important figure of merit, the Fabry-Perot effects that dramatically raise the contrast in a reflective device were not realized. In fact, in the first reflection device by Boyd et al.\textsuperscript{54}, the top surface is anti-reflection coated to eliminate Fabry-Perot effects.

The first attempts to exploit the Fabry-Perot cavity used refractive index modulation in high finesse devices\textsuperscript{55-56}. In this case, highly reflective mirrors were used along with a large cavity to obtain a sharp Fabry-Perot dip. As the refractive index is modulated, the dip shifts in wavelength, resulting in a reflectivity change. There are two problems with this approach. High finesse devices tend to be very temperature dependent. Since the refractive index depends on temperature and the Fabry-Perot dip is very sharp, the operating wavelength of the device shifts rapidly with temperature. The second problem is that to obtain large index modulation, one has to work close to the exciton wavelength. However, the closer to the exciton one operates, the larger the cavity loss, and the lower
the finesse. This tradeoff tended to limit such index modulation and these devices, despite the claims of the authors, operated more due to absorption changes than index modulation.

The use of absorption changes in an unsymmetric Fabry-Perot cavity was pioneered by the University College London group\textsuperscript{53} and further developed by the UC Santa Barbara group\textsuperscript{57}. We have shown analytically in chapter 3 how this method leads to large reflectivity modulation at low voltages with a large optical bandwidth.

In the last few years, there has been a very large number of papers that stress various aspects of these modulators. Contrast ratios of greater than 100 have been reported by both the University College group using the QCSE\textsuperscript{58}, and the Santa Barbara group using another QW electro-absorption process\textsuperscript{59}, the Wannier-Stark effect that we shall discuss in chapter 6. Very low voltage operation has also been achieved, either by shrinking the cavity and increasing the front mirror reflectivity\textsuperscript{60-61}, or by using wider quantum wells that require a smaller electric field\textsuperscript{62}. Temperature effects have been studied on individual devices\textsuperscript{63-64} and there has been successful operation of the GaAs/AlGaAs modulators grown on silicon\textsuperscript{18-19}.

4.2 GaAs/AlGaAs device

Although the rate of progress in modulator performance has been rapid, there was little systematic work on the limitations and optimization of the structures. In chapter 3, we outlined a general framework to examine modulator operation and to optimize their performance. As a first test of our theory, we attempted to maximize the reflective properties of the device by achieving to obtain the best insertion loss / modulation ratio performance at a reasonable operating voltage and optical bandwidth\textsuperscript{65-66}.

It is clear from FIG. 3.7 that the modulator's performance ultimately depends on X, the ratio of the maximum to minimum absorption. This ratio depends on the wavelength of operation as well as the nature of the quantum wells. Clearly, working directly at the exciton wavelength and reducing the absorption yields a very low X due to the large
residual absorption. The absorption ratio improves at energies below the exciton resonance. The largest absorption change, $\Delta \alpha = \alpha_{\text{max}} - \alpha_{\text{min}}$, is obtained at a particular wavelength above the zero bias exciton. If we go to longer wavelengths than this, the absorption ratio $X$ continues to improve but the $\Delta \alpha$ is severely reduced. From our previous analysis, we see that a high $X$ benefits the insertion loss/modulation ratio tradeoff, while a high $\Delta \alpha$ is necessary for a short cavity, lowering the operating voltage and increasing the optical bandwidth.

A systematic study of quantum well electro-absorption effects by Jelley et al. examined the excitonic behaviour in GaAs/Al$_{0.33}$Ga$_{0.67}$As as a function of the well width. They noticed that various electro-absorption parameters are dependent on the well width. Looking at the position where $\Delta \alpha$ is the largest, they reported that shrinking the well width from 100Å to 40Å causes the $X$ ratio to improve from about 4 to 6 and the $\Delta \alpha$ to increase from about 10,000/cm to about 22,000/cm. Unfortunately, the electric field required to obtain this change also increases in smaller wells from about 65KV/cm to about 180KV/cm for the same well widths.

The reasons for these changes are fairly straightforward to understand. Since the total electro-absorption in a quantum well is to a first approximation independent of well width, a smaller well will have a larger absorption coefficient since the absorption per unit length is larger. This increase in the exciton resonance leads to a larger $X$. However, $X$ cannot be increased indefinitely. At lengths smaller than about 40Å, the excitonic resonance becomes broader and shrinks in intensity. Jelley et al. attributed this to the greater interaction of the exciton with the LO (longitudinal optical) phonon, causing an increase in the thermal broadening. Other reasons could be that the thinner wells raise the electron confinement energy. Since the electron is at a higher energy, it leaks more into the barriers and becomes less confined. This reduces the overlap between the electron and hole states. The leakage also implies that the electron samples more of the AlGaAs barriers, where the ternary material quality is not as good. The reason why larger fields are required
for smaller wells is obvious from classical arguments. To obtain the same energy shift across a smaller well, one has to increase the tilt of the well, since potential energy is a product of the electric field and distance.

Almost all the devices prior to this work had used well widths of about 100Å, presumably because the first experiments with QCSE used this value. However, putting Jelley’s numbers into our equations from chapter 3, we see that decreasing the well width may be advantageous. The higher \( X \) should allow a lower insertion loss for a given modulation ratio. In a high contrast modulator, where the matching condition is satisfied, we should be able to improve the maximum possible on-state reflectivity from about 36% to 51% if we work at the energy where \( \Delta \alpha \) is maximum. The higher \( \Delta \alpha \) also allows us to raise the optical bandwidth by using a shorter cavity. This shorter cavity, however, does not translate to an improvement in the operating voltage, since a higher electric field is required for smaller wells.

4.2.1 Structure

![Figure 4.1 Conduction band diagram of 50Å GaAs / Al_{0.33}Ga_{0.67}As reflection modulator (not to scale).](image)

Following the same optimization routine described in section 3.2.6, we designed a modulator based on 50Å wells. The structure of the device is shown above in FIG. 4.1.
The cavity was composed of 19 x 50Å wells with 75Å Al$_{0.33}$Ga$_{0.67}$As barriers, giving a cavity order of $m=2$. Small 40Å spacers were put between the mirrors and the quantum wells to adjust the Fabry-Perot mode of the cavity. Using Jelley's data$^{51}$, we expected 5V operation, which is desirable because it is a typical value of voltage in logic switching circuits. To match the maximum absorption to the front mirror reflectivity, we used a 2 period front mirror, giving a calculated reflectivity of 50.3%. A 19.5 period back mirror with a calculated reflectivity of 98.8% was adequate to make the back mirror losses insignificant. Since the mirrors cannot be absorbing at the operating wavelength, we used quarter-wave thicknesses of AlAs and Al$_{0.33}$Ga$_{0.67}$As for both the top and bottom mirrors. The mirrors would have been more efficient, requiring a smaller number of pairs for the same reflectivity, if we had used a lower concentration of Al in the AlGaAs. From the energy gap considerations we could have gone down to a concentration of Al$_{0.13}$Ga$_{0.87}$As for the higher index material without appreciable absorption. However, the difficulties associated with ramping the aluminum furnace temperature up and down during growth prompted us to keep the same Al concentration in the mirrors as in the cavity.

The structure was grown on a n+ substrate at 640 °C. The back mirror was silicon doped n-type at $5 \times 10^{18}$/cm$^3$ while the front mirror was Be doped p-type to the same concentration except for the top quarter-wave layer which was doped at $4 \times 10^{19}$. We added a 50Å GaAs cap layer to prevent the AlGaAs from oxidizing. The optical and electrical properties of this cap layer are insignificant.

### 4.2.2 Processing

To measure the modulator characteristics, we needed to form individual devices. Experiments with the usual phosphoric etch (H$_3$PO$_4$;H$_2$O$_2$;H$_2$O) were unsuccessful, mainly because the AlAs layers were etched much faster than the AlGaAs layers. Consequently, the whole structure would be undercut causing layers to peel off in the solution. We experimented a good deal with sulfuric etches as they etch AlAs and AlGaAs
at approximately equal rates. The main problem with this etchant is that it also attacks photo-resist. The standard 5000 RPM spin of AZ1370 resist was not thick enough to protect the mesa regions. We performed a number of experiments both with the resist and the etch. We obtained fairly good results with 5:1:1 H$_2$SO$_4$:H$_2$O$_2$:H$_2$O at 20 °C using AZT1370 spun at 3500 RPM. The etch rate was measured to be roughly 240 - 300 Å/sec and highly temperature dependent. Although the etched surface was a little rough and etch rates were not very constant, it proved adequate for isolation purposes.

After the first lithographic mask step and the subsequent etching to form mesas, we performed a standard lift-off procedure to form the top contact. Resist was spun at 3500 RPM and treated with chlorobenzene to aid lift-off. After exposing and developing the resist, 400Å/400Å/1200Å of Ti/Pt/Au was evaporated and lifted off with acetone. The purpose of the titanium is to make the contact adhere to the wafer while the platinum is meant to prevent the diffusion of the gold in subsequent processing steps. An ohmic contact of 400Å/125Å/150Å/1500Å Au/Ge/Ni/Au was then evaporated on the back side of the wafer. The contact was annealed using a rapid thermal annealer (RTA) at 410°C for 10 seconds. To prevent problems with the other Ti/Pt/Au contact, it is important not to over anneal the wafer in this step. Despite the presence of the Pt layer in the top contact, diffusion problems frequently occur. With one such processing step, a 10°C overshoot in the anneal caused the top contact to diffuse down and short the diode, causing a drastic reduction in the diode breakdown voltage. Switching the order and annealing the backside contact first will eliminate this potential hazard, though wet processing is generally not recommended with gold already on the wafer.

The mask pattern contained many devices of different sizes. Mesas from 1mm square down to 100µm square were processed. The devices tested were 500 µm on each side. The mask pattern also contained structures to measure the resistivity and contact resistance of the top p-type layer. A diagram of a processed device is shown below in FIG. 4.2.
The processed wafer was then cleaved to 3 mm x 3mm pieces and epoxied with conductive adhesive in standard packages and wirebonded.

4.2.3 Measurement

The devices were checked electrically before being optically characterized. C-V measurements verified the cavity length, and the diode characteristics were checked with the HP4145 semiconductor parameter analyzer. The break-down voltages of the diodes were about 10V. Since this voltage corresponds to the break-down field in GaAs, the devices were not breaking-down prematurely. The leakage current was very low, on the order of picoamps, and dominated by the effect of the room lights. The turn-on voltage was about 1.2 volts with good diode characteristics.

The optical measurement was performed using a 20 W tungsten white light source from Oriel and a 1/2 meter spectrometer. The reflectivity measurement set-up is shown below in FIG. 4.3
An f=1.4 collimating lens produced a roughly parallel beam from the white light source. The light then passed through a non-polarizing beam splitter and was roughly focused on the device under test. The light reflected off the device again passed through the lens and the beam splitter and was imaged on a small pin hole on a white screen (aluminum foil painted white). The light was then analyzed by a spectrometer and photo-detector. For this device, operating at about 8300 Å, a silicon photo diode proved most appropriate. Alternatively, a photomultiplier tube with a GaAs photocathode could be used. For devices operating at longer wavelengths, a cooled germanium detector was also available. All the spectra were normalized to the reflectivity of gold by moving the sample to a region on the wafer where gold pads were evaporated and dividing our data by the reflectivity of gold at the wavelength of operation (about 98%).

Several aspects of this measurement technique merit further attention. Using the chopper to improve the signal to noise ratio forced us to pay special attention to the position
of the chopper. For example, we had to tilt the chopper blades away from the normal to prevent reflections from the chopper back into the spectrometer. Even though the chopper was painted black, one would get a substantial reflection from the chopper blades and a negative contribution to the signal if normal geometry was used. Though keeping the chopper normal improved our measured contrast ratios tremendously, we adopted the more honest tilted geometry. It is also important to chop close to the device. In this way continuous reflections from other surfaces, such as the focusing lens and beam splitter, do not contribute to the measured signal.

One difficulty with using a white light source rather than a laser is that the incident beam is not truly collimated. If the device reflectivity depends on the angle of the light, then the response will be averaged over the incidence angle and sharp resonances will be washed out, reducing the contrast ratio. Devices with small optical bandwidths tend to be more sensitive to this problem. The collimation can be improved at the cost of a smaller signal if apertures are placed in the beam. However, using a white light source does have some advantages, such as its easy imaging capability. In contrast with using an infra-red laser, such as a titanium-doped sapphire tunable source, the image of the device can be easily seen and the pinhole adjusted so only the reflection from the device of interest is measured. The alignment of invisible infra-red beams is much harder. The magnification is also easy to adjust with our set up. The enlargement is simply the ratio of the lens-image distance to the lens-device length. Thus, by using a lens of a different focal length, the magnification could be changed. The choice of this focusing lens proved to be critical. Simple plano-convex lenses were inadequate, both because of chromatic aberration and their inability to focus a large image as a result of spherical aberration. The image quality and the measured results were vastly improved by switching to a cemented doublet or a multi-lens microscope eye-piece. The best imaging and results were obtained by using a standard camera lens and an iris.
4.2.4 Results

The reflectivity of the device versus wavelength is displayed below in FIG. 4.4.

![Graph showing reflectivity vs wavelength with curves for 0 V, 3 V, and 5 V biases.](image)

Figure 4.4. Normalized reflectivity as a function of wavelength at three bias voltages.

At zero bias one can see the Fabry-Perot dip at 8300 Å, the heavy hole exciton at 8170 Å and a small dip due to the light hole exciton at 8030 Å. When a bias is applied, the excitons red shift and approach the Fabry-Perot resonance of the cavity. The higher absorption lowers the reflectivity at the F-P wavelength. At 5 V reverse bias, the heavy hole exciton position and the F-P resonance coincide, giving us our minimum reflectivity. The reflectivity as a function of reverse bias at the F-P resonance is shown in FIG. 4.5. At low voltages, the reflectivity drops slowly as the exciton redshifts are small and absorption is quite low. The drop becomes very steep between 3 and 4 volts where the edge of the exciton resonance passes the F-P position. The reflectivity reaches a minimum at 5 V, then rises as the exciton shifts to longer wavelengths and the absorption drops. Overall, the reflectivity changes from about 76% to 10%, yielding a contrast ratio of 7.6 and a reflectivity change of 66%. The optical bandwidth, as defined in section 3.2.5, is
measured to be about 70\AA, surprisingly close to the 72\AA value predicted by eq. (3-19). The reflectivity change, the insertion loss, and the optical bandwidth are all superior to any device so far reported.

![Graph](image_url)

**Figure 4.5.** Normalized reflectivity at 829nm as a function of reverse bias voltage.

The performance of the device is roughly as predicted even though we did not exactly achieve the matching condition. The optical bandwidth, the operating voltage, and the reflectivity modulation all agree with values computed from our equations in chapter 3. We compare the performance of this device to those reported in the literature in FIG. 4.9 at the end of the chapter.

Due to non-uniformities in the growth, the device characteristics vary across the wafer. Our Varian Gen II machine, using sample rotation, gives about a 2\% uniformity from the center to the edge of a 2" wafer. Table 4.1 gives the characteristics of some of the devices as a function of the distance to the center of the wafer.
<table>
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<th>dist (mm)</th>
<th>λ (Å)</th>
<th>R_{min}(%)</th>
<th>R_{max}(%)</th>
<th>V_{op}</th>
<th>X</th>
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<td>6.2</td>
<td>49.6</td>
<td>3.3</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Table 4.1. Device characteristics measured from the center to edge of a 2" wafer.

Since the optical bandwidth of the device is about 70Å, devices in a circle of 14mm diameter on the wafer show substantial reflectivity changes (ΔR > 30%). This figure amounts to 1/3 of the wafer area. The non-uniformity across the wafer is present in all the epitaxial layers, translating to less than half a monolayer change in the quantum well width. This corresponds to about a 40 Å change in the exciton wavelength. However, the same 2% non-uniformity causes the position of the Fabry-Perot dip to shift 170Å. Thus, as we move out from the center of the wafer, the wavelength difference between the exciton position and the F-P wavelength is reduced. We can therefore see how the absorption changes depend on this difference. The X values listed in the table are computed from the reflectivity changes using eq. 3.15. Note that this X value increases as we move away from the exciton peak (move toward the center of the wafer). This seems to agree with prediction. However, our contrast ratio becomes lower as X increases and Δα decreases. Higher reflectivity mirrors would compensate for this lower absorption but only at the expense of decreasing optical bandwidth.
Our excellent results with this modulator demonstrate the usefulness of the theories we developed in the previous chapter. As we noted earlier, our device performs better than other reported modulators in terms of reflectivity change, insertion loss, and optical bandwidth.

4.3 InGaAs/GaAs modulator

Our success with the previous device led us to design an optimized device in the strained InGaAs/GaAs material system using the methods outlined in the previous chapter. This material system is extremely useful due to its operating wavelength of about 1.0 μm. At these longer wavelengths, the GaAs substrate is transparent and devices are optically accessible from the back. Though not directly relevant to a reflection modulator, this added freedom permits novel optical interconnect architectures. The wavelength is also very useful due to the recent developments in low threshold InGaAs lasers that may provide efficient light sources for these modulators. Unfortunately, electro-absorption in InGaAs/GaAs is rather poor. Measurements performed by various groups show that, compared to the GaAs/AlGaAs material, the exciton in InGaAs rapidly deteriorates with field giving low absorption changes and absorption ratios. Even though discrete quantum wells below the critical thickness remain strained and single crystal, if one attempts to grow too many wells adjacent to each other, the strain couples to other wells and the material starts to dislocate and relax. This broadens the exciton absorption peak and lowers the intensity of the resonance. This is problematic in modulators where one tries to compensate for the poorer electro-absorption by incorporating a larger number of wells.

4.3.1 Design and Fabrication

Besides optimizing the cavity, we attempted to compensate for the poor electro-absorption by operating the device at a wavelength further away from the exciton. As our results with the GaAs modulator demonstrated, this increases the value of X, but at the
price of lowering the absorption change. We first grew a test wafer to obtain the absorption properties needed for the design.

The test wafer was grown on a semi-insulating substrate at about 500 °C. After growing a 1μm n-doped 10^{18}/cm^3 buffer region, 43 undoped In_{0.17}Ga_{0.83}As/GaAs quantum wells were grown. The wells were 100 Å thick and separated by 100Å GaAs barriers. We decided to use 100Å wells since no comparative study was available on the well width dependence of electro-absorption in this material system, and we wanted to compare our electro-absorption to previous results. The quantum wells were capped by a 0.5 μm thick p-type GaAs cap layer, the lower half of which was doped at 10^{18}/cm^3 and the top half at 10^{19}/cm^3. The reason for the semi-insulating substrate and the reduced doping in the first half of the p-type layer was to minimize residual free-carrier absorption.

The device processing was similar to the previous modulator structure, except that we used the regular phosphoric acid etchant to reach the n-type contact layer. Using 3:1:50 H_3PO_4:H_2O_2:H_2O at 20 °C, we measured the etch rate to be about 750 Å/sec in GaAs and about 1000 Å/sec in Al_{0.3}Ga_{0.7}As. Instead of a backside contact, we used a third mask step to apply the Au/Ge/Ni/Au ohmic contact to the device side of the wafer. The processed wafer was cleaved, epoxied, and wire-bonded into a drilled package.

The optical absorption was measured using a white light source. This time the entire wafer was directly illuminated from the back and the device was imaged on the pinhole using an infra-red viewer. The transmission was then normalized to the white light spectrum. To calculate the actual absorption coefficient from the spectra, we took into account partial reflections from the GaAs interface^42. The intensity of the transmitted light, I, is related to R, the reflection coefficient from the interface, t, the thickness of the material, and the absorption coefficient α as shown in equation 4-1:

\[
\frac{I}{I_0} = \frac{(1-R)^2 e^{-\alpha t}}{1 - R^2 e^{-2\alpha t}}
\] (4-1)
Though this method is simple to use, a reliable determination of the zero absorption level requires an extremely accurate value of R.

FIG. 4.6 below shows our results for the QCSE in the InGaAs structure. Despite the large number of wells, the material seems to have remained strained, with a zero field electro-absorption of about 1.2% per well. This is equal to the best that others have observed giving us confidence about the quality of our indium and InGaAs quantum wells. Although there is a large amount of noise in the data and errors in the zero absorption level, the data from the test wafer indicated approximately what absorption levels would be required in the modulator and at what wavelength we should design our cavity.

![Graph showing absorption coefficient vs. wavelength](image)

**Figure 4.6.** Measured electro-absorption in 43 x 100Å/100Å In$_{0.17}$Ga$_{0.87}$As/GaAs QWs at various reverse bias voltages

We then grew the actual modulator structure on an n+ substrate. Using the same cavity structure, we used a 16.5 period back mirror with a calculated reflectivity of 98.9% and a 4
period front mirror with a calculated reflectivity of 75.6%. The higher reflectivity front mirror and the larger number of wells are to compensate for the poorer electro-absorption in the material and to allow us to make use of the higher $X$ values further from the exciton. The quarter-wave layers used in the mirrors were nominally 717 Å/853 Å of GaAs/AlAs. To optimize the material quality of both the mirrors and the wells, we grew the mirrors at a higher temperature of 600 °C and the QWs at a temperature of 500 °C. The processing and measurement steps were identical to the GaAs modulator explained previously.

4.3.2 Results

![Graph](image)

Figure 4.7. Reflectivity as a function of wavelength at various bias voltages for InGaAs/GaAs reflection modulator.

FIGs. 4.7 and 4.8 show the results of the InGaAs/GaAs modulator. From FIG. 4.7, it is clear that the longer cavity and higher reflectivity have decreased the optical bandwidth from the GaAs/AlGaAs modulator case. The measured HWHM is now about 35 Å and the reflectivity modulation is quite good. The reflectivity changes from about 65% at zero bias
to 23% at 20V. Despite the poor electro-absorption, the 42% reflection change and the insertion loss - modulation ratio tradeoff is comparable to GaAs devices reported in the literature (See FIG. 4.9).

![Normalized Reflectivity vs Reverse Bias](image)

Figure 4.8 Normalized reflectivity at the Fabry-Perot mode ($\lambda=10060\text{Å}$) as a function of applied bias in InGaAs/GaAs reflection modulator.

In FIG 4.8 we see a similar behaviour for the reflectivity at the F-P position to the previous modulator. However, the reflectivity does not increase once the exciton has passed the cavity wavelength. This is simply because the excitonic absorption washes out easily at high fields. Since we are working quite far from the zero bias exciton wavelength, the absorption has become quite flat.

To compare the performance of our optimized GaAs/AlGaAs modulator to other reported devices, it is most useful to display the data in the form of FIG.3.7. Once again the solid lines represent the maximum achievable insertion loss modulation ratio tradeoff for a given absorption ratio $X$. We can see from FIG. 4.9. that most of the reported
Figure 4.9: Tradeoff between insertion loss and modulation ratio in optimized reflection modulators for different electro-absorption ratios. The solid lines present the limits, while the points represent fabricated devices. The open circles refer to the references, the filled circles represent our work. The InGaAs/AlGaAs device will be discussed in chapter 5.

devices follow a contour that corresponds to values between X=3 and 5. This is in agreement with Jelley's measured value$^{51}$ in 100Å wide GaAs/AlGaAs wells. We can see that our InGaAs/GaAs device, is not only the first reflection modulator in this material system, but compares favourably with the performance of reported GaAs/AlGaAs devices that utilize the better electro-absorption properties. This demonstrates that proper optimization of the cavity and increasing X by working away from the exciton can benefit the reflective properties. From the figure, we also see that our 50Å GaAs/AlGaAs modulator performs far better than the GaAs/AlGaAs devices due to the larger X in smaller wells.

4.4 F-P Peak and Reflectivity Adjustment

From our analysis so far, it is clear that the modulator operation is very sensitive to the growth parameters. Proper modulator operation requires precise positioning between the
exciton resonance and the cavity mode. Any slight errors in the width of the cavity cause the Fabry-Perot dip to occur at an incorrect wavelength where there is inadequate absorption modulation. The precise value of the exciton absorption is also crucial, since achieving high contrast operation requires matching this absorption to the front mirror reflectivity.

The tight tolerances needed for proper operation have prompted many to seek ways of adjusting an incorrectly grown wafer. A successful method of "trimming" modulator operation is to shift the quantum well exciton position by annealing. With both InGaAs/GaAs and GaAs/AlGaAs devices, high temperature anneals cause mixing between the well and barrier material. Since this averages out the potential of the well and barriers, it raises the exciton to higher energies, blue shifting the absorption. Frequently, these high temperature anneals have the added benefit of smoothing out the interface and improving the material quality. Such an improvement is manifested in a stronger and narrower photo-luminescence peak and is a well established test of material quality. In our group at Stanford we have seen this improvement reflected in lower laser thresholds implying a reduction in non-radiative recombination. The application of this technique is straightforward for modulators. If errors in fabrication cause the F-P dip to occur at an energy higher than desired, the exciton can be shifted by annealing to obtain the correct relative position. Ghisoni et al. used this technique to shift the exciton 52 meV, fabricating both normally on and normally off devices from the same wafer. If the F-P mode is at an energy lower than the exciton, the device has an increasing absorption in wavelength and is normally on, while if the two coincide at zero bias the device has decreasing absorption with field and becomes normally off.

This technique of being able to adjust the Fabry-Perot mode of the cavity after the wafer is grown may also have some relevance to surface-emitting laser structures. In this case the laser threshold depends critically on the relative spacing between the cavity mode
and the exciton gain profile. If growths are inaccurate, there will be too little gain at the F-P mode and the device will not lase.

As an alternative to moving the exciton bandgap by a high temperature anneal, we have developed a process where the cavity mode can be adjusted. In this method we slowly etch the top quarter-wave layer of the top reflector to adjust both the phase change and the reflectivity of the mirror stack. Since the position of the cavity mode depends on this phase change, we are able to tune the wavelength of operation. For relatively long etch depths the reflectivity of the stack is also affected, thereby allowing us to match the reflectivity of the mirror to the cavity absorption to obtain a high contrast device.

### 4.4.1 Calculations

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>No etch</td>
<td>Small etch</td>
</tr>
<tr>
<td>$\theta = 0$</td>
<td>$\theta$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium etch</td>
<td>Almost complete etch</td>
</tr>
<tr>
<td>$\theta$</td>
<td>$\theta \approx 0$</td>
</tr>
</tbody>
</table>

Figure 4.10. Schematic showing the effect of etching the last quarter-wave layer of a multi-layer stack on the reflectivity and the phase.

If a modulator structure is grown correctly with the mirror layers exactly quarter-wave thick, then the phase change from the mirror stacks will be exactly 0° or 180°, depending on whether the index of the cavity material or the first mirror layer is higher. Since some of the wave reaches the furthest interface and is reflected back by the dielectric / air
surface, decreasing the distance to this surface will affect the phase. This is shown schematically in FIG. 4.10.

![Graph showing mirror reflectivity and phase of the reflected wave as a function of thickness.](image)

**Figure 4.11.** Calculated reflectivity and phase of a 5 period GaAs/AlAs mirror stack as a function of the last layer thickness. By etching the last layer, both the reflectivity and the phase of the mirror can be adjusted.

In the figure, the smaller vector represents the contribution to the reflectivity from the last quarter-wave layer. The large thick vector represents the contribution from the rest of the stack. In diagram A, where the thicknesses are correct for maximum reflectivity, both contributions add in phase to give a large total reflectivity, represented by the vector sum of the two components. As some of the last layer is etched off (diagram B), the phase $\theta$ of the total wave changes without a substantial change in the magnitude of the reflectivity. With deeper etches, the magnitude changes rapidly while the phase remains roughly constant. When the top layer is almost completely etched away, we again obtain zero phase shift but at a much smaller reflectivity. The second to last layer, which has now
become the top layer in the structure, acts as a quarter-wave impedance matching layer, minimizing the reflectivity of the stack.

This picture is somewhat simplified and a more exact matrix calculation is required to obtain accurate results. To examine how this etch process would effect a modulator, we performed the matrix calculations summarized in section 3.2.7 on a 5 period GaAs/AlGaAs mirror optimized for 1.0 μm operation. Our results are shown in FIG. 4.11. where we plot the total reflectivity and the phase of the reflected wave as a function of the top layer thickness.

From the figure, we see that our original ideas about the phase and reflectivity changes are confirmed. With nothing etched (thickness = λ/4 = 715 Å), the reflectivity is high and the phase zero. If we etch a small amount, we get fairly large changes in phase without substantial changes in reflectivity. For longer etches, the reflectivity begins to decrease rapidly while the phase change has reached a maximum. Finally, for the deepest etches, the phase returns to zero while the reflectivity reaches a minimum.

4.4.2 Experimental Verification

To experimentally verify these ideas, we used a dilute 3:1:250 H₃PO₄:H₂O₂:H₂O solution where the measured etch rate was 75 - 85 Å/min in GaAs. We then cleaved a very small section of our InGaAs/GaAs modulator wafer and indium bonded it to a gold mirror (evaporated gold on glass). We measured the reflectivity on this bonded sample as described previously. The device was then etched in the solution for 2.5 minutes, rinsed and remeasured. We calculated this time to be enough to shift the F-P dip but not to significantly alter the reflection characteristics. Data for before and after the etch are shown in FIG. 4.12.
Figure 4.12  The results of removing about 175 Å from the top mirror stack of the InGaAs/GaAs modulator. The position of the F-P dip has shifted about 45 Å without appreciably changing the reflective properties.

One can see that this is a simple and effective technique to adjust a modulator whose operating wavelength as grown is slightly off. Although we shifted the operating wavelength by 45 Å, we only changed the reflectivity modulation $\Delta R$ from 49% to 52%. Note also that this method gives a blue shift to the F-P wavelength, moving it closer to the exciton. The annealing procedure explained earlier, causes a blue shift in the exciton, increasing the separation between the F-P wavelength and the exciton. Therefore the two methods are complementary, with each being useful in one situation.

With small etches, only the phase is affected, blue shifting the cavity mode. Using longer etch times should substantially affect the front mirror reflectivity as well as changing the phase. To investigate the effects of this reflectivity change, we used this method on a modulator wafer that had been grown incorrectly with the F-P mode far too close to the exciton. The structure of this wafer was similar to the previous InGaAs/GaAs wafer described in section 4.3 except that we used a 5 period front mirror and 45 wells. A 4
minute etch in the same etchant allowed us to raise the contrast ratio in this device from 3.9 to 22.

The reflectivity data of this modulator before and after the etch are shown in FIG. 4.13 A) and B) respectively. In this case the front mirror was too reflective. Errors in fabrication had placed the F-P mode too close to the exciton where the absorption is very high. Consequently the device was working to the left of the matching condition (see FIG. 3.6). As the exciton is redshifted with bias into the F-P dip, the absorption increases, moving the device further from the matching condition and increasing the reflectivity. Once the exciton has moved all the way through the F-P dip, the reflectivity drops again. Refractive index changes that accompany these absorption changes move the F-P dip appreciably, as the finesse of the cavity, indicated by the sharpness of the F-P dip, is quite high.

After a 4 minute etch, the front mirror reflectivity had dropped considerably. The phase change has also placed the F-P dip directly on top of the exciton. These two effects, though partially cancelling out, led to the matching condition being satisfied and reducing the reflectivity at zero bias. Now, as the exciton is redshifted, the reflectivity increases giving us a normally-off modulation characteristic.

Figure 4.13. 4 minute etch test results on another InGaAs/GaAs modulator. Plot A is before, and plot B after the etch. The contrast ratio has been increased from 3.9 to 22.
Though the effects of this technique in tuning the cavity are complicated to compute, the results can be quite impressive. The computational difficulty arises from the simultaneous change of phase and reflectivity. The interaction between the two characteristics are further complicated by the wavelength dependence of the excitonic absorption. The F-P mode sees a different cavity absorption if moved to a different wavelength.

The ability to change the cavity mode and modify the reflectivity depends on the size of the cavity and the initial reflectivity of the mirror. The smaller the size of the cavity, the more significant the phase change, and the further the cavity mode can be shifted. If the mirror stack is very large, this effect is reduced as the proportion of the light reaching the top interface is smaller. We would therefore expect this technique to be most useful for short cavity devices with small front mirror reflectivities. Detailed calculations are required to estimate the effects on a particular cavity design.
5. InGaAs/AlGaAs Electro-Absorption

Although using our optimization procedures enabled us to achieve good modulator performance characteristics from the rather poor electro-absorption in InGaAs/GaAs, we did not address the question of why the electro-absorption is poor in the first place. Even in the case of dislocation-free material, the exciton is smaller in InGaAs/GaAs wells and resonance is washed out easier with field than with similar GaAs/AlGaAs QWs. Comparing the best data for \( \Delta \alpha \) in 100\AA\ wells, the InGaAs/GaAs value\(^{70} \) of about 4,000/cm is much smaller than the 11,000/cm value in the GaAs/AlGaAs system\(^{51} \).

These two properties, the smaller exciton absorption and the quicker suppression of the resonance with field in InGaAs/GaAs, implied a reduction in the quantum confinement. Comparing QW excitonic features to those in the bulk, we get the same general trends. The presence of barriers tends to sharpen the excitonic features of bulk material and sustain the resonance at high fields. We therefore investigated the effects of increasing the barrier height in InGaAs/GaAs by adding aluminum to the barrier regions. Extending the trends from the bulk material, we would expect the higher barriers to increase the confinement and lead to more prominent excitonic features.

In general InGaAs/AlGaAs QWs are not used in devices. This is for two reasons: the poor quality of the InGaAs/AlGaAs interface and incompatible growth temperatures. The AlGaAs material is itself generally considered poor, and in many devices if one can reduce the fraction of aluminum, the characteristics improve. The reactive nature of the aluminum makes the AlGaAs particularly prone to traps and defects. Also, one would expect a high scattering rate from the InGaAs/AlGaAs interface since both materials are ternary alloys. The growth temperature problem, more severe with MBE than with MOCVD, has also discouraged InGaAs/AlGaAs growth. With MBE growth, the material quality of AlGaAs is quite poor unless grown at a high temperature where control of growth is complicated by gallium desorption from the wafer surface. InGaAs, however, cannot be grown at such
high temperatures since the indium desorbs easily with heat. Consequently, the growth temperature would need to be ramped at the QW interfaces and a few monolayers of GaAs added after the InGaAs growth to prevent the indium in the well from desorbing. These monolayers would reduce the quantum confinement effects of the AlGaAs barriers, while the relatively long interruption in the growth to adjust the temperature would increase the absorption of impurities from the background.

These basic notions of material quality, along with a few experimental validations\textsuperscript{38}, have discouraged work with the InGaAs/AlGaAs material system. Consequently, although there is a plethora of papers characterizing InGaAs/GaAs\textsuperscript{36,37,39,40,68,69,71} strained layers, only a few that deal with InGaAs/AlGaAs QWs\textsuperscript{38,76}. We speculated that since the absorption properties are less sensitive to material quality, as evidenced by the performance of GaAs/AlGaAs QW absorption modulators grown on heavily dislocated GaAs on Si material, that in an absorption device more may be gained from raising the barrier heights using AlGaAs than suffered through material problems.

5.1 Calculations.

We first theoretically investigated the effects of the quantum well barrier heights on the optical absorption. We restricted ourselves to working within the approximations of effective mass theory and envelope wavefunctions. We first derive an equation determining the optical absorption of excitons. Then, the excitonic wavefunction for In\textsubscript{0.2}Ga\textsubscript{0.8}As/Al\textsubscript{x}Ga\textsubscript{1-x}As is calculated and we compute the absorption coefficient at zero field as a function of the aluminum concentration. Our approach is similar to that taken by Miller\textsuperscript{45} and Bastard\textsuperscript{43} in similar calculations.

5.1.1 Basic Theory

From elementary quantum mechanics we know that in the presence of electro-magnetic radiation, the mechanical momentum operator \( \hat{P} \) for a particle of charge, \( e \), becomes
\( (\hat{P} + \frac{\mathbf{e}}{c} \mathbf{A}) \), where \( \hat{P} \) is the canonical momentum operator \( \hat{P} = -i \hbar \nabla \), \( \mathbf{A} \) is the vector potential of the e-m wave, and \( c \) is the speed of light. Thus the Hamiltonian becomes:

\[
\hat{H} = \hat{H}_0 + \frac{e}{2m_c} [\hat{P} \mathbf{A} + \mathbf{A} \cdot \hat{P}]
\]  

(5-1)

where \( \hat{H}_0 \) is the Hamiltonian in the absence of the field. Note that we have dropped the smaller second order terms and are treating the vector potential as a classical field. Using plane wave formalism for a monochromatic and plane polarized e-m wave (as in eq. 3-1), it is simple to show from the definition of the vector potential that

\[
\mathbf{A} = -\frac{e}{2i \omega} \frac{E_0}{c} \left[ e^{(\mathbf{\omega} \cdot \mathbf{r})} - e^{-(\mathbf{\omega} \cdot \mathbf{r})} \right]
\]  

(5-2)

The polarization vector of the e-m wave is denoted by \( \mathbf{e} \), the propagation vector by \( \mathbf{q} \), and the magnitude of the electric field by \( E_0 \). Putting eq.(5-2) into eq. (5-1) we get the perturbation potential to be

\[
\hat{V} = \frac{i e E_0}{4 m \omega} [\mathbf{e} \cdot \hat{\mathbf{p}} + e^{i \mathbf{q} \cdot \mathbf{r}} e^{-i \mathbf{q} \cdot \mathbf{r}} \mathbf{e} \cdot \hat{\mathbf{p}}] = \frac{i e E_0}{2 m \omega} \mathbf{e} \cdot \hat{\mathbf{p}}
\]  

(5-3)

The approximation is valid because the photon wavevector \( \mathbf{q} \) is very small (the wavelength is large) compared to electronic dimensions and we can ignore the exponential terms in the equation. Now that we have the perturbing term, we can compute the probability of a transition \( |i\rangle \rightarrow |f\rangle \) per unit time of an electron in the initial state, \( |i\rangle \), going to a final state, \( |f\rangle \), using the Fermi Golden Rule:

\[
P_{if} = \frac{2 \pi}{\hbar} |\langle f|\hat{V}|i\rangle|^2 \delta(E_f - E_i - \hbar \omega)
\]  

(5-4)
The matrix element $\langle f | v | i \rangle$ between the initial and final states of an electron in a solid is difficult to compute rigorously. However, using the envelope approximation, we assume that the actual wavefunction is given by the product of a rapidly changing Bloch wave at the zone center $u_v(\mathbf{r})$, and a slower changing envelope function $f(\mathbf{r})$, where the subscript $v$ for the Bloch wave denotes the band occupied by the electron. From eq. 5-3, we see that the perturbing potential is simply a constant times the momentum operator. Since this operator is simply a spatial derivative of the wavefunction, we can use the product rule to express $P_{if}$ as two terms.

$$
P_{if} = \text{const} \int u_v f \nabla u_v f \, d^3r = \text{const} \left[ \int u_v u_v f_if_r \, d^3r + \int f_if_r u_v u_vf_r \, d^3r \right]$$  \hspace{1cm} (5-5)

Since the Bloch waves vary rapidly compared to the envelope wavefunctions, we can take them out of the integral and integrate them separately. In the case where the initial and final bands are the same ($v_i=v_f$), such as a transition from the $n=1$ to $n=2$ state in the conduction band, then the second term will be zero because the expectation value for the momentum at the zone center is zero. If the transition occurs between separate bands, then the first term will be zero due to the orthogonality condition between the bands. The matrix term in this case will be proportional to the overlap integral of the initial and final electron envelope wavefunctions.

Rigorously computing the exact exciton wavefunction is also very difficult. We shall take a variational approach where we assume the exciton wavefunction is a product of the 1D electron and hole wavefunctions in the $z$ direction, multiplied by a hydrogenic 1-s wavefunction dependence in the $x$-$y$ plane.

$$\Psi_{\text{exciton}} = N \chi_e(z_e) \cdot \chi^h(z_h) \cdot e^{-\sqrt{x^2+y^2}/\lambda}$$  \hspace{1cm} (5-6)
where $N$ is a normalization constant and $\lambda$ is a variational parameter. It is simple to show that the exciton radius in the x-y plane, defined as $\sqrt{x^2 + y^2}$, is $\frac{3}{2} \lambda$. Eq. 5-6 is only valid for small quantum wells. However, if our quantum wells become larger and approach the size of the exciton in bulk, we need to put a $z$ dependent term in the exponential of eq. 5-6. The $\chi$s are the simple 1D solutions to the electron and hole wavefunctions, and they can be numerically calculated using the well known transmission matrix method. To find the approximate wavefunction, we calculate the expectation value for the exciton energy and minimize that value with respect to $\lambda$. The expectation value for the exciton energy is

$$<\psi|H|\psi> = <\psi| - \frac{\hbar^2}{2\mu} \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) - \frac{e^2}{K(x^2 + y^2 + (z_e - z_h)^2)^{1/2}} |\psi>$$

(5-7)

where $\mu$ is the reduced mass of the electron-hole pair and $K$ is the dielectric constant of the material. The first term in the potential is the kinetic energy and the second term is the potential energy of the exciton. We have ignored the confinement energy of the electron and hole due to the quantum wells since they are a constant and independent of $\lambda$.

Inserting the variational form for the wavefunction to equation 5-7, we get a number of terms out of the integral. The kinetic energy integral can be expressed in closed form, but the potential energy term cannot. However, we can express this second term as a sum of $Y_1$, the first order Bessel function of the 2nd kind and $H_1$, which is the Streuwe function.

$$<\psi|H|\psi> = \frac{\hbar^2}{2\mu \lambda^2} - \frac{4e^2}{K\lambda} \int \int \chi^{e2} \chi^{h2} \left( \int_0^{\infty} \frac{r e^{-2r}}{\sqrt{r^2 + (\frac{z_e - z_h}{\lambda})^2}} \ dr \right) dz_e dz_h$$

(5-8)
\[ \int_0^\infty \frac{r e^{-2r}}{\sqrt{r^2 + a^2}} \, dr = a \left\{ \frac{\pi}{2} [H_1(2a) - Y_1(2a) - 1] \right\} \]

Minimizing \( \lambda \) as a function of energy, we obtain an expression for the exciton. The matrix element and \( P_{if} \) can now be calculated from eqs. 5-4 and 5-5. To convert \( P_{if} \) to an absorption coefficient we take into account the 2D density of states and use energy considerations. We can also model the broadened exciton peak by replacing the delta function by a Gaussian with a width \( \Gamma \). Going through the math we obtain:

\[ L \alpha_{\text{peak}} = \frac{4 \pi e^2 E_p}{n c m_0 \omega \lambda^2} \left| \langle \chi^e | \chi^h \rangle \right|^2 \frac{1}{\Gamma \sqrt{2}} \]

(5-10)

where \( E_p \) is the matrix element between the electron and hole states in the material that comes out of eq. 5-5. It is calculated for different materials and is about 23eV in GaAs. \( n \) is the refractive index of the material, \( m_0 \) the mass of a free electron, and \( L \) is the width of the well. The important result is that the absorption is proportional to the square of the 1D overlap integral and inversely proportional to \( \lambda^2 \). Note also that if we assume \( \lambda \) and the overlap are independent of well width, then the right hand side of the equation is a constant and the absorption coefficient \( \alpha \) is inversely proportional to the well width. This explains why in chapter 4 we achieved larger absorption changes in a 50 Å well than in a 100 Å well.

5.1.2 Exciton Calculations

To estimate the absorption coefficient of the QWs, we first needed to calculate the 1D wavefunctions for the electron and holes, \( \chi_e \) and \( \chi_h \). Analyzing the case for 75 Å In\(_{0.2}\)Ga\(_{0.8}\)As/AlGaAs quantum wells, we wrote a numerical program in Pascal to implement the transfer matrix technique\(^7\). The algorithm computed the transmission
coefficient at energies below and above the peak. By iteratively bisecting this energy range, the program approached the maximum value corresponding to the energy of the confined level. The form of the wavefunction could then be calculated.

Once we had the normalized electron and hole wavefunctions, their overlap was simple to evaluate. Another Pascal program was written to numerically solve the two-dimensional integral expressed in eq. 5-8 and 5-9. Fortunately, we had a math library associated with the Pascal compiler that gave us numerical values for the Bessel and Streuve functions. We then looked at the output of this program and found the value of $\lambda$ at which the energy was minimized. The absorption coefficient could then be calculated from the overlap integral and our value for $\lambda$.

The calculations are somewhat sensitive to the values used for the band offsets and the effective masses. For the bandgap, we used eq. 2-4, which is the bulk bandgap adjusted for the strain using deformation potentials. As explained in chapter 2, there is no general consensus for the band offsets, however a 65%-35% rule is frequently used. For the effective mass in the growth direction, as in other previous calculations, we neglected the effect of strain and interpolated between bulk values. The value for the hole mass in the x-y plane is not as simple. The imposed potential in the growth direction mixes the various hole bands and gives an anomalous dispersion in the x-y plane. In some GaAs/AlGaAs wells, calculations predict a negative transverse effective mass at the top of the valence band. Somewhat surprisingly, the strained material is easier to analyze. The effect of the strain is to raise the light hole to higher energies, which reduces this band mixing drastically. In the first approximation, this permits us to neglect the bandmixing altogether and use the Luttinger parameters to compute the transverse mass. This simple technique yields $m=0.0754m_0$. Direct measurements using cyclotron resonance and Shubnikov-de-Haas (SDH) yielded experimental values of 0.09$m_0$ and 0.19$m_0$ respectively. Other calculations have used masses anywhere in this range. We decided to use a value of 0.1$m_0$, which gives a reduced mass of $\mu=0.038m_0$. 
The solid line in FIG. 5.1 expresses our theoretical results. Since the value for the width of the exciton resonance peak (\( \Gamma \)) is unknown, we plot the total absorption times \( \Gamma \). From our analysis, we would expect an increase of nearly 30% in the peak absorption at zero bias by going to 40% aluminum in the barriers. Though we did not repeat the calculations for biased cases, we would expect the percentage increase to be larger than for the unbiased case. The electric field would tend to lower the confinement since the electron and hole would be forced in opposite directions. The confining effect of the higher barriers would then be more significant.

5.2 Experimental Results

To check the predictions of our calculations, we grew three multi-quantum well samples with different aluminum concentration in the barriers. The samples were grown by MBE on semi-insulating GaAs substrates at about 500 °C. After growing a 1 \( \mu \)m thick n-doped contact region, doped at \( 10^{18} \) cm\(^{-3} \), twenty undoped 75Å In\(_{0.2}\)Ga\(_{0.8}\)As QWs were grown using 200Å Al\(_x\)Ga\(_{1-x}\)As barriers with \( x = 0, 0.15, \) and 0.33. On top of the undoped quantum wells, a 0.5\( \mu \)m thick p-doped region was added to complete the p-i-n structure. The reason for the large barrier widths is to insure that the material remains strained with negligible coupling between the wells.

The wafers were processed and measured in a similar way to previous occasions (see section 4.3.1). We etched down, forming mesas, and contacted the n-doped layer with an alloyed contact. The top p-type contact was annular to allow optical probing. After packaging, the measurements were taken with a white light source and 1/2 meter spectrometer using lock-in techniques.

Because of the built-in field of the diode, we could not achieve the zero field case experimentally. However, since the cavity length is quite large and as the exciton shape and position change slowly with field at small bias, we neglected these effects in the comparison with the calculations done at zero electric field. The width of the exciton is
measured at zero bias and compared to the calculations. In absolute terms, with no fitting parameters, our experimental data was only 20% different than the calculations. Given the large errors in the material parameters, especially in the value of $E_p$, we consider the agreement very good. With the uncertainties in $E_p$, we felt justified to scale our experimental results and compare the relative increase in exciton size with aluminum composition to the theoretical values. These are plotted as the open circles in FIG. 5.1. The error bars in the experimental data arise due to the difficulty in differentiating the exciton absorption from the absorption due to transitions into the continuum.

![Graph](image)

**Figure 5.1:** The exciton absorption as a function of aluminum concentration in the barriers. The y-axis is the exciton width $\Gamma$ times the peak absorption $\alpha$ times the well width $L$. Since the experimental data has been scaled, only the relative increase is significant.

We see close agreement between the theory and the experiment at zero bias, with the magnitude of the exciton absorption increasing with the aluminum concentration in the barriers. As an electric field is applied, the higher barriers also prevent the dissociation of
FIG. 5.2: Experimental plots of absorption versus wavelength for various reverse bias voltages. The samples consisted of $20 \times 75$ Å In$_{0.2}$Ga$_{0.8}$As quantum wells with 200 Å Al$_x$Ga$_{1-x}$As barriers in a p-i-n diode configuration. Plots a, b, and c are for $x=0$, 0.15, 0.33 respectively.
the exciton, thus maintaining the resonance at higher fields. This is confirmed in FIG. 5.2, where the absorption versus wavelength of the three samples at various reverse bias voltages is shown. The higher aluminum concentration allows us to shift the exciton to longer wavelengths without losing the resonance. For comparison, we can see that for a 150Å shift, the absorption remains three times as strong in the high aluminum sample compared to the InGaAs/GaAs sample. To evaluate the quality of the material, we also performed low-power 77 K photo-luminescence on the samples. The luminescence decreased by a factor of 75 in the sample with 15% aluminum in the barriers and by a factor of 130 for the sample with the 33% aluminum compared to the InGaAs/GaAs sample. Presumably this is due to the poor quality of AlGaAs grown by MBE at such a low temperature. So although using high aluminum barriers severely degrades the luminescence, it greatly improves the absorption properties.

5.3 InGaAs/AlGaAs Modulator

To exploit this superior electro-absorption in InGaAs / AlGaAs, we constructed a reflection modulator similar to our previous designs. The modulator was grown on an n-type substrate with an n-doped 18.5 period back mirror of GaAs/AlAs and a top 5 period p-type mirror of the same composition. The cavity consisted of 30 quantum wells, each with 75 Å In_{0.2}Ga_{0.8}As wells and 200 Å Al_{0.33}Ga_{0.67}As barriers. The device was processed and characterized in the same manner as previous modulators(see section 4.2). FIG. 5.3 shows the reflectivity versus wavelength of the modulator at different reverse bias voltages. We measured a maximum reflectivity change of 77% at the Fabry-Perot wavelength of 10255 Å and a contrast ratio of 37. This is by far the largest reflection modulation ever reported in such a device. Since the reflection modulation can be simply related to the absorption changes in the quantum wells, we attribute the superior performance of our device to the large absorption changes in this material system.
Figure 5.3. Normalized reflectivity as a function of wavelength for modulator incorporating 30 x 75Å In_{0.2}Ga_{0.8}As/Al_{0.33}Ga_{0.67}As QWs for various reverse bias voltages.

Although we have clearly shown that the excellent electro-absorptive properties of InGaAs/AlGaAs allow large modulation to be obtained, this material system may have some disadvantages compared to the GaAs/AlGaAs system. The larger barrier heights in this system will probably lower the saturation intensity of the modulator as the carriers have more difficulty tunneling out of the wells and being collected at the contacts\(^{46}\). The longer time delay associated with this tunneling slows the photocurrent generation and may slow the operation of Self Electro-optic Effect Devices (SEEDs) that rely on photocurrent feedback\(^{83}\). The operating voltages may also be higher in these structures due to the thicker barriers than in lattice matched systems. The 200 Å barriers used in this modulator are thicker than necessary and were chosen to permit comparison with an earlier test wafer. However, in general, barriers must be thick enough in this strained system to prevent lattice relaxation due to the large average indium concentration in the strained quantum wells. As we discussed earlier, such uncontrolled relaxation broadens and reduces the exciton resonance, thereby severely degrading performance\(^{71}\).
In this chapter, we have shown both theoretically and experimentally that adding aluminum to the barriers in the InGaAs/AlGaAs system greatly improves the electro-absorption characteristics, in spite of its clear degradation of carrier lifetime and increase in trap density. We have used such optimized wells to fabricate a reflection modulator with the largest reflectivity change reported to date.
6. Normally-off and Bistable Modulators

6.1 Operating Principles

Unlike ferro-electric modulators, such as lithium niobate waveguide switches, the semiconductor modulators discussed in the previous chapters can also operate as detectors. Since they are reverse biased p-i-n diodes, they generate photocurrent in response to external optical signals. No light is reflected and nearly 100% efficiency is obtained when the matching condition is satisfied. This is particularly interesting for optical interconnect schemes, since the modulator can both as a transmitter and a receiver.

Soon after the discovery of electro-optic effects in quantum wells, Miller et al. realized that using the photocurrent to control the reflectivity of the device can lead to interesting characteristics\textsuperscript{24}. The normally-on modulators discussed so far exhibit decreased reflectivity with applied bias. Decreased reflectivity causes increased photocurrent since more light is absorbed in the cavity. If we use a resistor as the feedback element (FIG. 6.1), for a normally-on modulator we obtain negative feedback that tends to stabilize the reflected light. If the incident light intensity increases, the photocurrent also increases. This causes a larger voltage to be dropped across the resistor, thus reducing the bias on the modulator and decreasing its reflectivity and hence reducing the intensity of the output beam.

![Modulator bias circuit](image)

Figure 6.1: Modulator bias circuit.
More interesting operation can be obtained with a normally-off modulator. In such a device, the reflectivity increases with applied bias, decreasing the light absorbed and thus the photocurrent. Since the photocurrent decreases with the bias, the device exhibits negative differential photoconductivity, a downward slope in the I-V curve. Such negative resistance effects lead to unstable regions which may be utilized to form bistable devices. The characteristics of such a structure are shown in FIG 6.2. Biased in the same way as before, an increase in the light input and photocurrent initially reduces the voltage on the device. The reduction causes the device to become less reflective. The lower reflectivity implies a higher absorption and photocurrent. Therefore we get positive feedback that causes switching in the device. A modulator with this form of bistable operation has generally become known as a SEED (self electro-optic effect device).\footnote{\textsuperscript{84}}

![Graph showing SEED characteristics](image)

**Figure 6.2:** SEED characteristics when biased with an external resistor.

The bistability allows the device to act as a latch or memory. If it is optically biased in the hysteresis region, a high power optical pulse will set the device in the non-reflective mode while a negative pulse in the bias will force it into the reflective mode. In this case the intensity required for the switching action depends on the external resistor and bias. Since the modulator does not generate any light, the reflected beam is always weaker than the incident light. Therefore the device is not cascadable.
The input-output characteristics improve if another normally-off modulator is used as the load instead of a resistor. This configuration is known as a S-SEED (symmetric-SEED), which can be cascaded since the state of the device does not depend on the absolute intensity of the light, but on the ratio of the intensities falling on the two devices. As a rough approximation, we can consider one of the devices to act as a resistor whose value depends on the amount of incident light. If the illumination on this device is varied, we change the amount of light required to switch the other device. This leads to what Miller calls "time-sequential gain." We can write the state of the latch with two low power beams, for example 1mW and 2 mW. With the devices set in a particular state, we can use high power beams of for example 1 W falling on both devices to read the state. The state of the device will not be affected by this high power reading beam as equal intensities are shining on both devices. Since the state of the S-SEED will modulate this 1W beam, smaller signals of 1 and 2 mW have modulated a 1W signal. In practice the gain is limited by the device leakage currents and saturation intensities.

As mentioned in chapter 1, this bistable nature of the S-SEED and its cascadability has inspired considerable investigation into its use for optical computers. Numerous articles deal with the properties in detail. The most important characteristic to notice is that the bistability is a simple result of the negative differential photoconductivity arising out of the normally-off characteristic.

Conventionally, such normally-off transmission or reflection modulators are designed to work in region A of FIG. 2.4. Thus the operating wavelength, or the F-P dip, is designed to be on the zero bias exciton resonance. When this peak is shifted with bias using the QCSE, the absorption is reduced and the reflectivity increases. However, operating in this region leads to low absorption ratios (X). Although the exciton has been shifted to longer wavelengths, there still remains a large residual absorption caused by transitions into the quantum well continuum which tends to lower performance, generally increasing the insertion loss in the on-state.
This problem of large residual absorption has prompted many to investigate methods of blue shifting the optical absorption with field. In one experiment, the wells were pre-biased by an intrinsic field caused by a misfit generated piezoelectric effect in $<111>$ InGaAs/GaAs. Thus an applied bias reduces the field and causes a blue shift in absorption. More common have been efforts to obtain blue shifts from coupled quantum wells.

6.2 Wannier-Stark Effect

6.2.1 Band Structure

One method of obtaining blue shifts in the quantum well absorption is known as the Wannier-Stark effect. When the barriers between quantum wells (QWs) are made sufficiently thin, the discrete energy levels of the QW broaden to form a miniband and the optical absorption edge occurs at the bottom of this miniband. Under an electric field, the energy degeneracy between the wells is broken and discrete levels are obtained. Since each discrete level lies approximately in the center of the previously existing miniband, the optical absorption suffers a blue shift of about half the miniband width.

![Figure 6.3: Energy band diagram illustrating the Wannier-Stark effect: The applied electric field in coupled quantum wells breaks the energy degeneracy between wells and the miniband shrinks to a discrete state. The optical absorption that occurred to the bottom of the miniband is shifted to a higher energy. There is a consequent blue shift in absorption.]
This simple picture is somewhat complicated by the presence of different types of excitons. In the zero field case, there is an M0 exciton present at the bottom of the miniband. Since the electron state is spread over many wells, the binding energy of the M0 exciton is quite small, and it forms a small resonance at the absorption edge. However, at the top of this miniband, a negative effective mass along the growth direction produces a Van Hove M1 singularity which leads to a two dimensional exciton with a larger binding energy of about 15 meV\textsuperscript{92}. This leads to a sharper resonance in absorption one binding energy below the top of the miniband. An applied electric field localizes the electron states to form decoupled QWs, and we retrieve the QW exciton. Since the barriers are thin, there is still some overlap between the electron and hole wavefunctions of adjacent wells, and small peaks in absorption should be expected at roughly +/- eF D, where F is the electric field, and D is the period of the superlattice. These are caused by transitions into adjacent wells.

Although this Wannier-Stark localization had been observed both in GaAs/AlGaAs\textsuperscript{92,93} and InP based material systems\textsuperscript{90}, there had been no report of this in the strained InGaAs/GaAs superlattices at room temperature\textsuperscript{94}. Though Niki et al.\textsuperscript{95} examined electroabsorption in this material system, only a shift similar to the Franz-Keldysh effect was reported, presumably because their miniband was too wide to allow localization.

We used our transmission matrix program, explained in chapter 5, to analyze the miniband in this material. Since the barrier heights are smaller, longer well and barrier dimensions are needed in order to prevent the coupling from getting too large. We attempted to grow an optimized sample with usable blue shifts in InGaAs/GaAs material\textsuperscript{96} keeping in mind the importance of blue shifts for SEED devices.

6.2.2 Growth Structure

The sample consisted of 150 periods of 50 Å In\textsubscript{0.2}Ga\textsubscript{0.8}As wells separated by 40 Å GaAs barriers. The superlattice was grown at about 520 °C by MBE on a semi-insulating
substrate. A 1μm thick 10^{18} \text{ cm}^{-3} \text{ Si doped n-type contact layer was first grown followed by the undoped superlattice and a two step 0.5 μm p-type Be doped contact layer, the first half of which was doped at 10^{18} \text{ cm}^{-3}, and the second half at 10^{19} \text{ cm}^{-3}. The device was processed and measured in the standard way (see section 4.3.1). FIG 6.4 is a diagram of our fabricated device, and FIG. 6.5 shows the results of the optical absorption measurements.

![Diagram of device structure](image)

Figure 6.4: Schematic diagram used for room-temperature optical transmission experiment.

6.2.3 Results

Although each 50Å quantum well is below the Matthews-Blakeslee critical thickness, for such a thick superlattice one might expect some relaxation through dislocations. As we discussed in chapter 2, at present there is no good theory to predict the critical thickness for an entire superlattice, and there is good evidence that one can grow pseudomorphic superlattices many times thicker than the Matthews-Blakeslee limit for the average indium concentration in the entire superlattice.\textsuperscript{39,68,71,95} Clearly, in our wafer, dislocations did not prevent us from seeing the Wannier-Stark effect. Computing the expected absorption edge for strained and relaxed material, we find the observed data to correspond closely to
the strained value. Nomarski microscopy also showed very little evidence of the characteristic cross-hatch pattern that is typical of relaxed InGaAs superlattices. We would therefore tend to believe that dislocations did not play a major role in the experiment.

![Absorption Spectrum](image)

Figure 6.5. Absorption spectrum of In$_{0.2}$Ga$_{0.8}$As (50Å)/ GaAs (40Å) superlattice measured at room temperature: (a) was obtained with the device open circuited, which under illumination corresponds to electric field $F=5$ KV/cm, (b) corresponds to -3V applied bias, or $F=32$KV/cm, (c) corresponds to -6 V, or $F=54$ KV/cm, (d) corresponds to -21 V or $F=165$ KV/cm. Plots (b), (c), and (d) are displaced by 3000, 6000, 9000 cm$^{-1}$ respectively for clarity. The "+1" and "-1" mark peaks due to transitions between adjacent wells.

Our results are in general agreement with theory. Qualitatively, FIG. 6.5 is similar to the previous results obtained in the GaAs/AlGaAs system $^{92}$, except the M$_0$ exciton is better defined, and since the strain lifts the light hole to higher energies, only the peaks due to the heavy hole transitions are observed. Using the values of Reithmaier et al. $^{38}$ for band discontinuities, strain, and effective masses, transmission matrix calculations predict the presence of an electron miniband about 35 meV wide at zero field. Although we cannot probe the zero field case experimentally, the built-in field of the diode can be reduced by
applying a small forward bias, or utilizing the self bias created by leaving the terminals open circuited under illumination. In the latter case, the built-in field decreases to approximately 5KV/cm, which effectively reduces the miniband width to about 21 meV. We would expect the separation between the M0 and the M1 exciton when the device is open-circuited to be a little less than this value since the M1 exciton has a larger binding energy by about 8 meV. The measured separation of about 20 meV seems a little too large, but the difference is not significant considering the sensitivity of the theoretical values to the physical parameters, the width of the peaks at room temperature, and possible non-uniformities between the wells. The expected blue shift should be half the effective miniband width plus the M0 exciton binding energy minus the QW exciton binding energy, minus any Stark shift. Since the QW exciton binding energy is about 10 meV, we would expect a total blue shift of about 3-5 meV, in close agreement with the measured value of approximately 5 meV. The position of the accompanying Stark shifts and the +1 and -1 transitions can also be checked simply and are close to the expected values. At high fields this Stark shift is very prominent and leads to a normalized absorption change $\Delta\alpha/\alpha$ of about 3 at 1.25 eV.

Although we were able to successfully observe the Wannier-Stark blue shift in InGaAs/GaAs, the blue shifts are not very large. This is because the band gap discontinuity in the material is small, so the initial miniband caused by the quantum coupling cannot be made very large. A possible solution would be to use the InGaAs/AlGaAs material system discussed in the previous chapter.

As we have already mentioned, the Wannier-Stark effect has been observed in GaAs/AlGaAs, and used to make a high contrast normally off modulator. However, even with the more prominent blue-shifts obtained with GaAs/AlGaAs, the absorption changes are small compared to the QCSE redshifts. Consequently, the best modulators so far are of the normally-on type.
6.3 Novel Cavity Design

From our analysis in chapter 3, it is clear that a normally-off modulator can be designed using an increase in absorption rather than a decrease, which has been the basis of prior designs. The possibility of such a cavity design was noticed by Boyd et al.\textsuperscript{52}, quoting earlier work. In fact, one of the early modulators nominally based on index changes, actually worked mostly due to this effect\textsuperscript{56}, where raising absorption increased the reflectivity. To make such a modulator with high contrast, the matching condition must be satisfied at $\alpha_{\text{min}}$ instead of $\alpha_{\text{max}}$. From FIG. 3.5, it is clear that with high front mirror reflectivities, about the same level of performance can be obtained in this type of cavity structure as with the conventional structure that satisfies the matching condition at $\alpha_{\text{min}}$. The only penalty to this new structure is that the optical bandwidth will be reduced due to the effect of a higher $R_f$. We can use eq. 3-19 to compute the optical bandwidth as a function of $R_f$ and cavity length. Eq.3-13 gives us the insertion loss as a function of $R_f$ and $X$. Using the matching condition and the QCSE parameters from Jelley's data for 50Å GaAs wells / 75 Å AlGaAs barriers, we can plot the trade off between optical bandwidth and insertion loss ($X=7$, $\lambda_0=830$nm, $n=3.5$, $n_h=3.33$, $n_l=3.0$, $\alpha_{\text{max}} = 10,000$ /cm). This plot is shown in FIG. 6.6.

On the left side of the plot, the optical bandwidth decreases with $R_{\text{on}}$. This is because we are operating in a regime where the optical bandwidth is dominated by the effect of the mirrors. If we try to obtain a lower insertion loss by going to a higher $R_f$, the optical bandwidth is reduced. With metal mirrors instead of semiconductor quarter-wave stacks, this decrease at larger $R_{\text{on}}$ would not occur, as the phase change from a metal mirror is not wavelength dependent. Using metal mirrors, the optical bandwidth would slowly increase reaching a maximum of about 45 Å. On the right side of the plot, both the on-state reflectivity and the optical bandwidth decrease. Clearly nothing is gained by working in this regime. In this case, the optical bandwidth is being limited by the size of the cavity. Metal mirrors would have little effect at these cavity lengths.
Figure 6.6: Trade off between optical bandwidth and on-state reflectivity in the novel cavity modulator. We match the front mirror reflectivity to the minimum cavity absorption for a normally-off modulator. Values for the QSCE in 50 Å wells/75Å barriers have been used.

6.3.1 Experimental Modulator

To demonstrate this concept, we optically coated the front surface of the previously fabricated 50Å/75Å GaAs/AlGaAs modulator (see section 4.2.3). We modified the modulator by adding three periods of SiO₂ / TiO₂ quarter-wave layers increasing the front mirror reflectivity from 50.3% to an estimated value of 93%. This value was chosen to approximately match the effective back mirror absorption Rₐ at zero bias. Since the optical coating was applied to the entire wire-bonded package, no further fabrication steps were necessary. The reflectivity was measured in the same manner as before using a white light source and a 1/2 meter spectrometer (see section 4.2.3).

FIG. 6.7 shows the total device reflectivity as a function of wavelength for various applied biases. In accordance with the previously discussed theory, we see the reflectivity at the bottom of the F-P dip first increases as absorption increases with voltage and then
Figure 6.7: Normalized reflectivity as a function of wavelength for various applied reverse biases.

decreases as the excitonic resonance moves beyond the F-P wavelength. The F-P dip also broadens, reaching a maximum width between 4 and 5 volts, when the absorption is the greatest and the cavity finesse is being maximally reduced by the absorption. At 11 volts bias, the finesse is partially recovered as the exciton resonance is now at the low energy side of the F-P dip, and severely reduced in strength by the high field. The accompanying changes in refractive index shift the F-P dip first to longer wavelengths as the exciton absorption peak approaches from the high energy side, and then to shorter wavelengths as it passes to the low energy side. Qualitatively, the direction and the magnitude of the shifts are in agreement with refractive index changes computed from the absorption data via the Kramers-Kronig relation.

FIG. 6.8 shows the normalized reflectivity versus bias at several wavelengths. At 8264Å, we obtain an increase in reflection of 47% and a measured contrast ratio of 15. We suspect that our contrast ratio was limited by our experimental setup as slight
misalignments caused severe reductions in this value. Using a tunable laser source might allow better collimation and lead to higher resolution. In order to examine the latching capabilities of our device, we then measured the photocurrent under monochromatic illumination generated by passing the white light through the monochromator.

FIG. 6.9 shows the photocurrent generated under 8264 Å wavelength light. The initial increase in photocurrent with field is due to the better collection efficiency of the photogenerated carriers at higher fields. However, the photocurrent rapidly decreases as the device reflectivity increases. Overall, there is more than a 30% reduction in photocurrent as the device becomes more reflective. Such a large negative differential conductivity region will prove useful in SEED configurations. Notice that the minimum in reflectivity corresponds to the maximum in the photocurrent, thus allowing high contrast ratios in bistable circuits. Although our device is far from optimized, having simply modified a
previously existing modulator, we have obtained very high performance in terms of insertion loss and modulation ratio.

![Graph](image)

**Figure 6.9.** Photocurrent as a function of voltage. For the experiment the device was illuminated with 8264 Å light.

In comparing our device to previous normally off modulators, we find that the highest reported reflectivity change using the QCSE was 38% with a 6:1 contrast ratio\(^2\), while the best using the Wannier-Stark effect is a very high contrast ratio device with 28% reflectivity change \(^5\). Though it is difficult to make a direct comparison, we see that our novel cavity design has the largest reflectivity change with a high contrast ratio. The only significant disadvantage to our cavity design is the narrow optical bandwidth caused by the high reflectivity mirrors. Measured characteristics agree closely to those calculated in FIG. 6.6. Of course, our structure is different from that modeled in the figure because we have neglected refractive index changes in the calculation and our structure contains the added SiO\(_2\)/TiO\(_2\) layers. However, the mathematical model can serve as a guideline to evaluate the device performance. We see that for \(R_f=0.93\), we calculate a reflectivity change of
about 50\% and an optical bandwidth of about 9\textmu m, in comparison to measured values of 47\% and 11\textmu m respectively. On FIG. 6.6, our device lies on a steep part of the curve, where increasing the cavity length and decreasing the front mirror reflectivity would increase the optical bandwidth by almost a factor of three with only about a 5\% penalty in $R_{on}$.

Though the Wannier-Stark effect results in a better performance SEED than the QCSE used in the conventional way, we find our novel cavity design, matching the front mirror reflectivity to the minimum cavity absorption, yields the best modulation characteristics.
7. Dynamic Grating Device

In chapter 1, we mentioned that the applications of quantum well modulators are not limited to optical interconnects. In this chapter we describe a novel application of such modulators for laser beam steering applications.

7.1 Background and Fundamentals

At present, the main methods for moving a laser beam, aside from rotating the laser itself, are mechanical mirrors and acoustic wave devices. Moving mirrors have found many applications in a vast variety of fields. In bar code scanners, for example, scanning patterns are produced by rapidly rotating a multi-faceted mirror. In laser printers, where accurate positioning of the beam is required, galvanic mirrors are used. Though such moving mirrors have high resolution, they are limited in speed and reliability.

A solid state alternative is to utilize acoustic waves in piezo-electric material. In a Bragg cell, acoustic waves generated by microwave transducers interact with an optical beam and cause diffraction. The compression and rarefactions of the acoustic wave in a crystal, such as tellurium oxide or lithium niobate, cause accompanying changes in refractive index. Consequently, such an acoustic wave produces an index diffraction grating that interferes with the beam. The angle of diffraction is set by the period of this index grating. Thus, higher microwave frequencies cause large diffraction angles. The operation of a SAW (surface acoustic wave) device is similar, except that the interaction between the acoustic wave and the light occurs on the surface.

In either case, acoustic wave devices are limited in speed and resolution. The time required to change from one scanning angle to the next is determined by the speed of the acoustic wave in the crystal and the interaction length. To keep the resolution high, larger interaction lengths are necessary with an accompanying decrease in speed. Typical numbers are resolutions of about 300 and speeds on the order of microseconds.
Theoretically, diffraction effects in spatial light modulators (SLMs) can also be used to change the far field pattern of a laser beam. However, bulk SLMs, such as liquid crystal displays, are usually too large for these diffraction effects to be useful. Recently, higher resolution SLMs that are optically addressed have been reported that allow interference properties to be exploited. Nevertheless, their complex structure clearly limits their performance and applicability.

In this chapter, we demonstrate how quantum well optical modulators can be used as a high resolution SLM to steer laser beams using diffraction effects. Since these modulators are extremely fast and can be made lithographically, they are useful in rapidly controlling far-field patterns of illumination and obtaining beam steering through diffraction.

The device is a dynamic grating constructed of Fabry-Perot reflection modulators. Other dynamically controlled gratings have been reported in the past, however, they operated at much longer microwave wavelengths. By using quantum wells and lithographically defining active stripes, we obtain control of the far field pattern in the optical regime. Since the far field is a Fourier Transform of the spatial reflectivity of the device, we can steer a laser beam by imposing a pattern that oscillates spatially on the stripes. The deflection angle of the modes being given simply by the grating formula

\[ d \sin(\theta) = m\lambda \]

Power efficiencies and accurate beam profiles can be calculated from the Huygens-Fresnel integral.

### 7.2 Experimental Demonstration

To demonstrate this idea, we fabricated such a structure working in the reflection mode in the GaAs/AlGaAs system. The reflective mode is preferred for two reasons. Since the GaAs substrate is opaque to the modulator's operating wavelength, constructing a transmissive device would require the removal of the substrate. Furthermore, as discussed in chapter 3, by working in the reflection mode, we can obtain higher contrast and lower loss due to the interaction of the Fabry-Perot cavity with the quantum wells. For the
experiment, we used the 50Å well width reflection modulator described in chapter 4. The total reflectivity of the device changed from about 10% to 76% when a 5 volt bias was applied. The reflectivity of the device as a function of wavelength for various applied bias voltages was shown in FIG. 4.4. We then used our previous wet etching technique (see section 4.2.2) to fabricate parallel, individually addressable stripes. The resolution in the lithography was fine enough to make functional devices with stripes as narrow as 2 µm. However, the scanning angle of these patterns was too large to be conveniently imaged on a CCD camera. Consequently, only the characteristics of a larger pattern will be presented. This pattern consisted of 16 stripes, each being 10 µm wide with a 2 µm wide spacing. The stripes were individually accessed with an ohmic contact pattern around the edge of the wafer. The device was packaged and wire bonded to allow an external bias to be applied to the stripes. One contact at the edge of the device failed mechanically during this procedure so only 15 of the 16 stripes were controllable. FIG. 7.1 is a schematic of the fabricated device.

![Diagram](image)

Figure 7.1: Schematic of fabricated laser beam steering device. The stripes were etched from the modulator wafer discussed in section 4.2. The contact pads allow the reflectivity of each stripe to be individually addressed thus forming an electrically controllable grating.
The device was tested using a tunable Ti:Sapphire laser. The laser beam was tuned roughly to the Fabry-Perot mode of the device and focused down using a single lens. When illuminating the device it is important to have a large enough spot size to illuminate as many of the stripes as possible without getting reflections from other areas, such as the contact pads. In this case the reflected beams were deflected with a small mirror onto an imaging lens and a silicon CCD camera. A schematic of our measurement set up is shown in FIG. 7.2.

![Diagram of measurement setup](image)

**Figure 7.2:** Experimental set up of measurement procedure for laser beam steering device

The experimental results are displayed in FIG. 7.3. Above each plot of intensity versus position we have noted the pattern of reflectivity imposed on the stripes. In the figure, a "1" corresponds to a reflective state, and a "0" a non-reflective state. The limited dynamic range of the camera led to detector saturation in the higher intensity peaks when the detector gain was raised high enough to observe clearly the lower intensity diffraction peaks.

Though our measured profiles are limited both by this saturation and by exactly where we
take the cross-section, the measurement of the position of the peaks is nevertheless accurate and we observe clear evidence of beam steering.

Figure 7.3. Observed intensity versus angular position for various stripe reflectivity configurations. The traces are offset vertically for clarity.

In the top curve (a), where all the elements are in a reflective state, we see the main reflected peak to the left and a peak corresponding to the spatial frequency of the isolation trenches to the right. Since this peak is due to the reflectivity difference between the trenches and the stripes, it occurs with differing intensity in almost all plots. Had these isolation regions been smaller in size, this peak would be correspondingly reduced. The main reflected peak on the left is due to the DC reflectivity value of the pattern and is the main power loss mechanism. In the second trace (b), the pattern 1:0:1:0:1... causes the main peak to occur near the center of the range. The position of this peak corresponds to the spatial frequency imposed on the stripes and is twice the stripe period (24 μm). In the next three curves (c,d,e), we see this peak move to the left as the spatial frequency decreases. The bottom curve (f) corresponds to all the elements in the off state, where we
see only the main reflective peak. The peak due to the trenches disappears in this plot since our off state reflectivity corresponds roughly to the reflectivity of the etched regions between the stripes.

7.3 Characteristics

7.3.1 Scanning Angle

The optical characteristics of such a device are simple to compute. The continuous scanning angle obtainable corresponds to twice the grating period. This is because the maximum spatial frequency that can be imposed on the stripes corresponds to the stripes alternately on and off. This defines an imposed grating with period twice that of the stripes. Although this scanning angle is small in our demonstration (2 degrees), larger angles were obtained from other patterns using smaller stripes. Standard optical lithography can produce grating spacings down to at least 2 μm, which permits a scanning angle of 12 degrees. Larger scanning angles can be obtained through the use of more sophisticated lithography, such as holographic or electron beam, or by using a higher order diffracted mode.

7.3.2 Resolution

In most applications, the resolution of the device is the most significant characteristic. If we define the angular width as the angular distance from the maximum of the mode to the adjacent minimum, then simple grating theory \(^{100}\) gives this width as

\[
\Delta \Theta = \frac{\lambda}{Nd}
\]

(7-1)

where \(Nd\) is the total width of the grating. The maximum number of resolvable beams is then equal to the number of stripes used. Since there are no fundamental limits to the number of stripes and the size of the grating, the performance of such a device can be tailored to one's needs.
7.3.4 Efficiency

The efficiency of this device is also simple to calculate. Since the far field pattern is a Fourier Transform of the reflectivity pattern, the efficiency is dependent on the harmonic content of the signal imposed on the stripes. An approximate number for the efficiency can be calculated by assuming that the mesas are small and that the addressing on the stripes is with half the devices on and the other half off. In this case, half the optical power is lost in the stripes that are off, an additional 80% is lost to the DC component and the other modes, and since we can only change the reflectivity of the stripes by 66%, the efficiency becomes $0.5 \times 0.2 \times 0.66 = 7\%$. Consequently, in simple reflection geometry devices, such as demonstrated, a great deal of power is wasted through absorption in the stripes that are off or reflection in the main lobe. These losses can both be decreased using modulators that change the phase and not the amplitude of the incident light. If an external Fabry-Perot cavity is employed, the wasted beam in the main lobe can be reflected back onto the device and thereby increase the efficiency by more than a factor of 3.

7.4 Discussion

In this particular demonstration, the device is clearly not optimized. The resolution is limited by the number of stripes and the speed and power-handling capacity by the resistance of the stripes. These can be improved by modifications to the design.

Since the resolution of the device depends on the number of stripes, this can be easily improved by increasing their number. It is fairly simple to fabricate electronic demultiplexers and ROMs on GaAs using, for example, standard MESFET techniques. Thus some electronic decoding can be integrated with the device to reduce the number of contact pads and wires. Since these modulators have already demonstrated good performance on silicon, it may be advantageous to fabricate the devices on silicon in order to use the mature silicon VLSI electronics technology. Alternatively, the device could be "flip-chip" mounted on a silicon circuit to operate in hybrid form.
The intrinsic optical power saturation intensities in quantum wells have been measured and are on the order of a few kW/cm². Based on this number, we would expect our device to be able to handle about 0.5 W of input power, deflecting about 40 mW into one of the first order modes. Of course, larger areas could handle higher powers. Another limiting factor in power-handling is the resistance of the stripes. As the input light intensity increases, the photocurrent produced increases, which causes a voltage drop across the stripes. In this particular device, we used the doped semiconductor top mirror as the conducting layer. For our doping profile and mirror thickness, the resistivity of this layer is about 250Ω/square. This translates to a power-handling capability of about 5 mW for a 0.5 Volt drop across each stripe. This number can be easily improved by using a thicker doped region or some form of transparent contact, such as indium-tin-oxide (ITO).

The potential applications of such a device are very large. These scanners can be used in any application where rapid control of a light beam is desired. Potential areas would include scanners (laser printers, bar code scanners), optical memories where rapid scanning is desired to read either a CD type or a holographic memory, and spectrum analyzers where the property that diffraction in the far field corresponds to the Fourier Transform of the near field is used. Another potential application could be a fiber optic switch. Currently lithium-niobate waveguide switches are used to switch the output of one fiber into one of two outputs. Although these are fast, they are not integratable with electronics and tend to be lossy. Such a 1 to 2 switch usually has a loss of about 3dB. If we desire to decrease the number of outputs, for example from 1 to 256, then we would need 8 layers of switches (2⁸=256). The power efficiency in this case would be less than 0.5%. Since the efficiency of our device does not scale with the number of outputs, even our 7% efficiency would prove advantageous when the number of outputs becomes larger than about 16.

In this chapter, we have demonstrated a novel application for quantum well modulators. Using the high resolution afforded by lithography, we demonstrated a spatial light
modulator that can control an optical beam through diffraction effects. Such a device could have numerous applications in a variety of fields.
8. Conclusions

8.1 Summary

In this work, we have discussed some reasons why quantum well optical modulators are interesting and mentioned a few of the areas where they might have applications. The most commonly quoted area is that of optical interconnects. As electronic integration reaches higher densities, the problems of interconnects increases. Up to this point, these limitations have been overcome by adjustments in the electronics design, such as using asynchronous circuits to overcome clock skew, and tricks in the circuit layout. However, it seems reasonable to expect that at some point in the future a radically new interconnect technology will be needed. For optical modulators to make a contribution to this field, they have to be integrable with silicon VLSI, since the likelihood of GaAs VLSI seems bleak at the present.

In chapter 3, we developed a simple mathematical model to optimize these devices. Although other researchers have made very complex computer codes that are more accurate, their models do not give the designer a feel for the effects of varying various design parameters. We used our equations to optimize devices both in GaAs/AlGaAs and InGaAs/AlGaAs modulators, resulting in the highest performance GaAs/AlGaAs device, and the first InGaAs/GaAs device with comparable performance to previous GaAs/AlGaAs devices. We also developed a technique to mechanically tune the modulators to correct for errors in the fabrication. If these modulators are to be made manufacturable, clearly some form of adjustment control is necessary.

In chapter 5, we looked at quantum well absorption from a theoretical standpoint. Our calculations showed that absorption can be improved by increasing the barrier height. We applied this method to the InGaAs/AlGaAs system and fabricated a modulator with the highest reflectivity change reported to date. Our work in this area showed that even though
the material quality may be "bad," in terms of traps and luminescence, the absorption properties can remain strong.

Discussing bistable modulators in chapter 6, we investigated the Wannier-Stark effect in InGaAs/GaAs, and were the first to obtain room temperature absorption changes. However, since the Quantum Confined Stark Effect gives larger absorption changes, we developed a method where these larger changes can be used to obtain bistability.

In chapter 7 we designed and implemented a novel method to apply quantum well modulators to steer laser beams. This method may have large potential in a vast variety of fields due to its speed, resolution, and potential of integration with solid state lasers and electronics.

8.2 Future Work

The area of optical modulators has become a very active field, with many research organizations expressing interest. Many groups are investigating modulators for particular applications. For example, there has been renewed interest in growing these modulators on silicon, and AT&T is focusing much of its resources towards that goal. Applications for fiber modulators and integrated optics are also continuing.

The reflectivity modulation and voltage levels demonstrated in this thesis and by other research groups is probably of an adequate level appropriate for optical interconnects. The reflectivity modulation is approaching unity, and the switching voltages are below 5V. The remaining issues for the actual incorporation of optical interconnects into real systems is no longer the actual devices, but the optical design and integration with electronics.

In chapter 1 we discussed some of the technological problems in the optical design of systems to connect large arrays of optical links. The precise alignments necessary, as well as wavelength and vibration control necessary makes the systems complex and expensive. To this point there has been no significant demonstration of integrated systems with potential for low cost and mass production. Though there are no theoretical problems why
such systems cannot be produced, clearly a great deal of routine engineering work is required.

The same difficulties apply to the integration of III-V modulators with VLSI electronics. Although good modulator performance on silicon substrates has been demonstrated by a number of groups, there are significant processing problems that need to be solved. These range from simple issues like different wafer size and lithography to the more difficult processing problems such as incompatible processing temperatures and chemistries.

Unlike the optical interconnect applications that may take a decade or more to mature, the beam steering idea demonstrated in chapter 7 may have some real short term potential. The high resolution and speed can clearly out-perform the acoustic wave devices in a number of applications. What is presently required is to move the invention from this early phase and develop the technology for a particular implementation, such as the fiber switch for telecommunications.

Potential problems that may be encountered are material uniformity and optical design. The performance of the device is related to the array size, obtaining better resolution and higher power handling as the number of stripes increases. To achieve very high performance, large arrays that may approach a centimeter are required. In such instances the wafer must be uniform and free of defects over a large area. These problems of uniformity and material quality pertain not only to such optical devices but also have limited the fabrication of VLSI circuits in GaAs and may not be very simple to solve.

The optical design can also be complicated with large stripe arrays. In a typical application for a high performance device the light from individual fibers must be expanded to fill the array and collimated back into other fibers. The large number of input and output beams and their relative positioning requires complex fabrication and exact alignment.

However, in the short term, even small arrays for beam steering can be potentially very useful. As discussed in chapter 7, an application for fiber switching requires only about
16 stripes to outperform lithium niobate waveguide switches. There is also an advantage for high speed applications, where other alternatives such as acousto-optic deflectors and mechanical methods are inadequate. Hopefully, the mathematical models and ideas developed in this thesis will play some part in the design of modulators for real systems.
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Chapter 3


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Chapter 5


Chapter 6


Chapter 7


