INFORMATION TO USERS

The most advanced technology has been used to photograph and reproduce this manuscript from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book. These are also available as one exposure on a standard 35mm slide or as a 17" x 23" black and white photographic print for an additional charge.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI

University Microfilms International
A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
313-761-4700    800-521-0600
Modulation of light by electronically tunable multi-layer optical interference devices

Yoffe, Gideon William, Ph.D.

Stanford University, 1988

Copyright ©1988 by Yoffe, Gideon William. All rights reserved.
MODULATION OF LIGHT BY ELECTRONICALLY TUNABLE
MULTI-LAYER OPTICAL INTERFERENCE DEVICES

A DISSERTATION
SUBMITTED TO THE DEPARTMENT OF ELECTRICAL ENGINEERING
AND THE COMMITTEE ON GRADUATE STUDIES
OF STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

By

Gideon William Yoffe

September 1988
I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

James S. Harris
(James S. Harris, Jr., Principal Advisor)

David M. Bloom
(David M. Bloom)

Fouad A. Tobagi
(Fouad A. Tobagi)

Approved for the University Committee on Graduate Studies:

Elizabeth Cross
Dean of Graduate Studies
ABSTRACT

Optical interconnects are attracting attention as a means to overcome the interconnection bottleneck in high speed electronic systems. The best type of light source for such schemes is sometimes a continuous-wave laser used in conjunction with a light modulator, which acts as an external switch. Modulators that operate in perpendicular geometry, with light directed normal to the plane of the device, allow simple fabrication of two-dimensional arrays; these are of interest for multiple parallel optical interconnections and for optical information processing.

The multiple quantum well electroabsorption modulator, the most common perpendicular modulator, suffers from two disadvantages: Its power handling capacity is low, and the operating wavelength is fixed by the material. We propose a new type of modulator, based on tunable optical interference filters, that is non-absorbing and can handle high optical power levels.

Optical interference filters contain alternating layers of two materials with different refractive indices. As a result of multiple reflections from the various interfaces, incident light may be either transmitted or reflected, depending on the wavelength and the layer thicknesses. Sharp transitions between strong reflection and nearly complete transmission occur over very small ranges of wavelength. Shifting these transitions electrically causes changes in the amount of light transmitted, and hence modulation.

Two types of device have been fabricated from gallium arsenide and aluminum gallium arsenide on gallium arsenide substrates by molecular beam epitaxy. The first was a "quarter wave stack". Strong electric fields across the structure caused shifts in the transmission spectrum that were sufficient to produce useful modulation. High voltages were required, however, making it unsuitable for most applications. The second was a Fabry-Perot interferometer, which was operated at lower voltage in two modes; one based
upon electric field, and a second by carrier injection. Modulation was achieved only by electric field, as spontaneous emission prevented operation by carrier injection.

The devices are very sensitive to material thickness accuracy and uniformity, and also to temperature. Improved epitaxial growth control is necessary before these devices prove useful. The most likely application is in the far infra-red region, operating in carrier injection mode.
ACKNOWLEDGEMENTS

Heartfelt thanks go first to my advisor, Professor James Harris, who has expertly guided me through the rocky path of graduate school. He was patient enough to give me, a fairly ignorant student, the time and space to learn the material and to find my own research topic. Seeing his role as that of an educator, he resists any temptation to create rapid publications by telling his students what to do, and instead lets them find their own interests and learn how to do their own research. He will always be a role model for me, although I don't think I'll be quite as willing to hold midnight discussions as he has been.

Thanks go to Professor David Bloom, my associate advisor, who leads a very prolific group in the field of optoelectronics. I have had many useful interactions with him and his students over the years. I would also like to thank Professor Fabian Pease for his friendly advice, encouragement, and interest during my whole Stanford career, beginning with kind words after I failed the qualifying exam, and ending by serving on my orals committee. I am grateful too to Professor Fouad Tobagi for chairing my oral, for reading this thesis, and for taking the time to discuss my work from a systems perspective.

None of the experimental work would have been possible without the cheerful assistance of Darrell Schlom, the current owner of the MBE guru's mantle. He was there to grow wafers and discuss future plans at some of the craziest hours. It was no coincidence that all of the work on my more complex devices was performed during the 18 month stay of Masaki Okajima, a visiting scientist from the Toshiba Corporation. He patiently and cheerfully shared his broad knowledge of optical devices and his astonishing repertoire of processing tricks. He has contributed immensely to the group's work and has been a wonderful ambassador.

There would have been no lab had it not been for the boundless energy of a number of students in the Harris group. Phil Pitner's enthusiasm created well equipped
laboratories; Eric Hellman, Alex Harwit, and Paul de la Houssaye kept things rolling in the early days. Tony Ma, Won-Seong Lee, Jim Adkisson, Kevin Lear, and William Liu have done far more than their fair share of gruntwork recently, and all have been very helpful with processing hints and other suggestions. The group extends further than the students, of course. Gail Chun-Creech, Lachen Pence, and Sherie Harvey have handled the administrative side efficiently, and I was rarely ready to start a day's work before getting a smile and a chat from their office.

I would also like to thank all of the people who have made the solid state lab the kind of place where one might want to spend five good years. While it gets a little quiet in there between 5 AM and 7 AM, at most hours it is easy to find a soulmate for a discussion on anything from optical data processing to Lithuanian guttersnipes. Maybe that's why it takes a few years to get a PhD.

Finally, I acknowledge the various agencies that have provided financial support. During my first year a Fulbright grant brought me to Stanford and kept me alive, while an Overseas Studentship from the Science and Engineering Research Council in England paid the tuition. An IBM fellowship kept me going for my second year, and the Defence Advanced Research projects Agency has supported me since then.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ABSTRACT</td>
<td>iv</td>
</tr>
<tr>
<td></td>
<td>ACKNOWLEDGEMENTS</td>
<td>vi</td>
</tr>
<tr>
<td>1</td>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>BACKGROUND MATERIAL</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>2.1 THE Al$<em>x$Ga$</em>{1-x}$As MATERIAL SYSTEM</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>2.1.1 General Description</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>2.1.2 Effects of an Electric Field - The Franz-Keldysh Effect</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>2.2 MOLECULAR BEAM EPITAXY</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>2.3 QUANTUM WELLS</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>2.3.1 General Description</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>2.3.2 Quantum Wells in an Applied Electric Field</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>2.4 PERPENDICULAR GEOMETRY LIGHT MODULATORS</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>TUNABLE QUARTER-WAVE STACK</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>3.1 QUARTER-WAVE STACK</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>3.1.1 General Description</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>3.1.2 Calculations of the Transmission Spectrum</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>3.1.3 Effect of Errors in Layer Thicknesses</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>3.1.4 Effects of Tilting and Conical Incident Light</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>3.1.5 Previous Work on Semiconductor Interference Filters</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>3.2 THEORY OF THE TUNABLE QUARTER-WAVE STACK</td>
<td>37</td>
</tr>
</tbody>
</table>
3.2.1 Effect of a Refractive Index Change on the Transmission Spectrum ............................................. 37
3.2.2 Franz-Keldysh Electroabsorption and Electrorefraction .................. 41
3.2.3 Electroabsorption and Electrorefraction in Quantum Wells........... 50
3.2.4 Effect of Temperature on the Refractive Index.............................. 58
3.2.4 Effect of Temperature on the Refractive Index.............................. 58

3.3 DESIGN OF EXPERIMENTAL STRUCTURES ................................................. 59
3.4 FABRICATION ......................................................................................... 66
3.5 EXPERIMENTAL APPARATUS ................................................................. 68
3.6 EXPERIMENTAL ZERO-FIELD OPTICAL TRANSMISSION RESULTS ......................................................... 70
   3.6.1 Zero-Field Transmission Spectra ............................................... 70
   3.6.2 Uniformity Across the Wafer .................................................... 72
   3.6.3 Effect of Tilt.............................................................. 73

3.7 EXPERIMENTAL MODULATION RESULTS ............................................. 74
   3.7.1 Effect of an Electric Field on the Transmission Spectra ........ 74
   3.7.2 Modulation of Light ............................................................ 75
   3.7.3 Effect of Temperature ....................................................... 77

3.8 DISCUSSION ......................................................................................... 77
   3.8.1 Comparison of Results with Theory ..................................... 77
   3.8.2 Advantages and Disadvantages ............................................. 81

4 TUNABLE FABRY-PEROT CAVITY ................................................................. 84

4.1 FABRY-PEROT CAVITY .................................................................. 85
   4.1.1 Description .............................................................................. 85
   4.1.2 Sharpness of the Transmission Spectrum ............................... 88
4.2 THEORY OF THE TUNABLE FABRY-PEROT CAVITY ................. 91
  4.2.1 Effect of Changing the Refractive Index of the Spacer Layer ... 91
  4.2.2 Device Concept: P-I-N Diode ................................... 93
  4.2.3 Modulation of the Refractive Index by Carrier Injection ........ 95

4.3 DEVICE DESIGN .................................................. 104
  4.3.1 Epitaxial Layers ............................................... 104
  4.3.2 Lateral Movement of Carriers ................................ 107
  4.3.3 Device and Heatsink Geometry .................................. 110
  4.3.4 Heat Flow Calculations ....................................... 113

4.4 DEVICE FABRICATION ............................................ 121
  4.4.1 MBE Growth .................................................. 121
  4.4.2 Device Processing ........................................... 123

4.5 EXPERIMENTAL RESULTS ........................................... 126
  4.5.1 Zero-Bias Optical Transmission Results ......................... 126
  4.5.2 Modulation Results .......................................... 129

4.6 DISCUSSION OF RESULTS ........................................ 132

5 CONCLUSIONS ....................................................... 136
  5.1 SUMMARY ...................................................... 136
  5.2 SUGGESTIONS FOR FUTURE WORK .................................. 138
  5.3 APPLICATIONS .................................................. 140

6 REFERENCES ....................................................... 142
LIST OF FIGURES

Figure 2.1. Energy band diagram of a quantum well. The lowest two allowed states in the conduction band, the lowest three heavy-hole states, and the lowest two light-hole states are indicated. ........................................... 13

Figure 2.2. Energy levels of the first three confined electron states, as a function of well width, in a multiple quantum well structure consisting of GaAs quantum wells and 50 Å Al$_{1.5}$Ga$_{0.5}$As barriers. Levels corresponding to states n=1, n=2, and n=3, are labelled E1, E2, and E3, respectively. ......................................................... 15

Figure 2.3. Photoluminescence spectrum of a sample containing GaAs quantum wells. The longer wavelength peak comes from a 90 Å well; the shorter wavelength peak is from a 50 Å well. ........................................... 16

Figure 2.4. Generation of multiple parallel optical signals by a two-dimensional array of perpendicular modulators, fed by a single off-chip laser. .......... 19

Figure 2.5. Operating principle for a solid-state light modulator. A sharp feature in the transmission spectrum is shifted, changing the transmittance for light tuned close to the feature. ........................................... 20

Figure 2.6. Schematic absorption spectra for bulk and quantum well materials. The sharp peaks result from confined exciton transitions. ........... 21

Figure 3.1. The constituent layers of a quarter-wave stack. .............................. 25

Figure 3.2. Typical transmission spectrum for a quarter-wave stack, designed for a central wavelength of 10000 Å. The simulated structure contained 40 periods of AlAs and Al$_{0.2}$Ga$_{0.8}$As. ................................. 25

Figure 3.3. Schematic diagram of the multiple reflections from the various layers in a quarter-wave stack. Strong reflectance is obtained if all of the reflections are in phase. .............................................................. 26

Figure 3.4. An assembly of thin films on a substrate. The films have thicknesses d$_1$ and d$_2$, and refractive indices n$_1$ and n$_2$, respectively. .... 27

Figure 3.5. Approximate curves of refractive index versus photon energy for GaAs and AlAs. ................................................................. 32

Figure 3.6. Refractive index of Al$_x$Ga$_{1-x}$As as a function of x for photon energies of 1.0 eV and 1.38 eV. ........................................... 32

Figure 3.7. Effect of random fluctuations in layer thicknesses on the transmission spectrum of a quarter-wave stack. Theoretical spectra are shown for maximum errors of 0 Å and 50 Å. .............................. 34

Figure 3.8. Effect of tilt on the path difference between consecutive reflections. ..... 35
Figure 3.9. Effect of a 0.4% change in refractive index on the transmission spectrum of a quarter-wave stack. The structure is the same as for Figure 3.2. .......................................................... 38

Figure 3.10. Schematic diagram of a quarter-wave stack with electrical contacts. .......... 41

Figure 3.11. Effect of an electric field of 300 kV/cm on the absorption spectrum of bulk GaAs. .......................................................... 43

Figure 3.12. Photon-assisted tunnelling in a semiconductor with a strong electric field applied. ......................................................... 44

Figure 3.13. The electro-optic functions, a) F(x) and b) G(x). ........................................ 47

Figure 3.14. Effect on the refractive index of GaAs of electric fields of 30 kV/cm and 300 kV/cm. ......................................................... 49

Figure 3.15. Change in the refractive index of GaAs as a function of field for photon energies of 1.2 eV, 1.25 eV, 1.3 eV, and 1.35 eV. ................. 50

Figure 3.16. Potential profile for the conduction band for tunnelling resonance calculations. Zero energy is the conduction band edge at the center of the quantum well. ............................................. 52

Figure 3.17. Calculated wave functions for the first three confined electron states in a 160 Å GaAs quantum well with 70 Å Al₅Ga₅As barriers for electric fields of a) 0 V/cm, and b) 300 kV/cm. ....................... 53

Figure 3.18. Calculated zero-bias absorption spectra for bulk GaAs and for a 160 Å GaAs quantum well with 70 Å Al₅Ga₅As barriers. .............. 54

Figure 3.19. Calculated absorption spectra for bulk GaAs and a) a 160 Å GaAs quantum well, b) an 80 Å well, in an applied field of 100 kV/cm. ....... 55

Figure 3.20. Logarithmic plots of the calculated absorption spectra for bulk GaAs and a) a 160 Å GaAs quantum well, b) an 80 Å well, in an applied field of 100 kV/cm. ..................................................... 56

Figure 3.21. The measure of sharpness, d, for the transmission spectrum of a quarter-wave stack, is the range of wavelength over which the transmittance doubles. ....................................................... 62

Figure 3.22. Theoretical transmission spectra for a) the 30-period symmetric GaAs/AlAs quarter-wave stack, and b) the 30-period asymmetric structure, consisting of three-eighths wavelength GaAs and one-eighth wavelength AlAs layers. ...................................................... 64

Figure 3.23. Schematic diagram of the modulator. The multi-layer reflector was a 30-period GaAs/AlAs quarter-wave stack in the first sample, a 30-period three-eighths wavelength GaAs/one-eighth wavelength AlAs stack in the second sample, and a 40-period multiple quantum well/AlAs quarter-wave stack in the third sample. ......................... 67
Figure 3.24. Schematic diagram of the apparatus used to measure transmission spectra .............................................. 69

Figure 3.25. Experimental zero-bias transmission spectra for a) the symmetric quarter-wave stack, b) the symmetric quarter-wave stack with quantum wells, and c) the asymmetric structure ............................................. 71

Figure 3.26. Percentage shift in the wavelength of the transmission peak at the short wavelength side of the high-reflectance band for the symmetric quarter-wave stack, as a function of the distance from the center of the wafer .................................................................................................................. 72

Figure 3.27. Effect of tilt on the transmission spectrum: spectra are shown for the symmetric quarter-wave stack at angles of 0° and 60° ............................................. 73

Figure 3.28. Normalized wavelength of a peak in the transmission spectrum of the quantum well quarter-wave stack, as a function of tilt angle ................. 74

Figure 3.29. Transmission spectra at the short-wavelength edge of the high-reflectance band of the symmetric quarter-wave stack for applied electric fields of 0 V/cm and 200 kV/cm: a) wide wavelength scale; b) expanded scale ........................................................................................................................................... 75

Figure 3.30. Transmittance at selected wavelengths as a function of electric field for a) the symmetric quarter-wave stack, on the short wavelength side of the high-reflectance band, and b) the quantum well quarterwave stack on the long wavelength side ......................................................................................................................... 76

Figure 3.31. Transmission spectra for the symmetric quarter-wave stack in ambient temperatures of 28°C and 49°C ........................................................................... 77

Figure 3.32. Band diagram of a hetero-nipi structure with zero bias ................................................................. 82

Figure 4.1. Schematic diagram of an all-epitaxial Fabry-Perot interferometer ................................................. 85

Figure 4.2. Theoretical transmission spectrum of a 6th order Fabry-Perot cavity, with a GaAs spacer layer and substrate, an 18-period upper reflector, and a 25-period lower reflector, each reflector consisting of quarter-wavelength layers of GaAs and Al₄Ga₆As ......................................................................................................................... 86

Figure 4.3. The central part of a first order Fabry-Perot interferometer. Each "H" or "L" labels a quarter-wavelength layer of high or low refractive index, respectively ......................................................................................................................... 87

Figure 4.4. Theoretical half-power width of the Fabry-Perot resonance as a function of the number of periods in the top reflector. The peak wavelength is 10000 Å, and the materials in the reflectors are GaAs and Al₄Ga₆As ......................................................................................................................... 90

Figure 4.5. Theoretical half-power width of the Fabry-Perot resonance as a function of the order of the spacer layer. The peak wavelength is 10000 Å, and the reflectors contain 18 and 25 periods of GaAs and Al₄Ga₆As ......................................................................................................................... 90
Figure 4.22. Effect of the diameter of the hole in the heatsink on the thermal resistance between the center of the chip and the heatsink. 121

Figure 4.23. Cross-sectional scanning electron micrograph of an unsuccessful Fabry-Perot structure. The dark stripes are GaAs layers, the light ones Al$_{4}$Ga$_{6}$As. 123

Figure 4.24. Photographs of finished devices: a) top view of an unmounted chip; b) close-up of the active device area; c) an inverted chip on a heatsink, with a bonding wire. 127

Figure 4.25. Zero-bias transmission spectra for the Fabry-Perot structures with spacer layer thicknesses of a) 3 wavelengths, and b) 6 wavelengths. 128

Figure 4.26. Expanded transmission spectra to show the Fabry-Perot resonances of a) the 3-wavelength device, and b) the 6-wavelength device. 129

Figure 4.27. Effect of reverse bias on a 6-wavelength device: transmission spectra of the Fabry-Perot peak for zero bias and for 20 V applied reverse bias. 130

Figure 4.28. Typical current-voltage characteristic for a Fabry-Perot device. 130

Figure 4.29. Spontaneous emission spectra near the Fabry-Perot resonance for a) a 3-wavelength device and b) a 6-wavelength device. 131
LIST OF TABLES

Table 3.1. Effect of the number of periods on the sharpness of the spectrum. ........... 62

Table 3.2. Experimental and theoretical values of $\delta (\text{Å})$. .......................... 72
**LIST OF SYMBOLS**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, B, C</td>
<td>Material Constants.</td>
</tr>
<tr>
<td>$A^*$</td>
<td>Rate of generation of heat per unit volume.</td>
</tr>
<tr>
<td>d</td>
<td>Thickness of a layer.</td>
</tr>
<tr>
<td>E</td>
<td>Energy.</td>
</tr>
<tr>
<td>$E_0$</td>
<td>Characteristic energy, dependent on electric field.</td>
</tr>
<tr>
<td>$E_g$</td>
<td>Bandgap energy.</td>
</tr>
<tr>
<td>$\vec{E}$</td>
<td>Electric field vector.</td>
</tr>
<tr>
<td>$\hbar$</td>
<td>Reduced Planck's constant.</td>
</tr>
<tr>
<td>$\vec{H}$</td>
<td>Magnetic field vector.</td>
</tr>
<tr>
<td>$I_{pq}$</td>
<td>Overlap integral for electron and hole states.</td>
</tr>
<tr>
<td>K</td>
<td>Thermal conductivity.</td>
</tr>
<tr>
<td>m</td>
<td>Effective mass.</td>
</tr>
<tr>
<td>$m_0$</td>
<td>Mass of an electron.</td>
</tr>
<tr>
<td>$m_{eh}$</td>
<td>Reduced effective mass of a hole/electron pair.</td>
</tr>
<tr>
<td>n</td>
<td>Refractive index.</td>
</tr>
<tr>
<td>$n_h$, $n_l$</td>
<td>Refractive indices of high-index and low-index layers.</td>
</tr>
<tr>
<td>N</td>
<td>Density of carriers.</td>
</tr>
<tr>
<td>$N_A$, $N_D$</td>
<td>Acceptor and donor doping densities.</td>
</tr>
<tr>
<td>q</td>
<td>Charge of an electron.</td>
</tr>
<tr>
<td>r</td>
<td>Amplitude reflection coefficient.</td>
</tr>
<tr>
<td>$r_e$</td>
<td>Electro-optic coefficient.</td>
</tr>
<tr>
<td>$\hat{r}$</td>
<td>Direction vector.</td>
</tr>
<tr>
<td>R</td>
<td>Reflectance.</td>
</tr>
<tr>
<td>s</td>
<td>Interface recombination velocity.</td>
</tr>
<tr>
<td>S</td>
<td>Stripe width.</td>
</tr>
</tbody>
</table>
\( T \)  Temperature.

\( T^* \)  Transmittance.

\( V \)  Potential energy.

\( x \)  Mole fraction of AlAs in Al\(_x\)Ga\(_{1-x}\)As.

\( Y \)  Optical admittance.

\( \alpha \)  Absorption coefficient.

\( \delta \)  Measure of sharpness of edge of high-reflectance band, or width of Fabry-Perot resonance.

\( \Delta y \)  Shift or change in quantity \( y \).

\( \delta_w \)  Width of high-reflectance band.

\( \varepsilon \)  Dielectric constant.

\( \varepsilon_0 \)  Permittivity of free space.

\( \mathcal{E} \)  Electric field.

\( \phi \)  Semi-angle of a cone.

\( \lambda \)  Wavelength.

\( \nu \)  Frequency.

\( \theta \)  Angle of incidence.

\( \tau \)  Lifetime.

\( \omega \)  Angular frequency.
1 INTRODUCTION

It is becoming clear that the speed of large computers and sophisticated electronic systems is limited by the interconnections between devices, integrated circuits, and circuit boards, rather than by the intrinsic speeds of the devices themselves. The reason for this lies in the difficulty in transmitting and terminating signals in the GHz range, along with the conflicting requirements of greater densities of interconnection lines and contact pads with no crosstalk or interference. These problems are starting to become apparent in high speed silicon technology, but they will be far more limiting as GaAs integrated circuit technology improves. Optical fibers are already widely used in telecommunications for transmitting information over long distances; a 1 Gbit/s signal was recently successfully transmitted 313 km without repeaters. There is now a growing interest in using optical interconnects over much shorter distances, such as chip-to-chip, board-to-board, or box-to-box in mainframe computers. A number of schemes, including free-space holographic interconnects, waveguide interconnects, and through-wafer interconnects, have also been proposed for on-chip interconnection.

The principal advantages of optics for these applications are its speed and its immunity from interference, either by external electromagnetic signals or by nearby or intersecting optical signals. The data rates that can be handled are quite enormous. A graded index multi-mode fiber has a bandwidth (data rate multiplied by fiber length) over 100 Mb.km/s for a GaAs light-emitting diode with a 30 nm spectral width, or over 1 Gb.km/s for a laser. These bandwidths translate to data rates of 10-100 Gb/s over 10 m lengths. Single-mode fibers can give a further order of magnitude of improvement. These speeds are far greater than those that can be attained by any production electronic devices, so fibers have the capacity to carry several multiplexed signals. The fastest three-terminal device reported to date is a heterojunction bipolar transistor that gave a ring
oscillator propagation delay of 5.5 pS per gate.\(^8\) In useful circuits with normal fan out and parasitics, this level of speed could not be achieved, but it provides a useful limit to examine.

In the quest for ever faster computers, some researchers are investigating the possibility of all-optical systems, with optical switching elements in addition to interconnects. The problem that they face is closely related to one of the principal benefits of optical interconnects; streams of photons do not tend to interact. True three-terminal all-optical switching elements are far from realization, although hybrid optoelectronic devices have been demonstrated, including a bistable self electro-optic device,\(^9\) an integrated phototransistor and modulator,\(^10\) and optical logic gates requiring different pump and probe wavelengths.\(^11\) Optical signal processing can certainly fulfill many useful tasks in coherent systems,\(^12\) including spectrum analysis, correlation, matrix-vector multiplication, and synthetic aperture radar. Research is also being done in the field of optical neural networks for pattern recognition applications.\(^13\)

Current implementations of optical communication systems use discrete laser diodes in conjunction with high speed driver circuitry. It is desirable to combine optical and electronic devices into integrated optoelectronic circuits wherever possible. Such chips would be smaller, more rugged, more reliable, and less expensive than electrically connected discrete devices. They would also perform better, since parasitic elements would be considerably reduced. Most of the research into integrated optoelectronic light sources to date has been focussed on integrating laser diodes with field-effect transistor drivers. Unfortunately the processing technologies for these two types of device are quite dissimilar. Most importantly, laser mirrors are usually formed by cleaving the substrate. This would limit the size of any chip to the length of the laser cavity, usually around 300 \(\mu\)m; this would severely restrict the number of transistors that could be constructed. The heat generated by lasers can seriously affect the performance of the driver circuitry, so low threshold currents are essential. Some promising results have been obtained, at the
cost of considerable processing complexity. A low threshold quantum well laser has been successfully integrated with four metal-semiconductor field-effect transistors (MESFETs),\textsuperscript{14} and vertical integration of a laser with a heterojunction bipolar transistor was recently demonstrated.\textsuperscript{15} There are several review papers describing the advantages and problems of such integrated light sources.\textsuperscript{16,17,18} Each source is very difficult to fabricate. It may well prove to be impossible to make them on silicon substrates.

For multiple parallel optical communication channels it would be advantageous to be able to position laser diodes anywhere on a chip. This requires emission of light perpendicular to the substrate. A number of devices of this type have been demonstrated, albeit with very sophisticated processing. Some of the successful devices have included grating coupled lasers\textsuperscript{19,20} and arrays,\textsuperscript{21} lasers\textsuperscript{22,23} and arrays\textsuperscript{24} with etched facets and monolithically integrated 45\degree mirrors, and a vertical cavity distributed feedback laser.\textsuperscript{25} The complex processing means that none of these devices is likely to have a very high yield. None of them has yet been demonstrated to have very high speed or a very low threshold current. The current benchmarks for these parameters for cleaved, edge-emitting lasers are 22 GHz\textsuperscript{26} and 0.55 mA\textsuperscript{27} at room temperature.

Many researchers are now investigating the possibility that a more promising approach toward making integrated optoelectronic light sources might be to use light modulators in conjunction with off-chip continuous wave (CW) lasers. If high speed, low-power, passive devices could be used to "shutter" an externally produced light beam, considerable savings of processing complexity could be achieved. Furthermore, passive devices should be inherently more reliable, allowing integration of large arrays. Since the optical power would not be generated on-chip, the use of modulators could offer the possibility of higher powers' being transmitted, reducing the need for repeater stages. As with lasers, modulators can be made in either waveguide or perpendicular (normal to the surface) geometry. Perpendicular geometry is required for two-dimensional arrays. In addition to their possible use for optical communications, such arrays could act as spatial
light modulators for optical data processing, or as cross-bar switches for routing signals in extensively interconnected systems.

Unfortunately, a perpendicular geometry modulator that can operate at high speed, handling high optical power levels and giving a large on/off modulation ratio, does not yet exist. The motivation behind the work described in this thesis was the desire to fill this gap. It was considered desirable to create a device that did not require reference light beams, since they add complexity. It was also a requirement that the modulator should work for light with a photon energy less than the bandgaps of the materials used in fabrication. This would allow transmission of light through the substrate, and would mean that the light would not affect the operation of electronic devices on the same chip. Moreover, non-absorbing devices would not tend to saturate or heat up, so high optical power levels could be handled.

To operate under these conditions, the device must have an optical transmission spectrum with sharp features below the bandgap. It is also necessary that these features of the spectrum be moved in wavelength (or energy) by an external electrical perturbation, so that light tuned close to the sharp features will see changes in the transparency of the structure; this will lead to changes in the transmitted and reflected intensities. The implementation selected was to fabricate all-epitaxial multi-layer optical interference filters using the Al<sub>x</sub>Ga<sub>1-x</sub>As material system; the peaks and valleys in the transmission spectra were to be shifted by application of electrical signals. The first approach was simply to apply a strong electric field across a "quarter-wave stack", which is a selective, highly reflecting optical element. Some success was obtained, although high voltages of around 100 V were required because of the thickness of the structure. A more advanced device, a tunable Fabry-Perot interferometer, was then developed. In this structure, only the central spacer layer needs to be affected by the applied electrical signal. This device was designed to function in two modes, either by application of a strong field or by injection of carriers into the spacer layer. These two perturbations should cause opposite shifts in the
transmission resonance, increasing the tuning range and allowing operation with switching
voltages of less than 10 V. Promising results were obtained. The very sharp transmission
peak was shifted enough by 20 V reverse bias to cause a 2:1 modulation ratio. Carrier
injection was also demonstrated, but spontaneous emission of light from the modulator
itself masked any modulation that may have been occurring.

Chapter 2 of this thesis provides some background information on the Al$_x$Ga$_{1-x}$As
material system. The properties are described, both for bulk material and for very thin
"quantum well" layers. A qualitative account of the behavior in the presence of an electric
field is given, but most of the equations are left for a later chapter. A brief description of
molecular beam epitaxy, the crystal growth technique that makes these structures possible.
is given. The chapter ends with an assessment of the present state-of-the-art in
perpendicular modulators, describing available devices, their properties, their
disadvantages, and why a new type of modulator is desirable. Chapter 3 describes the first
tunable interference element, the tunable quarter-wave stack. The optical element itself is
described first, with the mathematics necessary to calculate transmission spectra. An
overview is then given of multi-layer optical interference structures that have been
fabricated elsewhere. The physics behind the tunability is then presented, and device
design criteria are developed. The device's design, fabrication and performance are then
described, followed by comments on areas for improvement. Chapter 4 follows a similar
path in describing the more advanced Fabry-Perot device. Chapter 5 ties the work together
with a summary, ideas for future work in this area, and some possible applications.
In this chapter some background on the material and electronic properties of the Al$_x$Ga$_{1-x}$As material system is presented. The advantages that III-V semiconductors have over silicon in terms of electronic and optical properties are described, including the unique ability to form single crystal heterojunctions. This latter feature makes it possible to fabricate many totally new structures for devices and for observation of quantum phenomena. The effects of an electric field on the optical properties of GaAs and quantum well material are described. These effects are crucial to the operation of the modulators. The descriptions given in this chapter are qualitative only; equations that describe them will be presented when they are needed for calculating the projected performance of the devices.

A brief description of molecular beam epitaxy is presented. Multi-layer structures such as our modulators cannot be fabricated unless a crystal growth system is available that offers extremely precise control of layer thickness and composition. Molecular beam epitaxy, which allows control almost to the level of single atomic layers, has made possible a wide variety of exciting new structures that were scientists' dreams until a few years ago. Finally a brief description is given of the current state-of-the-art in perpendicular geometry modulators. The term "modulator" is defined, and the various implementations are described. The device that has received most attention so far, the multiple quantum well electroabsorption modulator, is presented, and its drawbacks are discussed. The chapter ends with the thought processes behind the development of our new type of device.
2.1 THE $\text{Al}_x\text{Ga}_{1-x}\text{As}$ MATERIAL SYSTEM

2.1.1 General Description

Gallium arsenide (GaAs) is the most extensively investigated III-V compound semiconductor. Its crystal structure is zincblende, consisting of two interpenetrating face-centered-cubic sub-lattices, very similar to that of silicon. Notwithstanding the joke in the silicon community that "GaAs is, was, and always shall be the material of the future"\textsuperscript{28}, there are many areas in electronics where GaAs has a decided advantage over Si. There are many books and review papers that describe its properties in exhaustive detail\textsuperscript{29,30,31,32,33} A brief summary is given here.

The higher electron mobility and saturated drift velocity mean that GaAs devices can operate at microwave frequencies that are inaccessible to silicon. The ability to produce semi-insulating substrates allows low parasitic conductances and reactances, and makes device isolation and true monolithic integration easier. Unlike silicon, GaAs has a direct bandgap. This allows the generation of light, and also makes absorption much more efficient. Lasers and light-emitting diodes cannot be fabricated from silicon, but are fairly straightforward to make with GaAs. The strengths of GaAs lie, therefore, in high-speed or optical devices.

The feature that makes possible many of the new devices that are being developed is the ability to form heterojunctions between GaAs and the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ternary alloy. This is made possible by the very close match (within 0.3\%) in the lattice constants of GaAs and AlAs. High quality interfaces, free from dislocations or strain, can be made between two layers of any alloy composition. This allows the electronic properties to be varied through the structure.
The bandgap of the alloy at 300 K varies between 1.424 eV for GaAs and 2.168 eV for AlAs. According to Casey and Panish\textsuperscript{34} the bandgap is direct for $x$ less than 0.45 and follows the relationship

$$E_g(x) = 1.424 + 1.247x \text{ eV.} \quad (2-1)$$

For AlAs mole fractions above 0.45, the smallest bandgap is indirect, at the X point in the band structure diagram, and obeys the equation

$$E_g^x(x) = 1.900 + 0.125x + 0.143x^2 \text{ eV.} \quad (2-2)$$

The proportions of the change in bandgap at a heterojunction that are taken up in the conduction and valence bands have been the subject of extensive research. From the work of Batey and Wright\textsuperscript{35} and references therein, it seems that a good compromise is to take the valence band discontinuity as

$$\Delta E_v = 0.50x \text{ eV} \quad (2-3)$$

for all $x$, and to calculate the conduction band discontinuity using equations (2-3) and either (2-1) or (2-2).

Most other properties are also strong functions of the composition. The refractive index is of particular interest in this work, since the operation of our devices relies on differences in the refractive indices of adjacent layers. The refractive indices of GaAs\textsuperscript{36} and AlAs\textsuperscript{37} have been measured for a wide range of photon energies, and that of Al$_x$Ga$_{1-x}$As\textsuperscript{38} at 1.38 eV. At a photon energy of 1.2 eV, the refractive index of GaAs is around 3.5, that of AlAs is 3.0, and for the alloy, the variation is close to linear. More precise fits to the published data will be presented in the next chapter.
The ability to form high quality heterojunctions has led to the development of several new electronic and optoelectronic devices, including heterojunction laser diodes,\textsuperscript{39} high electron mobility transistors (HEMT's), and heterojunction bipolar transistors.\textsuperscript{31} Integrated circuit technologies based on HEMT's are now becoming quite reliable, and heterojunction bipolar devices are the topic of extensive current research. The motivation for these two technologies is the speed advantage that they have over silicon, and there are many applications, including phased-array radar and direct-broadcast satellite links, where the best silicon devices are simply inadequate. It is in the field of optoelectronics, however, that III-V semiconductors are free from competition, since silicon cannot be used to generate light. Light-emitting diodes and semiconductor lasers are all fabricated from various III-V materials, the choice depending on the desired operating wavelength.

There is no question of GaAs ever replacing silicon in all applications. It is doubtful whether there is enough gallium in the world for that. Silicon is cheaper and easier to process. For most electronic applications silicon will remain the logical choice; GaAs and related materials will have certain niches in high speed circuits, and they will continue to dominate the world of optoelectronics.

2.1.2 Effects of an Electric Field - The Franz-Keldysh Effect

In 1958, Franz\textsuperscript{40} and Keldysh\textsuperscript{41} showed theoretically that a strong electric field would give rise to changes in the absorption spectrum of a semiconductor. Specifically, some absorption occurs for photon energies slightly below the bandgap of the material. The mechanism can be considered as photon-assisted tunnelling, as shown by Pankove.\textsuperscript{42} Tharmalingam\textsuperscript{43} and Aspnes\textsuperscript{44} developed analytical expressions involving Airy functions for the electron states and the absorption spectrum. Stillman et. al.\textsuperscript{45} performed electroabsorption measurements on high quality GaAs and confirmed the theory. They also
demonstrated that the effect could be used to modulate the intensity of light transmitted by a waveguide structure.

Seraphin and Bottka\textsuperscript{46} were the first to note that changes in the shape of the absorption edge could lead to correlated changes in the refractive index. This results from the interdependence of the real and imaginary parts of the dielectric constant, which are related by the Kramers-Kronig relations.\textsuperscript{47} Seraphin and Bottka used their numerical calculations to explain observed changes in the reflectance spectrum of germanium under an applied electric field. Aspnes\textsuperscript{48} extended the calculations, obtaining analytical expressions for the changes in both the real and imaginary parts of the dielectric constant. Bennett and Soref\textsuperscript{49} modified Aspnes's equations and plotted the results for several semiconductors over a wide range of photon energies. They showed that for strong electric fields of 200 to 300 kV/cm, there would be marked changes in the refractive index of GaAs well below the bandgap. This fact is exploited in the devices described in this thesis. The equations will be presented in chapter 3, when they are required for device modelling.

A separate effect that can also change the refractive index of a semiconductor is the linear electro-optic effect or Pockels effect.\textsuperscript{42} In electro-optic materials, the presence of an electric field induces biaxial birefringence. That is to say, the refractive indices perpendicular to the direction of the field are altered, by equal and opposite amounts. This leads to a phase shift for polarized light transmitted parallel to the field. The effect has been shown experimentally\textsuperscript{50} to be smaller than the Franz-Keldysh electrorefraction.

2.2 MOLECULAR BEAM EPITAXY

Molecular beam epitaxy, or MBE, is a technique for depositing high quality epitaxial layers of material on a crystalline substrate. It is basically an ultra-high-vacuum evaporation technique, but it allows very precise control over the beam fluxes and growth
conditions. Many commercial systems are now available, differing in implementation but conceptually the same. The growth chamber is kept at ultra high vacuum, with a background pressure below $10^{-10}$ Torr. Some form of load-lock is present to allow substrates to be loaded without opening the growth chamber to air. The substrate is mounted on a heater block. The elemental material sources are thermal Knudsen cells, electrically heated ovens, with the material itself in an inert crucible, usually boron nitride. A common selection of source materials is As, Ga, Al, Si (an n-type dopant) and Be (a p-type dopant). Mechanically or pneumatically controlled shutters are placed in front of each source to allow rapid switching on or off of the beam. Analytical tools to monitor the growth conditions are always available. Usually a quadrupole mass spectrometer, an ion gauge beam flux monitor, and a reflection high energy electron diffraction (RHEED) system are present. An excellent treatise on MBE, which can almost be used as a do-it-yourself manual, is Parker’s book.$^{51}$

When the substrate temperature and beam fluxes are correct, the product of the evaporation is a single crystal. For growth of GaAs, the usual substrate temperature is in the range 500°C to 700°C; a growth rate of around 1 μm/h is common, and the sources are usually set so that there is an excess of arsenic. Since Cho’s first demonstration of epitaxial growth,$^{52}$ great advances have been made, as greater understanding of the growth mechanisms has been gained. For a long time people were unable to fabricate good semiconductor lasers by MBE, but gradually it became clear that for optical quality $\text{Al}_x\text{Ga}_{1-x}\text{As}$ a higher substrate temperature and a low arsenic flux, consistent with arsenic-stabilized conditions, were required.$^{53}$ Now the lowest threshold current lasers are quantum-well devices fabricated by MBE.

In addition to providing the growth of high quality epitaxial layers, MBE offers very precise control of layer thickness. Rotation of the substrate is usually employed to reduce fluctuations across the wafer that result from the non-uniform evaporation patterns of Knudsen cells. Once the growth rate is known accurately, it is very stable. A growth rate
of 1 \( \mu \text{m/h} \) corresponds to roughly one atomic layer per second. The shutters are capable of switching the beam much more quickly than that, so it is possible to grow reproducible layers as thin as 10 Å. Such thin layers exhibit different properties from bulk material, and they are described in the next section. The most elegant method for monitoring the growth rate is to observe oscillations in the intensity of the specular beam of a RHEED pattern in the early stages of growth. Each "RHEED oscillation" corresponds to a monolayer growth. Since the first demonstration in 1981,\textsuperscript{54} RHEED oscillations have started to become a standard technique for growth rate calibration. They may one day be used in some "phase-locked epitaxy" system to control layer thicknesses to within a single monolayer.

The MBE system at Stanford is a Varian Gen II machine with computer control of all the source temperatures and shutters. It was one of the first machines to employ a substrate holder that does not require indium solder to mount the substrate.\textsuperscript{55} It has been used to fabricate a wide variety of electronic and optoelectronic devices, as well as simple layers for material characterization. It has a RHEED oscillation system for accurate growth rate calibration, and has proved to be an excellent tool for making complex multi-layer structures.

2.3 QUANTUM WELLS

2.3.1 General Description

A quantum well is formed when a thin layer of a semiconductor is sandwiched between layers of another material that has a larger bandgap. The wave functions of electron states in the well are no longer unrestricted free plane waves, but are quantized in the direction perpendicular to the wells, with very little amplitude in the cladding layers.
This restriction may be viewed as confinement of a particle in a one-dimensional potential well. With abrupt interfaces, as can be obtained by MBE, the well can be made very nearly rectangular in shape.

If the thickness of the confining layer is less than about 200 Å, the electronic and optical properties of the material are significantly altered. The density of states becomes stepped, rather than following the usual square-root law. The energies at which these steps occur can be calculated simply by solving the one-dimensional particle-in-a-box problem of quantum mechanics; the barrier height is the relevant band-edge discontinuity. A schematic

![Diagram of energy levels and bands in a quantum well](image)

**Figure 2.1.** Energy band diagram of a quantum well. The lowest two allowed states in the conduction band, the lowest three heavy-hole states, and the lowest two light-hole states are indicated.

A band diagram is shown in Figure 2.1, with confined states indicated in both the conduction and valence bands. The allowed states are solutions of Schrödinger's equation in one dimension,

\[
-\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} = [E - V(x)]\psi
\]

(2-4)
with continuity of wave function, $\Psi$, and particle flux, $\frac{1}{m} \frac{d\psi}{dx}$, across the boundaries. $E$ is the energy of the particle, $V(x)$ is the local potential, $\hbar$ is the reduced Planck's constant, and $m$ is the particle mass. The wave functions are imaginary exponentials or sinusoids in the well, and decaying exponentials in the barriers.

A simple computer program was written, based on the Kronig-Penney model to calculate confined electron states for GaAs sandwiched between layers of Al$_{0.5}$Ga$_{0.5}$As. This model matches wave functions and fluxes across interfaces for an infinite superlattice of alternating layers of the two materials. Kittel's equations were modified to take into account different effective masses in the two materials. The equation to be solved is

$$\left| \frac{Q^2}{2} \left( \frac{m_1}{m_2} \right)^2 - \frac{K^2 m_2^2}{2 K Q m_1 m_2} \sin(Ka) \sinh(Qb) + \cos(Ka) \cosh(Qb) \right| \leq 1$$

(2-5)

where $m_1$ and $m_2$ are the effective electron masses in the well and barrier; $K$ is the wavenumber in the well, given by $E = \hbar^2 K^2 / 2m_1$; $Q$ is the exponential decay length in the barrier, given by $V - E = \hbar^2 Q^2 / 2m_2$; $E = 0$ at the conduction band edge; $a$ and $b$ are the widths of the wells and barriers respectively. The conduction band discontinuity, from equations (2-2) and (2-3), was taken as 0.32 eV, and the effective masses for the GaAs and Al$_{0.5}$Ga$_{0.5}$As were taken as 0.067$m_0$ and 0.11$m_0$, where $m_0$ is the mass of a free electron, $9.11 \times 10^{-31}$ kg. The lowest three confined levels are shown as a function of well width, with constant 50 Å barriers, in Figure 2.2. Confinement is tighter for smaller wells, so energy increases with decreasing well width.

Dingle was the first to look at quantized states in the context of semiconductors. The clearest evidence of quantization is obtained optically, either from the absorption spectrum or by photoluminescence spectroscopy. The carrier confinement moves the
minimum energies for holes and electrons away from the band edges. Thus the optical absorption edge is at a higher photon energy than for bulk material. Above the absorption edge the absorption spectrum is stepped rather than a smooth curve, the steps corresponding to allowed transitions between valence band states and conduction band states. At each step is a sharp peak, corresponding to a confined exciton. Dingle observed these phenomena experimentally. Excitons in quantum wells are crucial to the operation of multiple quantum well electroabsorption modulators, and they are described more fully later in this chapter, in the section on modulators.

Photoluminescence spectroscopy is also a good technique for observing quantized energy levels. A laser beam, with photon energy well above the material's bandgap, is focussed onto a sample. Electrons are excited into the conduction band, well above the minimum, where they rapidly relax thermally to a quasi-equilibrium condition and then recombine. Any direct recombination results in the emission of light, which can be

Figure 2.2. Energy levels of the first three confined electron states, as a function of well width, in a multiple quantum well structure consisting of GaAs quantum wells and 50 Å Al$_x$Ga$_{1-x}$As barriers. Levels corresponding to states $n=1$, $n=2$, and $n=3$, are labelled E1, E2, and E3, respectively.
analyzed using a spectrometer. Bulk material exhibits a spectrum with a peak very close to the bandgap energy. For quantum well samples, the minimum photon energy is greater because of the quantized states, so the peak or peaks occur at higher energy. Figure 2.3 is the room-temperature photoluminescence spectrum of a wafer grown in Stanford’s MBE machine. The structure contains quantum wells of two different thicknesses, roughly 90 Å and 50 Å. There is no signal at 1.42 eV (8720 Å), the bandgap of bulk GaAs. The lower energy, longer wavelength peak results from recombination in the 90 Å wells, while the higher energy peak comes from the smaller wells.

![Photoluminescence spectrum](image)

**Figure 2.3.** Photoluminescence spectrum of a sample containing GaAs quantum wells. The longer wavelength peak comes from a 90 Å well; the shorter wavelength peak is from a 50 Å well.

Quantum wells have found applications in many devices, including resonant tunnelling diodes and quantum well lasers. Insertion of quantum wells in the active layer of semiconductor lasers has made possible a drastic reduction in the threshold current of these devices. Quantum wells also have interesting properties under applied electric fields. That is the topic of the following section.
2.3.2 Quantum Wells in an Applied Electric Field

When an electric field is applied across a quantum well, the shape of the confining potential is altered and thus the confined states change. The first proof of this was provided by Mendez et. al.\textsuperscript{59} who observed the effect of a field on the low temperature photoluminescence of GaAs quantum wells. As the field was increased, two effects were observed; the photoluminescence intensity decreased, as a result of the carriers' tunnelling out of the wells, and second, the peaks shifted slightly to lower energy. This red shift has been the subject of extensive theoretical and experimental investigation, and has been named the "Quantum Confined Stark Effect" by Miller et. al.\textsuperscript{60}, who have been the most prolific in this field. A number of techniques have been developed to calculate the magnitude of the effect, and Miller et. al. describe some. Of these methods, the easiest to implement is certainly the tunnelling resonance technique, which has been described in great detail by Harwit et. al.\textsuperscript{61}

As the quantized energy levels move, the absorption spectrum changes. The first observation of electroabsorption in quantum wells was by Chemla et. al.,\textsuperscript{62} who subsequently provided a more complete description.\textsuperscript{60} More recently, they presented another set of calculations,\textsuperscript{63} showing that in the limit of wide quantum wells, the bulk Franz-Keldysh effect is recovered. This electroabsorption has been exploited in a number of devices, most notably tunable photodetectors\textsuperscript{64} and electroabsorption modulators, which will be described in the next section.

As is the case with bulk material, changes in the absorption spectrum imply changes in the refractive index of the material. The first experimental observation of this was by Nagai et. al.\textsuperscript{65} Several other groups have now reported similar results. A number of theoretical treatments have emerged over the years.\textsuperscript{66,67,68} These theories have all concentrated on a photon energy range very close to the lowest allowed transition, where
the effect is greatest. Considering the pace at which this field has been moving, it is not surprising that a waveguide modulator using this effect has already been demonstrated.\textsuperscript{69}

In general, the field-induced shift is largest for the lowest allowed state in the well, which, being closest to the bottom of the well, sees more of the perturbation in the well potential than do the excited levels. Therefore the difference in energy between quantized levels in the conduction band changes with field. This has been observed experimentally by Harwit et al.,\textsuperscript{70} and may have applications for far infra-red optical devices.

### 2.4 PERPENDICULAR GEOMETRY LIGHT MODULATORS

A light modulator is, by definition, an optoelectronic device whose transmissivity at certain wavelengths can be altered electrically. Used in conjunction with a CW (continuous wave) laser, such a device can produce a modulated light beam. In some cases this is preferable to directly modulating a laser. As an analogy, flashing lamps are used by sailors to communicate from one ship to another. Rather than repeatedly switch the bright light on and off, the normal technique is to leave the lamp on and to open and close a shutter. Solid-state modulators can be considered as shutters, with a higher speed and a poorer on:off transmission ratio than mechanical shutters.

Modulators can be fabricated in two different geometries, waveguide or perpendicular. In the former case, light is propagated in the plane of the device, while in the latter light is directed normal to the plane, passing through the chip or reflecting off it. Since it becomes expensive to fabricate devices of more than about 10 μm thickness (not including the substrate), waveguide geometry offers the advantage of a greater interaction length between the light and the active device. This generally leads to a better modulation ratio. Perpendicular geometry devices have advantages if something more than a single discrete device is required. The main benefit is that two-dimensional arrays can be
fabricated, forming spatial light modulators. These are of interest for multiple parallel optical communication paths and for the various optical data processing systems mentioned in the introduction. So long as the substrate is transparent or removed, a single CW light source off-chip can be used to supply the array, as illustrated in Figure 2.4. Our attention has been focussed on perpendicular devices, since this is the area where the most improvement is required.

![Diagram](image)

**Figure 2.4.** Generation of multiple parallel optical signals by a two-dimensional array of perpendicular modulators, fed by a single off-chip laser.

There are many possible techniques for modulating light. Some require splitting the light beam into two paths and using the electro-optic effect to induce a phase shift in one of the halves; when the two beams are brought together again, they may interfere constructively or destructively, depending on the phase shift. These electro-optic modulators are widely used in integrated optics, and are usually fabricated in lithium niobate. Their disadvantages are complexity and size; a recently reported example\(^1\) was
2 cm long. Such devices obviously have to be in waveguide geometry. MBE growth of 2 cm of material would take over 2 years. This type of phase-shift modulator is therefore not a good candidate for a perpendicular device.

The type of device that we have concentrated on relies on shifting the transmission spectrum by means of an applied electrical signal. The concept is shown schematically in Figure 2.5. A transmission spectrum with sharp features is required. Light tuned close to the feature will see a considerable change in transmittance when the spectrum is shifted. To obtain a good modulation ratio, the width of the feature being shifted should be the same size as or smaller than the maximum shift that can be obtained. Suitable operating points are labelled on the figure.

![Diagram](image)

**Figure 2.5.** Operating principle for a solid-state light modulator. A sharp feature in the transmission spectrum is shifted, changing the transmittance for light tuned close to the feature.
For semiconductors, the most convenient sharp feature in the transmission spectrum is the absorption edge. It can be perturbed by an electric field, as described in section 2.1.2, and modulation has been demonstrated in GaAs waveguides. Unfortunately the bulk absorption spectrum at room temperature is not sharp enough to allow good modulation depth by this technique in perpendicular geometry. The situation is different, however, when quantum well structures are considered. Some very interesting results have been obtained with multiple quantum well electroabsorption modulators.

As was described in section 2.3.1, the absorption spectrum of a quantum well structure is step-like, with peaks at the steps corresponding to exciton transitions. Excitons in quantum wells have been the subject of much research.\textsuperscript{72,73} An exciton is a bound hole-electron pair, similar to a hydrogen atom, with a binding energy of 4.2 meV and a Bohr

![Absorption Spectrum](image)

**Figure 2.6.** Schematic absorption spectra for bulk and quantum well materials. The sharp peaks result from confined exciton transitions.

radius of approximately 150 Å in bulk GaAs. It forms a state close to the conduction band edge. In quantum wells, the holes and electrons are constrained to be closer together than in bulk material. This increases the binding energy to around 10 meV.\textsuperscript{74} This is sufficient
to make it observable in the room temperature absorption spectrum, as sketched in Figure 2.6.

The first excitonic transition makes the onset of absorption very sharp. As was described in section 2.3.2, the spectrum can be red-shifted somewhat by an applied electric field. The exciton transition keeps the absorption edge sharp for electric fields up to 70 kV/cm, which moves the peak by about 13 meV. The first actual devices contained 50 GaAs quantum wells in the intrinsic layer of a p-i-n diode. Electric fields were applied simply by reverse biasing the diode. These devices gave a modulation depth of 2.3 and a switching speed of 131 pS. More recently, other workers have achieved a modulation depth of 10 dB with a thicker structure. This represents the current state-of-the-art in perpendicular devices. Arrays of devices with very consistent characteristics have been demonstrated. A group at the Massachusetts Institute of Technology is working on spatial light modulators fabricated from arrays of these devices with an integrated charge-coupled device addressing system. Promising initial results have been obtained, albeit with poor modulation depth.

Electroabsorption modulators suffer from two main drawbacks. First, the exciton peak saturates at an optical power density of 600 W/cm², almost an order of magnitude lower than bulk material. This limits the power handling capacity of devices. Secondly, the devices only operate at photon energies very close to the bandgap of the material; the first allowed transition is approximately 50 meV above the bulk bandgap for typical quantum wells 100 Å wide. This means that the substrate will absorb any light that it sees, so it has to be removed. This is inconvenient, especially if large arrays are being made. An alternative to substrate removal is to fabricate a mirror underneath the quantum wells, for example an epitaxial multi-layer reflector, and to operate the device in reflection mode. This geometry is more difficult to use, especially for arrays. This restriction on the operating wavelength also eliminates the possibility of using such a device in conjunction with lasers that emit at wavelengths well away from the bandgap. For
example, it may become useful to have a modulator that could work in conjunction with a Nd:YAG laser at 1.06 μm wavelength.

These disadvantages acted as motivation for the development of a new type of device. The desired characteristic was a movable sharp feature in the transmission spectrum below the bandgap, to allow through-wafer operation and to permit very high optical power levels to be used. Multi-layer interference filters provide such spectra; selection of appropriate layer thicknesses allows the sharp features to be tuned to any desired wavelength. Electrically tunable multi-layer interference devices had not been reported prior to the start of this work, so they presented themselves as worthy of attention.
3 TUNABLE QUARTER-WAVE STACK

This chapter describes the first type of device that was investigated. A quarter-wave stack is the simplest multi-layer interference filter. It acts as an efficient reflector for a band of wavelengths, with oscillating transmission windows on either side of the band. The edges of the high-reflectance band can be very sharp, so any electrically induced shift in the spectrum will modulate the intensity of transmitted light, as described in the previous chapter.

The following sections begin with a description of a quarter-wave stack and a condensed theory of operation. The tunability is then covered in some detail, beginning with calculations of the required change in the refractive index, followed by calculations of what is achievable in bulk and quantum well material. Device design considerations are then presented, and experimental structures are described. Experimental modulation results follow. In the discussion section we explain why, despite the success of the experiments, the device is still far from practical, and why an improved type of modulator was considered desirable.

3.1 QUARTER-WAVE STACK

3.1.1 General Description

A quarter-wave stack consists of alternating layers of two materials with different refractive indices. The optical thickness of each layer, defined as the physical thickness multiplied by the refractive index, is a quarter of a selected wavelength. The structure is illustrated in Figure 3.1. A typical transmission spectrum for normally incident light is shown in Figure 3.2. The structure that was simulated for this spectrum contained 40
periods of alternating AlAs and Al$_2$Ga$_8$As layers. The refractive index difference is not very great, around 13\%, but the spectrum still has sharp features. The selected central wavelength was 10000 Å. There is a band of wavelengths centered around 10000 Å for which almost all of the light is reflected. At the edges of the band there are sharp transitions to nearly full transmittance, followed by oscillations.

![Diagram](image)

**Figure 3.1.** The constituent layers of a quarter-wave stack.

![Graph](image)

**Figure 3.2.** Typical transmission spectrum for a quarter-wave stack, designed for a central wavelength of 10000 Å. The simulated structure contained 40 periods of AlAs and Al$_2$Ga$_8$As.
For an intuitive understanding of why this efficient reflection is obtained, consider the structure shown in Figure 3.3. Incident light is partially reflected and partially transmitted at each interface. The amplitude reflection coefficient for light incident normally at an interface between materials of refractive indices $n_a$ and $n_b$ is

$$r = \frac{n_a - n_b}{n_a + n_b}.$$  \hspace{1cm} (3-1)

A derivation can be found in most textbooks on physics or optics, or in Macleod's very useful book on thin film optical filters. At each interface the same fraction of light is reflected. The phase shift is 0 or $\pi$ radians at alternate interfaces, depending on whether the incident refractive index is the greater or smaller one. The round-trip phase shift in each layer, neglecting the interface phase shift, is $\pi$ radians at the wavelength for which the layer

Figure 3.3. Schematic diagram of the multiple reflections from the various layers in a quarter-wave stack. Strong reflectance is obtained if all of the reflections are in phase.
is a quarter-wavelength thick. Thus it is clear that at this wavelength all the reflections are in phase. If there are enough layers, very nearly all of the light is reflected.

The quarter-wave stack is the single most important element in the devices described in this thesis. A basic description has been given. Some of the mathematics will be presented next.

### 3.1.2 Calculations of the Transmission Spectrum

The method described here is a condensed version of the technique described by Macleod, and is completely general for all multi-layer structures.

From Maxwell's equations it is possible to derive the following relationship (in CGS units) between the magnetic field vector, $\mathbf{H}$, and the electric field vector, $\mathbf{E}$, in any medium:

$$\mathbf{H} = n(\hat{r} \times \mathbf{E}) \quad (3-2)$$

where $\hat{r}$ is a unit vector along the direction of propagation and $n$ is the optical admittance or complex refractive index of the medium. For non-absorbing materials, $n$ is simply $n$, the

![Diagram of thin films](image)

**Figure 3.4.** An assembly of thin films on a substrate. The films have thicknesses $d_1$ and $d_2$, and refractive indices $n_1$ and $n_2$, respectively.

27
real refractive index. A straightforward extension of the simple interface reflection analysis yields the reflectance of an assembly of thin films. Consider the structure of Figure 3.4: If we can calculate the admittance of the structure, \( Y \), defined by \( \bar{H}_a = Y(\hat{r} \times \bar{E}_a) \), then we can calculate the amplitude reflection coefficient of the whole assembly, by analogy with equation (3-1), as

\[
r = \frac{n_{inc} - Y}{n_{inc} + Y}.
\]  

(Macleod developed a transmission matrix technique to calculate the field vectors at one interface if they are known at another one. Taking layer 1 in Figure 3.4, consideration of the phase shifts across the layer yields

\[
\begin{bmatrix}
\hat{r} \times \bar{E}_a \\
\bar{H}_a
\end{bmatrix} =
\begin{bmatrix}
\cos(\delta_1) & i \sin(\delta_1)/n_1 \\
in_1 \sin(\delta_1) & \cos(\delta_1)
\end{bmatrix}
\begin{bmatrix}
\hat{r} \times \bar{E}_b \\
\bar{H}_b
\end{bmatrix}.
\]  

The 2 by 2 matrix on the right hand side of equation (3-4) is known as the characteristic matrix of the film. \( \delta \) is the phase shift across a layer, and is related to the thickness, \( d \), and the angle between the propagating light and the normal, \( \theta \), through the equation

\[
\delta = \frac{2\pi n}{\lambda} d \cos(\theta);
\]

(3.5)

\( n = n \cos(\theta) \) for TE waves, and \( n/\cos(\theta) \) for TM waves. A simple extension to the two layer structure shows that

\[
\begin{bmatrix}
\hat{r} \times \bar{E}_a \\
\bar{H}_a
\end{bmatrix} =
\begin{bmatrix}
\cos(\delta_1) & i \sin(\delta_1)/n_1 \\
in_1 \sin(\delta_1) & \cos(\delta_1)
\end{bmatrix}
\begin{bmatrix}
\cos(\delta_2) & i \sin(\delta_2)/n_2 \\
in_2 \sin(\delta_2) & \cos(\delta_2)
\end{bmatrix}
\begin{bmatrix}
\hat{r} \times \bar{E}_c \\
\bar{H}_c
\end{bmatrix}.
\]  

(3-6)
In the substrate, the field vectors are related through equation (3-2), so that

\[
\begin{bmatrix}
\hat{r} \times \vec{E}_c^*
\hline
\hat{r} \times \vec{H}_c^*
\end{bmatrix}
= \begin{bmatrix}
\hat{r} \times \vec{E}_c
\hline
\hat{r} \times \vec{H}_c
\end{bmatrix}
\begin{bmatrix}
1
\hline
\eta_s
\end{bmatrix}.
\]  

(3-7)

In general, for a stack of \(m\) films on a substrate, we can write the characteristic matrix for the assembly as

\[
\begin{bmatrix}
B \\
C
\end{bmatrix}
= \prod_{j=1}^{m} \begin{bmatrix}
\cos(\delta_j) & i \sin(\delta_j) \eta_j \\
\eta_j \sin(\delta_j) & \cos(\delta_j)
\end{bmatrix}
\begin{bmatrix}
1 \\
\eta_s
\end{bmatrix}.
\]  

(3-8)

The admittance, \(Y\), is now simply

\[
Y = \frac{C}{B}.
\]  

(3-9)

The amplitude reflection coefficient can now be calculated from equation (3-3), and the reflectance, \(R\), is finally given by

\[
R = \left| \frac{\eta_{\text{inc}} - Y}{\eta_{\text{inc}} + Y} \right|^2.
\]  

(3-10)

For normal incidence, \(\eta\) can be replaced by \(n\) in every case. Sometimes it is more convenient to use the transmittance, \(T^*\), which is related to the reflectance through

\[
T^* + R = 1
\]  

(3-11)

29
when there is no absorption. Macleod describes how to deal with absorption; we neglect it in this thesis. The asterisk is used here to distinguish transmittance from temperature.

This transmission matrix technique lends itself very readily to computer simulations of arbitrary structures, and is the method used throughout this work. Various FORTRAN programs were written to perform the calculations. However, it is still useful to have algebraic expressions that can be used during the design phase. Macleod gives plenty of helpful equations. One of these gives the reflectance in air of a quarter-wave stack comprising \( p \) periods, with high and low refractive indices \( n_h \) and \( n_l \), a substrate index \( n_s \), and arranged with high index layers outermost on both sides, since this arrangement gives the highest reflectance:

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

(3-12)

If \( (n_h/n_l)^{2p}(n_h^2/n_s)^2 \approx 1 \), then \( R \approx 1 - 4(n_h/n_l)^2p(n_s/n_h)^2 \), and

\[
T^* \approx \left( \frac{n_l}{n_h} \right)^{2p} \left( \frac{n_s}{n_h} \right)^2.
\]  

(3-13)

So the addition of an extra period multiplies the transmittance by a factor of \( (n_l/n_h)^2 \).

Another useful equation gives the width of the high-reflectance band, labelled as \( \delta_w \) in Figure 3.2, defined as the distance between wavelengths with 50\% reflectance at the edges of the band. Some rearrangement of Macleod's result gives

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

(3-14)
where $\lambda_0$ is the wavelength at which the layers are a quarter-wavelength thick. This width is independent of the number of periods. Increasing the thickness of the stack sharpens the edges of the high-reflectance band, but does not move them. These equations will be referred to in the section on device design.

To make the calculations more accurate, wavelength dispersion of the refractive indices was taken into account. In our work, the energy range of interest is approximately 1.0 eV to 1.4 eV. Quadratic fits to the published data\textsuperscript{36,37} in that range yielded the following equations for the refractive indices as a function of energy, $E$, in eV:

For GaAs,

$$n(E) = 3.838 - 1.010E + 0.600E^2$$  \hspace{1cm} (3-15)

and for AlAs

$$n(E) = 2.793 + 0.102E + 0.019E^2.$$  \hspace{1cm} (3-16)

Equations (3-15) and (3-16) are plotted in Figure 3.5. There is no data available on the refractive index of the ternary alloy $Al_xGa_{1-x}As$ for all $x$ in this energy range. The data of Casey et. al.\textsuperscript{38} at 1.38 eV shows that the curve of $n$ versus $x$ bows slightly below a linear variation with $x$. At this energy, the refractive index of $Al_{0.5}Ga_{0.5}As$ is below the average of the refractive indices of GaAs and AlAs by 7.3% of the difference in the two indices. Assuming that this holds for lower photon energies too, we can fit a quadratic expression in $x$ to approximate the curve:

$$n(x,E) = n(0,E) - 1.29x[n(0,E) - n(1,E)] + 0.29x^2[n(0,E) - n(1,E)].$$  \hspace{1cm} (3-17)
Equations (3-15) through (3-17) were used in all the simulations of transmission spectra.

Equation (3-17) is plotted for photon energies of 1.0 eV and 1.38 eV in Figure 3.6.

![Graph](image1.png)

**Figure 3.5.** Approximate curves of refractive index versus photon energy for GaAs and AlAs.

![Graph](image2.png)

**Figure 3.6.** Refractive index of Al$_x$Ga$_{1-x}$As as a function of $x$ for photon energies of 1.0 eV and 1.38 eV.
3.1.3 Effect of Errors in Layer Thicknesses

The very sharp theoretical spectra would be of little consequence if minor fluctuations in layer thicknesses would destroy the sharp features. Three types of error are worth considering: the first is systematic error, with all layers too thick or too thin by a certain percentage; the second type is random vertical fluctuations, where each layer is flat and uniform but its thickness may be in error by a certain random amount; the third type is intra-layer fluctuations, where the interfaces are not perfectly parallel.

Since the wavelength at which any spectral feature occurs is proportional to the optical thicknesses of the layers, consistent errors in thickness will shift the whole spectrum. If both types of layer are in error by the same amount, then $\lambda_0$ is shifted and the wavelength scale is multiplied by the appropriate scaling factor. If only one of the layers is in error the situation is slightly more complicated. Computer simulations on a GaAs/AlAs quarter-wave stack showed that a 1% error in the thickness of the GaAs caused a shift of 0.5% in the center of the high-reflectance band, as expected, and also a slight broadening of the band; the short wavelength side moved by about 0.48%, while the long wavelength side moved by 0.53%. Very precise layer thickness control is required if spectral features need to be tuned to a precise wavelength. A small amount of tuning after fabrication is possible by tilting the wafer, as described in the next section.

Fortunately the effect of random vertical fluctuations with zero mean is not too great so long as the average thickness is correct. Macleod states that random fluctuations of up to a few percent inflict negligible damage, since averaging over a multi-layer structure compensates very well. Since we are looking for maximum sharpness of all features, our criteria for acceptability may be a little stricter. In Figure 3.7, results are presented from computer simulations in which random fluctuations of up to 50 Å were inserted in the layer thicknesses of a 30-period GaAs/AlAs quarter-wave stack, nominally tuned to 10000 Å. The technique used was to generate a random real number between -1 and 1, multiply it by
the maximum fluctuation, and add the result to the thickness of the layer. These fluctuations can be seen to cause noticeable changes to the shape of the spectrum. A 20 Å maximum fluctuation was found to have negligible effect. Since our method of fabrication was molecular beam epitaxy (MBE), the expected fluctuations were on the order of a few monolayers, maybe 5 to 10 Å. Therefore problems were not anticipated from this source.

![Graph showing transmittance vs. wavelength with two curves: Normal and With Errors.]

Figure 3.7. Effect of random fluctuations in layer thicknesses on the transmission spectrum of a quarter-wave stack. Theoretical spectra are shown for maximum errors of 0 Å and 50 Å.

Fluctuations across a structure are of more concern. Random fluctuations of zero mean tend to average out again. However, MBE grown layers are not perfectly uniform. With substrate rotation during growth, our machine produces layers that are approximately 3 to 5% thinner at the edge than in the center for two-inch wafers. Experimental proof will be presented later. The rate of change of thickness increases towards the edge. At the center the uniformity is quite good. To take variation of thickness across a sample into account, it would be necessary to calculate the spectra from each infinitesimal section and to add them together. In order for lateral fluctuations to have no effect on the spectrum, the fractional change in thickness across a device should be much less than the width of the
sharpest feature divided by its wavelength. In practice, this limits the maximum size of device that can be used.

3.1.4 Effects of Tilting and Conical Incident Light

Equation 3.5, giving the phase thickness of a layer, shows that the effective thickness is proportional to the cosine of the incident angle. While it might at first seem that a tilt should make the layers appear thicker, Figure 3.8 shows that the path difference for reflections off consecutive interfaces does indeed follow this law. The angle, \( \theta \), is the angle inside the structure. Refraction at the air interface severely limits the possible tuning range. The maximum value for \( \theta \) is the critical angle, \( \theta_c \), which from Snell's law is

\[
\theta_c = \sin^{-1}\left(\frac{1}{n}\right)
\]

where \( n \) is the refractive index of the material at the air interface. For GaAs, \( n = 3.5 \) and \( \theta_c \) is 16.6°. The cosine of this angle is 0.96, so the possible tuning range is only 4%. In the above calculations the effect of the angle on the optical admittance, \( \eta \), was completely

![Figure 3.8. Effect of tilt on the path difference between consecutive reflections.](image)

35
ignored. As indicated in section 3.1.2, the effect is opposite for TE and TM polarizations. For random polarization the net effect is likely to be some broadening in addition to the \( \cos(\theta) \) dependence, but this was not calculated explicitly.

Similar effects occur if the incident light is in the form of a cone rather than perfectly parallel. Macleod provides equations to deal with this situation too. Since any tilt will shift a peak to shorter wavelength, a cone of light, with all angles included from 0 to \( \phi \), its semi-angle, will move the peak to shorter wavelength and broaden it. Macleod shows that, if the wavelength of a feature at normal incidence is \( \lambda_0 \), the position of the feature given a cone of semi-angle \( \phi \) (in the material again) is

\[
\lambda_\phi = \lambda_0 - \Delta\lambda_\phi/2
\]

(3-18)

where

\[
\Delta\lambda_\phi = \lambda_0(1 - \cos\phi).
\]

(3-19)

The width of the peak is also broadened. If a feature has a half-power width of \( w_0 \) at zero incidence, a cone increases it to

\[
w_\phi = (w_0^2 + \Delta\lambda_\phi^2)^{1/2}.
\]

(3-20)

3.1.5 Previous Work on Semiconductor Interference Filters

While multi-layer interference filters have existed for nearly 50 years, only very recently have attempts been made to make optoelectronic or non-linear optical devices from such structures. Until the advent of MBE it was not practical to make such structures out
of GaAs and similar materials. In the last few years, however, interest in this field has increased rapidly.

A group at Sandia National Laboratories has demonstrated a number of interference filters fabricated by MBE from the Al_xGa_{1-x}As material system, beginning with quarter-wave stacks\textsuperscript{81} and continuing with optically tunable quarter-wave stacks\textsuperscript{82} and Fabry-Perot cavities.\textsuperscript{83} Optical tuning was achieved by exciting the material with light whose photon energy was greater than the bandgap; the absorbed light generated carriers and thus altered the refractive indices.

Semiconductor multi-layer reflectors have also been incorporated into other devices. The AT&T group that developed the multiple quantum well electroabsorption modulator demonstrated one device that had a quarter-wave high reflector underneath the quantum well layers.\textsuperscript{79} This device operated in reflection mode, eliminating the need for substrate removal and doubling the interaction length for the light. Quarter-wave reflectors have also been used as mirrors for vertical cavity distributed-feedback lasers.\textsuperscript{25} The very high reflectance of the mirrors allowed low threshold currents of around 2 mA to be obtained.

All of these devices were fabricated by MBE. The structures were all several microns thick. This will keep the devices at the research stage for some time yet, because MBE growth rates are rarely above 1 \( \mu \)m/h. MBE time is not cheap, so these structures are not attractive for mass production.

### 3.2 Theory of the Tunable Quarter-Wave Stack

#### 3.2.1 Effect of a Refractive Index Change on the Transmission Spectrum

The wavelengths at which the features in the transmission occur depend very strongly on the optical thicknesses of the layers. To shift a feature to a new wavelength it is
necessary to change the optical thickness of at least some of the layers. Since it is
impractical to alter the physical thickness, we require some technique to change the
refractive index.

If the refractive indices of both types of material are altered by the same amount, the
whole spectrum will shift, with the fractional shift in wavelength, \( \Delta \lambda / \lambda \), being equal to the
fractional change of refractive index, \( \Delta n / n \). Since it is possible to obtain quite sharp
features, as shown in Figure 3.2, these shifts do not need to be very large. Figure 3.9 is a
close-up of part of the spectrum of Figure 3.2, and shows the effect of an overall increase
of 0.4% in the refractive indices. It is clear that light tuned close to the edge of the high-
reflectance band will have its transmitted intensity greatly reduced when the shift is applied.
In this example, the modulation ratio would be greater than 3:1 at a wavelength of
10460 Å.

![Graph showing transmission vs. wavelength](image)

**Figure 3.9.** Effect of a 0.4% change in refractive index on the transmission spectrum of
a quarter-wave stack. The structure is the same as for Figure 3.2.

In principle, any shift of the spectrum could give useful modulation if the features in
the spectrum were sharp enough. The spectrum can theoretically be made arbitrarily sharp

38
by adding layers. There are several other limitations, however. Slight variations in thickness across a device will broaden spectral features, as described in section 3.1.3. Assuming a linear variation of 5% from center to edge of a wafer 5 cm in diameter, there will be a thickness change of 0.2% across a 1 mm sample, or 0.01% across a 50 μm device. The change in refractive index needs to be greater than this variation. The available change will limit the maximum size of a device. Another cause for concern is the stability of the laser source. Semiconductor lasers emit light stable in wavelength to a few Ångstroms, depending on temperature and current stability. It is necessary that the fractional change in the refractive index be greater than the fractional instability of the source wavelength. For operation around 1 μm wavelength, the minimum useful shift would be around 10 Å, or 0.1%, although shifts somewhat smaller would still be observable.

In practice the two types of layers will see different changes in their refractive indices. For Franz-Keldysh electrorefraction, described in the following section, only one type of layer will be affected. The effect of this is somewhat similar to the effect of changing the thickness of only one of the types of layers, which was discussed in section 3.1.3, namely, a shift and a slight broadening of the high-reflectance band. A simple analysis follows.

First, assume that the fractional shift in the spectrum that is caused by a change in the refractive index, n_h, of the high index layer by Δn_h is given by

$$\frac{\Delta \lambda_0}{\lambda_0} = \frac{\Delta n_h}{2n_h}. \quad (3-21)$$

To estimate the broadening, recall equation (3-14),

$$\delta_w = \frac{4\lambda_0}{\pi} \sin \left( \frac{n_h - n_l}{n_h + n_l} \right).$$
If \( n_h - n_l \) is small, as is the case for GaAs/AlAs structures, this can be rewritten as

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

(3-22)

To find the effect of a small change \( \Delta n_h \), we differentiate equation (3-22) to obtain

\[
\frac{d\delta_w}{dn_h} = \frac{8 \lambda_0}{\pi} \frac{n_l}{(n_h + n_l)^2}
\]

or

\[
\Delta \delta_w = \frac{8 \lambda_0}{\pi} \frac{n_l}{(n_h + n_l)^2} \Delta n_h.
\]  

(3-23)

The shifts in the two edges of the high-reflectance band will be, from equations (3-21) and (3-23),

\[
\frac{\Delta \lambda}{\lambda_0} = \frac{\Delta \lambda_0}{\lambda_0} \pm \frac{\Delta \delta_w}{2 \lambda_0} = \frac{\Delta n_h}{n_h} \left( \frac{1}{2} \pm \frac{4 n_l n_h}{\pi(n_h + n_l)^2} \right)
\]  

(3-24)

where the + sign refers to the long wavelength side, and the - sign to the short wavelength side. Inserting \( n_h = 3.5 \) for GaAs and \( n_l = 3.0 \) for AlAs, the fractional shifts \( \Delta \lambda/\lambda_0 \) are 0.82\( \Delta n_h/n_h \) and 0.18\( \Delta n_h/n_h \) on the long and short wavelength sides respectively. Brute-force computer simulations showed slightly greater shifts, of 0.86\( \Delta n_h/n_h \) and 0.21\( \Delta n_h/n_h \). The inaccuracy comes about mostly because of the approximation that we made for the arcsine in equation (3-22).
A 0.1% change in the refractive index should still have a noticeable effect on the spectrum. The simplest electrical perturbation to a quarter-wave stack would be an applied voltage. Whether this might affect the refractive indices is the topic of the next section.

3.2.2 Franz-Keldysh Electroabsorption and Electrorefraction

The idea, then, is to apply a voltage across the quarter-wave stack, as illustrated in Figure 3.10. As was mentioned in section 2.1.2, there was a flurry of interest in the

![Diagram of a quarter-wave stack with electrical contacts.](image)

Figure 3.10. Schematic diagram of a quarter-wave stack with electrical contacts.

effects of an electric field on semiconductors in the late 1950's and the 1960's. To re-
iterate a point made previously, the electro-optic effect\(^ {42} \) is a quite separate phenomenon. The magnitude of the change in refractive index perpendicular to the field is

\[
\Delta n = \frac{n^3 r_e}{2} \mathcal{E} \tag{3-25}
\]
where $E$ is the electric field and $r_e$ is the electro-optic coefficient. For GaAs, $n^3r_e$ is approximately $6.8 \times 10^{-9}$ at 1 $\mu$m wavelength, so a field of 300 $kV/cm$ would induce a refractive index change of 0.001. Randomly polarized light sees both positive and negative changes, so the main effect will be a slight broadening of the spectrum.

Returning now to the Franz-Keldysh effect, the equation for the absorption coefficient, $\alpha$, at a photon energy $E$ and in an applied electric field $E$, is given by Tharmalingam$^{43}$ and Aspnes$^{44}$ as

$$\alpha(E, E) = \frac{A}{E} \left( \frac{qE}{E_0} \right) \left\{ -x[Ai(x)]^2 + [Ai'(x)]^2 \right\}$$  \hspace{1cm} (3-26)

where $Ai(x)$ is the Airy function of the first kind, $Ai'$ is its first derivative, $q$ is an electron charge, $A$ is a constant, best determined by fitting to experimental data, $x$ is a normalized photon energy, given by $x = (E_g - E)/E_0$, and $E_0$ is a characteristic energy, dependent on the electric field, given by

$$E_0 = \left( qE \right)^{2/3} \left( \frac{\hbar^2}{2m_{eh}} \right)^{1/3}$$ \hspace{1cm} (3-27)

where $m_{eh}$ is the reduced effective mass of a hole/electron pair, and $\hbar$ is the reduced Planck's constant. In the zero-field limit, equation (3-26) reduces to

$$\alpha(E, 0) = \frac{A}{E} \left( \frac{2m_{eh} q}{\pi \hbar^2} \right)^{1/2} (E - E_g)^{1/2}.$$ \hspace{1cm} (3-28)

Equation (3-28) contains the familiar square-root dependence near the bandgap, although the $1/E$ factor is often ignored. It should be stressed that these equations only apply "close"
to the bandgap, that is, for photon energies less than 2 eV for GaAs. Using experimental data collected by Bennett et. al.,\textsuperscript{49} equation (3-28) can be written numerically as

\[ \alpha(E,0) = \frac{5.90 \times 10^4}{E} (E - E_g)^{1/2}. \]  

Equations (3-26) and (3-29) were used to plot the absorption coefficient for GaAs for electric fields of zero and 300 kV/cm. The results are shown in Figure 3.11. The values used were: \( m_{eh} = 0.059 m_0 \), where \( m_0 \), the free electron mass, is \( 9.11 \times 10^{-31} \) kg; \( q = 1.6 \times 10^{-19} \) C; \( \hbar = 1.0546 \times 10^{-34} \) Js. With these values, \( E_0 = 1.863 \times 10^{-5} \epsilon^{2/3} \) eV, where \( \epsilon \) is expressed in V/cm.

![Graph showing absorption spectrum with electric fields of 0 and 300 kV/cm](image)

**Figure 3.11.** Effect of an electric field of 300 kV/cm on the absorption spectrum of bulk GaAs.

Airy functions were generated by a FORTRAN subroutine to an accuracy of 4 significant figures. Reference was made to standard mathematical tables.\textsuperscript{84} Series expansions were used for \(-6 < x < 2.8\). Outside these limits the series did not converge well, so approximations involving exponentials, the fourth root of \( x \), and slowly varying
auxiliary functions, were used. Quadratic fits were made to the given numerical values to approximate the auxiliary functions.

The notable features of the spectrum with field are the absorption tail below the bandgap and the oscillatory nature above the bandgap. These result from the form of $\text{Ai}(x)$, which monotonically decreases towards zero for positive arguments and oscillates about zero for negative arguments. A more intuitive physical understanding can be gained from Figure 3.12. As described by Pankove,$^{42}$ the electron wave functions themselves become Airy functions, with their tails extending into the gap. A photon with energy slightly below the bandgap has some probability of being absorbed, since the wave function of the final state also has some amplitude inside the gap and overlaps slightly with the initial state. For photon energies above the bandgap, the oscillating parts of the wave functions overlap; the oscillatory absorption spectrum results from movement of the electron and hole Airy functions past one another as the energy difference is increased. Sub-bandgap electroabsorption has been observed,$^{45}$ as have oscillations above the bandgap.$^{42}$

![Figure 3.12. Photon-assisted tunnelling in a semiconductor with a strong electric field applied.](image)

44
Changes in the absorption spectrum cause changes in the refractive index. This is a result of the Kramers-Kronig equations, which relate the real and imaginary parts of the dielectric constant, or indeed of any complex function that satisfies certain criteria.\textsuperscript{47} An equation can be derived that relates changes in the refractive index to changes in the absorption coefficient:\textsuperscript{42}

\[
\Delta n(E) = \frac{\text{c}\hbar}{\pi} \int_{0}^{\infty} \frac{\Delta \alpha(E') \, dE'}{E'^2 - E^2}
\]

(3-30)

where c is the speed of light in vacuum. Inserting numerical values, one obtains:

\[
\Delta n(E) = 6.29 \times 10^{-6} \int_{0}^{\infty} \frac{\Delta \alpha(E') \, dE'}{E'^2 - E^2}
\]

(3-31)

with \(\alpha\) expressed in cm\(^{-1}\) and E in eV. Seraphin and Bottka\textsuperscript{46} performed this integration numerically, using field-dependent absorption data from equation (3-26). Aspnes\textsuperscript{48} showed that analytical expressions can be obtained for the changes in the real part, \(\varepsilon_1\), and the imaginary part, \(\varepsilon_2\), of the dielectric constant:

\[
\Delta \varepsilon_1(E, \mathcal{E}) = \frac{\mathcal{B} \hbar^2 (E_0/\hbar)^{1/2}}{E^2} m_{\text{eh}}^{3/2} G(x)
\]

(3-32)

\[
\Delta \varepsilon_2(E, \mathcal{E}) = \frac{\mathcal{B} \hbar^2 (E_0/\hbar)^{1/2}}{E^2} m_{\text{eh}}^{3/2} F(x)
\]

(3-33)
where all the symbols have their previously defined meanings, B is a material constant, and
F(x) and G(x) are called the electro-optic functions of the first and second kind, respectively, defined by

\[
F(x) = \pi \left\{ [\text{Ai}'(x)]^2 - x \text{Ai}^2(x) \right\} - (-x)^{1/2}u(-x) \quad (3-34)
\]

\[
G(x) = \pi \left\{ \text{Ai}'(x) \text{Bi}'(x) - x \text{Ai}(x) \text{Bi}(x) \right\} + x^{1/2}u(x). \quad (3-35)
\]

They are plotted in Figure 3.13. \( u(x) \) is the unit step function, and Bi(x) is the Airy function of the second kind.

Equations (3-32) and (3-33) assume only one valence band. GaAs has light and heavy hole bands, and taking this into account alters the magnitude of the changes. We modify the equations accordingly:

\[
\Delta \varepsilon_1(E, \mathcal{E}) = \frac{Bh^2}{E^2} \left\{ (E_0^1/\hbar)^{1/2} m_{\text{ehh}}^{3/2} G(x_1) + (E_0^2/\hbar)^{1/2} m_{\text{elh}}^{3/2} G(x_2) \right\} \quad (3-36)
\]

\[
\Delta \varepsilon_2(E, \mathcal{E}) = \frac{Bh^2}{E^2} \left\{ (E_0^1/\hbar)^{1/2} m_{\text{ehh}}^{3/2} F(x_1) + (E_0^2/\hbar)^{1/2} m_{\text{elh}}^{3/2} F(x_2) \right\} \quad (3-37)
\]

where \( m_{\text{ehh}} \) and \( m_{\text{elh}} \) are the reduced effective masses of the electron and heavy or light holes, and the subscripts 1 or 2 for \( E_0 \) and \( x \) indicate that heavy or light hole masses, respectively, should be used in calculating these values.

Bennett and Soref\textsuperscript{49} incorporate extra factors involving effective masses into each of the terms inside the large parentheses in equations (3-36) and (3-37). They further increase the electrorefractive effect, and make the light hole band dominant, but do not appear to be
consistent with Aspnes's derivation. Therefore we use the equations in the form presented here.

We now relate the absorption coefficient, \( \alpha \), and the refractive index, \( n \), to the dielectric constant, \( \varepsilon \):
\[ \varepsilon = \varepsilon_1 + i\varepsilon_2 = (n + ik)^2 \] (3-38)

where \( k \), the extinction coefficient, is related to \( \alpha \) through the equation \( \alpha = 4\pi k/\lambda \). Taking derivatives, and noting that \( n \) is much larger than \( k \) in the energy range of interest, it is easy to derive the following equations:

\[ \Delta n = \frac{\Delta \varepsilon_1}{2n} \] (3-39)

\[ \Delta \alpha = \frac{\omega \Delta \varepsilon_2}{cn}. \] (3-40)

Thus we can obtain an expression for \( \Delta n \):

\[ \Delta n(E,E) = \frac{B h^2}{2nE^2} \left( (E_0 / h)^{1/2} m_{e_h}^{3/2} G(x_1) + (E_0 / h)^{1/2} m_{e_l}^{3/2} G(x_2) \right). \] (3-41)

The constant \( B \) can be obtained by noting that it shows up in equation (3-33) for \( \Delta \varepsilon_2 \), which is related through equation (3-40) to \( \Delta \alpha \), which is known from equations (3-26) and (3-28). Tidying up, one obtains the equation:

\[ \alpha(E,0) = \frac{B h^{3/2}}{nc} (m_{e_h}^{3/2} + m_{e_l}^{3/2}) \left( \frac{E - E_g}{E} \right)^{1/2}. \] (3-42)

\( B \) can now be calculated by equating equations (3-29) and (3-42). Using \( m_{hh} = 0.45m_0 \) and \( m_{lh} = 0.084m_0 \), a numerical form is finally obtained:

\[ \Delta n(E,E) = \frac{3.589 \times 10^{-4} E^{1/3}}{E^2} \left[ G(x_1) + 0.549G(x_2) \right] \] (3-43)
with $\mathcal{E}$ expressed in V/cm and $E$ in eV. Equation (3-43) is plotted in Figure 3.14 for two electric fields, 30 kV/cm and 300 kV/cm. Note that $\Delta n$ is not linear with field. The vertical scale is logarithmic, and the abrupt change of slope near the bandgap indicates where $\Delta n$ becomes negative. The electro-optic function $G(x)$ is plotted on a linear scale in Figure 3.13 for comparison.

![Graph showing change in n (abs.) with energy (eV) for 30 kV/cm and 300 kV/cm.]

**Figure 3.14.** Effect on the refractive index of GaAs of electric fields of 30 kV/cm and 300 kV/cm.

As can be seen in Figure 3.14, an increase in refractive index of over 0.002 can be obtained close to the bandgap with an applied field of 300 kV/cm. The change is still 0.001 150 meV below the bandgap. Figure 3.11 shows that there will be very little electroabsorption in the energy range of interest. While the breakdown electric field of GaAs can be as high as 300 kV/cm, devices may break down at lower fields. Figure 3.15 shows $\Delta n$ versus electric field for several photon energies.

The quarter-wave stack contains two different materials. For our devices, one was GaAs and the other was Al$_x$Ga$_{1-x}$As. Equation (2-1) shows that the bandgap of material containing Al is considerably higher than that of GaAs. Thus any photon energy below the
bandgap of GaAs will be further below the Al$_x$Ga$_{1-x}$As bandgap. From Figure 3.14 we can conclude that the electrorefractive effect will be much weaker in the Al$_x$Ga$_{1-x}$As, so we will ignore it. For these devices, only the refractive index of the GaAs will be affected.

3.2.3 Electroabsorption and Electrorefraction in Quantum Wells

Most optoelectronic devices, such as semiconductor lasers, function better when quantum wells are incorporated. It was therefore reasonable to investigate whether or not we might obtain greater shifts in the spectrum by inserting quantum wells into some of the layers. Our approach to calculating electrorefraction in quantum wells was very similar to the established technique for bulk material. The intention was to determine electroabsorptive effects first, and to derive the electrorefraction by a Kramers-Kronig analysis.
As described in section 2.3, a quantum well consists of a thin layer of a semiconductor sandwiched between layers of material that has a greater bandgap. The resulting discontinuities in the conduction and valence bands confine electrons and holes to the thin layer. If the layer is thinner than 200 Å, discrete states become observable. The allowed levels can be calculated using the Kronig-Penney model (see section 2.3.1) or the tunnelling resonance technique. Since this latter technique also gives the energy levels in an applied field, it was used for our calculations.

Miller et. al.\textsuperscript{61} showed that the absorption coefficient in quantum wells can be expressed as

\[
\alpha(E) = \frac{C}{E} \sum_{p,q} u(E - E_g - E_{e_p} - E_{h_q}) I_{pq}
\]  
(3-44)

where \(C\) is a constant depending on the two-dimensional density of states and various material parameters, \(u(x)\) is the unit step function, \(E_{e_p}\) and \(E_{h_q}\) are the energy levels of the \(p^{th}\) confined electron state and the \(q^{th}\) hole state, respectively, and \(I_{pq}\) is the overlap integral of the hole and electron states, \(\phi_{e_p}\) and \(\phi_{h_q}\), given by

\[
I_{pq} = \frac{\left| \int \phi_{e_p}(z) \phi_{h_q}(z) \, dz \right|^2}{\int |\phi_{e_p}(z)|^2 \, dz \int |\phi_{h_q}(z)|^2 \, dz}.
\]  
(3-45)

The limits for the integrations cause some trouble. For quantum wells with infinite barriers, the wavefunctions go to zero at the edges of the well, so the appropriate limits are those edges. For finite barriers, some fraction of the wave function extends into the barrier material; this fraction can be quite large when strong electric fields are applied. Miller et.
al. only considered infinite barriers. With the easy boundary conditions, they were able to obtain exact Airy function solutions. Our calculations were all performed for finite barriers, to approach reality more closely.

The tunnelling resonance method was used to calculate the confined states for holes and electrons. Only the heavy-hole valence band was considered, to keep the mathematics simpler. The potential profile shown in Figure 3.16 was used for the conduction band, and an analogous one was used for the valence band. For the calculations, described at length by Harwit et. al., the sloping potential was approximated by a series of steps. Plane waves were propagated from step to step by a transmission matrix technique, very similar to the optical transmission matrix technique presented earlier. The zero-field solutions to Schrödinger's equation, equation (2-4), are imaginary exponentials or sinusoids in the well, and real exponentials in the barriers. With a field applied, the solutions become Airy
functions, although these were approximated by piecewise exponentials in the method we used. A boundary condition was required at one side of the structure. Best results were obtained by imposing a decaying real exponential at the left hand side.

Wave functions were calculated for GaAs quantum wells of 160 Å and 80 Å.

Figure 3.17. Calculated wave functions for the first three confined electron states in a 160 Å GaAs quantum well with 70 Å Al$_{0.5}$Ga$_{0.5}$As barriers for electric fields of a) 0 V/cm, and b) 300 kV/cm.
thickness, with 70 Å Al$_{0.5}$Ga$_{0.5}$As barriers. The first three electron states for a 160 Å well are shown in Figure 3.17 for zero field and for an applied field of 300 kV/cm. The sharp rise in amplitude at the right hand side of the structure is due to slight inaccuracies in the calculations of the energy levels. These anomalies suggested suitable limits for the integrations in equation (3.45), namely the points within which the hole and electron wave functions behaved properly! The hole states looked very similar, except that under applied field the wave functions were distorted toward the other side of the well.

Absorption spectra were then calculated using equations (3.44) and (3.45), the integrations being performed numerically using Simpson's method. For the 160 Å well, 4 electron states and 7 hole states were obtained. The constant C was determined by noting that the steps in the zero-bias spectrum should exactly hit the absorption spectrum of bulk material at the allowed transition energies. The calculated zero-bias spectrum for the 160 Å

![Absorption Spectrum](image)

**Figure 3.18.** Calculated zero-bias absorption spectra for bulk GaAs and for a 160 Å GaAs quantum well with 70 Å Al$_{0.5}$Ga$_{0.5}$As barriers.

well is shown in Figure 3.18, with the bulk spectrum given for comparison. Each point on the stepped curve corresponds to a possible transition between an electron level and a hole.
level. The size of the step at each point is proportional to the overlap integral of the two wave functions. In zero bias, the only allowed transitions are those between holes and electrons with the same principal quantum number, that is, for \( p = q \).

The calculated absorption spectra for the two different well sizes with an applied field of 100 kV/cm are shown in Figure 3.19. The absorption spectra are now much richer since

![Absorption spectra](image)

**Figure 3.19.** Calculated absorption spectra for bulk GaAs and a) a 160 Å GaAs quantum well, b) an 80 Å well, in an applied field of 100 kV/cm.
Figure 3.20. Logarithmic plots of the calculated absorption spectra for bulk GaAs and a) a 160 Å GaAs quantum well, b) an 80 Å well, in an applied field of 100 kV/cm.

The field breaks the symmetry of the structure, causing previously forbidden transitions to become allowed, strongly in some cases. The spectrum for bulk material is included for comparison. The spectra with applied field are shown on a logarithmic scale in Figure 3.20. While the shapes of the quantum well absorption curves follow the bulk curve fairly closely, the sub-bandgap tails are cut off sharply at the first allowed transition.
These spectra are quite similar to those calculated by Miller et. al.,\textsuperscript{63} and give a reasonably good qualitative picture of what should happen, apart from exciton effects. However, the difficulties in obtaining accurate wave functions for the quasi-bound states under strong applied field mean that actual numerical values are not very trustworthy. Miller et. al.\textsuperscript{85} derived sum rules for electroabsorption in quantum wells, showing that the total area under the absorption curve must stay constant with an applied field, and also that the total area for each state must stay constant. This last rule means, for instance, that the integrated absorption for all transitions involving the first electron state must not change with an applied field. Partial experimental confirmation has been published.\textsuperscript{86} These rules were not followed by our calculations. The total area decreased considerably with increasing field, especially when fields larger than 100 kV/cm were applied. Miller et. al. do not state whether their technique with infinite barriers leads to agreement with the sum rules. If it does, it could be the best method to use. The effect of finite barriers could be simulated by using an effective well width, so that the ground state zero-field energy level agrees with the corresponding level of the actual well. This method would not be satisfactory for excited states, however.

The difficulties described above make it impossible to derive electrorefraction accurately from the absorption spectrum. An attempt was made to use the Kramers-Kronig relationship, equation (3-30), but the results indicated a decrease in refractive index for all photon energies. This was a direct result of the decrease in integrated electroabsorption. Other authors have published calculations of quantum well electrorefraction. Most groups\textsuperscript{67,68} considered only the ground state exciton transition, since they were primarily interested effects very close to this energy. One group\textsuperscript{66} did however attempt the calculation following a similar approach to ours, neglecting excitons, although their technique for finding electron states was much more elaborate. They simulated a 300 Å GaInAsP/InP quantum well. Their calculations predicted that for an applied field of 100 kV/cm, there would be a sub-bandgap electrorefractive effect of considerable
magnitude; the change in refractive index increased from zero 25 meV below the bandgap to 0.15% 100 meV below. This, unfortunately, was where their graph stopped. It is difficult to understand how a quantum well, almost thick enough to be considered bulk, could give more electrorefraction than bulk material, with a very different wavelength dispersion.

To estimate the magnitude of the effect, therefore, we resort to intuitive arguments. Our calculations for a 160 Å quantum well, and Miller et. al.'s for a 150 Å well, show that at strong fields the stepped electroabsorption spectrum follows the shape of the bulk spectrum quite closely. For narrower wells this is not the case, since the states are not perturbed as much. Therefore, we can expect that wide quantum wells of around 150 Å should exhibit similar electrorefraction to bulk material, while narrower wells will show less. This will not necessarily be true for photon energies very close to exciton transitions.

Thus it appears that quantum wells will not enhance the performance of our devices in terms of spectral shift. However, the sharp cut-off of absorption for photon energies below the lowest transition means that structures containing quantum wells will absorb even less light than regular ones. This may prove to be useful if very high optical power levels are being used.

3.2.4 Effect of Temperature on the Refractive Index

The changes in refractive index that can be obtained electrically are very small. Therefore it is important to know how sensitive the devices will be to other external perturbations, the most important of which is temperature. Blakemore's review paper\textsuperscript{32} on GaAs contains useful information on this topic, showing (using data from Marple\textsuperscript{36}) that the refractive index increases at a rate of approximately $2.5 \times 10^{-4}$/K at a photon energy of 1.2 eV, the rate increasing slightly closer to the bandgap. No physical model is presented
for the behavior near the bandgap, although justification is given for the temperature
dependence of the long wavelength index, \( n_{\infty} \). It is shown that

\[
\frac{dn_{\infty}}{dT} = 1.5 \times 10^{-4}/\text{K.} \tag{3-46}
\]

The remainder of the temperature variation seen by Marple was due to the reduction in
the bandgap with increasing temperature. This brings the bandgap closer to the photon
energy. If the temperature dependence of the entire absorption spectrum were known, it
would be possible to perform Kramers-Kronig analysis to derive the temperature
dependence of the refractive index. This is not the case, however, so it is best to use
published experimental data.

No data is available on the temperature dependence of the refractive index of AlAs.
We would expect only to see a contribution from the long wavelength index, \( n_{\infty} \), since the
photon energies of interest will be a long way below the bandgap. As a first
approximation, we could assume that the refractive index of AlAs is independent of
temperature, so that the only effect is the \( 2.5 \times 10^{-4}/\text{K} \) change in the refractive index of
GaAs. Since we expect an electrically-induced change of 2 to \( 3 \times 10^{-3} \), the temperature
needs to be held stable to within a few degrees.

### 3.3 Design of Experimental Structures

The basic idea for the structure is shown in Figure 3.10. Devices need to have a
quarter-wave reflector structure and electrical contacts. The variables to consider were: the
wavelength of operation, what materials to use, the number of periods, and the method for
making electrical contact.
The operating wavelength had to be in the region where GaAs is non-absorbing, since it was intended that the structures would be fabricated by MBE on doped GaAs substrates. The bandgap of GaAs is 1.42 eV, which corresponds to a wavelength of 8720 Å. This was calculated using the simple relationship,

$$E\ (eV) = \frac{\hbar \nu}{q} = \frac{\hbar \omega}{q} = \frac{12400}{\lambda(\text{Å})}. \quad (3-47)$$

Doped substrate material absorbs some light at longer wavelengths because of bandtail states. In order to be well clear of any absorption the device should be designed to operate at a wavelength greater than 9200 Å. There is always some uncertainty, maybe ± 5%, in MBE growth rates, so it was decided that the devices should have their high-reflectance band centered at 1 μm wavelength. This should put the short wavelength edge of the band at around 9500 Å. In the event that the layers should come out much thinner than intended, the long wavelength edge would still be usable. As was mentioned in section 3.2.1, the long wavelength edge is expected to shift more for a given change in refractive index. Thus it would make sense to design devices with the long wavelength edge of the high-reflectance band at around 9500 Å and with the short wavelength edge buried by absorption. However, it was intended that these devices should demonstrate several effects, including the full high-reflectance band. A spectrum showing only half of it would be less interesting.

The choice of materials was simple. The main objective was to maximize the refractive index difference, since this would minimize the number of layers required. Within the Al$_x$Ga$_{1-x}$As material system, this is obtained by using GaAs and AlAs, with refractive indices at 1 μm of around 3.5 and 3.0 respectively. Quarter-wave thicknesses are therefore approximately 710 Å and 830 Å. It was also desired that a sample should be fabricated incorporating quantum wells, to ascertain whether a similar electrorefractive
effect could indeed be obtained. Therefore the GaAs layers were to be replaced by relatively thick GaAs quantum wells, with Al$_{0.5}$Ga$_{0.5}$As barriers. This choice of barrier material gave about the largest conduction band offset, and conveniently allowed equal growth rates of GaAs and AlAs in the MBE chamber. The barriers needed to be at least 50 Å wide, to minimize coupling between wells; it was also desired to keep them as thin as possible, so that the average refractive index of the quantum well layers would be as high as possible. Assuming that the wells were going to be rather thicker than the barriers, the refractive index of the quantum well material was estimated as 3.4. An average value was appropriate, since the layers were going to be too thin for the light to see them individually. A quarter-wavelength layer would therefore have a thickness of around 740 Å. Suitable thicknesses were therefore 160 Å for 3 GaAs quantum wells, and 65 Å for the 4 Al$_{0.5}$Ga$_{0.5}$As barrier layers.

The choice of the number of periods in the reflector layers was based on two main criteria and some secondary considerations. First, the transmission in the high-reflectance band had to be very low. 1% was arbitrarily selected as the maximum permissible. Insertion of the appropriate values into equation (3-13) showed that a minimum of 16 periods of GaAs and AlAs are required to meet that standard, or 20 periods of quantum wells and AlAs. Secondly, the edges of the high-reflectance band had to be sharp enough that the expected small spectral shifts would be sufficient to cause noticeable modulation in the transmitted intensity. From section 3.2.2, we expect a maximum change in refractive index on the order of 0.1% in the GaAs or quantum well layers. This translates to a spectral shift of around 9 Å on the long wavelength side of the band, and rather less on the short wavelength side. These shifts are quite small, of the same order as the stability of an average semiconductor laser source.

Computer simulations were performed to predict the sharpness of the edges. Since the edges are roughly parabolic, as shown in Figure 3.21, a convenient measure is the wavelength range, δ, over which the transmission doubles or halves, say between 20% and
40%. The predicted values for $\delta$, the same on each side, are given as a function of the number of periods in Table 3.1.

![Graph showing transmittance as a function of wavelength with $\delta$ indicated](image)

**Figure 3.21.** The measure of sharpness, $\delta$, for the transmission spectrum of a quarter-wave stack, is the range of wavelength over which the transmittance doubles.

**Table 3.1.** Effect of the number of periods on the sharpness of the spectrum.

<table>
<thead>
<tr>
<th># of Periods</th>
<th>$\delta$ GaAs/ AlAs (Å)</th>
<th>$\delta$ Quantum Well/ AlAs (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>30</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>40</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>50</td>
<td>2.5</td>
<td>3.5</td>
</tr>
</tbody>
</table>

It appears from Table 3.1 that one would like to have as many periods as possible. There are, however, a number of hazy upper limits. Firstly, the MBE machine has a limited quantity of source material and several people want to use it; several $10\,\mu\text{m}$ thick device structures would take a lot of time and seriously deplete the sources. Secondly, Figure 3.15 shows that a very strong electric field is required in order to see any effect.
For a given spectral shift, therefore, a thicker structure requires a greater voltage. A field of 300 kV/cm would drop 4.5 V across each 1500 Å period. A 50-period structure, therefore, would need over 200 V to drive it. This was regarded as excessive, but the device was obviously not going to be a low voltage one. Next, there comes a point where extra layers will not improve matters when laser light is unavailable, as was going to be the case for all of our measurements. The theory for multi-layer interference filters assumes that the incident light is coherent. For monochromated white light, as used in our experiments, the coherence length is only a few wavelengths. Structures more than "a few" wavelengths thick cannot be considered thin films, and the theory starts to break down. These then were the considerations. The compromise chosen was to put 30 periods in the regular quarter-wave stack and 40 periods in the quantum well sample. These numbers put the sharpness, δ, below 10 Å. It was anticipated that non-uniformities across the wafer would be limiting at this point.

As a side experiment, a third structure was designed with an asymmetric multi-layer reflector, containing three eighths wavelength GaAs layers and one eighth wavelength AlAs layers. Such a structure had been suggested, but not demonstrated, by Gourley. The theoretical transmission spectrum is asymmetric, but it still exhibits a band of high reflectance, albeit rather narrower than for a quarter-wave stack. The motivation for building this structure was two-fold: Firstly, a larger fraction of the structure is GaAs, and since only the GaAs will be affected by an applied electric field, this should increase any spectral shifts that might be obtained. Secondly, it was hoped that one of the edges of the high-reflectance band might be sharper and cover a wider range of transmittance than the corresponding edge for a symmetric quarter-wave stack. For comparison's sake, a 30-period structure was designed for this one too. The values of δ (compare with Table 3.1) were calculated to be 14 Å on both sides of the band. Theoretical transmission spectra for the symmetric and asymmetric 30-period structures are shown in Figure 3.22.
Figure 3.22. Theoretical transmission spectra for a) the 30-period symmetric GaAs/AlAs quarter-wave stack, and b) the 30-period asymmetric structure, consisting of three-eighths wavelength GaAs and one-eighth wavelength AlAs layers.

Finally, the question of electrical contacts had to be addressed. The simplest method for applying a strong electric field across the whole of a device structure is to use Schottky contacts. Schottky diodes, metal to semiconductor junctions, are described in every device physics textbook, and Sze\textsuperscript{30} gives a good description. Most metals in contact with GaAs form a Schottky diode with a barrier height of 0.62 eV to 0.75 eV.\textsuperscript{51} Aluminum is suitable
and easy to deposit. It is necessary to have clean contacts if good reverse bias characteristics are desired. A particular advantage of Al is that it is available in the MBE chamber, usually for growth of Al,Ga,As, and can therefore be deposited in-situ, without breaking the vacuum. A very thin layer is partially transparent to light. Aluminum forms an oxide of around 10 to 20 Å thickness in air, so the deposited layer needs to be thicker than this. Cho showed that in many cases the aluminum is deposited as a single crystal, and that the barrier height is around 0.7 eV. The characteristics are severely degraded if the Al sees temperatures high enough for annealing. Care must therefore be taken to allow the substrate to cool down before the metal is deposited.

To keep the electric field as uniform as possible, the whole reflector structure should be lightly doped. N-type silicon doping at 10^15/cm^3 was selected, since the background impurities in our MBE cause doping levels in the 10^14 range. Heavily n-type doped substrates were used. Alloyed ohmic contacts to the substrate could not be used, since the high temperature would damage the top Schottky contact, so Al was selected for the substrate too. The diode thus formed would be forward biased, with heavily doped material, so the voltage drop would be negligible.

The average electric field will be approximately the applied voltage divided by the thickness of the epitaxial layers. Because of the ionized impurities, however, the field will vary slightly. Poisson's equation can be written as

\[
\frac{d\mathcal{E}}{dx} = \frac{qN_D}{\varepsilon_0 \varepsilon}
\]

where \(N_D\) is the density of ionized donors, \(q\) is an electron charge, \(\varepsilon_0\) is the permittivity of free space, and \(\varepsilon\) is the dielectric constant. Assuming full carrier depletion, the change in field, \(\Delta\mathcal{E}\), across a layer of thickness \(d\) is given by
\[ \Delta \mathcal{E} = \frac{qN_D d}{\varepsilon \varepsilon_0}. \] (3-48)

For a 5 \( \mu m \) layer, with \( N_D = 10^{15} / \text{cm}^3 \), and \( \varepsilon \varepsilon_0 = 10^{-12} \text{ F/cm} \), equation (3-48) gives a change of field of 80000 V/cm. At the Schottky junction the field will therefore be 40 kV/cm higher than the average value. This variation of field across the structure will lead to some broadening of the spectrum, since different parts of the structure will be subjected to different applied fields and will therefore exhibit different shifts in their refractive indices.

### 3.4 FABRICATION

A schematic cross-section of the actual devices is shown in Figure 3.23. A thin buffer layer was incorporated to smooth out any irregularities in the substrate. The symmetric quarter-wave stack contained 30 periods of alternating layers of GaAs, 714 Å thick, and AlAs, 833 Å thick. In the 40-period stack with quantum wells, each GaAs layer was replaced by three 160 Å GaAs quantum wells with 65 Å Al\(_{0.5}\)Ga\(_{0.5}\)As barriers. In the 30-period asymmetric structure, the thicknesses were 1071 Å for GaAs and 417 Å for AlAs.

The structures were all grown on 5 cm diameter substrates in Stanford University's Varian Gen II MBE machine. A growth rate of 0.5 \( \mu m / h \) was selected for both GaAs and AlAs. This rather slow rate has been found experimentally to give smoother interfaces and to reduce the number of oval defects. The substrates were rotated at approximately 10 rpm for the sake of uniformity across the wafers.

The topic of substrate temperature is rather complex. The indicated substrate temperatures were 680°C for the GaAs/AlAs structures and 750°C for the sample containing quantum wells. It has been found\(^5\) that the quality of Al\(_x\)Ga\(_{1-x}\)As for optical
devices improves monotonically with increasing substrate temperature. At a certain point, however, GaAs begins to desorb, so the flux rates need to be increased to compensate for

![Diagram of a semiconductor structure](image)

**Figure 3.23.** Schematic diagram of the modulator. The multi-layer reflector was a 30-period GaAs/AlAs quarter-wave stack in the first sample, a 30-period three-eighths wavelength GaAs/one-eighth wavelength AlAs stack in the second sample, and a 40-period multiple quantum well/AlAs quarter-wave stack in the third sample.

...this loss. The amount of material that is lost is hard to predict and is different for GaAs and Al$_x$Ga$_{1-x}$As. In our system, 750°C has been found to be the point where this starts to be noticeable, and the Ga flux rate was increased by 3% to keep the required growth rate. The temperatures given by Ralston et. al. are rather lower than ours. This is a result of errors in the thermocouple readings in our machine. Since the wafer is not soldered to a block, but instead held on with wires, it does not become as hot as the thermocouple,
which is closer to the heater. Hellman et. al.\textsuperscript{55} compared thermocouple and pyrometer readings and found a considerable difference. An indicated temperature of 750°C corresponds to a pyrometer temperature of around 650°C, while 680°C indicated is probably close to an actual temperature of 600°C. Accurate measurement of substrate temperatures has always been a problem for MBE growers. The substrate was allowed to cool down to 50°C with arsenic overpressure before the Al Schottky layer was deposited. The thickness of the Al was nominally 200 Å, but uncalibrated. The growth rates of GaAs and AlAs had been calibrated using RHEED oscillations.\textsuperscript{54} The entire MBE growth process, including the setting of source and substrate temperatures and the operation of the shutters, was controlled by a Hewlett-Packard 9000 computer.

The post-growth processing was extremely simple. Aluminum dots were deposited, on both sides of the wafer, through a shadow mask in a bell-jar evaporator. The dots were approximately 3000 Å thick, and 0.25 mm to 1 mm in diameter. They served as robust contacts to allow probing on the epitaxial side of the wafer. An attempt was made to align the dots on the front and rear, so that light would be able to pass between them and through the whole structure. This was found to be no problem. The wafers were then cleaved into small pieces a few millimeters on a side.

\section*{3.5 Experimental Apparatus}

The sample holder consisted of a sheet of aluminum with a small hole, approximately 0.5 mm in diameter, drilled through it. A sprung steel clip, its end protected by insulating tape, was used to hold the sample in position over the hole. Ga/In paint, a liquid at room temperature, was applied to the sample to make good electrical and thermal contact to the aluminum sheet, which formed the positive, grounded, electrode. Tungsten wire, of 0.35 mm diameter, was bent into a suitable shape to act as a probe to make an electrical
connection between the front side of the wafer and a terminal block. The block was connected to the negative terminal of a DC voltage supply that was capable of providing up to 1000 V. A K-type thermocouple was attached to the regular quarter-wave sample with thermally conductive epoxy.

The apparatus for measuring transmission spectra is shown in Figure 3.24. The samples were illuminated with chopped, focussed white light. They were arranged so that
light passed through the substrate first, so that all of the light that might be absorbed was absorbed in the substrate rather than in the epitaxial layers. The light was then focussed into a Spex 1870B 0.5 meter spectrometer, with a cooled S-1 photomultiplier as the detector. Most spectra were taken with the spectrometer slits set to a width of 100 μm, giving 1.6 Å wavelength resolution. The output of the photomultiplier was taken to a lock-in amplifier. The lock-in and spectrometer were both under the full control of our HP 9000 computer.

3.6 EXPERIMENTAL ZERO-FIELD OPTICAL TRANSMISSION RESULTS

All of the zero-field spectra presented for these devices were normalized to take out system non-linearities. A spectrum was measured with the sample holder empty. The measured signal with a device in place was divided by the measured signal for the empty holder at that wavelength. Two effects were expected to reduce the measured transmittances below the theoretical ones presented in Figure 3.22: approximately 30% of the light would be reflected at the air to substrate interface (see equation 3-1), and an unknown amount would be reflected by the Al Schottky layer.

3.6.1 Zero-Field Transmission Spectra

Figure 3.25 contains experimental zero-bias transmission spectra for the three samples. These may be compared with the theoretical spectra presented in Figure 3.22. Measured values for the sharpness, δ, defined in section 3.3, are given in Table 3.2.
Figure 3.25. Experimental zero-bias transmission spectra for a) the symmetric quarter-wave stack, b) the symmetric quarter-wave stack with quantum wells, and c) the asymmetric structure.
Table 3.2. Experimental and theoretical values of $\delta$ (Å).

<table>
<thead>
<tr>
<th></th>
<th>SHORT WAVELENGTH</th>
<th>LONG WAVELENGTH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\delta$(theory)</td>
<td>$\delta$(experimental)</td>
</tr>
<tr>
<td>Quarter-wave</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td>Quantum Well</td>
<td>6</td>
<td>26</td>
</tr>
<tr>
<td>Asymmetric</td>
<td>14</td>
<td>26</td>
</tr>
</tbody>
</table>

3.6.2 Uniformity Across the Wafer

The peak on the short wavelength side of the high-reflectance band of the regular quarter-wave stack was selected for monitoring, since it was the sharpest feature in any of

![Graph showing percentage shift in peak wavelength as a function of distance from center (cm)](image)

Figure 3.26. Percentage shift in the wavelength of the transmission peak at the short wavelength side of the high-reflectance band for the symmetric quarter-wave stack, as a function of the distance from the center of the wafer.
the spectra. Its wavelength was measured at several points across the wafer. The percentage shift in the peak position is shown as a function of distance from the center of the wafer in Figure 3.26.

### 3.6.3 Effect of Tilt

The long wavelength peak of the quantum well sample was used in this case, since there was a danger that the peak used in 3.6.2 above might disappear into the band-edge absorption at a large angle of tilt. Transmission spectra were measured at various angles of tilt. Parts of the spectra for zero tilt and 60° of tilt are shown in Figure 3.27. The fractional shift in the peak compared to its position for normal incidence is plotted in Figure 3.28; the cosine of the internal angle (taking Snell's law into account) is also plotted for comparison.

![Graph showing transmission spectra for 0° and 60° tilt](image)

**Figure 3.27.** Effect of tilt on the transmission spectrum: spectra are shown for the symmetric quarter-wave stack at angles of 0° and 60°.
Figure 3.28. Normalized wavelength of a peak in the transmission spectrum of the quantum well quarter-wave stack, as a function of tilt angle.

3.7 EXPERIMENTAL MODULATION RESULTS

3.7.1 Effect of an Electric Field on the Transmission Spectra

Figure 3.29 shows the effect of a strong electric field on parts of the spectra for the two quarter-wave samples. The transmission spectrum for the asymmetric sample was considered not to be sharp enough for it to be worth testing under bias. The devices broke down catastrophically at average applied fields of 200 to 220 kV/cm. The breakdown was somewhat soft. Just below catastrophic breakdown, at an applied voltage of around 100 V, a current of 10 mA was flowing. The quarter-wave device reached a temperature of 40°C at this point, a rise of 17 K over room temperature.
3.7.2 Modulation of Light

The spectral shifts shown in Figure 3.29 were sufficient to cause modulation of light at various wavelengths. Figure 3.30 contains plots of transmission versus applied field at various wavelengths for the two samples tested. The field-induced shifts were between
10 Å and 15 Å. The selected wavelengths were on the sharpest parts of the spectra, naturally. The maximum modulation ratio was approximately 2.5 for the regular quarter-wave sample, at a wavelength of 9100 Å.

Figure 3.30. Transmittance at selected wavelengths as a function of electric field for a) the symmetric quarter-wave stack, on the short wavelength side of the high-reflectance band, and b) the quantum well quarter-wave stack on the long wavelength side.
3.7.3 Effect of Temperature

The short wavelength edge of the high-reflectance band of the symmetric quarter-wave stack is shown in Figure 3.31 for temperatures of 28°C and 49°C. A hot air blower was used to heat the sample stage; conduction of heat to the sample raised its temperature. The shift in the spectrum was approximately 10 Å, corresponding to 0.5 Å/K.

![Figure 3.31](image)

Figure 3.31. Transmission spectra for the symmetric quarter-wave stack in ambient temperatures of 28°C and 49°C.

3.8 DISCUSSION

3.8.1 Comparison of Results with Theory

The zero-bias optical transmission spectra showed quite good agreement with theory, as can be seen by comparing Figures 3.22 and 3.25. The symmetrical quarter-wave sample, in particular, gave a spectrum very similar in shape and position to the simulation. The width of the high-reflectance band was almost exactly the same as the theoretical value.
The maximum values of transmittance for all of the samples were much less than in the simulations because of reflections from the aluminum Schottky contact layer and from the substrate to air interface. Anti-reflection coatings on these surfaces could boost the maximum transmittance. It is likely that there would have been a small amount of absorption due to free carriers in the heavily doped substrates too. The transmittance in the high-reflectance band was very small for both quarter-wave samples, less than 1% even if the spectra are scaled up to give the predicted peak transmittances. The spectrum for the quantum well sample occurs at a slightly shorter wavelength than intended. The error is within the possible calibration error of our MBE machine. It may also be caused by GaAs desorption at the elevated substrate temperature that was not fully compensated for when the beam fluxes were set.

The asymmetric structure showed some asymmetry and a narrower reflectance band in its transmission spectrum, as expected, but the spectrum was generally not as sharp as the others. The reason for this is not clear. Possibly this type of structure is much more sensitive to irregularities in the layers. Our computer simulations showed that this structure is more sensitive to random thickness fluctuations than is the quarter-wave stack. Although Gourley\textsuperscript{87} proposed this structure, his group has never published any experimental spectra, so maybe it is very difficult to fabricate good devices of this type.

None of the reflectance band edges were as sharp as for the simulated spectra. There are several possible explanations for this. First, non-uniformities across the measurement area would broaden the spectrum. To increase a feature width from 8 Å to 13 Å would require only a 0.1% variation across the sample. From Figure 3.26 we expect rather less than that, since the sample was taken from close to the center of the wafer, and the spot size was approximately 0.5 mm. Some broadening would also have occurred because the light was conical, with a half-angle whose sine was 1/14, to match the input of the spectrometer. This would cause a $\Delta \lambda_\phi$, from equation (3-19), of 2 to 3 Å, which is fairly insignificant. Another cause of broadening could be oval defects, which are present in all MBE-grown
material to an extent dependent on the thickness of the layer. For these thick structures, our machine produces defect densities of several thousand per square cm, so there would certainly have been several inside the measurement area. These defects cause unevenness in the layers, and would therefore cause broadening of the spectrum. A final possible source of broadening lies in the thicknesses of the structures; it is possible that they were beyond the limit of what can be considered "thin films", so that the simulations, assuming coherent light, were not valid.

The reader may observe differences between the spectra of Figure 3.25 and our published spectra. The spectra presented here were taken more recently, with a smaller spot size and a much brighter white light source (a 100 W quartz halogen spotlamp). In the case of the asymmetric sample, it is possible that the new spectrum was taken for a sample closer to the center of the wafer than was the original spectrum. The difference in the vertical scales arises from a difference in the normalization techniques. The spectra presented here have been corrected for the response of the system, as described in the introduction to section 3.6. The published spectra were normalized with respect to a "dummy" wafer, which consisted of a heavily doped substrate with a thick layer of Al_{x}Ga_{1-x}As on it. The idea was to remove the effects of substrate absorption and reflection. The factors of 3 to 4 by which the published transmittances are higher is not fully accounted for by this. The dummy may have been more absorbing than the device substrates, as a result of heavier doping in the substrate or in the epitaxial layer.

The uniformity measurement, Figure 3.26, shows that the layer thicknesses varied by 3 to 4% between the center and the edge of the wafer. It is difficult to determine precisely the variation in thickness from the movement of a peak, since the flux non-uniformities may be different for the different sources.

The variation of the peak position with angle of tilt followed the cosine law very closely. As was predicted in section 3.1.4, there was some broadening of the spectrum too.
The maximum field that could be applied was 220 kV/cm, calculated by dividing the applied voltage by the total thickness of the epitaxial layers. As was noted in section 3.3, the field does in fact vary through the thickness of the structure because of ionized impurities. If the doping density was indeed $10^{15}$/cm$^3$ as intended, then the electric field at the contact at breakdown was 260 kV/cm, which is very respectable.

The shift in the spectrum that was obtained by increasing the temperature was not consistent with the assertion that only the refractive index of the GaAs would change. From section 3.2.4, we expect a refractive index change of $2.5 \times 10^{-4} /$K. From section 3.2.1, this should result in a spectral shift of roughly $0.2 \times 2.5 \times 10^{-4} /$K/$3.5 \times 10000$ Å, or 0.15 Å/K, on the short wavelength side of the high-reflectance band. This is much less than the observed shift of 0.5 Å/K, so the index of AlAs must have a similar temperature dependence to that of GaAs. If the two indices had the same temperature dependence, the shift would be around 0.7 Å/K; we can conclude that the refractive index of AlAs increases more slowly with temperature than that of GaAs.

Thermal effects also help to explain why the spectral shifts with applied electric field were rather larger than expected. The short wavelength side of the high-reflectance band of the regular quarter-wave stack shifted by about 13 Å with an applied field of 220 kV/cm. The 17 K temperature rise accounts for approximately 8 Å, or 60% of that shift. If the device had had a better heatsink or a more sophisticated structure to reduce leakage currents, poorer modulation results would have been obtained. From sections 3.2.1 and 3.2.2, considering electrorefraction and its effect on the spectrum, it seems unreasonable to expect electrorefraction alone to have produced shifts of more than 3 Å for either sample. For the regular quarter-wave sample, the peaks were very close to the absorption edge, so there would have been some electroabsorption too. Our simulations did not take absorption into account at all. To incorporate this effect, one could use the complex refractive index, $n + ik$, in place of the real refractive index, $n$, in equations (3-3) to (3-10). In addition to a reduction in the transmitted intensity, which partially accounts for the greater modulation
seen at 9100 Å wavelength in Figures 3.29 and 3.30, it may also cause some broadening or shift in the peaks. Absorption cannot explain the size of the shift seen for the quantum well sample, since the photon energy was well below the bandgap. Since the temperature of this device was not measured, it is possible that it heated up more than the regular quarter-wave sample.

3.8.2 Advantages and Disadvantages

Here we draw comparisons between the tunable quarter-wave stack and the multiple quantum well electroabsorption modulator. The clear advantages possessed by our devices are that they exhibit very little optical absorption and that they can be designed to operate over a wider range of wavelengths. The absence of absorption means that high optical power can be used without affecting the operation of the device. For electroabsorption devices, absorption of high intensity light causes photocurrents and also quenches the sharp excitonic features. Thus the optical and electrical behaviors are both degraded. A possible application for our device, that exploits these advantages, would be to modulate the 1.06 µm output of a Nd:YAG laser; these lasers can be extremely stable, so the small tuning range that our modulator can achieve might be sufficient. For operation at a wavelength so far removed from the bandgap of GaAs, it might be advantageous to replace the GaAs layers with InₓGa₁₋ₓAs, which has a smaller bandgap.

The tunable quarter-wave stack suffers from some serious drawbacks. First, the shift in the spectrum that can be obtained is very small, comparable to the stability of a typical source, and smaller than the widths of features that can easily be obtained in the transmission spectrum. The device is also extremely sensitive to temperature and to the thickness and uniformity of the layers. Therefore a well controlled environment is required, as are very close tolerances in fabrication. The latter problem may eventually be solved technologically by some variation on the theme of MBE; experimental techniques have been demonstrated\(^9\) in which individual atomic layers of Ga and As are deposited.
sequentially, giving thickness accuracy, in principle, to within one atomic layer, 2.8 Å. Current MBE technology can not provide this sort of accuracy. Individual devices can be tuned slightly by tilting the device, which shifts the spectrum toward shorter wavelength. This is unlikely to be a satisfactory solution in any real working environment, especially if large two-dimensional arrays of devices are desired.

The very high operating voltage of this type of device is also a serious drawback. The very strong electric fields that are required mean that a few volts need to be applied across each pair of layers. Since 30 or more pairs are required, the operating voltage will always be at least 100 V. There is a possible technological solution to this problem which places all the pairs of layers in parallel rather than in series, thereby reducing the required voltage to 4 V or so, at the cost of a considerable increase in processing complexity. The

---

**Figure 3.32.** Band diagram of a hetero-nipi structure with zero bias.
GaAs layers would be undoped, and the AlAs layers would be alternately n-type and p-type doped. Thus a "hetero-nipi" structure\textsuperscript{92,93} would be formed, as illustrated in Figure 3.32. Through a complex shadow-masking technique,\textsuperscript{94} selective contacts can be made to the p-type and n-type layers from the sides. Thus all of the p-type AlAs layers would be connected together through an ohmic contact on one side, and every n-type layer on the other side. The parallel connections would mean that only a single p-i-n diode would have to be reverse biased. The built-in electric field would further reduce the voltage required, possibly as low as 2 V. This type of structure could also be used in forward bias, using carrier injection to modify the refractive indices. A variation on this idea would be to dope the GaAs layers and to use reverse bias to deplete them.

The processing for such hetero-nipi structures is very complex and was not attempted. However, the idea of carrier injection was incorporated into a different version of the device, a tunable Fabry-Perot cavity, which is the subject of the next chapter.
4 TUNABLE FABRY-PEROT CAVITY

This chapter describes the second, more sophisticated, tunable interference device. A Fabry-Perot cavity consists of two reflectors separated by a spacer; its transmission spectrum exhibits a band of high reflectance, like the spectrum of the quarter-wave stack, but in this case there is a sharp peak of high transmittance at the center of the band. The idea for this device is to tune the light to that resonant peak, which, being very sharp, does not need to be shifted much to produce modulation. Changes in refractive index are employed again, but in this case only the spacer layer needs to be affected. Thus the required voltage will be much smaller than for the quarter-wave device.

A description of a Fabry-Perot interferometer follows, with calculations to find the sharpness of the central resonance. The succeeding sections follow the pattern of chapter 3, starting with calculations of the effect of changing the refractive index of the spacer layer, followed by an assessment of the magnitude of the change that can be achieved. For this device, two electrical techniques can be used to change the refractive index: a strong electric field, as before, and carrier injection. Device design considerations are then presented. The requirements for good carrier injection are more stringent than those for applying strong electric fields; several factors, including current spreading, device size, and heat flow, had to be considered carefully. Laser diode techniques were used extensively in the analysis and device design phases. The experimental structures are then described, including a detailed processing schedule. This is, to the author's knowledge, the first perpendicular geometry modulator to be designed to operate with carrier injection, and the requirements of bringing photons and electrons together in the active layer were not trivial to fulfill. Experimental results are then presented. Again, they can be described as promising but not at the point where commercial production of the devices is imminent. A cautiously optimistic note is struck in the discussion.
4.1 FABRY-PEROT CAVITY

4.1.1 Description

A Fabry-Perot interferometer, first described in 1899 by Fabry and Perot\textsuperscript{95}, consists of two mirrors separated by a spacer layer. In dielectric form, the mirrors are quarter-wave reflectors, which were described in chapter 3. A narrow transmission resonance occurs at wavelengths for which the thickness of the central spacer layer is an integer number of half wavelengths. A schematic of the structure is given in Figure 4.1, and a typical theoretical transmission, calculated using the transmission matrix method described in the previous chapter, is shown in Figure 4.2. We define $\delta$ to be the half-power width of the central

\begin{equation}
\begin{aligned}
n1d1 &= n2d2 \\
&= \frac{\lambda}{4}
\end{aligned}
\end{equation}

Figure 4.1. Schematic diagram of an all-epitaxial Fabry-Perot interferometer.
Figure 4.2. Theoretical transmission spectrum of a 6th order Fabry-Perot cavity, with a GaAs spacer layer and substrate, an 18-period upper reflector, and a 25-period lower reflector, each reflector consisting of quarter-wavelength layers of GaAs and Al_{0.4}Ga_{0.6}As.

peak. The high-reflectance band in which the resonances occur is generally quite narrow for semiconductor structures, so unless the spacer layer is very thick there will generally only be one resonant peak.

The effect of the spacer layer is to induce a $180^\circ$ phase shift between the reflected beams from the top mirror and the bottom mirror. It can be shown mathematically that if the reflectances of the two mirrors are equal then unity transmittance is obtained at the resonance. For an intuitive grasp on this fact, consider the structure in Figure 4.3, where $H$ and $L$ refer to high and low refractive indices respectively. The spacer layer is shown as a double quarter-wavelength layer of high refractive index. The characteristic matrix of the spacer layer, as defined in equation (3-4), is

\[
\pm \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}.
\]
This is the unity matrix and can have no effect on the reflectance of an assembly. The structure as a whole therefore behaves as though the layer were not there. Half-wavelength layers are sometimes referred to as "absentee layers". Removing the spacer layer would leave two adjacent "L" layers, which form another half-wavelength spacer. These can also be removed, and so on. If there are balanced reflectors, therefore, the transmittance goes to unity at the wavelength for which the spacer is a half-wavelength and the other layers are all a quarter-wavelength.

![Diagram](image)

Figure 4.3. The central part of a first order Fabry-Perot interferometer. Each "H" or "L" labels a quarter-wavelength layer of high or low refractive index, respectively.

Apart from the resonance, the overall spectrum looks quite similar to that of a quarter-wave stack. Clearly the central spacer layer is responsible for the resonance. The idea for a modulator, therefore, is that we may be able to shift the central peak by changing only the refractive index of the spacer layer. Since this layer can be much thinner than a whole quarter-wave stack, lower operating voltages should be possible.
4.1.2 Sharpness of the Transmission Spectrum

All of the theoretical spectra presented here were calculated by computer using the transmission matrix method described in section 3.1.2. As shown in Figure 4.2, there is a sharp resonance in the transmission spectrum, resulting from the spacer layer between the reflectors. For device purposes, the resonance should have as small a half-power width, $\delta$, as possible, and the peak transmittance should be as close to unity as possible.

In theory the central transmittance is unity if the two reflectors are matched. This does not necessarily mean equal numbers of layers in each reflector. The device structures were to be fabricated on GaAs substrates, which can be considered to be infinitely thick. On one side of the epitaxial layers there is air, and on the other side there is GaAs. Using equation (3-1), the reflectance of a GaAs to air interface can be shown to be approximately 0.3. On the substrate side, therefore, we need extra reflector layers that give the same reflectance. The required number of layers can be calculated using equation (3-12), modified so that the incident medium is no longer air:

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

(4-1)

where $n_{inc}$ is the refractive index of the incident medium. A reflectance of 0.3 is obtained with four periods of GaAs and AlAs with GaAs on both sides. Therefore, if the reflectors are made of these materials there should be four more periods on the substrate side than on the air side. More extra periods would be required if $Al_xGa_{1-x}As$ were used for one of the types of layer. For reasons that will be presented in a later section, our reflectors consisted
of GaAs and Al$_4$Ga$_6$As. For these materials, 7 extra periods on the substrate side balance the reflectors.

In addition to maximizing the height of the resonant peak, it is necessary to make its edges as sharp as possible or, equivalently, to minimize its half-power width. Since we expect a spectral shift of 10 Å or less, a peak width of less than 20 Å is desirable. Computer simulations were performed to measure the half-power width of the resonance as a function of the number of layers in the reflectors. The materials simulated were GaAs and Al$_4$Ga$_6$As, and in every case the lower reflector had 7 extra periods. Macleod$^{80}$ gives an approximate equation for the half-width of a first order structure, i.e. with a half-wavelength spacer layer:

$$
\delta = \lambda_0 \frac{4n_3n_1^{2x}}{\pi n_h^{2x+1}} \frac{n_h - n_1}{n_h}
$$

(4-2)

where \( x \) is the number of periods in the reflector on the substrate side, and \( \lambda_0 \) is the wavelength of the peak. The values used were 3.51 for \( n_h \) (GaAs) and 3.25 for \( n_1 \) (Al$_4$Ga$_6$As). The results from computer simulations and equation (4-2) are both plotted in Figure 4.4. The equation is quite close to the simulation, which demonstrates its usefulness in design.

Another variable is the thickness of the spacer layer. It is not clear how to modify equation (4-2) to calculate the effect of using a higher order cavity, since the original derivation was specifically for a first order cavity and quite elaborate. Therefore we relied on brute-force computer simulations to estimate the effect. Figure 4.5 shows how the half-power width decreases with increasing order, the order being defined simply as the number of half-wavelengths in the spacer layer. For this plot, there were 18 periods in the top (air side) reflector, and 25 on the substrate side.
Figure 4.4. Theoretical half-power width of the Fabry-Perot resonance as a function of the number of periods in the top reflector. The peak wavelength is 10000 Å, and the materials in the reflectors are GaAs and Al$_4$Ga$_6$As.

Figure 4.5. Theoretical half-power width of the Fabry-Perot resonance as a function of the order of the spacer layer. The peak wavelength is 10000 Å, and the reflectors contain 18 and 25 periods of GaAs and Al$_4$Ga$_6$As.
Figures 4.4 and 4.5 show that, in order to halve the peak width, one must add either 4 periods to both reflectors, for a total of 8 extra half-wavelengths of material, or approximately 12 half-wavelengths to the spacer. Thus it is slightly more efficient to add material to the reflectors if the peak has to be sharpened.

4.2 THEORY OF THE TUNABLE FABRY-PEROT CAVITY

4.2.1 Effect of Changing the Refractive Index of the Spacer Layer

Since the resonance in the middle of the high-reflectance band is the sharpest feature in the spectrum, only shifts of this peak are considered. It is necessary to determine how much shift, $\Delta \lambda$, is obtained for a given change in refractive index. The situation is illustrated in Figure 4.6. To re-iterate the idea behind this device, only the refractive index of the spacer layer will be altered.

![Diagram](image)

**Figure 4.6.** Shift in the Fabry-Perot resonance, obtained by changing the refractive index of the spacer layer.

Straightforward computer simulations were used again to determine the shift in the resonant peak that should be obtained with a given change of refractive index. Figure 4.7
shows the shift that is expected for an increase of 0.1% in the spacer layer's refractive index as a function of the order of the cavity. The reflectors comprised GaAs and Al₄Ga₆As layers again, with 18 periods on top and 25 on the substrate side. The peak wavelength was 10000 Å. If every refractive index in the structure were increased by 0.1% we would expect a proportional shift of 10 Å in the peak. Clearly the actual shift falls well below this. The reason lies in the distributed nature of the structure. The transmission characteristics of the interferometer depend on many reflections from every interface; both the mirrors and the spacer are tuned to the resonance, and since the mirrors are not being affected the resonance is not affected as much as the spacer layer. In the all-dielectric Fabry-Perot cavity the spacer and mirrors cannot be considered as separate entities. The change in refractive index of the spacer layer alters the phase shift across the structure as a whole, but only in proportion to the width of the spacer compared to that of the whole structure.

![Graph showing the shift of the Fabry-Perot resonance with spacer layer order](image)

**Figure 4.7.** Shift of the Fabry-Perot resonance obtained by a 0.1% change in the refractive index of the spacer layer, as a function of the order of the spacer layer.
According to that argument, it should be possible to obtain a greater shift in the peak by employing fewer layers in the reflectors. This is the case, but it is more than offset by the increased width of the peak. Reducing the number of reflector periods by four on each side increases the shift by approximately 2%, so that for a 20th order spacer the peak shifts by 5.5 Å rather than 5.4 Å, but the width of the peak doubles. By using GaAs/AlAs reflectors, with 10 periods on top and 14 on the substrate side, the peak shift for a 20th order could be increased to 6.9 Å.

It is clear from Figure 4.7 that a first order structure would need a very large change in the spacer's refractive index in order to have a chance of working. In the electrorefractive mode the maximum change of refractive index is around 0.1%, as shown in section 3.2.2. The 0.7 Å shift that would be obtained would not be visible. A higher order cavity would be required for this sort of device. In any case, the spectral shifts are expected to be somewhat smaller for this device than for the quarter-wave devices for a given refractive index change. The maximum obtainable change is the topic of the following sub-sections. The shift is proportional to the change in refractive index, so if some means could be found to increase the change then the tuning range might yet be greater than for the previous devices.

4.2.2 Device Concept: P-I-N Diode

The simplest type of structure in which a central layer can be affected selectively is a p-i-n diode. The two reflectors are doped, one p-type and one n-type, and the spacer layer is undoped. Since it was planned to use an n-type substrate, the lower reflector would be the n-type one. Figure 4.8 shows the concept. When such a device is reverse biased, most of the voltage is dropped across the intrinsic spacer layer. Thus the field across the spacer is approximately the sum of the applied voltage and the built-in voltage divided by the spacer thickness. In forward bias, carriers are injected into the spacer layer. The
compositional changes at the edges of the spacer layer confine most of the carriers, and ideally all of the current is due to recombination inside this layer. Band diagrams for the device under forward and reverse bias are shown in Figure 4.9, where the multi-layer reflectors are approximated by $\text{Al}_x\text{Ga}_{1-x}\text{As}$ of an average composition.

![Diagram of device structure](image)

**Figure 4.8.** Device concept: a p-i-n structure, with doped reflectors and an intrinsic spacer layer.

It will be shown that carrier injection leads to a reduction in the refractive index. This is opposite to the effect of an electric field, so an optimal mode of operation might be to drive the device from a bipolar power supply, switching between forward and reverse bias for the greatest total shift of the peak. Reverse bias will serve the additional function of sweeping out the carriers injected by forward bias, enabling switching times faster than the recombination lifetime to be used. In reverse bias, the maximum change of refractive index is expected to be about the same as for the quarter-wave structure, depending on how high
a breakdown electric field can be obtained. The effect of current injection is described below.

![Band diagram of a double-heterojunction P-i-N diode in reverse and forward bias](image)

**Figure 4.9**. Band diagrams of a double-heterojunction P-i-N diode in a) reverse bias and b) forward bias. \( E_{fp} \) and \( E_{fn} \) are the quasi-Fermi levels for holes and electrons, respectively.

---

**4.2.3 Modulation of the Refractive Index by Carrier Injection**

Calculations of the effect of carrier injection on the refractive index will be presented first, followed by calculations of the current that is required to achieve the necessary carrier density. There are two separate mechanisms by which the refractive index is altered by carrier injection, namely, the plasma effect and band filling, also known as the Burstein-Moss effect.
Kittel \textsuperscript{47} gives a simple derivation of the plasma effect. He starts with the equation of motion for a free electron in an electric field, and derives the induced polarization. From his equations the change in refractive index can be calculated:

\begin{equation}
\Delta n = \frac{1}{2n} \frac{N\hbar^2}{\epsilon_0 m_{eh} E^2}\end{equation}

where $N$ is the density of charged particles, $m_{eh}$ is the reduced effective mass, and $E$ is the photon energy in eV. Substituting $m_{eh} = 0.061m_0$ and $n = 3.5$ for GaAs, a numerical form can be obtained:

\begin{equation}
\Delta n = - \frac{3.23 \times 10^{-21}}{E^2 \text{ (eV)}} N \text{ (/cm}^3)\end{equation}

Unlike the electrorefractive effect, the plasma effect is larger for smaller photon energies. This is because there is a resonance in the response of the plasma at the "plasma frequency", which corresponds to an energy of less than 0.1 eV for carrier densities that can be achieved in semiconductors; the changes in the dielectric constant and the refractive index are greater the closer the photon energy is to this resonance.

Examination of equation (4-4) shows that for photon energies close to the bandgap of GaAs, say 1.2 eV, an injected carrier density of around $10^{18} /\text{cm}^3$ is required to cause a $\Delta n$ of 0.1%. This is quite similar to the typical injected density at threshold for a semiconductor laser.

Since the effective density of states in the conduction band is quite low for GaAs, around $4.7 \times 10^{17} /\text{cm}^3$, injected carrier densities of the required magnitude will put the Fermi level in the conduction band, so the states at the bottom of the band will be filled. This band filling causes a shift, the Burstein-Moss shift, in the absorption edge, since there
are no longer any states available to allow absorption of light right at the bandgap. This change in the absorption spectrum leads to a change in the refractive index, which can be calculated using the Kramers-Kronig relationship, equation (3-30). A simple analysis follows.

Close to the bandgap, the absorption coefficient can be approximated by

$$\alpha(E) = A (E - E_g)^{1/2} \tag{4-5}$$

where $A = 4.2 \times 10^4 \text{ cm}^{-1}\text{ev}^{-1/2}$, obtained by substituting the bandgap energy into equation (3-29). With carriers injected, filling the conduction band to a level $E_1$ above the band edge (we are treating the Fermi function as a step function), the induced change in the absorption spectrum is simply the removal of all absorption between $E = E_g$ and $E = E_1$. The Kramers-Kronig equation therefore becomes:

$$\Delta n(E) = \frac{\hbar A}{\pi q} \int_{E_g}^{E_1} \left( \frac{A (E' - E_g)^{1/2}}{(E')^2 - E^2} \right) dE' \tag{4-6}$$

with $E$ expressed in eV throughout. This can be re-written as

$$\Delta n(E) = \frac{\hbar A}{2 \pi q E} \int_{E_g}^{E_1} \left( \frac{(E' - E_g)^{1/2}}{(E') - E} - \frac{(E' - E_g)^{1/2}}{(E') + E} \right) dE'.$$

Substituting $X^2 = E' - E_g$ and $dE' = 2XdX$, 

97
\[ \Delta n(E) = \frac{\hbar A}{\pi qE} \int_0^{\sqrt{E_1}} \left\{ \frac{X^2}{X^2 + E_g - E} - \frac{X^2}{X^2 + E_g + E} \right\} dX \]

\[ = \frac{\hbar A}{\pi qE} \int_0^{\sqrt{E_1}} \left\{ \frac{E_g + E}{X^2 + E_g + E} - \frac{E_g - E}{X^2 + E_g - E} \right\} dX. \]

Any table of integrals will reveal that

\[ \int \frac{a}{a^2 + x^2} \, dx = \sqrt{a} \tan^{-1}\left( \frac{x}{\sqrt{a}} \right) \]

so:

\[ \Delta n(E) = -\frac{\hbar A}{\pi qE} \left\{ \sqrt{E_g + E} \tan^{-1}\left( \frac{\sqrt{E_1}}{\sqrt{E_g + E}} \right) - \sqrt{E_g - E} \tan^{-1}\left( \frac{\sqrt{E_1}}{\sqrt{E_g - E}} \right) \right\}. \quad (4-7) \]

Substituting for the constants, one obtains:

\[ \Delta n(E) = -\frac{0.264}{E} \left\{ \sqrt{E_g + E} \tan^{-1}\left( \frac{\sqrt{E_1}}{\sqrt{E_g + E}} \right) - \sqrt{E_g - E} \tan^{-1}\left( \frac{\sqrt{E_1}}{\sqrt{E_g - E}} \right) \right\}. \quad (4-8) \]

The extent of the band filling, \( E_1 \), can be estimated using the Joyce-Dixon approximation. At room temperature, an injected carrier density of \( 10^{18} /\text{cm}^3 \) gives 30 meV for \( E_1 \), while \( 2 \times 10^{18} /\text{cm}^3 \) gives 80 meV. Figure 4.10 shows the contributions of the plasma effect and the Burstein-Moss effect to the change in refractive index at these two
carrier densities. The band filling effect is greatest for photon energies close to the bandgap, like the electrorefractive effect. The two effects are of similar magnitude at around 1.2 eV. The total change in refractive index is quite encouraging.

Figure 4.10. Changes in refractive index through the plasma effect and band filling, induced by injected carrier densities of a) $10^{18} / \text{cm}^3$ and b) $2 \times 10^{18} / \text{cm}^3$. 
It should be noted that a photon energy of 1.2 eV, corresponding to a wavelength of 1 µm, is actually the worst possible operating energy from a device standpoint. However, since our measurement apparatus was set up for this energy range, and since the idea was to demonstrate both forward and reverse bias effects, this was still the chosen operating point.

It is now necessary to determine the current that is required to maintain such a carrier concentration. Assuming no leakage through the heterojunction barriers, an assumption that will be investigated shortly, and ideal interfaces, the current density is simply the rate, \( J_r \), at which injected carriers recombine in the active layer:

\[
J_r = \frac{qN_d}{\tau} \text{ A/cm}^2
\]  

(4-9)

where \( N \) is the carrier density, \( d \) is the thickness of the spacer, and \( \tau \) is the carrier lifetime.

There will also be recombination at the Al\(_{0.4}\)Ga\(_{0.6}\)As/ GaAs interfaces at the sides of the spacer layer. If the spacer layer thickness is much less than a diffusion length then the carrier concentration can be assumed to be constant across it. The interface recombination current density, \( J_i \), can then be written as

\[
J_i = 2qNs
\]

where \( s \) is the interface recombination velocity. The two current components can be combined:

\[
J = qN_d \left( \frac{1}{\tau} + \frac{2s}{d} \right).
\]  

(4-10)
In this form, the interface recombination velocity reduces the effective lifetime, and is important if 2s/d is similar in magnitude to 1/τ. For good laser material, τ = 4 nS and s = 450 cm/s. With these numbers, interface recombination would halve the lifetime if the spacer layer thickness were less than 360 Å. It is difficult to estimate s in general. If the material is sufficiently bad then s may be high enough to affect the operation of our devices.

Ignoring interface recombination, the required current density is given by equation (4-9). Inserting τ = 4 nS and N = 10^{18} /cm³, and expressing d in microns, we obtain

\[ J = 4000d \text{ A/cm}^2. \]  \hspace{2cm} (4-11)

For a structure with a 1 μm spacer layer, a 50 μm x 50 μm device would require 100 mA, and a 10 μm x 10 μm device would take 4 mA.

It is now necessary to verify the assumption that no carriers will leak out of the spacer layer over the heterojunction barriers. First it should be noted that rectification will not take place within the reflectors themselves, despite the large number of isotype heterojunctions between GaAs and Al₄Ga₆As layers. Only when the material is lightly doped does diode behavior manifest itself for these junctions. Since we are looking for low resistance, the material will be doped quite heavily, making all the depletion regions thin and making it easy for carriers to tunnel from one material to the other. The spacer layer, however, will be undoped, so the heterojunction barriers will be effective. A good presentation of heterojunction device physics can be found in the book by Casey and Panish.¹⁴

The band diagram of a P-i-N diode under strong forward bias is shown in Figure 4.11.
Figure 4.11. Band diagram of a device under strong forward bias, used in calculations of leakage current.

Using the usual simple diffusion current model for a short base diode, and following a similar calculation by Thompson, the leakage current of electrons into the P-\( \text{Al}_x\text{Ga}_{1-x}\text{As} \) is given by

\[
J_{\text{in}} = \frac{qD_n N_{\text{CA}}}{w_p} \exp\left( -\frac{F_{\text{CA}}}{kT} \right)
\]  

(4-12)

where \( D_n \) is the diffusion constant for electrons, \( N_{\text{CA}} \) is the effective density of states in the conduction band in \( \text{Al}_x\text{Ga}_{1-x}\text{As} \), and \( w_p \) is the total thickness of the p-type layers. With the various energies defined in the figure, and a bandgap discontinuity of \( \Delta E_g \), \( F_{\text{CA}} \) can be calculated using the equations:

\[
\delta E_v = \frac{kT}{q} \ln\left( \frac{N}{N_{\text{AA}}} \right)
\]

\[
F_{\text{CA}} = F_{\text{CG}} + \Delta E_g - \delta E_v
\]

(4-13)

102
where \( N_{AA} \) is the doping density in the P-Al\(_x\)Ga\(_{1-x}\)As, and \( F_{CG} \) is the same as \( E_1 \), defined for band filling earlier. For a doping level of \( 2 \times 10^{17} \text{ cm}^{-3} \), \( \Delta E_V = 60 \text{ meV} \). The appropriate alloy composition is the average composition of the reflector, Al\(_{1.2}\)Ga\(_{0.8}\)As, which from equation (2-1) gives \( \Delta E_g = 0.25 \text{ eV} \). Thus \( F_{CA} = 0.11 \text{ eV} \) from equation (4-13). With \( N_{CA} = 5 \times 10^{17} \text{ cm}^{-3} \), \( D_n = 90 \text{ cm}^2\text{s}^{-1} \),\(^{30,39} \) and \( w_p = 2.5 \text{ \( \mu \)m} \), \( J_{In} = 400 \text{ A/cm}^2 \).

Thus we see that the barrier is far from perfect, but recombination in the spacer should dominate. Interface quality will affect this leakage current too, since mid-gap states can act as tunnelling paths. The corresponding hole current into the n-type reflector will be rather smaller, since the quasi-Fermi level for holes, \( E_{fp} \), is above the valence band edge in the GaAs, making \( F_{VA} \) larger than \( F_{CA} \).

A figure of merit, suggested by Kemeny,\(^{97} \) can now be calculated to estimate the modulation depth for a given current as a function of the spacer layer thickness, \( d \). The refractive index change, proportional to \( N \) (plasma only), is inversely proportional to \( d \). However, increasing \( d \) causes a decrease in the half-power width, \( \delta \), and increases the shift for a given \( \Delta n \). Thus the figure of merit \( F_m \) can be written as

\[
F_m = \frac{\Delta \lambda(d) \Delta n(d)}{\delta(d)} \propto \frac{\Delta \lambda(d)}{d \, \delta(d)}
\]

(4-14)

where \( \Delta \lambda \), the shift of the resonance that is achieved with a \( \Delta n \) of 0.1\%, is obtained from Figure 4.7; \( \delta \), the resonance width, is obtained from from Figure 4.5. Equation (4-14) is plotted in Figure 4.12, with the proportionality taken as an equality and \( d \) taken as the order of the spacer. \( F_m \) is essentially constant. It does ignore interface recombination, which may be important for thinner layers, and it assumes that arbitrarily high carrier densities can be obtained.
4.3 DEVICE DESIGN

4.3.1 Epitaxial Layers

As was the case for the quarter-wave devices, a number of issues had to be addressed. This time the variables were: the wavelength of operation, the materials to use, the numbers of periods in the reflectors, the thickness of the spacer, and the method for contacting.

The wavelength of operation was chosen to be 1 μm again, even though this is about the worst point for forward bias operation. It was felt that some effect should be obtainable in forward bias, and it was considered desirable to test reverse bias operation too. For reverse bias, the operating wavelength needed to be close to the bandgap, as was the case for the quarter-wave devices. A peak wavelength of 1 μm allowed some errors in growth rate to be tolerated with little risk of losing the resonance to absorption.
The issue of what materials to use has already been touched on. Ideally one would like to be able to use GaAs and AlAs in the reflectors, since these materials would give the greatest refractive index difference and would therefore minimize the number of layers required. However, high mole-fraction Al$_x$Ga$_{1-x}$As from our MBE machine tends to have high resistance, probably because of the incorporation of trace amounts of oxygen. Since these devices were going to require large currents, high-resistance reflectors would cause serious series voltage drops and heating. The mole fraction selected was 0.4, the highest that has been used successfully for double heterojunction laser diodes fabricated at Stanford. Thus the device, illustrated conceptually in Figure 4.8, would have a GaAs spacer layer, with reflectors consisting of alternating layers of GaAs and Al$_{0.4}$Ga$_{0.6}$As.

The effects of changing the numbers of layers in the reflectors and the thickness of the spacer layer have been described in section 4.1.2. The concern in designing test structures was that some shift in the peak should be obtainable with a refractive index change of 0.1%; this would ensure that at least reverse bias should have some effect. Thus the spectrum had to be sharp enough that a shift of a few Ångstroms would be visible. The spacer layer needed to be fairly thick in order to give this much shift, as can be seen from Figure 4.7. It was decided that two structures would be built, one with a 6th order cavity (3 wavelengths) and one with a 12th order cavity (6 wavelengths). These would have thicknesses of around 0.85 µm and 1.7 µm. There would be little benefit obtained by going to still thicker layers; the main effect would be an increased operating voltage in reverse bias. As was shown in Figure 4.12, for forward bias the spacer thickness is irrelevant to first order. For operation close to the bandgap, a thinner layer might prove slightly advantageous despite the extra interface recombination; the higher injected carrier density for a given current would mean more band filling. The change in refractive index due to band filling can be seen in Figure 4.10 to be super-linear with carrier density.

A peak width, $\delta$, of around 10 Å was desired, in order that a small shift would cause noticeable modulation. From Figures 4.4 and 4.5, 18 periods in the top reflector and 25 in
the lower one can be seen to give the required resolution. These numbers were used in all of our structures.

Ohmic contacts are required for this type of structure. A heavily doped n-type substrate is easy to contact. A heavily doped p+ GaAs cap layer is required on top of the p-type reflector in order for a low resistance contact to be possible there. This p+ contact layer is also crucial to device operation in that it causes current spreading. This is the topic of the next sub-section.

For minimum resistance in the reflectors, high doping was required. The Be (p-type) doping level was set at $8 \times 10^{17}$ /cm$^3$ in the GaAs. This has been found to be the highest level at which rapid diffusion of Be does not take place at high substrate temperatures. It was vital that the Be did not diffuse into the spacer layer. Since the conductivity of n-type material is much higher than that of p-type material of the same doping density, there is no advantage to using higher n-type doping, and very high doping densities tend to degrade the crystal quality. Therefore the Si doping level was set to $5 \times 10^{17}$ /cm$^3$ in the GaAs. A higher doping level was required for the p+ contact layer, and $5 \times 10^{19}$ /cm$^3$ was selected. A thickness of 5000 Å was selected; this is typical for laser diodes. This layer would have to be grown at a low substrate temperature to avoid diffusion of Be.

Since the current density, estimated in equation (4-11), was going to be rather large, the maximum practical device dimensions were going to be on the order of 100 μm or less. Chips of this size would be very difficult to handle individually. Larger chips would therefore be used, and some means would be required for blocking the flow of current outside the small device area. Silicon dioxide, silicon nitride, and anodically oxidized insulating layers were rejected in favor of an n-type current blocking layer, that was to be etched away in the actual device area. An n-type layer on the top would form a reverse biased junction to the p+ contact layer, and would therefore prevent any current from flowing where it was present. The layers selected were 1000 Å of n-type Al$_4$Ga$_6$As and 2000 Å of n-type GaAs, with doping levels of around $10^{18}$ /cm$^3$, to be grown on top of the
p+ contact layer. The Al_{0.4}Ga_{0.6}As layer was to serve as a marker, so that cross-sectional scanning-electron-microscope (SEM) photographs could be used to determine whether the etch was complete. Since slight over-etch was anticipated, a thickness of 7000 Å was selected for the p+ contact layer, to ensure that at least 5000 Å were present everywhere.

### 4.3.2 Lateral Movement of Carriers

Lateral movement of carriers, via current spreading in the cladding layers and diffusion in the active layer, is an undesirable complication for designers of laser diodes, since they would prefer the carriers to be tightly confined laterally as well as vertically. For our devices, however, it is vital for the operation in carrier injection mode. Inspection of Figure 4.8 reveals the reason for this. If the current were to flow vertically from the contacts, and if there were no lateral diffusion in the spacer layer, then light directed between the metal contacts would never interact with the injected carriers, and there would be no modulation.

Casey and Panish\textsuperscript{98} have collected the work of several authors on the topic, and their results are summarized here. Considering the geometry in Figure 4.13, it can be shown that the current density, \( J \), through the active layer outside the stripe drops off with distance \( y \) from the center of the contact according to the equation:

\[
J = \frac{J_0}{\left[1 + (y - S/2)/l_0\right]^2} \tag{4-15}
\]

where \( J_0 \) is the uniform current density under the contact stripe, \( S \) is the width of the stripe, and \( l_0 \) is a spreading length given by
\[ I_0^2 = \frac{2nkT}{qR_sJ_0} \]

where \( q/nkT \) is the exponential junction current parameter, and \( R_s \) is the sheet resistance expressed in \( \Omega \) per square, calculated using the equation:

\[ R_s = \left( \sum \frac{d_i}{\rho_i} \right)^{-1} \]

where \( d_i \) and \( \rho_i \) are the thicknesses and resistivities of the p-type layers. \( R_s \) is dominated by the layer of least resistance, which in this case is the p+ contact layer.

Figure 4.13. Lateral movement of carriers in a device, by current spreading in the p-type layers, and carrier diffusion in the spacer layer.

GaAs, doped at 5 \( \times \) 10\(^{19} \)/cm\(^3\) p-type, has a resistivity of around 3 \( \times \) 10\(^{-3} \) \( \Omega \)-cm.\(^{30}\)

P-type Al\(_{0.4}\)Ga\(_{0.6}\)As, with a doping level of 5 \( \times \) 10\(^{17} \)/cm\(^3\), has a resistivity of around 0.25 \( \Omega \)-cm experimentally, two orders of magnitude larger. Therefore, so long as the thickness of the p+ contact layer is within a factor of ten of the thickness of the p-type
reflector, it will dominate. For contact purposes a p+ layer of 5000 Å thickness is normal. The reflector, containing 18 periods, is less than 3 μm thick, so the contact layer dominates. \( R_s \) then comes out to be 60 Ω. For a current density \( J_0 \) of 4000 A/cm², and with \( n k T/q = 0.026 \), the spreading length calculated using equation (4-16) is 4.7 μm. This could be increased by making the contact layer thicker, but that would move the air interface further from the p-type reflector, decreasing its efficiency.

Thus the current has spread out by the time it reaches the spacer layer. There the carriers spread laterally with a diffusion length \( L_n \). An estimate of the combined effect is presented by Casey and Panish, following a technique suggested by W.T. Tsang, wherein the expression for current spreading, equation (4-15), is replaced by an exponential form. The net results for the carrier densities in the active layer are:

\[
N(y) = \frac{J_0 \tau_n}{qd} \left[ 1 - \cosh \left( \frac{y}{L_n} \right) \exp \left( - \frac{S}{2L_n} \right) \right] + \frac{1}{(l_0 + L_n)(\cosh \left( \frac{y}{L_n} \right) \exp \left( - \frac{S}{2L_n} \right) \right)}
\]

for \( |y| < S/2 \)

\[
N(y) = \left[ \frac{J_0 \tau_n}{qd} \left( \frac{1}{l_0^2 - L_n^2} \right) \frac{1}{1 + \coth(S/2L_n)} \right] \exp \left( - \frac{|y| - S/2}{L_n} \right)
\]

\[
+ l_0 \left( \frac{1}{l_0^2 - L_n^2} \right) \frac{J_0 \sigma_n}{qd} \exp \left( - \frac{|y| - S/2}{l_0} \right)
\]

for \( |y| > S/2 \).

(4-17)

Equations (4-17) are plotted for positive \( y \) in Figure 4.14, with \( J_0 = 4000 \) A/cm², \( d = 1 \) μm, \( R_s = 60 \) Ω, and \( S = 5 \) μm. The stripe therefore extends as far as \( y = 2.5 \) μm. It can be seen that the injected carrier density falls to half of its value at the stripe edge over a distance of roughly 7 μm. Bearing in mind that each point will see carriers coming from
stripes on either side, the maximum allowable stripe spacing is in the range 10 μm to 15 μm.

![Graph](image)

Figure 4.14. Simulated profile of injected carriers in the spacer layer after current spreading and carrier diffusion. The parameters are given in the text.

### 4.3.3 Device and Heatsink Geometry

The epitaxial layers were fully described in section 4.3.1. Actual device dimensions also had to be determined. The active area of the device had to be kept small, so that the current would be reasonable, but needed to be large enough for a monochromated white light source to be able to drive a measurable quantity of photons through it. From equation (4-11) it is clear that current densities of over 10 kA/cm² are desirable. Our pulsed current source had a maximum output of around 400 mA, so the device area was limited to approximately 4000 (μm)². A 65 μm x 65 μm square was selected as suitable. Chips of this size would be very difficult to handle, so a chip size of 800 μm x 800 μm was selected as suitable. The current blocking layer would prevent much current from flowing outside the active area.
The p-side metallization was designed in stripes 5\(\mu\)m wide, connected at both ends. Gold stripes 5 \(\mu\)m wide and a few thousand Ångstroms thick have negligible resistance. The design called for a 5\(\mu\)m wide stripe of metal around the edge of the window to make sure that there was a good contact with the metal on top of the current blocking layer. Four different geometries, with 1, 2, 3, or 5 stripes and 25 \(\mu\)m, 15 \(\mu\)m, 10 \(\mu\)m, or 5 \(\mu\)m wide gaps, were designed. If the devices had worked well in forward bias, a comparison of the performances of the different geometries would have been a good test of the current spreading calculations.

![Figure 4.15. Schematic cross-sectional diagram of a Fabry-Perot modulator.](image)
A cross-section of the designed device is shown in Figure 4.15. The etch profile of the current blocking layer will be as shown in the (01\overline{1}) direction; in the (011) direction it will be quite different, either vertical or inward sloping. This is the usual pattern for wet etching of GaAs\textsuperscript{29} and results from the preferential exposure of one type of crystalline plane. Thus the metallization may well have breaks in the (011) direction, but it will be continuous in the (01\overline{1}) direction.

The opening in the n-side metallization was much larger than the window on the p-side. This allowed some error in the alignment of the backside lithography. Substrates are conductive enough that there is no problem with current spreading there.

The devices were to be operated at current densities very similar to those used for semiconductor lasers. Heatsinks were therefore required. Laser diodes are typically mounted p-side down on a copper heatsink, using indium as solder. The thermal resistance from the active layer to the heatsink for a typical device is around 20 K/W.\textsuperscript{99} If this could be achieved for these modulators, driving them at 100 mA and 2 V would cause a temperature rise of 4 K. This would cause a shift of around 4 Å in the resonance. Clearly CW operation was out of the question for these devices. Furthermore, the heatsink needs to have a hole in it to permit light to be shone through the modulator. Since the hole was going to be exactly adjacent to the area where heat is being produced, the thermal resistance was going to increase considerably.

The heatsink design, with a mounted device, is shown in Figure 4.16. Each heatsink was fabricated from a piece of copper with dimensions roughly 3 cm \times 2 cm \times 1.63 mm. The holes had a diameter of 150 \mu m, and were fabricated by electrical discharge machining by Extraction Engineering Inc. of Mountain View, California. Since the maximum height-to-diameter ratio of such holes is around 4, the copper was first milled down to a thickness of approximately 600 \mu m in the neighborhood of the hole. After the hole was drilled, more milling was performed in the Physics Department Machine Shop at Stanford to construct a raised mesa 800 \mu m square, with the hole at its center, to assist in location of the chips over
the hole. The heatsink itself was to serve as an electrical contact to the p side of the device, and some sort of bonding pad would be used to make contact to the substrate metallization.

![Diagram of heatsink with device mounted p-side down](image)

**Figure 4.16.** Schematic cross-section of a heatsink, with a device mounted p-side down.

### 4.3.4 Heat Flow Calculations

It was clear that CW operation in forward bias would not be possible. However, it was still necessary to have an idea of how big a problem heating was likely to be, so that a suitable mark to space ratio could be selected for the pulsed current. Heat flow simulations were performed to investigate this effect. Because of the three-dimensional nature of the problem, a three-dimensional numerical technique was used.
The basic equations\textsuperscript{100} for heat flow in steady state are the flux equation,

\[ \vec{f} = -K \nabla T \quad (4-18) \]

and the diffusion equation

\[ \nabla \cdot \vec{f} = -A^* \quad (4-19) \]

where \( \vec{f} \) is the flux, \( K \) is the thermal conductivity, \( T \) is the temperature, and \( A^* \) is the rate of heat generation per unit volume.

The most convenient technique for solving these equations is a simple relaxation method\textsuperscript{101}, where one sets up a grid and iterates to the solution. The situation in two dimensions is shown in Figure 4.17.

\[ \text{Figure 4.17. Two-dimensional form of the grid used for numerical calculations of heat flow.} \]

The first and second derivatives of a function, \( \psi \), at the central point can be approximated by

\[ \frac{\partial \psi}{\partial x} = \frac{\psi_1 - \psi_3}{a} \]
\[
\frac{\partial^2 \psi}{\partial x^2} = \frac{1}{a} \left[ \left( \frac{\psi_1 - \psi_0}{a} \right) - \left( \frac{\psi_0 - \psi_3}{a} \right) \right] = \frac{1}{a^2} (\psi_1 + \psi_3 - 2\psi_0)
\]

where \(a\) is the grid spacing. Analogous expressions can be written for the \(y\) and \(z\) directions. In 3 dimensions

\[
(\nabla^2 \psi)_0 = \frac{1}{a^2} (\psi_1 + \psi_2 + \psi_3 + \psi_4 + \psi_5 + \psi_6 - 6\psi_0)
\]

(4-20)

where \(\psi_5\) and \(\psi_6\) are the out-of-plane values. Where the heat conductivity is uniform, equations (4-18) and (4-19) can be combined to yield

\[
\nabla^2 T = -\frac{\mathbf{A}^*}{K}
\]

(4-21)

and the condition to be satisfied at every point is

\[
\frac{1}{a^2} \sum_{i=1}^{6} (T_i - 6T_0) + \frac{\mathbf{A}^*}{K} = 0
\]

(4-22)

where the \(T_i\) are the six neighboring temperatures.

The geometry that was simulated is shown in Figure 4.18, and is a fairly coarse approximation of the real structure. A 4 \(\mu\)m grid spacing was used in all directions, with a chip size of 400 \(\mu\)m \(\times\) 400 \(\mu\)m \(\times\) 100 \(\mu\)m. The real chips were larger, but the periphery plays little part in thermal conduction, so the simulated size was reduced in order to save computer time. Since the device was symmetrical about two axes, only a quarter of the plan view was used. This still involved over 60000 grid points. The heat generating
region, the device's spacer layer, was placed 4 μm from the surface, with plan view dimensions of 64 μm x 64 μm. The lower 8 μm (the chip being p-side down) were considered to be Al\textsubscript{x}Ga\textsubscript{1-x}As, and the remainder GaAs. Thermal conductivities of 0.45 W/cmK for GaAs and 0.22 W/cmK for Al\textsubscript{x}Ga\textsubscript{1-x}As (obtained by taking the average of the thermal resistivities of GaAs and Al\textsubscript{4}Ga\textsubscript{6}As) were used.\textsuperscript{99}

Figure 4.18. The geometry used for heat flow simulations, in a) cross-section and b) plan view.

The boundary conditions were quite simple. No heat flow was allowed across any interface to air, so the gradient of T was set to zero at such points. The entire bottom surface, apart from the area inside the hole of the heatsink, was considered to be in perfect thermal contact with an ideal heatsink and was held at zero temperature. At the boundary between GaAs and Al\textsubscript{x}Ga\textsubscript{1-x}As, equation (4-22) needed modifications. Here,
\[
\frac{\partial}{\partial z} \left( \frac{K}{a} \frac{\partial T}{\partial z} \right) = \frac{1}{a^2} \left[ K_G (T_5 - T_0) - K_A (T_0 - T_6) \right] \\
= \frac{1}{a^2} \left[ K_G T_5 - (K_G + K_A) T_0 + K_A T_6 \right]
\]

(4-23)

where \(K_G\) and \(K_A\) are the thermal conductivities of GaAs and \(\text{Al}_x\text{Ga}_{1-x}\text{As}\), respectively, and \(T_5\) and \(T_6\) are the temperatures of the neighboring points on the GaAs side and the \(\text{Al}_x\text{Ga}_{1-x}\text{As}\) sides, respectively.

The relaxation method used was to step through the structure systematically and to perform the following calculations at each point: First, the "residue", \(R\), was calculated, using

\[
R = \frac{1}{6} \left[ \frac{1}{a^2} \sum_{i=1}^{6} (T_i) + \frac{A^*}{K} \right].
\]

(4-24)

Next, a "new" temperature, \(T\), was calculated, based on the previous temperature at that point, \(T_p\), using the equation

\[
T = T_p + f(R - T_p)
\]

(4-25)

where \(f\) was a constant factor between 1 and 2, selected experimentally to give the fastest convergence. For a 10 \(\mu\)m grid \(f = 1.8\) was suitable, while a value of 1.95 was found to be appropriate for the 4 \(\mu\)m grid. The iteration was halted when none of the temperatures changed by more than a set amount, usually 0.01 K, from iteration to iteration.

Approximately 100 iterations were generally needed. Residues for boundary points were calculated by placing ghost points outside the boundary with the same temperatures as their
mirror images inside the material. This automatically set the gradient of temperature across the boundary equal to zero.

For all of our calculations, a total power of 0.2 W was used. A plan view of the central part of the active layer is shown in Figure 4.19. The number by each point corresponds to the steady-state temperature rise at that point. The area in which heat was

**Figure 4.19.** Results from the heat flow simulation of the device, with 0.2 W generated: plan view of the active layer.
generated is labelled "active region". The position of the heatsink, attached to the layer below, is also indicated. The bold lines are approximate isotherms, with temperatures indicated by the numbers in boxes. The chip center is located at the top left corner; the temperature profile for the whole device is symmetric about the top and left boundaries. Cross sections of the whole half-device and the central part are shown in Figures 4.20 and 4.21. In Figure 4.20, only every third data point is shown.

The simulations show that there is a large variation of temperature across the device. The thermal resistance, defined as temperature rise per watt at the center of the chip, is over 160 K/W. This is 8 times larger than the corresponding value for a laser diode, and is a direct result of the hole in the most important part of the heatsink, which makes the distance from the heat source to the sink much greater. The effect of reducing the hole size from its

---

**Figure 4.20.** Results from the heat flow simulation of the device, with 0.2 W generated: cross-section of a half-device, showing every third data point.
Figure 4.21. Results from the heat flow simulation of the device, with 0.2 W generated: cross-section of the central part of the device.

A nominal diameter of 150 μm is shown in Figure 4.22. The thermal resistance does not decrease very much as the diameter is reduced to 70 μm, corresponding closely to the actual active area size. The reason for this can be seen in the isotherms in Figures 4.20 and 4.21. Heat flow away from the active area is mostly vertical at first as the heat spreads out. Once it has spread through the chip, the distance to the heatsink is fairly unimportant since the area filled by the heat flux is large. A considerable improvement is obtained by
reducing the hole size to zero, when the resistance comes down to around 30 K/W. In this case the heat does not spread much, but flows straight down from the heat source to the sink. To achieve this low a resistance, a transparent heatsink such as diamond would be required.

![Graph showing thermal resistance vs. hole diameter](image)

**Figure 4.22.** Effect of the diameter of the hole in the heatsink on the thermal resistance between the center of the chip and the heatsink.

Thus we have to put up with a thermal resistance of over 160 K/W. To keep the temperature rise to less than 1 K with 0.2 W of instantaneous power requires pulsed current with an on:off ratio of less than 1:33.

### 4.4 DEVICE FABRICATION

#### 4.4.1 MBE Growth

The two device structures, 6th order and 12th order Fabry-Perot interferometers, were grown in the MBE chamber, under computer control again. A GaAs growth rate of
approximately 0.5 \mu m/h was used again. Experiments with semiconductor lasers had indicated that the optimum growth temperature for optical devices was around 850°C indicated (probably around 720°C actually). Unfortunately, at the time that the growths were performed the fluxes from the GaAs cells were not stable enough to give precise growth rate control at this high a temperature. As was mentioned in section 3.4, considerable GaAs desorption takes place with high substrate temperatures. At 850°C indicated, the loss rate was found to be equivalent to approximately 0.75 \mu m/h, so that an effective growth rate of 1.25 \mu m/h would be required to give an actual 0.5 \mu m/h growth rate. With the uncertainties in the effective rate it was not possible to obtain sufficient accuracy in the actual rates. Therefore an indicated temperature of 700°C was used.

Desorption had been found to be fairly insignificant below 750°C indicated, but the surface morphology of structures containing a lot of Al_xGa_{1-x}As had been found to be very poor if the substrate temperature was between 720°C and 800°C. In order to obtain good morphology and predictable growth rates, 700°C was the maximum safe temperature. The temperature was reduced to 600°C indicated for the p+ contact layer and the n-type current blocking layer, in order that the Be would not diffuse to the other layers. For these layers material quality and carrier lifetimes were not important.

The substrates were rotated during growth to improve the uniformity. To make the interfaces as smooth as possible the growth was interrupted after each layer. Growth interruption has been found to give much smoother interfaces, as a result of increased island size, but also allows the incorporation of more impurities at the interfaces if interruptions of longer than 30 seconds are used.\textsuperscript{102} Interruptions of 10 seconds after each GaAs layer and 30 seconds after each Al_xGa_{1-x}As layer were used; these times had been found by RHEED studies to be sufficient to give a significant improvement in the surface structure.

Cross-sectional scanning electron microscope (SEM) photographs were taken of some of the wafers. Small pieces were scribed off and dipped for a few seconds in a stain
etch, HF:H₂O₂:H₂O 1:1:20, which selectively attacks AlₓGa₁₋ₓAs and greatly increases the contrast between GaAs and AlₓGa₁₋ₓAs layers. The photographs generally showed very smooth, flat layers. They proved to be a very useful tool for diagnosis of our growth rate difficulties. Figure 4.23 is a photograph of an unsuccessful wafer that exhibited no Fabry-Perot resonance. While the layers were smooth, the layer thicknesses can be seen to be non-uniform, increasing toward the top of the wafer.

![Image of cross-sectional scanning electron micrograph of an unsuccessful Fabry-Perot structure. The dark stripes are GaAs layers, the light ones Al₄Ga₆As.](image)

**Figure 4.23.** Cross-sectional scanning electron micrograph of an unsuccessful Fabry-Perot structure. The dark stripes are GaAs layers, the light ones Al₄Ga₆As.

### 4.4.2 Device Processing

The processing for these devices was considerably more complex than for the quarter-wave structures and involved three masks. Quarter wafers were processed. A schematic of the finished device is shown in Figure 4.15.
The first step was to etch the windows in the current blocking layer. After a standard degrease in trichloroethane, acetone, methanol, and de-ionized water, the 65 \( \mu \text{m} \times 65 \mu \text{m} \) window areas were defined lithographically, using a standard process with AZ 1370SF positive photoresist. Since the chips were eventually to be separated by cleaving, care was taken to align the chip edges to the cleaved edges of the quarter wafers. The n-type current blocking layer was then etched in \( \text{H}_2\text{PO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O} \) 1:1:30 for 4.5 minutes at 15°C. This solution etches GaAs at 800 Å/min and \( \text{Al}_4\text{Ga}_6\text{As} \) at 1000 Å/min, approximately. An extra minute was given to obtain a slight over-etch, to ensure that the \( \text{Al}_4\text{Ga}_6\text{As} \) was all removed. The etch depth was checked by SEM using stain-etched samples, prepared as described in section 4.4.1. It was found that almost 2500 Å of the p+ contact layer had been removed, rather more than intended, but still leaving over 4000 Å, enough for contacting and for current spreading purposes. The photoresist was then removed with acetone.

The next step was application of the p-type metallization. Lift-off, incorporating a chlorobenzene soak,\(^{29}\) was used to define the pattern. After a full degrease, the photoresist was spun on at 3000 rpm, rather than the usual 5000 rpm, to give a thicker layer, around 1.4 \( \mu \text{m} \) according to the manufacturer's data sheet. After a pre-bake, the wafer was soaked in chlorobenzene for 20 minutes. This hardened the top layer of the resist, so that the developed profile would be undercut, making lift-off more likely to succeed. After a standard exposure, the required development time was roughly double that of untreated resist. The post-bake was done at the relatively low temperature of 85°C to make the resist easy to remove. Surface oxides on the GaAs were removed by dilute HCl followed by a 15 second water rinse. An electron-beam evaporator was then used to deposit 1000 Å of Ti and 3000 Å of Au. The amount of metal to be removed by lift-off was rather small, just the 5 \( \mu \text{m} \) to 25 \( \mu \text{m} \) stripes in the active area and 40 \( \mu \text{m} \) stripes between chips. After a long soak in acetone, gentle rubbing with a cotton swab was required to remove the unwanted metal.
The wafers were then thinned before application of the n-side metal. This was to facilitate accurate cleaving, both for final device separation and to provide clean references for alignment during backside lithography. The wafers were first thinned mechanically to approximately 110 µm, using 5 µm Al₂O₃ powder. Chemical polishing, using full-strength domestic bleach (a sodium hypochlorite solution), removed a further 20 µm. A mirror finish was obtained by polishing with heavily diluted bleach.

Preparation for the backside metal deposition was the next stage. The thinned wafers were cleaved carefully, and the exact positions of the cleaved edges with respect to the patterns were noted. The wafers were then attached p-side down to microscope coverglasses, using photoresist as an adhesive. This made them more robust for handling, and also protected the front side from the etches that were to be used on the backside. The backside was then etched in H₂SO₄:H₂O₂:H₂O 8:1:1 at room temperature for 30 seconds, to remove about 0.75 µm. After etching the backside had an uneven appearance, mirror-like in some areas, cloudy in others. This indicated that insufficient chemical polishing had been performed, and that there was still damage from the mechanical thinning. It would have been better to leave at least the last 30 µm of thinning to the chemical polish.

The electron-beam evaporator was then used to deposit, in sequence, 400 Å of Au, 100 Å of Ge, 125 Å of Ni, and 4000 Å of Au, a standard n-type ohmic contact. The pattern for etching was defined by the third photolithography stage, with the cleaved edges being used for alignment. Because photoresist was being used to attach the wafers to the coverglasses, the usual high temperature singe before application of the resist was omitted, and adhesion promoter was used instead. This was found to work well with the coarse geometries that were involved. The unwanted gold was removed using a proprietary gold etch, consisting of KI and I₂. The wafers were then removed from the coverglasses using acetone. After a full degrease, the metallization was annealed for 20 seconds at 440°C using a rapid thermal annealer.
The individual 800 µm x 800 µm chips were then cleaved along the gaps in the front side gold. It was found that the alignment of the lithographies on the front and back had been accurate to within 10 µm in all cases.

The copper heatsinks were then prepared. They were degreased and etched in HCl for 1 minute to remove all traces of oxide. A bell-jar evaporator was then used to deposit indium to an uncritical thickness of several microns. A chip was then placed carefully on the raised mesa of each heatsink, as illustrated in Figure 4.16. A small weight was lowered onto the chip, and the heatsink was then placed on a hotplate to melt the indium and to attach the chip securely. Large contact pads were glued to the heatsinks near the chips, using epoxy adhesive. These pads were waste thickness monitor crystals from the electron-beam evaporator, comprising quartz wafers coated with gold on one side. A wire bonder was used to connect the backside metal to the contact pad using aluminum wire.

The chips were now ready for testing. Figure 4.24 contains photographs of the front side of a typical chip before mounting, and a photograph of the backside of a mounted chip. The raised mesa on the heatsink is nearly completely hidden by the chip, which is nominally the same size, but its outline can just be seen, thanks to a slight misalignment. The close-up of the front side shows the pattern of stripes. The square just outside the stripes marks the edge of the etched window in the current blocking layer.

4.5 EXPERIMENTAL RESULTS

4.5.1 Zero-Bias Optical Transmission Results

The same apparatus was used for these devices as for the quarter-wave structures; it is shown in Figure 3.27. Zero-bias transmission spectra for the 3-wavelength structure and the 6-wavelength structure are shown in Figure 4.25. These spectra were taken using
unprocessed pieces of the wafer with a spot diameter of approximately 0.5 mm. The half-power widths of the Fabry-Perot resonances in these spectra were 26 Å for the 3-wavelength sample and 19 Å for the 6-wavelength structure. For processed devices, however, these widths were 19 Å and 9Å, respectively, as shown in Figure 4.26, because of the greatly reduced size of the probed area. The small size meant that it was not possible to obtain full spectra out to 11000 Å for the processed devices, since the sensitivity of our system (especially the photomultiplier) drops off very rapidly with increasing wavelength.
At this stage it was found that devices with shiny backside finishes exhibited multiple transmission peaks resulting from Fabry-Perot resonances from the whole wafer. Devices with cloudy backside finishes did not have this problem, so devices of this type were selected for testing. Of course, a better remedy would be to apply an anti-reflection coating to the backside.

Figure 4.25. Zero-bias transmission spectra for the Fabry-Perot structures with spacer layer thicknesses of a) 3 wavelengths, and b) 6 wavelengths.
Figure 4.26. Expanded transmission spectra to show the Fabry-Perot resonances of a) the 3-wavelength device, and b) the 6-wavelength device.

4.5.2 Modulation Results

Devices were selected for reverse-bias tests on the basis of their breakdown voltages. The maximum voltages that could be applied were around 20 V for the 6-wavelength devices and 10 V for the 3-wavelength devices.

No significant effect was seen on the spectrum of the 3-wavelength device, but a clear effect was seen with the 6-wavelength one. Figure 4.27 shows the effect of a reverse bias of 20 V. The peak shifted by 3 Å and decreased in size. A modulation ratio of 2:1 was obtained at a wavelength of 9198 Å. The reverse leakage current for 20 V applied was approximately 25 μA.

For forward bias, good current-voltage characteristics were required, to minimize heating. A typical characteristic is shown in Figure 4.28. This is not dissimilar to the curve for a laser diode of the same area. A forward voltage drop of 2 V for a current of
100 mA is very respectable, and indicates that the ohmic contacts and reflectors had low

Figure 4.27. Effect of reverse bias on a 6-wavelength device: transmission spectra of the Fabry-Perot peak for zero bias and for 20 V applied reverse bias.

Figure 4.28. Typical current-voltage characteristic for a Fabry-Perot device.
resistance. For optical testing pulsed current was required, as discussed earlier. A pulsed power supply designed for laser diodes was used. It provided 30 mA of DC current with pulses of up to 400 mA superimposed. Pulse widths of 1 µS to 5 µS were used.

Unfortunately it proved to be impossible to obtain modulation results, since the injection of carriers caused the emission of a lot of light. The devices were behaving as

![Graph A](image1.png)

![Graph B](image2.png)

**Figure 4.29.** Spontaneous emission spectra near the Fabry-Perot resonance for a) a 3-wavelength device and b) a 6-wavelength device.
light-emitting diodes. The spectra of emitted light for the two devices are shown in Figure 4.29, uncorrected for system errors. With 200 mA of bias the amount of light emitted at the peak wavelength of 9200 Å was almost an order of magnitude larger than the transmitted light that originated in the white light source. The same effect was found for the 3-wavelength device. The first effect that was obtained upon increasing the forward bias was a small increase in the signal at a current of around 300 mA. This increase was also due to radiation from the modulator. A commercial infra-red light-emitting diode, with an emission peak at 9400 Å was tried, but it too gave out insufficient light to mask the modulator's emissions.

Finally, to partially check the heat flow calculations, direct current was driven through a device, so that 100 mW were being dissipated. The peak shifted to longer wavelength by 15 Å.

4.6 DISCUSSION OF RESULTS

The zero-bias spectra are qualitatively in agreement with the theoretical spectrum of Figure 4.2. The resonant peaks are not quite as high as the edges of the high-reflectance band, which suggests that the reflectors were not perfectly matched. The overall magnitude of the transmittance is lower than that in the simulation because of reflections off the substrate and small amounts of absorption there. The position of the resonance for the 6-wavelength device was at a rather shorter wavelength than that for which it was designed, because of the unstable gallium source in our MBE machine. A number of wafers also came out with wildly inaccurate thicknesses. The designed widths of the peaks were 12 Å and 9 Å, so the obtained values of 19 Å and 9Å were quite satisfactory. The peak for the 3-wavelength device appears to be somewhat asymmetric. This wafer had the shinier
backside and greater problems with multiple peaks, so the shoulder on the peak may well be caused by extra reflections, despite the care that was taken to select a device with a cloudy backside. The considerable narrowing of the peak that was obtained for the tiny devices compared to pieces of unprocessed wafer demonstrates that the broadening irregularities were on a small scale.

The reverse bias modulation that was obtained with the 6-wavelength device was made possible by the growth rate inaccuracy, which put the peak very close to the bandgap. The sharpness of the peak meant that only a very small shift was required for modulation to occur. Electroabsorption was also taking place, as shown by the reduction in the height of the peak. There was no problem with device heating here. The 500 μW being dissipated would have caused a shift of less than 0.1 Å, according to the DC measurement made in forward bias. According to the calculations, 500 μW should cause a temperature rise of around 0.1 K, assuming a thermal resistance of 200 K/W. The modulation obtained was promising, especially since the applied field was only a little over 100 kV/cm, but the shift was still only of the same order of magnitude as the stability of a real source. Furthermore, this Franz-Keldysh shift is only possible very close to the bandgap, where some electroabsorption is taking place, and where quantum well electroabsorption modulators will generally be easier to use.

The forward bias results were disappointing. Carrier injection was clearly demonstrated by the emission of light. In order to see any shift in the spectrum, however, high carrier densities, close to those needed for superluminescent radiation, are required. The spontaneous emission spectrum is quite broad, and it was no real surprise that it extended through the 9200 Å peak of the 6-wavelength device. The long wavelength emission at 1 μm from the 3-wavelength device was probably due to donor-to-acceptor recombination; it may well have originated partly in the N-type Al₄Ga₆As, which frequently shows broad photoluminescence in the middle of the bandgap. The relative broadness of the peak, 19 Å, meant that a shift of only a few Ångströms would have been
hard to discern. It was hoped that a commercial light-emitting diode (LED) might produce
enough light to completely obscure the modulator's emission, but it proved to be
impossible to collect and focus sufficient light. The modulator had a tiny active area and
was being driven very hard, at up to 400 mA. The LED's active area was much larger,
probably by a factor of over 100, and only a small fraction of its radiation could be
focussed onto the modulator. Reflections off the backside of the modulator would have
further reduced the incident intensity. For operation at wavelengths so close to the
bandgap, a laser light source is required. Unfortunately that is a very difficult wavelength
range for both semiconductor lasers and dye lasers.

The DC measurement was a good demonstration of the heating problem. Injected
carriers should cause a small peak shift to shorter wavelength. The 100 mW dissipation
caused a large shift to longer wavelength by heating the whole device, not just the active
layer. For the Fabry-Perot structure we would expect that the fractional shift in the peak
per degree of temperature rise would be similar to that of the quarter-wave structure,
around 0.5 Å/K. The observed 15 Å shift therefore corresponds to a temperature rise of
around 30 K, indicating a thermal resistance of around 300 K/W, rather worse than the
calculated value. That particular sample was not attached very securely to the heatsink,
however, so this may not have been a typical result. No thermocouple measurements were
taken, because of the difficulties involved with attaching a thermocouple to a chip with
dimensions less than 1 mm.

Since no modulation results could be obtained in forward bias, it was not possible to
attempt high-speed measurements. Since the mechanism for operation is rather similar to
that of a laser diode, laser switching speeds give a guideline on the speeds that could be
expected. The carrier lifetime decreases with increasing carrier density, so an appropriate
mode of operation might be to bias the device well into the high-level injection regime and
to apply a modulating signal on top of that. Since higher carrier densities are obtained for a
given current in devices with thinner spacer layers, fast devices might be designed with a low-order spacer cavity.

The concept of the tunable Fabry-Perot structure has been demonstrated. Very sharp resonances have been obtained. These structures could form the basis of useful modulators if it were possible to cause appreciable shifts in the position of the peak. The shift that was obtained with reverse bias demonstrated that the spectrum can be tuned electrically, but it was not sufficient to make a useful device. For sub-bandgap operation, carrier injection appears to be the technique of choice. For our structures, the spectrum was too close to the bandgap, so that spontaneous emission from the highly pumped spacer layer obscured any shifts that may have been occurring. The quality of the Al$_{0.4}$Ga$_{0.6}$As was suspect because of the low growth temperature, and it is possible that insufficient numbers of carriers were being injected. The long wavelength emission seen from the 3-wavelength device may well have originated in an Al$_{0.4}$Ga$_{0.6}$As layer.

The plasma effect is greater at longer wavelengths, further from the bandgap. This type of device is therefore best suited to operation at such a wavelength. GaAs-based devices may prove to be useful at the common fiber-optics wavelengths of 1.3μm and 1.55 μm. Should optical communication systems ever be built to operate at even longer wavelengths, say 5 μm or 10 μm, these devices might really come into their own. The alternatives at present are HgCdTe devices, which have great problems with the material technology, and GaAs quantum well devices using inter-subband transitions.$^{70}$

Some of the problems associated with the quarter-wave device are also present in this device. Layer thickness control and uniformity are critical again; this one feature makes all tunable interference filters impractical with current MBE technology. Tilting is not so practical as a tuning mechanism for these devices, since the heatsink will block the light if it is tilted. These devices are also very sensitive to temperature. In the forward bias mode, care would have to be taken to ensure that the average current is kept constant.
5 CONCLUSIONS

5.1 SUMMARY

This work began with the desire to build a fast solid-state light modulator that did not rely on electroabsorption. The concept of a tunable optical interference filter was suggested. Such a device would have sharp features in its transmission spectrum at photon energies below the bandgaps of any materials used in fabrication, so that no light would be absorbed. Some perturbation by an applied electrical signal would cause parts of the spectrum to move, causing modulation in the intensity of the transmitted light.

The idea was first demonstrated by using a strong electric field to shift the transmission spectrum of a quarter-wave high-reflectance structure. The quarter-wave stack is the simplest multi-layer interference device. It consists of many alternating layers of two materials with different refractive indices. Each layer has an optical thickness, defined as the physical thickness multiplied by the refractive index, of a quarter of a particular wavelength. The optical transmission spectrum exhibits a band of high reflectance centered on that wavelength, with sharp transitions to oscillatory transmission on either side.

A strong electric field is the simplest form of electrical perturbation that can be applied. The effect of the electric field is to change the refractive index of one or both of the materials in the quarter-wave stack, thereby changing the optical thicknesses of the layers and moving the transmission spectrum. Extensive analysis was performed to determine the required and achievable sharpnesses of the spectrum, and the amount by which an electric field would be able to shift the spectrum. It was found that the maximum field that could be applied would just be sufficient to cause modulation of light. Device structures, designed to operate at around 1 μm wavelength, were fabricated by molecular
beam epitaxy (MBE), and sharp tunable spectra were obtained. The shifts that could be obtained were rather small, and the voltage required was 100 V, so, while the concept had been demonstrated, we did not yet have a practical device.

An alternative mechanism was required for low voltage operation, and carrier injection was the obvious electrical choice. At this point, attention was turned to a more sophisticated optical interference device, the Fabry-Perot interferometer. In its all-dielectric form, it consists of two quarter-wave high reflectors separated by a spacer layer, whose optical thickness is equal to an integer number of half-wavelengths. The effect of the spacer layer is to place a sharp transmission resonance at the central wavelength. To tune the spectrum it is enough to change only the refractive index of the spacer. The device that was investigated was a p-i-n diode structure, in which the reflectors were doped quite heavily, and the spacer layer was left undoped. This type of device can be reverse biased to change the refractive index via a strong electric field, as for the quarter-wave devices. Carrier injection can be obtained by forward bias.

The theoretical optical and electrical behaviors of the device were thoroughly analyzed. It was found that a change in the refractive index of the spacer layer would cause an even smaller spectral shift than did the universal change in the quarter-wave devices, so a larger change in refractive index would be required. Calculations showed that high levels of injected carriers in the spacer layer could give the required change through the plasma effect. Since the required injected carrier level was similar to that found in a semiconductor laser, considerable care had to be taken in the device design, from the choice of materials to the device geometry and the shape of the heatsink. A fabrication process involving 3 photolithography steps was developed. It successfully incorporated alignment of backside patterns to the front side patterns. Devices were fabricated, designed to operate at around 1 μm wavelength. Very sharp spectra were obtained, with a peak width of only 9 Å in one case. This spectrum was so sharp that the very small shift that could be obtained by reverse bias was sufficient to cause a modulation ratio of 2:1. In forward bias, however,
the spontaneous emission of light from the modulator masked any changes in the transmission spectrum. A stronger light source than our monochromated white light source, preferably a laser, would be needed for operation in this wavelength range.

There would have been a better chance of success if the device had been designed to operate at longer wavelength, since the obtained refractive index change there would be greater and there would be no possibility of light emission. Logical choices for an operating point would be at 1.3 μm or 1.55 μm for fiber optics. Since the plasma effect increases in proportion to the square of the wavelength, the device could well prove useful should long wavelength modulation, say at 5 μm or 10 μm, ever be desired. It may prove to be a worthy competitor to devices based on quantum well inter-subband transitions or HgCdTe.

5.2 SUGGESTIONS FOR FUTURE WORK

The devices that have been demonstrated are clearly well below any useful standard. The spectral shifts were on the order of the stability of a laser source, and well below the effects of expected errors in layer thicknesses. Fabricating devices to operate at a particular wavelength would be a low yield hit-and-miss exercise with today's technology.

One way to address this problem would be to try to improve the accuracy of layer thicknesses. If certain advanced MBE techniques ever become practical then it could become possible to control the thickness of a layer to within one atomic layer. Uniformity across a large wafer is another matter, however. With current technology, only a small fraction of each wafer will have the correct thickness. It will rarely prove worthwhile to process a whole wafer and to use only the very small part of it that has exactly the right thickness. The currently available control over layer thickness and uniformity are ample for
almost all electronic and optoelectronic devices. Only these vertical structures call for a vast improvement, and it is questionable whether there is sufficient incentive for the work.

If greater shifts in the spectrum were available, the requirements on the thickness control could be relaxed slightly. In the Franz-Keldysh mode, little can be done, other than designing the device to operate at the absorption edge of the material, in which case all advantages over other devices would be lost. Since electrorefraction has its greatest effect on the long wavelength edge of the high-reflectance band for the quarter wave devices, an optimized device of this type would have that edge as close as possible to the bandgap of GaAs.

In the carrier injection mode, however, there are possibilities. For a start, an improvement in material quality would reduce the current required for a given current density, and would also increase the maximum obtainable refractive index change. Considerable improvement could certainly be achieved by growing the epitaxial layers with a higher substrate temperature. The change in refractive index increases with the square of the wavelength, so longer wavelength applications should be sought. The change is also proportional to the injected carrier density and inversely proportional to the effective mass. The effective mass of an electron in GaAs is very small, but the holes are heavy. The reduced effective mass could be decreased by nearly a factor of two if the light hole band could be brought into prominence. In certain strained-layer structures, consisting of thin alternating layers of two materials with a slight lattice mismatch, the lifting of the valence band degeneracy can result in the light hole band's being the lower energy and more occupied one. Thus it could be worthwhile to incorporate strained-layer superlattices in a device structure. Higher injected carrier densities could be obtained with longer carrier lifetimes. Thus silicon may be a suitable material, even for an optoelectronic device such as this. The mirrors do not necessarily have to be epitaxial, so long as they are flat. Suitable materials might be MgF₂ and Si.
Other device geometries could also be investigated. The spectral shift increases with the fraction of the material that has carriers injected. Therefore transverse injection structures may prove to be better. The structure could be either a quarter-wave stack or a Fabry-Perot interferometer, etched into a mesa and surrounded by re-grown material of a higher bandgap. Current would then be injected from the sides, filling the whole device structure with carriers. This technique has been used successfully for surface-emitting lasers. In GaAs, the lateral device dimensions would be limited by the carrier diffusion length to approximately 5 to 10 μm. This mode of operation would greatly reduce the operating voltage of the quarter-wave devices; thus it would be an alternative to the hetero-nipi structure suggested in section 3.8.2.

There is a growing trend toward fabricating GaAs devices on silicon substrates. Therefore it would be an interesting exercise to fabricate one of these modulators on silicon. Semiconductor lasers on silicon have been demonstrated, so the material quality is now adequate. Silicon is transparent to wavelengths greater than 1.1 μm, so 1.3 μm or 1.55 μm would be suitable for demonstration purposes.

5.3 APPLICATIONS

These devices, non-saturating and non-absorbing, have potential advantages over their competitors where high optical power densities are encountered. The fact that any operating wavelength can be used, given adequate layer thickness control, means that the devices could be used as modulators for lasers based on completely different materials, so in some cases there may be no rivals. Long wavelength applications are the most promising.

There may also be a niche for this type of modulator if integration with silicon electronics is required. If, for example, a modulator on silicon operating at 1.3 μm or
1.55 μm is desired, an electroabsorption device would have to be based on the InGaAsP quaternary. The lattice constant of this material is considerably greater than that of GaAs, so the mismatch with the silicon substrate could be as high as 8 or 9%. While the 4% mismatch between Si and GaAs is gradually being overcome after many years of research, anything much greater may prove to be insuperable for device quality material. If a silicon based modulator is not possible, a GaAs-based tunable interference modulator may be the best alternative.

It may be possible to make a virtue out of a problem and use a semiconductor optical interference filter into a sensor. The devices are extremely sensitive to temperature, as has been seen, and applied pressure would also shift the spectrum. Thus changes in temperature or pressure will cause changes in the transmitted and reflected intensities at appropriate wavelengths. A laser beam could be used to probe the sensor from a large distance, so the sensor could be placed in a hostile environment where it would be very difficult to make electrical connections. With spectra as sharp as the ones we obtained, temperature changes of just a few degrees could be detected.

The very narrow bandwidth of the Fabry-Perot resonance means that such a device could be used in conjunction with a standard photodetector to make a highly wavelength-selective detector. Monolithic integration would be quite simple. These detectors could be used in wavelength division multiplexed optical communication systems. If very rapid tuning could be achieved then a single detector could be used to scan several different signals.

The idea of tunable optical interference devices is so new that little thought has been given to where they might be used. With improvements in device performance, two-dimensional arrays of modulators with high modulation ratios may become available. Many optical information processing applications would then arise, making the device more than just an interesting research topic.
6 REFERENCES


J.D. Plummer, Public communication.

R.E. Williams, Gallium Arsenide Processing Techniques (Artech House, Dedham, Massachusetts, 1984).


M. Shur, GaAs Devices and Circuits (Plenum, New York, 1987).


84 M. Abramowitz and I.A. Stegun, Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables (U.S. Government Printing Office, Washington, D.C., 1964)


97 P.C. Kemeny, J. Appl. Phys. in press.


101 R.V. Southwell, Relaxation Methods in Theoretical Physics (Clarendon, England, 1952)