Silicon on Insulator Integrated Optical Waveguides

by

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PhD Thesis

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To Nikki, George, Edward and Rebecca
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Abstract

This research project explored the potential of forming an integrated optics technology based on silicon core waveguides suitable for application in sensors and communications in the wavelength range 1.2 to 1.6 μm. Integrated optics has evolved around the use of compounds such as lithium niobate and III-V semiconductors due to their available electro-optic properties. By contrast silicon has received relatively little attention as its indirect band gap has prevented the fabrication of light sources in the material and its centrosymmetric crystal structure means that it has no useful linear electro-optic effect. The lack of a demonstrated low loss integrated optical waveguide compatible with single mode optical fibres has been a further limitation. However, these major drawbacks in silicon waveguide technology may be more than offset by the potential advantages of forming silicon integrated optical devices using well established silicon microelectronics fabrication methods.

The project focused research on waveguiding in silicon-on-insulator (SOI) structures with the aim of developing a practical low loss waveguide in these structures and understanding the various loss mechanisms. In principle the optical absorption of pure crystalline silicon over the wavelength range of interest allows waveguides with losses less than 0.1 dB/cm to be formed. SOI material formed by ion implantation has been developed for microelectronic applications and provides a commercial source of a silicon planar waveguide structure with high quality interfaces and low defect density. The project studied waveguides based on this material.

Initially planar waveguides with silicon thickness from 0.57 to 7.3 microns and buried oxide thickness of 0.07 to 0.4 microns were studied. Fabrication methods and structures were identified which allowed multi-microns planar SOI waveguides to be formed with losses less than the benchmark of 1 dB/cm. For these structures a buried oxide thickness of 0.4 microns was found to be sufficient to prevent substrate leakage loss. It has been concluded that the predominate loss mechanism is scattering of light at the silicon to buried oxide interface.
Rib waveguides were formed in SOI following the insight into loss mechanisms gained in the planar waveguide studies. Optical rib waveguides with widths from 2.73 to 7.73 microns were formed in SIMOX (Separation by IMplantation of OXygen) based SOI structures consisting of a 4.32 micron thick surface silicon layer and a 0.398 micron buried oxide layer. The effect of waveguide width, bend radius, Y-junction splitting and interface roughness on loss and mode characteristics were studied at wavelengths of 1.15 and 1.523 microns. The experimental results support the hypothesis that certain rib dimensions can lead to single mode waveguides even though planar SOI waveguides of similar multi-micron dimension are multimode. The propagation losses of waveguides 3.72 microns wide were found to be 0.0 dB/cm and 0.4 dB/cm for the TE and TM modes respectively when measured at 1.523 microns. The measurement uncertainty was estimated to be +/-0.5 dB/cm. These results are thought to be the lowest loss measurements for silicon integrated optical waveguides reported to date.

During the course of the project other researchers have demonstrated useful electro-optic properties in silicon semiconductor junctions based on the free carrier plasma dispersion effect and room temperature electroluminescence in silicon based junctions. The combination of these developments with the practical waveguide structure demonstrated in this project now makes the possibility of developing a practical silicon based integrated optics technology a reality.
Publications


Contents

Acknowledgements ii
Abstract iii
Publications v
Contents vii

1. Introduction 1
   1.1 Introduction 2
   1.2 Thesis Overview 3
   1.3 Integrated Optics 4
   1.4 Silicon Integrated Optics 9
   1.5 Project Objectives 10
   1.6 Project Approach 10

2. Review of Silicon Integrated Optics Technology 13
   2.1 Introduction 14
   2.2 Comparison of Alternative Technologies 14
   2.3 Silicon Related Technologies 16
   2.4 Waveguiding in Silicon 21
   2.5 Active Optical Devices in Silicon 30
   2.6 Conclusions 34

3. SOI Planar and Rib Waveguide Theory 37
   3.1 Ray Optic Model of Planar Optical Waveguides 38
   3.2 Electromagnetic Theory of Planar Optical Waveguides 44
   3.3 Loss Mechanisms in SOI Optical Waveguides 55
   3.4 Effective Index Model of SOI Rib Waveguides 58
   3.5 Application Example of the Effective Index Model. 64
4. SOI Waveguide Fabrication
   4.1 Introduction
   4.2 SIMOX Manufacture
   4.3 Waveguide Polishing
   4.4 Thermal Oxidation
   4.5 Rib Waveguide Fabrication

5. Optical Measurement Techniques
   5.1 Introduction
   5.2 Optical Characterisation Apparatus
   5.3 Excitation of Modes
   5.4 Fresnel Reflection
   5.5 Experimental Procedure
   5.6 Waveguide Loss Measurement
   5.7 Experimental Accuracy

6. SOI Planar Waveguide Experimental Characterisation
   6.1 Introduction
   6.2 SOI Waveguide Specifications
   6.3 Experimental Methods
   6.4 Planar Waveguide Optical Losses
   6.5 Planar Waveguide Mode Profiles
   6.6 Substrate Optical Losses
   6.7 Silicon Guiding Layer Thickness
   6.8 Discussion of Results
   6.9 Conclusions
Chapter 1.
Introduction

1.1 Introduction
1.2 Thesis Overview
1.3 Integrated Optics
1.4 Silicon Integrated Optics
1.5 Project Objectives
1.6 Project Approach
1.1 Introduction

The aim of this three year project was to develop a practical silicon integrated optical waveguide structure which could form the basis of silicon integrated optical waveguide circuits. The motivation for the work was the longer term objective of developing a low cost manufacturing process for making integrated optical components based on well established silicon microelectronics production techniques. Though a range of basic waveguide structures could be formed with silicon as the core, the project selected one structure, silicon-on-insulator (SOI), to study in detail.

Various forms of SOI have been developed for radiation hard, high speed and high power microelectronics applications. The structure preferred today consists of a silicon crystal (c-Si) layer on a buried silicon dioxide layer. This structure forms a ready made planar waveguide with the surface silicon as the core with a refractive index of approximately 3.5 and air forming the upper cladding and the buried oxide (refractive index approximately 1.5) providing the lower cladding. With the commercial availability of SOI wafers it would certainly be attractive if they could be easily adapted to optical circuit applications.

The demand for integrated optical components has been and continues to be driven by the expansion of a fibre optical telecommunication infrastructure and, to a lesser extent, by the potential application of the technology in physical, chemical and biological optical sensors. Silicon as a waveguiding medium is potentially suitable for telecommunication applications as it has very low optical loss at the optimum dispersion and loss wavelengths of communication optical fibre, 1300 and 1550 nm respectively. This is also a valuable attribute for sensor applications as the devices may take advantage of light source and detector technology already produced in volume for telecommunication applications.

Though silicon does not have a high electro-optic coefficient, the refractive index within a silicon waveguide can, in principle, be modulated by varying the electron and hole densities. The refractive index change is due to free carrier dispersion [1]. This may allow
a silicon integrated optical technology to include intensity and phase modulators and switches.

1.2 Thesis Overview

In this chapter the technological environment in which the project took place is described along with the consequential project objectives and project approach. The objectives and methodology employed in the project were formed following a review of silicon integrated optics technology which can be found in Chapter 2.

In order to advance SOI integrated optics technology it was necessary to understand the physics of SOI waveguiding, and, for example, understand the loss mechanism in these guides as part of aiding the design of more efficient integrated optics devices.

To help characterise SOI waveguides the project has devised an approach to waveguide measurement supported by computer aided theoretical modal analysis. Chapters 3 to 5 describe the appropriate theory, sample preparation and waveguide characterisation techniques. Chapters 6 and 7 report the experimental results, make comparisons with theoretical predictions, model the significant waveguide loss mechanisms and conclude by explaining the elements behind a low loss SOI waveguide. The overall project conclusions and suggestions for future work can be found in Chapter 8.

1.3 Integrated Optics

Integrated optics is analogous to integrated microelectronics. Photons, rather than electrons, are guided in an integrated optical circuit by means of optical waveguides. The fabrication of a number of optical waveguide components on a single substrate can allow a useful optical system to be formed. There are a number of distinct levels of integrated
optics which include passive and active devices and the integration of optical and
electronic functions on the same substrate.

The structure of waveguides in integrated optics is either planar, where light is confined in
a plane parallel to the substrate, see figure 1.1, or strip waveguides, where the light is
confined in two dimensions and guided in a third, see figure 1.2. In both structures the
refractive index of the core material must be higher than the surrounding cladding material
for waveguiding to be achieved. The waveguide guiding medium must be transparent at
the optical wavelength(s) to allow guiding. In addition, the waveguide's media must be
highly homogenous and the interfaces between the core and the cladding must be smooth
if significant loss from the waveguide due to scattering is to be avoided.

The telecommunications industry is the major driving force behind integrated optics
research [2]. High speed fibre optic communication links require optical transmitter and
receiver systems. Integrated optics offers reduced system size and cost, increased system
integration with electronic components and increased bandwidth and transmission rates.

Of additional significance is the use of integrated optics and electronics for ULSI (Ultra
Large System Integration) devices and ULSI systems interconnection. The objective is the
elimination of device intra and inter communication bottlenecks by the use of optical
signals in place of electrical signals. The continued advance of ULSI operation speeds will
increase the demand for IC device optical interconnection. Optical computer buses have
been proposed, which may require integrated optics. Taking the philosophy one step
Figure 1.1 Planar Optical Waveguide
Figure 1.2 Strip Optical Waveguide
further, the development of optical logic gates has opened the way to the development of the all integrated optical computer [3], which, in principle, will operate in the order of 1000 times faster than existing electronic computers. A prototype system was predicted by 1993 [4].

The field of optical sensing technology has prompted specific research into integrated optics. Many applications exist and include displacement interferometers [5], evanescent field chemical sensors [6] and fibre optic gyroscopes [7]. Device specifications are often very different to those for telecommunication applications. For example, the fibre optic gyroscope, illustrated in figure 1.3, requires an integrated phase modulation system operating at only 10-100kHz [8], whereas phase modulation based telecommunication intensity modulators are being pushed beyond 20GHz [9].

The preferred materials for integrated optics have been:

Glasses
Silicon dioxide or silicon nitride on silicon
Electro-optic crystals (e.g. lithium niobate)
III-V Semiconductor alloys (e.g. GaAs/AlGaAs, InP - which also have useful electro-optic coefficients)
Polymers

The first two are in general limited to passive device application (e.g. a passive optical spectrum analyser [10]).

Those materials with high electro-optic coefficients (e.g. lithium niobate's electro-optic coefficient can be as high as $30.8 \times 10^{-12} \text{mV}^{-1}$ [11]) have been favoured for active devices. Active devices are based on controllable changes in the local refractive index of the waveguiding structure, which allows light to be deflected and waveguide effective lengths altered. Electro-optic effects are preferred to the alternatives of magneto-optic,
Figure 1.3 Integrated Optical Fibre Optic Gyroscope
acousto-optic and thermo-optics due to the relative ease of creating an electric field via two simple electrodes. However, the scope for total optical and electronic circuit monolithic integration with the favoured electro-optic materials is not possible due to their insulator properties. These limitations do not apply to monolithic integration in III-V semiconductors which have become the most popular total solution. These compound semiconductor crystals can also have high electro-optic coefficients.

General integrated optics devices requirements include directional couplers, switches and modulators, filters and wavelength multiplexers/demultiplexers, lasers and amplifiers, detectors and bistable elements.

1.4 Silicon Integrated Optics

Until recently waveguiding in silicon had received limited research and development. A review of silicon integrated optics can be found in Chapter 2. The key points arising from the review are summarised here and in the next section. The review has identified the following factors which have been responsible for the increased importance of silicon for integrated optics.

1) Silicon, which is highly transparent above its absorption edge of 1.1 μm, is compatible with the standard telecommunication wavelength range of 1.2-1.6 μm.

2) Light emitting properties of irradiated carbon doped and rare earth element doped silicon diodes have focused attention on silicon optics [12,13,14]. (Note that the indirect nature of silicon's band gap has been the limiting factor in producing light sources in the material, see Chapter 2.)

3) Silicon does not exhibit a linear electro-optic effect present in, for example, lithium niobate. This is due to the inversion symmetry of silicon's diamond lattice. However, the potential for active device fabrication in silicon by free carrier dispersion suppression of
the refractive index has now been demonstrated [1]. The refractive index of silicon can be
depressed by a few parts per thousand by injecting or generating electrons (or holes) in an
undoped region using a forward biased pin junction or short wavelength (below the silicon
band gap) light. A short wavelength (0.4μm) light modulated silicon optical switch
operating in the wavelength range 1.2–1.6 μm [15] has demonstrated a free carrier lifetime
of less than 1 ns and a device operation switching frequency in excess of 76 MHz with a
near 100% modulation depth achieved using 150 pJ short wavelength pulses.

4) Silicon integrated optics benefits from established and well developed microelectronics
fabrication techniques and the potential for monolithic integration with existing integrated
electronic circuit technology.

5) For those optical functions not practical within silicon, silicon micro-machining
techniques offer methods of device hybridisation [16,17]. For example, a III-V laser diode
can be positioned to an accuracy of less than 0.3 μm relative to a waveguide on silicon.
Efficient coupling between the light source and a silicon waveguide could be aided by the
similarity in refractive index between III-V semiconductor alloys and silicon (n=3.5).

As with the other materials technologies, silicon must provide a low loss (typically less
than 1 dB/cm) single mode stripe waveguide structure. Single mode operation is important
as it is essential to many device operation principles (e.g. interferometry). It is also
required by most applications in order to be compatible with single mode optical fibres.

At the beginning of this work no silicon waveguide had been reported with a loss below
4.4 dB/cm [18]. It is generally considered that for a waveguide technology to be viable for
integrated optics applications, then losses of less than 1 dB/cm require practical
demonstration.
1.5 Project Objectives

Following the review of silicon integrated optics research and the technological environment, it was possible to state the project's objectives from a relatively informed position. The key point from the review is that the potential benefits of silicon as a waveguiding medium in the wavelength range 1.2-1.6 µm are currently unattainable due to the relatively high waveguide losses demonstrated. The project aimed to research this obstacle. The objectives were as follows:

1) To experimentally research optical losses in silicon-on-insulator waveguides (as this materials technology was selected as the most promising approach from the technological review) and develop low loss planar and stripe waveguides.

2) To utilise the development in 1) to construct passive components and provide a foundation for subsequent fabrication of active functional elements, e.g. a phase modulator.

1.6 Project Approach

The project was planned as a sequence of logical steps, each of which required completion before continuing to the next step. The sequence was as follows:

1) Review existing SOI and related integrated optics research.

2) Achieve an optimum SOI planar structure. This involves varying:
   a. SOI manufacture procedure and specification
   b. buried oxide layer thickness
   c. silicon guiding layer thickness
   d. theoretical modal and loss modelling
3) Identify critical loss mechanisms in the optimised planar structure.

4) Use the results of 1), 2) and 3) to aid in the design of a low loss stripe SOI waveguide.

5) Produce and optimise the stripe waveguide structure.

6) Use the results of 1)-5) to select the most viable and appropriate device application to develop in SOI.

7) Develop and demonstrate the necessary passive structure for 6) and the basic structure in which active functional elements could subsequently be integrated.
Chapter 2.
Review of Silicon Integrated Optics Technology

2.1 Introduction
2.2 Comparison of Alternative Technologies
2.3 Silicon Related Technologies
2.4 Waveguiding in Silicon
2.5 Active Optical Devices in Silicon
2.6 Conclusions
2.1 Introduction

Increasing interest is being paid to silicon integrated optical devices for fibre optic communication, electronic circuit interconnections, all optical signal processing and optical sensor applications. The potential benefits are seen as the realisation of a range of optical system applications in an inexpensive and robust form. Significant advances in this concept have been made utilising III-V semiconductors. However, a similar implementation based on silicon technology may allow ease of integration with existing silicon electronics and will take advantage of the well characterised properties of silicon and lower cost production techniques.

Integrated optics can potentially play a significant role in a range of physical, biological and chemical sensor technologies. Silicon based sensors are forecast to become the most important sensor types over the next decade [19]. It follows that the integration of optical circuits on silicon substrates may also play an important role in optical sensing technology.

This review of silicon integrated optics aims to discuss the advances made thus far and identify a number of goals that must be realised before the field will have a significant impact on commercial technology.

2.2 Comparison of Alternative Technologies

The majority of integrated optics research effort in the last ten years has been concentrated on III-V semiconductors, ferroelectric materials (most notably lithium niobate), glasses and polymers. III-V semiconductors (on GaAs and InP substrates), lithium niobate and various glasses are commercially available in wafer form of high optical quality, compatible with microelectronics fabrication techniques, and capable of supporting waveguides with optical losses as low as 0.1 dB/cm [20,21].
The significant property of lithium niobate is its high electro-optic coefficient which has been the key to modulators and switching devices. However, the material has no direct scope for integrated electronics, though some work has reported grafting GaAs by epitaxial lift off onto lithium niobate [58,59] with subsequent electronic device, source and detector fabrication potential.

The major advantages of the III-V semiconductors lie in their direct bandgap, which provides efficient radiative recombination necessary for light emitting diodes (and laser diodes), and a linear electro-optic (Pockels) effect useful for optical modulation and switches. III-V compounds have been successfully engineered to allow a variety of useful light emitting and laser diodes in the visible and near infrared wavelength ranges to be commercialised. The materials also have a wide range of optical device capabilities, both active and passive, and high speed integrated electronic device applications.

By comparison, silicon is an indirect band-gap semiconductor and has a centrosymmetric crystal structure. This means that the direct transitions commonly used to produce light sources in semiconductors and the linear electro-optic effect are not present [22,23].

The fundamental physical obstacles to the construction of silicon light emitting diodes and Pockels electro-optic modulators have meant that silicon has not been generally regarded as an important materials technology for integrated optics, though recent developments in this field, discussed later, have done much to increase attention on silicon optics.

However, these apparent disadvantages of silicon as a basis for integrated optics may well be offset by the potential for low cost manufacture of devices using conventional silicon microelectronics fabrication techniques.

It is clear from a scientific perspective why a number of materials have been preferred to silicon for integrated optics. However, from a technological standpoint the driving forces are different. The need for integrated optics to be combined with electronic functions implies substantial advantages for the silicon industry. It is seen that many of silicon's
optical limitations may be balanced by electronic, technological and commercial advantages.

Further interest in silicon optics has developed with the increased use of low loss optical fibre transmission in the infrared range 1.2-1.6 μm as the material is highly transparent between these wavelengths, (see figure 2.1), and it is here where the major potential lies.

2.3 Silicon Related Technologies

A variety of waveguiding structures on silicon substrates have been demonstrated. Table 2.1 lists a number of reported structures and associated optical losses.

Silica and Silicon Nitride on Silicon

Passive silica and silicon nitride waveguides on silicon substrates represent the most advanced silicon waveguiding technology at present [5,24,25,26].

The waveguides are formed by thermal oxidation of a silicon substrate or silicon dioxide deposition, which can be carried out by a wide variety of techniques (e.g. chemical vapour deposition, sputtering, sol-gel spin coating). For the silica guide a core region is usually doped with phosphorous (to raise the refractive index) or, to improve reproducibility of optical characteristics (and mainly the refractive index difference) all the silica is doped with a phosphorous concentration of 2 to 3%, with a higher concentration of 5 to 10% in the core region. This typically yields a refractive index difference of 0.007. Alternative dopants have been used (e.g. arsenic).

The silicon nitride waveguide utilises a lower silica cladding layer with a nitride core which is covered by a silica top cladding layer.
Figure 2.1 Optical Absorption Spectrum of n-type Crystalline Silicon [35]
<table>
<thead>
<tr>
<th>Waveguide Structure</th>
<th>Measured Loss (dB/cm)</th>
<th>Measurement Wavelength (nm)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 µm Si on SIMOX</td>
<td>8</td>
<td>1150 TE</td>
<td>7</td>
</tr>
<tr>
<td>Standard SIMOX</td>
<td>4.4</td>
<td>1300</td>
<td>8</td>
</tr>
<tr>
<td>Ge$<em>x$Si$</em>{1-x}$ on Si</td>
<td>1.9</td>
<td>1300 TM</td>
<td>9</td>
</tr>
<tr>
<td>p/p* silicon</td>
<td>10</td>
<td>1200-1600</td>
<td>6</td>
</tr>
<tr>
<td>Doped silica on silicon</td>
<td>0.2</td>
<td>600-1600</td>
<td>10</td>
</tr>
<tr>
<td>Silicon nitride on silica on silicon</td>
<td>0.2</td>
<td>600-1600</td>
<td>11</td>
</tr>
</tbody>
</table>

Table 2.1 Silicon Based Waveguide Optical Loss Reported Measurements
These structures have proved to be very low loss (0.2 dB/cm [24,27], see Table 2.1) and a number of passive devices including lenses, beam splitters, spectrum analysers, Michelson interferometers and vibration and displacement sensors have been produced [5,25,27].

The significant advantages of these insulator materials on silicon include ease of manufacture and low optical loss. For the silica doped waveguides the electromagnetic mode field profiles are similar to those of single mode optical fibres, which allows efficient coupling to these fibres. Coupling losses as low as 0.2dB have been reported [28]. Physical coupling is aided by the ease of construction of fibre locating grooves by anisotropic etching [28].

The demonstration of practical active devices in silica waveguides has been limited to phase modulators based on a thermally induced change in silica's refractive index [29]. There is no electrical device capability due to the insulating nature of the material. (However, electronic integrated circuits could in principle be fabricated in the silicon supporting substrate prior to waveguide fabrication.) The silica based devices are weakly guiding structures and this limits the maximum curvature of the waveguides [30] and hence limits minimum device size. The all silica waveguide's small refractive index difference (~0.007) between core and cladding also limits the engineering scope of passive integrated devices such as lenses and mirrors. To achieve passive optical components it is necessary to alter the effective index of a guided mode. This can be done by changing the refractive index of the guide, changing the refractive index of the adjacent media or changing the thickness of the waveguide. Effective refractive index changing of the adjacent cladding media by variations in cladding thickness represents the simplest means of changing the effective guided mode index. However, in many cases an effective index change of 0.01 to 0.1 is desirable, for example in the construction of integrated Fresnel lenses [10], which is not achievable using this simple method with the weakly guiding silica structures.
The growth of device grade III-V semiconductor crystalline structures on silicon is possible [31] and is now conducted on a commercial scale for GaAs on silicon. One method of making III-V compound semiconductor waveguides on silicon involves depositing a buffer layer of a few hundred angstroms of, say, amorphous GaAs on the silicon substrate, followed by annealing and then depositing further layers, and solid phase epitaxy recrystallisation, to build up the required waveguide heterostructure [32]. The technical problems associated with the technique arise from the lattice mismatch between silicon and the III-V semiconductors (e.g. the lattice constant of GaAs is 0.565 nm which is about 4% larger than that of Si, 0.543 nm), hence the inclusion of an initial amorphous buffer layer which alleviates strain in the structure.

It has been found [32] that if a Si(100) wafer with a small offset angle towards the [110] direction is used this facilitates single-domain growth of GaAs. The offset angle effectively lengthens the silicon lattice constant on which the GaAs can grow. This effective lattice spacing is made to match the actual spacing of the GaAs crystal. Therefore interface stress between the two crystal structures is reduced and fewer defects result.

The importance of III-V passive waveguides on silicon will probably be less significant than the construction of III-V light sources and other active III-V devices on silicon. These are discussed later in the Chapter.
2.4 Waveguiding in Silicon

Waveguiding in silicon on silicon substrates has the potential for the construction of a number of active devices unavailable to the silica and silicon nitride waveguides. It may also lead to a simpler manufacturing process than depositing III-V materials on silicon.

Waveguides in which silicon is the core material have been demonstrated in two basic structures. Firstly, where silicon in various doped states and/or a semiconductor compound of silicon are used (e.g. silicon germanium) and, secondly, silicon clad by an insulator. These technologies will be discussed in turn.

*Semiconductor/Semiconductor Silicon Waveguides*

One example of a silicon waveguide structure that has been demonstrated is a lightly doped (9x10^{14} \text{ cm}^{-3}) silicon core on a heavily doped (3x10^{19} \text{ cm}^{-3}) substrate [33]. The surface cladding of the waveguide is either air, silicon nitride or silicon dioxide. Theoretical predictions indicate that a n/n' or p/p' waveguide could be produced with losses less than 1 dB/cm in the wavelength range 1.2 to 1.6 \mu m [34]. However, losses no lower than 10 dB/cm have been reported experimentally [35]. (Loss due to interface scattering and/or volumetric scattering arising from the difficulties of growing defect free intrinsic silicon on highly doped silicon may account for the higher than predicted losses.) The Si cladding/substrate has its refractive index depressed by the presence of excess carriers. Typically the core of the waveguide has a refractive index of 3.5 and the heavily doped cladding/substrate has an index of 3.49 [35]. The disadvantages of this structure are both the high absorption in the highly doped cladding and, due to relatively weak confinement at the silicon/silicon interface, a large evanescent field in this cladding.

Low-loss (1.9 dB/cm) waveguides at 1.3 \mu m have been constructed in Ge_{0.1} Si_{0.9} by chemical vapour deposition upon an undoped silicon substrate [36]. This structure, which follows a similar philosophy to low loss waveguides in III-V materials, does not suffer from the high evanescent field substrate absorption characteristic of the high doped/lightly
doped silicon waveguides discussed above. The structure is also potentially useful in the construction of photodiodes in the wavelength range 1.2 - 1.6 μm. This is explored in more detail in Section 2.5 Active Optical Devices in Silicon. It may also have a useful linear electro-optic coefficient.

Silicon on Insulator Waveguides

Figures 2.2 and 2.3 illustrate two silicon-on-insulator (SOI) rib waveguide structures. Figure 2.2 is silicon on sapphire and figure 2.3 is silicon on silicon dioxide. The guide is formed by the silicon (which should be undoped in order to avoid absorption from free carriers) which has a refractive index of approximately 3.5 and a lower insulator cladding layer with a lower refractive index, for example, approximately 1.5 in the case of SiO₂. The upper cladding may be air or could be a thermal oxide layer. Very little theoretical difference is found to exist in the planar waveguide modal properties for these two options as the modal solution of the waveguiding structure is insensitive to the difference between the refractive index for air and that of 1.5 for SiO₂.

The development of SOI was originally driven by its application in radiation hard electronics for military and satellite applications. An additional benefit of SOI includes the increase in isolation between electronic devices on the same chip and hence the potential for increased device operation speed and packing density. Two processes that have come to the forefront of this technology are Separation by Implantation of OXYgen, known as SIMOX, and Bond-and-Etchback Silicon-On-Insulator, BESOI (both types of wafers have been commercially available for several years). Waveguides formed from BESOI have reported losses lower than 2.0 dB/cm [37,38]. Manufacturers of both SIMOX and BESOI claim similar defect density and buried oxide interface roughness. However, the SIMOX process is thought to lead to better uniformity of the surface silicon layer over the area of a wafer and may therefore provide a better basis for the manufacture of consistent waveguide devices as compared with BESOI. SIMOX and SIMOX waveguides are discussed further in the next section.
Figure 2.2 Silicon on Sapphire Rib Waveguide

Figure 2.3 Silicon on SiO₂ Rib Waveguide
SIMOX Preparation and Waveguiding

SIMOX offers a readily available basic starting point for integrated optics. The "as manufactured" wafer represents a high confinement single mode (at a wavelength of 1.3 μm [40]) planar waveguide with a silicon core layer 0.2 μm thick. Rib [35] and SiO₂ strip loaded (SiO₂ strip 3.0μm wide and 0.5μm thick)[49] waveguides have been produced in SIMOX using standard photolithographic and etching techniques.

SIMOX is manufactured by ion implanting the surface of a silicon wafer with a dose of 1.6-2.0x10¹⁸ O⁻/cm² at 160-200 keV followed by high temperature (1300 °C) annealing in a nitrogen atmosphere or vacuum (typically 6 hours duration). This process results in a silicon top layer about 0.12-0.25μm thick and a buried SiO₂ layer 0.35-0.45 μm thick. The silicon top layer can be increased in thickness by expitaxial growth (thereby altering the modal properties of the waveguiding structure).

From both an electronic and optical point of view, the quality of SIMOX is defined by three important parameters:

(1) Defect density in the crystalline silicon guiding layer (defect optical losses for good quality SIMOX have been predicted to be less than 1 dB/cm at a wavelength of 1300nm [40]).

(2) The roughness of the silicon guiding layer and buried oxide layer interface (optical scattering loss will become prohibitive if roughness exceeds 20 angstroms RMS for the standard SIMOX structure [34]).

(3) Minimising the formation of silicon islands in the SiO₂ layer and SiO₂ islands in the silicon surface layer.

Various alternative dimensions have been investigated for SIMOX. A maximum oxide thickness achievable without significantly degrading the quality of the silicon top layer is
about 0.6-0.65μm using a dose of $2.2 \times 10^{18}$ O$^+$ cm\(^{-2}\) at 180 keV. However, a small increase in dose to $2.5 \times 10^{18}$ O$^+$ cm\(^{-2}\) leads to a heavily damaged top layer with many defects [40].

Thicker buried oxide layers can be produced by growing epitaxial silicon on a standard SIMOX wafer to a thickness that allows a subsequent oxygen implantation to merge with the front of the existing buried SiO\(_2\) layer. Taking this idea further, a thicker epitaxial layer will allow a dual SIMOX structure to be formed, silicon top layer/SiO\(_2\)/silicon/SiO\(_2\)/silicon substrate. Figure 2.4 illustrates this structure [40] which has been found to have a similar optical quality to that of standard SIMOX.

**SIMOX Optical and Electronic Circuits**

It has been suggested [40] that two level SIMOX offers the potential for 3D optoelectronic integration. Two possibilities that have been considered are:

1. Optical interconnects in both levels and

2. Electronic ICs in the top level with a subterranean optical interconnect in the lower level.

Silicon layers separated by a SiO\(_2\) layer greater than 0.4 μm thick will not couple optically. With the layer thickness locally reduced to say less than 0.1μm, strong coupling would result.

**Waveguiding Crystallographic SIMOX Studies**

The investigations of SIMOX's waveguiding properties have yielded an additional diagnostic technique relevant to both the optical and electronic uses of the material [38]. The three main quality issues with SIMOX discussed above all lead to optical losses. In other words, low loss waveguiding in the top silicon layer of a SIMOX wafer may be an indication of good electronic quality silicon. Because of the similar requirements of SOI
Figure 2.4 Dual SIMOX Structure [40]
for both integrated electronics and integrated optics applications, SIMOX waveguide understanding and optimisation has benefited from the much larger research effort directed towards electronics applications of the materials.

**SIMOX Waveguiding Performance**

As illustrated in Table 2.1, optical loss in standard SIMOX waveguides is relatively high. The minimum recorded loss is thought to be 4.4 dB/cm [39] for a strip SiO$_2$ loaded guide, illustrated in figure 2.5. Here a number of sequential oxygen implantation and annealing cycles were used in the manufacture of the SIMOX wafer. This method leads to substantially reduced dislocation densities [41,42].

Kurdi and Hall [43] have predicted losses of less than 1 dB/cm at 1.3µm, for the fundamental electric (TE) propagation mode through 0.2µm Si on a greater than 0.5µm buried oxide layer. These results have not yet been experimentally verified and the reasons for the higher than predicted losses actually measured remain in question. It has been suggested that these high losses may result from optical scattering due to crystal defects in the Si guiding layer and surface scattering due to roughness at the Si/SiO$_2$ interface [43]. It is also noted than none of the reported SIMOX waveguides have used buried oxide layers in excess of 0.5µm, which suggests that substrate coupling losses should not be ignored as a loss mechanism. Comparisons have been made with III-V semiconductor waveguides on InP and GaAs substrates which can have losses of 0.1 dB/cm [20]. Silicon has a similar refractive index to III-V semiconductors, but the mode wavefront propagation is very different in equivalent dimension waveguides due to the large index difference between silicon and SiO$_2$ (delta n=2), as opposed to the small differences between the epitaxial alloy layers used in III-V waveguides.

Experimental loss comparisons have been carried out on various silicon guiding layer thicknesses [44]. SIMOX with a top silicon layer thickness of 2µm, achieved through epitaxial growth, on a 0.45µm buried oxide layer, has been evaluated for optical insertion loss at 1.15 and 1.523µm wavelengths. Guiding layer thickness was then reduced in
Figure 2.5 SiO₂ Strip Loaded SIMOX Waveguide
several steps by thermal oxidation. The guides tested were predicted to be highly multimode. Therefore, it is not possible to establish an accurate waveguide loss for the fundamental mode. However, the results demonstrate lower insertion loss for an increasing silicon layer thickness. With increasing silicon layer thickness a lower proportion of the optical power is transmitted in the waveguide cladding and in the region of the cladding/core interface. Scattering losses at this interface, which have been identified as a significant loss mechanism in SIMOX waveguides [34], will therefore be reduced. This may be one explanation for the experimental observations.

Multi and Single Mode SIMOX Waveguides

Planar waveguide theory predicts that a single mode SIMOX waveguide at a wavelength of 1.3µm will require a guiding layer thickness of less than 0.2µm. This is convenient from one point of view as it is a typical SIMOX wafer dimension. However, two serious limitations must be considered. Firstly, if SIMOX optical devices are to be used in fibre optic applications, they will need to be butt coupled to single mode optical fibres. The coupling efficiency, predicted from electric field overlap integral calculations, will only be approximately 3%. Secondly, waveguiding loss may dictate a thicker Si layer before losses can be reduced to acceptable levels.

Based on planar waveguide theory [45], the dimension of a strip waveguide to meet the above parameters will be multimode. This may limit the range of applications that SOI waveguides will be appropriate for.

However, mode-matching and beam propagation analysis of strip SOI and GeSi/Si waveguides have indicated that planar theory leads to a misconception regarding maximum single mode waveguide dimensions [46]. In fact predictions indicate that rib and strip loaded waveguides of several microns in dimension will allow only fundamental modes to propagate. Experimental observation [39] tended to support this theory, but further experimental work was warranted and was carried out as part of this project.
2.5 Active Optical Devices in Silicon

Electro-optical Effects

Electro-optical effects are changes in the refractive properties of a material in the presence of an electric field. A large electro-optic coefficient has been considered as essential for any integrated optics technology to be practical, particularly relating to the construction of integrated optical switches and modulators.

The Pockels effect is a linear electro-optic effect related to the redistribution of bound charge in a crystal. Both lithium niobate and various III-V semiconductors possess useful Pockels electro-optic coefficients. Unfortunately the effect does not exist in silicon due to the inversion symmetry of its diamond lattice.

The only practical electro-optic effect in silicon is thought to be free carrier plasma dispersion [1,35]. The refractive index of silicon can be depressed by a few parts per thousand by injecting electrons (or holes) into an undoped region using a forward biased pin junction. Alternatively they can be swept out of a locally doped region. The refractive index depression is accompanied by an increase in absorption. Soref and Bennett [1] have predicted that a phase modulator based on the free carrier effect will have an additional loss $<1$ dB for a $\pi$ phase shift.

Typically, the current density for carrier injection devices range from 500 to 2000 A/cm$^2$ or 10 to 40 mA/mm of junction, when $10^{18}$ carriers/cm$^3$ are injected into the waveguide. By contrast, depletion mode devices offer the advantages of a lower current technique. The construction of devices in SIMOX based on these principles might be a practical proposition.

Altering the refractive index in a silicon waveguide by changing the free carrier density has also been demonstrated using an incident beam of short wavelength light ($\lambda_0=0.4\mu m$) below silicon's band gap [47,48]. A guiding structure of silicon on doped silicon no longer
guides when the core index is reduced through the creation of electron hole pairs generated by the incident light. By modulating the incident short wavelength light the silicon waveguide acts as an intensity modulator in the range 1.2-1.6\mu m. The free carriers generated by the short wavelength light were reported to have a lifetime of less than 1 ns (It was predicted that the lifetime is of the order of 100 ps, but the bandwidth of the experimental equipment prevented accurate measurement). To achieve this speed a 5 nm layer of gold was deposited on the back surface of the wafer. Gold is a very efficient recombination centre. Near 100% modulation depth was achieved with a 150 pJ pulse of 0.4\mu m wavelength light. Stable device operation was measured up to 76 MHz (limited by experimental apparatus and not necessarily the silicon device).

A similar alteration of guide index using short wavelength light may also be useful for phase modulator construction in silicon on insulators e.g. SIMOX. The achievable index change is sufficient to, for example, construct a Mach-Zehnder interferometer, see figure 2.6.

A thermally operated silicon on insulator Mach-Zehnder interferometer has been demonstrated with a modulation depth of 40% for a switching power of 30 mW and a switching time of 50 \mu s [49]. (This compares poorly with the 1 ns recovery rate reported in the optically modulated device, reference 47). The switching mechanism is based on the thermally induced variation of the refractive index of crystalline silicon [50]. A similar device has been demonstrated in silica on silicon waveguides [26] but it required over ten times the power compared with the silicon waveguide device.

It has been suggested that an acoustic transducer bonded to a silicon waveguide could produce light modulation due to the large photoelastic coefficient of silicon [35]. It is thought that this technique has still to be demonstrated.
Figure 2.6 Optically Controlled Intensity Modulator
Silicon Light Sources and Detectors

The light emitting properties of silicon are seriously limited by the indirect nature of its band gap. Two main techniques are currently being developed to overcome the problem.

1.3 µm light emitting forward-biased irradiated carbon-rich silicon pn junctions have been demonstrated [12,13] with internal quantum efficiency of more than $10^5$ times higher than that of band-to-band recombination in an unirradiated, but otherwise identical diode. The formation of interstitial carbon by irradiation leads to the creation of a variety of radiative Si-C complexes which account for the increase in quantum efficiency.

An alternative approach is the doping of silicon diodes with rare earth elements [14]. The light emitting properties of rare earths are largely independent of their host structures (as demonstrated, for example, in fibre optic amplifiers [51,52,53]). Erbium doped diodes have received the most attention as the 1.54 µm emitted wavelength is compatible with low loss and minimum dispersion fibre optic communications.

Post annealing of erbium ion implanted silicon tends to cause precipitation of the rare earth. This difficulty appears to be reduced by implantation into SIMOX [54].

For detectors, strained layer GeSi heterostructure photodiodes have been demonstrated [55]. These strain layer structures also exhibit the Pockels effect [56].

Silicon Schottky-barrier detectors are being developed, and for operation close to the band gap of silicon (e.g. at a wavelength of 1.1µm) a more conventional silicon photodetector may be applicable given a sufficient absorption length.

Heteroepitaxy of InP based alloys on silicon has also been demonstrated in the laboratory [35]. If perfected, this approach will allow on-board InGaAsP lasers and detectors that operate at 1.2 to 1.6µm.
A similar approach which utilises the technology of silicon micro-machining allows complete III-V devices to be accurately positioned and bonded to silicon opto-electronic circuits [16,17,57]. Silicon offers excellent electrical, mechanical and thermal properties making it an ideal substrate for hybrid integrated optics. The substrate provides a convenient laser diode heat sink. Lateral positioning of a laser diode butt coupled to a waveguide with a similar electric field mode profile must have a tolerance less than approximately 0.3 μm if high light source to waveguide coupling efficiency is to be achieved. Results from reference 16 predict, from an overlap integral calculation, a coupling efficiency of 90%. However, in practice 30% efficiency was measured.

2.6 Conclusions

The optical disadvantages of silicon as a basis for integrated optics may be more than balanced by the potential benefits arising from compatibility with silicon integrated electronics and the manufacturing advantages of silicon as the basis for a hybrid integrated optics technology.

Silicon Waveguide Technology

Oxide and nitride waveguides on silicon substrates are comparatively well developed with many passive optical advantages. However, their structure precludes the development of essential active devices without some major advances in materials technology. Waveguiding in silicon itself may help to overcome this problem provided that a basic guiding structure can be demonstrated with losses below 1 dB/cm, single mode operation and with field profiles that couple efficiently to, for example, single mode optical fibres.

Silicon waveguides formed by an intrinsic layer of silicon on doped silicon could be produced at very low cost with established process technology. However, the structure has a fundamental loss minimum in the region of 1 dB/cm due to the high absorption of the doped cladding layer. In the case of SOI waveguides formed with a buried oxide, provided
that the structure is defect free, waveguide losses could be theoretically as low as the losses arising from the intrinsic losses within silicon and the silicon dioxide waveguide cladding. The loss for pure silicon at $\lambda_0 = 1.523 \, \mu\text{m}$ is 0.004 dB/cm [60].

Considerable research effort is being focussed on developing low defect SIMOX for electronics applications. SIMOX provides an ideal SOI starting point for the development of waveguides as the electronics industry's material process technology developments are coincident with the requirements for ultra low loss and consistent waveguiding structures i.e. the electronics work aims to achieve very low crystal defects in the surface silicon layer, interface roughnesses of the order of a few atomic layers and film thickness uniformity across a wafer of <20nm. It is for these reasons that this new research work, reported in the following chapters, has concentrated on SIMOX based optical waveguide technology.

There are certainly other related active silicon waveguide technologies worthy of further research (e.g. silicon germanium), but their investigation was not within the scope of this project.

**Silicon Light Emitting Technology for Integrated Optics**

Silicon light emitting diodes and lasers require substantial development. They are at a considerable technical disadvantage to III-V devices and have, by comparison, a significant research gap to bridge. A more practical approach may involve perfecting epitaxial growth of III-V alloys on silicon and utilising established LED, laser and photodiode technology. Alternatively, one might use hybrid circuits where III-V devices are accurately positioned and bonded on silicon opto-electronic chips using micro-machined location structures.

If low loss silicon waveguides can be easily constructed, the next focus may be on electro-optic effects with the goals of switches and modulators. Device speed may be limited compared with that achievable in III-V materials due to free carrier recombination
speed limitations, but there will inevitably be a trade off between performance and the total integrated optical and electronic environment.

*Future Prospects for Silicon Integrated Optical Devices*

In the short term it is envisaged that silicon integrated optics could be of significant interest in the construction of a range of simple fibre optics components (e.g. NxM switches and phase modulators) and find uses in optical sensors including fibre optic gyroscopes and evanescent field chemical/biological sensors. Longer term, with the successful development of silicon phase and intensity modulators working in the range 100 MHz to 10GHz combined with hybrid LD/PD technology, devices may find application within optical fibre telecommunication transceivers.
Chapter 3.
SOI Planar and Rib Waveguide Theory

3.1 Ray Optic Model of Planar Optical Waveguides
3.2 Electromagnetic Theory of Planar Optical Waveguides
3.3 Loss Mechanisms in SOI Optical Waveguides
3.4 Effective Index Model of SOI Rib Waveguides
3.5 Application Example of the Effective Index Model.
3.1 Ray Optic Model of Planar Optical Waveguides

Optical waveguides serve the purpose of confining and propagating light. This is accomplished by the principle of total internal reflection. Figure 3.1 illustrates a three layer planar waveguide. The refractive index of the film, $n_p$, which is known as the core, is chosen to be higher than the upper and lower layer refractive indices, $n_c$ and $n_s$, known as the cover and substrate cladding layers respectively. Light guided in this structure can be thought of as a ray bouncing along a zig-zag path in the core region, with the ray totally reflected from the cladding layers.

In the ray treatment of a waveguide it is necessary that the angle of incidence of the ray, $\theta$, is greater than the critical angles for both the substrate and cover interfaces. For simplicity, we assume $n_s = n_c$, then $\theta > \arcsin(n_p/n_s)$, according to Snell's law of reflection. However, this is not a complete picture of the operation of three layer waveguides.

In the ray model illustrated in figure 3.1, the ray can be considered as normal to the wavefront. Inside the core film one can picture two plane wavefronts, one travelling up while the other is travelling down, both propagating at angle $\theta$. For a guided mode to be supported, these plane waves need to form a standing wave pattern across the core region. For this condition to be satisfied the propagation angle must result in a plane wave experiencing a phase change equal to an integer multiple of $2\pi$ as a result of one transverse round trip across the core.

The round trip phase change consists of a phase change through the distance travelled in the zig-zag across the waveguide and a phase change caused by the reflections at the core/cladding interfaces. The phase change due to the zig-zag is given by $2k_o h \cos \theta$, where $h$ is the width of the core, $k_o$ is the free space wave vector $k_o = 2\pi/\lambda_o$ and $\lambda_o$ is the free space wavelength of light.

Figure 3.2 illustrates the ray optic picture of light incident at the core/cladding interface.
Figure 3.1 Ray of light propagating down a waveguide by total reflection
Figure 3.2 Reflection and refraction of light at an interface
Considering the problem in general terms as a reflected and a refracted (transmitted) ray at the interface, the reflection and transmission coefficients are given by the Fresnel formulae [79].

These coefficients are dependent on the refractive indices of the two media, the angle of incidence and the polarisation of the light. For s-plane polarized light (perpendicular to the plane of incidence) the reflection coefficient is

\[ R_\perp = \frac{n_1 \cos \theta_1 - n_2 \cos \theta_2}{n_1 \cos \theta_1 + n_2 \cos \theta_2} \quad (3.1) \]

For the p-plane polarised light (parallel to the plane of incidence) the reflection coefficient is

\[ R_\parallel = \frac{n_2 \cos \theta_1 - n_1 \cos \theta_2}{n_2 \cos \theta_1 + n_1 \cos \theta_2} \quad (3.2) \]

In common with the rest of the waveguide literature the s polarisation is referred to as Transverse Electric (TE) and the p polarisation is referred to as Transverse Magnetic (TM). Using Snell's law for isotropic materials \( n_1 \sin \theta_1 = n_2 \sin \theta_2 \) in equation 3.1 and 3.2 to eliminate \( \theta_2 \) the reflection coefficients become, for the TE polarisation

\[ R_{\text{TE}} = \frac{n_1 \cos \theta_1 - \sqrt{n_2^2 - n_1^2 \sin^2 \theta_1}}{n_1 \cos \theta_1 + \sqrt{n_2^2 - n_1^2 \sin^2 \theta_1}} \quad (3.3) \]

and for the TM polarisation
It is necessary for total internal reflection that \( n_1 > n_2 \) and that the angle of incidence, \( \theta_1 \), be greater than the critical angle \( \theta_c \). For \( \theta \) less than \( \theta_c \) the light will only be partially reflected and the reflection coefficient is a real value and less than unity. However, if the incident angle exceeds the critical angle the reflection coefficient becomes complex with an absolute value of unity. In this case the reflection coefficients can be rewritten as

\[
R_{TE} = \frac{n_1 \cos \theta_1 - i \sqrt{n_1^2 \sin^2 \theta_1 - n_2^2}}{n_1 \cos \theta_1 + i \sqrt{n_1^2 \sin^2 \theta_1 - n_2^2}}
\]

(3.5)

and

\[
R_{TM} = \frac{n_2 \cos \theta_1 - i n_1 \sqrt{n_1^2 \sin^2 \theta_1 - n_2^2}}{n_2 \cos \theta_1 + i n_1 \sqrt{n_1^2 \sin^2 \theta_1 - n_2^2}}
\]

(3.6)

If these equations are written using exponential notation as \( R = \exp(-i2\phi) \), then the phase changes \( \phi_{TE} \) and \( \phi_{TM} \) for the TE and TM polarisations are found to be

\[
\phi_{TE} = \arctan \frac{\sqrt{n_1^2 \sin^2 \theta - n_2^2}}{n_1 \cos \theta}
\]

(3.7)

and

\[
\phi_{TM} = \arctan \frac{(n_1/n_2)^2 \sqrt{n_1^2 \sin^2 \theta - n_2^2}}{n_1 \cos \theta}
\]

(3.8)
These phase shifts associated with total internal reflection are known as the Goos-Hänchen phase shifts.

It is now possible to express the total phase shift condition which must be satisfied for a waveguide mode

\[ 2k_0 n_f h \cos \theta - 2\phi_s - 2\phi_e = 2m\pi \] (3.9)

where \( m \) is any positive integer corresponding to the mode number. There are discrete solutions to this equation for \( \theta \) which correspond to integer mode numbers. If only one solution each for the TE and TM polarisations exists then the waveguide is referred to as single mode.

Substituting the condition for the waveguide defined in figure 3.1 the phase changes \( \phi_s \) and \( \phi_e \) in equation 3.9 become

\[ \phi_s = \arctan \left[ \frac{(n_f^2 \sin^2 \theta - n_r^2)^{1/2}}{(n_f \cos \theta)} \right] \] (3.10)

\[ \phi_e = \arctan \left[ \frac{(n_f^2 \sin^2 \theta - n_r^2)^{1/2}}{(n_f \cos \theta)} \right] \] (3.11)

for the TE waves, and

\[ \phi_s = \arctan \left[ \frac{(n_f/n_r)^2(n_f^2 \sin^2 \theta - n_r^2)^{1/2}}{(n_f \cos \theta)} \right] \] (3.12)

\[ \phi_e = \arctan \left[ \frac{(n_f/n_r)^2(n_f^2 \sin^2 \theta - n_r^2)^{1/2}}{(n_f \cos \theta)} \right] \] (3.13)

for the TM waves.
The ray optic model of a planar waveguide is useful in order to obtain an intuitive understanding and it does provide a satisfactory solution to the discrete mode angles. However, one must look to a more detailed analysis starting with Maxwell's equations in order to determine mode electric field profiles, see figure 3.3, and understand in more depth the loss mechanisms in imperfect waveguides.

### 3.2 Electromagnetic Theory of Planar Optical Waveguides

There is a considerable number of textbooks which deal with the theory of optical waveguides (e.g. [61-65, 45, 66]). This section aims to provide a sufficiently in-depth treatment of a three layer waveguide to enable an understanding of the characteristics of an SOI waveguide. However, the reader is recommended to consult the aforementioned texts to provide a wider perspective on the problem.

For the SOI waveguides studied in this thesis, the materials contain no additional charges and conduction currents. Maxwell’s four field equations are

\[
\nabla \times \mathbf{H} = \dot{\mathbf{D}} \\
\n\nabla \times \mathbf{E} = -\dot{\mathbf{B}} \\
\n\nabla \cdot \mathbf{D} = 0 \\
\n\nabla \cdot \mathbf{B} = 0
\]

where the dot superscript indicates partial differentiation with respect to time, and \( \mathbf{E} \) is the electric field vector, \( \mathbf{D} \) is the displacement vector, \( \mathbf{H} \) the magnetic field vector, and \( \mathbf{B} \) the magnetic flux density. In isotropic and linear media the constitutive relations are
Figure 3.3 Planar waveguide mode TE₀
\[
\mathbf{D} = \varepsilon \mathbf{E} \quad (3.18)
\]
\[
\mathbf{B} = \mu \mathbf{H} \quad (3.19)
\]

where \(\varepsilon\) is the permittivity and \(\mu\) is the permeability of the medium.

The usual wave equations to describe the electric, \(\mathbf{E}\), and magnetic, \(\mathbf{H}\), fields in a waveguide are given by

\[
\nabla^2 \mathbf{E} = \mu \varepsilon \ddot{\mathbf{E}} \quad (3.20)
\]
\[
\nabla^2 \mathbf{H} = \mu \varepsilon \ddot{\mathbf{H}} \quad (3.21)
\]

where the second double-dot superscript indicates second partial differentiation with respect to time.

In analysing waveguide structures, the usual method is to find the functions for each waveguide layer that satisfy the wave equations and match the fields at each waveguide interface according to the boundary conditions.

**Transverse Electric (TE) Modes**

For this wave equation treatment of a three layer waveguide the same notation is used as in the previous ray optics approach. The TE modes of a planar optical waveguide are defined as electromagnetic field solutions that have no electric field component along the direction of propagation. Thus the electric field is only in the \(y\)-direction and is referred to as \(E_y\).

Following the insight gained from the ray optic view, the field functions that should exist in the cover and the substrate layer are exponentially decaying evanescent fields resulting
from total internal reflections within the core layer. Inside the core of the waveguide the field profile should resemble the superposition of two plane waves. Therefore, the waveguide field equations can be expressed as

\[ E(x) = \begin{cases} jE_c \exp[-\gamma_c(x-h)] \exp[i(\beta z - \omega t)] & h < x \\ j[A \exp(ik_x x) + B \exp(-ik_x x)] \exp[i(\beta z - \omega t)] & 0 < x \leq h \\ jE_z \ \exp(\gamma_z x) \ \exp[i(\beta z - \omega t)] & x \leq 0 \end{cases} \]  (3.22)

and the expressions for the x-component of the wave vector for the three layers are

\[ \gamma_c = (\beta^2 - n^2 c^2 k^2)^{1/2} \]  (3.23)

\[ \gamma_z = (\beta^2 - n^2 z k^2)^{1/2} \]  (3.24)

\[ k_f = (n_f^2 k_0^2 - \beta^2)^{1/2} \]  (3.25)

where \( k_0 = \frac{2\pi}{\lambda_0} \).

For exponential decay of the electric field in the cladding layers the x-component vectors in these layers must be positive and this means that \( \beta \) must be greater than \( n_f k_0 \) and \( n_z k_0 \). \( \beta/k_0 \) is often referred to as the effective index, \( N \), of the guided mode. For a guided mode \( N \) will be greater than \( n_c \) and \( n_z \) but will be less than \( n_f \). Referring back to the ray optics model of a guided mode, \( N \) can be expressed in terms of the mode propagation angle as \( n_f \sin \theta \).
In order to arrive at the waveguide dispersion relation, the next step is to apply the necessary boundary conditions to the waveguide field forms that were written earlier. The continuity of the tangential field components at \( x = h \) (figure 3.1) requires that

\[
E_c = A \exp(ik_f h) + B \exp(-ik_f h) \quad (3.26)
\]

\[
\gamma_c E_c = -ik_f [A \exp(ik_f h) - B \exp(-ik_f h)] \quad (3.27)
\]

and also the continuity of the same field components at \( x = 0 \) results in the following pair of equations

\[
E_s = A + B \quad (3.28)
\]

\[
\gamma_s E = ik_f (A - B) \quad (3.29)
\]

Combining each set of equations for \( x = h \) and \( x = 0 \) interfaces gives

\[
-\gamma_c [A \exp(ik_f h) + B \exp(-ik_f h)] = ik_f [A \exp(ik_f h) - B \exp(-ik_f h)] \quad (3.30)
\]

\[
\gamma_s (A + B) = ik_f (A - B) \quad (3.31)
\]

and rearranging they become

\[
(\gamma_c + ik_f)A \exp(ik_f h) + (\gamma_c - ik_f)B \exp(-ik_f h) = 0 \quad (3.32)
\]

\[
(\gamma_s - ik_f)A + (\gamma_s + ik_f)B = 0 \quad (3.33)
\]
By moving the second term in each equation to the right-hand side, dividing the first equation by the second and after multiplying numerators and denominators by \( i \) these equations can be combined to give

\[
2k_f h - 2 \arctan (\gamma_s / k_f) - 2 \arctan (\gamma_e / k_f) = 2m\pi \quad (3.34)
\]

where \( m \) is an integer.

This equation is the waveguide dispersion relationship which is also known as the waveguide eigenvalue equation. The presence of the integer \( m \) in this equation indicates that the bound waveguide modes form a discrete set rather than a continuum. For each integer \( m \) there is a unique effective index of refraction and each waveguide mode has its own field profile. In terms of ray optics, this results in discrete values of the propagation angles for the existence of a zig-zag ray pattern as discussed in the earlier section of this chapter.

The electric field profile of an SOI planar waveguide \((n_i = n_g = 1.5, n_f = 3.5, h = 6\mu m \text{ and } \lambda_o=1300nm)\) for \( m=0 \) and \( m=1 \) are shown in figure 3.4 and as can be seen there exists a correlation between the mode number \( m \) and the number of zero crossings of the field in the planar waveguide structure. If one defines \( E_j = 2A \exp(i\phi) \) where \( \phi = \arctan(\gamma / k_f) \), the waveguide field forms given earlier can be simplified to

\[
E = \begin{cases} 
\hat{y} E_e \exp[-\gamma_e (x-h)] \exp[i(\beta z - \omega t)] & \text{for } h < x \\
\hat{y} E_f \cos(k_f x - \phi_e) \exp[i(\beta z - \omega t)] & \text{for } 0 < x \leq h \\
\hat{y} E_s \exp(\gamma_s x) \exp[i(\beta z - \omega t)] & \text{for } x \leq 0
\end{cases}
\]
If one also lets $\phi_c = \text{arctan}(\gamma/k)$, the waveguide dispersion relationship can be expressed in a more compact form

$$k_fh - \phi_s - \phi_c = m\pi$$

(3.36)

This dispersion relationship contains all the necessary information about the properties of the guided modes supported by a waveguide, because it determines the propagation constant of a guided mode as a function of waveguide parameters. However, it cannot be solved for propagation constants directly, instead numerical solution methods must be employed. When the problems of analysing planar optical waveguides were first addressed graphical methods were employed to solve the dispersion relationship. Sets of universal curves of normalised variables for three layer structures were calculated. The reader is referred to a number of texts for more information on these methods [61-65, 45, 66].

With the advent of powerful personal computers it has become relatively easy and convenient to solve the dispersion relationship with a computer programme. The method employed in this work involved rearranging the dispersion relationship

$$2k_fh = 2\phi_s + 2\phi_c + 2m\pi$$

(3.37)

and generating two arrays of data for the left hand and the right hand sides of the dispersion relationship over a range of values for the propagation constant, $\beta$, from $n_k$ or $n_{k_0}$ which ever was the greater, to $n_k$, which, as previously mentioned represents the range of potential propagation constants possible for a guided mode. The solution to the equation for a given value of $m$ could then be found by the values for $\beta$ for which each array had the same value. An iterative computation was then conducted to eliminate any error arising from the coarseness of the initial arrays. The value of $m$ was initially set to 0 and the solution computation run for values of $m$ incremented by 1. When no solution
Figure 3.4 SOI planar waveguide electric field ($E_y$) profiles for modes $TE_0$ and $TE_1$. 
could be found for the next value of $m$, this determined that the waveguide could only support up to the previous mode number of guided modes. For example, the method was used to determine that for the 6 μm SOI waveguide previously discussed it will theoretically support 34, 30 and 26 TE modes at $\lambda_c = 1.15$, 1.3 and 1.523μm respectively.

**Transverse Magnetic (TM) Modes**

After the insight provided by the previous section on TE modes supported by a planar waveguide, the solution for TM modes that can be supported can be developed in much the same way. For TM modes the y-axis component of the magnetic field is the only component of the magnetic field and the functional form of this field for each waveguide layer can be written as

\[
\begin{align*}
\mathbf{H} &= \hat{y}H_c \exp \left[-\gamma_c (x-h)\right] \exp \left[i(\beta z - \omega t)\right] \quad \text{for } h < x \\
&= \hat{y}H_f \cos (k_f x - \phi) \exp \left[i(\beta z - \omega t)\right] \quad \text{for } 0 < x \leq h \\
&= \hat{y}H_e \exp (\gamma_e x) \exp \left[i(\beta z - \omega t)\right] \quad \text{for } x \leq 0
\end{align*}
\]  

(3.38)

Following the same procedure as for the TE modes the same dispersion relationship is obtained, see equation 3.37. But for TM modes the phases $\phi$ and $\phi_e$ are given by

\[
\begin{align*}
\phi &= \arctan \left[ (n_f/n_s)^2 (\gamma_e / k_f) \right] \\
\phi_e &= \arctan \left[ (n_f/n_e)^2 (\gamma_e / k_f) \right]
\end{align*}
\]  

(3.39)  

(3.40)

The dispersion relationship for the TM modes can be solved using the same computer method as used for the TE modes. The magnetic field profile, $H_z$, is given by 3.38. The
electric field $E_x$ is proportional to $H_y$ and the $E_z$ component is proportional to the partial derivative of $H_y$ with respect to $x$.

The electric fields for the TM modes have components in the $z$ and $x$ directions. The electric field wavefront for a given mode can be pictured as two plane waves travelling in opposite directions across the waveguide core at propagation angle $\theta$. Provided that $\theta$ is close to $\pi/2$ the major component of the electric field is in the $x$ direction. As will be discussed later in this Chapter, the scattering loss from imperfections in planar waveguide is proportional to $E^2$ at the scattering centre. Therefore, it is useful to compare the electric field profiles of $E_y$ for TE modes with $E_x$ for TM modes. Figure 3.5 illustrates these field profiles for an SOI waveguide, $h = 2 \mu m$, TE$_0$ and TM$_0$ modes. The fields are normalised to unity which means that they are not directly comparable, but, they do serve to show that the electric field for the TM$_0$ mode in an SOI waveguide is more confined than the TE$_0$ field. This suggests different loss characteristics for the two modes arising from scattering at waveguide core/cladding interface roughness.
Figure 3.5 Predicted electric field profiles of a planar waveguide

\( n_\text{c}=1.5, n_f=3.5, h=2\mu\text{m} \) and \( \lambda_0=1.3\mu\text{m} \)
3.3 Loss Mechanisms in SOI Optical Waveguides

Before experimental characterisation of SOI waveguides was conducted it was helpful to consider the various loss mechanisms that might impair the waveguide performance and estimate their relative effects. Equation 3.41 summarises the main loss mechanisms in SOI waveguides.

\[ L_t = L_a + L_{as} + L_{vs} + L_c \]  

(3.41)

- \( L_t \) = total loss
- \( L_a \) = absorption loss
- \( L_{as} \) = core/cladding interface induced scattering
- \( L_{vs} \) = volumetric refractive index inhomogeneity scattering
- \( L_c \) = coupling of guided modes to substrate modes

\( L_a \) for pure silicon at \( \lambda_o = 1.15 \mu m \) is 2.87 dB/cm [67] and at \( \lambda_o = 1.523 \mu m \) it is 0.004 dB/cm [60] (0.22 dB/cm for silicon \( N_d = 1 \times 10^{16} \) cm\(^{-3} \) [35]).

Interface induced scattering was shown by Marcuse to be proportional to \( E^2(n_x^2-n_1^2) \) and \( A^2 \) where \( A \) is the rms roughness for planar waveguides [68]. For SOI waveguides \( (n_x^2-n_1^2) \) is large. Using Marcuse's perturbation analysis [68] of symmetric planar waveguide scattering loss, the scattering loss for a silicon core/ silicon dioxide clad planar waveguide (fundamental mode) with 20 nm rms interface roughness (this roughness is a maximum for commercial grade SIMOX and also corresponds to the roughness on the side wall of rib waveguides studied in Chapter 7) was investigated. The results for TE\(_0\), \( \lambda_o = 1.523 \mu m \), \( n_c = n_x = 1.5 \) and \( n_f = 3.5 \) are plotted in figure 3.6 for varying waveguide width. The results are...
Figure 3.6 Scattering loss predicted for a symmetric planar waveguide, rms roughness (A) 20nm, correlation length (B) 1μm, λ₀ = 1.523μm [68].
very similar for a silicon core/surface air clad planar waveguide. The resonant nature of the loss with width is due to interference effects. The sharp falls in loss with increasing width are attributed to resonances passing beyond the critical angle of the waveguide. With reference to figure 3.5, which illustrates the TE₀ and TM₀ electric field profiles, it can be seen that the TE electric field is an order of magnitude higher than the TM field at the core cladding interface. This would suggest that for SOI waveguides the interface scattering loss for TE modes will be two orders of magnitude higher than for TM modes based on scattering loss being proportional to $E^2(n_e^2-n_i^2)$. As the fundamental modes are the most confined modes it is reasonable to assume that higher order modes will have higher scattering loss due to interface roughness.

Volumetric refractive index inhomogeneity could be an important loss mechanism in silicon waveguides. The process of wafer manufacture, implanting and expitaxial growth, potentially forms islands of impurities, including silicon dioxide, and crystal defects. It has been shown [69] that volumetric scattering loss will be proportional to $1/\lambda$ for long roughness correlation lengths and $1/\lambda^3$ for correlation lengths similar to or smaller than the wavelength of the light. (One might have expected the scattering loss to be proportional to $1/\lambda^4$, i.e. the Rayleigh scattering relationship. However, as demonstrated in [69] the reduction in the confinement of the guided wave for longer wavelengths counters the Rayleigh effect.) It is worthwhile noting that $10^6$ and $10^4$ defects cm$^{-2}$ for a 5 μm square waveguide represents 25,000 and 125 defects cm$^{-1}$ within the waveguide respectively. Defect density is thought to be correlated to buried oxide interface roughness due to the nature of the implanting process and, hence, is correlated to loss indirectly.

Coupling of the fundamental mode to the substrate for SIMOX based waveguides with a buried oxide layer of 0.5 μm has been predicted to be negligible provided the silicon core is greater than 0.25 μm in thickness [70]. Evans has studied the problem and predicted that the leaky mode losses at $\lambda_0 = 1.32\mu$m for the TE₀ and TE₁ in an SOI waveguide with a buried oxide thickness of 0.4 μm and a 0.25 μm silicon core thickness will be 3.5 dB/cm and 4434 dB/cm respectively [70]. The much higher loss for the second mode is due to the greater penetration of the evanescent mode into the buried oxide and beyond into the
silicon substrate and hence, greater coupling to substrate modes. For waveguides with silicon thickness greater than 1 μm, which is the main interest of this thesis, a 0.3 μm buried silicon dioxide layer is predicted to be thick enough so as a negligible loss arises from the leakage to the silicon substrate from the fundamental guided modes. Higher order modes, with accordingly larger evanescent fields, may couple to substrate modes. The penetration of the evanescent field, for a given mode, into the buried oxide reduces as the silicon top layer increases. Evans and Hall [70] predicted that the TM modes will couple more strongly to substrate modes than TE guide modes. This prediction is experimentally investigated in Chapter 6 for various buried oxide thicknesses.

3.4 Effective Index Model of SOI Rib Waveguides

The problem of theoretically modelling a three dimensional stripe waveguide is far more complex than for the two dimensional planar waveguide. A wide range of approximate techniques have been developed, some suitable for stripe SOI waveguides [71 to 76].

The SOI stripe waveguides investigated in this thesis were of the rib form, see figure 3.7. The reason for selecting this type of waveguide was their ease of fabrication by standard photolithographic and etching techniques (see Chapter 4). In addition, Petermann et al [46] have postulated that the guided modes that these three dimensional waveguides can support are far more limited than for an equivalent dimension planar SOI waveguide. This leads to the possibility of producing relatively large (multimicron) rib waveguides in SOI which could be single mode. The planar waveguide analysis discussed earlier in this Chapter predicts than the core thickness of a single mode planar waveguide (i.e. only supporting the guided modes TE₀ and TM₀) must not be greater than 0.2 μm at λ₀=1.3 μm. The possibility of larger dimension single mode rib waveguides compatible in size with, for example, single mode optical fibre would make SOI waveguide technology much more attractive.
Figure 3.7 SOI rib waveguide
The method considered most suitable to analyse SOI rib waveguide was the effective index method [64] as it provides a useful method of identifying the range of modal solutions possible in an otherwise complicated problem. At first sight one might imagine that a rib waveguide (see figure 3.7) would only support leaky modes which would leak into the surrounding planar waveguide slab regions. However, the effect of the rib region of silicon is to make the effective index under the rib, $N_r$, larger than the effective index, $N_s$, in the slab region. The matching of the electric field boundary conditions across the imaginary interface between the slab and the rib approximates to the problem of matching the boundary condition for the planar waveguide interface discussed earlier. However, now the core index is $N_r$ and the cladding index is $N_s$.

The method of effective index analysis of a rib waveguide utilises the planar waveguide model to match the vertical and horizontal boundary conditions. The procedure involves solving firstly the planar waveguide dispersion relationship (equation 3.37) for $h =$ height of the rib, $r$, and $h =$ height of the slab, $s$. This is carried out for both TE$_0$ and TM$_0$. Then the effective indices $N_r$ and $N_s$ are used in the planar dispersion relationship, with $h$ set equal to the width of the rib, $w$, to find the horizontal solution. The TE and TM generated effective indices, $N_r$ and $N_s$, are used in the TM and TE dispersion relationship respectively for the two horizontal solutions. The resultant orthogonal modes are no longer truly TE or TM as they have electric fields and magnetic fields in more than one direction respectively. However, the predominant component of the electric field for the rib waveguide excited by a transverse electric field is transverse and we continue to refer to these modes as TE modes (though not strictly correct). And the predominant magnetic field for the waveguide excited by a transverse polarised magnetic field is also transverse, and hence we continue to refer to these modes as TM modes (though not strictly correct).

To arrive at an overall effective index for the rib waveguide guide modes, $N$, it is helpful to consider it in terms of two propagation angles from the ray optic model, $\theta_h$ and $\theta_v$, see figure 3.8. $N$ for the rib can then be expressed as

$$N = n_r \sin \theta_h \sin \theta_v$$  \hspace{1cm} (3.42)
The effective index model assumes that the electric field is zero in the regions not directly above and below the rib (excluding the slab region). For many low confinement waveguides this is a poor approximation, but in the case of SOI waveguides which have comparatively small evanescent fields in all regions (excluding the evanescent field travelling in the slab waveguide region), the approximation is good.

The effective index approximation also ignores the boundary effects of the sides of the rib. It is known that the approximation tends to slightly over-estimate $N$ [77]. If the rib side boundaries are taken into account, then the estimated $N$ is reduced. This is because the region of the core in the top of the rib will have an effective index to match the side wall boundaries which in turn must reduce the vertical effective index of the mode under the rib and hence reduce the estimate of $N$. More advanced methods of the effective index method can be found in [78].

So far we have only considered the effective index method of analysing a rib waveguide based on the fundamental modes of planar waveguides. In the case of an SOI waveguide greater than $h = 0.2$ μm in the wavelength range 1.15 to 1.6 microns the planar dispersion relationships for both TE and TM polarisations will yield more than one solution (mode). However, Petermann et al [46] pointed out that the effective index of the fundamental mode of the slab region of a SOI rib waveguide is greater than all of the modes under the rib excluding the fundamental mode. Therefore, all higher order modes of the rib waveguide should radiate power to slab modes and cannot be regarded as modes bound under the rib. These conditions only hold for the situation where $N_p$, $N_t$, and $\omega$ lead to only a single mode solution from the planar waveguide dispersion relationship. Therefore, this condition represents a straightforward method of predicting whether a SOI rib waveguide is single or multimode.

In practical terms, higher radiative modes supported by a rib waveguide, which may be apparently observed as higher order modes, could have very low radiation loss into the slab waveguide. No attempt has been made to model this possibility, but the problem is explored through experimentation in the work reported in Chapter 7.
Figure 3.8 Vector diagram illustrating the effective index, $N$, as a function of $N_h$ and $N_v$. 
Petermann et al [46] have used normalised parameters to produce an equation which will approximately predict if an SOI rib waveguide is single mode or not. The equation is

\[ \frac{a}{b} \leq 0.3 + \frac{t}{\sqrt{1 - t^2}} \]  

(3.43)

and it can be used provided that the ratio, \( t \), of the slab height, \( s \), over the rib height, \( r \), is greater than or equal to 0.5 \( (t = \frac{s}{r} \geq 0.5) \). \( a \) and \( b \) are functions of waveguide dimensions and wavelength, \( a = w/2\lambda \) and \( b = r/2\lambda \). The notation in figure 3.7 has been used rather than that in [46]. Equation 3.43 was derived by a curve fit to normalised data generated using a rib waveguide mode-matching technique. As an effective index mode-matching technique was implemented in this project in a PC computer program, it was relatively easy to predict the modal characteristic of a particular waveguide directly. Therefore, equation (3.43) was not used in this work. However, reasonable agreement between (3.43) and this work was found. It was preferred to use the direct computer based numerical method of modal prediction as it avoided the assumptions used to generate equation (3.43).
3.5 Application Example of the Effective Index Model.

The fundamental theory behind the effective index method of modelling rib waveguides is based on the planar model discussed earlier in this Chapter. The extension of the planar model to the effective index model is made relatively simple by ignoring the interface boundary conditions arising from the sides of the waveguide rib.

An example SOI rib waveguide analysis was conducted using the computer programme mentioned in Section 3.4 to investigate the impact of the simplified boundary conditions and confirm Petermann et al [46] prediction regarding the modal properties of these waveguides. The example also aims to help the reader apply the analysis technique.

The waveguide used for the example is illustrated in figure 3.9. The dimensions are:

- Rib Height $r = 4.32\mu$m
- Rib Width $w = 2.73\mu$m
- Etch Depth $e = 1.70\mu$m

and the slab height ($s$) is therefore equal to $2.62\mu$m. This waveguide is investigated experimentally in Chapter 7. The refractive index of silicon ($n_i$) is taken to be 3.5. The upper and lower cladding is silicon dioxide with a refractive index ($n_1$ and $n_3$) of 1.5.
The lower and upper cladding layers are assumed to extend to infinity. This assumption is investigated during the analysis. The wavelength used for the analysis was $\lambda = 1.523\mu$m.

Following the effective index modelling steps discussed in section 3.4, the analysis of the example SOI rib waveguide is set out below.

**Step 1:**
The effective $\text{TE}_0$ and $\text{TM}_0$ indices for planar waveguides with heights ($h$) set to the rib height ($r$) and the slab height ($s$) are calculated using the planar theory, equations 3.34, 3.37, 3.39 and 3.40.
all dimensions in microns

regions where the effective index model assumes the electric field is zero

imaginary boundaries

Figure 3.9 Example SOI rib waveguide (predicted to be single mode)
The effective index for $h = r$ TE$_0$ mode, $N_r$(TE)$_0$ = 3.495903
The effective index for $h = r$ TM$_0$ mode, $N_r$(TM)$_0$ = 3.495623

The effective index for $h = s$ TE$_0$ mode, $N_s$(TE)$_0$ = 3.489217
The effective index for $h = s$ TM$_0$ mode, $N_s$(TM)$_0$ = 3.488193

Step 2:
In the first step the horizontal boundary conditions have been satisfied for the electric field. In this second step it is assumed that the vertical boundary conditions are defined by the difference between the rib effective index and the slab effective index. The planar model is used again with the waveguide height ($h$) set to the width ($w$). The core ($n_c$) and cladding ($n_c$ and $n_e$) refractive indices are set to $N_r$(TE) and $N_r$(TE) respectively and the effective refractive index of the mode is calculated using the planar model assuming a p-plane polarised field. The same procedure is repeated using $N_s$(TM) and $N_s$(TM) with an s-plane polarised field to calculate the orthogonal mode's effective index.

In this example the transverse effective indices differences were found to be:

\[ \Delta N \text{ for TE modes} = 0.00669 \]
\[ \Delta N \text{ for TM modes} = 0.00743 \]

from $N_r$(TE) - $N_r$(TE) and $N_s$(TM) - $N_s$(TM). For the dimensions of the example waveguide it was found that the effective indices differences will only support a single mode. (This is approximately the same index difference required in similar size single mode waveguides formed with a core region completely surrounded by cladding, for example silica based single mode waveguides [5,24,25,26]). The effective indices from the planar model for these orthogonal modes are:

The effective index from the p-plane polarised solution, $N_p = 3.496963$
The effective index from the s-plane polarised solution, $N_s = 3.496778$
Step 3:
The overall effective indices for the fundamental orthogonal modes of the waveguide can now be calculated using equation (3.42). The horizontal, $\theta_\alpha$, and vertical, $\theta_\gamma$, propagation angles can be found from the definition of effective index for a planar waveguide,

\[ N = n \sin \theta \].

It follows that the :

- Rib $\text{TE}_\infty$ effective index, $N(\text{TE}_\infty) = 3.492862$
- Rib $\text{TM}_\infty$ effective index, $N(\text{TM}_\infty) = 3.492396$

Although the effective index model has matched boundary conditions across the imaginary rib to slab interfaces, the matching of boundary conditions at the vertical rib walls and the horizontal imaginary boundary between the top of the rib region and the bottom has not been completed. The effective index across the rib for the TE mode is found to be $N_p = 3.49010$ ($N_p$ was calculated based on the planar waveguide theory with $h = w$, $n_f = n_z$ and $n_e$, $n_z = n_y$). This compares with the effective index estimate of $N_p = 3.49696$. The difference in $N_p$ and $N_p$ (0.00686) indicates a discontinuity in the electric field between the top of the rib and the lower region. This is theoretically impossible and highlights a limitation in the effective index model. To improve the effective index model, matching of vertical and horizontal boundary conditions must be conducted in a set of simultaneous equations.

Extended versions of the technique based on this principle can be found in [78]. However, comparisons between the effective index model and other methods indicates that the general conclusions that can be drawn from this example analysis are unaffected by the comparatively small estimation errors expected from the boundary condition simplifications.
To investigate the claim made by Petermann et al [46] that all modes in the vertical sense under the rib, excluding the fundamental modes, have lower effective indices than the fundamental slab mode, the second order effective indices under the rib were calculated for the example waveguide. They were found to be:

\[ N_{\text{TE}}(\text{TE}) = 3.483406 \]
\[ N_{\text{TE}}(\text{TM}) = 3.482312 \]

Which, as predicted by Petermann et al, are lower than the fundamental vertical slab mode effective indices, \( N_{\text{TE}}(\text{TE}) = 3.489217 \) and \( N_{\text{TE}}(\text{TM}) = 3.488193 \). Analysis of a range of waveguide dimensions up to \( r = 10 \, \mu\text{m} \) also found this condition to be true. If the condition holds for the second order vertical modes under the rib it must also be the case for any higher order modes as they will have even lower effective indices. Therefore, providing the rib waveguide is single mode in the horizontal sense, the higher order modes can potentially couple to the fundamental mode of the slab waveguide i.e. they will be radiative modes losing power to the slab waveguide.

For the example waveguide the electric field, \( E_y \), for the \( \text{TE}_{\infty} \) mode was calculated in the vertical dimension under the rib. It was found that \( E_y^2 \) (i.e. power) at a position equivalent to the buried silicon dioxide/silicon substrate interface was \( 10^7 \) times less than the peak \( E_y^2 \) value in the centre of the waveguide, i.e. the guided power is negligible at this interface. This supports the validity of using the three layer planar waveguide solution in the effective index model for the example waveguide, where the buried oxide is assumed to extend to infinity. As the \( \text{TM}_{\infty} \) mode is more confined in the vertical direction than the \( \text{TE}_{\infty} \) mode the assumption holds good for both orthogonal modes.

Though the analysis discussed here and in section 3.4 strongly suggests that various multi micron dimension rib SOI waveguides may be single mode, the work has not provided conclusive theoretical proof. In this project it was chosen to investigate the problem further by experiment. However, it could also be useful to use a more complete modelling technique, such as the finite difference method [75], to establish whether there
are any modal solutions which cannot be predicted by the effective index method due to its various assumptions.

Two further practical points arising from the theoretical consideration of SOI waveguides are worth considering. Firstly, the radiation and scattering of light into the slab waveguide region must be absorbed in some way in a region just beyond the bound mode evanescent field if cross-talk between waveguides is to be avoided (though this may be an intention, for example, in directional couplers). Secondly, the effective indices of the two orthogonal modes TE\textsubscript{00} and TM\textsubscript{00} are found to converge for an increasing size of waveguide. For example, letting \( \lambda_0 = 1.3 \mu m \), \( n_e=n_s=1.5 \) and \( n_p=3.5 \), if \( r=3.17 \), \( w=5.47 \) and \( s=2.83 \mu m \) then \( N(\text{TE}_{00})=3.483963 \) and \( N(\text{TM}_{00})=3.483474 \) which results in a difference in the effective indices of the two modes of \( 4.9 \times 10^{-4} \). However, for the taller waveguide, \( r=7.67 \), \( w=5.82 \) and \( s=4.77 \mu m \) then \( N(\text{TE}_{00})=3.498444 \) and \( N(\text{TM}_{00})=3.498390 \) which results in a difference in the effective indices of the two modes of only \( 5.4 \times 10^{-3} \), i.e. an order of magnitude less than the 3.17 \( \mu m \) high waveguide. This can be an important design point for integrated optical devices which must be polarisation insensitive (e.g. optical filters interfacing to single mode optical fibres where both orthogonal modes may be excited).
Chapter 4.
SOI Waveguide Fabrication

4.1 Introduction
4.2 SIMOX Manufacture
4.3 Waveguide Polishing
4.4 Thermal Oxidation
4.5 Rib Waveguide Fabrication
4.1 Introduction

Sample preparation concerned the processing of SOI wafer materials prior to optical characterisation. The samples used were SIMOX obtained from Spire Inc. and Ibis Technology Inc. with varying silicon top layer and silica buried layer thicknesses and manufacturing methods.

Optical characterisation of SOI waveguides was carried out using the end fire excitation method (see Chapter 5). It is essential for this technique to polish the optical waveguide faces to a high optical quality. For those waveguides which utilised a top cladding of thermal oxide, samples were first oxidised prior to edge polishing.

The thermal oxidation of sample surfaces also provided a convenient means of reducing the silicon guiding layer thickness which allowed a range of planar test samples to be prepared. The characterisation results can be found in Chapter 6.

Photolithography and wet etching of oxidised samples provided a means of determining oxide thickness and producing trial strip oxide loaded waveguides.

4.2 SIMOX Manufacture

SIMOX wafers are manufactured by implanting the surface of a silicon wafer with typically a dose of 1.6-1.8x10¹⁸ O⁺/cm² at 160-200 keV, see figure 4.1, followed by high temperature (1300 °C) annealing in a nitrogen atmosphere or vacuum (typically 6 hours duration). This process results in a silicon top layer between 120-250 nm thick and a buried SiO₂ layer of 350-450 nm. The defect density in the surface silicon layer varies from 10¹ to 10⁸ cm⁻² and the roughness of the buried oxide/surface silicon layer is reported by the material manufacturers to vary from 1.8 to 20 nm depending on wafer processing parameters. For all SIMOX samples the surface silicon layer thickness was increased by epitaxial growth, thereby creating guiding layers of various thicknesses.
Oxygen ion implantation
dose: 1.6—1.8x10^{18} cm^2
energy 160—200 V V

Si 0.12—0.25 um
SiO_2 0.35—0.45 um

Si wafer

Figure 4.1 SIMOX Manufacture
4.3 Waveguide Polishing

Experimental procedures which utilise end fire coupling excitation of waveguides require that the parallel edge faces of a waveguide sample should be of high optical quality. It is possible to cleave SIMOX wafers to yield the necessary edge face quality, but the methods employed are unreliable. A reliable alternative is to cleave samples somewhat larger than desired and subsequently polish the edge faces.

Samples were cleaved by first scoring the wafer with a diamond scribe and then breaking the wafer along the scribed lines. Typical cleaved sample size was 10mm wide by 3.5mm long.

Samples were then mounted on one of their longest edges, in twos, on high thermally conductive 25mm diameter blocks using glass supports produced from microscope slides and bonded together using a wax with a melting point of approximately 100 °C. Figure 4.2a illustrates the arrangement, which was assembled on a 150 °C hot plate and then allowed to cool before further processing. The samples stood approximately 1mm proud of the glass supports. The ultimate sample width was dependent on the number of glass support components used. Typically, two layers of 1.1mm and two layers of 0.17mm thick supports were used.

It was important that the polishing process provided a good optical edge surface and did not bevel the edges in the region of the waveguide. This was achieved by placing two samples in a mounting assembly with waveguide surfaces facing one another.

Once mounted, the samples exposed edge faces were levelled by hand on a 1000 grit wetted silicon carbide paper. The samples were then remounted to expose their second optical edge face and again levelled by hand. Once the 'hand' levelling process was complete the samples still stood proud of the glass supports by approximately 0.5mm.
Figure 4.2a Waveguide polishing mounting assembly
Figure 4.2b Waveguide polishing clamping fixture
Three mounting assemblies were then transferred to a clamping fixture which is illustrated in figure 4.2b. The assemblies were positioned at the corners of a triangle on the fixture, with each sample assembly protruding beyond the fixture by the same distance.

The fixture was then mounted in a Struers Pedemax 2/Planopol 2 polishing machine, see figure 4.2c. The sample fixture rotated clockwise at 100rpm while the polishing surface, mounted on a flat disk, rotated anti-clockwise at 150rpm. The polishing pressure was solely due to the weight of the fixture (1kg).

The Struers machine polishing procedure was developed through trial and error. The optimum method is described below.

1) Firstly the samples were levelled using 1000 grit silicon carbide paper and water lubrication on both edges which took approximately 30 seconds per edge. The procedure required the samples to be removed from their mounting assemblies and replaced the other way up. The samples then protruded above the glass mountings by approximately 0.25mm.

2) Polishing with 2400 grit silicon carbide paper for 2 minutes with water lubrication.

3) Polishing with 4000 grit silicon carbide paper for 2 minutes with water lubrication.

4) Polishing with a 1μm diamond spray impregnated cloth disk for 10 minutes using an oil/water lubricant.

Between each process the sample fixture (with samples) was washed in running tap water and immersed in an ultrasonic cleaner for 20 seconds.

Steps 2 to 4 were conducted without removal of the samples from the fixture. Then they were turned in the mounting assemblies and the processes were repeated. Before turning, the samples stood approximately 0.2mm proud of the mounting assemblies. After the
Figure 4.2c Plan view of the waveguide polishing arrangement/machine
reversed edge polishing the samples were between 0.2mm protruding or flush with the glass mountings.

If the first run through processes 2 to 4 inadvertently polished the samples flush with the glass mounting, a 0.17mm glass support layer could be removed during the turning of the samples.

All sharp edges and corners on the samples and glass mounts were beveled off by hand using 1000 grit silicon carbide paper before process 4 to avoid damaging the polishing cloth.

Once the polishing process was completed the samples were removed from their mountings and immersed in gently boiling trichloroethylene in order to remove any excess wax. After approximately two minutes in the trichloroethylene the samples were transferred to an acetone wash and finally rinsed in propan-2-ol which leaves no drying residue.

On inspection of samples using an optical microscope, polishing quality was consistently high. The buried oxide layers were always observed and no apparent edge chips or other polishing defects could be seen.

4.4 Thermal Oxidation

The growth of high quality silicon dioxide films on silicon between 900-1100 °C is a common and well characterised process in the silicon semiconductor device industry. For SOI waveguides it provides a means of reducing silicon guiding layer thickness, generating a top cladding layer and, combined with photolithographic techniques, producing strip loaded waveguides.

There are two commonly used chemical reactions in oxidation. One is due to oxidation with oxygen and is known as dry oxidation. The second is due to oxidation with water
amorphous SiO$_2$ temperature 1100 °C wet oxygen flow

Figure 4.3 Thermal oxidation of silicon
vapour [31]. Wet oxidation proceeds faster than dry oxidation and was used for sample preparation in this work. The chemical reaction of wet oxidation is given by.

\[
\text{Si(solid) + 2H}_2\text{O(vapour)} \longrightarrow \text{SiO}_2(\text{solid}) + 2\text{H}_2
\]  

(4.1)

The oxidation process is illustrated in figure 4.3. Oxidation species move through the oxidation layer to react with the silicon. The process leads to a contamination free Si/SiO\(_2\) interface with initial and process impurities tending to migrate to the oxide surface. A Si\(_2\text{O}_x\) thickness consumes 0.45\(x_0\) Si layer thickness.

Thermally grown SiO\(_2\) is amorphous with a density between 2.15 to 2.27 g/cm\(^3\) compared with crystalline SiO\(_2\) (2.65 g/cm\(^3\)). The more open amorphous structure allows certain impurities to diffuse through it (e.g. water and oxygen). It is known that the presence of water in silica waveguides gives rise to waveguide losses as high as 10.5 dB/cm at a wavelength of 1.508 \(\mu\)m which can be reduced to 0.2 dB/cm after 3 hours annealing at 1000 °C [80]. This same phenomenon and remedy may be relevant to SOI waveguide evanescent field losses in a top thermally grown oxide cladding.

Initially oxidation rate is linear and is governed by the reaction kinetics. With the build up of the oxide, the rate of oxygen growth becomes dependent on the diffusion rate of the oxygen species to the reaction interface. This rate is governed by a parabolic law [81]. The overall wet oxidation relationship is given by:

\[
x_0 = \frac{A}{2}\left[\left(1 + \frac{t + \tau}{A^2/4B}\right)^{\frac{1}{2}} - 1\right] 
\]  

(4.2)

where the oxidation constants A, B and \(\tau\) are given in table 4.1.

Equation 4.2 provides a guide to wet thermal oxidation of SOI which was checked and adjusted for the particular apparatus used.
<table>
<thead>
<tr>
<th>oxidation temp. (°C)</th>
<th>A (μm)</th>
<th>B (μm²/hrs)</th>
<th>B/A (μm/hrs)</th>
<th>τ (hrs)</th>
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</thead>
<tbody>
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<td>0.72</td>
<td>14.4</td>
<td>0</td>
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</tr>
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<td>0.23</td>
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</table>

source:[91]

Table 4.1 Rate constants for wet oxidation of silicon
Figure 4.4 Wet oxidation furnace
The wet oxidation apparatus is shown in figure 4.4. Oxygen is passed through deionised water held at 96°C at a rate of 1 litre/minute using a submerged diffuser. The wet oxygen enters one end of a three element furnace and passes over SOI specimens held at a temperature of 1100 °C. Specimens are pushed into and pulled out of the furnace at a rate of approximately 0.5 m/minute to avoid thermal shock.

The objective of the system calibration was to allow accurate prediction of thermal oxide thickness for SOI specimens after oxidation for a given time without having to repeat destructive thickness measurements (the measurement methods are described in section 4.5).

Initially the system was approximately characterised with waste silicon (100) wafer (p type 10-20 ohm cm). These results are shown in table 4.2. Table 4.3 illustrates the results for SIMOX which started with a 6 μm top Si layer. These results can be used to adjust the relationship in equation 4.2 and constants of oxidation in table 4.1 to characterise the specific apparatus used.

4.5 Rib Waveguide Fabrication

A matrix of rib waveguide structures were fabricated from various SIMOX samples with surface silicon layers of 3.17, 4.32 and 7.67 microns. The details and justification of the structures are discussed in Chapter 7. The construction of a rib waveguide was achieved by defining a photoresist mask on a SIMOX sample using photolithography. The unmasked areas were then etched. Etching was conducted using a Plasma Technology Reactive Ion Etcher. The steps of the etching process are illustrated in figure 4.5.

The various waveguide structures were defined using a CAD system before being written onto a photolithographic mask by electron beam lithography. The mask was used to pattern a photoresist layer (Hoechst AZ1505) which had been spun onto samples approximately 15x15 mm cleaved from 100 mm diameter SIMOX wafers. The spin speed
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<th>actual $X_0$ (μm)</th>
<th>$t$ (hrs)</th>
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</tr>
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Table 4.2 Wet oxidation calibration with Si(100)
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<th>actual $X_0$ (μm)</th>
<th>$t$ (hrs)</th>
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</tbody>
</table>

Table 4.3 Wet oxidation results with SIMOX(100)
Figure 4.5 Fabrication of SOI rib waveguides
was 3000 rpm and the resist was prebaked at 90 °C on a vacuum hot plate for 2 minutes.
Following a 12 second exposure in a SET mask aligner, the photoresist was developed for
approximately 2 minutes in Hoechst AZ400K developer. The samples were then washed in
deionised water and post baked on the vacuum hot plate at 90 °C for 4 minutes.

The rib waveguide etching was conducted using reactive ion etching with CH$_3$Br at 200
mtorr, 200 watts and a flow rate of 50 sccm. The process produced near vertical rib walls
with an rms roughness value of approximately 20 nm. Rib etch depths were measured
using a step profiler and rib widths were confirmed using a scanning electron microscope.

10 mm long rib waveguide samples were end face polished parallel using the same
methods as that used for the planar waveguide samples.
Chapter 5.
Optical Measurement Techniques

5.1 Introduction
5.2 Optical Characterisation Apparatus
5.3 Excitation of Modes
5.4 Frensel Reflection
5.5 Experimental Procedure
5.6 Waveguide Loss Measurement
5.7 Experimental Accuracy
5.1 Introduction

The purpose of the optical measurement techniques were to provide a means of measuring waveguide insertion losses, propagation losses and intensity mode profiles at various wavelengths. These parameters are important for the design of devices, the determination of device losses and coupling losses experienced between devices.

This chapter describes the characterization of waveguides using the end fire coupling technique (described in detail later in this chapter).

5.2 Optical Characterisation Apparatus

Figure 5.1 illustrates the optical measurement apparatus. The measurement system was supported on a pneumatically vibration isolated steel bench.

Collimated TE polarised laser light sources at wavelengths of 1.15 and 1.523 μm were provided by HeNe and IRNe gas lasers respectively. Both sources had an approximate power of 1 mW. The HeNe laser is simultaneously a 1.16 μm source. This longer wavelength was separated by means of a 1 μm line width, 600 lines/mm blaze diffraction grating. The 1.16 μm beam, which was less bright than the 1.15 μm beam, was blocked after separation.

The laser beams were focused by means of a Zeiss F40/NA0.65 microscope objective lens onto the polished end face of the waveguide under test. The light was collected from the output of the waveguide using an identical lens. The aperture size of the second lens ensured that all the emerging light was collected. The lenses were mounted on stages with fine x,y,z position adjustment. The first lens also had x,y,z adjustment through piezoelectric actuators. The waveguide was positioned on a separate
Figure 5.1 Optical waveguide characterisation system
stage which could be adjusted in x and y. In addition, limited angular adjustment was possible normal to the beam in the horizontal and vertical planes.

The second lens was used to focus the beam emerging from the waveguide onto a 4mm square Ge infrared photodiode. 65% of the beam was split off using a pellicle beam splitter into a RT Lab infrared video camera with its lens removed.

To aid in the alignment of the lenses relative to the test sample, initial focussing was done with visible wavelength 0.63 μm HeNe lasers (see figure 5.1). Once the two lens stages had been focussed, the visible laser sources were shuttered and the required excitation laser beam unblocked. The focal length of the lenses vary with wavelength. Therefore, both stages had to be moved further away from the test sample for correct focussing of the infrared beams.

The laser beam source was chopped at approximately 120 Hz. The chopper provided an encoder signal to a lock-in-amplifier which amplified the Ge photodetector current. The arrangement eliminates ambient light detection from the photodetector, allowing only the laser light to be detected. This meant that the laboratory lights could be left on during optical measurements.

The recording of mode intensity profiles was achieved using a Colorado Video Analyser 321 in conjunction with the infrared camera. The analyser allowed the scanning of the waveform detected by the camera in both the horizontal and vertical directions. It also provided a voltage output proportional to position in the direction of scanning on one channel and a voltage related to the camera monitored intensity waveform amplitude on a second channel. The position channel was connected to the x axis of a Gould 6000 Series x-y plotter and the intensity signal to the plotter's y axis.

Calibration of the analyser system's 'x' axis was achieved by placing a 25 μm pin hole on the sample stage and illuminating it with the 0.63 μm wavelength laser source via a F50 lens (in place of the usual F40 lens). The second stage lens was used to focus the light on
to the camera. Using a 0.05 x range on the x-y plotter, the system's horizontal and vertical calibrations were found to be 23.3 +/-0.2 mm/μm and 27.2 +/-0.2 mm/μm respectively.

Calibration of the video system in terms of intensity was not practical due to the non-linear response of the camera. However, 1/e intensity profile widths could be measured by 1/e attenuation of the beam's intensity using a set of neutral density filters at position B (see figure 5.1). This procedure is discussed in the next section.

To change the TE polarised laser sources to TM polarisation a half waveplate was placed at position A (see figure 5.1). To accurately set the waveplate angular position for TM polarisation the laser beam was focussed onto the photodetector using the two F40 lenses (no sample present). A polarising filter was placed at position B and rotated until a minimum photodetector current was observed. The polarising filter was then rotated a further 90° and the half waveplate rotated until a minimum detector current was again found. The polarising filter was then removed from the system leaving the laser beam TM polarised.

The intensity linearity response of the Ge photodetector was checked for the wavelengths 1.15 and 1.523 μm. The relative optical intensity focussed onto the photodetector was varied by placing neutral density filters at position B. The calibration results are shown in figure 5.2. A maximum uncertainty in the data of +/- 0.13 μA was determined by linear regression analysis. The results show that the photodetector was linear. However, surprisingly the output for the TM 1.523 μm wavelength beam compared with the TE polarisation was significantly greater, hence data for both polarisations is plotted in figure 5.2. It is thought that placing the half waveplate at point B causes an increased feedback to the laser and there by alters its power output. Provided all photodetector readings for this wavelength and TM polarisation were conducted with the half waveplate in position and undisturbed, the feedback phenomenon caused no additional error to the optical measurements.
Figure 5.2 Photodetector calibration curves
5.3 Excitation of Modes

Two methods of excitation of SOI waveguides have been considered, end fire coupling, see figure 5.3, and butt-coupling, see figure 5.4. These excitation techniques are relevant to both waveguide characterisation measurements and integrated optical device design.

End fire coupling involves the focusing of a collimated laser beam onto a polished end face of a waveguide. Butt-coupling is achieved by butting an optical fibre source up against the polished waveguide face.

The efficiency of coupling light into a waveguide is dependent on the following parameters.

a) The degree to which the excitation and waveguide fields match.

b) The degree to which the fields coincide spatially.

c) The parallelism of the optical phase fronts.

The electric field overlap coupling efficiency, η, is a function of a) and b), and is given by [82]:

\[
\eta = \frac{\left( \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E \cdot E_g \, dx \, dy \right)^2}{\left( \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E^2 \, dx \, dy \right) \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E_g^2 \, dx \, dy}
\]  

(5.1)

were \( E \) is the input (excitation) field and \( E_g \) is the guided field. This is a power normalised version of the overlap integral between the two fields.

For end fire coupling a focused laser beam field approximates to a circular Gaussian distribution:
\[ E = \exp(-(x^2/k_x^2 + y^2/k_y^2)) \] (5.2)

2k\(_x\) and 2k\(_y\) are the 1/e electric field beam depth and width \((2k_{x,y} = \sqrt{2} f_{x,y} \text{, where } f_{x,y} = 1/e \text{ intensity depth or width})\).

The two dimensional overlap efficiency, as given by equation 5.1, with a single mode planar waveguide, is only dependent on the x dimension because the waveguide field in the y direction is assumed to be unrestricted.

The \(E_g\) field profile can either be obtained from experimental observation of the waveguides intensity profile and subsequent calculation or from theoretical calculations (see Chapter 3). The software developed within this work for planar and rib waveguide modal analysis also allows the calculation of the overlap integral between numerically calculated fields and/or Gaussian field approximations.

The overlap of \(E\) and \(E_g\) is only significant in end fire coupling when the waveguide electric field profile is narrower than the focussed excitation field. For mode profiles which are broader than the focussed excitation field, near 100% overlap coupling efficiency can be obtained in practice by defocussing the excitation beam until the coupling is optimised. This option is not possible with butt-coupling. In practical applications, where integrated optical devices must be connected to optical fibres, it is important to design the integrated waveguide so that its field profile is closely matched to that of the fibre.
Figure 5.3 End-fire coupling
Figure 5.4 Butt-coupling
For end fire coupling, matching of the phase fronts of the excitation and waveguide fields is achieved by using a focusing lens of the correct numerical aperture (NA). Figure 5.5 illustrates the necessary conditions.

\[ \theta \] is the wavefront propagation angle for the mode to be excited. It follows that the required NA of the focusing lens is:

\[ NA = \frac{n_2}{n_1} \cos \theta \]  \hspace{1cm} (5.3)

For butt-coupling, \( \theta \) in figure 5.5 represents the propagation angle of the optical fibre mode.
Figure 5.5 Phase front matching

\[\text{NA} = \sin \theta_1\]
5.4 Fresnel Reflection

Reflections at the air/waveguide end interfaces must be accounted for in the calculation of waveguide propagation loss from measured waveguide insertion loss. The interface transmitted power can be found from Fresnel's equations. The transmitted powers, $T_T$ and $T_M$ for TE and TM polarised input beams are given by equation 5.4 and 5.5 respectively [45].

$$T_{TE} = \frac{4(n_1/n_2)\cos \theta_I \cos \theta_R}{[\cos \theta_I + (n_1/n_2)\cos \theta_R]}$$

$$T_{TM} = \frac{4(n_1/n_2)\cos \theta_I \cos \theta_R}{[(n_1/n_2)\cos \theta_I + \cos \theta_R]}$$ (5.4)

(5.5)

$\theta_I$ and $\theta_R$ are defined in figure 5.5. For a normally incident beam the reflection loss calculated using equations 5.4 and 5.5 for both polarisations from air ($n_1 = 1.0$) to silicon ($n_2 = 3.5$) and back to air is found to be 3.22 dB.

Of interest to waveguide loss measurement accuracy is the sensitivity of this reflection loss due to misalignment of the waveguide end faces to the normal axis of the waveguide. It is estimated that for SOI waveguide sample preparation this misalignment is no greater than +/- 3 degrees, which represents an increase in reflection loss of 0.02 dB per face or, in percentage terms, a 0.2% error in the Fresnel loss estimated at either end of the waveguide.

It is possible to reduce Fresnel reflection using an anti-reflective coating on the input and output surfaces of the waveguide. Correct design of the coating will ensure that reflected light is destructively interfered through multiple reflection within the coating layer. The necessary coatings refractive index is given by $((n_2 + n_1)/2)+n_i$ and its thickness should be
1/4 of a wavelength (referring to the wavelength of the light travelling in the coating) to ensure maximum destructive interference of the reflected light [83].

5.5 Experimental Procedure

Refering back to the test apparatus in figure 5.1, the 1.15 and 1.523 µm wavelength lasers were found to take one hour to stabilise after switching on and no waveguide measurements were made during this time.

Before a waveguide measurement was made the two F40 lenses were brought together in order to focus the selected laser source onto the centre of the photodetector. The photodetector output was then recorded \( (P) \). This provided a relative value for the laser source powers. To prevent photodetector overload and to optimise the useable range of the photodetector a selected neutral density filter at point B, see figure 5.1, was used throughout the experiments.

As mentioned in section 5.3, the focussed laser beam profile approximates to a circular Gaussian distribution. The constants, \( k_x \) and \( k_y \), in the Gaussian equation 5.2 can be calculated from the width of the horizontal \( (y) \) and vertical \( (x) \) intensity profiles at some known relative intensity level. This could simply be achieved by recording the intensity profiles with the video analyser system. However, the non-linear intensity response of the equipment prevented this. Instead a waveform was recorded and then a 1/e neutral density filter was placed at position B and the profile rerecorded over the previous data. Figure 5.6 shows the results for \( \lambda_0 = 1.15 \) µm TE polarised vertical profiles and demonstrates the measurement of the 1/e intensity width, f. 1/e intensity spot sizes varied from 1.35-2.03 µm dependent on \( \lambda \) and polarisation. The uncertainty in these measurements, determined from the worst case spread in the data, was +/-0.1 µm.

The lenses were then moved apart and a waveguide sample of typically 1 to 10 mm length and 7-15 mm width was placed on the sample stage. With the infrared laser shutter closed,
the 0.63 µm wavelength lasers were used to approximately adjust the lens focussing. These lasers were then closed off and the selected infrared source's shutter opened. The sample stage was then adjusted until waveguiding was observed as one or a number of closely spaced horizontal bright lines, characteristic of single and multimode planar waveguiding respectively. For rib waveguide samples one or a number of bright spots were observed in place of the planar waveguide bright lines. The photodetector output was maximised (i.e. waveguiding was optimised) by further fine focussing, sample stage, second lens stage and piezoelectric actuator adjustments. The photodetector current provided a measure of relative waveguide transmitted optical intensity. Once the system was fully optimised the photodetector current \( P_r \) was recorded. The waveguide was then removed from the sample stage, replaced and the optimization process repeated to provide confidence in the first reading.

Next the waveguide was removed from the sample stage and the lenses focused together to provide a second 'no sample' photodetector current measurement. The whole procedure was repeated for the combinations of wavelengths 1.15 and 1.523 µm and polarisations TE and TM.

For planar waveguides the emerging beam was found to be relatively broad in the horizontal plane (typically a 1/e intensity width of 60-100 µm) and therefore direct measurement of the output intensity was not possible. Once magnified and focussed on to the photodetector by the second stage lens not all the light fell on the active region of the detector. To overcome the problem, horizontal profiles, and their relationship to peak photodetector current, were measured by scanning the photodetector across the profile in the y direction. The detector was initially positioned at the middle of the intensity profile i.e. at the position of maximum detector current. The detector was then moved 4 mm (the width of its active area) and the current recorded. This displacement procedure was repeated until the detector current fell to zero. Only half of the profile was measured due to the limitations in the photodetectors.
Figure 5.6 1/e waveform measurement, focused HeNe 1.15μm laser beam
Figure 5.7 Magnified horizontal intensity waveform, sample (a), $\lambda=1.523\mu$m TM
traversing system. The assumption was made that the waveforms' horizontal profiles were symmetrical. The actual intensity was then obtained by integrating the intensity profile with an x unit of 4 mm. A typical horizontal intensity profile is illustrated in figure 5.7.

The uncertainty in optical measurements which this scanning technique generated were caused by the positioning accuracy, +/- 0.05 mm, of the photodetector and the uncertainty in the photodetector reading. The effect of the positioning uncertainty on the photodetector reading varies with the position on the profile being measured. The photodetector uncertainty will be highest for measurements made on the steepest part of the intensity profile. This worst case can be determined by plotting the data as in figure 5.7. The uncertainty has been determined as +/- 0.02 μA.

A similar procedure to the above was used to measure the substrate loss of the waveguiding samples, though the scanning of the photodetector was not necessary because the beam emerging from the samples, once focussed, fell within the dimensions of the photodetector. It was possible to collimate the laser beams through the mid height of waveguide samples of approximately 3mm width with little guiding influence from the surrounding structure.

For those waveguides where only the fundamental mode was excited, the guided waveform was assumed Gaussian and a 1/e intensity width measurement conducted in the same manner as used for the measurement of the collimated focussed laser beam waveforms.
5.6 Waveguide Loss Measurement

Waveguide loss, $L$ (dB/cm), was determined using equation 5.6.

$$L = \left( \frac{\Gamma - F - K}{l} \right)$$  \hspace{1cm} (5.6)

where $\Gamma$ is the insertion loss (dB) of the waveguide.

$F$ is the Fresnel reflection loss (dB) at the air/silicon interfaces.

$K$ is the loss (dB) due to the modal mismatch between the input laser beam and the waveguide mode, i.e. the mode overlap coupling efficiency, $\eta$, expressed in dB.

$l$ is the sample length (cm).

The insertion loss was found from the ratio of the laser input power measured using the no sample photodetector current ($P_i$), to the photodetector current ($P_o$) transmitted via the waveguide sample.

$$\Gamma = 10 \log \frac{P_i}{P_o}$$  \hspace{1cm} (5.7)

Fresnel reflection is discussed in section 5.4. For silicon waveguides it was determined to be $3.22 \pm 0.04$ dB.
The mode overlap coupling efficiency is described in section 5.3. Input and waveguide mode 1/e widths required for the calculation of $K$ are determined from 1/e measurement technique described in section 5.5. The uncertainty in $K$ is a function of the uncertainty in the 1/e width measurements and the misalignment of the two mode profiles due to operator adjustment limitations. The 1/e width uncertainty is described in section 5.5. The profile alignment can be optimised and therefore the uncertainty arising from misalignment of waveforms is limited to the positioning accuracy of the first lens stage.

### 5.7 Experimental Accuracy

The uncertainty in the waveguide loss measurement is defined as the sum of the contributions from:

a) Photodetector readings $\pm 0.13$ µA.

b) Waveguide length measurement $\pm 0.001$ cm (accuracy of the vernier instrument used).

c) Fresnel uncertainty $\pm 0.04$ dB.

d) The overlap integral efficiency $\pm 0.1$ dB

An overall uncertainty value for all waveguide loss measurements is not applicable as errors a) to d) cannot be wholly expressed in percentage terms. Hence, the error range for each set of results has to be calculated independently (see Chapters 6 and 7).
Chapter 6.
SOI Planar Waveguide Experimental Characterisation

6.1 Introduction
6.2 SOI Waveguide Specifications
6.3 Experimental Methods
6.4 Planar Waveguide Optical Losses
6.5 Planar Waveguide Mode Profiles
6.6 Substrate Optical Losses
6.7 Silicon Guiding Layer Thickness
6.8 Discussion of Results
6.9 Conclusions
6.1 Introduction

In this chapter the optical waveguide loss measurements for a range of SIMOX waveguides with epitaxially grown Si surface layers between 0.57 and 7.5 μm with various buried layer oxide thicknesses, ion implantation energies and annealing cycles are reported and discussed. The main objective of the work reported in this chapter has been to further understand the various loss mechanisms in SIMOX waveguides in an attempt to explain the higher than predicted waveguide propagation loss results that were reported prior to this work [43].

6.2 SOI Waveguide Specifications

Table 6.1 lists the preparation specifications of the SIMOX samples tested. The oxygen ion implantation doses are expressed as sequential implantation and annealing cycles. For example, 5 + 5x10^17/cm^2 means that the silicon wafer was implanted with 5x10^17 oxygen ions per cm^2, annealed, and then further implanted with a dose of 5x10^17/cm^2 and annealed again.

After ion implantation and annealing the SIMOX wafers Si top layer thicknesses ranged from 0.12 to 0.25 μm depending on implantation dose and energy. This layer was increased on all samples by epitaxial growth.

Samples a to f all have a similar thickness silicon guiding layer (~6 μm). However, variations in ion implantation energy, oxygen dosage and annealing methods enables this set of samples to be used for the study of substrate coupling losses and silicon top layer and interface quality.

Sample g, with a silicon guiding layer thickness of 0.57 μm, provides a valuable comparison to the 6 μm set for interface scattering and substrate coupling loss studies.

The upper cladding layer for all samples was air unless otherwise stated.
All samples were prepared using annealing cycles of 6 hours at 1300 °C

Table 6.1 SIMOX planar waveguide specifications

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<th>Sample #</th>
<th>Oxygen dose (cm$^2$)</th>
<th>Implant energy (KeV)</th>
<th>Si wafer orientation/doping</th>
<th>Buried oxide layer thickness $X_o$ (μm)</th>
<th>Si top layer thickness $X_n$ (μm)</th>
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<td>200</td>
<td>111p</td>
<td>0.37</td>
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</tr>
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<td>c</td>
<td></td>
<td></td>
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<td>0.46</td>
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</table>
6.3 Experimental Methods

Waveguide loss and mode profile measurement were carried out using a He-Ne laser and IReNe laser operating at 1.15 and 1.523 μm respectively. Samples were cleaved and the end faces polished using a variety of diamond pastes down to 1 μm to provide parallel surfaces into and out of which light was coupled using X40 microscope lenses. The output beam was focused onto a Ge photodiode in order to measure intensity and an IR camera to aid optimization of the coupling process. A video analyser interfaced to the IR camera allowed modal intensity profiles to be recorded and their 1/e widths determined. The waveguide insertion loss in dB was given by 10xlog of the ratio of the no guide photodetector current to the current for waveguide transmission (see Chapter 5 for more details on experimental procedure).

Waveguide samples a to f were all predicted to be highly multimode from the planar waveguide model, therefore, individual mode excitation and loss measurement was not possible. For sample g the planar model predicts 3 and 4 modes at λ equal to 1.523 and 1.15 μm respectively, therefore, excitation of the fundamental mode on its own may have been achieved. The model also predicts that for λ = 1.523 μm the TE0 mode 1/e intensity width will be 433 nm and 404 nm for λ = 1.15 μm.

It was assumed that 100% overlap coupling efficiency between the light source field profile and the waveguide modal profile was achieved. This is justified as an optimum Gaussian excitation beam will theoretically couple to a planar SOI waveguide electrical field with an efficiency greater than 98%. This was determined using methods described in Chapter 5. The total Fresnel reflection loss at the waveguide input and output (air/waveguide/air) interfaces was calculated in Chapter 5 to be 3.22 dB.
6.4 Planar Waveguide Optical Losses

Table 6.2 lists the measured insertion and waveguide propagation losses for the samples in table 6.1. Waveguide propagation loss was calculated from insertion loss by subtracting Fresnel reflection loss and then dividing by the waveguide length. Uncertainty in the measurements was calculated as the worst case from the contributions of the photodetector readings, waveguide length measurement and Fresnel reflection uncertainties.

The waveguide losses for samples a and e to f, which were all formed on Si(100) wafers, are plotted against buried oxide thickness in figure 6.1. Waveguide loss was not expected to be only a function of SiO$_2$ buried layer thickness. Other manufacturing processes, such as implantation energies and annealing cycles were also expected to be factors. Therefore, it was not possible to plot curves through the data. However, the data does show trends towards reduced losses with increased buried SiO$_2$ layer thickness and an increase in TM mode losses compared with TE modes for a reduced buried layer thickness.

6.5 Planar Waveguide Mode Profiles

Modal intensity profiles for samples a to f excited by TE and TM polarised light were recorded to experimentally verify that these waveguides were multimode. The TE and TM profiles were found to be similar for a given excitation wavelength. Figure 6.2 is an intensity profile for sample a at a wavelength of 1.523 μm. Figure 6.3 is a profile for sample f at 1.15 μm.

The profiles could be altered in width and shape by focusing and alignment adjustments of the measurement system's lenses. Establishing whether the profiles were in focus or not was difficult. Accordingly, the range of overall profile widths measured for samples a to f varied from 7 to 14 μm.
<table>
<thead>
<tr>
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<th>$X_o$ (µm)</th>
<th>Sample length (mm)</th>
<th>Insertion loss (dB)</th>
<th>Waveguide propagation loss (dB/cm)</th>
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<td></td>
<td></td>
<td></td>
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<td>TM</td>
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<td>d</td>
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<td>0.2</td>
<td>2.6</td>
<td>4.37</td>
<td>4.32</td>
</tr>
<tr>
<td>e</td>
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<td>0.15</td>
<td>2.6</td>
<td>4.75</td>
<td>4.62</td>
</tr>
<tr>
<td>f</td>
<td>6</td>
<td>0.07</td>
<td>2.8</td>
<td>5</td>
<td>5.6</td>
</tr>
<tr>
<td>g</td>
<td>0.57</td>
<td>0.46</td>
<td>1.52</td>
<td>10.4</td>
<td>10.6</td>
</tr>
</tbody>
</table>

All waveguide propagation loss results are subject to an uncertainty of +/-0.5dB/cm except those marked * which are subject to an uncertainty of +/-2dB/cm.

Table 6.2 Insertion and waveguide loss measurements
Figure 6.1 SIMOX planar waveguide losses, Si guiding layer ~6μm thick
Figure 6.2  Intensity waveform sample (a), \( \lambda = 1.523 \mu \text{m} \) TE
Figure 6.3 Intensity waveform sample (f), $\lambda=1.15\mu m$ TE
The profiles indicated that the waveguides a to f are multimode. The less complicated profiles for the wavelength 1.523 μm are characteristic of the lower number of modes theoretically predicted from the simple planar model at this wavelength compared with 1.15 μm (34 modes for 1.15 μm and 26 modes for 1.523 μm).

Figure 6.4 is the TE modal intensity and 1/e attenuated intensity profiles at 1.523 μm for sample g. Table 6.3 contains the 1/e measurements for sample g. The results suggest that the F40 lens used in the test system to image the output of the waveguide onto the video camera could not focus down to the spot size of this waveguide. Sample g has a silicon guiding layer thickness of 0.57 μm and is theoretically expected to support 3 and 4 TE modes at wavelengths 1.523 and 1.15 μm respectively. The small peak observed in the left hand evanescent tail of the profile, which is travelling in air, is thought to be caused by reflection from the top surface of the waveguide.

### 6.6 Substrate Optical Losses

Optical loss measurements of the substrates were conducted for samples a to f. The measurement procedure was the same as for the waveguides. However, the microscope lenses were focused to a point within the waveguide substrate in order to collect the transmitted light.

The substrate optical loss results are listed in table 6.4. These losses were calculated from measured substrate insertion losses using the same method previously described for waveguide loss calculation. Those results that are negative are statistically relevant because of the uncertainty in the measurements, but are obviously not possible in practice. Also included in the table are losses for a pure single crystal of silicon [67,60] and n doped silicon (N_d=1 x 10^{16} cm^{-3}) [35]. The mean loss of the two polarisations for all the specimens was 3.02 dB/cm at a wavelength of 1.15 μm and 0.40 dB/cm at 1.523 μm.

117
Figure 6.4 1/e waveform measurement, SIMOX planar waveguide sample (g), λ = 1.523 μm, TE, intensity waveform
<table>
<thead>
<tr>
<th>Wavelength (μm)</th>
<th>Experimental 1/e intensity width (μm) +/-0.1</th>
<th>TE₀ theoretically predicted 1/e intensity width (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.15 TE</td>
<td>1.35</td>
<td>0.4</td>
</tr>
<tr>
<td>1.15 TM</td>
<td>1.32</td>
<td>-</td>
</tr>
<tr>
<td>1.523 TE</td>
<td>1.73</td>
<td>0.43</td>
</tr>
<tr>
<td>1.523 TM</td>
<td>1.72</td>
<td>-</td>
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</table>

Table 6.3 1/e Intensity waveform widths, SIMOX planar waveguide sample (g)
<table>
<thead>
<tr>
<th>Sample #</th>
<th>$\lambda=1.15\mu m$ substrate loss (dB/cm)</th>
<th>$\lambda=1.523\mu m$ substrate loss (dB/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TE</td>
<td>TM</td>
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<tr>
<td>a</td>
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<td>b</td>
<td>2.66</td>
<td>2.73</td>
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<tr>
<td>c</td>
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<tr>
<td>d</td>
<td>3.17</td>
<td>3.44</td>
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<td>2.61</td>
<td>2.91</td>
</tr>
<tr>
<td>silicon [67,60]</td>
<td>2.87</td>
<td></td>
</tr>
<tr>
<td>$N_d=1x10^{16}cm^3$ doped silicon [35]</td>
<td>5.65</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.4 SIMOX samples (a) to (g) substrate losses
The results in table 6.4 give confidence in the operation of the optical bench and measurement procedure when a comparison is made with the optical losses known for similarly doped silicon. They also provide an indication of the minimum expected waveguide loss possible (i.e. assuming absorption loss only).

6.7 Silicon Guiding Layer Thickness

As suggested earlier, interfacial roughness and resultant optical scattering may be a significant contributor to waveguide loss in SOI structures. The relative optical power density transmitted at the Si/SiO₂ interface is increased when the modal confinement of the waveguide decreases, and this provides a means of studying interface losses. A reduction in modal confinement can be achieved by reducing the Si guiding layer thickness. One method of varying this thickness is to thermally oxidise the silicon as illustrated in figure 6.5 [44]. Silicon is consumed to form a SiO₂ over-layer. This layer replaces air as the upper waveguide cladding.

Samples of specimen a were used for the experiment because of its low loss (reported in section 6.4) and availability. Samples were prepared by wet oxidation. One litre per minute of oxygen was passed through a diffuser immersed in deionised water, held at a temperature of 96 °C, before flowing over samples in a 1100°C furnace. Oxidation times varied over 1 to 30 hours yielding a range of samples with Si guiding layer thicknesses from 6 μm down to 4.4 μm. The samples' insertion losses and propagation losses are recorded in table 6.5. The propagation losses are also illustrated in figure 6.6.

The results show no significant variation in waveguide loss over the Si thicknesses range of 4.4 to 6 μm. Losses for samples a to a₅ at λ = 1.523 μm, TM polarisation, are lower than the TE polarisation. Plotted in Figure 6.6, in addition to the experimental data, is the scattering loss prediction at λ = 1.523 μm TE calculated using the theory discussed in Chapter 3 for a planar SOI waveguide with 15 nm rms interface roughness (data obtained from Ibis Technology Inc.) and roughness correlation length of 1 micron. The correlation length describes the characteristic periodicity of the roughness [68]. Loss arising from
Figure 6.5 Reducing Si guiding layer thickness by thermal oxidation
Sample # | X<sub>s</sub> (μm) | X<sub>a</sub> (μm) | Sample length (mm) | Waveguide propagation loss (dB/cm)
| | | | | \( \lambda=1.15\mu\text{m} \) | \( \lambda=1.523\mu\text{m} \) |
| | | | | TE | TM | TE | TM |
| a | 6 | 0 | 2.8 | 4.23 | 4.57 | 0.7 | 0.42 |
| a<sub>1</sub> | 5.71 | 0.64 | 3.66 | 4.48 | 4.19 | 0.92 | 0.16 |
| a<sub>2</sub> | 5.5 | 1.11 | 3.52 | 4.66 | 4.75 | 0.76 | 0.17 |
| a<sub>3</sub> | 4.92 | 2.41 | 3.52 | 4.65 | 4.43 | 1.12 | 0.45 |
| a<sub>4</sub> | 4.65 | 3.01 | 3.82 | 4.49 | 4.4 | 0.92 | 0.29 |
| a<sub>5</sub> | 4.41 | 3.52 | 3.82 | 4.18 | 3.6 | 0.66 | 0.4 |

All waveguide propagation loss results are subject to an uncertainty of +/-0.5dB/cm

Table 6.5 Waveguide loss measurements, SIMOX samples a to a<sub>5</sub>,
0.4μm buried oxide layer
Figure 6.6 SIMOX planar waveguide losses, Si guiding layer 4.4 to 6μm
absorption and volumetric scattering are thought to be significantly lower than surface scattering loss. Therefore, the reasonable match between the predicted surface scattering loss and actual loss indicated good agreement between theory and experiment. The lower TM scattering loss at $\lambda = 1.523 \, \mu m$ is also supported by the theory which predicts a lower loss for TM modes as compared with TE (see Chapter 3, Section 3.3). The effect of the surface thermal oxide was not expected to be significant because its refractive index of 1.5 compared to air has only a small effect on mode profiles and a thermally grown silicon dioxide generally has a good interface quality [31].

6.8 Discussion of Results

A number of overall observations can be made from the test results reported in Section 6.4 to 6.7. However, the following discussion of the test results firstly reviews the individual sample results before discussing the overall trends.

Discussion of Sample Test Results

Samples a to g and a₁ to a₅ represent a partial test matrix of samples where SIMOX manufacturing processes have been varied to yield a variety of defect densities, interface roughness, buried oxide thickness and silicon guiding layer thickness. The discussion looks at the results of each sample and uses them to limit the range of possible conclusions.

Sample a was produced by multi-implant steps which were expected, according to the material manufacturer, to yield a material defect density of $\sim 10^3 \, \text{cm}^{-2}$ and a buried oxide interface roughness of less than 20nm with a periodicity of approximately 1μm. The losses of 0.7 and 0.4dB/cm for the TE and TM modes respectively at $\lambda = 1.523 \, \mu m$ were thought to be the lowest SOI waveguide losses observed at the time of the experiments. Due to the experimental error of +/- 0.5 dB it was not possible from these results to say that there was any difference in loss between the two orthogonal modes. However, the results from sample a₁ to a₅, table 6.5 and figure 6.6, show a statistical difference in the TE and TM losses, with the TE having the higher loss. This is consistent with the
predictions in Chapter 3, Section 3.3, that interface roughness will cause greater loss from the TE modes as compared to the TM modes.

The mode profile at $\lambda = 1.523\mu m$ (TE), illustrated in figure 6.2, is characteristic of a multimode waveguide. It was not possible with the experimental equipment used (see Chapter 5) to excite any of the samples a to f to yield a single peak mode shape. This may be due to the relatively large divergence of the excitation beam which inevitably launches light into higher order modes as well as the fundamental mode.

Exciting the waveguides with a butt coupled single mode fibre source of $\lambda = 1.3\mu m$, did result in a single peak output mode shape from the waveguide. This may be because the lower launch angle from the fibre into the silicon waveguide is restricted to the acceptance angle of the silicon waveguide's fundamental mode.

Sample a, to a_s, loss results have been plotted in figure 6.6 with the TE_0 scattering loss predictions from Chapter 3, Section 3.3, for $\lambda = 1.523\mu m$ and an rms interface roughness of 15nm, for comparison. Since the wall roughness data is expected to only be accurate within an order of magnitude, the comparison with the experimental results is reasonable. However, the increase in loss over the reducing guiding layer thickness from sample a to a_s predicted by the theory was not reflected in the experimental results. Ideally the matrix of test samples a to a_s would have been extended to include data points for guiding layer thicknesses down to less than 2\mu m, where, as mentioned in Chapter 3, Section 3.3, the loss due to scattering is expected to have risen considerably. Sample g does potentially represent a data point for the graph in figure 6.6. However, the manufacturing process for g was thought to be different to sample a and, therefore, other loss factors may confuse the comparison.

The results for sample b have not been compared graphically with the others in the group a to f (see figure 6.1) because the sample was produced from a (111) oriented silicon wafer, whereas all the other samples where produced using (100) silicon wafers. The loss for the sample at $\lambda = 1.523\mu m$ was lower for TE modes (0.2dB/cm) as compared to TM
(1.8dB/cm). There may be some effect of orienting the silicon crystal differently relative to the ion implanting direction during the fabrication of the material. This may change the characteristics of volumetric and interface defects or may present these defects in a different orientation to the guided optical wave. What is certain is that there is a statistically significant difference in the characteristic of the (111) sample at \( \lambda = 1.523 \mu m \), compared with the other samples to warrant further research, although this was outside the scope of the project.

Sample c was thought to have been produced with a single implanting step, though the manufacturers records could not confirm this. The sample is compared with sample a in figure 6.1. Sample a data relates to points lying on the 0.4 \( \mu m \) buried oxide thickness X axis position, where as the sample c points are the next set to the left with a buried oxide thickness of 0.37\( \mu m \). The abrupt rise in loss from sample a to c is thought to be due to the poorer quality of sample c in respect of defect density and interface roughness arising from a single implantation process, though this cannot be confirmed due to incomplete material data.

Sample d data, which is represented by the points with buried oxide thickness 0.2\( \mu m \) in figure 6.1, has been produced with a reduced oxygen implant dose to yield a thinner buried oxide layer. The sample is thought to have been produced using otherwise identical procedures to sample c. There is no statistical difference in loss between the two sets of orthogonal modes or as compared with the losses of sample c. This suggests that the reduction in the buried oxide from 0.37\( \mu m \) to 0.2\( \mu m \) has little effect on waveguide loss.

For sample e loss results, shown in figure 6.1 for a buried oxide thickness of 0.15 \( \mu m \), there appears to be an increase in the TM loss over the TE loss at \( \lambda = 1.523 \mu m \) and an overall increase in loss at both measurement wavelengths. This may indicate the onset of loss due to coupling of guided modes to substrate modes as the evanescent field of the guided modes extend beyond the thinner buried oxide layer. This situation is further confirmed with results from sample f (buried oxide thickness of 0.07\( \mu m \)). With sample f loss has increased significantly for both wavelengths and polarisations. In addition, the
TM modes have higher loss for both wavelengths. The TE modes are less well confined than the TM modes, and one would therefore have expected them to couple more strongly to a substrate mode if the buried oxide was thin. This is contrary to the results. However, the coupling mechanisms for the two orthogonal sets of modes are not simply related to confinement as predicted by a three layer planar model. The limitations of this model have been reported in the literature [43] and, as previously mentioned, the TM modes are expected to have a stronger coupling coefficient to substrate modes if a five layer system is modelled. This planar structure is represented by a top cladding layer, a surface silicon guiding layer, the buried oxide, the substrate and a lower substrate cladding.

Further theoretical investigation of the five layer waveguide problem was not pursued in this project. The reason for this was based on the fact that if a low loss SOI waveguide is to be produced, the buried oxide must be sufficiently thick so as to be effectively infinite, i.e. resulting in no substrate coupling. This was investigated in Chapter 3, Section 3.5 where a 0.4μm buried oxide layer was considered more than sufficient for a waveguide core height of 4.32μm at λ = 1.523μm. In addition, the results in this Chapter indicate that loss due to substrate coupling for a waveguide with a guiding layer thickness of approximately 6μm is not measurable until the buried oxide is reduced below 0.2μm.

The substrate loss results for samples a to g reported in table 6.4 show good agreement with measurements by others, also included in the table. The mean silicon absorption loss at λ = 1.523μm from the experimental data is 0.41 dB/cm. The substrate material used to form the samples was lightly doped of the order of 10^16 cm^-3. The SIMOX process is reported by the manufacturers to reduce the doping level of the surface silicon layer as compared to the substrate by at least an order of magnitude. It is not fully understood why this is the case, but it may be due to the diffusion of the dopants into the buried oxide region during the annealing stage(s). Subsequent epitaxial growth of silicon on the samples was undoped, though impurities of the order of 10^14 cm^-3 are typically present in such samples [60]. These lower doping levels in the waveguide cores suggest that the absorption losses due to impurities in the waveguides themselves will be lower than the substrate material. Absorption loss in the wavelength range studied relates approximately
linearly to doping levels [1]. Therefore, if the guiding layers have a doped level of say one tenth of the substrate density, the loss due to doping related effects could be ~0.04 dB/cm in the guiding layers, calculated from the results reported here.

**General Discussion**

Though the test matrix was considered incomplete, the previous analysis of the results shows that general trends in the data can be supported. These general trends are now discussed further and additional comparisons are made with results reported by others and with the theory.

The SIMOX waveguide losses measured at a wavelength 1.523 µm for samples a to f are lower than any previously reported losses. The previous lowest loss for a single mode silicon core waveguide was 4.4 dB/cm in a strip loaded SIMOX waveguide illustrated in figure 2.5 at a wavelength of 1.3 µm [39]. However, as mentioned earlier, the loss measurements cannot be attributed solely to one mode, therefore they only provide an indication of fundamental mode losses.

Our lowest measured multimode SIMOX planar waveguide losses, at a wavelength of 1.523 µm, are 0.14 dB/cm for a p type (111) SIMOX sample, TE polarisation, and 0.4 dB/cm for a (100) SIMOX sample, TM polarisation. Both samples had a Si guiding layer thickness of 6 µm. The uncertainty range for these measurements was +/- 0.5 dB/cm.

By contrast, the losses measured for the Si 0.57 µm, sample g, were of the order of 45-65 dB/cm. To help understand why the losses measured are so much lower for a 6 µm Si guiding layer it is useful to review the potential optical loss mechanisms in SIMOX waveguides:

1) Absorption losses in silicon are directly related to the free carrier density [1]. Losses increase with increasing free carrier density. Figure 2.1 is a plot of absorption coefficient against wavelength for n type silicon ($N_d=10^{16}$ cm$^3$). The predicted absorption loss from this data is 5.7 and 0.4 dB/cm for wavelengths of 1.15 and 1.523 µm, $N_d=10^{16}$ cm$^3$. 
2) Scattering losses from defects and interface roughness. Defect density in the top Si layer of SIMOX can be reduced by repeated implantation and annealing [67,41,86].

3) Coupling of the evanescent field to the substrate through the buried oxide layer.

Various loss coefficients can be assigned to these loss mechanisms (see Chapter 3, Section 3.3). There is the absorption loss coefficient which is function of wavelength, see figure 2.1. The scattering loss coefficient is expected to be proportional to $1/\lambda^2$ (see Chapter 3, Section 3.3). In addition, interface scattering is a function of modal confinement i.e. an interface scattering loss coefficient will increase with wavelength and is inversely related to Si guiding layer thickness. The substrate coupling loss coefficient is a function of modal confinement in a similar relationship to interface scattering and is inversely related to buried oxide layer thickness.

Figure 6.7 illustrates relative $TE_0$ mode power density loss coefficients based on the predicted relative electric field ($E_r$) at the interfaces for the Si/SiO$_2$ and the SiO$_2$/substrate interfaces (for a buried oxide thickness of 0.4 μm) calculated from the theoretical fundamental mode profiles at a wavelength of 1.15 μm (the curves are similar at 1.523 μm). The relative power density loss coefficients assume that the square of the relative electric fields at the respective interfaces are proportional to the power loss at these interfaces. Therefore the transmissions, assuming no other loss mechanism, will be proportional to: $(1 - E^2)$, where $E^2$ is the square of the relative electric fields. In turn, the relative loss coefficients are proportional to: $\log(1/(1 - E^2))$ in common with, for example, the calculation of waveguide losses expressed in dB/cm for given transmission measurements. The assumption that loss is directly proportional to the relative power density at the interface regions is reasonable for interface scattering, but is an over simplification for substrate coupling loss [43]. However, if interface losses are significant, the model indicates that they will be reduced by several orders of magnitude over the range of waveguide thickness from 0.2 to 2.0 μm, but by less than a factor of ten over the increasing range 2.0 to 6.0 μm. The model also indicates that the substrate coupling loss
coefficient is likely to increase at a greater rate with reducing Si guiding layer thickness compared to the Si/SiO₂ interfacial scattering coefficient. This is illustrated in figure 6.7 by the relative slopes of the coefficient curves.

For the 0.57 μm Si waveguide interfacial and/or substrate coupling may be the significant loss mechanisms. The known absorption coefficient is negligible by comparison. If bulk Si guiding layer scattering loss was a primary mechanism, losses for the longer wavelengths would be lower. However, the converse is the case.

For the 6-4.4 μm Si/0.4 μm SiO₂ waveguide set (samples a to aₐ) absorption loss is dominant at λ = 1.15 μm. If absorption loss is subtracted from total loss the data shows that the remaining loss for a wavelength 1.523 μm is less than for 1.15 μm. This would support the hypothesis that the additional significant loss mechanisms are inversely related to wavelength which indicates bulk waveguide scattering loss rather than substrate coupling or interfacial scattering. The relative changes in interfacial and substrate coupling losses predicted in figure 6.7 are typically an increase of 2 over the range 6 μm to 4.4 μm of Si guiding layer thickness. No such factor is indicated in the results illustrated in figure 6.6, again supporting the hypothesis that losses are dominated by absorption and bulk Si guiding layer scattering. However, the higher TE mode loss at λ = 1.523 μm compared with the TM mode loss is indicative of interface scattering loss where the TE modes lower confinement leads to potentially greater scattering at a rough core/cladding interface (see Chapter 3, Section 3.3).

Figure 6.1 indicates that TE and TM propagation losses are similar for waveguides with a buried oxide layer greater than approximately 0.15 μm. Below this thickness the TM modes are more lossy. This is characteristic of the greater TM coupling coefficient to substrate modes as compared with the TE modes [43].
Figure 6.7 Relative interface and substrate power density loss coefficients for SIMOX planar waveguides, $\lambda = 1.15\mu m$
6.9 Conclusions

The results reported here provide valuable data on SOI waveguide loss mechanisms. For the first time the results show that SIMOX planar waveguides could be produced with losses low enough to consider the material suitable for device applications.

The results support the following suggestions regarding SOI planar waveguides.

1) A buried oxide layer thickness in excess of 0.4 \( \mu \text{m} \) is sufficient to prevent significant substrate coupling losses for 4.4-6.0 \( \mu \text{m} \) guides.

2) Minimising defects in the guiding layer of SIMOX waveguides by manufacturing using multiple implantation and annealing cycles may reduce waveguide loss.

3) For the waveguides studied in this report interface scattering and substrate coupling losses probably become significant for waveguides less than a few microns in depth due to reductions in wavefront confinement and resulting increases in relative power transmitted in the region of the Si/SiO\(_2\)/substrate interfaces. The commercial availability of SOI material with only a few monolayers of interface roughness suggests that interface scattering loss can be reduced below 0.01 dB/cm for waveguides with multimicron dimensions (prediction using the theory in Chapter 3, Section 3.3).

4) SOI planar waveguides of several microns are multimode in the near infrared wavelength range.

The relatively high losses associated with single mode SIMOX planar waveguides of typical Si core dimension 0.2 \( \mu \text{m} \) may be inherently limited by the SIMOX manufacturing process. For SIMOX that has a guiding Si layer increased by epitaxial growth beyond 4 \( \mu \text{m} \), fundamental mode losses in the range \( \lambda = 1.2 \) to 1.6 \( \mu \text{m} \) can be expected to be less than 1 dB/cm based on the material samples tested in this work (losses are potentially much lower with better quality SOI). Measurements reported here are for multimode loss.
may be greater than the fundamental mode loss because higher order modes are less confined and therefore likely to be more lossy than the fundamental.

Though planar waveguides with Si guiding layer thickness of several microns will be multimode, mode matching theoretical analysis of rib SIMOX waveguides by J Schidtchen et al [46] suggest that several micron dimension single mode rib SIMOX waveguides are possible. These predictions were experimentally investigated [85], and within the limits of experimental accuracy the results agreed with the theory. This theory has been investigated and expanded upon in Chapter 3, Sections 3.4 and 3.5, using the effective index model. Since the contribution to loss of the fundamental mode is likely to be lower than that of higher order modes, such single mode guides can be expected to be very low loss. However, with the increase in the number of interfaces from planar to rib guides, interface effects may increase. The next chapter investigates the modal and loss characteristics of these rib waveguides.
Chapter 7.
SOI Rib Waveguide Experimental Characterisation

7.1 Introduction
7.2 SOI Rib Waveguide Specifications
7.3 SOI Rib Waveguide Loss Characteristics
7.4 Experimental Procedure
7.5 Results and Discussion
7.6 Waveguide Bends and Y-Junction Design
7.7 Waveguide Bends and Y-Junction Losses
7.8 Conclusions
7.1 Introduction

The results reported in Chapter 6 confirmed that planar SOI waveguides, formed from SIMOX material, with core dimension of a few microns can be low loss, i.e. below 1 dB/cm. In Chapter 3 the problem of producing single mode strip SOI waveguides with good coupling efficiency to single mode fibre was investigated and it was concluded that certain rib waveguide structures would be single mode for dimensions similar to those of optical fibres. The work reported in this Chapter brings together these results and demonstrates practical SOI single mode rib waveguides, see figure 7.1. The work extended to the initial study of bends and Y-junctions using an optimum waveguide rib structure, see figure 7.2.

7.2 SOI Rib Waveguide Specifications

The SIMOX material used to make an initial batch of rib waveguides was formed by implanting $2.0 \times 10^{18}$ cm$^{-2}$ oxygen ions at 200keV into p type 100 silicon wafer, followed by annealing for 6 hours at 1300 °C. This formed a 0.478 micron buried oxide layer and a 0.172 micron crystalline silicon surface layer. Defect density measurements revealed a density of the order of $6 \times 10^6$ defects cm$^{-2}$. Following annealing the surface silicon layer was epitaxially grown to 3.17 microns and 7.67 microns on separate wafers to allow two sets of rib waveguides to be fabricated. These structures represent planar waveguides where the buried oxide is the lower cladding ($n=1.5$), the surface silicon layer ($n=3.5$) is the waveguide core and the top cladding is air ($n=1.0$).

A second batch of waveguides were formed from a different specification SIMOX. The SIMOX material used to make the second batch of rib waveguides was formed by implanting $1.8 \times 10^{18}$ cm$^{-2}$ oxygen ions at 200keV into n type 100 silicon wafer, followed by annealing for 6 hours at 1300 °C. This formed a 0.398 micron buried oxide layer and a 0.26 micron crystalline silicon surface layer. Defect measurements revealed a density of the
Figure 7.1 SOI rib waveguide
Figure 7.2 Waveguide bends (w=3.73 microns, Rb=2.5, 5, 7.5 and 10 mm) and Y junction (Ry=10 mm)
order of $10^5$ defects cm$^2$. Following annealing, the surface silicon was epitaxially grown to 4.57 microns.

From the solution of the eigenvector equations for a planar 3 layer waveguide (see Chapter 3), SOI waveguides are predicted to be single mode for silicon thickness of less than 0.2 microns in the wavelength range 1.15 to 1.55 microns. Lowest reported propagation loss measurement for SIMOX waveguides of these dimensions has been 4.4 dB/cm at a wavelength of 1.3 microns [38]. This loss is higher than practical for many applications and the single mode planar waveguide size is incompatible with fibre optical interfacing where waveguide core dimensions are of the order of 40 times greater. However, when one considers rib SOI waveguide dimensions, the electric field boundary conditions become much more restrictive than for the simpler planar structure. It was proposed [46], and subsequently demonstrated [85], that if a rib waveguide is single mode in the lateral direction, due to a small effective refractive index difference between the slab and the rib fundamental vertical modes, then the waveguide can be single mode for multi-micron dimensions. This is because higher order modes have lower effective indices than the fundamental mode of the surrounding slab waveguide, and are therefore lost as radiation modes. This phenomenon is discussed in more depth in Chapter 3.

Based on these predictions, a matrix of rib waveguides was formed from the 3.17 and 7.67 micron SOI samples. The variables were rib waveguide width (w) and etch depth (e). Table 7.1 shows the range of waveguides fabricated and mode predictions based on the theory in the previous paragraph (also see Chapter 3). The waveguide widths were defined by standard photolithography and the rib etching was conducted using reactive ion etching with CH$_2$Br at 200 mtorr, 200 watts and a flow rate of 50 sccm. The reactive ion etch process produced rib roughness with an rms value of approximately 20 nm (measured with a scanning electron microscope).

For the second batch of waveguides based on the 4.57 micron Si layer, waveguides of various widths straddling the predicted maximum single mode width for a rib etch depth
<table>
<thead>
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<tr>
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</tr>
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* = TE$_{00}$ and TM$_{00}$ only
# = multimode
+ = TE$_{00}$ only

Table 7.1 Predicted modal properties of SOI rib waveguides
of 1.5 microns were fabricated, see Table 7.1. Following etching in the same manner as for the first batch of rib waveguides, the samples were wet thermally oxidized at 1100 °C to form a 0.5 micron surface oxide. This step accounts for a final rib depth (e) of 1.7 microns and height (r) of 4.32 microns. The final waveguide widths were 2.73, 3.73, 4.73, 5.73, 6.73 and 7.63 microns. Waveguides were predicted to be single mode for a width less than 3.52 and 3.34 microns for TE and TM modes respectively, independent of wavelength, in the wavelength range 1.15 to 1.6 microns.

In addition to the set of straight waveguides, a set of waveguides 3.73 microns wide with 2.5, 5.0, 7.5 and 10.0 mm radii bends and a Y-junction based on the 10.0 mm bends were also fabricated (see figure 7.2).

All samples were cut down to 10 mm long and the end faces were polished parallel using diamond paste with a grit size down to 1 micron. This enable efficient coupling of light into and out of the waveguides.

### 7.3 SOI Rib Waveguide Loss Characteristics

Before discussing experimental procedures and test results it may be helpful to the reader to refer back to Chapter 3, Sections 3.4 and 3.5, which provide background to SOI waveguide characteristics. Equation 3.41 summaries the main loss mechanisms in SOI waveguides.

\[
L_t = L_a + L_{ss} + L_v + L_c
\]

\[ (3.41) \]

- \( L_t \) = total loss
- \( L_a \) = absorption loss
- \( L_{ss} \) = interface induced scattering
- \( L_v \) = volumetric refractive index inhomogeneity scattering
- \( L_c \) = coupling of guided modes to substrate modes
These various causes of loss are investigated here and results from the characterisation of planar waveguides in Chapter 6 are also included in the analysis and discussion.

7.4 Experimental Procedure

Waveguide insertion loss measurement for the rib waveguides were made at wavelengths of 1.15 and 1.523 microns for both orthogonal polarizations. Insertion loss results were then converted to propagation loss of the combined excited modes by assuming a 100% overlap between the electric field profile of the input beam and that of the sum of the modes of the waveguide. This approximation introduced a maximum predicted error of 0.2 dB calculated using the rib waveguide effective index model (see Chapter 3). Corrections were also made for the Fresnel reflection loss at the two waveguide endfaces, which was calculated to be 3.22 dB assuming a normally incident beam.

The convergence of the focused light used to excite the waveguides was 12.1 degrees. This convergence ensured that higher order modes of the waveguides were excited. However, it also meant that for some waveguide samples with low lateral confinement (i.e. relatively small rib height) the lateral numerical aperture was insufficient to confine all of the excitation beam. This contribution to the loss was predicted using estimates of the lateral electric field profiles and numerical aperture from the effective index model. These results were used to correct the propagation loss measurements. The complete procedure of calculating propagation loss from insertion loss was checked to within +/-0.5 dB/cm by cutting back and remeasuring a number of samples. The overall maximum error in the loss measurements is estimated to be +/-0.5 dB/cm.

The vertical and horizontal 1/e electric field widths were measured using an infrared camera and calibrated video analyzer for those waveguides where the fundamental mode could be solely excited. The accuracy of the measurements were estimated to be +/- 0.3 microns. Excitation of high order modes was achieved by exciting the waveguides off-centre in various positions with variations possible in both the vertical and lateral
directions and presenting the end facet of the waveguide at an angle of up to 5 degrees to the excitation beam.

7.5 Results and Discussion

The loss results for the first batch of waveguides are summarised in Table 7.2. The lowest loss was 0.9 +/- 0.5 dB/cm for a waveguide with \( r = 3.17 \) \( \mu m \), \( e = 0.34 \) \( \mu m \) and \( w = 6.37 \) \( \mu m \) at \( \lambda = 1.523 \) \( \mu m \) (TE polarised). The lowest loss over and above the intrinsic absorption of pure silicon was measured to be 0.23 +/- 0.5 dB/cm at \( \lambda = 1.15 \) \( \mu m \) (TM polarised), for a waveguide with \( r = 7.67 \) \( \mu m \), \( e = 1.0 \) \( \mu m \) and \( w = 9.83 \) \( \mu m \). This sample might be expected to have low scattering loss because the relatively large width will reduce the effect of scattering from the rib etch roughness and because the relatively small etch depth reduces the rough rib boundary (but is still sufficiently deep to confine the light). Furthermore, the short wavelength also effectively reduces the interface roughness effects as compared to the longer wavelength of 1.523 \( \mu m \).

The results in Table 7.2 are consistent with multi-micron SOI planar waveguides with a defect density of the order of \( 10^6 \) cm\(^{-2} \) [88]. The losses over and above the intrinsic loss of silicon for \( \lambda = 1.523 \) \( \mu m \) were higher on average than for \( \lambda = 1.15 \) \( \mu m \). This is consistent with interface effects playing a greater part in waveguide loss than volumetric effects as previously discussed. The lower confinement of the \( \lambda = 1.523 \) \( \mu m \) modes leads to greater power available for scattering at the waveguide interfaces.

There is no apparent difference in the losses in Table 7.2 for \( \lambda = 1.523 \) \( \mu m \) between the total loss and the loss-less intrinsic material loss. This is because the data is only to two decimal places and the intrinsic loss of silicon at \( \lambda = 1.523 \) \( \mu m \) is 0.004 dB/cm [60].

The TE losses are consistently lower than the TM losses. This is thought to be due to the higher surface scattering at the rough rib side walls for an electric field polarised parallel to the interface as predicted from the planar waveguide analysis in Chapter 3 (see figure 3.6).
### Total Propagation loss

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### Loss over and above the intrinsic absorption of pure silicon

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#### Key

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Table 7.2 Summary of SOI rib waveguide propagation loss measurements
At a first glance this is in contrast to the results for $\lambda = 1.523 \, \mu m$ for planar waveguides reported in Chapter 6. In particular, the reader's attention is drawn to figure 6.6 which shows that for a planar waveguide the TE mode has a higher loss than the TM. This reverse of the polarisation dependence of loss between the planar and rib waveguide results may be due to greater roughness in rib waveguide structures on vertical interfaces as compared with the horizontal planar interfaces. There is clearly no vertical interface confinement in the planar waveguide. As the rib wall roughness is thought to be greater than the horizontal buried interface roughness, the roughness on the vertical interfaces may play the predominant role in scattering loss for rib waveguides. With no vertical interfaces in the planar waveguide, the horizontal interfaces, and in particular the buried interface, will be the sole cause of interface scattering. The planar interface scattering model also predicts a slight decrease in interface scattering for the shorter wavelength due to the greater confinement at this wavelength.

Figures 7.3, 7.4 and 7.5 are plots of waveguide loss against rib width for various rib etch depths. Figure 7.3 shows an increase in loss with reduced waveguide width for the sample set where $r = 3.17 \, \mu m$. Previous studies of the planar waveguide structure for guiding layer thickness below 2 $\mu m$ indicate a rapid rise in loss due to interface scattering. These effects in narrow ribs (i.e. 2 $\mu m$ or less) are expected to produce similar levels of loss.

The difference in loss for the two measurement wavelengths and polarisations in figure 7.3 provides additional information and support to the hypothesis that interface effects dominate the waveguide loss. Firstly, as waveguide width reduces the loss for the longer and less well confined wavelength, $\lambda=1.523\mu m$, increases more rapidly than for $\lambda=1.15\mu m$. And secondly, on average the TM modes are more lossy which (assuming that the interface roughness is similar or greater on the side walls as compared to the horizontal interfaces) is consistent with greater interface induced loss from the TM modes which are less well confined in the horizontal direction.

The variation in loss for the waveguides wider than or equal to 3.62$\mu m$ in figure 7.3 may be attributed to the resonant nature of the interface scattering loss as predicted in Chapter
Section 3.3 (see figure 3.6). However, the predicted resonance in figure 3.6 has a shorter period than the experimental data in figure 7.3. This may be due to the relatively few data points in figure 7.3 and the fact that the prediction was based on a planar waveguide rather than a rib waveguide. The fact that the experimental loss data at both measurement wavelengths varies up and down in a similar way with waveguide width does suggests that the resonance effect is real and cannot be attributed to experimental error.

Figure 7.4 shows a similar result to those in figure 7.3 (r = 3.17 μm), but with a discrepancy at λ = 1.523 μm for the narrowest waveguide which may be due to the resonant nature of the scattering loss mechanism. The increase in etch depth from e = 0.68 μm (see figure 7.3) to e = 2.01 μm has reduced losses by approximately a factor of two. This could be due to the increase in confinement of the guided modes in the lateral direction with increased etch depth. However, although the confinement has increased, the area of roughness has also increased. It is suspected that in this case the reduction of loss due to greater confinement predominates over the effect of increased scattering interface area. With a reduction in interface scattering due to greater confinement one might also expect more consistent results from one width to the next. This is the case when one compares data in figure 7.3 with the data in figure 7.4.

Figure 7.5 is data from a sample with r = 7.67 μm and e = 2.6μm. There are no waveguides with widths below 3 μm in the sample set and there is no indication of an overall increase in loss for reduced waveguide width over the range tested. This is a similar result to that from tests conducted on the planar samples a to a_s reported in Chapter 6, where reducing guiding layer thickness from 6 μm to 4.41 μm had no measurable effect on waveguide loss, see figure 6.6.

It is unclear why the loss at λ=1.15 μm for w=5.82 μm in figure 7.5 is so much higher than the other waveguides at the same wavelength. The experimental data was checked, so it is unlikely that the result is due to experimental error. It is possible that a resonant coupling effect is the cause of the higher loss.
Figure 7.3 Measured propagation loss v waveguide width (w).

\[ r=3.17 \text{ microns, } e=0.68 \text{ microns} \]
Figure 7.4 Measured propagation loss v waveguide width (w).

$r=3.17$ microns, $e=2.01$ microns
Figure 7.5 Measured propagation loss vs waveguide width (w).

r=7.67 microns, e=2.6 microns
In comparing data from the narrower and thinner waveguides in figures 7.3 and 7.4 with the wider and thicker waveguide results in figure 7.5, it can be seen that the polarisation dependence of loss at \( \lambda = 1.523 \mu m \) is less obvious for the larger waveguides. One can also see that the TE/TM loss dependency at \( \lambda = 1.15 \mu m \) has reversed for the larger waveguides as compared to the smaller ones. This may be due to the competing scattering loss mechanisms generated by both vertical rib wall roughness and horizontal buried oxide roughness. For the narrower waveguides the vertical roughness dominates, i.e. the TM modes have the highest loss, and for the wider and thicker waveguides the horizontal interface roughness begins to dominate and the TE modes become the most lossy.

The primary difference in overall loss between the 3.17 and the 7.67 \( \mu m \) samples is related to the waveguide width. For single mode waveguides in the 3.17 sample set the rib widths must be narrower than for the 7.67 sample set. Therefore, as predicted from the data in figure 3.6, losses for widths less than 4\( \mu m \) have a significant element of loss for the TM modes arising from the rib wall roughness. However, the previous discussions have not taken account of the relative power confined within the rib region of the waveguide or the proximity of radiation modes into which the interface scattered light may couple. These factors may help in future analysis aimed at investigating why TE loss data at \( \lambda = 1.15 \mu m \) in figure 7.5 is higher than TM, while at the same time there is little difference in TE and TM loss at \( \lambda = 1.523 \mu m \).

The relatively inconsistent results from one sample to the next reported in figures 7.3 to 7.5, as previously mentioned, may be due to two periodic loss systems as functions of waveguide width. Firstly, as previously discussed, the data in figure 3.6 shows that for waveguides narrower than 4\( \mu m \) the scattering loss as a function of width will give rise to very large loss variations over width variations of the order of 0.1\( \mu m \). Secondly, as the width of the waveguide increases the number of modes that the waveguide will support also increases. Power travelling in these higher order modes may be more readily scattered into radiation modes because the higher order modes are less well confined than the lower order modes.
The data in figure 7.6 is for the second batch of waveguides, \( r = 4.43 \mu\text{m} \). Here the better SIMOX material quality (lower defect density and buried interface roughness) results in lower loss waveguides, though a higher relative TM loss attributed to the rib wall roughness, is evident. The losses for the 3.73 \( \mu\text{m} \) waveguide at \( \lambda = 1.523 \mu\text{m} \) were TE 0.0 +/- 0.5 dB/cm and TM 0.4 +/- 0.5 dB/cm. The measurement error was estimated to be +/- 0.5 dB/cm (negative loss implies a gain which is not theoretically possible for these waveguides). These results are thought to be the lowest reported propagation losses for silicon integrated optical waveguides to date.

The contrast between the planar waveguide polarisation dependent loss and that of the rib waveguides is well illustrated by the comparison of figure 7.6 with figure 6.6. The significant interface roughness plane has been effectively rotated by 90° from the planar waveguides, were it was due to a poor buried oxide interface, to rib waveguides, were it is the vertical plane of the etched rib walls. Reduction in the buried oxide layer roughness by an order of magnitude from the planar waveguides to the set of waveguides reported in figure 7.6, combined with a rib wall roughness which is thought to be comparable with buried oxide interface roughness for samples a to a_s in Chapter 6, has led to close to exact reversal of polarisation dependent loss at \( \lambda = 1.523 \mu\text{m} \).

Figures 7.7 and 7.8 are plots of measured 1/e electric field width against predictions from the effective index model for the transverse direction fundamental mode profile. The results are in reasonable agreement with theoretical predictions for \( r=7.67 \mu\text{m} \) waveguides, but, they are slightly lower than expected for \( r=3.17 \mu\text{m} \). The theoretical lines in figure 7.7 show that the TE_{00} lateral field profile is more confined than the TM_{00}. The experimental results are consistent with this for waveguide widths less than 3\( \mu\text{m} \). However, above this width they are not statistically different. This may be due to the multimode nature of the wider waveguides. Only the fundamental mode is modelled in the theory. The trends of both experimental results and theory show a distinctive trough, where the minimum lateral field width is achieved. For this sample the minimum is at approximately 3\( \mu\text{m} \). This minimum arises due to two opposite dependencies of the
Figure 7.6 Measured propagation loss v waveguide width (w).

r=4.32 microns, e=1.7 microns
Figure 7.7 1/e electric field width. Fundamental mode predictions and measurements for lateral field profiles v waveguide width (w). $r=3.17$ microns, $e=0.68$ microns, $\lambda_v=1.523$ microns
Figure 7.8 1/e electric field width. Fundamental mode predictions and measurements for lateral field profiles vs waveguide width (w). r=7.67 microns, e=2.6 microns, $\lambda_0=1.523$ microns
waveguide modal solution on the width. As the width reduces the lateral mode size reduces but at the same time the confinement also reduces. Above \( w = 3 \ \mu m \), in figure 7.7, the size of the waveguide dominates. Below \( 3 \ \mu m \) the confinement of the guided mode reduces rapidly and becomes the dominant factor in determining mode size.

The agreement between theory and experimental results for the lateral \( 1/e \) electric field widths for \( r = 7.67 \ \mu m \) and \( e = 2.6 \ \mu m \), illustrated in figure 7.8 were better than the results in figure 7.7 for \( r = 3.17 \ \mu m \) and \( e = 0.68 \ \mu m \). It was found from the theory that the mode width for the small waveguides was a stronger function of rib etch depth (e). Therefore, only a small error in the measurement of e will cause a larger discrepancy in mode width prediction for small waveguides as compared to taller ones.

Figures 7.9, 7.10, 7.11 and 7.12 are plots of theoretical predictions of etch depth against width for single mode waveguides formed in 3.17 and 7.67 \( \mu m \) silicon core SOI material. (Tables 7.3 and 7.4 allow direct comparison of results with the theoretical predictions in Table 7.1). The continuous and dash lines represent the boundaries between the theoretically predicted single mode to multimode waveguide operation, single mode to the left of the lines and multimode to the right. The curves were generated using a computer program based on the effective index model discussed in Chapter 3, Sections 3.4 and 3.5. Each graph is for a different polarisation and waveguide rib height (r) combination. The points plotted on each graph relate to an observation of apparent single mode operation of a waveguide with a given width (w) and etch depth (e) (which can be read off the graph axes) at either \( \lambda = 1.523 \) or \( 1.15 \mu m \).

The experimental results were in reasonable agreement with the theory for the \( r = 3.17 \), i.e. figures 7.9 and 7.10. Although the basic waveguide theory predicts little difference in modal characteristic with wavelength, the experimental results indicated that smaller waveguides are required for single mode operation at shorter wavelengths. This may be due to the closer spacing of radiative modes to the fundamental mode at shorter wavelengths, and hence greater loss to these modes due to waveguide defects. This then increases the total loss and forms a mode pattern influenced by the radiative modes.
For the second batch of rib waveguides (r= 4.32µm, see figure 7.6 for loss data) only one etch depth was used (e=1.7µm, see Table 7.1), so data was not available to plot in the format of figures 7.9 to 7.12. The modal observation results can instead be found in Tables 7.3 and 7.4. It was observed that for both wavelengths the 2.73 and 3.73µm wide waveguides in the batch appeared single mode. The results are in agreement with the theoretical predictions for the 2.73µm wide waveguide, but are not for the 3.73µm waveguide. The theoretical predictions indicated that the 3.73µm wide waveguide's second order mode will be very close to cut-off. Waveguides were predicted to be single mode for widths less than 3.52 and 3.34 µm for TE and TM modes respectively, independent of wavelength, r=4.32µm and e=1.7µm. Therefore, the 3.73µm waveguide results are in reasonable agreement with the theory. All the other waveguides exhibited a second order mode with a two spot horizontal intensity profile and were therefore in direct agreement with the theoretical predictions.

As discussed above, the 3.73 µm wide waveguide was predicted to be close to the boundary between single mode and multimode. This means that the fundamental mode will be close to optimum confinement, while the second order mode will either be radiative or, if supported, will be only weakly bound and therefore potentially very lossy. The high predicted confinement of the fundamental mode leads one to suspect that this is the reason why the lowest loss is attributed to this waveguide (w=3.73µm), as shown in figure 7.6. The narrower waveguide, w = 2.73 µm, is single mode but the confinement has reduced compared to w = 3.73 µm, therefore, one could expect an increase in loss due to increased interface roughness interaction. For the waveguides with w> 3.73 µm, loss could become a function of the confinement of guided higher order modes. For example, the increase in loss from the width w = 3.73 µm to 4.73 µm may be due to loss from the second order mode. As the waveguides become less square with increased width (i.e. w>r) it becomes more difficult to excite only the fundamental mode with a symmetrical input spot.
Figure 7.9 Theoretical single mode boundary line and observed experimental single mode waveguides (TE polarisation, r=3.17 microns)
Figure 7.10 Theoretical single mode boundary line and observed experimental single mode waveguides (TM polarisation, r=3.17 microns)
Figure 7.11 Theoretical single mode boundary line and observed experimental single mode waveguides (TE polarisation, \( r = 7.67 \) microns)
Figure 7.12 Theoretical single mode boundary line and observed experimental single mode waveguides (TM polarisation, $r=7.67$ microns)
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# = multimode  
+ = TE∞ only  
@ = TM∞ only

Table 7.3 Experimental modal observations for SOI rib waveguides, λ = 1.523µm
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* = TE∞ and TM∞ only
# = multimode
+ = TE∞ only
@ = TM∞ only

Table 7.4 Experimental modal observations for SOI rib waveguides, λ = 1.15μm
Referring back to figure 7.11 and 7.12, only a relatively few samples with 7.67 micron rib height (\(r\)) were observed to be single mode. For shallow etches, the lateral boundary discontinuity caused by the rib will be small, hence the second order vertical mode in both the slab region and rib will closely match. If the electric field does have a continuous solution across the interface for the second order vertical mode, then it is found that the effective index difference between these modes is greater than the effective index difference between the fundamental modes. Hence, if the discontinuity formed by the rib is small, then this could increase the mode variation in the lateral dimension as well as in the horizontal.

For the discontinuity to be greatest between the higher order vertical modes of the slab and the rib, the etch depth should be maximised. For practical reasons there is a limit to the etch depth. As etch depth increases the waveguide width must reduce to maintain only single mode operation. At some point this width may be too narrow for the fabrication technology and/or introduce unacceptable surface scattering loss and be incompatible with other optical systems (e.g. optical fibres).

Every effort was made to excite higher order modes during the characterisation of the waveguides. This included input at an angle and/or offsetting the input beam. It was noticed that planar waveguides in the height range 4.32 to 7.67 microns could not have their fundamental mode alone excited using the test rig. They always produced a multimode pattern similar to those in figures 6.2 and 6.3. However, for the rib waveguides reported in this chapter, exactly the same excitation apparatus was used, yet many rib waveguides could only be excited to yield a typical single mode intensity profile. This strongly suggests that the vertical modal characteristics of rib SOI waveguides are significantly different from those of planar SOI waveguides.
7.6 Waveguide Bends and Y-Junction Design

In order to produce useful waveguide circuits with SOI rib waveguides, basic functional elements such as waveguide bends and branching junctions are required. When an electromagnetic wave travels along a waveguide with a uniform bend radius, some of its energy is lost. For a single mode waveguide this energy is lost as leaky modes.
In the case of bends in SOI rib waveguides the leaky modes are expected to couple to slab modes due to their proximity.

A method of estimating waveguide bend loss which can be applied to SOI rib waveguides can be found in [66]. The method used is referred to as the velocity approach. The tangential phase velocity of a guided wave in a curved waveguide must be proportional to the distance from the centre of curvature. This is because the phase front would otherwise not be preserved.

Radiation from a waveguide bend can be visualised as a portion of the guided mode field on the outside of the bend radius travelling with a faster tangential phase velocity than portions of the wave travelling in the tangential directions at shorter radii. At some extreme radius, and beyond it, the tangential phase velocity would need to exceed the theoretical limit in the material. Since this is impossible, this part of the wave will be radiated away into, in the case of the SOI waveguides, the slab waveguide region.

The radiation loss for a given mode is determined by the mode shape, waveguide physical parameters and the bend radius. [66] has expressed loss in terms of two constants $C_1$ and $C_2$ in equation 7.1

$$\alpha = C_1 \exp(-C_2 R)$$

(7.1)
where \( \alpha \) is the bend loss coefficient (dB/cm) and \( R \) is the bend radius in cm to the centre of the waveguide. \( C_1 \) and \( C_2 \) are in units of dB/cm and cm\(^{-1} \) respectively.

Based on a SOI rib waveguide width \( r = 4.32\mu m \), \( e = 1.7\mu m \) and \( w = 3.73\mu m \), the effective index model described in Chapter 3, Section 3.4 and 3.5, has been used to determine the lateral field profile constants for this waveguide at \( \lambda = 1.523\mu m \) TE\(_{00} \). Using this data in the velocity approach to bend loss [66] the constants \( C_1 \) and \( C_2 \) in equation 7.1 were found to be 18000 dB/cm and 31.6 cm\(^{-1} \) respectively. From this data a curve for the TE\(_{00} \) mode bend loss against radius was generated, see figure 7.13. The analysis predicts that waveguide bend loss will be negligible for bends with radii greater than 4 mm.

It is expected that for \( \lambda < 1.523\mu m \) the bend loss will reduce as the mode will be more confined. For the TM\(_{00} \) mode the loss may be greater as the lateral field is less well confined than for TE\(_{00} \). In addition, bend losses for both modes may be increased by rib side wall roughness which is not included in the model of [66].

A set of SOI rib waveguide bends were fabricated (see figure 7.2) in order to investigate bend loss. The range of bends fabricated was limited by available SOI material. At the same time as the SOI rib waveguide bends were fabricated, a Y-junction using 10mm radius bends was also produced.

[89] provides a method of analysing rib Y-junctions. Whilst this has not been carried out here, a junction geometry was selected based on predicted low loss bends and the combination of two bends to form a gradual transition from a single mode waveguide to two single mode waveguide branches.

Y-junctions operate through the coupling of local mode in the transition region of the Y where the single mode input waveguide increases in width. The transition region extends to the point where the spacing of the two branch waveguides has grown to a dimension where the fundamental modes supported in each branch no longer couple. In the
Figure 7.13  Predicted TE_{\infty} waveguide bend loss, \lambda_o=1.523 microns, w=3.73 microns
transition region, local mode theory can be used to predict the evolution of the mode distribution through the transition [89].

It was unlikely that without detailed design modelling the Y-junction fabricated in this project would have a good performance. However, the demonstration of the principle of Y-junction splitting in SOI rib waveguides was considered a worthwhile exercise.

### 7.7 Waveguide Bends and Y-Junction Losses

Figures 7.14 and 7.15 are graphs of bend loss for the 3.72 micron wide waveguides. The losses that are attributed to the bends (see figure 7.2 for bend geometry) do not include the straight waveguide loss. The bend losses are higher than predicted in Section 7.6, and this may be because the prediction does not taken into account the effects of rib wall roughness (note that the length of the tested waveguide bends were all approximately 1mm). The bends increase the electric field at the outer rib wall as discussed in Section 7.6. The scattering centres on the rib walls due to etch roughness will be relatively strong because of the large refractive index step (2.5) between the rib side walls and air. In addition, the effective index of the fundamental slab mode is predicted to be only ~0.006 lower than the rib guided mode. The combination of strong scattering centres and a close radiative mode for the guided mode to couple to are likely to be the cause of the high measured loss. This is partly supported by the observation of slab waveguide guided light of the power levels lost by the bends emerging from the test samples around the rib waveguide output.

By slight extrapolation of the data in figures 7.14 and 7.15 it can be seen that for a 12mm bend radius, losses of less than 0.1 dB and 0.5 dB are expected for TE and TM modes respectively. The TM bends are more lossy than the TE, probably due to the lower horizontal confinement of the TM mode as discussed earlier.
Figure 7.14 Waveguide bend loss, \( \lambda_0 = 1.15 \) microns, \( w = 3.73 \) microns
Figure 7.15 Waveguide bend loss, $\lambda_0=1.523$ microns, $w=3.73$ microns
The Y junction tested (figure 7.2) was based on the 10 mm radius bend. The losses attributed to the Y junction alone were TE 1.92 dB / TM 2.235 dB at \( \lambda = 1.15 \) microns and TE 1.82 dB / TM 3.51 dB at \( \lambda = 1.523 \) microns. The maximum measured imbalance in the Y junction arms was 3%. The higher TM loss again illustrated the lower confinement of this mode. The losses may be reduced if the waveguides are made to initially diverge at a gentler rate so that the transmission remains adiabatic. The fabrication method led to a non ideal feature between the two diverging arms of the the Y-junction (see figure 7.2). This feature is likely to scatter light out of the waveguide structure. This is partly supported by the observation of slab waveguide guided light of the power levels lost by the Y-junction emerging from the test samples around the rib waveguide outputs in a similar fashion to the lost light in the bends.

To reduce the loss caused by the undesirable feature in the Y-junction, its size may be reduced using finer photolithography and etching methods. Consequently the results presented are the worst-case figures which are likely to be improved in time. Further improvements may be achievable using design modelling based on local mode theory methods [89].

7.8 Conclusions

The results reported in this Chapter have provided support to the hypothesis that certain multimicron rib dimensions can lead to single mode SOI waveguides in the wavelength range 1.15 to 1.6 \( \mu \text{m} \) since close agreement was observed with predictions. The experimental data has illustrated limitations in the theory for shallow etch waveguides. However, the theory is reliable for waveguides having relatively large rib etch depth. Waveguides with a defect density in the core material of the order of \( 10^5 \text{ cm}^2 \), have approximately 500 defects per cm. Therefore, it is unlikely that significant waveguide loss can be attributed to volumetric scattering in the waveguide core for this relatively high quality material, which is now the norm for commercial SIMOX. It is more likely that waveguide loss is dominated by the buried oxide interface and rib wall roughness. The
buried oxide interface roughness can be controlled by implantation conditions. An absorption loss of 2.87 dB/cm at \( \lambda = 1.15 \) µm adds to the other loss mechanisms for this wavelength.

The demonstration of SOI rib waveguide bends and a Y-junction have shown the practical fabrication of these waveguide elements. However, the losses reported are too high to allow their use in many practical devices. The waveguide bend losses may be reduced by increasing the bend radius to greater than 12mm and reducing the rib etch roughness which is thought to be the most significant cause of loss. The redesign of the Y-junction using theoretical modelling [89] combined with finer photolithography should improve performance.
Chapter 8.
Conclusions and Future Work

8.1 Conclusions
8.2 Future Work
8.1 Conclusions

The principal aim of this research project was to establish the practicality of SOI waveguides as the basis for a silicon integrated optics technology. A review of previous research and current materials technology trends directed the research work towards waveguide structures formed in SIMOX material. SIMOX was chosen as the basis for the waveguide because of its ready availability and predictions as to the ultimate commercially available material quality.

For silicon waveguide cores of greater than 1 micron, upon which the project concentrated, the thickness of the buried oxide layer of 0.4 microns in standard radiation hard electronics grade SIMOX was found to be more than sufficient to prevent the leakage of optical power from the fundamental guided modes to the silicon substrate. Though SOI can be formed by other methods (e.g. Bond and Etchback Silicon-on-Insulator, BESOI), SIMOX leads to the best film uniformity (< 20 nm over a 100mm diameter wafer) and comparable interface roughness to the best alternatives.

The project set about a systematic way of developing a suitable SOI stripe waveguide structure. Firstly, planar waveguides with the surface silicon layer epitaxially grown were tested. Modelling of these waveguides indicated that the thinner the guiding layer, the greater the potential loss from interface scattering and leakage to the silicon substrate. The possibility of multimicron dimension rib waveguides was attractive from the point of view of minimising interface scattering loss and maximising coupling efficiency to/from single mode optical fibres. Characterisation of these planar waveguides showed that SOI material could guide light with losses less than the benchmark figure of 1 dB/cm. Previously the best result had been 4.4 dB/cm.

Having determined and proven the practicality of a planar SOI waveguide from the point of view of loss, the work then focused on three dimensional waveguide structures with multimicron dimensions. The drawback to this approach was the expected multimode behaviour of these large dimension SOI waveguides. However, as pointed out by
Petermann et al [46], the use of correctly designed rib waveguide structures could overcome this problem and hence the work concentrated on furthering the understanding of rib SOI waveguides.

The final set of characterised rib waveguides (height 4.32 µm and width 3.73 µm) demonstrated the lowest loss yet reported in silicon waveguide technology, 0.0 +/-0.5 dB/cm for the TE\textsubscript{00} mode and 0.38 +/-0.5 dB/cm for the TM\textsubscript{00} mode measured at λ\textsubscript{0}=1.523 µm. The potential loss mechanisms in the waveguides could be characterised as substrate leakage, absorption, volumetric scattering and interface scattering. Leakage to the substrate was found to be negligible for multimicron dimension of the silicon core. Absorption in pure crystalline silicon is of the order of 0.004 dB/cm in the wavelength range 1200 to 1600 nm. This poses no practical limits on silicon waveguides in this wavelength range. Higher absorption at λ\textsubscript{0}=1.15 µm of 2.98 dB/cm was found from experimentation and compared well with the previously reported loss at this wavelength for pure c-Si, 2.87 dB/cm. Loss in silicon is known to increase with doping levels, for example, the loss at λ\textsubscript{0}=1.523 µm for N\textsubscript{d}=1x10\textsuperscript{16} cm\textsuperscript{-3} is 0.22 dB/cm [35].

The results that were obtained from measurements at two different wavelengths and polarizations have enabled separation of volumetric and interface scattering effects in the waveguides to a first order approximation. Loss due to interface scattering is relatively insensitive to wavelength, but, volumetric scattering was expected to be proportional to 1/λ\textsuperscript{3} [69]. There was no statistically significant difference in measured loss attributed to scattering for the two wavelengths (0.00 and 0.02 dB/cm for TE\textsubscript{0} at λ\textsubscript{0} = 1.523 and 1.15 µm respectively for best grade samples) which implies that volumetric scattering is not the dominant loss mechanism. The best grade samples tested had a defect density, according to the manufacture, of better than 10\textsuperscript{5} cm\textsuperscript{-2}. For 10\textsuperscript{6} defects cm\textsuperscript{2} in a 5 micron square section waveguide this represents only 125 defects/cm of waveguide. In addition, the defects are reported to be mostly threading dislocations and their strength as scattering centres will be limited by size and their small local refractive index perturbations effect.
The strong dependency of waveguide loss on polarisation confirms that by far the most important loss mechanism in SIMOX based multimicron waveguides is core/cladding interface scattering. In planar waveguides the TM mode loss was found to be of the order of half the loss of the TE mode. This is attributed to buried oxide/silicon core interface roughness where the higher confinement of the TM modes provides less power to be scattered at this interface roughness than for the TE modes. For the final set of rib waveguides fabricated and tested, the planar material loss was measured to be less than 0.05 dB/cm for the TE₀ mode at λ₀=1.523 μm. This implies a buried oxide interface roughness of approximately 2 nm. SIMOX material is now commercially produced to a specification of 1.8 nm rms interface roughness with a periodicity of approximately 1 μm.

The higher TM₀₀ loss for rib waveguides compared to TE₀₀ is due to the roughness of approximately 20 nm rms on the side walls of the rib generated by the reactive ion etching process employed. Marcuse's planar waveguide interface scattering model can be used to understand this (see Chapter 3, Section 3.3). The lateral field confinement for the TM₀₀ mode is less than the TE₀₀ mode and hence there is more power available to be scattered at the interface roughness for the TM₀₀ mode than the TE₀₀ mode. However, the extent of the roughness is only partially over the horizontal confinement (vertical plane) of the rib waveguides, so using the planar waveguide scattering estimates will tend to over predict loss due to rib roughness.

If the roughness of the side walls of the rib waveguides can be reduced to that comparable with the available SIMOX buried oxide interface roughness (i.e. <2 nm) then SIMOX based SOI rib waveguides with dimensions similar to those of a single mode fibre (core diameter ~9.0 μm) can be expected to have a loss less than 0.05 dB/cm for both TE₀₀ and TM₀₀ over the wavelength range 1.2 to 1.6 μm. Figure 8.1 illustrates the scattering loss for varying planar waveguide thickness with 2 nm rms interface roughness. Rib roughness might be reduced to this level by a combination of photoresist reflowing, post etch annealing and oxidation or by the use of wet etching in place of reactive ion etching.
Figure 8.1 Scattering loss predictions for a symmetric planar SOI waveguide. rms roughness (A) 2 nm, correlation length of the roughness (B) 1 micron, $\lambda_o=1.523$ microns
Bends fabricated with rib SOI waveguides performed as expected with exponentially increasing loss with reducing bend radius. Losses for the 3.73 μm wide waveguides were predicted to be acceptable for practical application for radii greater than 12 mm. The bend losses were observed to be higher for the TM$_{00}$ mode which provides further confirmation of the scattering loss caused by the rib wall roughness.

The Y junction tested (see figure 7.2) was based on the 10 mm radius bend. The losses attributed to the Y junction alone were TE 1.92 dB / TM 2.235 dB at $\lambda=1.15$ microns and TE 1.82 dB / TM 3.51 dB at $\lambda=1.523$ microns. The maximum measured imbalance in the Y junction arms was 3%. The higher TM loss again illustrated the lower confinement of this mode. The losses may be reduced if the waveguides are made to initially diverge at a gentler rate so that the transmission remains adiabatic. The fabrication method led to a non ideal feature between the two diverging arms of the Y-junction (see figure 7.2). This feature is likely to scatter light out of the waveguide structure. To reduce the loss caused by this undesirable feature its size may be reduced using finer photolithography and etching methods. Consequently the results presented are the worst case figures, which will inevitably improve with development.

The characterisation of rib SOI waveguides have provided additional support to the hypothesis that certain rib dimensions (up to at least a rib height of 7.67 microns) can lead to single mode waveguides in the wavelength range 1.15 to 1.55 microns. Limitations on theoretical predictions have been proposed. In particular the validity of the single mode theory for very shallow ribs and for waveguide overall heights in excess of a few microns.

The combination of these low loss results for SOI rib waveguides, their modal characteristics, fibre optic compatibility and the potential to modulate the refractive index of these waveguides efficiently [87] in the MHz range makes them a potential candidate for high accuracy interferometric sensors and optical fibre transceiver applications. For example, interferometric measurement requiring closed loop AC dither fringe detection could be addressed by SOI waveguide technology. One potential application is an integrated optical circuit for the fibre optic gyroscope. For optical fibre communication
applications switches and wavelength demultiplexing functional elements integrated in SOI waveguide technology may prove practical and low cost.

8.2 Future Work

The practicality of SOI waveguides has been demonstrated, but, further studies of the physical structure of SOI/SIMOX and correlating this with optical waveguide characteristics may lead to greater understanding of loss mechanisms and allow ultra low loss (<0.01 dB/cm) integrated optical waveguides to be fabricated. These physical studies might involve investigating the interface roughness by etching back surface silicon films and characterising the interface roughness with an Atomic Force Microscope.

Beyond the understanding of loss mechanisms in SOI based waveguides there are the challenges of fabricating and studying a range of useful passive and active integrated optical devices. These devices in turn may allow greater understanding of waveguide modal characteristics and accurate loss determination.

Useful passive components that could be fabricated and studied include directional couplers, grating couplers, ring resonators and interferometers. These elements form the basis of useful integrated optical devices for fibre optic communication (e.g. switches and wavelength filters) and sensors (e.g. interferometry).

Free carrier plasma dispersion represents a relatively straightforward method of modulating the refractive index of a silicon waveguide. Free holes and electrons can be injected or depleted in a silicon waveguide by means of a semiconductor junction. Methods must be found which minimise the power requirements and maximise switching speed. Further experimental investigations into loss caused by free carrier plasma dispersion are also required.
Recent work on light sources in silicon have shown some promise. The main areas of research in this fields are in quantum confinement (e.g. porous silicon), isoelectric impurities in silicon (e.g. silicon with carbon impurities) and rare-earth impurities (e.g. silicon doped with Erbium). However, the technical lead that III-V semiconductor LEDs, laser diodes and photodetectors have built up in the near infrared range suggests that combining potentially low cost active silicon integrated optics with established III-V technology could represent a more practical near term solution. This approach requires hybridisation techniques to be developed which will allow the III-V devices to be accurately attached to silicon optical chips. These techniques have been extensively researched for silica on silicon waveguide technology and some of this work could be directly transferable to SOI integrated optics.
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