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NOVEL SI/SI_{1-x}GE_x OPTICAL SWITCH AND OPTOELECTRONIC MODULATOR

by

MODERAGE CHANDANA FERNANDO, B. ENG., M. ENG.

**A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of**

Doctor of Philosophy

**Ottawa-Carleton Institute for Electrical Engineering
Department of Electronics
Faculty of Engineering
Ottawa, Canada**

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submitted by
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in partial fulfillment of the requirements
for the degree of Doctor of Philosophy

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May 1995

Abstract

The successful integration of optical and electronic components will be crucial to the future design of optical communications systems. Silicon germanium, $\text{Si}_{1-x}\text{Ge}_x$, alloys provide a means of implementing novel optoelectronic devices which could be readily integrated with existing Si electronics on Si substrates. In this work two novel $\text{Si}_{1-x}\text{Ge}_x$ optoelectronic components were investigated. These are an all optical $\text{Si}/\text{Si}_{0.7}\text{Ge}_{0.3}$ multilayer distributed feedback (DFB) switch, and a $\text{Si}/\text{Si}_{0.85}\text{Ge}_{0.15}/\text{Si}$ electro-optic PIN waveguide modulator.

A multilayer semiconductor bistable DFB switch, grown on a Si substrate, was designed and tested using light at a wavelength of $1.06\text{ }\mu\text{m}$. This structure, designed for the first time on $\text{Si}/\text{Si}_{1-x}\text{Ge}_x$ alloy will, in principle, be integrable with existing electronics on a common Si substrate. A numerical algorithm to model the performance of the DFB design, and an optical technique to study the free carrier lifetime of the implemented structure are also presented. The $\text{Si}/\text{Si}_{1-x}\text{Ge}_x$ DFB demonstrated thermal switching characteristics with reflectivity contrast ratios, $\Delta R/R$, of 100% and 50% for increase and decrease reflectivity switching respectively. Lifetime measurements revealed a carrier lifetime of 100ps in the structure. This indicated that an improvement in the material quality, and hence the free carrier lifetime, is required before optical bistability can be observed in these devices.

The optical waveguiding and modulation characteristics of a novel

Si/Si_{0.85}Ge_{0.15}/Si PIN modulator were analyzed theoretically using several optical and electronic device simulation packages. The modulator was implemented using molecular beam epitaxy (MBE) growth techniques on a heavily doped N⁺ substrate. Experimentally, it displayed a modulation speed in excess of 12.5MHz and a maximum modulation depth of 85% at a current density of 4200A/cm². This work represents the first demonstration of a PIN Si/Si_{1-x}Ge_x/Si electro-optic modulator using the electro-absorption effect.

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List of Symbols

A	cross sectional area of the diode (cm^2)
α	absorption coefficient (cm^{-1})
α_0	linear absorption coefficient (cm^{-1})
α_2	nonlinear absorption coefficient (cm^{-3}/W)
c	speed of light ($3 \times 10^8 \text{ m/s}$)
D_p	diffusion coefficient for holes (cm^2/s)
e	charge of an electron ($1.6 \times 10^{-19} \text{ C}$)
ϵ_L	high frequency permittivity
ϵ_0	free space permittivity ($8.854 \times 10^{-12} \text{ F/m}$)
ϵ_s	permittivity of silicon (11.8)
Φ_0	total photon flux ($\text{photons cm}^{-2} \text{ s}^{-1}$)
γ	trap escape rate (s^{-1})
Γ	proportionality constant between the free carrier density and injected current ($\text{cm}^{-3}/\text{A}^{1/2} \text{ s}$)
h	Plank's constant ($6.626 \times 10^{-34} \text{ J s}$)
I_0	incident intensity in (W/m^2)
J	incident current density (A/cm^2)
K	Boltzman's constant ($8.617 \times 10^{-5} \text{ eV/K}$)
k	DFB coupling constant

L_p	diffusion length for holes (cm)
m^*	effective electron-hole mass (Kg)
m_e^*	electron effective mass (Kg)
m_{eh}	effective mass of an electron-hole pair (Kg)
m_h^*	hole effective mass (Kg)
N	carrier density (cm^{-3})
n	real part of the refractive index
n_a	average refractive index of the material
n_0	linear refractive index
n_2	nonlinear refractive index coefficient (cm^2/W)
ΔN_e	excess electron concentration (cm^{-3})
ΔN_h	excess hole concentration (cm^{-3})
N_0	density of empty traps (cm^{-3})
N_t	trap density (cm^{-3})
ν	incident frequency (s^{-1})
ω	angular frequency (rad/s)
ω_p	plasma frequency (rad/s)
p	empirical constant
p_{nn}	hole concentration on the n side (cm^{-3})
q	magnitude of the electronic charge ($1.6 \cdot 10^{-19}$ C)
Q_d	charge per unit area in the depletion region (C/cm^2)
Q_p	charge per unit area in the quasi-neutral regions (C/cm^2)

σ	trap capture cross section (cm^3/s)
τ_R	average recombination time of an electron-hole pair (s^{-1})
T	temperature (K)
μ_e	electron mobility ($\text{cm}^2 \text{ V}^{-1} \text{ s}^{-1}$)
μ_h	hole mobility ($\text{cm}^2 \text{ V}^{-1} \text{ s}^{-1}$)
V_a	externally applied voltage (V)
V_b	device breakdown voltage (V)
W	depletion width (m)

1.0 Introduction

1.1 Background

During the past decade there has been a tremendous growth in the field of optical communications. Currently, most optical communications systems are a hybrid of optical and electronic subsystems. Typically, the electronics performs the signal and data processing while the optics handles the data transmission functions. However, it has long been realized that optical systems offer many advantages such as greater speed, larger bandwidth and better electromagnetic interference (EMI) tolerance over their electronic counterparts. Therefore, an overall improvement in system performance can be achieved if most of the electronics is replaced by optical components. At present, as optical technology is still in its infancy, there are very few commercially available optical components which can be substituted for the standard electronic ones. In order to use electronic and optical technology to their full potential, circuits of the future would have to integrate both electronics and optics on the same chip. To date very primitive optoelectronic integrated circuits, each consisting of a few optical and electronic components, have been demonstrated [1]. The development of these circuits has been hindered by the incompatibility between electronic and optical device fabrication techniques. Once integration technology matures it will offer OEIC's which have superior performance and a higher degree of integratability than present day electronic integrated circuits, IC's. With further advances in optical technology the optoelectronic integrated circuits, OEIC may one day be replaced by very sophisticated all optical integrated circuits(OIC).

In both electronics and optics there has been wide use of both the III-V and group IV semiconductor materials in the fabrication of electronic integrated circuits, microwave monolithic integrated circuits (MMIC), optical components and optoelectronic modules. GaAs and InP have been used in the design of basic MMIC amplifier [2], oscillator [3] and mixer circuits [4]. In the field of electronics, GaAs has been used in the fabrication of heterojunction bipolar transistors (HBT) [5], metal semiconductor field effect transistors, (MESFETs) [6] and high electron mobility transistors (HEMTs) [7]. Basic analogue circuits such as analogue-to-digital and digital-to-analogue converters have also been implemented using HBT's [8,9]. Also, GaAs has higher carrier mobilities, and hence, faster switching speeds than Si. In optics GaAs and GaAlAs have been used in the fabrication of low loss waveguides [10]. GaAs, GaAlAs and GaInAsP have been used in the implementation of dual-channel directional couplers [11,12], intensity modulators [13], multiple quantum well (MQW) modulators [14] and electro absorption modulators [15,16]. Furthermore, avalanche and p-i-n diode detectors grown on GaAsSb and InP substrates have also been demonstrated [17,18]. One of the most important uses of III-V materials is in the implementation of lasers. Several different types of lasers such as double heterostructure (DH) [19], distributed feedback (DFB) [20] and separate confinement structures [21] have been designed using GaAs and InP materials. Complex photonic integrated circuits (PIC) which include integrated laser and modulator devices [22], multi-channel transmitters [23] and OEIC photoreceivers [24] have been fabricated using III-V materials. The III-V material system has gained popularity partly due to the existence of several near lattice matched alloys which can be grown epitaxially

on one another. This enables heterostructure engineering of high quality, dislocation free devices to be grown with relative ease. Also, the direct gap of the III-V material systems permits the fabrication of lasers, which are of vital importance to both optical and optoelectronic applications. Extensive work on lasers using the InP/InGaAsP and GaAs/GaAlAs alloy systems has been documented in the literature [19,20,21].

Another material system that has been under intense scrutiny in the past few decades is group IV, particularly Si, Ge and $\text{Si}_{1-x}\text{Ge}_x$ alloys. Silicon has found phenomenal success in the field of integrated circuits in the implementation of various devices from the simplest logic gates to complex microprocessors. The success in Si microelectronics has been partly due to advances in Si growth and fabrication. Currently, Si is the cheapest and the highest quality commercially available semiconductor material. A 4" Si wafer costs approximately \$15 compared to about \$200 for a GaAs wafer of the same size. Also, commercially available Si wafers have almost a zero dislocation density compared to approximately $10^4/\text{cm}^2$ for GaAs. Currently, state of the art fabrication processes use 8" Si wafers. GaAs circuitry is currently grown on 4" wafers and growth on 6" substrates are expected in the near future.

Silicon-Germanium alloy, $\text{Si}_{1-x}\text{Ge}_x$, can be epitaxially grown on Si and has been used in the implementation $\text{Si}/\text{Si}_{1-x}\text{Ge}_x$ heterojunction bipolar transistors (HBT) operating in the microwave range of frequencies [25,26]. In optics, $\text{Si}_{1-x}\text{Ge}_x$ has been used in conjunction with Si in the fabrication of low-loss waveguides [27,28], couplers [29], optoelectronic Mach-Zehnder modulators [30], distributed Bragg reflectors [31], optoelectronic switches [32] and various types of detectors [33,34].

To date, the growth of $\text{Si}_{1-x}\text{Ge}_x$ is in its infancy. Improvements in the growth of $\text{Si}_{1-x}\text{Ge}_x$ will enable Si electronic and Si/ $\text{Si}_{1-x}\text{Ge}_x$ optics to be grown on the same Si substrate. Also, the vast processing knowledge accumulated over the years on Si electronic devices can be applied to the growth and fabrication of Si/ $\text{Si}_{1-x}\text{Ge}_x$ optical components. The integration of optics and electronics on a common Si substrate would facilitate the design of more complex OEIC's than those available at present. Furthermore, as the base cost of Si is less and the material quality better than that of GaAs, Si/ $\text{Si}_{1-x}\text{Ge}_x$ circuits should be cheaper and should also have better yield than comparable circuits designed in GaAs. Also, the ability to process larger diameter wafers enables Si components to have a lower unit area component cost than GaAs devices.

Currently, there is a lack of basic optical circuitry for use in the design of complex optical or opto-electronic circuitry. The phenomenon of optical bistability enables the design of basic optical components such as switches, pulse shapers, limiters and logic units all of which are essential for the implementation of optical subsystems. Currently, most of the high speed and processing intensive electronic components are based on planar silicon or planar GaAs integrated circuit technology. Over the past few decades optical bistability has been demonstrated in several materials including the group III-V, GaAs/AlGaAs semiconductor system [35,36]. However, due to growth difficulties, caused mainly by the lattice mismatch between constituent elements, the implementation of optical components on Si/ $\text{Si}_{1-x}\text{Ge}_x$ alloys has been more difficult than in the III-V system. Hence, one of the main goals of this work is to design and implement optically bistable devices, for the first time, in $\text{Si}_{1-x}\text{Ge}_x$ alloys. Currently, $\text{Si}_{1-x}\text{Ge}_x$ alloys have the

most mature growth technology compared to other Si alloys such as silicon carbide, silicon germanium carbide and diamond. Optically bistable devices grown on a Si substrate can be easily integrated with existing Si electronic or opto-electronic components to form complex Si hybrid or integrated circuits.

A basic characterization of $\text{Si}_{1-x}\text{Ge}_x$ is still incomplete. Therefore, another aim of this work is to determine the free carrier lifetime in the implemented $\text{Si}_{1-x}\text{Ge}_x$ devices using optical measurement techniques. An accurate knowledge of the carrier lifetime is essential for device implementation as it determines parameters such as device speed, the output ON/OFF ratio (contrast ratio) and input switching threshold.

Another component which performs switching functions in an optical subsystem is an optical modulator. Silicon, being an indirect gap material, is unsuitable for the implementation of laser sources. Although, several studies have been conducted on direct bandgap engineering Si, the demonstration of lasing has not been achieved in this system [37]. Therefore, in any wholly Si circuit, in which all the relevant circuitry but the laser source is located on chip, a modulator would perform the vital role of imprinting data onto an externally derived laser beam before it is passed on to other circuitry on the chip for processing. Traditionally, optical modulators have been implemented as either all optical modulators or electrooptic modulators. In the former device both the input and the control are optical signals, whereas in the latter device the input is optical and the control is an electrical signal.

Optoelectronic modulators implemented to date [30,32,38], in Si, can be subdivided into refraction and absorption devices. The refraction devices use changes

in the refractive index, while absorption devices use changes in the absorption coefficient, to modulate the input signal. To date, absorption modulators have been demonstrated in all-Si PIN waveguide modulators [38]. A study of heterostructure bandgap theory for Si/Si_{1-x}Ge_x materials reveals that Si/Si_{1-x}Ge_x/Si PIN diodes should have better performance than the Si structures [39]. The second main goal of this work is to design, implement and characterize a Si/Si_{1-x}Ge_x/Si waveguide PIN electrooptic absorption modulator. This work represents the first demonstration of the electro-absorption effect in a Si/Si_{1-x}Ge_x/Si PIN modulator. This structure, grown using planar Si technology, can be integrated with other circuitry on OEIC's or be used in a hybrid fashion in an optoelectronic system.

1.2 Thesis Outline

Chapter 2 is divided into three sections. The first section presents the electrical and optical properties of Si_{1-x}Ge_x. The second section describes the free carrier effect which is used to control the refractive index and absorption coefficient of this alloy. The third section outlines the growth of Si_{1-x}Ge_x on lattice mismatched substrates.

Chapter 3 is divided into three sections. The first section describes the phenomena of optical bistability and the design and operation of Fabry-Perot and distributed feedback structures. Also, this section outlines the design of a DBR multilayer stack using Winful's equations. The second section describes the numerical modelling algorithm used to calculate the input versus output characteristics of any general multilayer structure. The third section of chapter 3 outlines the modelling of the multilayer distributed

feedback structures.

The implementation and testing of a distributed feedback multilayer structure, designed for the first time on $\text{Si}/\text{Si}_{1-x}\text{Ge}_x$ alloy, as well as the growth and analysis of dislocation inhibiting buffer layers is outlined in the first section of Chapter 4. The second section of this chapter presents the lifetime measurement technique as well as the results obtained from these measurements. The third section presents the design of novel Fabry-Perot and combined Fabry-Perot structures. The fourth section summarizes the notable results obtained for the work conducted on the $\text{Si}/\text{Si}_{1-x}\text{Ge}_x$ multilayer.

Chapter 5 is divided into three sections. The first section describes the general operating characteristics of PN photodiodes. It also gives a brief description of the different types of PN photodiodes as well as various fabrication geometries. The second section describes the operation of the novel $\text{Si}/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ electrooptic waveguide PIN modulator. The third section details the theory of optical waveguiding in a planar three layer waveguide structure. This section also presents the design equations required for the implementation of symmetric and asymmetric waveguides.

Chapter 6 is divided into four sections. The first section describes the $\text{Si}/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ modulator design. The second section presents the simulation results for the optical waveguiding, modulation and switching characteristics of the optimized $\text{Si}/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ modulator structure presented in the first section. The processing methodology used to fabricate the rib waveguides and the testing of the $\text{Si}/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ modulator structures are outlined in section three. The experimentally observed

modulation and switching characteristics are also presented in this section. Section four gives a short summary of this work.

A summary of the thesis and also an outline of future work for both the $\text{Si}/\text{Si}_{1-x}\text{Ge}_x$ multilayer stack and the $\text{Si}/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ modulator are presented in chapter 7.

2.0 General Properties of $\text{Si}_{1-x}\text{Ge}_x$

2.1 Optical and Electronic Properties

In its crystalline form, $\text{Si}_{1-x}\text{Ge}_x$ possess a diamond structure similar to its parent constituents. The band diagrams for Si and Ge, having lattice constants of 5.43 Å and 5.65 Å, are illustrated in figures 1 and 2 respectively. Si, Ge and $\text{Si}_{1-x}\text{Ge}_x$ are all indirect gap materials in that the minimum energy of the conduction band does not have the same crystal momentum as the maximum of the valence band. This can be seen by comparing the band diagrams of a direct gap material such as GaAs, illustrated in figure 3, with those of Si or Ge presented in figures 1 and 2.

Figure 1. E-k Diagram of Si [40]

Figure 2. E-k Diagram of Ge [40]

Figure 3. E-k Diagram of GaAs [40]

In an indirect gap material, the absorption process, in which an electron moves from the valence to conduction band, requires both a change in energy and momentum, as illustrated in figure 4. The energy is provided by a photon and the momentum by the absorption or emission of a phonon. Absorption in direct gap materials requires only the interaction of a photon having energy greater than the bandgap of the material. Generally speaking, in direct gap materials, the absorption coefficients are higher than those of indirect gap materials.

Figure 4. E - k Diagram for an indirect bandgap material [41]

When electrons and holes recombine the energy released can lead to the emission of photons (radiative recombination) or the emission of phonons (non-radiative recombination). In certain direct gap materials such as GaAs, radiative recombination is observed. However, in Si, Ge and $\text{Si}_{1-x}\text{Ge}_x$ materials nonradiative recombination is the

more dominant of the two recombination processes due to the fact that the probability of getting the exact phonon carrier interaction required for photon emission is quite small. The emitted phonons heat up the crystal lattice and can give rise to thermal effects in these materials. At cryogenic temperatures probably of radiative recombination is greater because the free carries can form excitons which can recombine radiatively by releasing the excess momentum to trapping or doping centre resident in the material.

Due to the lattice mismatch between constituent elements, the growth of a $\text{Si}_{1-x}\text{Ge}_x$ epilayer on a Si substrate results in a biaxial in-plane compression of the alloy and an extension normal to the interface. The strain in the $\text{Si}_{1-x}\text{Ge}_x$ epilayer leads to the splitting of the degenerate conduction and valence bands which in turn reduces the bandgap of the indirect gap material well below that of the unstrained $\text{Si}_{1-x}\text{Ge}_x$ alloy. Knowing the indirect bandgap of $\text{Si}_{1-x}\text{Ge}_x$, the bandgap of strained $\text{Si}_{1-x}\text{Ge}_x$ alloy can be calculated using the theory of deformation potentials [42]. Figure 5 illustrates the energy gap for strained and unstrained $\text{Si}_{1-x}\text{Ge}_x$, grown on (001) Si at 300K, as a function of the Ge content in the alloy [43]. The hatched region associated with the strained curve is due to uncertainties in the measurement of the deformation potentials. This figure shows that for a given Ge content the bandgap of the strained alloy is much smaller than that of its unstrained counterpart. This property has been exploited by many researchers in the growth of novel strained $\text{Si}_{1-x}\text{Ge}_x$ optoelectronic components [44]. It should also be noted that the bandgap of $\text{Si}_{1-x}\text{Ge}_x$ is suitable for the implementation of optoelectronic devices operating in the fiber communications wavelengths of 1.3 and 1.5 μm . Using interpolation

Soref [44] has approximated the refractive index of strained $\text{Si}_{1-x}\text{Ge}_x$, at $1.3\mu\text{m}$, to be given by

$$n_{\text{SiGe}} = n_{\text{Si}} + 1.45x \quad (1)$$

for x between 0 and 0.25.

In III-V materials several nonlinear mechanisms can be used to generate nonlinear behaviour. The main nonlinearities are the linear (Pockels) and nonlinear (Kerr) electro-optic effects and the free carrier effect. However, group IV materials such as Si, Ge

Figure 5. Bandgap for strained and unstrained $\text{Si}_{1-x}\text{Ge}_x$ [43]

and $\text{Si}_{1-x}\text{Ge}_x$, being centrosymmetric, display no Pockels effect. Studies conducted by Soref [45] have revealed that the Kerr effect is also quite small in Si. However, the free carrier effect, in which carriers generated by optical or electrical means alters both the refractive index and absorption coefficient, can be used to vary the optical properties of group IV materials.

2.2 Calculation of Free Carrier Effects

Light incident on a nonlinear material generates a change in refractive index, n , and absorption coefficient α . The refractive index change can be divided into an electronic, Δn_e , and thermal, Δn_t , perturbation. Therefore

$$\Delta n = \Delta n_e + \Delta n_t \quad (2)$$

According to the Drude model [46] the permittivity, ϵ , of a material is given by

$$\epsilon = \epsilon_L \left[1 - \frac{e^2 N}{\epsilon_L \epsilon_0 \omega} \left[\frac{m_e^{*-1}}{\omega + i\tau_e^{-1}} + \frac{m_h^{*-1}}{\omega + i\tau_h^{-1}} \right] \right] \quad (3)$$

After simplification the real part of ϵ , $\text{Re}(\epsilon)$, is given by

$$\text{Re}(\epsilon) = \epsilon_L - \frac{e^2 N}{\omega} \left[\frac{m_e^{*-1} \omega}{\omega^2 + (\tau_e^{-1})^2} + \frac{m_h^{*-1} \omega}{\omega^2 + (\tau_h^{-1})^2} \right] \quad (4)$$

Now

$$\frac{1}{m^*} = \frac{1}{m_e^*} + \frac{1}{m_h^*} \quad (5)$$

Assuming that both τ_e^{-1} and τ_h^{-1} are less than ω and substituting equation 5 into 4 the $Re(\epsilon)$ is related to the plasma frequency, ω_p , by

$$Re(\epsilon) = \epsilon_L \left(1 - \frac{\omega_p^2}{\omega^2}\right) \quad (6)$$

where the plasma frequency, ω_p , is given by

$$\omega_p^2 = \frac{N_{eh} e^2}{m^* \epsilon_0 \epsilon_L} \quad (7)$$

Substituting 7 into 6 the following is obtained

$$Re(\epsilon) = \epsilon_L - \frac{N e^2}{m^* \epsilon_0 \omega} = n^2 - k^2 \quad (8)$$

If the imaginary part of the refractive index k , is near zero, equation 8 yields;

$$\Delta n = - \frac{\Delta N e^2}{2 m^* n \epsilon_0 \omega} \quad (9)$$

where n is the refractive index of the material.

The carrier generation rate due to an incident beam with intensity I_0 is

$$\frac{\delta N}{\delta t} = \frac{\alpha I_0}{h\nu} - \frac{N}{\tau_R} \quad (10)$$

where αI_0 is the total energy absorbed and $h\nu$ is the energy of the incident photon. As each absorbed photon leads to the creation of one electron-hole pair, the first term in the above equation represents the rate of carrier generation per unit volume. The second term describes the rate of carrier recombination per unit volume. Therefore, at steady state

$$\frac{N}{\tau_R} = \frac{\alpha I_0}{h\nu} \quad (11)$$

Thus,

$$N = \frac{\alpha I_0 \tau_R}{h\nu} \quad (12)$$

Therefore, substituting 12 into 9 gives,

$$\Delta n_c = - \frac{e^2 \alpha I_0 \tau_R}{2nm_{ch} \epsilon_0 \omega^2 h\nu} \quad (13)$$

The change in refractive index due to a change in temperature, ΔT , is given by

$$\Delta n_1 = \frac{\delta n}{\delta T} \Delta T \quad (14)$$

Therefore the total refractive index change can be represented as follows

$$\Delta n = -\frac{e^2 \tau_R \alpha(T) I_0}{2nm_{eh} \epsilon_0 \omega^2 h\nu} + \frac{\delta n}{\delta T} \Delta T \quad (15)$$

The first term in equation 15 arises from the generation of free carriers as determined by the Drude model and yields a decrease in refractive index proportional to the incident intensity. The positive thermal term, due to the heating of the crystal lattice, gives a refractive index change which increases with temperature for silicon. This thermal refractive index change is brought about by corresponding changes in the bandgap due to thermal carrier generation and crystal expansion. In general, the electronic nonlinearity yields a faster device response than the thermal term. This is because the thermal term depends on heat diffusion which, in most materials, is a much slower process than the electronic component which is determined by the free carrier recombination and diffusion processes. The magnitude of the thermal contribution depends on the rate of energy transfer from the excited electron-hole pairs to the lattice. In impurity and dislocation free material, in which the free carrier lifetime is of the order of several tens of nanoseconds or longer, at moderate input intensities, the magnitude of the thermal component is small compared to the electronic nonlinearity.

According to the Drude model, the imaginary part of the dielectric

constant, $\text{Im}(\epsilon)$ can be represented as

$$\text{Im}(\epsilon) = \frac{e^2 N}{\omega} \left[\frac{(\tau_e)^{-1} m_e^{*-1}}{\omega^2 + (\tau_e)^{-2}} + \frac{(\tau_h)^{-1} m_h^{*-1}}{\omega^2 + (\tau_h)^{-2}} \right] \quad (16)$$

Assuming that both τ_e^{-1} and τ_h^{-1} are less than ω and that $N_e = N_h = N$ the above equation reduces to

$$\text{Im}(\epsilon) = \frac{e^2}{\omega^3} [(\tau_e)^{-1} m_e^{-1} N_e + (\tau_h)^{-1} m_h^{-1} N_h] \quad (17)$$

Substituting equation 7 for ω_p and equating $\epsilon_1 = 2nk$ the following is obtained

$$\Delta k = \frac{e^2}{2n\omega^3} [(\tau_e)^{-1} m_e^{-1} \Delta N_e + (\tau_h)^{-1} m_h^{-1} \Delta N_h] \quad (18)$$

The change in absorption coefficient, $\Delta\alpha$, is equal to

$$\Delta\alpha = \frac{4\pi \Delta k}{\lambda} \quad (19)$$

also

$$\tau_{e/h} = \frac{\mu_{e/h}^* m_{e/h}^*}{e} \quad (20)$$

Substituting equations 19 and 20 into 18 yields,

$$\Delta\alpha = \frac{e^3 \lambda^2}{4\pi^2 c^3 \epsilon_0 n} \left[\frac{\Delta N_e}{m_e^*{}^2 \mu_e} + \frac{\Delta N_h}{m_h^*{}^2 \mu_h} \right] \quad (21)$$

The first and second terms in this equation represent the change in absorption due to electrons, $\Delta\alpha_e$, and holes, $\Delta\alpha_h$, respectively. These changes in absorption, $\Delta\alpha_e$ and $\Delta\alpha_h$, are plotted for various carrier concentrations, along with experimental data gathered by Soref [45], for $\lambda = 1.3\mu\text{m}$, in figures 6(a) and 6(b) respectively.

(a)

(b)

Figure 6. Changes in absorption (a) for electrons (b) for holes at $1.3\mu\text{m}$ [45].

If it is assumed that the electron and hole carrier concentrations, mobilities and masses are equal then equation 21 reduces to

$$\Delta\alpha = \frac{e^3\lambda^2}{2\pi^2c^3\epsilon_0n} \left[\frac{\Delta N}{(m^*)^2\mu} \right] \quad (22)$$

2.3 Growth of $\text{Si}_{1-x}\text{Ge}_x$ Alloy

Preparation of homogeneous bulk $\text{Si}_{1-x}\text{Ge}_x$ alloys was first mentioned by Stohr and Klemm in 1939. However, much of what we know today about the bulk properties of this alloy comes from research conducted on $\text{Si}_{1-x}\text{Ge}_x$ crystals at the RCA Laboratories in the 1950's. These studies were the first to investigate properties such as optical bandgap, energy band structure and absorption coefficients [47,48]. In this early study, electrical characteristics including electrical resistance, electron mobility and magnetoresistance [49,50] were also investigated. Later studies conducted in the 1960's and 1970's investigated the Raman frequency shifts [51] and the electroreflectance [52] properties of these alloys.

In the last 15 years there has been considerable effort expended in studying the growth of amorphous silicon germanium, $a\text{-(Si,Ge):H}$, alloys [53]. Research on amorphous $\text{Si}_{1-x}\text{Ge}_x$ has been of great interest due to its use in the fabrication of multijunction solar cells [53]. An extensive number of studies have also been conducted on epitaxially grown crystalline $\text{Si}_{1-x}\text{Ge}_x$ alloys. Some of the reported growth techniques are chemical vapour deposition (CVD), vacuum vapour epitaxy method [54,55], liquid phase epitaxy (LPE) [56] and molecular beam epitaxy (MBE) [57]. Research on

epitaxially grown $\text{Si}_{1-x}\text{Ge}_x$ has been of considerable interest due to its application in Si optics and microelectronics. MBE growth of $\text{Si}_{1-x}\text{Ge}_x$ on Si was first demonstrated by Bean et al. [57] in 1984. Of all the growth techniques mentioned previously the MBE and CVD are the most suitable for the fabrication of complex optical and electronic devices. The monolayer deposition capability of the MBE makes it ideal for growth of high precision optical and electronic devices in which layer thickness and doping profile is of the utmost importance. Generally, MBE systems have monolayer deposition capabilities and can be used to grow thinner layers than those achievable using CVD systems [58].

Recently there has been a great deal of work on $\text{Si}/\text{Si}_{1-x}\text{Ge}_x$ superlattices[34,59]. Several photoluminescence studies have been reported in the literature on these structures and some of these have been used in the design of $\text{Si}/\text{Si}_{1-x}\text{Ge}_x$ optoelectronic components [34].

Most amorphous $\text{Si}_{1-x}\text{Ge}_x$ materials, which have high dislocation densities, are inappropriate for the fabrication of optoelectronic circuits. The large number of dislocations reduce the free carrier lifetime to such an extent that the thermal nonlinearities greatly exceed the desired optical nonlinearities in these materials. The fabrication of microelectronics requires the use of epitaxially grown, low dislocation density, $\text{Si}_{1-x}\text{Ge}_x$. As mentioned earlier the most suitable methods for microelectronic and optoelectronic device fabrication are the MBE and CVD epitaxial growth techniques.

In thin layers of epitaxially grown $\text{Si}_{1-x}\text{Ge}_x$ alloy, the strain due to the lattice mismatch in the constituent elements can be accommodated by the compression of the $\text{Si}_{1-x}\text{Ge}_x$ crystal lattice. However, when some critical thickness is exceeded the

accumulated strain partially relaxes by forming dislocations within the structure. As the thickness of the $\text{Si}_{1-x}\text{Ge}_x$ alloy increases, more strain builds up thereby leading to an increase in the dislocation density. Transition metals resident in the material find it energetically favourable to congregate around dislocations. These dislocation structures are commonly known as decorated dislocations. Decorated dislocations act as recombination centres and reduce the carrier lifetime in the material. Figure 7 illustrates the critical thickness variation of $\text{Si}_{1-x}\text{Ge}_x$ alloy with growth temperature and composition. At high temperatures (800°C - 900°C) strained structures located in the metastable region of this figure relax forming dislocations. However, structures located within the pseudomorphic region of this figure will remain dislocation free even at high incident temperatures.

Figure 7. Critical thickness data for $\text{Si}_{1-x}\text{Ge}_x$ as a function of the fractional Ge content [60].

In general, thick relaxed layers of epitaxially grown material have two basic types of dislocations known as edge and screw dislocations. In an edge dislocation, shown in figure 8, the slip plane is perpendicular to the dislocation line AB. In a screw dislocation, illustrated in figure 9, the slip plane is parallel to the dislocation line. However, most slip planes contain mixed dislocations which have a combination of both edge and screw characteristics. Misfit and threading dislocations common to relaxed $\text{Si}_{1-x}\text{Ge}_x$ materials are both examples of mixed dislocation structures. Misfit dislocations which propagate in the $[100]$ growth direction form a grid like pattern at heterostructure interfaces. Threading dislocations form at the ends of the misfit dislocations and usually propagate in the $[111]$ direction. An example of a mixed dislocation crystal is illustrated in figure 10 [61]. This crystal has screw and edge characteristics on the facets of the crystal and a mixed orientation in the interior.

Figure 8. Edge dislocation [61]

Figure 9. Screw dislocation [61]

Figure 10 Mixed dislocation[61]

In relaxed $\text{Si}_{1-x}\text{Ge}_x$ alloys the high dislocation densities drastically reduce the free carrier lifetime of the material. In 1991 Fitzgerald demonstrated the MBE growth of a dislocation inhibiting compositionally graded $\text{Si}_{1-x}\text{Ge}_x$ buffer layer [62,63]. Fitzgerald's technique, which entails the growth of a high temperature $\text{Si}_{1-x}\text{Ge}_x$ buffer between the Si substrate and the desired structure, reduces the mismatch and hence the number of misfit dislocations in the graded buffer. This in turn reduces the number of threading dislocations that propagate through the buffer into the desired structure. The high growth temperature also relaxes the strain in the buffer thereby preventing the nucleation of additional dislocations that may have developed at lower growth temperatures.

Impurities resident in the forbidden energy gap of the material can also function as recombination or trapping centres. Trapping centres confine carriers until they gain enough thermal energy, from the lattice, to escape. Shallow traps, found close to either the valence or conduction bands, require less detrapping energy than the deep level traps located near the centre of the forbidden gap. Traps which confine two or more carriers simultaneously can act as recombination centres. Analysis of recombination dynamics reveal that deep level impurities act as better recombination centres than shallow impurities. Studies have shown that Au impurities in Si are located towards the centre of the midgap region and hence act as good recombination centres [64].

When two materials having different bandgaps are brought together they form a heterojunction having one of three possible energy band alignments illustrated in figure 11. In a type I heterostructure the electrons and holes move towards the material

with the smaller bandgap. In a type II heterostructure the electrons move to the material having the smaller E_c while the holes move in the opposite direction. In a type III structure the electrons are unaffected while the holes move to the material having a higher E_v .

Figure 11. Heterostructure bandgap alignments between $\text{Si}_{1-x}\text{Ge}_x$ and Si [40].

Studies conducted by People [42] indicate that strained $\text{Si}_{1-x}\text{Ge}_x$ grown on unstrained Si form a type I heterostructure. Strained Si grown on unstrained $\text{Si}_{1-x}\text{Ge}_x$ form a type II structure. From People's work, illustrated in figure 12, it can be seen that in the $\text{Si}/\text{Si}_{1-x}\text{Ge}_x$ type I heterostructures ΔE_v is much larger than ΔE_c . The relationship between ΔE_c and ΔE_v as a function of the Ge composition is illustrated in figure 13 [65]. Also, it should be noted that this type of band alignment favours the migration of electrons and holes from the Si substrate into the $\text{Si}_{1-x}\text{Ge}_x$ material. This carrier accumulation phenomena has been used in the design of the $\text{Si}/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ PIN electro-optic modulator described in chapter 5.

Figure 12. Type I $\text{Si}_{1-x}\text{Ge}_x$ heterostructure band alignment for $x=0.2$ [42].

Figure 13. Energy offsets in $\text{Si}_{1-x}\text{Ge}_x$ heterostructures [65]

3.0 Theory of Optical Bistability

3.1 Optical bistability

A system is said to be bistable if it has two stable output states, $V_o = L_+$ and $V_o = L_-$, for the same value of input, V_i , over some range of input values, $V_{T1} < V_i < V_{T2}$, as illustrated in figure 14.

Figure 14. Input versus output for a bistable device [66]

Bistability plays an important role in both analogue and digital electronic circuitry. For example bistable devices can be used to eliminate output jitter in most circuitry which may arise due to noise pick up on the inputs. Consider the comparator

and its associated transfer function, illustrated in figure 15. Also assume that changes in the comparator output level are monitored to count the zero crossings of an input signal such that the count is incremented each time the comparator changes state. Then, for the noise free signal depicted in figure 16a the comparator reference voltage, V_R , would be set to zero and the circuit would have little trouble counting the zero crossings. If an input signal, corrupted by noise illustrated in figure 16b, is input to the comparator then it is clearly seen that the output of this device would change several times at each zero crossing thereby giving an erroneous count of the zero crossings. However, if a comparator, having the hysteresis characteristic illustrated in figure 14, is used then the device output only changes once at each zero crossing as long as the noise fluctuations are less than the hysteresis width I_w . Therefore, the use of a bistable comparator gives error free operation even though the input signal is corrupted by noise.

Figure 15. Voltage comparator block diagram and transfer characteristic [66]

Figure 16. (a) Noise free (b) Noise corrupted signals [66]

Another important function for bistability is its ability to provide a memory function. Consider the hysteresis characteristic in figure 14. When the device is in output state L_+ or L_- the input can be set to zero without causing a change in output. The device will stay in this output state as long as $V_{T1} < V_i < V_{T2}$. This memory function is used extensively in set-reset and JK flip flops.

Prior to discussing the phenomenon of optical bistability an analogy will be presented from the more commonly encountered electrical bistability effect, or hysteresis as it is commonly known in the field of electronics, so as to enable the reader to gain a better understanding of the workings and issues related with the bistability effect.

Consider the comparator circuit having input and feedback resistors R_1 and R_2 , respectively, with input and output voltages as indicated in figure 17. The input

versus output voltage characteristics for this circuit is illustrated in figure 14. From nodal analysis it can be seen that

$$V_{T1} = -L_+ \frac{R_1}{R_2} \quad (23)$$

$$V_{T2} = -L_- \frac{R_1}{R_2} \quad (24)$$

where L_- and L_+ are the rail voltages of the device. The arrows on figure 14 illustrate the operation of this circuit. As the input voltage is increased to $V_I > V_{T2}$ the output voltage, V_O , switches from L_- to L_+ following the operation curve ABC indicated in figure 14. When the input voltage is now decreased to a value V_{T1} the output voltage switches from L_+ to L_- following curve CDA. This circuit is said to display bistable behaviour in that it has two stable states L_+ and L_- . These states are joined by a hysteresis loop as illustrated in figure 14. The device can traverse between these states by changing the input voltage monotonically. The circuit can stay in either state indefinitely. This bistable characteristic can be moved to any input voltage by changing the bias of the V_- terminal of the comparator.

Consider the optically bistable device illustrated in figure 18. The input and output are the incident and transmitted beams of light I_i and I_t respectively. At low input intensities the bistable device is highly reflective and has a low transmission. When the input intensity is increased the refractive index or absorption nonlinearity tunes the structure to a high transmission state. In this state the intensity inside the structure is high

such that when the input intensity is decreased the output intensity characteristics of the bistable device follow a different switching characteristic to that followed on switch up. A typical input versus output characteristic for this type of circuit is illustrated in figure 19. In this figure, the input switching thresholds and two stable output levels are given by I_{T1} , I_{T2} and I_{o1} , I_{o2} respectively.

Figure 17. Comparator with hysteresis loop [66]

Figure 18. Optically bistable device with an absorption or refractive index nonlinearity

Figure 19. Variation of transmitted intensity with incident intensity for bistable device of figure 18

Optical bistability has many applications in the field of optical communications and signal processing. The hysteresis characteristics of the bistable devices can be used for pulse shaping, optical limiting, logic operations, differential amplification and optical switching. For optical switching, the hysteresis characteristics can be used to control the reflected and transmitted intensity of an output signal as illustrated in figure 20. The control and input signals are coincident on the optically bistable semiconductor. At low intensities the reflection coefficient is close to one and the output intensity is high. As the intensity of the control signal increases the reflection coefficient decreases thereby reducing the output intensity and giving rise to the desired switching effect. By varying the number and power of the control signals simple AND, OR, NOR and XOR logic gates can be designed using the same technique as outlined for the switching implementation. In fact, such devices have already been demonstrated using GaAs nonlinear Fabry-Perot etalons [67]. Figure 21 illustrates the implementation of a two input NOR gate. Initially, the bistable device is detuned from the input wavelength so that the output from the device is at logic '1'. If either of the control signals are set high then the grating is tuned to the input wavelength and its transmission is reduced, thereby giving a logic '0' at the output. For efficient operation, the frequency of the input signal has to be selected such that the losses in the device are minimal for low intensities of either control signal.

Figure 20. Implementation of an optical switch using an
optically bistable semiconductor device

To obtain effective differential amplification, the hysteresis characteristics have to be modified so that the hysteresis width is zero. Figure 22a and b present the hysteresis characteristic for differential amplification and output waveform obtained for a given input function respectively. As illustrated in figure 22a, a small change in the input about the threshold point, V_t , leads to a large change in the output signal. This characteristic, studied by Gibbs and Mcall [68], also known as the optical transistor mode, has been demonstrated to give AC gains exceeding 2 at a modulating frequency of 1KHz

**Figure 21. Implementation of a two input NOR gate using
an optically bistable semiconductor device**

Optical limiting and pulse shaping are essentially the same characteristic. In both cases, the amplitude of the input is forced to follow the output bistability curve. From figure 23a and b it is seen that any large amplitude fluctuation in the input is 'filtered out' in the output as long the input intensity remains above V_t . For proper optical limiting the top of the hysteresis curve AB should be essentially flat. However, depending on the application this may not be an essential requirement for pulse shaping.

Figure 22a. Variation of transmitted intensity with incident intensity
for differential amplification characteristic

Figure 22b. Input and output waveforms for the differential amplification
characteristic

Figure 23a. Optical limiting and pulse shaping using bistability characteristic

Figure 23b. Input and output waveforms for the limiting and pulse shaping characteristic

For a device to exhibit bistability it must have a nonlinear medium in which the refractive index or absorption changes with incident light intensity as indicated by the following equations.

$$n = n_0 + n_2 I \quad (25)$$

$$\alpha = \alpha_0 + \alpha_2 I \quad (26)$$

Also, the device must have some form of feedback either internal or external to it. The nonlinear medium changes the transmission and reflection of the device as a function of the incident light intensity while the feedback enables this transmission/reflection characteristic to exhibit bistable behaviour.

Over the years different types of optically bistable devices have been demonstrated. Some of these include ring cavities [69], various forms of Fabry-Perot's [68,70], hybrid devices consisting of optical and electronic circuitry [71], self electro-optic effect devices (SEED) [72] and distributed feedback structures [35].

The structures of interest to this body of work, due to their past success in producing high quality bistable devices using planar GaAs/AlGaAs semiconductor technology, are the semiconductor based multilayer Fabry-Perot cavities and distributed feedback (DFB) structures. Also, multilayer FP and DFB structures can be used in two dimensional signal processing applications. A detailed description of each of these devices is given in the following section.

3.1.1 Fabry-Perot Cavities and Distributed Feedback (DFB) Structures

Fabry-Perot cavities have played an important role in the development of bistable devices not only due to their simplicity, which allows for ease of fabrication, but also due to their adaptability which enables them to be fabricated from several different types of material systems.

The basic Fabry-Perot etalon, illustrated in figure 24, consists of a cavity with a feedback mirror on either side. A complete semiconductor implementation of this structure, in which the mirrors are replaced by $\lambda/4$ reflector stacks, is illustrated in figure 25. There are two basic types of Fabry-perot cavities: symmetric and asymmetric cavities. In the symmetric structure the reflectivities of the two mirrors are the same. That is

$$r_f = r_b = r \quad (27)$$

where r_b and r_f are the reflectivities of the front and back mirrors respectively.

Figure 24. Fabry-Perot cavity

For an asymmetric structure

$$r_f \neq r_b \quad (28)$$

Except for this difference the operating characteristics of these two cavities are generally the same.

Figure 25. Semiconductor Fabry-Perot cavity

The transmissivity, T and the reflectivity, R of a linear, symmetric Fabry-Perot cavity are :

$$T = \frac{I(t)}{I(i)} = \frac{1}{1 + F \sin^2 \delta / 2} \quad (17)$$

$$R = \frac{I(r)}{I(i)} = \frac{F \sin^2 \delta / 2}{1 + F \sin^2 \delta / 2} \quad (18)$$

where the finesse, F , and the phase difference for each additional round trip through the cavity, δ , are given by

$$F = \frac{4r^2}{(1 - r^2)^2} \quad (31)$$

$$\delta = \frac{4\pi h n_c}{\lambda_i} \quad (32)$$

In the above equations h is the core thickness, r the reflectivity of the mirrors, n_c the refractive index of the core and λ_i the incident wavelength.

Note that for a lossless Fabry-Perot cavity,

$$T + R = 1 \quad (21)$$

Since the effective wavelength inside the core is

$$\lambda_e = \frac{\lambda_i}{n_c} \quad (34)$$

the resonance condition for a Fabry-Perot cavity occurs when

$$h = \frac{m\lambda_i}{2n_c} = \frac{m\lambda_e}{2} \quad m=1,2,3,\dots \quad (35)$$

and

$$\delta = 2m\pi \quad (36)$$

Therefore, at resonance, the transmission equals one and the reflectivity equals zero for a lossless cavity.

For a given range of frequencies there will be several discrete wavelengths that satisfy the resonance condition. A typical reflectivity versus wavelength characteristic for the Fabry-Perot cavity is illustrated in figure 26. The number of resonance wavelengths over a given frequency range is proportional to the cavity thickness, h . If the incident wavelength, λ_i is increased monotonically, the operating point of the cavity goes through several resonance points. The same effect can be observed if the cavity length, h , is varied over several λ .

Figure 26. Reflectivity versus wavelength for a FP cavity

For a symmetric nonlinear Fabry-Perot, having a cavity with an intensity dependent refractive index, the transmissivity, T and the reflectivity, R are given by

$$T = \frac{I(t)}{I(i)} = \frac{(1-r^2)^2 \gamma}{(1-r^2 \gamma)^2 + 4r^2 \gamma \sin^2 \delta} \quad (37)$$

$$R = \frac{I(r)}{I(i)} = \frac{((1-\gamma)^2 + 4\gamma \sin^2 \delta) r^2}{(1-r^2 \gamma)^2 + 4\gamma r^2 \sin^2 \delta} \quad (38)$$

The loss coefficient, γ , in the nonlinear material is given by

$$\gamma = e^{-\alpha d} \quad (39)$$

where d is the length of the cavity

For a nonlinear Fabry-Perot the change in refractive index, n leads to a variation in the phase traversed in a single pass in the cavity. This can be represented by the following expression

$$\delta = 2\pi(n + \Delta n)\frac{d}{\lambda} = \delta_0 + \frac{2\pi d}{\lambda}\Delta n \quad (40)$$

In the above equation Δn is the intensity dependent change in refractive index.

Eichler [70] has shown the effect of a thermal nonlinearity in producing optical bistability. If it is assumed that the refractive index change, Δn is given by

$$\Delta n d = \beta I_a \quad (41)$$

where β is a constant, and I_a the intensity absorbed in the nonlinear medium is given by

$$I_a = I(i) - I(t) - I(r) \quad (42)$$

Substituting equations 37 and 38 into equation 42 the following is obtained

$$I_a = I(i) \frac{(1 - r^2 \gamma^2 - \gamma(1 - r^2))}{(1 - r^2) \gamma} \quad (43)$$

then the transmitted intensity, $I(t)$ can be represented by

$$I(t) = I(i) \frac{(1-r^2)^2 \gamma}{(1-r^2 \gamma)^2 + 4r^2 \gamma \sin^2 \left(\delta_0 + \frac{2\pi}{\lambda} \beta I(t) \frac{(1-r^2 \gamma^2 - \gamma(1-r^2))}{(1-r^2) \gamma} \right)} \quad (44)$$

Eichler has computed this equation, illustrated in figure 27, for $R=0.32$, $\gamma=0.58$, $\lambda=1.06\mu\text{m}$, and $d=0.5\text{mm}$. As the output intensity, I , is a multivalued function of the input, I_0 , the input intensity was calculated as a function of the output intensity and then the axes were inverted to obtain the plot illustrated in figure 27. Both the input and output intensities have been normalized with respect to I_{norm} which is given by

$$I_{\text{norm}} = \frac{2}{\lambda} \beta \frac{(1-R\gamma^2 - \gamma(1-R))}{(1-R)\gamma} I(t) \quad (45)$$

Figure 27. Input versus output characteristics for a bistable thermal nonlinearity in a Fabry Perot cavity [70]

The dashed multivalued input-output curve is a characteristic of a nonlinear Fabry-Perot structure. The solid curve indicates the practical input versus output relationship for increasing input intensities.

A similar bistability characteristic can also be observed if either of the Fabry-Perot feedback mirrors are made of a nonlinear material. In such a device, the incident light detunes the nonlinear mirror thereby changing its transmission and reflection properties. If the dimensions of the mirror are selected such that the operating point of the device passes through a reflection dip or a transmission peak then the input-output characteristics of the device will display bistable behaviour.

Over the years distributed feedback (DFB) structures have been implemented using a variety of architectures. Another bistable device which can be implemented using semiconductor materials is the DFB structure illustrated in figure 28. First proposed by Winful [73,74] in 1979, this design combines the feedback mechanism with the nonlinear medium of the device. Each mode propagating in the waveguide has an effective refractive index associated with it. The effective index, defined as ,

$$N_{eff} = \frac{\beta}{k} \quad (46)$$

is directly related to the thickness of the waveguiding layer above cutoff. When a guided optical mode travels past an abrupt guiding layer thickness variation the effective refractive index of the mode changes at this abrupt junction and this in turn leads to the formation of several diffracted, transmitted and reflected modes. For this design, the optical feedback is obtained through the periodic variation of the guiding layer thickness

which causes a similar variation in the effective index along the length of the device. If the thickness variation has a periodicity of $\lambda/2$ then the waves reflected from each refractive index perturbation add in phase and this leads to the creation of two counter propagating waves within the structure. The electric field $E(z,t)$ within the medium is a sum of these two waves.

$$E(z,t) = A_F(z)e^{i(\beta z - \omega t)} + A_B(z)e^{-i(\beta z + \omega t)} \quad (47)$$

where the complex amplitudes $A_F(z)$ and $A_B(z)$ are assumed to vary little within an optical wavelength.

The incorporation of the feedback mechanism with the nonlinear material eliminates the need for external feedback structures and in general leads to a more compact design. In a planar semiconductor implementation, illustrated in figure 29, the refractive index variation can be implemented by means of a periodic change in the grating composition on an one dimensional waveguide [75] or a two dimensional multilayer stack structure [35]. If the switching threshold of a multilayer DFB is compared with that of an equal thickness FP, implemented using similar alloys, it is seen that the DFB has a lower switching threshold due to greater device feedback. The multilayer stack design is of particular interest as it corresponds to the design implemented in this work.

Figure 28. Distributed feedback structure (DFB) [76]

Figure 29a. Waveguide implementation of a DFB structure

Figure 29b. Multilayer stack implementation of a DFB structure

Using coupled-wave mode theory Winful [76] analyzed the operation of the distributed feedback structure (DFB) of length L , having a sinusoidally varying refractive index described by

$$n(z) = n_0 + n_1 \cos 2\beta_0 z \quad (48)$$

In this model $n_0 \gg n_1$ and β_0 is the propagation constant at the designed Bragg frequency. The polarization density due to a single monochromatic beam of field strength E is given by

$$p = \frac{1}{4\pi}(n^2(z)-1)E + \frac{1}{4\pi}n_0n_2|E|^2E \quad (49)$$

where n_2 is the nonlinear intensity dependent refractive index.

Using Maxwell's equation

$$c^2 \frac{\delta^2 E}{\delta z^2} = \frac{\delta^2 (E + 4\pi p)}{\delta t^2} \quad (50)$$

and substituting equations 48 and 49 into 50 the following is obtained

$$\frac{\delta^2 E}{\delta z^2} + [\beta^2 + 4\beta k \cos 2\beta_0 z]E = -\gamma \beta |E|^2 E \quad (51)$$

The coupling constant, k which determines the interaction between the forward and reverse electric fields, the wavenumber, β , and the nonlinearity constant, γ , are given by

$$k = \frac{\pi n_1}{\lambda_0} \quad (52)$$

$$\beta = \frac{n_0 \omega}{c} \quad (53)$$

$$\gamma = \frac{\pi n_2}{\lambda_0} \quad (54)$$

Substituting equation 47 into 51, invoking the slowly varying amplitude approximation ($|\delta^2 A / \delta z^2| \ll |\beta \delta A / \delta z|$) and comparing terms with equal exponentials, the following coupled wave equations are obtained

$$-i \frac{\delta A_F}{\delta z} = k A_B e^{-2i\Delta\beta z} + \gamma(|A_F|^2 + 2|A_B|^2) A_F \quad (55)$$

$$i \frac{\delta A_B}{\delta z} = k A_F e^{2i\Delta\beta z} + \gamma(|A_B|^2 + 2|A_F|^2) A_B \quad (56)$$

where $\Delta\beta = \beta - \beta_0$. β is the propagation constant. A_F and A_B are the complex amplitudes of the forward and backward propagating waves respectively.

These equations describe the wave propagation in a periodic structure having an intensity dependent refractive index. The physical interpretation of these equations is that each wave (A_F and A_B) grows in amplitude as it propagates. However, each falls out of phase synchronism due to the detuning $\Delta\beta$. The effect of the intensity dependent terms is to cause an additional phase change of the two waves with respect to one another.

Equations 55 and 56 can be solved by the method outlined below. The complex amplitudes A_F and A_B are written as

$$A_F = |A_F| \exp^{i\phi_F} \quad (57)$$

$$A_B = |A_B| \exp^{i\phi_B} \quad (58)$$

Substituting equations 57 and 58 into equations 55 and 56 and equating the real and imaginary parts leads to the following constants.

$$|A_F|^2 - |A_B|^2 = |A_T|^2 = \text{constant} \quad (59)$$

where $|A_T|$ is the transmitted flux and

$$\Gamma = |A_F| |A_B| \cos\theta + (2\Delta\beta - 3\gamma |A_T|^2) \frac{|A_F|^2}{2k} + 3\gamma \frac{|A_F|^4}{2k} \quad (60)$$

The forward flux, y , within the structure of length, L , is given as

$$\left(\frac{1}{2} \frac{\delta y}{\delta(z/L)}\right)^2 = (y - J)[(kL)^2 y - (y - J)(\Delta\beta L - 2y)^2] = Q(y) \quad (61)$$

where

$$y = \frac{|A_F|^2}{|A_C|^2} \quad (62)$$

$$|A_c|^2 = \frac{4n_0\lambda}{3\pi n_2 L} \quad (63)$$

$$J = \frac{|A_T|^2}{|A_c|^2} \quad (64)$$

This equation can be integrated to yield the relationship between the incident, I and transmitted, J intensities given below

$$I = y_3(J) + \frac{y_3(J) - y_2(J)}{\left(\frac{y_1(J) - y_2(J)}{y_1(J) - y_3(J)} \right) \text{sn}^2(u/m) - 1} \quad (65)$$

Where $y_1 > y_2 > y_3 > y_4$ are the roots of $Q(y)$ and $\text{sn}(u/m)$ is the Jacobian elliptic function with argument

$$u = [(y_1 - y_3)(y_2 - y_4)]^{1/2} \quad (66)$$

and modulus

$$m = \frac{(y_1 - y_2)(y_3 - y_4)}{(y_1 - y_3)(y_2 - y_4)} \quad (67)$$

Equation 65 can be evaluated numerically for any value of kL and $\Delta\beta L$. Figure 30 gives the bistability curves for $kL=2.0$ and $\Delta\beta L=-2, 0, 1.5$.

Figure 30. Bistability curves from Winful's equations [76]

Using the analysis outlined in reference [76] Winful showed that for a DBF structure to display bistability the product of the coupling constant, k , and device length, L , had to be greater than 2, $kL > 2$ for $\Delta\beta L = 0$. Using these equations Winful calculated the switch ON and OFF thresholds as a function of kL and $\Delta\beta L$ and obtained the curve presented in figure 31. From this curve it can be seen that the switch ON threshold increases with increasing kL and decreases with increasing $\Delta\beta L$.

The periodicity of the DFB grating, Λ , is described by

$$\Lambda = \frac{\lambda_0}{2n_0} \quad (68)$$

For a periodic square wave structure in which alternating layers are $\Lambda/2$ thick, such as the multilayer DFB design implemented in this thesis, n_1 can be approximated

Figure 31 Switching thresholds for a DFB structure
as a function of kl and $\Delta\beta l$

by

$$n_1 = \frac{2\Delta n}{\pi} \quad (69)$$

Where Δn is the refractive index difference between adjacent layers.

Therefore the coupling constant is equal to

$$k = \frac{2\Delta n}{\lambda_0} \quad (70)$$

Using Winful's equations a multilayer DFB structure was designed using the Si/Si_{1-x}Ge_x material system.

When designing a Si/Si_{1-x}Ge_x DFB multilayer structure it is seen from equation 70 that to maximize the coupling constant, k , a large refractive index difference, Δn , between adjacent Si and Si_{1-x}Ge_x layers is required. The refractive index of Si is fixed for a given wavelength of operation. However, the refractive index of Si_{1-x}Ge_x is proportional to the Ge content in the alloy. Nevertheless, its critical thickness varies inversely with the Ge content. Therefore, when selecting an appropriate Si_{1-x}Ge_x alloy composition a compromise has to be reached between the critical thickness and the refractive index of the alloy. For this design Si_{0.7}Ge_{0.3} was seen to offer the appropriate compromise. The operating wavelength of this structure was selected from the commercially available laser outputs such that the photon energy is below the bandgap for Si but above that of Si_{1-x}Ge_x alloy. This would enable the light to pass directly through the Si with very little absorption and hence enable the device to be tested in both transmission and reflection. The wavelength selected for this design was $\lambda = 1.06\mu\text{m}$.

The refractive indices of Si and Si_{1-x}Ge_x at $1.06\mu\text{m}$ are 3.54 and 3.78 respectively. The average index, n_a , of the multilayer structure is given by

$$n_a = [(1-r)n_{\text{Si}}^2 + rn_{\text{SiGe}}^2]^{1/2} \quad (71)$$

where r is given by

$$r = \frac{t_{\text{SiGe}}}{t_{\text{SiGe}} + t_{\text{Si}}} \quad (72)$$

and t_{SiGe} and t_{Si} are the thicknesses of the $\text{Si}_{1-x}\text{Ge}_x$ and Si layers respectively.

For this design, in which the thicknesses of the Si and $\text{Si}_{1-x}\text{Ge}_x$ are equal to half the layer periodicity, we have $r=0.5$ and $n_s=3.66$. The refractive index difference between alternate layers, Δn , is 0.24 and the amplitude of the fundamental, n_1 is 0.153. The coupling factor, k , equals $4.53 \times 10^5 \text{m}^{-1}$.

Winful has shown that bistability occurs for kL greater than 2.0. However, to account for any minor deviations that might occur in the specified design during fabrication this structure was designed for kL equal to 3.0. Therefore $L=6.63 \mu\text{m}$ and the Bragg period $\Lambda=145\text{nm}$. Thus the total number of periods, TP, in the structure equals 46 (i.e 92 layers).

When deriving the above equations Winful assumes that the envelope of the intensity profile changes slowly across the length of the structure (slowly varying envelope approximation) and also that in the vicinity of the Bragg frequency the higher order diffraction terms are negligible. Furthermore, Winful develops his equations based on the Kerr effect. Therefore, his equations do not account for the diffusion and recombination behaviour of free carriers generated in the nonlinear media which are of great importance in the structures analyzed in this thesis.

To analyze the behaviour of any general multilayer structure a numerical model based on a multilayer matrix method [77] was implemented. This model is described in the next section.

3.1.2 Numerical Modelling

This model was developed to calculate the input versus output intensity characteristics of any general multilayer structure. It is assumed that the multilayers are of sufficient quality such that only the refractive index changes due to the fast electronic term, outlined in section 2.1, are of significance.

A rigorous model of any optically excited material has to account for carrier lifetime, carrier diffusion and lattice temperature profile dynamics in the entire structure. The usual method of analysis involves the incorporation of all the aforementioned effects into several coupled differential equations which are solved using the method of finite differences [78]. The approximate algorithm described in this section accounts for carrier lifetime through the electronic term of equation 15. In this model the carrier lifetime is assumed to be 10ns [79]. Carrier diffusion is assumed to occur normal to the structure such that the carrier density in all layers is equal. As the lateral diffusion of carriers is neglected this approximate model generally overestimates the carrier concentration in the multilayer structure. Therefore, the simulation results will be slightly different from those derived from an exact model. However, the general shape of the input-output characteristics obtained from this model should be similar to those obtained from the exact algorithm.

This model uses a multilayer matrix method [77] to calculate the input versus output intensity characteristics of any general multilayer structure. In this method, each layer is described by a transfer matrix containing the transmission and reflection coefficients, and also by a phase shift matrix which describes the phase shift of a wave

travelling in that layer. To find the output field of the multilayer structure, the input field is multiplied by individual transfer and phase matrices of each layer. For example to determine the input field at layer 3, in which layer 2 has a thickness equal to D , the input field, $e_1(0)$ has to be multiplied by the transfer matrices M_{32} and M_{21} and by the phase matrix M_2 . Therefore, the output field given by $e_3(D)$ is equal to

$$e_3(D) = M_{32}M_2M_{21}e_1(0)$$

The input field $e_i(z)$ is given by

$$e_i(z) = \begin{vmatrix} \exp(iw_z z) \\ \exp(-iw_z z) \end{vmatrix} \quad (73)$$

The transfer matrix M_{ij} has the general form

$$M_{ij} = \frac{1}{t_{ij}} \begin{vmatrix} 1 & r_{ij} \\ -r_{ij} & 1 \end{vmatrix} \quad (74)$$

where the transmission and reflection coefficients between medium i and j are given by r_{ij} and t_{ij} for TM polarized light and r_{ij} and t_{ij} for TE polarized light respectively

$$r_{ij}^p = \frac{w_i \varepsilon_j - w_j \varepsilon_i}{w_i \varepsilon_j + w_j \varepsilon_i} \quad (75)$$

$$t_{ij}^p = \frac{2n_i n_j w_i}{w_i \varepsilon_j + w_j \varepsilon_i} \quad (76)$$

$$r_{ij}^s = \frac{w_i - w_j}{w_i + w_j} \quad (77)$$

$$t_{ij}^s = \frac{2w_i}{w_i + w_j} \quad (78)$$

Where ω is the wave vector perpendicular to the multilayer structure and is given by

$$\omega = [k^2 - k_0^2]^{1/2} \quad (79)$$

k is the wave vector in the direction of propagation and k_0 is the wave vector parallel to the multilayer structure.

The phase shift matrix $M_i(z)$ is given by

$$\begin{vmatrix} e^{(i\omega z)} & 0 \\ 0 & e^{(-i\omega z)} \end{vmatrix} \quad (80)$$

As the bistability curve is multivalued for certain input intensities this

numerical algorithm was seen to have difficulty converging to a solution at these points. Therefore, to avoid this problem, the input intensity was calculated for monotonically increasing values of output intensity for which the bistable curve is single valued. For a given output intensity this program selects an arbitrary device input intensity and determines the transmitted and reflected intensities in each individual layer and also the transmitted output intensity of the structure. It then calculates a correction factor based on the difference between the desired and calculated transmitted intensities. This correction factor is then used to modify the input intensity. Using the modified input intensities and the electronic portion of equation 15, the appropriate changes to the refractive indices, Δn , are calculated for all the nonlinear layers. The corrected device input intensity and the modified refractive indices are then used to recalculate the output intensity. This process is repeated until the calculation converges to an equilibrium input intensity corresponding to the required output value. Using this algorithm, illustrated in figure 32, the input versus output intensity for a given structure is calculated. The multilayer algorithm, used to calculate the input versus output intensities of any general multilayer structure, was implemented by S. Janz [80]. The bistability algorithm, used to calculate the bistable behaviour of these multilayer devices, was implemented by the author. This model was then used to analyze the DFB structure designed in this thesis. The results obtained from this model are presented in section 4.1.

Figure 32. Multilayer algorithm

3.1.3 Modelling of DFB Multilayer Structures

For a DFB structure to function effectively as an optically bistable device it must have a reflectivity versus wavelength characteristic similar to that shown in figure 33. The finesse of the reflectivity characteristic depends not only on the total number of layers in the structure but also on the refractive index difference, Δn , between alternate layers. At low incident intensities the device operating point should be located to the left (such as point A on figure 33) of the reflection minimum. When the incident intensity increases the characteristic should sweep to the left past the operating point such that the minimum reflection point is now on the left. This large change in reflection leads to the desired bistable behaviour illustrated in figure 34. The "S" like shape of the bistability characteristic is due to a mathematical artifact. In reality, all points between C and D are unstable points of operation and are physically unrealizable[76]. Therefore the output intensity is described by curves ABCEF and FEDBA for monotonically increasing and decreasing values of incident intensity respectively.

Figure 33. Reflectivity response as a function of wavelength

Figure 34. Bistability characteristic for a nonlinear DFB structure

Using the multilayer model, described in section 3.1.2, the relationship between the switch ON threshold, I_s , and the hysteresis width, H_w , were observed for several multilayer stack thicknesses as a function of $\Delta\beta = \beta_0 - \beta$. The observed results are summarized in figures 35 and 36 which present the I_s and H_w as a function of the multilayer detuning, $\Delta\beta$. The detuning of the multilayer structure can be selected by varying the thickness of the Si/Si_{1-x}Ge_x layers. As can be seen from these figures both I_s and H_w decrease with $\Delta\beta$. In this analysis the maximum number of layers in a given design was limited to a value of between 90-100 layers. This upper limit is set by the growth time on the MBE machine which is usually limited to a maximum of 6 to 6.5 hours. From a design point of view one wants to maximize the number of multilayers as this minimizes I_s and maximizes H_w for a given detuning. Therefore, for this design the multilayer stack number, determined by the maximum growth time on the MBE, was chosen to be 92 layers.

Figure 35. Switch ON threshold as a function of $\Delta\beta$ for
92, 64 and 50 layer Si/Si_{0.7}Ge_{0.3} stacks

Figure 36. Hysteresis Width as a function of $\Delta\beta$ for
92, 64 and 50 layer Si/Si_{0.7}Ge_{0.3} stacks

The compositional dependence of the Si/Si_{1-x}Ge_x multilayer structures was also analyzed as a function of $\Delta\beta$ for 92 layer stacks with Ge compositions in the range $0.2 \leq x \leq 0.45$. Figures 37 and 38 present the switch ON threshold and the hysteresis width results from this analysis. From these figures it can be seen that both I_s and Hw decrease with decreasing Ge content for $x \geq 0.3$. For Ge contents below 0.3 the switch ON threshold increases. The I_s is determined by several factors such as the absorption of light inside the structure and the refractive index difference, Δn , between the Si and Si_{1-x}Ge_x layers. The Hw is determined by the feedback of the structure. Higher the feedback the larger the hysteresis width of the device. Also, higher the Δn , the larger the reflectivity of the stack for a given $\Delta\beta$. It is seen from figure 38 that for low values of $\Delta\beta$ the I_s for the Si/Si_{1-x}Ge_x designs, having Ge compositions ranging from $0.3 \leq x \leq 0.4$, are nearly equal. This convergence in I_s is due to the fact that in this range of Ge composition the decrease I_s that should occur due to the decrease in Δn is offset by the decrease in optical absorption in the Si_{1-x}Ge_x layers. At higher values of $\Delta\beta$ the higher Ge composition structures display higher values of I_s and Hw than the lower composition designs. This is because for a given $\Delta\beta$ the reflectivity of the lower Ge designs reduce more than that for the higher composition structures [76]. This enables more light to enter and detune the lower composition structures thereby enabling them to switch at a lower intensity than a higher composition designs.

For low Ge composition structures, $x \leq 0.25$, the decrease in absorption outweighs the smaller refractive index difference, Δn . Therefore, I_s increases with decreasing Ge composition for a given $\Delta\beta$. As the Δn in these lower Ge content devices

is quite small, the multilayer stack reflectivity, and hence, I_s decreases rather rapidly with $\Delta\beta$. The device feedback and hence the hysteresis width is seen to decrease with both the Ge composition and $\Delta\beta$.

Figure 37. Switch ON threshold as a function of Ge composition

Figure 38. Hysteresis width as a function of Ge composition

When selecting a Ge composition for a Si/Si_{1-x}Ge_x stack there is a tradeoff that has to be made between hysteresis width and the switching threshold. From a device point of view a large hysteresis width is desirable as this gives a better contrast between ON/OFF states and also better noise immunity. However, a higher switching threshold means that a greater input intensity has to be used to observe the hysteresis characteristic. For small Ge concentrations, $x \leq 0.25$, the hysteresis width is quite small and is nonexistent for several values of $\Delta\beta$. Also, from a growth point of view the lattice mismatch between the Si and Si_{1-x}Ge_x alloys and hence the device dislocation density increases with increasing Ge content. As mentioned in section 2.3 dislocation act as recombination centres and reduce the carrier lifetime in the material thereby reducing the magnitude of the optical effect at a given input intensity. From figure 37 it is seen that a Ge composition of 0.3 has lowest overall switching threshold for all values of $\Delta\beta$. For this design a reasonable compromise between I_s , Hw and device dislocation density was offered by a 92 layer Si/Si_{0.7}Ge_{0.3} multilayer stack. This design is seen to correspond to the Winful structure designed in section 3.1.1. Simulations indicate that a 92 layer Si/Si_{0.7}Ge_{0.3} stack yields a hysteresis width ranging from 3% to 48% for switching thresholds between 2 to $6 \times 10^{12} \text{ W/m}^2$. Figures 39 and 40 present the bistability transmission characteristics for the 92 layer Si/Si_{0.7}Ge_{0.3} stack at a $\Delta\beta$ of $0.06 \mu\text{m}^{-1}$ and $0.09 \mu\text{m}^{-1}$ respectively.

The implementation of the 92 layer Si/Si_{0.7}Ge_{0.3} DFB multilayer structure is outlined in chapter 4.

Figure 39. Transmission characteristic for a 92 layer Si/Si_{0.7}Ge_{0.3}
DFB structure at $\Delta\beta=0.06\mu\text{m}^{-1}$

Figure 40. Transmission characteristic for a 92 layer Si/Si_{0.7}Ge_{0.3}
DFB structure at a $\Delta\beta=0.09\mu\text{m}^{-1}$

4.0 Implementation and Testing of Bistable Structures

This chapter is divided into three sections. The first section describes the implementation and testing of a $\text{Si}_{1-x}\text{Ge}_x$ DFB multilayer stack designed using Winful's design equations. This section also presents results obtained on the high temperature growth of SiGe multilayers on graded buffers. The second section describes the optical pump-probe measuring technique and the measurement of the free carrier lifetime in MBE grown Si/ $\text{Si}_{1-x}\text{Ge}_x$ multilayers. The third section summarizes the important performance characteristics of the Si/ $\text{Si}_{1-x}\text{Ge}_x$ DFB structure.

4.1 Implementation of a DFB Multilayer Structure

The DFB Multilayer design was grown on a Si wafer using the MBE growth technique. As the thickness accuracy of the MBE machine deviates up to 10% from the desired values, the Si/ $\text{Si}_{1-x}\text{Ge}_x$ multilayer thicknesses and the $\text{Si}_{1-x}\text{Ge}_x$ alloy composition were graded across the diameter of the wafer to ensure that one portion of the wafer would have the required dimensions. Grading was achieved by keeping the wafer stationary during growth. A transmission electron micrograph (TEM) analysis conducted on the wafer after growth revealed an area approximately 0.5cm to the left of the centre to have the required dimensions. A cross sectional TEM analysis also showed that the dislocation count was approximately $10^8/\text{cm}^2$ and $10^9/\text{cm}^2$ in the Si and Ge rich areas respectively. A high dislocation density was expected as the total $\text{Si}_{0.7}\text{Ge}_{0.3}$ alloy thickness of $3.31\mu\text{m}$ was far in excess of the $700\text{\AA}$ critical thickness of $\text{Si}_{0.7}\text{Ge}_{0.3}$ alloy.

The variation in dislocation density across the width of the sample was due to the increase in Ge concentration which increased the mismatch and, hence, the number of dislocations in the relaxed structure. The reflectivity measurements conducted at $\lambda=1.06\mu\text{m}$ indicated the presence of a 80% reflectivity peak in the region having the desired structure. The measured reflectivity response is illustrated in figure 41.

Figure 41. Reflectivity response as a function of wavelength

Pump-probe measurements conducted using a pulsed, 25ns pulse width, $\lambda=0.53\mu\text{m}$ pump and a CW, $\lambda=1.06\mu\text{m}$ probe are depicted in figure 42. $1.06\mu\text{m}$ and $0.53\mu\text{m}$ notch filters were placed in front of the laser outputs to remove any $1.06\mu\text{m}$ and $0.53\mu\text{m}$ light from the pump and probe beams respectively. The high intensity $\lambda=0.53\mu\text{m}$ pump excited free carriers in the material which caused a reflectivity change at the $\lambda=1.06\mu\text{m}$ probe wavelength. The two beams coincident on the sample were spatially separated to facilitate

the spatial isolation of the reflected beams. A low intensity reference from the pump and the reflected probe beams were monitored on photodetectors #1 and #2 respectively. The results of these observations revealed that the peak switching characteristic was, as expected, proportional to the slope of the reflectivity response.

Figure 42. 0.53/1.06μm Pump-probe measurement setup

2

PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISIONSM RESOLUTION TARGETS

By observing the reflectivity change on either side of the reflectivity peak, illustrated in figure 41, both positive and negative switching effects were observed. The maximum switch up (maximum increase in reflection) and switch down (maximum decrease in reflection) characteristics observed for this sample are depicted in figures 43 and 44 respectively. For this test the $\lambda=0.53\mu\text{m}$ laser output was focused to a 0.2mm diameter spot size on the sample. Room temperature measurements on various $\text{Si}_{1-x}\text{Ge}_x$ materials have shown the recombination lifetimes to be no greater than several microseconds[81]. Therefore the slow 10-15 μs recovery time constants associated with these responses can only be attributed to the presence of a thermal switching effect. Also, by analyzing the thickness grading profile of the DBR and the reflectivity responses from the wafer it was determined that the observed switching characteristics were due to a positive change in refractive index. Equation 15 in section 2.2, confirms that a positive perturbation in refractive index can only be due to the presence of a thermal nonlinearity.

Figure 43. 1.06 μm CW increase reflectivity response(bottom curve) of sample #1300 when excited with a 0.53 μm , 25ns probe pulse (top curve)

Figure 44. $1.06\mu\text{m}$ CW decrease reflectivity response(bottom curve) of sample #1300 when excited with a $0.53\mu\text{m}$, 25ns probe pulse (top curve)

Further testing of sample #1300 using a single $\lambda = 1.06\mu\text{m}$ pulsed laser illustrated the switching effect very clearly. In this experiment, illustrated in figure 45, the laser output was focused to a spot diameter of $35\mu\text{m}$ and power flux of $1.8 \times 10^6 \text{ W/cm}^2$ at the surface of the sample. The pulsed laser output served as both a pump and probe beam. The incident and reflected signals were monitored on photodetectors #1 and #2 respectively.

Figure 45. $\lambda = 1.06\mu\text{m}$ probe setup

The measured switch up and switch down change in relative reflectivity, $\Delta R/R$ obtained from these tests are presented in figure 46. In this figure, R is the multilayer reflectivity prior to switching and $\Delta R = R' - R$, where R' is the multilayer reflectivity during switching. Due to the reduction in spot size the fall time constant associated with the switching response is much shorter than in the previous $\lambda = 0.53/1.06\mu\text{m}$ pump-probe test. The decrease in spot size allows the heat generated by the laser to diffuse faster from the illuminated area thereby reducing the switching time constants of the device. Using the heat flow equation [82], the peak lattice temperature at the multilayer surface was calculated to be 710°C . Note the positive and negative $\Delta R/R$ switching characteristics illustrated in this figure were observed at different spots on the wafer. Also, from this figure it can be seen that there is a 250ns delay between the input optical

pulse and the switching characteristics. This delay is due to fact that in the first 250ns the refractive index change due to the thermal and optical components cancel giving no noticeable change in reflectivity.

Figure 46. $\Delta R/R$ as a function of time for different spots on sample #1300

The magnitude of the electronic and thermal nonlinearities are largely dependent on the free carrier lifetime in the material. If this lifetime is longer than the incident laser pulse width then the carrier density can build up during the length of the pulse resulting in a large electronic nonlinearity for nanosecond pulse widths. If the free carrier lifetime is of the order of several hundred picoseconds while the illuminating pulse has a length of several nanoseconds, then the optically generated carriers recombine almost instantaneously resulting in a very small carrier concentration and hence a small

electronic nonlinearity in the material. The carrier diffusion length is proportional to the free carrier lifetime and the magnitude of the thermal component, in the illuminated area varies inversely with the free carrier lifetime. Therefore, materials with short lifetimes would have larger thermal component than those with longer lifetimes.

It is thought that the desired bistability characteristics were not observed in this sample due to the presence of a large number of decorated dislocations which caused the premature nonradiative recombination of electron-hole pairs excited by the incident light. Fast recombination reduces the free carrier lifetime and therefore the magnitude of the electronic nonlinearity in the material. The energy emitted by the nonradiative recombination heats the crystal lattice, and changes its refractive index giving the observed change in reflection. After several microseconds the heat diffuses away from the illuminated area allowing the refractive index and hence the reflectivity to return to their original values.

To reduce the dislocation density in the multilayer structure several samples were grown using the buffer layer approach outlined by Fitzgerald[62]. In all, four samples, each testing a different growth aspect of the buffer layers, were implemented. Sample 1, grown on a Si substrate, was composed of a 6 layer, 700Å per layer, Si/Si_{0.7}Ge_{0.3} multilayer stack. Samples 2 and 3, similar in structure to sample 1, each had a compositionally graded buffer layer inserted between the Si substrate and the multilayer stack. The composition of these buffer layers was graded from pure Si at the substrate to Si_{0.85}Ge_{0.15} at the buffer-multilayer interface. The arbitrarily chosen Ge grading rates of the buffers were 25% μm^{-1} and 10% μm^{-1} giving a total buffer thickness

of $0.60\mu\text{m}$ and $1.5\mu\text{m}$ for sample 2 and sample 3 respectively. The function of the buffer layers was not only to reduce the lattice mismatch between the substrate and multilayers, but the end composition of $\text{Si}_{0.85}\text{Ge}_{0.15}$ was also chosen to symmetrize the opposite strains applied by the Si and $\text{Si}_{0.7}\text{Ge}_{0.3}$ layers. Strain symmetry minimizes misfit dislocations from forming at the $\text{Si}/\text{Si}_{0.7}\text{Ge}_{0.3}$ interfaces thereby reducing the overall dislocation density throughout the entire structure[83]. Sample 4 was similar to samples 2 and 3 except that the multilayer stack was replaced with a homogenous $\text{Si}_{0.85}\text{Ge}_{0.15}$ layer of equivalent thickness.

A TEM analysis of samples 1, 2 and 3 revealed large numbers (i.e 10^8 - 10^9 cm^{-3}) of threading and misfit dislocations at the $\text{Si}/\text{Si}_{0.7}\text{Ge}_{0.3}$ interfaces. These results, expected for sample 1 in which no buffer layer was grown, indicate an absence of strain symmetrization in samples 2 and 3. This is most likely due to a problem with the buffer layer composition at the buffer-multilayer interface and/or too fast a compositional gradient of the buffer during growth. Some researchers terminate the growth of the buffer with a constant composition layer[84]. This in effect gives an equistrain pedestal on which subsequent growth can be conducted. The merit of this pedestal, which adds to the overall thickness and growing time of the structure, are not fully understood as yet.

A TEM profile of sample 4 revealed very few misfit dislocations and approximately $2.5 \times 10^6/\text{cm}^2$ threading dislocations at the top of the homogeneous layer. To evaluate the threading dislocation density only in the top portion of the crystal it was necessary to remove some material from the back of the wafer. This leaves an open

surface through which dislocations can relieve their strain and subsequently disappear. Therefore, the dislocation count obtained using this method may be slightly lower than that present in the strained crystal.

In summary, samples 1, 2 and 3 had dislocation densities of approximately 10^8 to 10^9 cm^{-2} while sample 4 had a density of about $2.5 \times 10^6/\text{cm}^2$. The smaller dislocation density in sample 4 compared to those in the other samples confirms the dislocation reduction capabilities of Fitzgerald's technique. However, the presence of a large number of dislocations in samples 2 and 3 indicate a lack of strain symmetrization in these structures which is most likely due to incorrect buffer layer compositions at the buffer-multilayer interface.

4.2 Lifetime Measurement Theory and Results

From equation 15 in section 2.2 it can be seen that the change in refractive index, Δn is directly proportional to the lifetime of the free carriers, τ_R . Therefore, the intensity required for bistable switching decreases with increasing τ_R . If the free carrier lifetime is very small, then the input intensity required to induce bistability may heat the material to temperatures in excess of its melting threshold. Thus from a device point of view, an accurate knowledge of τ_R is essential for the proper design of devices in a given material.

Several optical and electrical techniques are currently available to measure the electron lifetime in a material. The time resolution of each technique depends on the time response of the measurement system as well as on the duration of the optical or

electrical pulse used to excite the material. In this work, the pump-probe method, owing to its high time resolution and simplicity, was used to determine the free carrier lifetime in the $\text{Si}_{1-x}\text{Ge}_x$ alloy. The pump-probe method has been used by researchers for many years to examine the carrier densities and lattice-plasma temperature characteristics in several materials [85,86]. This technique involves the excitation of carriers in the test sample by a high intensity, picosecond, above bandgap pump beam and the monitoring of the transmission or reflection change by a low intensity below bandgap probe. To simplify the experimental apparatus, a delayed low intensity replica of the pump beam can be used for the probe. This eliminates the need for two lasers and any associated synchronization circuitry. The setup used for this measurement is illustrated in figure 47. To ensure the probe beam does not excite many carriers in the sample, it is attenuated to 2% of the pump power. To suppress interference between the pump and probe beams their polarizations are set orthogonal to one another. Furthermore, the two beams are spatially separated with the pump and probe incident from either side of the sample normal. The probe beam is split into two and one output serves as a reference while the other is incident on the sample. The pump is chopped at a frequency of 1KHz prior to illuminating the sample. Using a lock-in amplifier the changes in reflection, ΔR , are measured from the reflectivity difference between the reference and reflected probe signals. This setup enables the change in reflectivity, ΔR , to be determined for all time delays between the pump and probe pulses. Using similar apparatus researchers have been able to detect reflectivity changes down to 1 part in 10^6 [87].

Figure 47. Pump-probe apparatus

The optical excitation of a material with an above bandgap source generates an electron-hole plasma which alters the reflectivity and transmission of the illuminated area. The change in refractive index, n , can be estimated using the Drude model presented in section 2.2.

For high levels of excitation where the carrier density is larger than $10^{21}/\text{cm}^3$, ω_p exceeds ω (for wavelengths greater than $1.0\mu\text{m}$ in Si) and n becomes imaginary causing a large increase in the reflected signal. For very low levels of excitation (number of carriers less than $10^{18}/\text{cm}^3$) $\omega_p \ll \omega$ the fractional change in the refractive index, Δn , and reflectivity, ΔR , are directly proportional to the carrier density and are given by

$$\frac{\Delta n}{n_0} = \frac{-2\pi N^2}{\epsilon m^* \omega^2} = \frac{\Delta R}{R_0} \quad (81)$$

For high power picosecond excitation pulses, the carrier dynamics are determined by lattice heating, electron-hole diffusion and Auger and defect recombination. Auger recombination is the dominant recombination mode for high carrier concentrations [41]. Linearly interpolating between the electron mobilities for Si and Ge, the diffusion length for electrons in $\text{Si}_{0.70}\text{Ge}_{0.30}$, assuming an electron lifetime of 100ps, is approximately $0.76\mu\text{m}$. If the illuminated spot size is several microns wide and the illuminating beam has an absorption length of several microns then the effect of electron diffusion can be neglected. For holes the diffusion length is only about $0.48\mu\text{m}$ and would be far less if the hole confinement properties of the multilayer stack are taken into account. The ambipolar diffusion length is approximately $0.5\mu\text{m}$.

If the pump and probe fluences are kept low, then the lattice heating will be negligible. If, as a first order approximation, diffusion is neglected, then according to equation 81 the change in carrier density, N_c , can be estimated from the temporal change in the sample reflectivity. A typical reflectivity curve obtained for a silicon on sapphire sample is shown in figure 48 [87]. Using a curve fitting technique the carrier decay time can be determined from this reflectivity response. The time resolution capability of this technique, which is only limited by the time delay between pulses and the finite pulse widths of the laser, can be as low as 200 to 300 fs.

Figure 48. Reflectivity curve for silicon on sapphire [87]

The Mira 900 femtosecond laser has a pulse width of 150 fs, operation wavelength of $0.92\mu\text{m}$ and a pulse repetition frequency of 76MHz. At this wavelength the absorption mechanisms in both the Si and $\text{Si}_{1-x}\text{Ge}_x$ are indirect processes. The output of this laser was split to serve as both the pump and probe beams. The probe pulse was delayed, using a variable delay line, and attenuated with respect to the pump beam. The pump beam was chopped at a reference frequency of 1KHz. The two beams were positioned on the sample such that the probe spot was completely within the pump spot at the point of incidence. The average probe and pump powers were 1.5mW and 63mW respectively. The reflected probe signal was incident on a photodetector the output of which was connected to a lock-in amplifier. Using the 1kHz reference frequency the output of the lock-in amplifier measured the difference in reflectivity, ΔR incurred by the probe beam due to carriers generated by the pump pulse. A computerized data acquisition system was used to record the output of the lock-in amplifier as a function of the probe pulse delay. The measured ΔR as a function of the probe pulse delay is illustrated in figure 49.

The fall time constant of the above figure represents the free carrier lifetime. In actuality this reflectivity characteristic could be made up of a composite of several different lifetimes, each corresponding to a different type of trap resident in the material. If a material has approximately equal numbers of two types of traps with vastly different lifetimes then the reflectivity characteristic would be the sum of two decay characteristics having two distinct slopes. However, it is difficult to generalize on the shape of a reflectivity curve not knowing the individual lifetime and numbers of each trap population. Most researchers tend to use one or two curves to best represent their

Figure 49. Observed reflectivity (sample #1300)

experimental data. In this experiment, one curve was seen to be adequate to describe the reflectivity data. This indicates that either there is only one dominant type of trap in the

material or that there are approximately equal numbers of several types of traps all having similar lifetimes. Not knowing either the relative trap densities or the number of different traps, the lifetime obtained from this fit should be taken as the average lifetime of the traps found in most abundance in this material. The curve of best fit to this data was found using the equation to be

$$f(t) = e^{-t/\tau} \quad (82)$$

where $\tau = 100\text{ps}$

From these measurements it can be seen that the free carrier lifetime in the Si/Si_{1-x}Ge_x multilayer stack is approximately 100ps. The average ambipolar diffusion length of the free carriers in 100ps was calculated to be a maximum of 0.5 μm . Therefore, as the pump beam spot size is 0.05mm in diameter and its absorption depth is calculated to be approximately 20 μm the effects of carrier diffusion in contributing to the observed decrease in probe beam reflectivity during the lifetime of the carriers is negligible. As the decay time of the electronic $\Delta R/R$ term is much smaller than the decay of the thermal component the electronic term appeared as a time varying component on a constant thermal background. The electronic $\Delta R/R$ was measured to be 0.052% and the thermal $\Delta R/R$ was seen to be 8 to 10 times larger.

4.3 Novel Fabry-Perot and Combined Fabry-Perot Structures

Novel FP structures can be designed using a combination of linear and nonlinear mirrors. The use of linear mirrors increases the feedback of the structure for a given device thickness. Figure 50 illustrates the typical reflectivity characteristic for a FP structure. For a FP structure to exhibit optical bistability due to an electronic nonlinearity, the low intensity operating point has to be located on the left hand side of the reflectivity dip (for example point A illustrated in figure 50). As in the DFB structure, when the incident light increases the operating point goes through the reflectivity minimum thereby enabling the device to display optical bistability.

Figure 50. Typical reflectivity characteristic for a FP cavity

Using the multilayer program, described in section 3.1.2, the performance characteristics of a novel FP structure consisting of a linear top mirror, a linear core and a nonlinear bottom mirror was analyzed for different linear and nonlinear mirror combinations as well as different stack periodicities. Similar to the nonlinear DBR structure presented in section 3.1.3 both the switch ON threshold, I_t , and the hysteresis width, Hw , vary with changing stack periodicity. A suitable combination of switching threshold and hysteresis width were obtained for a structure consisting of a 8 layer, $\lambda/4$ thick $\text{SiO}_2/\text{Nb}_2\text{O}_5$, top mirror, a λ thick Nb_2O_5 linear core and a 72 layer $\text{Si}/\text{Si}_{0.7}\text{Ge}_{0.3}$ bottom mirror having individual layer thicknesses of 72.5nm and 73.5nm respectively. The switching characteristics of this structure are presented in figure 51. Tables I and II in appendix A present the changes in I_t , Hw and transmission, t , as the number of linear and nonlinear layers are increased and decreased from that of the aforementioned design. When the linear mirror layer number is decreased the device transmission increases due to a decrease in the top mirror reflectivity. With a decrease in the top mirror reflectivity more light reaches the nonlinear layers and therefore the switch ON threshold decreases. For an increase in the linear layer number the reflectivity of the top mirror increases causing the device transmission to decrease. Therefore, less light reaches the nonlinear layers and this in turn causes I_t to increase. The hysteresis width also increases due to the increase in feedback brought about as a result of the increase in mirror reflectivity. If the nonlinear mirror layer number is increased the device transmission is reduced due to an increase in absorption. Also, I_t increases because of the increase in the nonlinear stack number and the hysteresis width increases due to an increase in device feedback. A

Figure 51. Input versus output intensity for 81 layer FP design

decrease in the nonlinear mirror number decreases both I_L and Hw . Figure 52 illustrates the switch ON characteristics of this device as a function of the nonlinear mirror layer number.

Another design that gives good switching performance is a combined Fabry-Perot/DFB, FP/DFB, structure illustrated in figure 53. This structure consists of two FP linear end mirrors and a nonlinear DFB core. The performance of this type of a structure was analyzed for different linear and nonlinear mirror combinations as well as layer periodicities of the nonlinear stack. A reasonable combination of switching and hysteresis width was obtained for a design consisting of a 10 layer, $\text{SiO}_2/\text{Nb}_2\text{O}_5$, $\lambda/4$ thick, top mirror, a 6 layer $\text{Si}/\text{Si}_{0.7}\text{Ge}_{0.3}$ nonlinear core, having 74.5nm and 72.5nm layer

Figure 52 Input versus output intensity as a function of the nonlinear mirror number for 81 layer FP design

Figure 53 Typical FP/DFB structure

thicknesses respectively and a 12 layer, $\text{SiO}_2/\text{Nb}_2\text{O}_5$, $\lambda/4$ thick linear bottom mirror. Figure 54 illustrates the switching characteristics of this device. Tables III, IV and V in appendix A illustrate the changes in device performance for increases and decreases in the linear mirror and nonlinear core numbers. As the bottom mirror number is decreased the device transmission increases and the switch ON threshold decreases due to a decrease in mirror reflectivity and a decrease in the device finesse. Also, a reduction in the mirror reflectivity causes the device feedback to decrease thereby leading to a decrease in the hysteresis width. When the bottom mirror layer number is increased its reflectivity increases leading to an increase in the device feedback and device hysteresis width. The higher mirror reflectivity leads to greater device finesse which in turn leads to a higher device switch ON threshold. The transmission through the device is also seen to decrease as a result of the increase in mirror reflectivity. An increase in the nonlinear core layer number increases the device switch ON threshold. The hysteresis width is also seen to increase due to an increase in device in the feedback brought about by these additional layers. A decrease in the core layer number leads to a decrease in both absorption and feedback leading to a decrease in hysteresis width and Switch ON threshold. Figure 55 illustrates the device switching characteristics as a function of the core layer number. An increase in the top mirror number reduces the transmission through the device and increases both the hysteresis width and the Switch ON threshold. A decrease in the top mirror layer number increases the transmission and reduces both the hysteresis width and the switch ON threshold. Figure 56 illustrates the impact on device switch ON threshold of increasing and decreasing the top mirror layer number.

Figure 54. Input versus output characteristics for 28 layer FP/DFB

Figure 55. Input versus output characteristics for 28 layer FP/DFB design
as a function of the core layer number

Figure 56. Input versus output characteristic for the 28 layer FP/DFB design
as a function of the top mirror layer number

This FP/DFB design is difficult to build as it is impossible to separate the $\text{Si}/\text{Si}_{0.7}\text{Ge}_{0.3}$ layers from the growth substrate. Therefore, a more practical design would have only one linear mirror at the top multilayer-air interface. A single mirror FP/DFB design having a 8 layer $\text{SiO}_2/\text{Nb}_2\text{O}_5$, $\lambda/4$ thick, linear top mirror and a 64 layer $\text{Si}/\text{Si}_{0.7}\text{Ge}_{0.3}$ nonlinear bottom mirror with alloy thicknesses of 72.5nm and 73.5nm respectively was analyzed for different combinations of linear and nonlinear mirror numbers. Figures 57 and 58 illustrate the changes in switch ON threshold as a function of increasing and decreasing linear and nonlinear mirror number for this design. The data for these graphs along with the transmission and Hw characteristics are presented in tables VI and VII in appendix A.

Figure 57. Input versus output characteristic for the single mirror FP/DFB design as a function of the linear mirror number

From these results it is seen that the switch ON characteristics for these novel FP and FP/DFB structures are better than those for the nonlinear DFB structure presented in section 3.1.1. However, it must be noted that the simulations for the FP and FP/DFB structures were conducted assuming a free carrier lifetime of 10ns and if the experimentally determined lifetime of 100ps is used then it is seen that the switch ON thresholds for the FP and single mirror FP/DFB designs increase to approximately $8 \times 10^{12} \text{ W/m}^2$. The melting threshold of Si is between $2\text{--}4 \times 10^{12} \text{ W/m}^2$ [88]. Therefore, even with these lower switching thresholds the measured free carrier lifetime is too small to observe bistable behaviour in these devices.

Figure 58. Input versus output characteristic for the single mirror FP/DFB design as a function of the nonlinear mirror number

4.4 Conclusion

The two main aims of this chapter, which were to study the feasibility of implementing optically bistable devices in $\text{Si}_{1-x}\text{Ge}_x$ and the determination of free carrier lifetime in these structures, were successfully completed.

A novel $\text{Si}/\text{Si}_{1-x}\text{Ge}_x$ multilayer distributed feedback structure was designed and implemented using MBE growth techniques. A multilayer analysis program was also built to analyze the performance of this and several other bistable multilayer structures. Simulations indicated that for a given multilayer stack thickness the FP/DFB structure had the best input switching threshold. The $\text{Si}/\text{Si}_{1-x}\text{Ge}_x$ structure displayed thermal switching, which is a precursor to optical bistability, at $\lambda = 1.06\mu\text{m}$ with a $\Delta R/R$ of over 100% for switch up and 50% for switch down. The thermal switching off times, which are determined by heat diffusion from the illuminated spot, were measured to be approximately 100ns.

Free carrier lifetime in the $\text{Si}/\text{Si}_{1-x}\text{Ge}_x$ multilayer stack was measured, using optical pump-probe techniques, to be approximately 100ps. It is believed that low carrier lifetime is predominantly due to the high dislocation density in the structure. The low carrier lifetime leads to low carrier densities and gives rise to very small reflectivity changes which were measured to be $\Delta R/R = 0.052\%$. The thermal $\Delta R/R$ was seen to be approximately 8 to 10 times larger.

This structure can be used in either OEIC's or hybrid circuits for signal routing and other switching functions where switching speed is not important. Also, this structure can be used to implement logic gates in which several high power control

signals can be used to alter the reflectivity of a data signal as outlined in section 3.1. As this device works on the thermo-optic effect any high frequency noise on the optical control signals would not effect the operating characteristics of these devices. Once there is an improvement in device growth these structures can be used to implement various optically bistable devices such as logic gates, differential amplifiers, optical limiters and optical switches as outlined in section 3.1. In conclusion it can be said that this work represents the first demonstration of switching in a multilayer $\text{Si}/\text{Si}_{1-x}\text{Ge}_x$ DFB structure [89].

5.0 PIN Diode Electro-optic Waveguide Modulator

A modulator is a device which alters the propagation characteristics of an input in response to corresponding changes in a control signal. In an optoelectronic modulator, the input and control signals are optical and electrical inputs respectively. Depending on their implementation, optoelectronic modulators can be divided into three main categories. These are, the single waveguide, dual waveguide and the Mach-Zehnder waveguide modulators. Waveguides are ideally suited for modulation purposes as the switching strength of a modulator can be tailored by the length of the guide. Therefore, even relatively weak nonlinearities can be used for optical modulation as long as the waveguide is sufficiently long.

In an optoelectronic modulator, the propagation characteristics of the optical mode are altered by either an index of refraction or absorption change in the modulating waveguide. In electro-optic modulators, the refractive index is changed by the application an electric field across the device. The applied field produces both linear and nonlinear changes in the refractive index known as the Pockels and Kerr effects respectively. These changes are anisotropic and the Pockels effect is only present in noncentrosymmetric crystals. Several materials, such as GaAs, GaP, LiNbO₃, used to make low loss waveguides have significant Pockels effects in certain crystal orientations. Therefore, the electro-optic effect has been widely used to make switches and modulators in these materials. In the simplest type of modulator structure, the single waveguide device illustrated in figure 59, the input signal can be phase, polarization, or amplitude modulated by changing the refractive index of the waveguide [38]. These devices, which

use changes in refractive index for modulation, are also termed electro-refraction modulators. Another type of modulator, which uses absorption changes for modulation is referred to as an electro-absorption modulator. Electro-absorption modulators often use the Franz-Keldysh effect to modulate the input light wave [39]. The Franz-Keldysh effect describes the shift of the modulator's absorption edge, to lower wavelengths, due to the application of an electric field. This effect is quite strong in direct gap materials, such as GaAs, in which the absorption increases rapidly with wavelength. This type of modulator, demonstrated in several III-V materials [15], has been used to produce efficient modulators operating around the $\lambda=0.9\mu\text{m}$. Kaminow et al. have implemented a lithium niobate phase modulator at $\lambda=0.633\mu\text{m}$ having a switching speed of 10ns, and a phase modulation of 1 radian for an applied voltage of 1.2V. Campbell et al. have fabricated an intensity modulator having a 95% modulation depth, a switching speed of 40ns and a power requirement of 45mW. Reinhart has demonstrated a Franz-Keldysh modulator at $\lambda=0.9\mu\text{m}$ and having a 90% intensity modulation for an applied bias of 4V.

Figure 59. Single waveguide modulator implemented in a Si/Si_{1-x}Ge_x heterostructure

The quantum confined Stark effect [90], QCSE, found in quantum wells can also be used to build electro-absorption modulators. In bulk materials, electrons and holes can form bound pairs known as excitons. The binding energy of excitons are very small and hence they only exist at cryogenic temperatures. At higher temperatures, these excitons are ionized by exciton-phonon interactions. In quantum wells, QW, the physical confinement of the electrons and holes leads to much higher binding energies than in bulk materials. In QW structures, excitons are known to survive to temperatures greater than 20° C [90]. Excitons increase the slope of the absorption versus wavelength curve around the absorption edge of the material. In bulk materials, the application of an electric field causes the exciton peak to shift to longer wavelengths. This is due to a decrease in the binding energy brought about by an increase in the electron hole separation. This effect, known as the Stark effect, produces very small wavelength shifts in bulk materials. Also, this wavelength shift is usually masked by an energy broadening of the exciton peak, therefore it is not of much use for any practical device implementations. In quantum wells, the application of an electric field causes the electrons and holes to move in opposite directions. However, the maximum separation of the electron-hole pair is limited by the physical dimensions of the well. Therefore, exciton ionization is inhibited and a wavelength shift of the exciton peak with little energy broadening is obtained. This effect, referred to as the quantum confined Stark effect (QCSE), has been used to build switches and modulators in a variety of III-V material systems [91]. For example, Wood has demonstrated a QCSE modulator at $\lambda = 1.55\mu\text{m}$, operating at a drive voltage of 3V, an on/off ratio of 10.5dB and a 3dB bandwidth of 3.7GHz. Also, Koren et al. have

demonstrated a InGaAs/InP multiple quantum well device (MQW) at $\lambda=1.06\mu\text{m}$, having an on/off ratio of 47:1, a 7V drive voltage, an insertion loss of 2.9dB and a 3dB bandwidth of 3GHz.

In an electro-optic, dual channel modulator, illustrated in figure 60, the amount of light coupled from guide 1 to guide 2 can be altered by changing the voltage difference, ΔV , and hence the refractive index between them. When $V=0$, the modulator has a certain interaction length over which all the light input to guide 1 is coupled to guide 2. When ΔV is increased the propagation constants change such that a propagation constant difference, $\Delta\beta$, is formed between the modes propagating in the two guides. This $\Delta\beta$ difference alters the interaction length required for 100% power transfer and leads to a modulation of the optical power at the output of guide 2. However, it is seen that in practical implementations of these devices even small temperature and bias variations significantly alter the device output. Different variations of the dual channel structure have been demonstrated in GaAs and LiNbO₃ materials[92]. Campbell has demonstrated a dual channel modulator fabricated on GaAs, operating at $\lambda=1.06\mu\text{m}$, having a bandwidth of 100MHz and a modulation depth of 95% at an applied bias of 35V [13].

The Mach-Zehnder electro-optic modulator, illustrated in figure 61, uses interference effects between coherent light waves to modulate the guided signal. Light input to the device is divided equally between the two arms of the modulator. By applying a voltage to guide 1 the refractive index, and hence the phase of the light propagating in that arm, can be changed with respect to that in the unmodulated arm.

Figure 60. Dual waveguide modulator [39]

Figure 61. Mach-Zehnder modulator [32]

When the two light beams are combined, the phase offset produces interference between the two beams. Therefore, by changing the modulation voltage the phase change in guide 1, and hence the output power of the device, can be varied. Ideally, the length of the two arms should be equal so that when no voltage is applied the phase shift is zero and the device output is a maximum. In practice, equal arm lengths are difficult to achieve. Even minute processing variations can cause the optical path lengths in the two arms to be different though their physical lengths might be the same. Also, it is seen that even small temperature variations across the device can cause the device output to fluctuate. This type of device, first proposed by Zernike, has been implemented in III-V, II-VI and LiNbO_3 materials. Martin has fabricated a ZnSe modulator operating at $\lambda = 1.06\mu\text{m}$, having a maximum switching depth of 60% at a bias of 25V. Also, Becker has demonstrated a LiNbO_3 modulator which had an on/off ratio of 2.7:1 at $\lambda = 1.3\mu\text{m}$ and a 180 degree phase change voltage of 4V [93].

In unstrained Si there is no linear electro-optic effect due to the centrosymmetry of the crystal. Furthermore, Soref has shown that the nonlinear Kerr effect is also very small in this material [45]. However, the free carrier effect in Si is of sufficient magnitude to implement practical optoelectronic devices and has been used to build a variety of basic optical components such as detectors, modulators and optical switches [38]. By analyzing the equations for the Drude model it is observed that to obtain a moderate change in absorption of $\Delta\alpha = 5\text{ cm}^{-1}$ a high carrier density of $1 \times 10^{18}\text{ cm}^{-3}$ is required. One of the simplest methods of obtaining a high carrier concentration in a given material is by implementing a PN or PIN diode in it. When the diode is driven

into high forward bias, carriers are injected into the device from both electrodes and a high carrier concentration is obtained in all regions of the diode. The PIN diode can also serve the dual purpose of acting as an optical waveguide. Waveguides are ideally suited for modulation purposes as the strength of the switching mechanism can be tailored by altering the length of the guide. Therefore, even relatively weak nonlinearities can be used for optical modulation as long as the waveguide is sufficiently long. An optical waveguide can be implemented by implanting dopants into the areas adjoining the optical guiding layer as illustrated in figure 62. These dopants, when implanted in a sufficient quantity, reduce the refractive index in the implanted regions and create a refractive index profile suitable for optical waveguiding. The optical mode propagating in this structure is mainly contained in the guiding region. A more detailed discussion of optical waveguiding is deferred to section 5.3. If P and N dopants are implanted on either side of the guiding region then a PIN diode is formed with the I region functioning as the guiding region of an optical waveguide.

Figure 62. Implementation of a waveguide

The free carrier nonlinearity, unlike the electro-optic or the Franz-Keldysh effects, is isotropic, and hence insensitive to the input polarization. This eliminates the need for complex alignment of the input wave polarization to the appropriate crystal orientation of the modulator. Devices which can manipulate both polarizations equally are a great asset especially in the field of fibre communications where the output of most non-polarization preserving fibers is elliptically polarized. The free carrier effect in Si devices works well over the wavelength of range 1.06 to 2.0 μm . The broadband characteristics of the free carrier effect makes this effect ideal for use in the fibre communication band of 1.3 to 1.55 μm . The performance of these devices over this wavelength range is limited mainly by the guiding properties of the waveguide and not by the free carrier effect. The operational wavelength of the electro-absorption modulator, using the Franz-Keldysh effect, is limited to wavelengths around the absorption edge of the device. If the modulator were implemented in GaAs the operating wavelength would approximately extend from 0.87 μm to 1.0 μm .

The Si modulators implemented thus far can be divided into two broad categories. These are the refractive index modulators and the absorption modulators. The refractive index modulators use free carrier induced refractive index changes to alter the guiding properties of the modulator. Modulators of this type have been demonstrated by Fisher et al. [32] in Ge diffused Si waveguides and also by several other researchers in the field of Si optoelectronics [94]. Absorption modulators use the free carrier absorption effect to attenuate light propagating through the modulator structure. Treyz et al. have demonstrated an all Si, $\lambda = 1.3\mu\text{m}$, PIN waveguide modulator which uses this effect[38].

In this work, a PIN diode $\text{Si}/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ electro-optic modulator was built for operation at $\lambda = 1.3\mu\text{m}$. The P^+ and N^+ region are made of Si while the intrinsic I region is made of $\text{Si}_{1-x}\text{Ge}_x$. Light propagating in the intrinsic region is modulated by forward biasing the diode thereby enabling carriers to enter the I region and absorb the guided light. Research conducted by People [43] indicates that unstrained Si and strained $\text{Si}_{1-x}\text{Ge}_x$ form a type I heterostructure in which most of the band offset is in the valence band. These valence and conduction band offsets set up an electric field that confines electrons and holes in the $\text{Si}_{1-x}\text{Ge}_x$ material. Thus, under a given forward bias, the intrinsic region of the $\text{Si}/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ diode has a much higher electron/hole density and hence a greater modulation depth than an ordinary all Si PIN diode. This heterostructure carrier confinement feature can be used to build modulators having larger modulation depths than those obtained from all Si devices. The carrier confinement feature can be observed from the device simulation results presented in section 6.2.2.

In the field of optical communications one of the most widely investigated areas is that of photodiodes. Although, photodiodes perform a function different to that of modulators, a brief description both of the theory of operation and the different photodiode geometries helps to present the basic terminology and underlying theory associated with PN diode structures. Furthermore, this section also serves to introduce the basic waveguide PIN diode, a modified version of which was implemented in this thesis as an electro-optic waveguide modulator.

Section 5.1 outlines the general characteristics of PN photodiodes. This section compares mesa and waveguide photodiode structures and gives a brief

description of avalanche and PIN diode operation. Section 5.2 describes the operation of the novel electrooptic heterojunction modulator. Equations for the modulation depth and device capacitance for these diodes are also presented in this section. Section 5.3 outlines the conditions required for optical waveguiding, which requires vertical confinement of light, in a three layer planar optical guide. This section also describes several methods for lateral light confinement in the three layer structure.

5.1 General Operating Characteristics of PN Photodiodes

A typical PN mesa photodiode geometry is illustrated in figure 63. When light having energy greater than the bandgap of the material is incident photons are absorbed by the entire structure, forming electron-hole pairs. In the depletion region the electric field accelerates the electrons and holes to the N and P regions respectively. Minority carriers generated less than a diffusion length (which is the distance a carrier travels on average before recombination) from the edge of the junction will diffuse into the depletion region and be swept across the junction by the electric field. Once on the other side of the junction, carriers that diffuse to the device contacts contribute to the external device photocurrent. Most minority carriers generated more than a diffusion length from the junction will recombine before reaching the depletion layer and therefore do not contribute to the external photocurrent.

In these devices, the depletion layer forms mainly on the lower doped side and assuming that only the minority carriers on that side of the junction contribute significantly to the device output current the total current density in a P^+N junction is

given by

$$J_T = q\phi_0 \left(1 - \frac{e^{-\alpha w}}{(1 + \alpha L_p)}\right) + q p_{no} \frac{D_p}{L_p} \quad (83)$$

The first term in equation 83 is the photocurrent from carriers generated in the depletion region, and those generated on the N side within one diffusion length of the depletion region. The second term is the dark current which arises due to thermally generated holes in the N doped material. The quantum efficiency, η , which gives the number of electron-hole pairs generated per incident photon is given by

$$\eta_q = 1 - \frac{e^{-\alpha w}}{(1 + \alpha L_p)} \quad (84)$$

Figure 63. Mesa photodiode [39]

For this type of PN detector η is between zero and one. From equation 84 it is seen that to maximize η the diffusion length, L_p , and the depletion width, w , must be as large possible. If w is quite small, then to obtain a high quantum efficiency the absorption coefficient, α , should be moderately high. A small depletion width also leads to a large junction capacitance which limits the high frequency response of the device. Furthermore, the time required for carriers to diffuse from the N region to the edge of depletion layer limits the response of conventional photodiodes.

Another type of PN diode geometry that provides good detector characteristics is the waveguide structure illustrated in figure 64. In this detector, the light enters the diode by means of an optical waveguide. The photodiode current density is given as

$$J = q\phi_0(1 - e^{-\alpha L}) \quad (85)$$

Figure 64. Waveguide photodiode

By choosing the reverse bias voltage, V_a , appropriately, the depletion layer can be made to extend across the entire thickness of the guide. In this design w and L can be chosen independently and L can be selected such that $\alpha L \gg 1$. Thus, the η of this structure can be designed to be close to 1.0. As all the electrons are generated in the depletion layer, the response time of this device is faster than that of a mesa structure which has a slower carrier diffusion component from the depletion region.

Under normal operating conditions the quantum efficiencies of both the mesa and waveguide diodes are at most equal to 1.0. However, if these devices are biased at the point of avalanche breakdown then the resulting carrier multiplication yields an η greater than unity. The current-voltage characteristics for an avalanche device are illustrated in figure 65. Under low bias conditions the photocurrent is I_{ph0} and the dark current, resulting from thermally generated carriers, is I_{d0} . When biased at the avalanche breakdown point carrier multiplication leads to an increase in both the dark current, I_d and the photocurrent, I_{ph} [95].

Figure 65. Current-voltage characteristics for an APD [39]

The photocurrent multiplication factor M_{ph} is given by

$$M_{ph} = \frac{I_{ph}}{I_{pho}} \quad (86)$$

Miller [96] has determined the following equation for M_{ph}

$$M_{ph} = \frac{1}{1 - \left(\frac{V_a}{V_b}\right)^n} \quad (87)$$

Fabrication of avalanche photodiodes (APD) is a little more complicated than that of PN or PIN structures. Certain APDs consists not only of a photon absorption region where carriers are created but also of a high field region where carrier multiplication takes place. These types of devices are known as separate absorption multiplication, SAM, APD's. To avoid a spatial accumulation of carriers, (caused by regions of low breakdown voltages and excessive current leakage), it is essential that the carrier multiplication process be uniform through the device. Therefore materials with high defect densities should be avoided and care should be taken during processing to minimize impurity contamination of the material.

The speed of APD's are primarily dependent upon the transit time of the photogenerated carries and the capacitance of the device.

A variation of the PN diode is the PIN diode illustrated in figures 66a and 66b. In this structure an intrinsic region, I, is grown between the P and N layers. Under

normal operation the depletion layer extends across the entire I region. From equation 84 it can be seen that by widening the depletion region in the mesa structure the αw product can be increased thereby increasing the quantum efficiency of the device. In PIN waveguide devices the replacement of the N doped waveguide associated with the PN devices by a low doped I layer reduces the propagation loss of the input waveguide. This is because optical waves undergo relatively high losses when travelling through even N and P type Si. Also, the presence of a relatively thick I region reduces the depletion layer capacitance and increases the high frequency response of the device. Devices having response times in the order of tens of picoseconds have been demonstrated [97]. Another important feature of these devices is their low dark current which is approximately a few nanoamps at room temperature [98]. Campbell et al. have demonstrated InGaAs devices with dark currents as low as $5 \times 10^{-7} \text{ A cm}^{-2}$ at -10V reverse bias [17]. The quantum efficiency, which depends upon the applied reverse bias, is approximately 70% in PIN devices.

Figure 66a. Mesa PIN

Figure 66b. Waveguide PIN

PIN photodiodes are used in a wide variety of applications such as signal detection, spectrophotometry and optical power measurement. These devices are compact and are available in a wide variety of packages suitable for commercial, space and military applications. In the past, PIN photodetectors were built with Si and Ge materials. Recently, due to advancements in InP growth, InGaAs PIN diodes on InP substrates have also become commercially available. Over the past two decades improvements in processing and materials growth have enabled PIN diode operating characteristics to improve dramatically. A number of heterostructure PIN photodiodes have also been demonstrated [34]. These structures can be designed to offer better light and carrier confinement than homojunction diodes.

In the following section the operation of the Si/Si_{1-x}Ge_x/Si PIN diode waveguide electro-optic modulator is described.

5.2 Operation of Novel Si/Si_{1-x}Ge_x/Si PIN Diode Waveguide Electro-optic Modulator

The PIN Si/Si_{1-x}Ge_x/Si waveguide modulator, illustrated in figure 67, consists of a P⁺ layer, a P layer, a Si_{1-x}Ge_x guiding layer, a N layer and a N⁺ layer. Vertical confinement of the guided mode is obtained by the refractive index difference between the intrinsic Si_{1-x}Ge_x layer and the adjacent Si N and P cladding layers. The purpose of the P⁺ and N⁺ layers is to provide a good electrical contact between the diode and the metal electrodes located on the top and bottom of this structure. Lateral confinement of the guided mode is achieved via a rib etched into the Si planar waveguide.

Figure 67. Practical implementation of PIN waveguide modulator using a $\text{Si}/\text{Si}_{1-x}\text{Ge}_x$ heterostructure

Light is end coupled to the waveguide by means of $\langle 100 \rangle$ cleaved facets located on either side of the modulator structure. As the guiding layer of this waveguide is quite thin, portions of the guided mode propagate in the surrounding cladding. With no externally applied bias the device functions as a low loss waveguide. The depletion layer, as predicted by theory, extends completely across the intrinsic region and into parts of the N and P layers. The width of the depletion layer can be observed using the electrical simulation package ATLAS described in section 6.2.3. When the device is forward biased, the built in potential which restricts carrier flow is lowered and carriers enter the junction from both sides of the device. If the bias voltage is increased

monotonically the carrier concentration continues to increase until it is initially larger than the background doping density in the I region of the diode. As the bias voltage is further increased the carrier concentration in all regions begins to exceed the background doping levels. When this occurs the diode is said to be operating in high level injection. Due to the heterostructure energy offset, which favours carrier accumulation in the intrinsic $\text{Si}_{1-x}\text{Ge}_x$ region, the carrier concentration in the intrinsic region will be higher than that in the surrounding Si cladding layers by a factor dependent on the applied bias.

The output power of a wave propagating over a distance, l , with an attenuation of $\Delta\alpha \text{ cm}^{-1}$ is given by

$$f(l) = e^{-\Delta\alpha l} \quad (88)$$

where $\Delta\alpha$ is given by equation 19 in section 2.2

Therefore the modulation depth, M_d , can be expressed as

$$M_d = \frac{P_i - P_{out}}{P_i} = 1 - e^{-\Delta\alpha l} \quad (89)$$

The carrier density, ΔN is directly proportional to the current density, J so that

$$\alpha \propto kJ$$

Therefore,

$$M_d = 1 - e^{-\Delta\alpha l} = 1 - e^{-kJl} \quad (90)$$

Where k is a proportionality constant.

The transient behaviour of the minority carrier stored charge in these

devices is of great importance as it determines the maximum modulation bandwidth capabilities of the device. Charge stored in a diode gives rise to a device capacitance, C_T . The device capacitance C_T is the sum of the depletion and diffusion capacitances.

$$C_T = C_{depl} + C_{diff} \quad (91)$$

The depletion and diffusion capacitances represent the charge storage in the depletion and quasi-neutral regions of the diode respectively. The depletion and diffusion capacitances are given by

$$C_{depl} = A \frac{dQ_d}{dV_a} = A \frac{\epsilon_s}{W} \quad (92)$$

$$C_{diff} = A \frac{dQ_p}{dV_a} + A \frac{dQ_n}{dV_a} \quad (93)$$

Sze has shown [64] that for a one sided abrupt P+N diode the depletion and diffusion capacitances are given by

$$C_{depl} = A \frac{\epsilon_s}{W} = A \left[\frac{q\epsilon_s N_d}{2(V_{bi} - V_a)} \right]^{1/2} \quad (94)$$

$$C_{diff} = A \frac{q^2 L_p P_{no}}{KT} e^{qV_a / KT} \quad (95)$$

Equation 95 shows that under reverse bias C_{diff} is quite small and the major contribution to the device capacitance is from the depletion capacitance. Under low forward bias, both capacitance terms contribute more or less equally to the total device capacitance. However, as the diffusion capacitance grows exponentially with applied voltage, under high bias operation, the diffusion capacitance is much larger than the depletion term.

Another important factor that plays a crucial role in the determination of transient time is parasitic capacitance, inductance and resistance associated with both the device and the measurement apparatus. To obtain high speed device operation it is essential to keep both sources of parasitics to a minimum.

In the following section the conditions required for optical waveguiding in a three layer planar waveguide are outlined.

5.3 Optical Waveguiding

A three layer slab waveguide, illustrated in figure 68, can be designed to provide vertical confinement for several modes at discrete values of the propagation constant, β . Other modes which are not well confined can also propagate in this guide. However, these modes are greatly attenuated over very short distances. In the first part of this section, the equations describing the propagation constants for transverse electric, TE and transverse magnetic, TM modes are outlined. In the latter part, the methods of obtaining lateral optical confinement in a three layer planar waveguide are described.

In most waveguide designs, the guided mode is confined to layer 2. Vertical mode confinement in layer 2 requires that the refractive index in layer 2, n_2 , be greater than those in layer 1, n_1 , and layer 3, n_3 . All layers of the planar three layer waveguide are assumed to be infinite in the Z and Y directions and layers 1 and 3 are assumed to be infinite in the X direction. A wave propagating in the guide obeys Maxwell's wave equation which is given by

$$\nabla^2 E(r,t) = \frac{n^2(r)}{c^2} \frac{\partial^2 E(r,t)}{\partial t^2} \quad (96)$$

For a transverse electric, TE plane wave travelling in the Z direction in an isotropic medium Maxwell's equation reduces to

$$\nabla^2 E_y = \frac{n_i}{c^2} \frac{\partial^2 E_y}{\partial t^2} \quad i=1,2,3... \quad (97)$$

Figure 68. Three layer slab waveguide [39]

Using the methods outlined in reference 39 this equation can be used to obtain the propagation constants, β , of the TE modes guided in the waveguide. These propagation constants are given by the following transcendental equation

$$\tan(h t_g) = \frac{p+q}{h(1 - \frac{pq}{h^2})} \quad (98)$$

where t_g is the thickness of the waveguide

$$q = (\beta^2 - (n_1 k)^2)^{1/2} \quad (99)$$

$$h = ((n_2 k)^2 - \beta^2)^{1/2} \quad (100)$$

$$p = (\beta^2 - (n_3 k)^2)^{1/2} \quad (101)$$

$$k = \frac{\omega}{c} \quad (102)$$

Each value of β which satisfies equation 98 represents the propagation constant of a TE mode propagating in the planar waveguide.

For a TM wave the form of the transcendental equation is given as

$$\tan(ht_s) = \frac{h(p' + q')}{h^2 - p'q'} \quad (103)$$

where

$$p' = \frac{n_2^2}{n_3^2} p \quad (104)$$

$$q' = \frac{n_2^2}{n_1^2} q \quad (105)$$

In the special case of a symmetric waveguide where $n_1 = n_3$, the refractive index difference required for waveguiding is given by

$$\Delta n \geq \frac{m \lambda_o^2}{4t_c^2(n_2+n_1)} \quad m=0,1,2,3,4 \quad (106)$$

For an asymmetric waveguide where $n_3 \gg n_1$

$$\Delta n \geq \frac{m_s \lambda_o}{4(2t_c)^2(n_2+n_3)} \quad (107)$$

where m is the mode number.

where m_s , the mode number is given by

$$m_s = (2m+1) \quad m=0,1,2,3,4,\dots$$

Equation 107 holds for all TE modes and all TM modes as long as $n_2 \approx n_3$. This equation says that for $m=0$, Δn can be equal to zero. In practice there has to be at least an infinitesimally small Δn or else the propagating mode would not be confined vertically inside the waveguide.

In most optical applications both vertical and lateral confinement of the guided mode are required to prevent excessive loss due to mode spreading in the waveguide. Vertical confinement is achieved, as discussed earlier, by selecting the refractive index of the confining layer to be greater than those of the surrounding cladding layers. Lateral confinement can be achieved in much the same manner by inducing a lateral refractive index difference between adjacent regions of the planar waveguide. Lateral confinement can be induced using many methods. A few of these methods will be described in the following discussion so as to provide the reader with a sampling of the practically implementable techniques by which this type of

confinement is achieved.

One popular method of achieving lateral confinement is by placing a strip of rectangular material having a lesser index than the guiding layer on the desired area of confinement. The presence of the rectangular strip makes the effective refractive index in that region larger than that of the adjacent areas thereby providing the required lateral confinement.

Lateral confinement can also be achieved using metallic loading strips placed on either side of the confinement area. This type of structure is depicted in figure 69. The presence of the metal strips makes the effective refractive index in these regions lower than that in the centre, thereby providing lateral optical mode confinement for a mode propagating in the centre of the waveguide.

Another method of achieving lateral confinement is by forming a ridge in the planar waveguide as illustrated in figure 70. In this structure, confinement is achieved by removing material from areas adjacent to the desired region of confinement. The removal of material causes the effective refractive index in these regions to decrease. The reduction in effective index is proportional to the depth of the rib. Therefore, the larger the ridge depth the greater the optical confinement. This method of confinement has gained wide acceptance in the field of commercial and experimental optics and is the method used to obtain lateral confinement in the electro-optic waveguide PIN modulator fabricated in this work.

In the next chapter the design, growth, modelling and testing of the novel heterostructure $\text{Si}/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ PIN waveguide electro-optic modulator is described.

Figure 69. Vertical confinement in a slab waveguide
using metal strips [39]

Figure 70. Rib waveguide [39]

Chapter 6.0 Design, Growth, Modelling and Testing of Electro-optic PIN Modulator

This chapter describes the design, growth, processing and testing of the electro-optic PIN diode modulator. Section 6.1 outlines the design of the modulator. The trade offs that had to be considered between opposing design parameters are also discussed in this section. Section 6.2 presents the simulation results for the waveguiding, modulation and transient response characteristics of the optimized PIN diode design obtained in section 6.1. Section 6.3 describes the processing of the Si/Si_{1-x}Ge_x/Si waveguide to fabricate the electro-optic modulator. The experimental modulation and switching characteristics are also presented in this section.

6.1 Modulator Design

The PIN diode waveguide modulator was designed to exhibit low loss waveguiding, for $\lambda = 1.3\mu\text{m}$ light, with no applied bias, and a high propagation loss in high forward bias. To achieve good optical modulation characteristics the guided mode has to be confined to the intrinsic region of the diode as much as possible. The confinement of the guided mode is proportional to the thickness of the intrinsic region and also to the refractive index difference between the intrinsic and surrounding Si cladding, N and P, regions. The respective refractive index and the critical thickness of the Si_{1-x}Ge_x intrinsic region are directly and inversely proportional to the Ge content in the Si_{1-x}Ge_x alloy. Therefore, a compromise has to be reached between these two opposing quantities when selecting the Ge content for the intrinsic region. Also, to

minimize absorption the doping in the N and P regions should be as low as possible. However, for good carrier injection the cladding regions should be moderately doped. Therefore when selecting an appropriate doping for these layers a trade off has to be made between minimizing the optical absorption and maximizing the modulation depth for a given current density.

Two simulation packages, MENU and SEDAN were used to analyze various PIN modulator designs. MENU is an optical simulation package developed at the National Research Council of Canada (NRC) for determining the propagation characteristics of optical waveguide structures. SEDAN is a commercially available one dimensional device simulator capable of modelling transistors and diodes. Given the refractive indices, the absorption coefficients and the individual layer thicknesses for a given design, MENU can determine the optical mode shapes and absorption losses of the modes propagating in the waveguide. In SEDAN, a given waveguide design is specified in terms of individual layer dopings, Ge content and layer thicknesses. SEDAN was used to determine the current density and the free carrier density profile through the device as a function of the applied forward bias voltage.

The propagation characteristics of the optical waveguide modulator were analyzed for different combinations of $\text{Si}_{1-x}\text{Ge}_x$ guiding layer thicknesses, Ge concentrations, P and N cladding thicknesses and several doping concentrations. The data for P and N cladding layer dopings of $5 \times 10^{16} \text{ cm}^{-3}$ and P^+ and N^+ contact doping of $1 \times 10^{20} \text{ cm}^{-3}$ are presented in tables VIII-XX in appendix B. Each of these tables present the TE and TM mode losses for different P and N cladding layer thicknesses at fixed Ge

concentrations and fixed $\text{Si}_{1-x}\text{Ge}_x$ guiding layer thicknesses. Simulations indicated that the TE and TM mode losses decrease quickly with increasing P and N cladding layer thickness. This is because the proportion of the guided mode travelling in the lossy P^+ and N^+ regions increase, thereby causing the loss to increase, with decreasing cladding dimensions. This can be clearly seen by comparing figures 71, 72 and 73 which illustrate the TE vertically guided mode for P and N cladding layer thicknesses of 2.5, 1.0 and $0.5\mu\text{m}$. For cladding thicknesses greater than $2.5\mu\text{m}$ the decrease in waveguide loss due to an increase in cladding thickness is very small. Therefore in our analysis the maximum cladding thicknesses were restricted to an upper value of $2.5\mu\text{m}$.

Figure 71. Vertically guided TE mode for cladding thicknesses of $2.5\mu\text{m}$

Figure 72. Vertically guided TE mode for cladding thicknesses of $1.0\mu\text{m}$

Figure 73. Vertically guided TE mode for a cladding thickness of $0.5\mu\text{m}$

The TE and TM waveguide loss as a function of the Ge content in the $\text{Si}_{1-x}\text{Ge}_x$ guiding layer, for a guiding layer thickness of 0.1 μm , is presented in figure 74. From this figure it is seen that the lowest TE loss occurs for a Ge concentration of 10%. However, for a waveguide to function as a good modulator it must not only have low TE and TM mode losses but also these losses must in theory be equal to one another. In practice the TE and TM mode losses will be different. Therefore from a design point of view the object is to not only minimize the TE and TM losses but also to minimize the difference between them. The minimization of these losses reduces the distortion of elliptically polarized waves travelling in the waveguide. At low Ge concentrations the mode confinement in the guide is rather poor so that losses are high due to mode absorption in the heavily doped P^+ and N^+ contact regions. The absorption coefficient of strained $\text{Si}_{1-x}\text{Ge}_x$ increases rapidly with Ge concentration. Therefore, at high Ge concentrations the TE and TM mode losses increase due to absorption in the $\text{Si}_{1-x}\text{Ge}_x$ region. For this waveguide design a Ge concentration of 15% is seen to yield both a minimum TM loss as well as a minimum loss difference between TE and TM losses.

By comparing data for equal values of Ge in the $\text{Si}_{1-x}\text{Ge}_x$ guiding layer it is seen that minimum TE and TM losses are obtained for the thickest $\text{Si}_{1-x}\text{Ge}_x$ guiding layers. The thicker the guiding layer the better the guided mode confinement and smaller the mode power guided in the lossy P^+ and N^+ contact regions. Figure 75 illustrates the TE and TM mode losses as a function of the $\text{Si}_{0.85}\text{Ge}_{0.15}$ guiding layer thickness. Figures 76, 77, 78 and 79 present the waveguide losses for symmetric waveguides having equal P and N cladding thicknesses for Ge concentrations, x , ranging from 0.05 to 0.2. As can

Figure 74. TE and TM loss as a function of Ge content in a $0.1\mu\text{m}$ thick guiding layer waveguide. P and N cladding thickness is $2.0\mu\text{m}$

Figure 75. TE and TM loss as a function of the guiding layer thickness on a $\text{Si}_{0.85}\text{Ge}_{0.15}$ waveguide

Figure 76. TE and TM loss as a function of the cladding layer thickness
in a $\text{Si}_{0.95}\text{Ge}_{0.05}$ waveguide

Figure 77. TE and TM loss as a function of the cladding layer thickness
in a $\text{Si}_{0.90}\text{Ge}_{0.10}$ waveguide

Figure 78. TE and TM loss as a function of the cladding layer thickness
in a $\text{Si}_{0.85}\text{Ge}_{0.15}$ waveguide

Figure 79. TE and TM loss as a function of the cladding layer thickness
in a $\text{Si}_{0.80}\text{Ge}_{0.20}$ waveguide

be seen from these figures, for thin cladding layers the lower Ge content guides have higher losses due to lower mode confinement. Also, for P and N cladding thicknesses greater than $1.5\mu\text{m}$ the absorption in the P^+ and N^+ regions is small and most of the guided mode losses arise due to absorption in the $\text{Si}_{1-x}\text{Ge}_x$, P and N regions. Taking all these design criteria, as well as critical thickness of $\text{Si}_{1-x}\text{Ge}_x$, into account the following modulator design was selected.

Material	Doping type	Thickness(μm)	Doping density(cm^{-3})
Si	P^+	0.1	1×10^{20}
Si	P	2.0	5×10^{16}
$\text{Si}_{0.85}\text{Ge}_{0.15}$	I	0.1	1×10^{14}
Si	N	0.1	5×10^{16}
Si	N^+	2.0	1×10^{20}

This design, illustrated in figure 80, was chosen to minimize the TE and TM mode losses. The Ge content of the $\text{Si}_{1-x}\text{Ge}_x$ guiding layer is 0.15. The maximum strained layer thickness for this Ge content is $0.15\mu\text{m}$. However it was felt that a $0.1\mu\text{m}$ thick $\text{Si}_{0.85}\text{Ge}_{0.15}$ layer would be preferable as it gives the design a safety margin of $0.05\mu\text{m}$. As mentioned earlier the lowest losses are obtained for the waveguides with the largest P and N cladding dimensions. For this design it is seen that the difference in TE and TM losses for a waveguide having $2.5\mu\text{m}$ thick P and N cladding layers as

compared to a guide with $2.0\mu\text{m}$ dimensions is 0.45dB/cm and 1.34dB/cm respectively. The $2.0\mu\text{m}$ P and N cladding was selected in order to reduce the device growth time. The carrier injection characteristics were seen to be rather insensitive to P and N cladding doping levels between 1×10^{16} - $1 \times 10^{17} \text{ cm}^{-3}$ and injection currents greater than 400A/cm^2 . Therefore, a value of $5 \times 10^{16} \text{ cm}^{-3}$ was selected for the P and N cladding doping levels. The P^+ and N^+ contact layers were doped to $1 \times 10^{20} \text{ cm}^{-3}$ to ensure the formation of good ohmic contacts with the electrodes located at the top and bottom of the device.

The next section describes the simulation results obtained for the optical waveguiding, modulation and switching characteristics of this design.

Figure 80. Selected PIN design

6.2 Simulation of Si/Si_{1-x}Ge_x/Si PIN Diode Electro-optic Waveguide Structure

The performance characteristics of the optimized waveguide design, presented in figure 80, were analyzed using several software packages. The waveguiding characteristics and modulation performance were analyzed using MENU and SEDAN respectively. The transient switching analysis was studied using ATLAS. ATLAS is a commercially available two dimensional optical and electrical device simulation package which can simulate homojunction and heterojunction transistors, diodes and optical structures. In this section the results obtained from each of these packages will be presented.

6.2.1 Optical Waveguiding Characteristics

The vertically guided mode for the optimized waveguide structure, calculated using MENU, is illustrated in figure 81. The guiding layer confinement factor, which gives the percentage of the guided mode power confined to the Si_{0.85}Ge_{0.15} guiding layer, was calculated to be 15%. The confinement factor for a region containing the guiding layer and 0.2 μ m of Si on either side was calculated to be 60%. From these results it is easily seen that the guided mode is mostly confined to the immediate vicinity of the guiding layer.

Simulations indicate that the mode confinement could be increased by widening the guiding layer. However, due to critical thickness restrictions, an increase in the Si_{1-x}Ge_x thickness would require a reduction in its Ge content to maintain a strained crystal structure. This in turn would reduce the refractive index difference between the

Figure 81. Vertically guided optical mode

guiding layer and the cladding thereby reducing the guiding layer confinement factor.

The propagation loss for the vertically guided mode, illustrated in figure 81, was calculated, using MENU, to be 4.4 dB/cm and 4.9dB/cm for TE and TM modes respectively. Some of the lateral modes supported by this guide, for a rib depth of $1.5\mu\text{m}$, are illustrated in figures 82, 83 and 84 for $75\mu\text{m}$, $37.5\mu\text{m}$ and $25\mu\text{m}$ wide rib waveguides respectively. These rib dimensions correspond to the dimensions of the implemented guides. From these figures it can be clearly seen that all the guides support several lateral modes. Therefore although this waveguide supports a single mode vertically it is multimode in the lateral direction. Monomode guides supporting only one lateral mode can be fabricated by reducing the rib width and/or the rib depth.

Figure 82. Calculated lateral modes for a 75 μm wide rib

Si/Si_{0.85}Ge_{0.15}/Si Waveguide

Figure 83. Calculated lateral modes for a 37.5 μm

wide rib Si/Si_{0.85}Ge_{0.15}/Si waveguide

Figure 84. Calculated modes for a 25 μm wide rib

Si/Si_{0.85}Ge_{0.15}/Si waveguide

6.2.2 Electro-optic Modulation Characteristics

Using the theoretical curves presented in section 2.2, and the bias current versus carrier density relationship obtained from SEDAN, the modulation depth as a function of the input device current was studied for 75 μm , 37.5 μm and 25 μm wide, 2mm long rib waveguides. In performing these calculations SEDAN assumes that the energy band offset between the Si and Si_{1-x}Ge_x is all in the valence band. Also, for Si_{1-x}Ge_x the effective density of electron and hole states is determined using Si_{1-x}Ge_x parameters for the conduction band and Si parameters for the valence band. The

modulation results obtained from these simulations are plotted in figure 85. The variation in the modulation depth due to carrier density variations through the PIN structure, were also included in this analysis. The attenuation is proportional to the injected carrier density. Hence the modulation depth varies directly with total current and inversely with the electrode area, as shown in figure 85.

Figures 86a and b illustrate the carrier density profile at injection currents of $0.15\mu\text{A}/\text{cm}^2$ and $196\text{A}/\text{cm}^2$. At low injection currents the carrier confinement in the $\text{Si}_{1-x}\text{Ge}_x$ is not noticeable. However, at high injection levels the carrier confinement is clearly visible.

Figure 85. Theoretical modulation depth

Figure 86a. Carrier profile in PIN structure at a injection current of $0.15 \mu\text{A}/\text{cm}^2$

Figure 86b. Carrier profile in PIN structure at a injection current of $196 \text{ A}/\text{cm}^2$

6.2.3 Transient Response Characteristics

Simulations indicate that the transient characteristics of the Si/Si_{1-x}Ge_x/Si diode are very similar to that of an all Si diode. The switch-up/down characteristics, corresponding to an increase/decrease in absorption, shown in figures 87, have time constants of $\tau_{up} = 5\text{ns}$ and $\tau_{down} = 3\text{ns}$ and for both the Si/Si_{1-x}Ge_x/Si and all Si devices. The switch up transient is determined by the diffusion and depletion capacitances of the device while the switch down is dependent not only on these capacitances but also on the electric field in the depletion region.

With no voltage applied to the device the depletion region extends across the intrinsic layer into $0.15\mu\text{m}$ and $0.1\mu\text{m}$ of the P and N regions, respectively. Under high forward bias the built in electric field, E , which restricts carrier flow across the depletion region, is reduced to a fraction of its value at zero bias. This allows a large number of carriers to flow across the junction and leads to high level injection as described in section 5.2. In high level injection, the depletion region is also occupied by a large concentration of free carriers which absorbs the light propagating in the intrinsic and in the surrounding cladding regions. The energy absorbed by the electrons is emitted as phonon modes which heat the crystal lattice. When the applied bias is removed the built in E field begins to recover to its original value. Under the influence of this E field the free electrons and holes in the depletion region are propelled into the N and P regions respectively. Therefore, the carrier density inside the depletion region decays faster than that on the outside. Simulations indicate that the E field takes approximately 6.6 ns to recover to its original unperturbed value. Outside the depletion region the free

carrier movement is determined by carrier diffusion. The influence of the E field on the carriers is thought to be the primary reason that the switch-off transient is faster than the switch-on value. Another factor that could contribute to the switch-off response is carrier recombination. If the recombination time is very small then on switch-off the carrier density inside the device will diminish due to carrier recombination rather than diffusion.

Figure 87. Theoretical transient response of modulator

6.3 Growth, Processing and Testing of the Modulator

The PIN waveguide modulator was grown on a 4" diameter, 350 μ m thick, $2 \times 10^{19} \text{cm}^{-3}$ N doped wafer using MBE growth techniques. A secondary ion mass spectroscopy, SIMS, analysis of the grown wafer revealed the following layer thicknesses and compositions

Material	Doping type	Thickness (μm)	Doping density (cm^{-3})
Si	P^{++}	0.1	1×10^{20}
Si	P^+	2.8	7×10^{15}
$\text{Si}_{0.85}\text{Ge}_{0.15}$	I	0.1	$< 1 \times 10^{15}$
Si	N^+	2.0	5×10^{16}
Si	N^{++}	350	2×10^{19}

To end couple light in and out of the waveguide it is essential that the waveguide end facets be perpendicular to the sample. However, Si has a natural tendency to cleave along the $\langle 111 \rangle$ plane at 35.7° to the sample normal. At this facet orientation it is extremely difficult to couple light in and out of the waveguides. Two methods of facet preparation were considered to obtain perpendicular end facets. The first technique uses a process of trial and error to cleave samples while the second technique involves cleaving and subsequent polishing of the end faces to obtain perpendicular end faces. Past experience seemed to suggest that the polishing technique was only successful on waveguides with guiding layer thicknesses on the order of several microns. As this design has a very thin guiding layer it was realized that the polishing technique would not yield optical quality faces necessary for coupling to and from the modulator. Therefore the trial and error cleaving technique was adopted to cleave these samples. The size of the cleaved samples were approximately 4mm x 2.0cm. Several 2.0mm long waveguides having rib dimensions of $75\mu\text{m}$, $37.5\mu\text{m}$ and $25\mu\text{m}$ were fabricated on these samples.

The next section describes the processing methodology used to fabricate the aforementioned rib waveguides on cleaved $\text{Si}/\text{Si}_{0.85}\text{Ge}_{0.15}/\text{Si}$ samples.

6.3.1 Processing Methodology

The processing methodology used for rib waveguide fabrication is illustrated in figure 88. The 14 steps in the figure below can be subdivided into two subprocesses. Process I, which contains steps 1 through 9, describes the fabrication of metal electrodes and the metalization of the front and back of the sample. Process II, which contains steps 10 through 14, describes the fabrication of the rib waveguides.

Figure 88. Processing methodology

As it is difficult to obtain perpendicular cleaves in most Si materials, which is vital for efficient optical coupling of light in/out of the waveguide devices, a

method of sample prescreening was adopted whereby only those Si/Si_{0.85}Ge_{0.15}/Si samples having perpendicular end facets and good waveguiding characteristics were selected for subsequent processing. During each processing step extreme care was taken to minimize contamination of the cleaved facets. During the metalization and plating steps contamination is minimized by applying photoresist, PR, to the end facets. Another technique that is used for edge protection is to cover the facets with Al foil during metalization. The method of edge protection used for a particular step is determined mainly by the processing environment and also by the sample orientation inside the processing equipment.

In process I the samples are precleaned in a 10% HF solution for 30sec and then rinsed in deionized water for 15 minutes. The cleaved facets are then protected with Al foil and 1.0 μ m of Al is deposited on the backside of the sample. This deposition is done in a cryopumped Blazer CV8 evaporation chamber at a pressure of 1×10^{-6} T. The end facets are then protected with a positive photoresist, HPR504, and the front side of the sample is metalized with 0.15 μ m of Ti. Ti deposition was performed with a Materials Research Corporation (MRC) RF diode sputtering system at a base pressure of 6×10^{-7} T. The photoresist is then removed and the samples are sintered for 20 seconds at a temperature of 400 $^{\circ}$ C in a Ag Associates, Heatpulse 2100 rapid thermal annealer. The PR has to be removed for this process as it is incapable of withstanding temperatures greater than 250 $^{\circ}$ C. The sintering process allows the Al and Ti to react with the Si and provide a low resistance contact. Next the HPR504 is reapplied to the facets and a 500 $\text{\AA}$ thick seed layer of Au is sputtered onto the front of the sample. Then the PR on the

facets is removed and the sample is placed in an oven at 250° for 2 hours to remove any adsorbed moisture. This is a necessary step as moisture degrades PR adhesion.

Titanium acts as a barrier to limit the diffusion of Au into the silicon. Studies have shown that even minute concentrations of Au, which is the material used for the top electrode, act as effective lifetime limiters of free carriers thereby reducing the free carrier density inside the device [99]. Next a $2.0\mu\text{m}$ layer of HPR504 is spun on the front and a dark field mask consisting of $75\mu\text{m}$, $37.5\mu\text{m}$ and $25\mu\text{m}$ rib widths is used to pattern electrodes onto the sample. The dark field mask used for patterning is illustrated in figure 89. After patterning, most of the top surface of the sample is covered with PR except for those areas under the transparent regions of the mask where the gold seed layer is exposed. The sides and back of the sample are covered with PR and then the sample is electroplated in a Au solution and Au electrodes are grown on the exposed Au seed layers. The plating rate varies with the applied current as well as with the plating area. Using this method Au electrodes having an average thickness of approximately $5.0\mu\text{m}$ are grown on the $\text{Si}/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ sample. The top electrodes were fabricated using Au as it has a very low resistivity, thereby minimizing the voltage drop across the electrode at high bias currents. This problem could have also been solved by contacting the top electrode at multiple points. However, this was not possible due to the dimension of the probe apparatus. Once the electrode growth is complete the remaining PR is removed and the Au seed and Ti layers are etched in indium potassium iodide, IKI, and 10% HF acid etches respectively.

In process II a $2.0\mu\text{m}$ thick layer of PR is applied to the front of the wafer

and a light field mask, illustrated in figure 90, is aligned with the wafer so that the dark lines lie directly on top of the metal electrodes. After developing the PR is removed from

Figure 89. Dark field mask

Figure 90. Light field mask

all areas corresponding to the light field area of this mask as illustrated in figure 91. The PR lines created by this patterning process acts as a template for the subsequent Si etching process. The sample is then etched in a Technics PEIIA planar plasma etcher at a power of 100W, pressure of 0.3T and a plasma consisting of 95% CF_4 and 5% O_2 . At these operating conditions the Si etch rate is approximately $0.25\mu\text{m}/\text{min}$. This etching process removes Si from those areas of the sample that are unprotected by PR. After

etching for 12min the remaining PR is removed and the rib depth of the waveguide is measured. It was noticed that the PR was also being etched during the Si etching period. However, if the etching was conducted with sufficient cooling periods the protective PR layer was seen to remain in intact at the end of the etch cycle. Further details on the etch cycle is provided in the latter part of this section.

Figure 91. Waveguide rib template

During processing several problems were encountered. One of the main problems that persisted throughout most of the fabrication steps was the difficulty in handling such small samples. Most of the fabrication equipment that was used was designed for the field of microelectronics processing where the sample sizes are traditionally much larger. Initially 2cmx2cm samples having several sets of parallel electrodes, depicted in figure 92, were processed without much difficulty. However, the

cleaving process required to separate adjacent sets of electrodes produced samples with skewed facets thereby making it impossible to optically couple in/out of these devices. Therefore this approach was discarded in favour of the aforementioned prescreened cleaved sample technique.

Also, due to the size of the samples, PR edge beading was found to be a problem. Edge beading is a phenomena where the spun PR is much thicker at the edges of the sample than in the middle. This thickness variation, which arises due to the surface tension of the PR, affects the patterning of the electrodes at the edges of the samples. When the sample is developed all the PR at the edges is not removed. Therefore, after plasma etching the rib waveguide does not extend all the way to the sample edges as depicted in figure 93. The lack of rib definition at the edges reduces the lateral confinement of the guided mode. In the field of microelectronics edge beading is not a problem as the sample edges are discarded after processing.

Tests performed on the plasma etcher indicated that the etch rate was quite nonuniform. The edges of a sample were preferentially etched compared to the centre, also the etch rate was quite sensitive to sample position and to the total area of Si in contact with the plasma inside the etcher. To eliminate the edge and area effects a dummy 2" Si wafer was placed in the etcher and the samples were placed on the centre of this wafer. Also the sample position inside the etcher was not varied and the etch rate was calibrated for a particular sample position. Etch tests also indicated that the PR lines that served as a template for the fabrication of the waveguide ribs were damaged due to excessive heating if etched continuously for more than 8 min at the specified operating

conditions. Experiments revealed that line damage could take on two forms. First, the most common type of damage was the serration of the line edges leading to the formation of jagged edged waveguides. The second type of damage was the disintegration of entire pieces of the guide. The first type of damage was more common than the latter. To preserve the PR line definition during etching the samples were etched in stages with a cooling interval in between each etch period. This technique proved to be successful in stopping the PR line degradation.

2cmX2cm sample

Figure 92. 2cmx2cm samples

Figure 93. Edge beading

Using this processing methodology rib waveguides were fabricated on prescreened $\text{Si}/\text{Si}_{0.85}\text{Ge}_{0.15}/\text{Si}$ samples. The next section presents the experimental modulation and switching characteristics of these devices.

6.3.2 Experimental Modulation Characteristics

The modulation characteristics of the $\text{Si}/\text{Si}_{0.85}\text{Ge}_{0.15}/\text{Si}$ rib waveguide were observed using the setup illustrated in figure 94. The 160mW, $\lambda = 1.3\mu\text{m}$, CW output of the Lightwave Electronics ring Nd:YAG laser was end coupled into a monomode fiber using a precision lens coupler. The monomode fibre had a core diameter of $8\mu\text{m}$ and a numerical aperture of 0.12. The output of the fibre was end coupled into the input of a rib waveguide modulator. The light at the output of the modulator was focused through

a x10 microscope objective on to a detector. The output of the detector was observed on a LeCroy 9400 oscilloscope. An iris placed in front of the detector was used to block any extraneous scattered light from reaching the detector.

Figure 94. Modulation setup

The output light was modulated by forward biasing the diode thereby causing a current to flow through the device. To forward bias the device and drive it into high level injection voltage of between 50-100V was applied to the top electrode using a metal probe. The bottom electrode was glued on to an Al block, using conducting epoxy, and was grounded through a 50 Ω resistor. The positive voltage pulse was supplied

by a HP204 pulse generator. The modulating pulse was 0.5ms wide and the operating duty cycle was 0.05. A typical modulation pulse and the corresponding modulator output, observed on the oscilloscope, are illustrated in figure 95. The slope in the detected signal is due to noise on the laser output.

Figure 95. Experimentally observed modulation (Sample #1489)

The measured modulation characteristics of the $75\mu\text{m}$, $37.5\mu\text{m}$ and $25\mu\text{m}$ wide rib waveguides are presented in figure 96 along with the corresponding theoretical curves. As can be seen the theoretical modulation depths are much larger than the experimentally obtained results. The discrepancy between these two sets of data can be attributed to the presence of traps in the material. The effect of traps can be analyzed using a simple model which assumes that

$$n = \Gamma J^{1/2} - N_0 \quad (108)$$

and that

$$\frac{\delta n}{\delta t} = \frac{1}{2} \Gamma J^{-1/2} \frac{\delta J}{\delta t} - n \sigma (N_t - N_0) + N_0 \gamma \quad (109)$$

where

- σ is the capture cross section
- N_t is the trap density
- N_0 is the density of empty traps
- J is the incident current density
- γ is the trap escape rate
- Γ is a constant

Simulations on SEDAN revealed that the free carrier concentration, n , varied as $J^{1/2}$.

At steady state $\delta n / \delta t = 0$, $\delta J / \delta t = 0$ and equation 109 reduces to

$$n \sigma (N_t - N_0) = N_0 \gamma \quad (110)$$

Equations 108 and 110 are solved simultaneously to obtain the free carrier density, n , as a function of σ, γ and N_t .

The theoretical curves obtained using this model, illustrated in figure 97, bear a close correlation to the corresponding experimental values. For the curves illustrated in this figure the best correlation between the experimental and theoretical data

Figure 96. Experimentally observed modulation characteristic (Sample #1489)

Figure 97. Modulation characteristics accounting for traps (Sample #1489)

were obtained for average cladding and core trap densities of $1 \times 10^{18} \text{ cm}^{-3}$ and $5 \times 10^{18} \text{ cm}^{-3}$ respectively.

In the next section the experimentally determined transient data for the rib waveguide modulators are presented.

6.3.3 Experimental Transient Characteristics

The experimentally observed switching characteristics for the $\text{Si}/\text{Si}_{0.85}\text{Ge}_{0.15}/\text{Si}$ electro-optic modulator are illustrated in figure 98 for a $37.5 \mu\text{m}$ wide rib waveguide at an input current of $I=0.6\text{A}$. From this figure it is seen the response occurs in four unique components. Components I and II are associated with the switch up, (increase in absorption), while components III and IV are related to the switch down (decrease in absorption).

Figure 98. Switching characteristic for a $37.5 \mu\text{m}$ waveguide (Sample #1489)

When the diode is forward biased, carriers enter the device from the N and P regions and

begin to fill the traps resident in the material. The results shown in figure 82 suggest that this material has two different types of traps, each having a distinct time constant. The fast time constant, measured to be 80ns, associated with component I is due to the trapping and detrapping of fast, shallow traps. Transient measurements conducted with and without the modulator indicated that the lowest measurable time constant was limited by the bandwidth of the driving circuitry to 80ns. Therefore, the transition time measured for component I is a measured upper limit, and the intrinsic device rise time is expected to be closer to the theoretical limit of 5ns. The slow component, denoted by II, having a time constant of $4\mu\text{s}$, is primarily due to the filling and emptying of the slow, deep level traps. In forward bias these traps are continually filled and emptied at their associated trapping and detrapping time constants. When the applied bias is removed at switch off, the excess carriers recombine leading to a decrease in the device modulation depth. Also, at the same time the trapped carriers begin to empty. If this material has two types of traps, each having different detrapping times, then it is clearly seen that the detrapping of one type of carrier leads to an increase in the device modulation depth which will once again diminish when the opposite carrier type is released. This type of detrapping behaviour will lead to the presence of components III and IV observed in this device. The slow rise and fall transients, components II and IV, have been observed before in amorphous silicon PIN diodes [100]. The authors of this paper attributed these transients to the filling and emptying of traps resident in the material. In this work, the deep level traps may have been introduced by the gold seed layer diffusing into the Si during processing and/or due to impurities resident in the original growth material. Gold

is known to form both a deep level acceptor and donor trap in Si and may be responsible for the presence of transient components III and IV. The shallow traps may also have been introduced during processing or they may have been present in the original growth material. To date no deep level transient spectroscopy (DLTS) measurements have been performed on this material to confirm this hypothesis. It was observed that the slow transient components only become noticeable at input currents exceeding 0.15A. From this it can be concluded that the deep level traps only begin to fill once all the shallow traps are filled.

In the absence of traps the switching transient should have very fast switch up and down characteristics similar to those observed at low bias voltages. The slow switching transients associated with the traps should be absent from the switching transient response.

6.4 Conclusion

A novel Si/Si_{1-x}Ge_x/Si PIN diode electro-optic waveguide modulator was designed and implemented using MBE growth techniques for the first time. Prescreened pieces of planar waveguide were processed into rib waveguides having electrode dimensions of 75 μ m, 37.5 μ m and 25 μ m by 2mm. The maximum modulation depths of these waveguides were 54%, 66% and 85%, at an input current of 2.1A for the 75 μ m, 37.5 μ m and 25 μ m devices respectively. At 2.1A the device current densities were 1400A/cm², 2800A/cm² and 4200A/cm² respectively.

The transient analysis of this device revealed fast and slow rise and fall

time components. The measurement of the fast time components, observed to have a time constant of 80ns, was limited by the parasitics of the measuring apparatus. The slow components, having a half power decay time of $4\mu\text{s}$, are believed to be caused by traps in the material.

This device is suitable for use with other optoelectronics in either an OEIC or hybrid form. As this modulator employs free carrier absorption, its performance is insensitive to both the input light polarization and the guided optical wavelength for wavelengths between 1.3 and $2.0\mu\text{m}$. Although this modulator was designed for use at $\lambda = 1.3\mu\text{m}$, simulations indicate that it also works well at $1.55\mu\text{m}$. Hence, this device is ideal for use in fiber communication environment in the range of $\lambda = 1.3\mu\text{m}$ and $1.55\mu\text{m}$, and modelling suggests that it is capable of operating at speeds of up to 200MHz.

The aim of this work, which was the design, implementation and testing of a $\text{Si}/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ modulator, has been successfully completed. Furthermore, this work represents the first demonstration of a $\text{Si}/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ PIN diode electro-absorption modulator grown using molecular beam epitaxy.

7.0 Conclusions and Future Work

7.1 Conclusions

In this work, an all optical switch and an opto-electronic modulator were designed and implemented for the first time using Si/Si_{1-x}Ge_x alloy. The optical switch, operating at $\lambda = 1.06\mu\text{m}$, and designed using 46 layers of Si/Si_{1-x}Ge_x, was grown on a Si substrate using MBE growth techniques. This structure demonstrated thermal switching with reflectivity contrast ratios, $\Delta R/R$, of 100% and 50% for the increase and decrease reflectivity switching characteristics respectively. In this structure optical bistability was not observed due to the short free carrier lifetime brought about by the high dislocation density in the Si/Si_{1-x}Ge_x multilayers.

Using a numerical multilayer algorithm the performance characteristics of several multilayer structures were analyzed. Using an optical pump-probe technique the free carrier lifetime in the implemented DBR structure was measured to be 100ps. These measurements indicate that an improvement in the Si/Si_{1-x}Ge_x material quality is required for optical bistability to be observed in these materials.

The Si/Si_{1-x}Ge_x/Si optoelectronic modulator, operating at $\lambda = 1.3\mu\text{m}$, was analyzed using optical and electronic device simulation packages and was grown on a Si substrate using MBE growth techniques. Devices having rib widths of $75\mu\text{m}$, $37.5\mu\text{m}$ and $25\mu\text{m}$ and lengths of 2mm were implemented. The maximum modulation depths for these devices were 54%, 66% and 85% respectively at an input current of 2.1A. Transient

analysis of this device revealed fast and slow rise and fall time components. The measurement of the fast time component was not possible because of the 80ns response time of the measurement apparatus. Modelling suggests that these devices are capable of operating at speeds of up to 200MHz.

The development of optics in Si/Si_{1-x}Ge_x would enable these components to be integrated with existing Si electronics on a common Si substrate, thereby facilitating the design of more complex OEIC's than those available at present.

7.2 Future Work

The Si/Si_{1-x}Ge_x multilayer stack implemented in this work did not display all optical switching due to the high dislocation density in the structure. However, it did demonstrate thermo-optic switching, the characteristics of which have been described in chapter 4. It has long been realized that the implementation of high quality Si_{1-x}Ge_x optical devices is not only dependent on device design but also on the material quality of the Si_{1-x}Ge_x. Preliminary work on dislocation reducing buffer layers indicate that the deposition of an accurate, low compositionally graded buffer would lead to better strain symmetrization and hence lower dislocation counts than those achieved in the initial growths described in section 4.1. To evaluate the variation in dislocation density with low buffer grading rates several structures having grading rates of 2%, 3% and 6% Ge/ μ m could be grown with and without the equistrain pedestal. Figure 99 illustrates two of the proposed structures. The equistrain pedestal is a homogeneous capping layer which has the same alloy composition as that corresponding to the top of the graded buffer. As

compositional accuracy of the graded buffer is of utmost importance for proper strain symmetrization any growth variations in the MBE machine would have to be corrected. On occasion the MBE machine has been known to suffer from long term drifts in growth parameters. This could be corrected by periodically resetting the deposition parameters during growth or by dividing long growth cycles into shorter ones. TEM and etch pit tests could be used to determine the dislocation density in the material while photoconductivity tests performed at various temperatures could be used to evaluate the deep and shallow trap levels associated with the impurities in the samples. The cross sectional TEM analysis can also be used to determine the deposition accuracy of the multilayer structure. This information can then be used to correct the deposition rates of the MBE machine if necessary. The pump-probe measurement technique outlined in section 4.2 can be used to evaluate the lifetime characteristics of the material.

Once the material quality of the $\text{Si}/\text{Si}_{1-x}\text{Ge}_x$ multilayers is improved and found to be suitable for device fabrication, various devices as outlined in section 2.1 can be implemented using Fabry-Perot(FP), Distributed feedback (DFB) and combined FP/DFB structures. These devices, as mentioned previously, can perform a variety of basic circuit functions and would be invaluable to the design of both hybrid and integrated Si optical and opto-electronic integrated circuits .

The modulation and switching performance of the $\text{Si}/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ modulator was seen to be adversely affected by the high density of traps in the material. The experimentally observed modulation depth was much smaller than the theoretically calculated values. The traps are thought to be associated with Au atoms from the top seed

layer which diffused into the material during the two hour, 250C, oven bake prior to the patterning of the gold electrode on the planar waveguide. As mentioned earlier gold forms an effective trapping centre in Si. In a subsequent implementation of this design the gold seed layer and electrode could be replaced by Al. The Al could be deposited by a sputter technique in which the rib is first etched in the planar Si guide and then an oxide layer is deposited on top of the guide partially covering the rib. Then the Al is deposited on top thereby directly contacting the top of the rib. The bottom electrode can be fabricated using Al as was done in this design. This type of design in which the top metal electrode has a larger dimension than the area of the Si rib makes for easier contacting with probes or bondwires. This fabrication technique is already used to manufacture semiconductor lasers so there should be little difficulty in adjusting it to implement this type of modulator. The only additional requirement in this fabrication process is the need to protect the end facets of the samples during metalization steps. This has been done with great success in the implementation of the devices tested in this work so little trouble is anticipated in repeating these steps with the new process.

According to the theoretical calculations for modulation depth as a function of the input current, presented in section 6.3.2, the reduction of trap density in the material would greatly increase the modulation depths at all input currents. The largest increase in modulation depth is expected at input currents less than 1.2A. Also, it can be easily seen that the input currents for the present designs could be reduced by using smaller rib widths.

Two other interference modulators, the Mach-Zehnder and the dual

channel directional coupler designs described in section 5.0, could also be implemented. These devices, which require only a phase change between the light propagating in the two arms to produce modulation, require greater processing complexity than the single rib waveguide. As only a refractive index change is required to obtain a phase change in the propagating light, far fewer carriers are required than in the case of the electro-absorption modulator in which a very high carrier density was needed. Therefore, the same modulation depths as those observed for the single rib electro-absorption waveguide modulator could be obtained using only a fraction of the input current. However the operation of these structures is more sensitive to ambient temperature changes.

Figure 99. Buffer layer growths

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Appendix A

Data for Fabry-Perot and combined Fabry-Perot/DFB structures as a function of linear and nonlinear mirror number.

Fabry-Perot data**Table I** Change in switch ON threshold, hysteresis width and transmission as a function of the FP linear mirror number

Linear mirror number	Switch On Threshold(W/m ²)	Hysteresis Width (%)	Transmission (%)
Opt Num = N	8.3×10^{10}	41	9.1
N+2	1.6×10^{11}	63	4.6
N+4	3.3×10^{11}	72	2.2
N+6	7.0×10^{11}	77	1.0
N-2	5.4×10^{10}	37	10.7
N-4	-	-	-

Fabry-Perot data**Table II** Change in switch ON threshold, hysteresis width and transmission as a function of the FP nonlinear mirror number

Nonlinear mirror number	Switch On Threshold(W/m ²)	Hysteresis Width (%)	Transmission (%)
Opt Num = NL	8.3×10^{10}	41	9.1
NL+10	9.0×10^{10}	55	4.7
NL+20	9.9×10^{10}	62	2.5
NL+30	1.1×10^{11}	66	1.4
NL+40	1.2×10^{11}	67	0.7
NL-10	8.2×10^{10}	16.4	12.2
NL-20	-	-	-

FP/DFB 2 mirror data

Table III Change in switch ON threshold, hysteresis width and transmission as a function of the FP/DFB bottom linear mirror number

Bottom Linear Mirror Number	Switch On Threshold(W/m ²)	Hysteresis Width (%)	Transmission (%)
Opt Num = BL	6.4×10^{10}	67	17.8
BL+2	7.1×10^{10}	77	9.2
BL+4	7.8×10^{10}	80	4.3
BL+6	8.7×10^{10}	81	2.0
BL+8	9.6×10^{11}	84	1.0
BL-2	6.1×10^{10}	42	33.1
BL-4	-	-	-

FP/DFB 2 mirror data

Table IV Change in switch ON threshold, hysteresis width and transmission as a function of the FP/DFB top linear mirror number

Top Linear Mirror Number	Switch On Threshold(W/m ²)	Hysteresis Width (%)	Transmission (%)
Opt Num = TL	6.4×10^{10}	66	17.8
TL+2	1.5×10^{11}	80	9.1
TL+4	3.6×10^{11}	86	4.5
TL+6	8.4×10^{11}	88	2.1
TL+8	2.0×10^{12}	89	1.0
TL-2	3.0×10^{10}	31	32.1
TL-4	-	-	-
TL-6	-	-	-

FP/DFB 2 mirror data**Table V** Change in switch ON threshold, hysteresis width and transmission as a function of the FP/DFB nonlinear core layer number

NonLinear Core Number	Switch On Threshold(W/m ²)	Hysteresis Width (%)	Transmission (%)
Opt Num = NC	6.4×10^{10}	66	17.8
NC+2	8.9×10^{10}	79	10.8
NC+4	1.2×10^{11}	85	6.3
NC+6	1.5×10^{11}	88	4.8
NC+8	1.8×10^{11}	90	3.6
NC-2	4.3×10^{10}	42	34.6
NC-4	-	-	-
NC-6	-	-	-
NC-8	-	-	-

FP/DFB Single mirror data**Table VI** Change in switch ON threshold, hysteresis width and transmission as a function of the FP/DFB single mirror design linear mirror number

Linear mirror Number	Switch On Threshold(W/m ²)	Hysteresis Width (%)	Transmission (%)
Opt Num = N	8.0×10^{10}	17	16.0
N+2	1.6×10^{11}	41	6.9
N+4	3.4×10^{11}	53	3.5
N+6	7.1×10^{11}	57	1.7
N+8	-	-	-
N-2	-	-	-

FP/DFB Single mirror data**Table VII Change in switch ON threshold, hysteresis width and transmission
as a function of the FP/DFB single mirror design nonlinear mirror number**

Nonlinear	Switch On	Hysteresis Width	Transmission
Opt Num = NL	8.0×10^{10}	17	16.0
NL+10	8.4×10^{10}	44	7.6
NL+20	9.1×10^{10}	57	4.2
NL+30	1.1×10^{11}	66	1.1
NL+40	-	-	-
NL-10	-	-	-

Appendix B

Data for the TE and TM mode losses in a Si/Si_{1-x}Ge_x/Si modulator as a function of Si_{1-x}Ge_x guiding layer thickness, Ge composition (between 0.05 and 0.20) and P and N cladding layer thicknesses.

Table VIII TE and TM mode losses for Si/Si_{1-x}Ge_x modulator, x=0.05,

$$t_{\text{sigc}} = 0.05 \mu\text{m}$$

P cladding (μm)	N cladding (μm)	TE waveguide loss(dB/cm)	TM waveguide loss(db/cm)
0.5	0.5	635	-
0.5	1.0	265	415
0.5	1.5	137	211
0.5	2.0	80.9	123
0.5	2.5	52.1	77.8
1.0	0.5	276	384
1.0	1.0	127	180
1.0	1.5	68.8	101
1.0	2.0	42	63.3
1.0	2.5	27.8	43
1.5	0.5	164	210
1.5	1.0	79.6	104
1.5	1.5	44	59.4
1.5	2.0	26.9	37.7
1.5	2.5	17.7	25.9
2.0	0.5	112	137
2.0	1.0	57.7	70.9
2.0	1.5	32.5	41
2.0	2.0	19.9	26
2.0	2.5	13	17.7
2.5	0.5	82.7	97.1
2.5	1.0	45.2	53.2

2.5	1.5	26.1	31.2
2.5	2.0	16.1	19.8
2.5	2.5	10.5	13.4

Table IX TE and TM mode losses for Si/Si_{1-x}Ge_x modulator, $x=0.05$

$$t_{\text{sigc}} = 0.100 \mu\text{m}$$

P cladding (μm)	N cladding (μm)	TE waveguide loss(dB/cm)	TM waveguide loss(db/cm)
0.5	0.5	427	728
0.5	1.0	177	321
0.5	1.5	91.5	173
0.5	2.0	54.3	106
0.5	2.5	35.3	70.1
1.0	0.5	207	287
1.0	1.0	84.1	127
1.0	1.5	41.3	69.9
1.0	2.0	23.1	44.5
1.0	2.5	14.3	31.3
1.5	0.5	142	174
1.5	1.0	57.9	75.5
1.5	1.5	27.5	39.4
1.5	2.0	14.7	23.8
1.5	2.5	8.6	16.1
2.0	0.5	111	128
2.0	1.0	46.7	55.6
2.0	1.5	22.1	27.9
2.0	2.0	11.6	16
2.0	2.5	6.6	10.2
2.5	0.5	93.5	103
2.5	1.0	40.7	45.8

2.5	1.5	19.3	22.7
2.5	2.0	10.1	12.5
2.5	2.5	5.7	7.6

Table X TE and TM mode losses for Si/Si_{1-x}Ge_x modulator, x=0.05

$$t_{\text{sigc}} = 0.200 \mu\text{m}$$

P cladding (μm)	N cladding (μm)	TE waveguide loss(dB/cm)	Tm waveguide loss(db/cm)
0.5	0.5	203	400
0.5	1.0	71.3	190
0.5	1.5	32.6	118
0.5	2.0	18.6	85.5
0.5	2.5	12.2	68.4
1.0	0.5	120	165
1.0	1.0	36.4	63.7
1.0	1.5	13.8	34.8
1.0	2.0	6.60	24.8
1.0	2.5	4.0	20.9
1.5	0.5	98.8	116
1.5	1.0	29.3	38.5
1.5	1.5	10.6	17.2
1.5	2.0	4.9	10.3
1.5	2.5	2.9	7.9
2.0	0.5	90.6	99.4
2.0	1.0	26.7	31.0
2.0	1.5	9.5	12.2
2.0	2.0	4.2	6.2
2.0	2.5	2.4	4.2
2.5	0.5	87.0	92.6
2.5	1.0	25.8	28.4

2.5	1.5	9.1	10.5
2.5	2.0	4.0	4.9
2.5	2.5	2.3	2.9

Table XI TE and TM mode losses for Si/Si_{1-x}Ge_x modulator, x=0.05

$$t_{\text{sep}} = 0.300 \mu\text{m}$$

P cladding (μm)	N cladding (μm)	TE waveguide loss(dB/cm)	TM waveguide loss(db/cm)
0.5	0.5	107	244
0.5	1.0	31.3	129
0.5	1.5	26.1	97.7
0.5	2.0	10.1	87.3
0.5	2.5	8.9	83.5
1.0	0.5	72.0	99.2
1.0	1.0	17.1	34.6
1.0	1.5	6.0	20.8
1.0	2.0	3.5	17.5
1.0	2.5	2.9	16.6
1.5	0.5	64.8	74.7
1.5	1.0	14.6	19.4
1.5	1.5	4.5	8.0
1.5	2.0	2.3	5.3
1.5	2.5	1.8	4.7
2.0	0.5	62.8	68.8
2.0	1.0	14.0	16.1
2.0	1.5	4.2	5.3
2.0	2.0	2.1	2.9
2.0	2.5	1.6	2.3
2.5	0.5	62.2	67.2
2.5	1.0	13.8	15.4

2.5	1.5	4.2	4.7
2.5	2.0	2.1	2.3
2.5	2.5	1.6	1.8

Table XII TE and TM mode losses for Si/Si_{1-x}Ge_x modulator, $x=0.05$

$$t_{\text{sig}} = 0.400 \mu\text{m}$$

P cladding (μm)	N cladding (μm)	TE waveguide loss(dB/cm)	TM waveguide loss(db/cm)
0.5	0.5	61.4	163
0.5	1.0	16.5	97.5
0.5	1.5	9.0	84.5
0.5	2.0	7.6	81.6
0.5	2.5	7.3	80.9
1.0	0.5	44.9	62.0
1.0	1.0	8.9	20.4
1.0	1.5	3.4	13.6
1.0	2.0	2.5	12.5
1.0	2.5	2.3	12.3
1.5	0.5	42.2	48.3
1.5	1.0	7.9	10.4
1.5	1.5	2.6	4.4
1.5	2.0	1.8	3.4
1.5	2.5	1.6	3.2
2.0	0.5	41.6	45.9
2.0	1.0	7.7	8.8
2.0	1.5	2.5	2.9
2.0	2.0	1.7	2.0
2.0	2.5	1.5	1.8
2.5	0.5	41.5	45.5
2.5	1.0	7.6	8.5

2.5	1.5	2.5	2.7
2.5	2.0	1.6	1.7
2.5	2.5	1.5	1.5

Table XIII TE and TM mode losses for Si/Si_{1-x}Ge_x modulator, x=0.10

$$t_{\text{age}} = 0.050 \mu\text{m}$$

P cladding (μm)	N cladding (μm)	TE waveguide loss(dB/cm)	TM waveguide loss(db/cm)
0.5	0.5	470	823
0.5	1.0	193	356
0.5	1.5	99.0	189
0.5	2.0	58.9	115
0.5	2.5	38.7	75.5
1.0	0.5	222	313
1.0	1.0	89.0	139
1.0	1.5	43.8	76.3
1.0	2.0	24.8	48.6
1.0	2.5	15.6	34.3
1.5	0.5	151	188
1.5	1.0	61	81.4
1.5	1.5	29.1	42.8
1.5	2.0	15.8	26.1
1.5	2.5	9.6	18
2.0	0.5	118	136
2.0	1.0	49.1	59.4
2.0	1.5	23.3	30.2
2.0	2.0	12.4	17.6
2.0	2.5	7.4	11.6
2.5	0.5	99.1	108
2.5	1.0	42.8	48.7

2.5	1.5	20.4	24.5
2.5	2.0	11.0	13.9
2.5	2.5	6.4	8.8

Table XIV TE and TM mode losses for Si/Si_{1-x}Ge_x modulator, x=0.10

$$t_{\text{sigc}} = 0.100 \mu\text{m}$$

P cladding (μm)	N cladding (μm)	TE waveguide loss(dB/cm)	TM waveguide loss(db/cm)
0.5	0.5	238	499
0.5	1.0	81.9	234
0.5	1.5	37.7	142
0.5	2.0	21.6	100
0.5	2.5	14.9	77.9
1.0	0.5	136	194
1.0	1.0	39.8	74.2
1.0	1.5	15.1	40.6
1.0	2.0	7.5	29.1
1.0	2.5	4.9	24.5
1.5	0.5	111	134
1.5	1.0	31.3	43.5
1.5	1.5	11.0	19.2
1.5	2.0	5.0	11.5
1.5	2.5	3.0	8.8
2.0	0.5	102	114
2.0	1.0	28.6	35.4
2.0	1.5	9.8	13.4
2.0	2.0	4.3	6.8
2.0	2.5	2.5	4.5
2.5	0.5	98.1	106
2.5	1.0	27.7	31.7

2.5	1.5	9.4	11.7
2.5	2.0	4.1	5.3
2.5	2.5	2.4	3.2

Table XV TE and TM mode losses for Si/Si_{1-x}Ge_x modulator, x=0.10

$$t_{\text{sigc}} = 0.200 \mu\text{m}$$

P cladding (μm)	N cladding (μm)	TE waveguide loss(dB/cm)	TM waveguide loss(db/cm)
0.5	0.5	74.5	239
0.5	1.0	19.3	147
0.5	1.5	11.6	129
0.5	2.0	10.4	126
0.5	2.5	10.3	125
1.0	0.5	52.9	78.9
1.0	1.0	9.2	24.9
1.0	1.5	3.7	17.3
1.0	2.0	2.9	16.0
1.0	2.5	2.8	15.9
1.5	0.5	50.0	60.8
1.5	1.0	8.1	11.7
1.5	1.5	2.9	4.9
1.5	2.0	2.2	3.9
1.5	2.5	2.1	3.7
2.0	0.5	49.6	58.0
2.0	1.0	7.9	9.9
2.0	1.5	2.7	3.3
2.0	2.0	2.0	2.3
2.0	2.5	1.9	2.1
2.5	0.5	49.5	57.6
2.5	1.0	7.9	9.6

2.5	1.5	2.7	3.0
2.5	2.0	2.0	2.0
2.5	2.5	1.9	1.9

Table XVI TE and TM mode losses for Si/Si_{1-x}Ge_x modulator, x=0.15

$$t_{\text{sigc}} = 0.050$$

P cladding (μm)	N cladding (μm)	TE waveguide loss(dB/cm)	TM waveguide loss(db/cm)
0.5	0.5	346	-
0.5	1.0	131	305
0.5	1.5	63.7	169
0.5	2.0	36.5	107
0.5	2.5	23.5	73.8
1.0	0.5	179	260
1.0	1.0	60.8	107
1.0	1.5	25.9	57.5
1.0	2.0	13.1	37.7
1.0	2.5	7.9	28.3
1.5	0.5	135	167
1.5	1.0	45	63
1.5	1.5	18.1	30.2
1.5	2.0	8.6	17.7
1.5	2.5	4.9	12.4
2.0	0.5	117	131
2.0	1.0	39.7	48.8
2.0	1.5	16.1	22.0
2.0	2.0	7.8	12.0
2.0	2.5	4.6	7.9
2.5	0.5	108	114
2.5	1.0	37.0	42.5

2.5	1.5	15.0	18.5
2.5	2.0	7.2	9.6
2.5	2.5	4.2	5.9

Table XVII TE and TM mode losses for Si/Si_{1-x}Ge_x modulator, x=0.15

$$t_{\text{sig}} = 0.100$$

P cladding (μm)	N cladding (μm)	TE waveguide loss(dB/cm)	TM waveguide loss(db/cm)
0.5	0.5	138	337
0.5	1.0	39.8	196
0.5	1.5	20.4	145
0.5	2.0	15.9	127
0.5	2.5	14.7	119
1.0	0.5	90.3	137
1.0	1.0	20.4	47.3
1.0	1.5	8.4	29.1
1.0	2.0	6.1	24.9
1.0	2.5	5.6	23.8
1.5	0.5	81.8	101
1.5	1.0	17.6	25.8
1.5	1.5	6.7	11.3
1.5	2.0	4.7	8.1
1.5	2.5	4.3	7.40
2.0	0.5	79.9	93.0
2.0	1.0	17.1	21.6
2.0	1.5	6.4	7.9
2.0	2.0	4.4	4.9
2.0	2.5	4.0	4.4
2.5	0.5	79.2	90.8
2.5	1.0	16.9	20.6

2.5	1.5	6.3	7.2
2.5	2.0	4.4	4.3
2.5	2.5	4.0	3.6

Table XVIII TE and TM mode losses for Si/Si_{1-x}Ge_x modulator, x=0.15

$$t_{\text{sig}} = 0.150$$

P cladding (μm)	N cladding (μm)	TE waveguide loss(dB/cm)	TM waveguide loss(db/cm)
0.5	0.5	66.0	251
0.5	1.0	20.4	168
0.5	1.5	15.7	155
0.5	2.0	15.2	152
0.5	2.5	15.1	152
1.0	0.5	48.5	75.3
1.0	1.0	10.9	25.2
1.0	1.5	7.4	19.4
1.0	2.0	7.0	18.7
1.0	2.5	7.0	18.6
1.5	0.5	46.8	59.0
1.5	1.0	10.1	12.6
1.5	1.5	6.7	7.4
1.5	2.0	6.3	6.7
1.5	2.5	6.3	6.7
2.0	0.5	46.5	57.1
2.0	1.0	10.0	11.2
2.0	1.5	6.6	6.0
2.0	2.0	6.2	5.4
2.0	2.5	6.2	5.4
2.5	0.5	46.5	56.7
2.5	1.0	10.0	11.0

2.5	1.5	6.6	5.9
2.5	2.0	6.2	5.2
2.5	2.5	6.2	5.2

Table XIX TE and TM mode losses for Si/Si_{1-x}Ge_x modulator, $x=0.20$

$$t_{\text{age}} = 0.050 \mu\text{m}$$

P cladding (μm)	N cladding (μm)	TE waveguide loss(dB/cm)	TM waveguide loss(db/cm)
0.5	0.5	-	-
0.5	1.0	83.5	-
0.5	1.5	39.1	157
0.5	2.0	23.7	109
0.5	2.5	17.5	82.7
1.0	0.5	141	-
1.0	1.0	40.9	82.9
1.0	1.5	16.7	45.9
1.0	2.0	9.6	33.0
1.0	2.5	7.4	28.0
1.5	0.5	117	147
1.5	1.0	32.8	48.7
1.5	1.5	12.7	22.4
1.5	2.0	7.1	14.0
1.5	2.5	5.4	11.1
2.0	0.5	110	124
2.0	1.0	30.4	39.0
2.0	1.5	11.6	16.1
2.0	2.0	6.4	8.9
2.0	2.5	4.9	6.4
2.5	0.5	106	116
2.5	1.0	29.7	34.7

2.5	1.5	11.3	14.0
2.5	2.0	6.2	7.3
2.5	2.5	4.7	5.0

Table XX TE and TM mode losses for Si/Si_{1-x}Ge_x modulator, x=0.20

$$t_{\text{sig}} = 0.100 \mu\text{m}$$

P cladding (μm)	N cladding (μm)	TE waveguide loss(dB/cm)	TM waveguide loss(db/cm)
0.5	0.5	84.3	307
0.5	1.0	28.3	192
0.5	1.5	22.0	171
0.5	2.0	21.2	166
0.5	2.5	21.1	165
1.0	0.5	61.5	-
1.0	1.0	16.6	34.1
1.0	1.5	12.3	25.7
1.0	2.0	11.8	24.4
1.0	2.5	11.7	24.3
1.5	0.5	59.1	75.9
1.5	1.0	15.5	18.4
1.5	1.5	11.2	11.0
1.5	2.0	10.7	9.9
1.5	2.5	10.6	9.8
2.0	0.5	58.6	72.9
2.0	1.0	15.4	16.4
2.0	1.5	11.0	9.2
2.0	2.0	10.6	8.1
2.0	2.5	10.5	7.9
2.5	0.5	58.6	72.2
2.5	1.0	15.4	16.0

2.5	1.5	11.0	8.8
2.5	2.0	10.5	7.8
2.5	2.5	10.5	7.7

END

2 1-1 1-9 5

FIN