An Electronically-Tunable Bragg Grating in Silicon-On-Insulator

By

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Submitted by Kevin Ramdas, B. Sc.
in partial fulfillment of the requirements for the degree of
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Carleton University
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Abstract

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In this thesis, we will present an electronically-tunable first order Bragg grating filter for $1.5\ \mu\text{m}$ light that has been designed in silicon-on-insulator (SOI) rib waveguide technology. Tuning is achieved by modifying the refractive index in the SOI rib through the injection of free carriers. Prototypes were fabricated using e-beam direct write lithography and ECR plasma etching to define a grating with 225 nm period. This thesis will cover theory and design, but will focus on the fabrication and testing of the device. Because the only sample fabricated showing good electrical characteristics shattered during preparation for optical tests, we simulated electrooptic modulation by optically-generating carriers. The peak filter wavelength was found to shift to a shorter wavelength by approximately 0.08 nm from 1534.7 nm when free carriers were generated in the grating by illumination with a 25 mW HeNe laser.

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Chapter 1: Introduction

1.1 Overview

Silicon photonic devices, especially those operating in the fibre-optic telecommunication band, are drawing increasing attention. The idea of integrating photonic components on chip with CMOS technology opens up a vast range of commercial opportunities. The ability to mass produce this type of device causes the resulting chips to have significantly lower fabrication costs [Nay99].

Silicon-on-Insulator (SOI) substrates provide a platform to integrate electronic and optic devices. The SOI substrate is considered to have a high-index contrast (HIC), meaning that there is a large difference between the core index of refraction and the cladding index of refraction in a waveguide. The result is that abrupt changes in light direction and flow can be made in relatively short distances in comparison to standard low index contrast materials. This leads to smaller devices and lower unit costs.

A number of passive optical devices on SOI have been thoroughly examined, such as filters, waveguides and couplers. Recent research has focused on active silicon-based optical devices. The Bragg grating is the focus of this thesis. In the past, thermal and mechanical modulation have been used for tuning silicon photonic devices [Fis95], at the expense of speed and cost. Hence more recently, researchers have been examining the plasma dispersion effect for modulating the refractive index of silicon [Zha95, Wal02, Bar03].

Cutolo *et al.* proposed a Bragg grating filter on a SOI waveguide that can be electronically-tuned. To our knowledge, this device has not been physically-realized.

Figure 1.1: Proposed Device [Cut97]

1.2 Previous Work

Cutolo *et al.* proposed and analyzed the electronically-tunable Bragg grating. Electronic tuning is achieved by placing a lateral pin diode across the Bragg grating. By introducing holes and electrons into the intrinsic region of the diode (which is located under the rib), the index of refraction in the waveguide region is modulated and hence also, the wavelength in which the Bragg grating is designed to reflect. The change in refractive index is due to the plasma dispersion effect. The heavily-doped contact regions of their device are placed very close to the waveguide. As a result, the contact regions overlapped the mode and attenuated the signal. Their subsequent works included the fabrication of a Bragg grating, but did not include the addition of contacts, precluding any possibility of tuning.

Murphy *et al.* outlined the fabrication process of a Bragg grating on SOI. The measurements of the optical response of their device corresponded well with their theoretical predictions [Mur01].

Barrios *et al.* have proposed tunable optical resonators using the electrooptic effect to modulate the refractive index of silicon [Bar03, Bar04].

Waldron *et al.* looked at several design and fabrication techniques to promote electrooptic modulation while suppressing any thermo-optic modulation [Wal00].

1.3 Structure of the Thesis

A preview of previous research on Bragg gratings on SOI and electrooptic modulation of silicon-based devices was presented in Chapter 1.

An overview of the theory used in designing the waveguide, the Bragg grating and the doped contact regions will be presented in Chapter 2.

Chapter 3 will look at, in detail, the factors considered in designing the waveguide, the Bragg grating and the contacts.

Chapter 4 will provide details of the processes used and the challenges faced in fabricating prototype devices. There are pictures of the device at various points of its fabrication.

Chapter 5 will look at the electrical and optical testing of the device. It will provide grating response results, electrical characteristics of the diode and results from optically-modulating the grating response.

Finally, a set of conclusions regarding this experiment will be given in Chapter 6, and recommendations for improvement and future work to be done in this topic will be presented.

Chapter 2: Theory

2.1 Overview

This section will be an overview of the theory necessary to understand the design and operations of an electronically-tunable Bragg grating on a planar waveguide. We will look at the three main aspects of the device: the rib waveguide, the Bragg grating and the plasma dispersion effect. Initially, we will look at the physical interpretation of modes in optical waveguides. Next, we will examine the effective index method and the finite element method. A brief overview of the Bragg effect and the plasma dispersion effect will follow.

2.2 Physical Understanding of Modes

Optical waveguides are designed to control the propagation of light. In general, optical waveguides confine light using two main regions: a core region and a cladding region. The core region is surrounded by the cladding region, as shown in figure 2.1. After light enters the waveguide system, it propagates through the core region and is confined by the cladding region. The waveguide achieves the confinement by total internal reflection and follows the condition:

$$\sin \theta = n_1 \sin\left(\frac{\pi}{2} - \phi\right) < \sqrt{n_1^2 - n_0^2} \quad (2-1)$$

where,

n_1 – core index of refraction

n_0 – cladding index of refraction

Figure 2.1: Basic structure and refractive index profile of the optical waveguide [Oka92]

From this equation, one can see that the index of refraction of the core region needs to be higher than the index of refraction of the cladding region. Also, there is a $\phi_{\max}$ value which is defined to be the critical angle. All light entering the system at an angle greater than the critical angle will refract out and not totally reflect in the core.

Waveguides do not propagate light at any arbitrary angle, ϕ , smaller than the critical angle. There are discrete angles at which light can propagate. Each discrete angle can be considered a mode. All light that totally reflects at a core-cladding interface is affected by a phase shift, Φ , called the Goos-Hanchen shift. This phase shift causes the following phase matching condition to arise [Oka92]:

$$\tan\left(kn_1a \sin \phi - \frac{m\pi}{2}\right) = \sqrt{\frac{2\Delta}{\sin^2 \phi} - 1} \quad (2-2)$$

where,

$$k = 2\pi/\lambda$$

$$\Delta = \frac{n_1^2 - n_0^2}{2n_1^2}$$

m – mode number

The above equation indicates that there are discrete solutions for ϕ depending on the integer value of m . Each one of these discrete solutions is considered to be a mode of the waveguide. A distinct propagation constant β is associated with each mode. The propagation constant can be otherwise referred to as an eigenvalue. The relationship between ϕ and β can be seen in Figure 2.2.

Figure 2.2: Light Rays and their Phase Fronts in Waveguides [Oka92]

The fundamental mode is associated with the minimum angle $\phi_{\min}$. Figure 2.3 shows a representation of a fundamental mode and a higher mode in terms of standing waves. The solid lines represent positive wavefronts and the dashed lines represent negative wavefronts. The standing wave is null where a positive wavefront interferes with a negative wavefront, at a maximum where two positive wavefronts intersect and at a minimum where two negative wavefronts intersect.

Figure 2.3: Formation of Modes [Oka92]

2.3 Basis for Effective Index Method

The effective index method is a simple analytical method for treating rib waveguides. The method divides the waveguide into three regions, as shown in the below diagram. First, the effective index is solved for each region. Then, using the effective indices calculated in the previous step, the effective index of the final structure is calculated.

Figure 2.4: Steps of effective index method

Each region is treated as a planar isotropic waveguide. The effective index can be obtained by solving the dispersion equations. This section will derive the dispersion equation. Starting with Maxwell's equations, we have

$$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0 \quad (2-3a)$$

$$\nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} = \mathbf{J} \quad (2-3b)$$

$$\nabla \cdot \mathbf{D} = \rho \quad (2-3c)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (2-3d)$$

where,

$\mathbf{E}$ – electric field vector

$\mathbf{H}$ – magnetic field vector

$\mathbf{D}$ – electric displacement

$\mathbf{B}$ – magnetic induction

$\mathbf{J}$ – current density

ρ – electric charge density

In general optics problems, the region of space in which the light propagates has a current density and an electric charge density of zero ($\mathbf{J} = 0$ and $\rho = 0$).

In order to uniquely determine the field vectors, Maxwell's equations need to be supplemented with the constitutive relations:

$$\mathbf{D} = \epsilon_r \epsilon_0 \mathbf{E} = \epsilon_0 \mathbf{E} + \mathbf{P} \quad (2-4a)$$

$$\mathbf{B} = \mu \mathbf{H} = \mu_0 \mathbf{H} + \mathbf{M} \quad (2-4b)$$

where,

$\mathbf{P}$ – electric polarization

$\mathbf{M}$ – magnetic polarization

ϵ_r – dielectric constant

μ – magnetic permeability

In general, the dielectric constant and the magnetic permeability are tensors of rank 2. In our case, where the waveguide medium is isotropic, both the dielectric constant and the magnetic permeability can be reduced to scalars.

$$\mu = \mu_0 \quad (2-5)$$

$$\epsilon = n^2 \epsilon_0 \quad (2-6)$$

In analyzing the Bragg grating, the electric polarization term becomes particularly important. The electric polarization takes into account any perturbations of the dielectric constant in the waveguide. We will see that we use these perturbations in developing the coupled-mode equations for Bragg gratings.

By defining the electric and magnetic field to be

$$\mathbf{E} = \mathbf{E}(x, y) e^{j(\omega t - \beta z)} \quad (2-7)$$

$$\mathbf{H} = \mathbf{H}(x, y) e^{j(\omega t - \beta z)} \quad (2-8)$$

in other words, by assuming propagation in the z-direction, it is possible to obtain the following set of equations for the electromagnetic field components:

$$\frac{\partial E_z}{\partial y} + j\beta E_y = -j\omega\mu_0 H_x \quad (2-9)$$

$$-j\beta E_x - \frac{\partial E_z}{\partial x} = -j\omega\mu_0 H_y \quad (2-10)$$

$$\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} = -j\omega\mu_0 H_z \quad (2-11)$$

and

$$\frac{\partial H_z}{\partial y} + j\beta H_y = j\omega\epsilon_0 n^2 E_x \quad (2-12)$$

$$-j\beta H_x - \frac{\partial H_z}{\partial x} = j\omega\epsilon_0 n^2 E_y \quad (2-13)$$

$$\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} = j\omega\epsilon_0 n^2 E_z \quad (2-14)$$

In the case of the planar waveguide, there is no dependence in the y-direction.

Hence, $\frac{\partial E}{\partial y} = 0$ and $\frac{\partial H}{\partial y} = 0$. Two independent modes result, a TE mode and a TM mode.

The TE mode satisfies the wave equation:

$$\frac{d^2 E_y}{dx^2} + (k^2 n^2 - \beta^2) E_y = 0 \quad (2-15a)$$

where,

$$H_x = -\frac{\beta}{\omega\mu_0} E_y \quad (2-15b)$$

$$H_z = \frac{j}{\omega\mu_0} \frac{dE_y}{dx}$$

$$E_x = E_z = H_y = 0$$

With the understanding that the EM waves are confined to the core and exponentially decay in the cladding, the electric field can be expressed as:

$$E_y = \begin{cases} A \cos(\kappa \cdot a - \phi) e^{-\sigma(x-a)} & (x > a) \\ A \cos(\kappa \cdot x - \phi) & (-a \leq x \leq a) \\ A \cos(\kappa \cdot a - \phi) e^{\xi(x+a)} & (x < -a) \end{cases} \quad (2-16)$$

where,

$$\kappa = \sqrt{k^2 n_2^2 - \beta^2}$$

$$\sigma = \sqrt{\beta^2 - n_1^2 k^2}$$

$$\xi = \sqrt{\beta^2 - n_3^2 k^2}$$

$$k = \frac{2\pi}{\lambda} = \frac{\omega}{c}$$

The boundary conditions dictate that the tangential electric field and the tangential magnetic field need to be continuous at the top and bottom interfaces of the core region with the cladding in the planar waveguide. This means that for the TE mode, E_y and H_z need to be continuous. Looking at equation 2-15b, to say H_z needs to be continuous is equivalent to saying $\frac{\partial E_y}{\partial x}$ needs to be continuous. Hence, from equation 2-16 we get:

$$\frac{\partial E_y}{\partial x} = \begin{cases} -\sigma A \cos(\kappa \cdot a - \phi) e^{-\sigma(x-a)} & (x > a) \\ -\kappa A \cos(\kappa \cdot x - \phi) & (-a \leq x \leq a) \\ \xi A \cos(\kappa \cdot a - \phi) e^{\xi(x+a)} & (x < -a) \end{cases} \quad (2-17)$$

Applying this final equation at $x = \pm a$, a is defined in figure 2.5, we get:

$$\tan(\kappa \cdot a + \phi) = \frac{\xi}{\kappa} \quad \text{and} \quad \tan(\kappa \cdot a - \phi) = \frac{\sigma}{\kappa} \quad (2-18)$$

leading to the solution:

$$\kappa \cdot a = \frac{m\pi}{2} + \frac{1}{2} \tan^{-1}\left(\frac{\xi}{\kappa}\right) + \frac{1}{2} \tan^{-1}\left(\frac{\sigma}{\kappa}\right) \quad (2-19)$$

$$\phi = \frac{m\pi}{2} + \frac{1}{2} \tan^{-1}\left(\frac{\xi}{\kappa}\right) - \frac{1}{2} \tan^{-1}\left(\frac{\sigma}{\kappa}\right) \quad (2-20)$$

At this point, it will be useful to present the refractive index profile of our waveguide, shown in figure 2.5, and to introduce some normalized parameters to help with later analysis. An asymmetry constant, γ , a normalized frequency, v , and an effective index, n_{eff} , will be introduced:

Figure 2.5: Refractive index profile of SOI waveguide

$$\begin{aligned}
\gamma &= \frac{n_3^2 - n_1^2}{n_2^2 - n_3^2} \\
v &= ka\sqrt{n_2^2 - n_3^2} \\
n_{eff} &= \frac{\beta}{k}
\end{aligned} \tag{2-21}$$

The asymmetry constant will be useful to analyze the waveguide that we are using because our top cladding has a different index of refraction than our bottom cladding. Note that n_3 , instead of n_1 , is used for the normalized frequency. This is because we assumed $n_3 > n_1$, and the cutoff condition for the waveguide occurs when the normalized propagation constant lowers to the refractive index of the higher cladding region. From this, we can look at one more useful parameter, the normalized propagation constant:

$$b = \frac{n_{eff}^2 - n_3^2}{n_2^2 - n_3^2} \tag{2-22}$$

where the cutoff condition clearly, from the above descriptions, is $b = 0$.

The dispersion equation from equation 2-18 can be rewritten as

$$2v\sqrt{1-b} = m\pi + \tan^{-1}\left(\sqrt{\frac{b}{1-b}}\right) + \tan^{-1}\left(\sqrt{\frac{b+\gamma}{1-b}}\right) \tag{2-23}$$

The following is a plot of normalized frequency vs normalized propagation constant of the TE modes. For our specific case $n_1 = 1$, $n_2 = 3.46$ and $n_3 = 1.45$.

Figure 2.6: Dispersion curves for TE modes

Similar results to figure 2.6 can be derived for TM modes.

From the theory derived above, we can easily implement the effective index method in Matlab.

2.4 Finite Element Method

FEMlab uses the finite element method to solve boundary value problems. The method is based on upon dividing the unknown region into non-overlapping triangles or elements. Each element has a field associated with it. The total field in an element is the superposition of the effects of every other element in the region. The method uses an expression called a functional which is formulated using the magnetic field from Maxwell's equations.

$$F = \int_{\Omega} (\nabla \times H)^* \cdot \left(\frac{1}{\epsilon_r} \nabla \times H \right) d\Omega - k_0^2 \int_{\Omega} H^* \cdot H d\Omega \quad (2-24)$$

where Ω is the cross-sectional area [Kos92-1]. By differentiating the functional with respect to each nodal value, the eigenvalue problem is obtained in the form

$$[A][x] - \lambda[B][x] = 0 \quad (2-25)$$

where $[A]$ and $[B]$ are sparse matrices, $[x]$ is the nodal matrix and λ is the eigenvalue of the problem. The above equation is solved using numerical iterative techniques.

2.5 Bragg Effect

A Bragg grating is a series of reflectors that, in total, couples a forward-traveling mode into a backward-traveling mode. Each reflection is due to a perturbation in the effective index of the optical waveguide. Gratings can be analyzed from basic optics theory. The reflectivity due to a change in refractive index is:

$$R = \left(\frac{n_2 - n_1}{n_2 + n_1} \right)^2 \quad (2-26)$$

This reflection occurs at each interface as shown in figure 2.7. The total reflection, however, is not the simple addition of the reflections in the Bragg grating. The total reflection can be obtained by multiplying successive transfer matrices as described in Yeh [Yeh88].

Figure 2.7: Periodic Structure showing reflections at each interface

In order to get a strong overall reflection, it is important that the reflected waves interfere constructively. This means that the period of the gratings needs to be half of the wavelength of the light in the waveguide. The Bragg condition is:

$$\Lambda = \frac{M\lambda_0}{2n_{eff}} \quad (2-27)$$

where Λ is the physical period of the Bragg grating (sometimes referred to as the pitch of the grating), $\frac{\lambda_0}{N}$ is the wavelength of light in a dielectric material and M is the order of the grating. As the order of the grating is increased, the gratings become weaker because the number of reflections decreases.

Figure 2.8: Reflections in Bragg Grating

The simplest example of a Bragg grating is the alternating of two dielectric media of equal thicknesses. In our case, a change in the index of refraction will not be due to a change in material, but a physical etch in the optical waveguide. The difference in rib height will introduce a change in effective index of refraction.

2.6 Electrooptic Effect in Silicon

For the electrooptic effect, there are several mechanisms that can cause a change in the effective index of refraction in a material. These mechanisms can be classified as electric field effects or plasma dispersion effects. The electric field effect occurs when an external electric field induces tunneling between the valence and conduction bands of silicon. In general, these effects require an enormously high field. Plasma dispersion effects, however, occur when a change in concentration of charge carriers are introduced into a material. In crystalline silicon, charge carrier effects dominate. Please note that all discussion hereafter concerns crystalline silicon.

2.6.1 Electric Field Effects

Kramers-Kronig coupling relates changes in optical absorption with changes in the index of refraction:

$$\Delta n(\omega) = \left(\frac{c}{\pi}\right) P \frac{\int \Delta \alpha(\omega') d\omega'}{\omega'^2 - \omega^2} \quad (2-28)$$

The Franz-Keldysh effect describes the shift in absorption edge of a semiconductor to an external electric field. The absorption spectrum of crystalline silicon changes, near its band-gap edge (near 1.15eV), when a strong electric field is applied. Soref *et al.* calculated the change in index of refraction due to the effect to be in the order of $\Delta n = 1 \times 10^{-6}$ at a wavelength of 1550 nm and an electric field of 100 kV/cm [Sor87].

Soref *et al.* also examined the Kerr effect. The Kerr effect, also, is an electric field effect. Using the approximation $\omega \ll \omega_0$, Soref approximates the Kerr effect to be:

$$\Delta n = \frac{-3e(n^2 - 1)E^2}{2nM^2\omega_0^4 x^2} \quad (2-29)$$

where e is the electron charge, n is the unperturbed refractive index, M is the effective mass, ω_0 is the oscillator resonance frequency and x is the average oscillator displacement. The equation predicts a change in refractive index of 10^{-5} at an electric field of 3×10^5 V/cm. Figure 2.9 shows the change in refractive index versus electric field.

Figure 2.9: Kerr effect in c-Si [Sor87]

The Pockels effect is another electric field effect which is used many other materials such as Lithium Niobate and Gallium Arsenide. The Pockels Effect can only be shown in crystals with a lack of a center of symmetry. The crystal structure of silicon does have a center of symmetry.

The conclusion from the above discussion is that the Kerr, Pockels and Franz-Keldysh effects are very weak in silicon and cannot contribute enough to see any sizable shift in the Bragg grating response in the telecom band. However, in other materials, these effects can be rather large.

2.6.2 Plasma Dispersion Effects

The plasma dispersion effect (also known as charge carrier effect) arises because the optical properties of silicon are affected by introducing free carriers into an undoped sample. The relationship between a change in the refractive index and a change in optical absorption due to a change in free carrier concentration is given by:

$$\Delta n = \left(\frac{e^2 \lambda^2}{8\pi^2 c^2 \epsilon_0 n} \right) \left[\frac{\Delta N}{m_{ce}} + \frac{\Delta P}{m_{ch}} \right] \quad (2-30)$$

$$\Delta \alpha = \left(\frac{e^3 \lambda^2}{4\pi^2 c^3 \epsilon_0 n} \right) \left[\frac{\Delta N}{m_{ce}^2 \mu_e} + \frac{\Delta P}{m_{ch}^2 \mu_h} \right] \quad (2-31)$$

where e is the electron charge, ϵ_0 is the permittivity, n is the unperturbed refractive index, m_{ce} is the conductivity effective mass of electrons, m_{ch} is the conductivity effective mass of holes, μ_e is the electron mobility and μ_h is the hole mobility. Soref [Sor87] simplified the equations to:

$$\Delta n = \Delta n_e + \Delta n_p \quad (2-32)$$

$$\Delta n = -[8.8 \times 10^{-22} \cdot \Delta N + 8.5 \times 10^{-18} \cdot (\Delta P)^{0.8}] \quad (2-33)$$

$$\Delta \alpha = \Delta \alpha_e + \Delta \alpha_p \quad (2-34)$$

$$\Delta \alpha = 8.5 \times 10^{-18} \cdot \Delta N + 6.0 \times 10^{-18} \cdot \Delta P \quad (2-35)$$

where Δn_e and Δn_p are the refractive index change due to electron and hole concentration change respectively, ΔN and ΔP are the electron and hole concentration change respectively and $\Delta \alpha_e$ and $\Delta \alpha_h$ are the absorption coefficient changes due to

changes in electron and hole concentration respectively. Figure 2.10 is a graphical representation of the results.

Figure 2.10: Change in Refractive Index due to plasma dispersion [Sor87]

The plasma dispersion effect will dominate the electric field effects with respect to altering the index of refraction of crystalline silicon. In the design chapter, we will look at methods of using the plasma dispersion effect to tune the filter response of a Bragg grating fabricated on a SOI substrate.

Chapter 3: Design

3.1 Overview

This section will be divided into three parts: the waveguide design, the grating design and the diode/contact design.

3.2 Waveguide Design

3.2.1 SOI Substrate

Bond and etch back SOI wafers supplied by SEH were used for this project. The dimensions of the wafer are 2.5- μm silicon, 1.0- μm oxide, 525- μm silicon. The structure can be seen in the below figure. The manufacturer specifications are attached in Appendix 1.

Figure 3.1: SEM IMAGE: Cross section of SOI wafer with waveguide

3.2.2 Single Mode Condition

Waveguides need to operate in the single-mode regime. Multi-mode waveguides are affected by the problem of intermodal dispersion. This occurs because different modes have different propagation constants, and hence travel at different speeds and spread over time. Soref *et al.* analyzed the single-mode condition for rib waveguides [Sor91]:

$$\frac{w}{H} < 0.3 + \frac{\frac{h}{H}}{\sqrt{1 - \left(\frac{h}{H}\right)^2}} \quad (3.1)$$

Figure 3.2: Definition of Variables for the Single-mode Equation

The variables of the above equation are defined in figure 3.2. Our initial waveguide dimensions followed the confines of the above equation. We ensured that our final design was single-mode with the use of FEMLAB. FEMLAB is a multi-physics simulation tool that uses the finite element method to solve. The final waveguide design is shown below:

Figure 3.3: Final waveguide design

3.2.3 FEMLAB Simulation and Determination of Propagation Constant

The FEMLAB simulation shows the fundamental mode of our waveguide design and where the mode is confined in relation to the rib. Note that the mode is physically confined below the rib. The rib only defines the lateral confinement. In FEMLAB, the simulation used perpendicular hybrid modes at 1550 nm with a refractive index of 3.48

Figure 3.4: FEMLAB simulation result: TE fundamental mode

The FEMLAB simulation was able to find the propagation constant, and hence the effective index of the waveguide structure.

$$\beta = n_{\text{eff}} k \quad (3.2)$$

The effective index is important in the analysis of the grating. The effective index was found to be 3.464.

3.3 Grating Design

Using the coupled mode theory implemented in Matlab, we are able to simulate different scenarios in order to choose appropriate grating dimensions for the final design. We would like the final design to have as strong a reflection as possible while minimizing the bandwidth of the response.

3.3.1 Coupled Mode Theory

The analysis of the Bragg grating was done using coupled-mode theory. By the end of this section, we would like to have a numerical model of the Bragg grating. The coupled mode theory considers the periodic variation of the dielectric scalar as a perturbation that couples the unperturbed normal modes of the structure [Yar03]. The dielectric constant can be expressed as:

$$\epsilon'' = \epsilon + \Delta\epsilon \quad (3.3)$$

where ϵ is the unperturbed dielectric constant and $\Delta\epsilon$ is the change in the dielectric constant due to the perturbation, namely the Bragg grating in our case. The existence of $\Delta\epsilon$ gives rise to a new perturbation polarization:

$$\begin{aligned} P_{pert}(r, t) &= \Delta\epsilon E(r, t) \\ &= n^2(r)\epsilon_0 E(r, t) \end{aligned} \quad (3.4)$$

and because, as was developed in the theory section, $n(r)$ is a scalar as opposed to a tensor, TE modes can only be coupled to other TE modes and likewise for TM modes.

Substituting the expression for P_{pert} into Maxwell's equations gives [Yar85]:

$$\nabla^2 E_y - \mu\epsilon(r) \frac{\partial^2 E_y}{\partial t^2} = \mu \frac{\partial^2}{\partial t^2} [P_{pert}(r, t)]_y \quad (3.5)$$

If we expand the total electric field in the perturbed waveguide as a superposition of confined modes, we get:

$$E_y(r, t) = \frac{1}{2} \sum_m A_m \xi_y^{(m)}(x) e^{i(\omega t - \beta z)} \quad (3.6)$$

where m denotes the m^{th} discrete mode that satisfies Maxwell's equations and the boundary conditions.

Using equations 3.5 and 3.6, and after a little manipulation, we can get the coupled mode equation [Yar85]:

$$\frac{dA_s^{(-)}}{dz} e^{i(\omega t + \beta_s z)} - \frac{dA_s^{(+)}}{dz} e^{i(\omega t - \beta_s z)} = -\frac{i\epsilon_0}{4\omega} \frac{\delta^2}{\partial t^2} \sum_m \int_{-\infty}^{\infty} \Delta n^2(x, z) \xi_y^{(m)}(x) \xi_y^{(s)}(x) dx e^{i(\omega t - \beta_m z)} \quad (3.7)$$

The right hand side of the equation takes into account the perturbation in the waveguide and can be thought of as the source term that is driving the waves. The (-) term on the left-hand side represents the backward-traveling wave and the (+) term on the left-hand side represents the forward-traveling wave. In general, the source and the driven waves need to have the same frequency and the same phase dependence in order not to average out to be zero. Theoretically, an infinite number of mode amplitudes are involved. However, in practice, only two modes are strongly coupled near the condition of resonant coupling [Yar03]. Resonant coupling refers to the condition where:

$$\beta_s - \beta_m - l \frac{2\pi}{\Lambda} = 0 \quad (3.8)$$

where l is the order of the grating and is some integer value.

When the coupling involves two modes, the coupled-mode equation becomes:

$$\begin{aligned} \frac{dA_s^{(-)}}{dz} &= \kappa A_s^{(+)} e^{-i2(\Delta\beta)z} \\ \frac{dA_s^{(+)}}{dz} &= \kappa^* A_s^{(-)} e^{i2(\Delta\beta)z} \end{aligned} \quad (3.9)$$

or

$$\begin{aligned} \frac{dA}{dz} &= \kappa B e^{-i2(\Delta\beta)z} \\ \frac{dB}{dz} &= \kappa^* A e^{i2(\Delta\beta)z} \end{aligned} \quad (3.10)$$

where A is the backward-traveling mode, B is the forward-traveling mode, κ is the coupling coefficient, and

$$\Delta\beta = \beta_s - \beta_m - l \frac{2\pi}{\Lambda} \quad (3.11)$$

For our specific case, the perturbation in the waveguide can be represented as a square wave. The index of refraction can be expanded using a fourier series [Yar85].

$$\begin{aligned} \Delta n^2(x, z) &= \Delta n^2(x) \left[\frac{1}{2} + \frac{2}{\pi} (\sin \eta z) + \frac{1}{3} \sin \eta z + \dots \right] \\ &= \Delta n^2(x) \sum_l a_l e^{i\eta l z} \end{aligned} \quad (3.12)$$

where

$$\Delta n^2 = \begin{cases} n_2^2 - n_1^2 & -a \leq x \leq 0 \\ 0 & \text{elsewhere} \end{cases}$$

$$\eta = \frac{2\pi}{\Lambda}$$

and

$$a_l = \begin{cases} \frac{-i}{\pi l} & l \text{ odd} \\ 0 & l \text{ even} \\ \frac{1}{2} & l = 0 \end{cases}$$

The coupling coefficient is solved in [Yar85] in terms of known variables.

$$\kappa \approx -\frac{2\pi^2}{3l\lambda} \frac{\Delta n^2}{n_2} \left(\frac{a}{t} \right)^3 \left[1 + \frac{3}{2\pi} \frac{\lambda/a}{\Delta n} + \frac{3}{4\pi^2} \frac{(\lambda/a)^2}{\Delta n^2} \right] \quad (3.13)$$

where

a = grating depth

t = thickness of silicon layer

l = order of grating

Figure 3.5: Variables for coupling coefficient equation

The Bragg grating can be represented by the following figure.

Figure 3.6: Bragg grating block diagram

The solution to the coupled-mode equations, equation 3.9, for $A(L) = 0$ is:

$$A(z)e^{i\beta z} = B(0) \frac{i\kappa e^{i\beta_0 z}}{-(\Delta\beta/2) \sinh SL + iS \cosh SL} \sinh[S(z-L)] \quad (3.14)$$

$$B(z)e^{-i\beta z} = B(0) \frac{i\kappa e^{-i\beta_0 z}}{-(\Delta\beta/2) \sinh SL + iS \cosh SL} [(\Delta\beta/2) \sinh[S(z-L)] + iS \cosh[S(z-L)]] \quad (3.15)$$

where

$$S = \sqrt{\kappa^2 - (\Delta\beta/2)^2}$$

$L = \text{grating length}$

The reflectance of the system is defined as:

$$R = \left| \frac{A(0)}{B(0)} \right|^2 \quad (3.16)$$

Substituting the forward- and backward-traveling wave into the above equation gives:

$$R = \frac{\kappa^2 \sinh^2 SL}{(\Delta\beta/2)^2 \sinh^2 SL + S^2 \cosh^2 SL} \quad (3.17)$$

The maximum reflectance occurs under the phase matching conditions, $\Delta\beta = 0$.

$$R_{\max} = \tanh^2 |\kappa| L \quad (3.18)$$

The Matlab code can be found in Appendix 2.

3.3.2 Grating Period

The goal of the grating design was to make a grating response that fell in the 1.55- μm telecommunication region so that it could easily be tested with standard equipment available at the McMaster University Engineering Physics Department.

The response could be between the wavelengths of 1520 nm and 1570 nm.

According to equation 2.25,

$$\Lambda = \frac{M\lambda_{br}}{2n_{eff}} \quad (3.19)$$

the grating period could be in the range of 219 nm and 227 nm, assuming an effective index of 3.46. The final grating design used a period of 225 nm. The fundamental mode was found to be centered at 1558.8 nm.

3.3.3 Grating Depth

Figure 3.7: Matlab simulation: Variations in grating depth

The simulations indicate that the depth of the gratings affects the strength and the bandwidth of the response. Deeper gratings create a larger perturbation and cause a stronger reflection. The simulations also show that deepening the gratings causes an increase in response bandwidth.

Intuitively, there is a limit to the depth of the grating. As the grating depth approaches the depth of the waveguide, the mode becomes less confined by waveguide structure and will result in the degradation of power.

3.3.4 Grating Length

Figure 3.8: Matlab Simulation: Variations in grating length

From the figure above, the longer grating lengths decrease the bandwidth of the response and increase the strength of the reflection.

3.3.5 Grating Order

Figure 3.9: Matlab simulation: Variations in grating order

The higher order grating gives a weaker response. The higher order grating has fewer perturbations in a given length. The simulations show that the bandwidth is not affected by the order of the gratings as shown in the figure above.

3.3.6 Final Design

Figure 3.10: Matlab simulation: Theoretical response of final design

It was decided to fabricate the longest grating that we could pattern. The main concern of the design was to keep the bandwidth small so that we could better observe any shifts in grating response during the testing phase of the project. Maintaining this reasoning, a shallower grating depth was also decided on.

3.4 Diode/Contact Design

The goal of the electrooptic design is to ensure that the device has sufficient tuning range. A shift of 0.8 nm is desired. This section will ensure that, first, we are able to tune the device electrooptically and that second, we can sufficiently suppress any thermal effects.

3.4.1 Suggested Design

Figure 3.11: Suggested diode design in order to give desired modulation response

As stated earlier in the introduction, the initial design by Cutolo *et al.* placed the contacts very close to the waveguide. As a result, the contacts overlapped the mode and attenuated the signal. After some simulations, we decided that we would like to place the contacts as far apart as possible in order to reduce any thermo-optic effects. The maximum distance apart was determined by the electron diffusion length. The contacts needed to be placed a distance apart shorter than the diffusion length of electrons in the silicon layer.

3.4.2 Necessary Number of Minority Carriers

According to our CMT-based simulation, shown in figure 3.12, the effective index needs to change by 1.8×10^{-3} in order to get a shift of 0.8 nm in the filter central wavelength. Assuming that a majority of the shift is due to the plasma dispersion effect, from figure 2.10, we would need a change in hole and electron concentration of $5 \times 10^{17} \text{ cm}^{-3}$.

Figure 3.12: Matlab simulation: Theoretical shift due to change in refractive index

3.4.3 Electrical Characterization

The device electrical characteristics were simulated using Medici. Medici used a two-dimensional model representing the layout shown in the suggested design. Similar simulations were made in a previous Carleton work [Win03]. The base files used in this simulation were derived from the efforts of Wen Jiang and Phil Waldron.

The simulation results are attached in Appendix 3. The simulations indicated that an applied bias voltage of 0.9 V with a current of 15.52 $\mu\text{A}/\mu\text{m}$ was necessary to generate enough carriers to shift the response by 0.8 nm.

3.4.4 Thermal Considerations

The effective index can also be changed because of the thermo-optic properties of silicon. An increase in temperature causes an increase in effective index; this is a change in the opposite direction of the change caused by an increase in carriers. For small changes in temperature, the effective index varies linearly with temperature in Celsius according to [Dai00]:

$$\Delta n = 1.9 \times 10^{-4} \Delta T \quad (3.20)$$

It is important that we identify the heat sources of the device. The power dissipation in the device can be modeled with:

$$H = H_n + H_p + H_U \quad (3.21)$$

where H_n and H_p represent the lattice heating due to electron and hole transport respectively, and H_U is the lattice heating due to carrier recombination or generation [Med00]. H_n , H_p , and H_U are calculated using the equations below:

$$H_n = J_n \vec{E} \quad (3.22)$$

$$H_p = J_p \vec{E} \quad (3.23)$$

$$H_U = U_{SRH} \left[E_g + \frac{3K}{2}(2T) \right] \quad (3.24)$$

J_n and J_p are the current density of electrons and holes, $\vec{E}$ is the electric field. The U_{SRH} is the Shockley-Read-Hall recombination rate, E_g is the bandgap energy of silicon, K is Boltzmann's constant and $T = 300K$.

The number of carriers needed to make a significant change in the refractive index under the rib is much higher than the background doping level. The diode must be biased far into the high level injection regime to achieve these carrier densities. Carriers can recombine in the bulk, at free surfaces and in the contact regions. In junction diodes under normal low level injection conditions, the recombination in the bulk usually dominates the recombination in the heavily-doped n+ or p+ regions. As shown in the Medici recombination simulation (figure 3.13), under high level injection conditions, the majority of the recombination may occur in the contact regions.

From the Medici simulation (results summarized in Table 3.1), we are able to show that the majority of the heating comes from recombination and most of the recombination occurs in the contact regions. This is a surprising result which guides the strategy to minimize heating. From a quick calculation of each type of heating using the values found in the simulation and equations 3.22-3.24, we find that the heating due to

electron/hole transport is around 3100 W cm^{-3} and the heating due to recombination is 57000 W cm^{-3} . This shows that the majority of the heating is due to recombination.

$J_n (\text{A/cm}^2)$	$J_p (\text{A/cm}^2)$	$U_{\text{SRH}} (\#/\text{cm}^2)$	$E (\text{V/cm})$
2.167×10^2	3.5×10^2	3×10^{23}	5.4787

Table 3.1: Medici simulation values taken at the center of the rib

The following diagram shows the recombination distribution across the device. At peak areas in the contact regions, the recombination rate exceeds that in areas under the waveguide by two orders of magnitude.

Figure 3.13: Medici simulation: Recombination rates ($\#/\text{cm}^3/\text{s}$) in the device

Based on this information, Harpreet Panesar, a current Carleton Master's candidate, used a thermal simulator called ATAR designed by Dr. Tom Smy to simulate the total heating in the grating [Smy01]. It was estimated that half of the total power dissipated by the device occurred in each contact. As long as the contacts are closer than the diffusion length of the electrons and holes, the above estimation should be accurate. From his simulations, he found it reasonable to infer that, in order to lower the temperature in the grating, either the amount of power dissipated at the contacts needed to be reduced or the contacts must be moved farther away from the rib. For the suggested

design, operating with $5 \times 10^{17} \text{ cm}^{-3}$ injected carriers, the thermo-optic change in index of refraction was found to be 3.04×10^{-5} [Win03]. This simulation showed that electrooptic effect would dominate over the thermo-optic effect.

To lower power dissipation, we must decrease the amount of recombination occurring. The design takes measures to decrease the volume of the recombination centers and density of carriers in recombination centers. These measures will try to force recombination to happen elsewhere in the device.

- 1) Contact region made very shallow, decreasing the volume available for recombination.
- 2) Contact region made as heavily doped as possible, decreasing the number of back injected minority carriers available for recombination.
- 3) Heavily-doped polysilicon contacts are used (effectively, “polysilicon emitter” structures, suppressing the back injection component of current that is, current resulting from hole injection into the n+ contact region, and electron injection into the p+ contact). [Pat86]
- 4) The n+ and p+ contact regions (via holes) are made as small as possible on the mask layout to minimize the area available for recombination. These minimum geometry contacts are placed as far apart as possible (a distance equal to one half the estimated minority carrier diffusion length in the silicon film).

Figure 3.14: Via holes in oxide layer

Chapter 4: Fabrication

4.1 Overview

The fabrication runsheet is included in Appendix 4. The process consists of three main stages: the making of the gratings, the rib and the diodes. It is described graphically in figure 4.1.

Figure 4.1: Fabrication process steps to make grating on waveguide (metal structure shown in figure 4.12)

4.2 Gratings

The fabrication of the gratings, due to the small feature size (on the order of 100 nm), is the most critical step of the fabrication process.

4.2.1 Patterning Options

There are several options in terms of the methods of patterning the gratings. The gratings could be patterned using a deep UV stepper lithography, a UV holographic setup or by electron beam (e-beam) direct write. Table 4.1 compares the patterning methods.

	Able to Resolve Grating	Maximum Length of Grating	Method Available at CMFL
Deep UV stepper	Yes, but very expensive	1 cm+	No
UV holographic	Yes	1 cm+	Not at time of fab
Electron beam	Yes	200 micron at CMFL 1 cm+ NRC	Yes

Table 4.1: Comparison of Patterning Methods

The only option available to write the gratings was electron beam direct write. The deep UV stepper option was eliminated due to cost issues and the lack of accessible equipment. Two drawbacks of e-beam lithography are the insufficient maximum length available at the CMFL and the amount of time it takes to expose the pattern. For electron beam lithography beam currents must be kept low to avoid beam broadening due to the mutual repulsion of electrons. Low beam currents lead to long write times.

4.2.2 Resist Selection

The first consideration in making the gratings is to decide which e-beam resist to use and what thickness. At the CMFL, there is a choice of three e-beam resists: SAL601, PMMA and ZEP520A. Table 4.2 compares the three choices.

	Tone	Resolution	Contrast	Dry Etch Resistance	UV Sensitivity
SAL601	Negative	High	High	High	Low
ZEP	Positive	High	High	High	High
PMMA	Positive	Very high	Low	Low	Low

Table 4.2: Comparison of Electron-beam resists

SAL601 was eliminated because it is a negative resist. For writing small patterns without having to etch the surrounding silicon, it is preferable to use a positive resist. Our process needed a high resolution and etch resistance. ZEP520A was decided to be more useful than the traditional e-beam resist PMMA for our purposes (spec sheet attached in Appendix 5).

In general, the finer the feature sizes to be resolved, the thinner the layer of resist needs to be. The thickness of the resist is a function of the viscosity of the resist and the spin speed used to apply the resist. The viscosity was decreased by adding the appropriate solvent. Maintaining the spin speed at 4000 rpm, the thickness of the applied resist was controlled by using different dilutions of ZEP520A and its solvent, anisole thinner. The best test results came from 1:1 dilution of thinner to ZEP520A. The final film thickness was 160 nm.

After the e-beam resist was applied and developed, the remaining solvent was removed by baking the sample as specified in the data sheet.

4.2.3 Writing the Pattern

The first set of working samples was patterned on the JEOL 840 SEM lithography system at the CMFL. The Nanometer Pattern Generation System (NPGS) software controls the electron-beam write system. It relays write patterns as a series of discrete pixels. The electron beam scans quickly to each pixel and is held in position for a time determined by the dose specified for that pixel. The NPGS needs several write parameters to be specified: beam current, center-to-center spacing, line-to-line spacing and dosage.

The highest possible accelerating voltage was used because the highest accelerating voltage gives the least amount of backscattering and consequently the smallest linewidths. As noted above, the lowest reasonable beam current was used. [Nab]

Figure 4.2: Definition of line-to-line and center-to-center spacing

As the name suggests, the center-to-center spacing is the distance between the centers of successive pixels. Line-to-line spacing is the distance between the centers of two pixels on adjacent lines. The parameters are shown in figure 4.2. The center-to-center and line-to-line are chosen close enough to ensure that a solid pattern is exposed. As a result, we wanted the e-beam to make at least two passes for each grating. The line-to-line spacing was chosen in order to get at least three passes of the e-beam per grating. For example, if each grating needs 60 nm to be exposed, the maximum line-to-line spacing would be $60/3 = 20$ nm (figure 4.3).

Figure 4.3: Number of passes of each grating defined by line-to-line spacing

After determining the other write parameters, the proper dose was found experimentally by writing a series of patterns with varying doses. The best dose was chosen based on samples that were subsequently developed and etched, shown in figure 4.4.

Figure 4.4: Grating Pattern written with different doses: (a) underexposed, (b) good exposure, (c) overexposed

The final write parameters for the SEM are summarized in the table below:

Accelerating voltage	35 kV
Beam current	3 pA
Center-to-center spacing	12.9 nm
Line-to-line spacing	12.9 nm
Dose (area)	$170 \mu\text{C}/\text{cm}^2$

Table 4.3: Final write parameters for SEM at CMFL

The final set of samples was patterned by the NRC with the help of Dr. Jean Lapointe. The NRC patterned the grating using a JEOL JBX-6000 FS/E. The SEM at CMFL faced two important limitations to producing gratings capable of providing a strong enough response for our final experiments. The first limitation was field size. The e-beam write system has a limited field within which it can write at a given magnification. The result was that the maximum length of the grating that the CMFL could produce was $200 \mu\text{m}$. The second limitation was the ability of the e-beam write system to field stitch accurately. Field stitching is the ability of the system to shift the writing stage accurately enough to make a continuous pattern. The NRC write system

has a field size of 800 microns with a field stitch tolerance of 60 nm. We were able to pattern gratings up to 8 mm in length using the NRC facilities.

4.2.4 Development

After the patterning step, the samples were developed in O-xylene for 45 seconds and rinsed in iso-propanol for 30 seconds. It is vital for the ambient conditions during this step to remain constant. Any fluctuations in temperature or humidity have a drastic effect on the outcome of the development. Earlier attempts at developing the pattern used an ultrasonic agitation. It was found that no agitation was necessary to develop the samples.

Afterwards, the sample was hard-baked for 3-4 minutes at 120°C. The final bake is necessary in order to promote adhesion during wet etching or increase selectivity during dry etching [Plu00].

4.2.5 Etching

The final step in producing the gratings was the etching step. The goal of this step was to etch straight down to make rectangular gratings. In general, wet etching tends to be isotropic. The only dry (or plasma) etching system available in the CMFL is the Electron Cyclotron Resonance plasma etcher (ECR). Plasma etchers usually combine physical and chemical etching. The physical etching is due to ion bombardment and the chemical etching is due to the reaction of fluorine (or another halogen) with silicon. The ECR system produces high density plasmas and uses a separate power source to bias the wafer and control ion bombardment. The rate of chemical etching can be controlled with gas flows. In the ECR system, with the decoupling of the plasma density and the ion energy, many ions can be produced at low pressures with low ion energies. As result, ion bombardment damage can be kept low while maintaining high etch rates and anisotropic etching. In addition, a lower ion energy usually gives better selectivity than higher ion energy. The ion bombardment supplies enough energy to raise the substrate temperature and cooling the wafer is required to keep the temperature below 400°C [Plu00].

E-beams resists generally have a lower selectivity than photoresists. This further becomes an issue because only 160 nm of ZEP acts as the mask. Unless the conditions

are perfect, ECR etches are slightly isotropic leading to a little bit of lateral etching. In addition, the corners of the photoresist do not come out perfectly rectangular after development (as seen in figure 4.5). If the selectivity is not high, the mask could be etched leading to more lateral etching. To sum up, the gratings will be wider than intended in the writing stage of the process. In order to compensate, the original write file used for the grating only exposed 60 nm gratings at a period of 225 nm (see figure 4.6).

Actual etch profiles that can occur. (a) Lateral etching under mask. (b) Rounded photoresist which is further eroded during etching, leading to even more lateral etching. (b) also illustrates etch selectivity.

Figure 4.5: Actual etch profiles that can occur (above)

Figure 4.6: Actual design: Grating patterned to 60 nm, but expanded out to 112.5 nm after etching

Ideally, the ECR should have a prescribed etch rate for a given set of conditions (eg. gas flows, bias voltages, pressure, etc.). The ECR proved to be very finicky. We were not able to get a stable etch rate. As a result, samples needed to be etched for a

short period of time and then be measured and re-etched. This made it very difficult to have consistent grating depths. Also, it was observed that the etch rate differed for different sections of the same sample. Stabilizing the behaviour of the ECR was not accomplished and considered to be beyond the scope of this project.

4.3 Ribs

After the grating is patterned and etched, the rib needs to be formed above it. The ribs were patterned using photolithography. There were two options for the mask. The mask could either be an emulsion mask or a chrome mask. The emulsion mask could be made in the CMFL. The patterns here are limited to a maximum size of 4 mm. The other option was to get a chrome mask made at Adtek Photomasks with a maximum size of 9.8 mm. The chrome mask option was chosen for two reasons. Firstly, the maximum size limitation: the preferred length of the gratings we wanted to fabricate was longer than the 4 mm limitation. Also, when coupling light from a fiber to an SOI waveguide, it takes about 2 mm for the modes to fully develop [Sor91]. Secondly, according to some sidewall roughness tests, the emulsion masks formed sidewalls that were rougher than the sidewalls formed using the chrome masks. Sidewall roughness introduces some loss into the waveguide. In general, the smoother the waveguides are, the less loss there is. A waveguide with photoresist is shown in figure 4.7.

Figure 4.7: SEM image: Sidewall roughness on waveguide

Alignment is a major concern. It is necessary for the gratings to sit entirely on top of the rib. To alleviate the problem, the gratings were patterned during the e-beam step to

be slightly wider than the waveguide causing the gratings to have a small overlap over the rib structure.

The ribs were patterned to be 5 μm wide. A foreseeable consequence of patterning the rib a certain size is that the final structure would be smaller. Any overdevelopment of the photoresist after the exposure step, or any isotropy or poor selectivity in the ECR etch, would effectively decrease the width of the rib. The final rib width was 4.5 μm .

4.4 Diode/Contact Region

The first step in making the diodes is to make an electrical passivation layer to ensure that electric contact only occurs in regions where it is intended. A silicon dioxide layer was grown for this purpose. The growth of the passivation layer had some unintended consequences. Because the thermal oxide consumes some of the silicon layer, it tends to smooth out any roughness on the silicon. As a result, this step may have reduced the duty cycle and slightly decreased the depth of the grating. Another concern was that the square corners of the gratings would become slightly rounded. According to the figure below, the sharpness of the corners should remain relatively unaffected.

Typical experimental result from Kao [6.28, 6.29]. The drawing on the bottom labels the structure shown experimentally on the top. The oxide is thinner on both concave and convex corners than it is on flat regions. Reprinted with permission from IEEE.

Figure 4.8: Results from oxidizing corners [Plu00]

At this point, we patterned the pinhole contact windows in the oxide discussed in the design section, and deposited undoped polysilicon which was patterned and etched to overlap the contact windows.

Figure 4.9: Positioning of contact region with respect to the rib

The N+ and P+ regions were positioned on the opposite sides of the rib as seen in figure 4.9. The desired depth of the implants was 0.2 microns with a peak concentration of about $2 \times 10^{20} \text{ cm}^{-3}$. A rough estimate of the implant energies and doses was calculated using the equation 4.1:

$$Q = \sqrt{2\pi} \Delta R_p C_p \quad (4.1)$$

where Q is the dose in cm^{-2} , ΔR_p is the standard deviation at a certain implant energy of a specific dopant in μm and C_p is the peak concentration of the implant in cm^{-3} [Plu00].

Values for ΔR_p can found in figure 4.10.

Figure 8-3 Plot of the range R_p (top) and standard deviation ΔR_p (bottom) of common dopants in crystalline silicon tilted and rotated to simulate a random direction. (After [8.1].)

Figure 4.10: Implantation range and standard deviation of various dopants [Plu00]

The results were simulated in SUPREM4. The final energies and doses are summarized in Table 4.4.

Ion	Implant Energy	Dose
75As+	20 keV	$3 \times 10^{15} \text{ cm}^{-2}$
11B+	10keV	$3 \times 10^{15} \text{ cm}^{-2}$

Table 4.4: Summary of implant data

Below are the simulated doping profiles:

Figure 4.11: SUPREM4 simulations: Ion implant profiles

A standard metallization scheme for contacting shallow junctions was used to complete the diodes. A 40 nm layer of Ti was deposited to make initial contact to the silicon. The Ti layer was overlaid with 200 nm of TiW pseudo alloy to avoid “spiking” of Al from overlying interconnect layers into the silicon. The latter point is necessary because silicon has a high solubility in aluminum and sometimes if the two materials are in contact, the aluminum can short the junction. The Ti and TiW layers were deposited in the same vacuum cycle using a multi-target sputtering system. The Ti/TiW stack was patterned using a lift-off technique with LOR3A photoresist. Following patterning and resist removal the samples were heated to 600°C for 30 seconds in a Heatpulse 210 Rapid Thermal Annealer to react the Ti with the underlying silicon to form TiSi_2 , breaking down any interfacial oxide which might be present and reducing contact resistance. A 1- μm thick layer of Al interconnect was then deposited using e-beam evaporation and patterned by lift-off with LOR3A. Following resist removal, the samples were given a 10 minute anneal at 400°C in a pure hydrogen ambient to minimize resistance between the metal layers and passivate the silicon surface.

The final metal structure is diagramed below:

Figure 4.12: Metal Contact structure

4.5 SEM/AFM Images

The initial sample made at CMFL was sent to the Surface Science Department of the University of Western Ontario to be imaged by their Atomic Force Microscope (AFM). The AFM uses a fine tip to measure surface morphology and properties through an interaction between the tip and surface.

AFM

Grating #41, Centre

Depth = 115 nm

Period = 225 nm

Figure 4.13: AFM IMAGE: grating made entirely at CMFL

Figure 4.14: SEM IMAGE: grating patterned at NRC viewed at 30000X

Figure 4.15: Microscope image (top view): sample before metallization

4.6 Possible Changes to the Process

One problem with the process is that the gratings are etched before the rib is etched. The alignment issue presented earlier causes the grating to be patterned into the silicon beside the rib and could alter the desired response. A possible solution to this fabrication problem is to pattern the gratings into a hard mask first, for example in oxide; then pattern the waveguide on top of the gratings and etch the waveguide and then etch the gratings.

Chapter 5: Testing and Results

5.1 Overview

The testing phase of this thesis can be divided into three parts: optical, electrical and electrooptical.

5.2 Experimental Setup

Optical testing was performed using the facilities in the Engineering Physics Department of McMaster University. An optical testing system, as shown in figure 5.1 was set up on a vibrationally-isolated optical bench. The optical source was either a broadband source or a tunable laser depending on which tests needed to be performed. The signal was fed through an Erbium-Doped Fiber Amplifier (EDFA), then a polarization controller. The signal was coupled into the SOI waveguide using a polarization-maintaining tapered fiber. The polarization of the light was ensured to be TE. After passing through the device, the light was then coupled into another fiber and was sent for data acquisition, either to an optical spectrum analyzer or a power meter.

Figure 5.1: Optical test setup at McMaster

5.3 Sample Preparation

In order to be tested, samples need to be cleaved to produce a flat facet perpendicular to the waveguide. The cleaving procedure used at McMaster University is outlined below:

- 1) Attach sample facedown to a cylindrical, level steel block that has an evenly-distributed weight using Crystal Bond adhesive.
- 2) Place block into a circular outer ring (used to ensure block remains level). Using a fine grit silicon carbide sandpaper (around 320), thin samples to a 300- μm thickness. A micrometer can be used to measure relative thicknesses.
- 3) Using a 500-grit sandpaper, thin samples to 200-250 μm .
- 4) Detach sample from block, remove Crystal Bond residue with acetone.
- 5) Scribe front side of sample.
- 6) Assert pressure on sample from backside along scribe line to cleave sample.

Unfortunately this procedure does not always work as intended. Sometimes samples cleave to produce ragged edges which scatter light and cannot be used for optical testing.

5.4 Grating Optical Response

Initial optical tests made use of gratings fabricated entirely in the CMFL. This test setup used a tunable laser as an input and an optical power meter to measure the output light. A 200- μm long grating with a depth of 115 nm exhibited a reflection of 0.75 dB with a bandwidth of several nanometers. The graph below shows relative transmission power.

Figure 5.2: Experimental results from grating entirely made at CMFL

The experimental results of the CMFL Bragg grating corresponded well with the expected results from the simulations in terms of location of response, expected bandwidth and depth of the response.

	Simulated	Measured
Center Wavelength	1558.8 nm	1556 nm
Bandwidth	3 nm	4 nm
Relative Transmission dip	-0.7 dB	-0.75 dB

Table 5.1: Comparison of simulated and measured results for CMFL sample

The response of the first set of gratings fabricated in the CMFL provided confidence to request assistance from NRC in producing much longer gratings using the commercial JEOL JBX-6000 e-beam lithography system located there. Sets of gratings with lengths ranging from 2 to 8 mm were written by Dr. Jean Lapointe of NRC at 60 locations covering a 100 mm diameter SOI wafer. The wafer was then cleaved into small pieces, each piece carrying a complete set of gratings, and all subsequent processing was done in the CMFL.

The 6-mm grating had a transmission notch of 6.7 dB with a bandwidth of 0.6 nm.

Figure 5.3: Experimental Results of grating patterned at NRC

The experimental results showed a transmission dip much weaker than anticipated from the simulated results. However, the bandwidth of the response was close to the 0.55-nm simulated bandwidth.

	Simulated	Measured
Center Wavelength	1558.8 nm	1558.8 nm
Bandwidth	0.55 nm	0.6 nm
Relative Transmission dip	-50 dB	-6.7 dB

Table 5.2: Comparison of simulated and measured results for NRC-written sample

5.5 Electrical Testing

After a grating response was successfully obtained on test devices resulting from the lithography run at NRC, a set of eight samples with gratings was processed to include n+ and p+ diode contacts and metallization required to produce a complete electronically tunable grating. Electrical testing of these devices was carried out at Carleton using a wafer prober and an HP4155 Semiconductor Parameter Analyzer.

The diodes across the waveguides were tested to ensure that the structures exhibited diode-like behaviour and that large quantities of minority carriers were being injected into the region under the rib.

Minority carrier injection was investigated using an improvised lateral bipolar transistor. Using the p+ region as a base contact, the n+ region on the opposite side of the rib was forward biased to serve as an emitter. The n+ contact region on the adjacent rib was held at zero bias and used as a collector. In this way the transistor was operated in a common-base configuration.

Figure 5.4: Probe placement for diode characterization

Unfortunately, the above probe placement was a last resort. Diode test structures were designed on the samples to do this step, but a mistake in applying the masks resulted in the P+ and N+ regions being switched. Luckily, we were still able to observe

minority carrier current in the collector of our makeshift test structure. Current-voltage characteristics for the best sample produced are shown below.

From our structure, we can calculate the approximate dissipated power in order to get $5 \times 10^{17} \text{ cm}^{-3}$ carriers in the intrinsic region of the diode. From the BJT structure, we can assume that the collector collects about 50% of the minority carriers. Our Medici simulation showed that we needed a current of $1.31 \times 10^{-5} \text{ A}$ to get the correct number of carriers. Accordingly, the diode is injecting the correct number of carriers when the collector current is approximately $6.5 \times 10^{-6} \text{ A}$. The diode at this point has an emitter current of $2.81 \times 10^{-5} \text{ A}$ at a voltage of 0.4 V. The total dissipated power at this point is approximately $11.24 \text{ } \mu\text{W}$.

Figure 5.5: Diode electrical results

5.6 Electrooptic Modulation Results

Of the eight samples which began fabrication of n+ and p+ diode contacts, only one survived processing to give diodes with good electrical characteristics and strong minority carrier injection. When this one prime sample was being cleaved for testing, it shattered, making optical testing impossible. As a fallback position, we decided to simulate the effect of minority carrier injection from diode contacts by photogenerating carriers in the rib using illumination from a HeNe laser directed perpendicular to the rib.

A 25 mW Helium-Neon laser operating at 632.8 nm was used for this experiment. The Bragg grating exhibited a small but measurable shift in center wavelength. The maximum shift observed was 0.08 nm. The figure below shows the shift in response due to different laser intensities. The shift agrees with theory in both direction and magnitude.

Figure 5.6: Experimental Results: Shift in response due to focusing laser on grating

The change in the index of refraction was calculated and substituted into the coupled-mode theory simulations from the design section. The area illuminated by the laser could be approximated with a 2-mm-radius circle. In a separate experiment carried out by Phil Waldron, a Ph.D. candidate from McMaster University using the same substrate and similar devices, the diffusion length was found to be approximately 60 μm . Using this information, we were able to estimate the expected Bragg grating response shift from the laser.

The reflectance at the air-silicon interface is calculated to be 0.34 using the equation:

$$R = \left(\frac{n_2 - n_1}{n_2 + n_1} \right)^2 \quad (5.1)$$

with the index of refraction of air being 1 and the index of refraction of silicon at 632.8 nm being approximately 3.8. The power of the laser not reflected by the silicon is $25mW(1 - R) = 16.5mW$.

The generation rate from the absorption of photons is:

$$G_{op} = \frac{dI(x)}{dx} \frac{1}{E_{gSi}} \quad (5.2)$$

where E_{gSi} is the smallest bandgap of silicon and $I(x)$ is the light intensity dependent on the penetration, x , into the substrate.

$$\begin{aligned} -\frac{dI(x)}{dx} &= \alpha I(x) \quad [\text{Str00}] \\ &\cong \alpha I_0 \end{aligned} \quad (5.3)$$

where α is the absorption coefficient and I_0 is the incident intensity. The approximation above is valid because the figure below shows that the penetration depth is comparable to the sample thickness. The absorption coefficient is also obtained from the figure below and estimated to be $5 \times 10^3 \text{ cm}^{-1}$.

Figure 5.7: Absorption coefficient vs. wavelength [Int04]

Using the radius of the illuminated area, we can calculate the incident intensity. The optical generation rate is estimated to be $3.69 \times 10^{21} \text{ cm}^{-3}/\text{s}$.

From the experimental diffusion length, the carrier lifetime can be found using the electron diffusion coefficient, D_n :

$$\tau_n = \frac{L_n^2}{D_n} \quad (5.4)$$

Assuming an electron diffusion coefficient of $35 \text{ cm}^2/\text{s}$ [Str00], the carrier lifetime for our samples is calculated to be $1.03 \text{ }\mu\text{s}$.

From the carrier lifetime and the optical generation rate, we can calculate the change in minority carrier concentration due to the laser:

$$\Delta N = G_{op} \tau_n \quad (5.5)$$

The change in concentration of minority carriers is approximately $3.69 \times 10^{15} \text{ cm}^{-3}$. Finally the change in refractive index can be calculated from the equation presented in the theory section:

$$\Delta n = -[8.8 \times 10^{-22} \cdot \Delta N + 8.5 \times 10^{-18} \cdot (\Delta P)^{0.8}] \quad (5.6)$$

The change in index of refraction was calculated to be 2.8×10^{-5} . The corresponding shift in response is 0.013 nm . This is in fairly good agreement with the measured result.

Figure 5.8: Theoretical Result: Optically-modulated response

Wavelength (nm)	Tx(dB)- shifted	Tx(dB)	
1558.821	-52.852	-52.345	
1558.822	-52.871	-52.403	
1558.823	-52.886	-52.459	
1558.824	-52.898	-52.511	
1558.825	-52.908	-52.561	
1558.826	-52.914	-52.607	
1558.827	-52.916	-52.649	max
1558.828	-52.916	-52.689	
1558.829	-52.913	-52.725	
1558.83	-52.906	-52.759	
1558.831	-52.896	-52.789	
1558.832	-52.883	-52.816	
1558.833	-52.867	-52.839	
1558.834	-52.848	-52.86	
1558.835	-52.826	-52.877	
1558.836	-52.8	-52.891	
1558.837	-52.772	-52.902	
1558.838	-52.74	-52.91	
1558.839	-52.705	-52.915	
1558.84	-52.666	-52.917	max
1558.841	-52.625	-52.915	
1558.842	-52.58	-52.91	
1558.843	-52.532	-52.903	
1558.844	-52.481	-52.892	

Table 5.3: Data table for figure 5.8

Chapter 6: Conclusion

This work can be divided into two main subcomponents: the fabrication of a Bragg grating on a Silicon-on-Insulator substrate and a study and demonstration of the plasma dispersion effect on the response of the Bragg grating.

We were able to show that a Bragg grating, and hence other devices of this dimension, can be entirely fabricated in the Carleton Microelectronics Fabrication Laboratory using its JEOL 850 SEM and the ECR plasma etcher. The maximum size of such a structure has to be in the range of 200 micron. Experimentally, we showed that the 200-micron long Bragg grating with a grating depth of 115 nm showed a response of 0.75dB and had a bandwidth of several nanometers.

Afterwards, we fabricated other Bragg gratings, patterned at the NRC with a JEOL JBX-6000, to a length of 6 mm. Experimentally, the response of the grating was not as strong as the simulations had predicted, but did have a predictable bandwidth and center wavelength. The gratings tested had a grating depth of 40 nm and a length of 6 mm and showed a reflection of 6.7 dB with a bandwidth of 0.6 nm.

Working pin diodes were fabricated across the Bragg gratings. We were able to observe considerable minority carrier injection for the geometry of the device tested. The diode fabrication process did not have a very high yield and as a result we were only able to have one sample fit for testing. During the sample preparation phase, the sample was shattered.

The plasma dispersion effect on the grating was tested optically. The peak filter wavelength was found to shift to a shorter wavelength by approximately 0.08 nm from

1534.7 nm when free carriers were generated in the grating by illumination with a 25 mW Helium-Neon laser.

6.1 Recommendations for Future Work

In the immediate future, several samples are in the final stages of diode fabrication and can be tested in the upcoming months.

We have fabricated a novel structure for modulating the refractive index of silicon-based devices. The results from this experiment are very promising for implementing silicon-based active devices and can be viewed as an important step in the development of high-density silicon photonic circuits.

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Appendix 1

SEH SOI Specification Sheet

Specifications		
■ Standard		
SOI	Diameter	200 mm
	thickness	100~200 nm
	uniformity	< ±5%
	type	P-type
	resistivity	8.5~11.5 Ω·cm
	orientation	< 100 >
BOX	Notch/Flat	Notch
	Thickness	400 nm
Base wafer	uniformity	< ±2.5%
	Thickness	725 μm
	type	P-type
	resistivity	14~22 Ω·cm
	orientation	< 100 >
	HF defect	< 0.3 /cm ²
Sacco defect		1×E3 /cm ²
Pipe density		none
Roughness (rms)		< 0.2 nm
Metal contamination		< 2×E10 /cm ²
Edge exclusion		5 mm

Appendix 2

Matlab Code: Coupled Mode Theory

```
% CMT
% this file implements the couple mode theory for a bragg grating as
% outlined in Yariv "Introduction to Optical Electronics"

function [reflectance,wavelength]=CMT(a,t,L,n1,n2,m)
% a - grating depth
% t - height of slab waveguide
% L - length of grating
% n2 - refractive index of waveguide
% n1 - lower refractive index of grating
% m - order of gratings

LAMBDA=225e-9; % grating period

K=2*pi/LAMBDA;

lambda=[1557.5e-9:1e-12:1560e-9];

beta=2*pi*n2./lambda;

dk=(2.*beta)-K;      %deltak

dN=sqrt(n2^2-n1^2); % deltaN

kappa=-
((2*pi^2*dN^2)*(a/t)^3)/((3*m).*lambda*n2).*(1+3/(2*pi*dN).*(lambda./a)
+(4/(4*pi^2*dN^2)).*(lambda./a).^2);

S=sqrt(kappa.^2-(dk/2).^2);

%from CMT2

R=((kappa.^2).*((sinh(S.*L)).^2))./((((dk./2).*(sinh(S*L))).^2)+((S.*(co
sh(S*L))).^2));

wavelength=lambda;
reflectance=R;
```

Procedure used to call function

```
%final design
Clear

t=2.5e-6;
n1=1;
n2=3.46402;
a=80e-9;
L=6e-3;

figure(1)
hold on
m=1;
[refl,wl]=CMT(a,t,L,n1,n2,m);
tx=10*log10(1-refl);
plot(wl,tx);
hold off
```

Appendix 3

MEDICI Input File

```

TITLE SOI waveguide

$ Output file
mesh out.file=soi_mesh

X.MESH width=44 h1=0.5
y.mesh depth=3.4 h1=0.1

region num=1 oxide x.min=0.0 x.max=44.0 y.min=0 y.max=0.4
region num=2 silicon x.min=0.0 x.max=44.0 y.min=1.0 y.max=3
region num=3 oxide x.min=0.0 x.max=20.5 y.min=0.4 y.max=1.0
region num=4 silicon x.min=19.5 x.max=24.5 y.min=0.4 y.max=1.0
region num=5 oxide x.min=23.5 x.max=44.0 y.min=0.4 y.max=1.0
region num=6 oxide x.min=0.0 x.max=44.0 y.min=3.0 y.max=3.4

electr name=ele x.min=0.0 x.max=2.0 y.min=1.0 y.max=1.0
electr name=hole x.min=42.0 x.max=44.0 y.min=1.0 y.max=1.0

profile p-type n.peak=1e15 uniform
profile n-type n.peak=3e20 y.min=1.0 y.max=1.3 y.char=0.15 x.min=0
x.max=2.0
+x.char=0.15
profile p-type n.peak=2e20 y.min=1.0 y.max=1.3 y.char=0.15 x.min=42
x.max=44
+x.char=0.15

material region=2 TAUN0=1.0e-6 TAUP0=1.0e-6
material region=4 TAUN0=1.0e-6 TAUP0=1.0e-6

models SRH conmob auger bgn fermidir print

symbolic newton carriers=2

solve
solve v(ele)=0.0 v(hole)=0.9282 outfile=test.sol currents

print x.min=21.95 x.max=22.05 y.min=1.09 y.max=1.11 E.FIELD solution
+currents que recomb
print x.min=0.9 x.max=1.1 y.min=1.0 y.max=1.5 E.FIELD solution
+currents que recomb

```

```
plot.2d    device="cl/postscript" boundary junction depletio
plot.out=doping.ps
contour    fill logarithm doping
plot.2d    device="cl/postscript" boundary junction depletio
plot.out=recomb.ps
contour    fill logarithm recomb
end
```

MEDICI Output File

*** Solution ***

Electrode	Applied Bias	Terminal Voltage	Terminal Current	Terminal Flux
Name	(volts)	(volts)	(amps/micron)	(coul/micron)
ele	0.0000000E+00	0.0000000E+00	-1.5519021E-05	7.9357770E-18
hole	9.2819995E-01	9.2819995E-01	1.5519021E-05	-9.3547137E-18

Node	X-Coord	Y-Coord	Jn	Jp	Jcond	Jdisp
(#)	(microns)	(microns)	(Amps/cm^2)	(Amps/cm^2)	(Amps/cm^2)	(Amps/cm^2)
1552	2.2000E+01	1.1000E+00	2.1671E+02	3.4997E+02	5.6668E+02	0.0000E+00

Node	v	n	p	qfn	qfp
(#)	(Volts)	(#/cm^3)	(#/cm^3)	(Volts)	(Volts)
1552	4.5647E-01	5.0140E+17	5.0240E+17	7.7353E-03	9.0553E-01

Node	Region	Material	X-coord	Y-coord	Q	QA
(#)	(#)	Name	(microns)	(microns)	(#/cm^3)	(#/cm)
1552	2	Sili	2.2000E+01	1.1000E+00	2.1903E+09	1.0951E+00

Integrated density for nodes in print window = 1.0951E+00

Node	Region	Material	X-coord	Y-coord	U	UA
(#)	(#)	Name	(microns)	(microns)	(#/cm^3/s)	(#/cm/s)
1552	2	Sili	2.2000E+01	1.1000E+00	2.9885E+23	1.4942E+14

Integrated density for nodes in print window = 1.4942E+14

Node	x coord	y coord	EX	EY	E
(#)	(microns)	(microns)	(V/cm)	(V/cm)	(V/cm)
1552	2.2000E+01	1.1000E+00	-5.4729E+00	-2.5153E-01	5.4787E+00

*** Solution ***

Electrode	Applied Bias	Terminal Voltage	Terminal Current	Terminal Flux
Name	(volts)	(volts)	(amps/micron)	(coul/micron)
ele	0.0000000E+00	0.0000000E+00	-1.5519021E-05	7.9357770E-18
hole	9.2819995E-01	9.2819995E-01	1.5519021E-05	-9.3547137E-18

Node	X-Coord	Y-Coord	Jn	Jp	Jcond	Jdisp
(#)	(microns)	(microns)	(Amps/cm^2)	(Amps/cm^2)	(Amps/cm^2)	(Amps/cm^2)
81	1.0000E+00	1.0000E+00	4.4592E+02	1.3433E+00	4.4727E+02	0.0000E+00
82	1.0000E+00	1.1000E+00	4.4323E+02	3.2845E+00	4.4651E+02	0.0000E+00
83	1.0000E+00	1.2000E+00	4.3271E+02	1.1986E+01	4.4469E+02	0.0000E+00
84	1.0000E+00	1.3000E+00	4.0329E+02	4.4024E+01	4.4731E+02	0.0000E+00
85	1.0000E+00	1.4000E+00	3.2241E+02	1.5947E+02	4.8188E+02	0.0000E+00

86 1.0000E+00 1.5000E+00 1.8431E+02 2.5193E+02 4.3624E+02 0.0000E+00
4.3624E+02

Node (#)	v (Volts)	n (#/cm ³)	p (#/cm ³)	qfn (Volts)	qfp (Volts)
81	6.2848E-01	3.0000E+20	6.5256E+00	0.0000E+00	0.0000E+00
82	6.2848E-01	3.0000E+20	6.4741E+13	2.1910E-06	7.7361E-01
83	6.2849E-01	3.0000E+20	2.5486E+14	4.3435E-06	8.0904E-01
84	6.2849E-01	3.0000E+20	9.4006E+14	6.3964E-06	8.4278E-01
85	5.9216E-01	1.9236E+20	8.2541E+15	8.4093E-06	8.6662E-01
86	5.2815E-01	5.0793E+19	8.9840E+16	1.0594E-05	8.7636E-01

Node (#)	Region (#)	Material Name	X-coord (microns)	Y-coord (microns)	Q (#/cm ³)	QA (#/cm)
81	2	Sili	1.0000E+00	1.0000E+00	-1.9238E+08	-4.8094E-02
81	3	Oxid	1.0000E+00	1.0000E+00	0.0000E+00	0.0000E+00
82	2	Sili	1.0000E+00	1.1000E+00	-2.0028E+09	-1.0014E+00
83	2	Sili	1.0000E+00	1.2000E+00	4.5551E+10	2.2775E+01
84	2	Sili	1.0000E+00	1.3000E+00	2.3692E+15	1.1846E+06
85	2	Sili	1.0000E+00	1.4000E+00	1.8055E+15	9.0276E+05
86	2	Sili	1.0000E+00	1.5000E+00	-8.8420E+14	-4.4210E+05

Integrated density for nodes in print window = 1.6453E+06

Node (#)	Region (#)	Material Name	X-coord (microns)	Y-coord (microns)	U (#/cm ³ /s)	UA (#/cm/s)
81	2	Sili	1.0000E+00	1.0000E+00	-1.7925E+08	-4.4813E-02
81	3	Oxid	1.0000E+00	1.0000E+00	0.0000E+00	0.0000E+00
82	2	Sili	1.0000E+00	1.1000E+00	1.6315E+24	8.1576E+14
83	2	Sili	1.0000E+00	1.2000E+00	6.4227E+24	3.2113E+15
84	2	Sili	1.0000E+00	1.3000E+00	2.3690E+25	1.1845E+16
85	2	Sili	1.0000E+00	1.4000E+00	8.5526E+25	4.2763E+16
86	2	Sili	1.0000E+00	1.5000E+00	6.5028E+25	3.2514E+16

Integrated density for nodes in print window = 9.1149E+16

Node (#)	x coord (microns)	y coord (microns)	EX (V/cm)	EY (V/cm)	E (V/cm)
81	1.0000E+00	1.0000E+00	-2.7454E-03	-2.1937E-01	2.1938E-01
82	1.0000E+00	1.1000E+00	-9.8474E-03	-2.2366E-01	2.2388E-01
83	1.0000E+00	1.2000E+00	-2.1882E-02	-1.8637E-01	1.8765E-01
84	1.0000E+00	1.3000E+00	-3.2817E-02	1.8162E+03	1.8162E+03
85	1.0000E+00	1.4000E+00	-4.7278E-02	5.0169E+03	5.0169E+03
86	1.0000E+00	1.5000E+00	-1.4783E-01	5.7233E+03	5.7233E+03

Two dimensional contour plot
Input line # 28

Values plotted:
-2.030062E+01 -1.622289E+01 -1.214516E+01
-8.067423E+00 -3.989689E+00 8.804417E-02
4.165778E+00 8.243511E+00 1.232125E+01
1.639898E+01 2.047671E+01

Values not plotted:
-2.437836E+01 2.455445E+01

Two dimensional contour plot
Input line # 30

Values plotted:
-8.320787E+00 -4.886346E+00 -1.451905E+00
1.982537E+00 5.416978E+00 8.851419E+00
1.228586E+01 1.572030E+01 1.915474E+01
2.258918E+01 2.602362E+01

Values not plotted:
-1.175523E+01 2.945807E+01

*** END MEDICI ***

TOTAL CPU TIME = 1.50 minutes

Appendix 4

Fabrication Runsheet

1. PATTERN: GRATING

Bake 2 hours at 220°C
Spin HMDS adhesion promoter: 30 sec at 4000 rpm
Bake 60 sec at 105°C
Spin Diluted ZEP; 1:1 with anisole thinner: 30 sec at 4000 rpm
Bake 4 min at 180°C
Expose pattern using E-beam system controlled by NPGS software
Develop in O-Xylene; no agitation, process temperature 21°C: 2 min
Rinse in Iso-propanol: 30 sec

2. ETCH: GRATING

Attach sample to 4" wafer using S1805 photoresist as glue
Bake 5 min at 105°C
Descum sample in Planar Plasma Etcher: 5 sec at 0.3 torr, 50 watts
Etch sample in ECR plasma etcher: 15-30 sec
Remove remaining ZEP in Planar Plasma Etcher: 2 min at 0.5 torr, 300 watts
Remove sample from 4" wafer

3. PATTERN: RIB

Attach sample to 2" wafer using S1805 photoresist as glue
Bake 5 min at 105°C
Spin HMDS adhesion promoter: 30 sec at 4000 rpm
Bake 60 sec at 105°C
Spin S1805 photoresist: 30 sec at 4000 rpm
Bake 60 sec at 105°C

Expose "9x9-6" optical mask using Mask Aligner: 20 sec
Develop sample in MIF321 developer, process temperature 21 °C: 45 sec
Rinse in DI water: 30 sec

4. ETCH: RIB

Attach sample to 4" wafer using S1805 photoresist as glue
Bake 5 min at 105°C
Descum sample in Planar Plasma Etcher: 75 sec at 0.3 torr, 100 watts
Etch sample in ECR plasma etcher: 60-120 sec
Remove remaining S1805 in Planar Plasma Etcher: 5 min at 0.5 torr, 300 watts
Remove sample from 4" wafer

5. OXIDATION

- a) RCA clean
- b) Oxidation wafers L5, L6, M3, N1, N3, N4 tube temperature 1100°C
 - 5 min preheat O₂
 - 3 min push O₂
 - 11 min oxidation dry O₂
 - 20 min anneal N₂
 - 2" every 15 sec pull N₂
 - 10 min cool N₂
 - target thickness: 50 nm thickness measured on test wafer: 50 nm
- c) Oxidation wafers M8, N₂ tube temperature 1000°C
 - 5 min preheat O₂
 - 3 min push O₂
 - 19 min oxidation dry O₂
 - 20 min anneal N₂
 - 2" every 15 sec pull N₂
 - 10 min cool N₂
 - target thickness: 25 nm thickness measured on test wafer: 28.5 nm

6. ACTIVE REGION P.E. Mask CU238-01

- a) apply, prebake, expose, develop, postbake, descum S1811
- b) etch in buffered HF to hydrophobia in contact windows
 - etch times: 60 sec
- c) strip PR in Caro's acid

7. POLYSILICON DEPOSITION

- a) RCA clean (end with 60 s in 1% HF- must clear windows)
- b) undoped poly deposition
 - Place samples flat in covered boat, top open
 - tube temperature: 625°C deposition time: 8 min

target thickness: 100 nm (or slightly less)

8. N+ PE Mask CU238-02

apply, prebake, expose, develop, postbake, descum S1811

9. N+ IMPLANT

- a) ship to Kroko Implant Services for implant
- b) implant 75As+, 20 keV, $3 \times 10^{15} \text{ cm}^{-2}$
- c) plasma strip PR, followed by Caro's acid clean

10. P+ PE Mask CU238-03

apply, prebake, expose, develop, postbake, descum S1811

11. P+ IMPLANT

- a) ship to Kroko Implant Services for implant
- b) implant 11B+, 10 keV, $3 \times 10^{15} \text{ cm}^{-2}$
- c) plasma strip P.R., followed by Caro's acid clean

12. POLYSILICON P.E. Mask CU238-04

- a) apply, prebake, expose, develop, postbake, descum S1811
- b) etch in aqueous poly etch
 - estimated etch time: 20 sec
 - actual etch times: 23-25 sec
- c) strip PR in Caro's acid

13. IMPLANT FURNACE ANNEAL

- a) RCA clean
- b) tube temperature: 900°C
 - 5 min preheat N₂
 - 30 sec push to center N₂
 - 20 min anneal N₂
 - 30 sec pull N₂
 - 10 min cool N₂

14. IMPLANT RAPID THERMAL ANNEAL

Rapid thermal anneal: set temperature of 1000°C (actual 1050°C) 20 s N₂
ambient at 50 mm

15. METAL 1 LITHOGRAPHY

apply, prebake, expose, develop, postbake, descum Microchem LOR3A

HMDS spin 2000 rpm, bake 105°C for 1 min

LOR3A spin 2000 rpm (no spread), bake 175°C for 5 min

S1811 spin 4000 rpm, bake 105°C for 1 min

Exposure 26 sec

Develop 1 min, add 10 sec until good result

16. Ti/TiW DEPOSITION

a) Etch 30 sec in 1%HF to clear contact windows

b) Pre-sputter targets for 5 min

c) Sputter etch for 2 min at 100 W

d) Sputter deposit Ti at 100 W for 5 min (target thickness 50 nm)

e) Sputter deposit Ti/W alloy at 100 W for 20 min (target thickness 200 nm)

17. METAL 1 LIFT-OFF

a) Dissolve PR in acetone

b) Strip residual resist in Microstrip 2001, rinse 30 min

18. SILICIDE FORMATION

Rapid thermal anneal 600°C 30 s N₂ ambient

19. METAL 2 LITHOGRAPHY

apply, prebake, expose, develop, postbake, descum Microchem LOR10B

HMDS spin 2000 rpm, bake 105°C for 1 min

LOR10B spin 2000 rpm (no spread), bake 175°C for 5 min

S1811 spin 4000 rpm, bake 105°C for 1 min

Exposure 26 sec

Develop 2 min, add 15 sec until good result

20. ALUMINUM DEPOSITION

Deposit 1 µm Al by e-beam

21. METAL 2 LIFT-OFF

a) Dissolve PR in acetone

b) Strip residual resist in Microstrip 2001, rinse 30 min

22. METAL ANNEAL

tube temperature: 400°C

5 min preheat N₂

5 min tube purge H₂

20 sec push H₂

10 min anneal H₂

20 sec pull H₂

5 min cool H₂

10 min tube purge N₂

Appendix 5

ZEP Specification Sheet

ZEP SERIES

Positive tone, chemically amplified type for device fabrication

The ZEP series encompasses positive-tone, chemically amplified electron beam resists with high resolution and excellent dry-etching resistance for device fabrication. The series is ideally suited to the creation of photo masks and X-ray masks as well as ultra-fine processing.

Characteristics

- Excellent dry-etching resistance, as high as photo resists
- Extremely high resolution
- Wide process margin

Product name	Molecular weight	Viscosity (mPa·s)	Solvent	Recommended developer	
				For masks	For direct writing
ZEP520	57,000	12, 22	o-Dichlorobenzene	ZEP-SD	ZED-N50
ZEP520A		7, 11	Anisole	ZMD-G	ZR-100
ZEP810	143,000	16	Diethylene glycol dimethyl ether	ZED-2DK	ZEP-RD
ZEP7000	340,000	22.5		ZED-500	n-hexyl acetate
ZEP7000B		32, 48	o-Dichlorobenzene	ZED-300	ZED-500

Pattern Profile

ZEP520	ZEP7000B
<p>0.15 μm L/S</p> <p>Process conditions Substrate: Si Resist: ZEP520 Film Thickness: 0.5 μm Prebake: 180°C Exposure: 55 μC/cm² at 20 kv Development: ZEP-RD Dip</p>	<p>0.05 μm line/0.01 μm space</p> <p>Process conditions Substrate: Si Resist: ZEP7000B Film Thickness: 0.09 μm Exposure: 180 μC/cm² at 45 kv Development: n-hexyl acetate</p>

Coating Properties

Constant X 60 sec., 180°C X 20 min.