Optical Ring Resonator and Other Photonic Devices (May 2008)

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Abstract—**This project aimed to design, simulate, fabricate and test optical ring resonators and other wave guide devices. The computational technique used to simulate our devices was beam propagation method (BPM) in RSOFT CAD software. These devices were developed to be fabricated on 4" silicon-on-insulator (SOI) wafers and fabricated in toe Rochester Institute of Technology fabrications laboratory.**

Index Terms—**Optics, Photonics, Ring Resonator, Waveguides**

THE understanding and application of photonics has continued to mature as a necessary component of the information revolution. Communication with light has displayed some remarkable advantages over their electronic counterparts, such as speed, bandwidth, and power consumption [1]. Without a doubt, photonics will continue to play a large role as our society increases their demand for greater amounts of information traveling across longer distances. In the past 15 years photonic fabrication has benefited tremendously from the microelectronics infrastructure. The ability to produce waveguides on a micron scale has introduced new avenues in switching, filtering, and the modulation of light. It's important to continue developing our understanding of photonic fabrication for the advancement of the microelectronic revolution.

In this project, 1μm optical ring resonators will be designed, simulated, and then fabricated on 4" silicon-on-insulator (SOI) wafers. The 4" substrates were chosen over the 6" substrates for budget reasons.

Photons has continued to grow and mature since the times of James C. Maxwell first successfully described the propagation of electromagnetic waves with his equations in 1878. Through the invention of the laser in 1960, the use of optics as a method of information transfer became more achievable. Communicating with light waves displayed some remarkable advantages over electronics. One such element in photonics is the enormous bandwidths possible. To comprehend the rational of ultra high bandwidths (5THz or 10^{12}Hz), one must understand the nature of electromagnetic waves in comparison to an electric current. In respect to single signal speeds, light waves propagate at speeds greater then electrons. However, the greatest advantage characteristic to light is the consequences of the lack of charge in photons. Since these particles carry no charge, their interference with each other carries very specific requirements in frequency and location. Therefore, a multitude of waves can coexists in the same medium while exhibiting negligible interference as they pass through each other. Such parallel processing allows optical systems to achieve the superior bandwidths.

I. Design of the Photonic Devices

A. Waveguides

One of the first hurdles in the goal of optical communication was finding a suitable medium of propagation. A wave traveling in through the atmosphere is far too susceptible to multiple variables such as temperature, scattering, and line-of-sight transmission. The natural attempt at a remedy to this issue was to enclose the wave in a protective pipe with an internal reflective coating. After years of examining methods to emend to huge problems of attenuation, dispersion, and scattering of the waves, the solution resolved into the form of waveguides such as modern fiber optics.

Traditionally, 1550nm wavelength has been used for its low dispersion over long transmission distances, and negligible absorption through glass.

Building upon the enormous microelectronic fabricating infrastructure, nano-photonics platforms are using Silicon-on-Insulator (SOI) platforms for their devices. While silicon is conveniently transparent to the traditional 1550nm light, photonics on silicon also benefit from the mature etching methods of silicon which prove critical when developing low loss devices. Furthermore, the use of silicon solves the cladding question since it has a natural oxide (SiO_2) which grows from its surface. This glass layer retains an index of refraction of n=1.46 which is advantageously discrepant from the silicon waveguide (n=3.45). This contrast assists the total internal refraction necessary for information transfer.

These waveguides will house electromagnetic radiation (light) which propagates with an electric and magnetic component. Maxwell's equations below in Fig1 describe the relationship between the electric field (E), Magnetic field (H), charge density (ρ), and current density (J).

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} - \vec{M}$$

$$\nabla \times \vec{H} = -\frac{\partial \vec{D}}{\partial t} + \vec{J}$$

$$\nabla \cdot \vec{D} = \rho$$

$$\nabla \cdot \vec{B} = 0$$

Figure 1: Maxwell's Equations

B. Ring Resonator

In photonics, a ring resonator is simply a waveguide which exist in a closed loop. Such a loop is usually coupled with another straight waveguide where power can be transferred via the evanescent wave which exists outside the donor waveguide boundary. This phenomenon can be physically explained through Maxwell's equations stating that the electric and magnetic fields must be continues at boundaries. Light with the tuned wavelength will travel in the ring and will eventually build up due to constructive interference. Because this coupling is highly sensitive to the wavelength of the light, ring resonators can be used as filters; an essential function in the goal of photonic logic. [5]An all-pass filter with a single resonating ring is shown below.

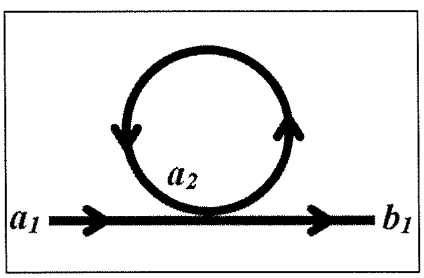

Figure 2: Optical ring resonator comprised of a straight waveguide and a ring adjacent to it.

As depicted in Fig 3, the waveguides are silicon slabs resting on a silicon surface. Surrounding these waveguides is SiO2 which will act as an optical cladding. Total internal reflection needed for photon propagation is enabled by the difference in the refractive indexes between the silicon waveguide and the oxide. The dimensions shown in Fig. 1 are the optimum designed values of the coupling region. A primary restriction in this design was the lithography equipment which allowed a minimum dependable feature size of 1um. The key dimensions of the optical devices where the waveguide slab height, minimum bending radius, and racetrack length in the ring resonators.

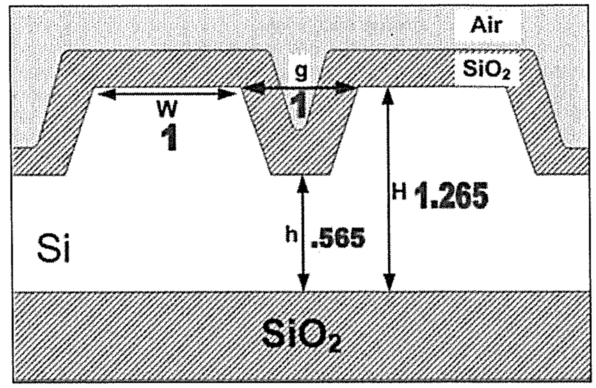

Figure 3: Cross section of the coupling region of two straight waveguides traveling into and out of the page plane.

C. Simulations

Simulations were done using RSOFT CAD software using the Beam Propagation Method as a calculations model.

Fig. 4displays the simulated transfer of a signal through coupling of two straight waveguides over 185um. The dimensions of these wave guides match the cross section shown in Fig. 3. Fig 4 is just one example of the several iterations tested while varying etch depth, slab height, and bending radius.

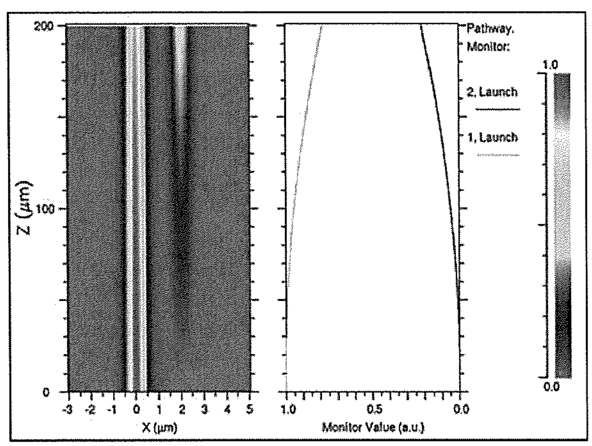

Figure 4: Simulation using BPM showing the transfer of power from one waveguide to an adjacent waveguide.

. Fig. 5 below shows a compilation of the data describing the relationship between device sizes and etch depths. The Coupling line represents the length of racetrack needed to achieve a 10% transfer. The Bend line describes the radius of curvature which would result in a loss of 10% of power. The ability to match power loss and coupling is needed to achieve a resonating system.

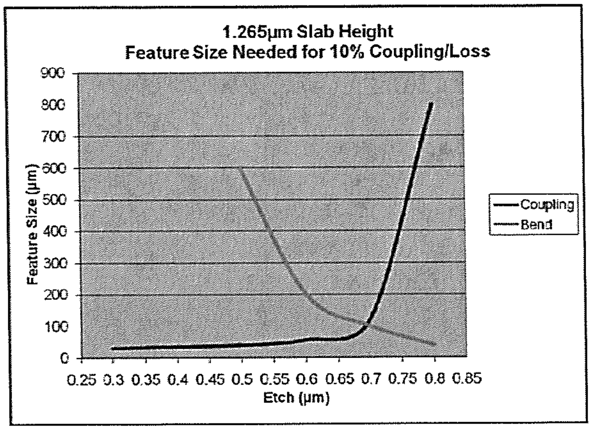

Figure 5: Simulation information describing the device size needed to attain the 10% coupling gain and 10% loss.

D. Processing

Several challenges arise in the fabrication photonics using the semiconductor technology. One such step, is the development of Silicon-on-Insulator (SOI) wafers which house a layer of Buried Oxide (BUX) thick enough to isolate the waveguides from interacting with the substrate. One method of creating this layer of oxide is Separation by implantation of Oxygen (SIMOX) [7] which uses a high energy implant of oxygen ions combined with high temperature anneals. This process yields great uniformity but requires very high implant voltages to produce sub sufficient thickness. Another method of producing BOX is called Smart Cuttm [6] where a wafer is prepared with an oxide layer grown on the surface. Another sacrificial wafer is then implanted with hydrogen atoms. These wafers are then sandwiched together to bond. Then after heat treatment, the implanted wafer will cleave at the hydrogen implanted projected range creating a single SOI wafer. All of these methods are not viable at RIT and wafers will need to be ordered for further steps.

A thin layer of oxide can be used as the hard mask for defining the silicon structures. This material is beneficial because it is not a contaminate in most tools and its resistance to the reactive ion etch (RIE) used in the process. Photoreisst has a much lower melting point and shows poor selectivity compared to silicon in a reactive ion etcher. The layer of oxide will be deposited using the P5000 TEOS chamber.

Lithography was done using the GCA 4" stepper. Even though the Cannon has a smaller resolution, the GCA was used because the wafers were not large enough to be accepted in the Cannon tool. Shown in Fig 6 are the photonic devices written to the aluminum mask.

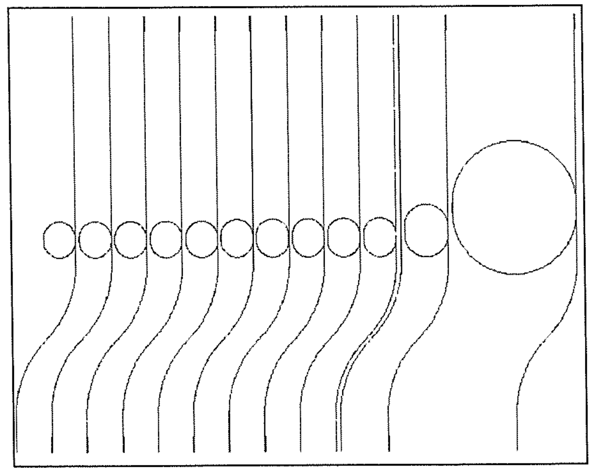

Figure 6: CAD picture of the mask used to fabricate the ring resonators.

As shown in Fig 6, several rings were placed on the same die with various racetrack lengths. This was done in hopes of achieving critical coupling at the 1550nm wavelength.

Fig 7 shows the substrate reflectivity simulated in PorLith simulation tool as a function of TEOS thickness. In order to avoid the standing wave effect, a minimal amount of reflectivity is desired from the substrate. A thickness of 375um of TEOS was used.

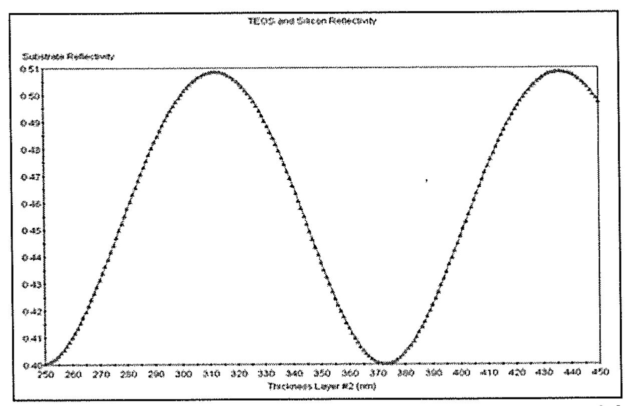

Figure 7: Substrate reflectivity as a function of TEOS thickness simulated in ProLith.

The original mask made at RIT contained stitching errors. This was caused by a slight miss-alignment in the writing tool used to pattern the mask. As shown in Fig. 8, such stitching errors which occurred several times across our 7mm long devices would cause a substantial loss in the wave signal. This issue was avoided by using an outside mask provider.

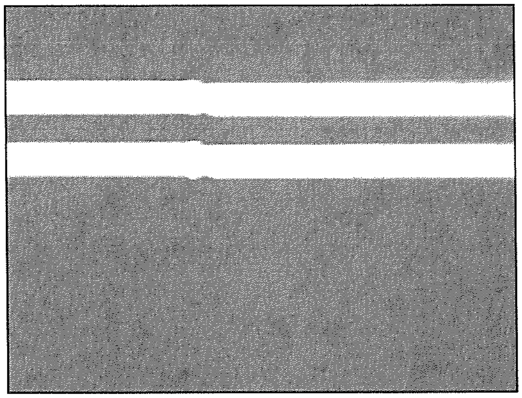

Figure 8: Snitching error shown on the aluminum mask made with the RIT MEBES tool

E. Results

Proof of concept was achieved in fabricating the waveguide devices in the RIT SMFL. Shown below in Fig 9 are the fabricated ring resonators.

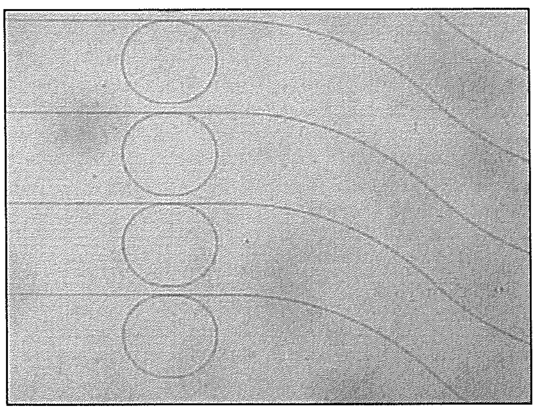

Figure 9: The fabricated ring resonators Ring resonators fabricated. The step height between the base silicon and the waveguides is 0.7µm with a .07µm layer of oxide on top. Other devices include straight and curved waveguides for control testing..

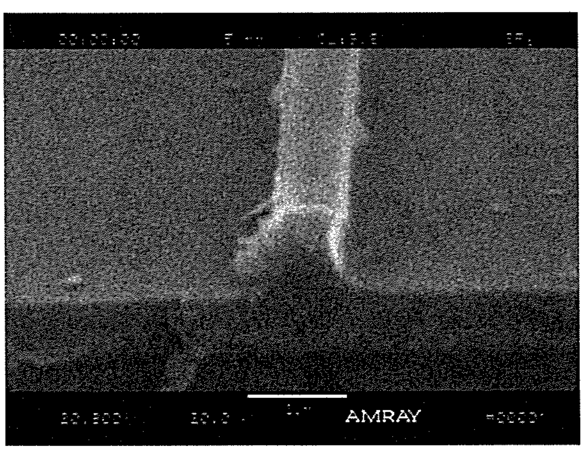

Figure 10: AMRAY SEM picture of a single waveguide. The white line is a 1µm marker. The oxide is shown right below the silicon layer and is slightly darker.

In Fig 10, one can see a single waveguide with some oxide left over on top. The waveguide and silicon layer is on top of the lowest layer buried oxide.

F. Future Work

The reproduction of this project would include active devices using a PIN diode to enable switching through use of the electro-optical effect. The electric field placed across the ring only, would slightly skew its effective refractive index. This in turn would shift the filtered wavelength.

Furthermore, a more selective anisotropic etch is needed for the silicon etch. The DryTek Quad used for this project had some isotropic characteristics and left some rough sidewalls.

G. Conclusion

Photonic devices were successfully fabricated using microelectronic fabrication technology. There were several processes steps which needed to be customized such as using photoresist as a thermal transferring agent in the P5000 REI. Future projects should consider using 6" substrate since technology favors their tool set.

ACKNOWLEDGMENT

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