Novel Fabrication Techniques for Silicon Photonics

G. T. Reed[1], P. Y. Yang, W. R. Headley, P. M. Waugh, G. Z. Mashanovich,
D. Thomson and R. M. Gwilliam
Advanced Technology Institute, University of Surrey, Guildford,
Surrey, GU2 7XH, United Kingdom

E. J. Teo and D. J. Blackwood
Department of Materials Science and Engineering, 9 Engineering Drive, National University of Singapore, Singapore 117546

M. B. H. Breese and A. A. Bettiol
Centre for Ion Beam Analysis (CIBA), Department of Physics, National University of Singapore,
2 Science Drive 3, Singapore 117542

ABSTRACT

In this paper we report two novel fabrication techniques for silicon photonic circuits and devices. The techniques are sufficiently flexible to enable waveguides and devices to be developed for telecommunications wavelengths or indeed other wavelength ranges due to the inherent high resolution of the fabrication tools. Therefore the techniques are suitable for a wide range of applications. In the paper we discuss the outline fabrication processes, and discuss how they compare to conventional processing. We compare ease of fabrication, as well as the quality of the devices produced in preliminary experimental fabrication results. We also discuss preliminary optical results from fabricated waveguide devices, as measured by conventional means. In these preliminary results we discuss fundamental properties of the waveguides such as loss and spectral characteristics, as it is these fundamental characteristics that will determine the viability of the techniques. Issues such as the origins of the loss are discussed in general terms, as resulting fabrication characteristics such as waveguide surface roughness (and hence loss), or waveguide profile and dimensions may be traded off against cost of production for some applications. We also propose further work that will help to establish the potential of the technique for future applications.

Keywords: Silicon-On-Insulator (SOI), directional couplers, silicon photonics, rib waveguides, single-mode condition

1. INTRODUCTION

Silicon-On-Insulator (SOI) is becoming well established as a practical material for optical devices with a range of applications [e.g. 1-3]. Because of its large refractive index, strong optical confinement is possible, which in turn allows for relatively small device dimensions so that a higher packing density can be achieved. A further benefit to using this material system comes from the mature field of silicon processing associated with microelectronics. However, in this paper we consider alternative fabrication processes based upon the use of ion beams. Fabrication of waveguides is considered via proton beam writing, together with fabrication of grating structures based upon ion implantation.

The first part of the paper discusses a novel waveguide fabrication technique via proton beam writing. Most conventional waveguides in silicon photonics are fabricated in the Silicon-On-Insulator (SOI) material system in the form of a strip or a rib waveguide. These waveguides, however, are not suitable for longer wavelengths greater than approximately 1800 nm (except in the 3-3.5 μm region) due to the absorption of the silicon dioxide insulating layer [4]. Silicon-based long wave infrared photonics could find applications in several areas including sensing, communications, signal processing, missile detection and imaging. Therefore, in this paper we discuss the fabrication and propagation

[1] g.reed@surrey.ac.uk; phone +44 1483 689122; fax +44 1483 534139

Silicon Photonics II, edited by Joel A. Kubby, Graham T. Reed, Proc. of SPIE Vol. 6477
64770E, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.705180

loss measurements of a new structure, the free standing waveguide. As this waveguide has an air cladding, it is a viable structure for long wavelength applications [4]. Alternatively, to make the device more robust, any other suitable cladding could easily be deposited to make the structures suitable for specific wavelength ranges.

The second part of the paper discusses another ion beam fabrication process. This time ion implantation is used to fabricate Bragg gratings in silicon waveguides. We have implanted oxygen ions into selected sections of the waveguide surface to form a periodic structure at the waveguide surface. This technique has the potential to produce grating via two methods: a refractive index change via crystal damage, or a refractive index change via silicon dioxide synthesis after annealing. Thus far only the former is reported, but the latter will be part of our future work.

2. WAVEGUIDE FABRICATION VIA PROTON BEAM WRITING

Proton beam writing (PBW) is an advanced lithographic technique for micromachining on the submicron scale. Polesello et al. [5] and Mistry et al. [6] have demonstrated PBW as a method to fabricate three dimensional structures directly in Si and GaAs respectively, thereby eliminating the need for a resist. There are several potential advantages of PBW. The first is that it is a direct write process which eliminates the need for a potentially costly mask. Furthermore, prototype devices which require small structural modifications can be produced by simply modifying the scan of the microbeam whereas modifications to a device using photolithographic methods would require the layout and fabrication of a new mask. A second benefit is that the protons are deposited in the semiconducting material in a well-defined range thereby allowing for good vertical control in the fabrication process. Furthermore, the high energy protons deviate little from the ideal straight path due to multiple small-angle Coulomb scattering. The result is that much smaller lateral straggle occurs as compared to e-beam lithography and hence a tighter control on the lateral dimensions of the structure.

A schematic of the electrochemical etching process of proton irradiated silicon is shown in Figure 1 [7, 8]. A focused proton microbeam is selectively scanned over the silicon surface, causing high energy protons to penetrate the silicon substrate and stop within a well-defined range, the depth being controlled by the proton energy. As the protons propagate through the silicon, they undergo a series of collisions, and are deflected away from an ideal straight path, resulting in a beam cross section increasing in size with depth. The energy deposited due to nuclear collisions per unit length is fairly constant during the early part of the penetration depth but increases sharply at the end of range, because the speed of protons is reduced by energy loss, thereby increasing the probability of nuclear collisions. The penetration range and energy deposition profiles can be simulated using SUSPRE [9], an ion implantation simulation package. Figure 2 shows the resulting disorder produced by 2 MeV protons in silicon, which have a projected range of 50 μm below the surface. Silicon vacancies are created along the path of the protons, with most of the damage occurring towards the end of their range. Two regions, a low and a high defect density have been approximated from this profile and result in the cross-sectional schematic shown in Figure 1(a). After irradiation, the sample is electrochemically etched in a 1:1:2 electrolyte mixture of 48% HF, water and ethanol. Once the silicon becomes porous, it can be removed by a subsequent dilute KOH solution. In the irradiated regions, the density of defects at the surface of the silicon is high enough to significantly reduce the electrical hole current flow and therefore inhibit the electrochemical reaction at the damaged silicon-electrolyte interface. The result is a significant reduction in the probability of producing porous silicon in the proton irradiation regions (Figure 1(b)) as compared to the un-irradiated region. The final structure produced after etching is a three dimensional representation of the scanned area (Figure 1(c)), which determines the dimensions of the final structure. The height of the structure is controlled by the etching time and current.

Free standing waveguides are undercut silicon wires supported periodically by pillars. To fabricate free standing waveguides via proton beam writing, two different ion energies are required. A high energy implant is used to create the pillars and a lower energy implant is subsequently used to create the waveguides. According to the simulation results obtained from SUSPRE, 2 MeV and 1 MeV protons have ranges of approximately 50 μm and 17 μm respectively.

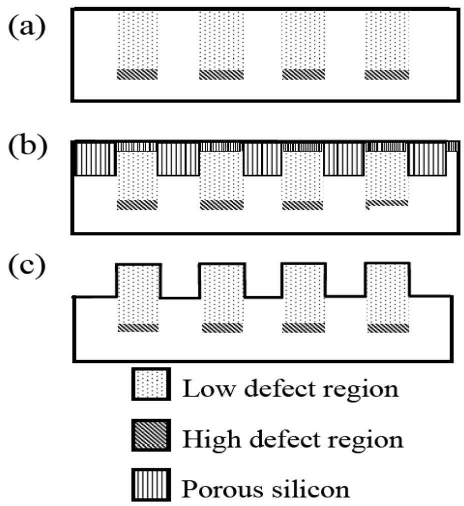


Figure 1 A schematic of the fabrication process of free standing waveguides via Proton Beam Writing

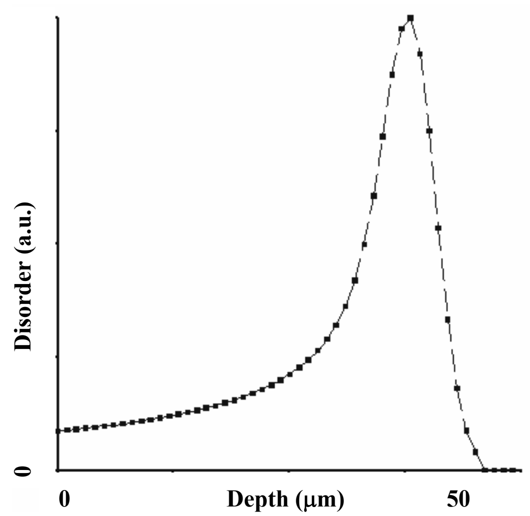


Figure 2 Simulation of disorder in silicon produced by 2MeV protons, via simulation software SUSPRE

Therefore the pillars were created with a dose of 0.7 x 10^{15} proton/cm^2 at an energy of 2 MeV and the waveguides with a dose of 0.6 x 10^{15} proton/cm^2 at an energy of 1 MeV. The localized damage pattern was created by scanning a microbeam of protons. The doses are significant enough to inhibit the current flow in the irradiated regions, thereby limiting the formation process of porous silicon during electrochemical etching. Figure 3 shows that the etching goes beyond the range of the 1 MeV protons (~17 μm), where undercutting of the waveguides occurs. Eventually the waveguides are fully detached from the substrate and supported only by the pillars. A Scanning Electron Micrograph (SEM) of the waveguide cross section is shown in Figure 4. The waveguide has a 'tear-drop' shape with a height of 17 μm, and width of 3.7 μm at the top and 8 μm at the bottom. This shape is due to lateral spreading of the beam with depth but it can be altered by alternative choices of irradiation energies.

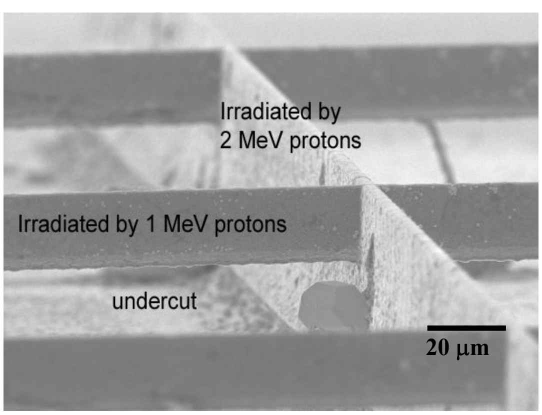


Figure 3. SEM of several free standing waveguides supported by a transverse pillar.

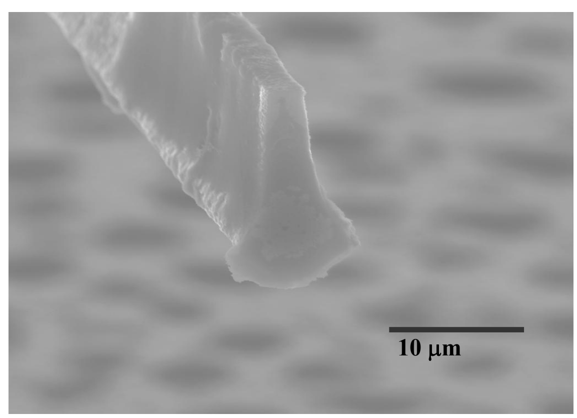


Figure 4. SEM of the cross section of a free standing waveguide. Considerable surface roughness is evident.

Loss measurements were performed at the wavelength of 1550 nm in order to compare it with the loss of standard (SOI) silicon. A free-space 1550 nm laser was coupled to the free standing waveguides using an objective lens. Prior to the objective lens a polarizing beam splitter and half-wave plate were inserted into the beam path which enabled discrimination between the TE and TM polarization. Propagation loss was determined using the cut-back method [10] to be 13.4 ± 0.7 dB/cm for TE and 14.6 ± 0.6 dB/cm for TM polarized light respectively. It is likely that there are two main reasons for the high propagation losses obtained: sidewall roughness and irradiation damage. It is expected that the irradiation damage could be reduced by modification of the fabrication process to include an annealing step. Oxidizing the waveguides may also help to alleviate the roughness issue of the waveguide sidewalls. Additional loss may be a result of the shape and dimensions of the waveguide, and the intersection with the support pillars. Therefore, we are currently investigating fabrication of the square cross section waveguides with smaller dimensions, and minimizing interaction with the supports. Future work will also include loss measurements at longer wavelengths.

3. BRAGG GRATING FABRICATION VIA ION IMPLANTATION

Ion implantation is a well established and flexible way of introducing either a dopant species, or alternatively, crystal lattice damage, into the near surface region of a material. From a photonics perspective this is potentially interesting as either doping or damage can result in a change of the refractive index of the material. Bragg gratings are interesting and flexible components in photonics technology. In silicon photonics, most gratings have been fabricated by carrying out a physical etch on the surface of a waveguide. However, this results in a non planar surface, making any subsequent processing more complex. By utilising selective ion implantation through a mask, a periodic variation in refractive index is possible, thus forming the grating structure. Furthermore, apart from small changes in the volume of the implanted region, a near planar surface is retained. In this work we have carried out oxygen ion implantation to form the gratings. Oxygen was chosen so that we can carry out a two stage experiment. Firstly, the oxygen will result in crystal damage and thus a refractive index change in the 'as-implanted' samples, thus forming a grating. However, the samples can subsequently be annealed to substantially remove the damage. Therefore, the oxygen will combine with the silicon to form periodic structures of SiO_2 in a process similar to the process used to form the buried oxide layer in the SIMOX process [9]. The fabrication process is summarised in the schematic diagram of figure 5.

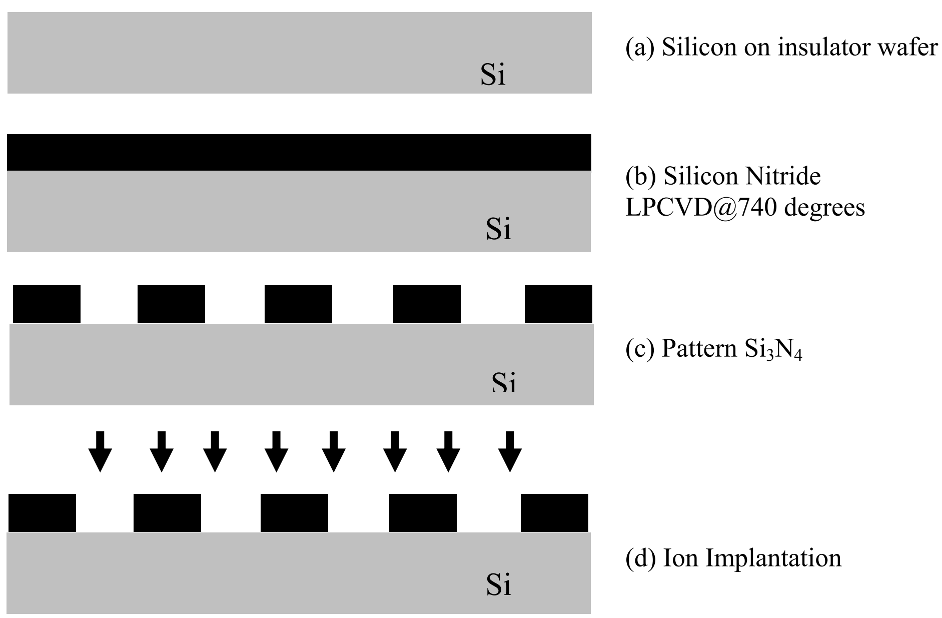


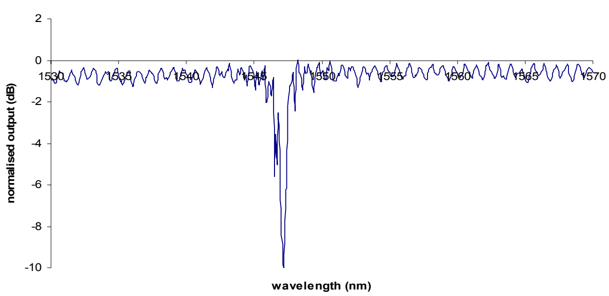
Figure 5. Schematic of the Bragg grating fabrication process via ion implantation of oxygen

The figure demonstrates the simplicity of the process. A silicon on insulator wafer has a silicon nitride layer deposited upon the surface which is subsequently patterned, to act as an ion implantation mask. The surface is then implanted with the desired ion, in this case oxygen. The mask is then removed, and subsequent processing carried out such as etch of waveguides and devices. Subsequent annealing can take place at a convenient step in the process.

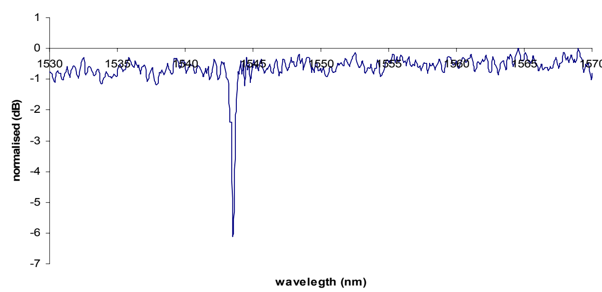
In this work the waveguide height was 1.5 μm, and modelling suggests a suitable grating depth is of the order of 70 nm. The implantation range was modelled using the SUSPRE implantation simulator. In order to achieve a uniform implant from the surface down to 70 nm, a dual implant process was utilised. The first implant utilised an ion energy of 20 keV with a dose of 1.6 x 10^{17}, O^+ ions/cm^2. The subsequent implant was a surface implant at 10keV, with a dose of 0.8 x 10^{17}, O^+ ions/cm^2.

The resulting devices were measured in the as-implanted state, in order to determine whether the radiation damage had caused sufficient refractive index variation to form a grating. They were initially measured in transmission, by launching a polarised laser, using the experimental set-up described in section 2 above. The resultant data for TE and TM polarised input waves is shown in figure 6. The peak responses are at wavelengths of approximately 1547nm for the TE polarised input wave, and 1544nm for TM. Discrimination is of the order of 10 dB and 6 dB for the TE and TM respectively, which is promising for preliminary results. This also suggests a significant refractive index variation within the grating region. Data of Pelaz et al [11], suggests that implantation damage results in an incremental change in refractive index of up to a saturation level of 0.1, which is consistent with these experimental results.

Thus far these results have been obtained for planar waveguides, and only in transmission. Our future work will include etching of ribs containing gratings, and further measurements both in transmission and reflection. We will also move on to anneal the devices to form 'oxide gratings', which are anticipated to produce an entirely different grating response due to different changes in refractive index due to oxide formation, as well as an entirely different grating profile when the oxide synthesis occurs.



(a)



(b)

Figure 6 Experimental response of ion implanted Bragg gratings.
(a) TE response and (b) TM response

4. CONCLUSIONS

We have presented two novel fabrication techniques for silicon photonics components. The first has been used to fabricate free standing waveguides and the second to fabricate Bragg gratings.

The propagation loss of the free standing waveguides reported here are rather high, they are nonetheless promising especially when compared to the propagation loss of ~ 25 dB/cm that was measured for early SOI waveguides [e.g. 12]. Therefore, it can be expected that further improvements of the fabrication process will result in much lower propagation loss of the free standing waveguides, increasing the viability of this technology for mid and far IR photonic applications, because no lossy SiO_2 is included in the structure. In this study, we have demonstrated that it is possible to fabricate free standing waveguides with an air cladding, in a single etch step, using proton beam writing. In the future, the propagation loss measurement of mid-IR wavelengths will be characterized with newly fabricated free standing waveguides. The new waveguides will be modified to have improved dimensions. Thermal oxidation and annealing processes will also be included in the fabrication in an attempt to reduce the high optical loss presently observed.

The grating structures that we have fabricated by ion implantation show promise, with up to 10 dB discrimination at the resonant wavelengths, close to 1.55 μm, when measured in transmission. These devices have been fabricated with both damage and doping based gratings in mind, so are probably far from optimised. Therefore we expect to be able to improve the response for planar waveguides, and to fabricate gratings in rib structures in the future.

5. ACKNOWLEDGEMENTS

We are grateful to the EPSRC, UK for funding, and to the Royal Academy of Engineering for a contribution to travel expenses.

REFERENCES

1. Q. Xu, B. Scmidt, S. Pradhan, and M. Lipson, *Micrometre-scale silicon electro-optic modulator,* Nature**,** 435, 325-327, 2005.
2. G. T. Reed and C. E. Png, *Silicon optical modulators*, Materials Today, 8, 40 – 50, 2005.
3. G. Z. Masanovic, G. T. Reed, W. Headley, B. Timotijevic, V. M. N. Passaro, R. Atta, G. Ensell, and A. G. R. Evans, *A high efficiency input/output coupler for small silicon photonic devices*, Opt. Express, 13, 7374-7379, 2005.
4. R. A. Soref, S. J. Emelett, and W. R. Buchwald, *Silicon waveguided components for the long-wave infrared region*. European Optical Society Topical Meeting: Optical Microsystems, Capri, Italy, 15-18 September 2005.
5. P. Polesello, C. Manfredotti, F. Fizzotti, R. Lu, E. Vittone, G. Lerondel, A.M. Rossi, G. Amato, L. Boarino, S. Galassini, M. Jaksic, and Z. Pastuovic, *Micromachining of silicon with a proton microbeam.* Nuclear Instruments and Methods in Physics Research B, 158, 173-178. 1999.
6. P. Mistry, I. Gomez-Morilla, G. W. Grime, R. Webb, C. Jeynes, R. Gwilliam, A. Cansell, M. Merchant, and K. J. Kirkby, *Proton beam lithography at the University of Surrey's Ion Beam Centre.* Nuclear Instruments and Methods in Physics Research B, 242 387–389, 2006,
7. M. B. H. Breese, F. J. T. Champeaux, E. J. Teo, A. A. Bettiol, and D. J. Blackwood, *Hole transport through proton-irradiated p-type silicon wafers during electrochemical anodisation*. Physical Review B. 73, 035428. 2006.
8. E. J. Teo, M. B. H Breese, E. P. Tavernier, A. A. Bettiol, F. Watt, M. H. Liu and D.J. Blackwood, *Three-dimensional microfabrication in bulk silicon using high-energy protons.* Applied Physics Letters 84 3202 (2004).
9. http://www.ee.surrey.ac.uk/ibc/index.php?target=6:35.
10. G. T. Reed, and A. P. Knights, *Silicon Photonics: An Introduction*, John Wiley and Sons, 2004. ISBN: 0-470-87034-6.
11. L. Pelaz , L. A. Marques, and J. Barbolla, *Ion-beam-induced amorphization and recrystallization in Silicon,* J Appl. Phys., 96, 5948 – 5976, 2004
12. B. L. Weiss, G. T. Reed, S. K. Toh, R. A. Soref, and F. Namavar, *Optical waveguides in SIMOX structures*. IEEE Photon. Technol. Lett., 3 , 19-21, 1991.