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Fabrication of smooth silicon optical devices using proton beam writing

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ABSTRACT

This work gives a brief review of proton beam writing and electrochemical etching process for the fabrication of smooth optical devices in bulk silicon. Various types of structures such as silicon-on-oxidized porous silicon waveguides, waveguide grating and disk resonators have been produced. Optical characterization has been carried out on the waveguides for both TE and TM polarization using free space coupling at 1.55 μm. Various fabrication and processing parameters have been optimized in order to reduce the propagation loss to approximately 1 dB/cm. A surface smoothening technique based on controlled oxidation has also been used to achieve an RMS roughness better than 3 nm.

1. Introduction

For many years, achieving lasing and optical modulation in silicon has been a challenge for scientists due to its indirect bandgap and weak electro-optical properties. Recently, several breakthroughs have been made in the development of silicon-based device and technology. Intel has demonstrated the first continuous-wave silicon laser using stimulated Raman emission [1]. It is not much later that they demonstrated the first 40 Gbps optical modulator, which uses free carrier injection to modulate light signals [2].

This paper gives a brief review of a newly developed technique that utilizes ion beam irradiation and electrochemical etching for the fabrication of smooth low loss photonic devices in bulk silicon. Previously, three-dimensional microstructures have been successfully demonstrated using this process [3–5]. In order to extend this technique to waveguide and optical devices fabrication, we have devised two ways of achieving optical isolation from the substrate. In the first approach, the structure is undercut by prolonged etching so that it becomes surrounded by porous silicon cladding [6]. The second approach uses double energy irradiation to create a free-standing waveguide with air cladding [7]. Surface roughness plays an important role in affecting the quality of the optical devices. We demonstrate that performing a post-oxidation smoothening process enables us to achieve smooth surfaces of less than 3 nm. Other factors such as ion fluence and scanning parameters are also shown to affect the surface roughness and propagation loss.

2. Results

2.1. Channel or strip waveguides

Waveguides are the main building block for a silicon-based photonics circuit. Most conventional waveguides are built on silicon-on-insulator (SOI) substrate formed by separation by implantation of oxygen (SIMOX). Due to the high-index-contrast between Si and SiO_2, ultracompact devices with small bending radius can be formed. SOI substrate also offers a compatible platform for Si photonics to be integrated with microelectronics. Standard lithography and reactive ion etching are normally carried out to define waveguides in the form of strip or rib geometry.

Here, we describe an alternative technique of fabricating high-index contrast channel waveguides directly in silicon without the need for SOI substrate. Waveguide patterns are irradiated into bulk *p*-type silicon of medium resistivity of 0.5 Ω cm resistivity using a highly focused beam of protons, produced from a single-ended ultra-stable accelerator at the Centre for Ion Beam Applications at National University of Singapore. After irradiation, the sample is electrochemically etched in hydrofluoric acid solution. Due to the increased resistivity caused by the ion irradiation, the migrating holes are deflected from the irradiated region, as shown by the arrows in Fig. 1a, inhibiting the rate of porous silicon formation [8]. By prolonged etching beyond the end of the ion-range, the resultant structure becomes completely isolated in porous silicon. It should be noted that surface relief structures can also be fabricated with this process. Instead of etching the whole structure in a single

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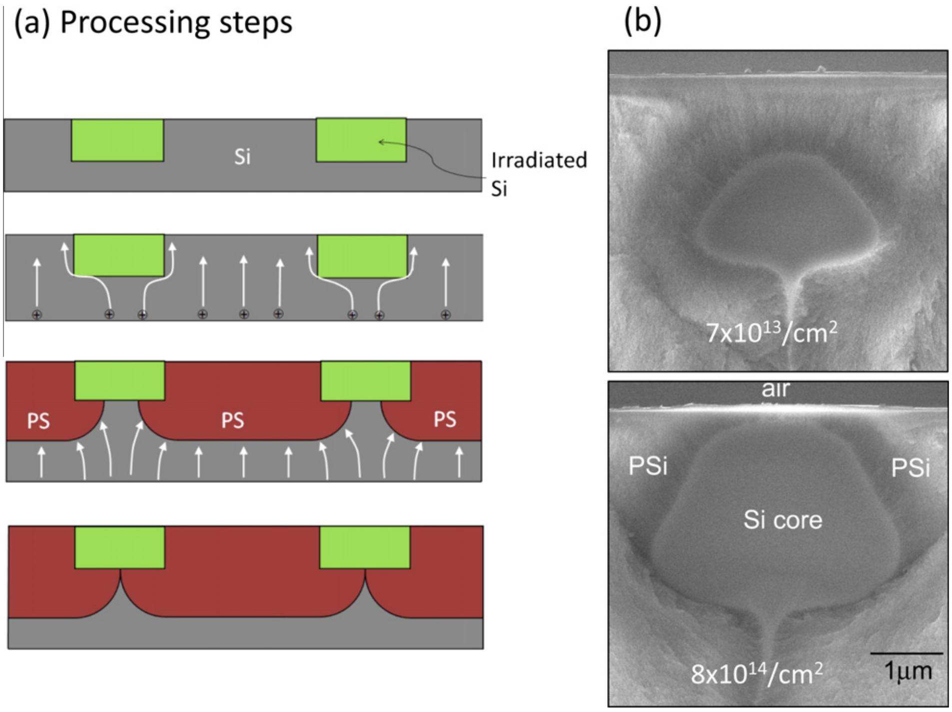

Fig. 1. (a) Schematic fabrication process for waveguide fabrication (b) Cross sectional SEM of the channel waveguides irradiated with 250 keV protons at fluencies of 7 and $8 \times 10^{14}/cm^2$.

step, the first few microns of PS is removed before etching it again to isolate the Si core. More details can be found in reference [9].

Fig. 1b shows the cross sectional scanning electron micrograph (SEM) of a channel waveguides with porous silicon cladding, irradiated using focused 250 keV protons and etched to a depth of 5 μm. It can be seen that the core size becomes larger with increasing fluence. In this case, the porous silicon acts as a cladding and supporting layer for the silicon core. Instead of a square cross section, the waveguides have a trapezoidal or a tear-drop profile. This is because of the sharp increase in damage at the end of range, causing the holes to be deflected furthest away from the irradiated regions. As a result, the lateral width over which reduced current arrives at the surface is widened. The top of the waveguide spreads from the initial scan size of 2–4 μm at the end of range. As the fluence reduces, the current is able to flow through the low defect region, leaving behind only the end-of-range damage.

Optical characterization of the waveguide irradiated with $1 \times 10^{15}/cm^2$ was carried out at a wavelength of 1550 nm using a tunable laser. Cutback measurements show that losses of about 6.7 dB/cm in both TE and TM polarization can be obtained after argon annealing [6]. This is dramatically reduced to 1 dB/cm after oxidation at 1000 °C for 6 h [9]. For a high-index-contrast waveguide, surface roughness plays an important role in affecting the loss. Factors contributing to surface roughness include etching process, beam intensity fluctuations and ion fluence. Oxidation results in a formation of a thin thermal oxide around the circumference of the waveguide, reducing the sidewall and bottom roughness of the Si core by about 20 nm [9–10].

In order to optimize the parameters of the writing process, we have investigated the top surface roughness as a function of the number of loops and ion fluence using 2 MeV protons. The higher energy irradiation prevents the structure from detaching from the substrate. After etching, PS is removed by potassium hydroxide to reveal the surfaces, which is then measured using Atomic Force Microscopy. By increasing the number of loops in the scanning pattern from 1 to 10, the beam intensity fluctuation can be averaged out, so that the surface roughness is reduced from 9 to 3 nm (Fig. 2a). Fig. 2b shows a plot of surface roughness with fluence. At the unirradiated regions, surface roughness is introduced at the dissolution front of the PS/Si interface, resulting in a high surface roughness of 14 nm. As the fluence increases, the rate of PS formation slows down, reducing the surface roughness significantly. At an optimum fluence of $1 \times 10^{15}/cm^2$ when no etching occurs, the surface approaches that of virgin silicon.

2.2. Tapers

Optical integrated circuits have been developed to a high level of maturity such that sources, modulators and detectors with increasing performance have been regularly reported. However, there is still a problem of efficient coupling optical fibers into these systems due to the large mismatch between the mode size and geometries of the waveguides and fibers. Therefore, several approaches such as prism coupling [11], tapered optical fibers and grating couplers [12] have been proposed. An ideal structure would be one that adiabatically tapers in both the vertical and lateral directions and can be monolithically integrated with optical circuits. However, this cannot be readily achieved using standard binary lithography techniques. Recently, grayscale mask lithography of high-energy beam sensitive glass is used to transfer 3D structures into photoresist and then into silicon through inductively coupled plasma etching [13].

In Fig. 1b, we have seen that the size of the core depends on the ion fluence. Combined with the high spatial beam resolution, this means that it is possible to write three-dimensional taper waveguides with accurate control of the ion fluence. In order to demonstrate this, we have irradiated 50 shapes with linearly increasing fluences from 1 to $5 \times 10^{15}/cm^2$ using 2 MeV protons. It can be seen that the height of the structure increases from about 3–7 μm (Fig. 3). This process eliminates the complex processes associated with dynamic etch mask [14], and diffusion limited etch technique [15], which is normally not very reproducible.

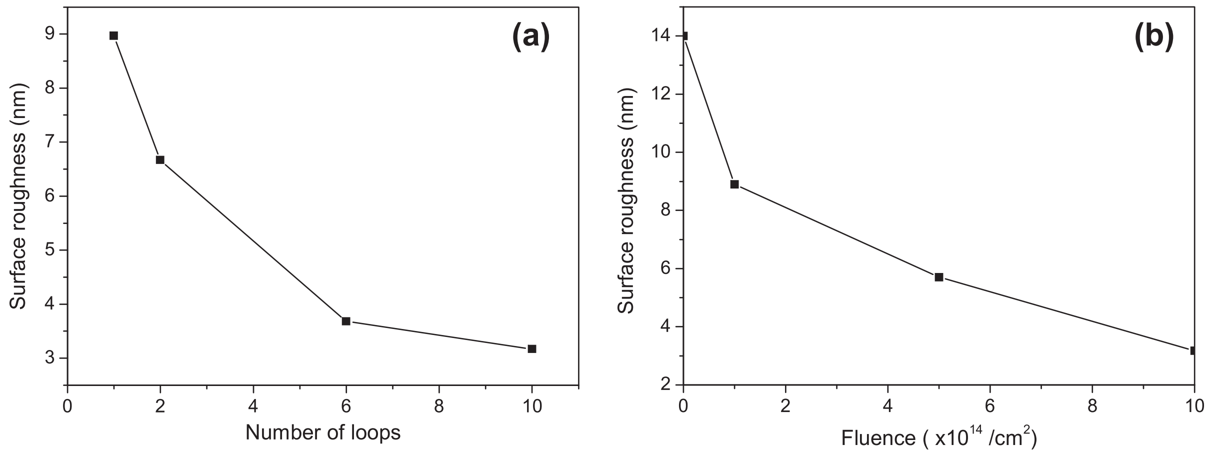

Fig. 2. (a) Plot of surface roughness vs number of loops and (b) ion fluence.

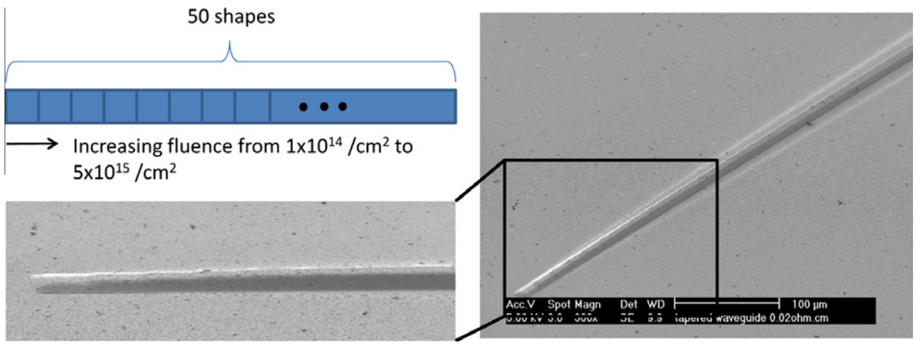

Fig. 3. Irradiation of a taper profile with fluence linearly increasing from $1 \times 10^{14}/cm^2$ to $1 \times 10^{15}/cm^2$ (from left to right). Also shown are the SEM images of the tapered profile.

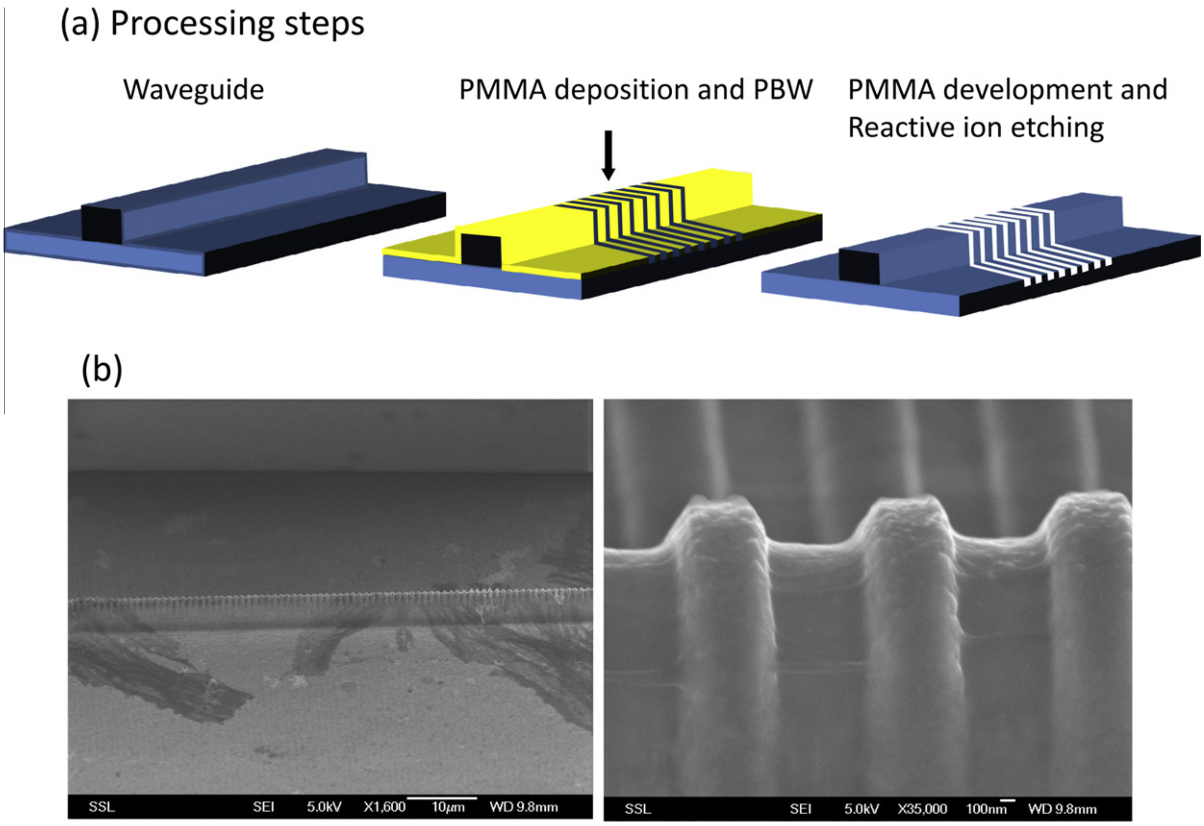

Fig. 4. (a) Schematic diagram of the processing steps. (b) SEM images of a waveguide grating.

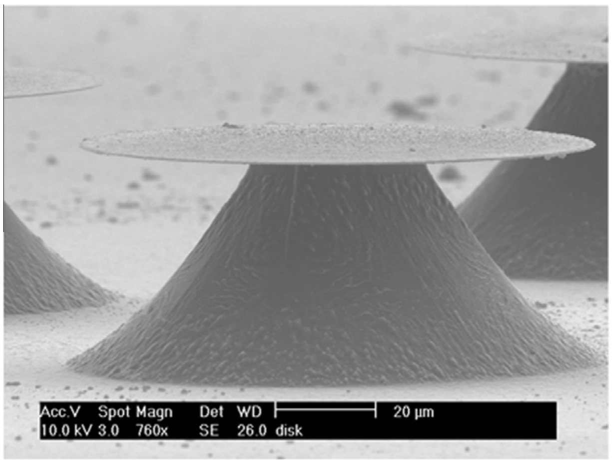

Fig. 5. SEM image of a 200 nm thick silicon disk resonator supported on a pedestal.

2.3. Waveguide gratings

By incorporating a grating structure over the top of a waveguide, we are able to fabricate a wavelength filter for integrated photonics applications. However, high density grating structures with sub-micron periodicity has stringent requirement on the beam resolution, beam stability and development time. Previously, Bettiol et al. [16] successfully demonstrated the ability to write precise, sub-micron grating structures in PMMA with a 600 nm periodicity.

Here, we attempt to make a waveguide grating in silicon using a combination of proton beam writing and reactive ion etching. In order to obtain a surface relief strip waveguide, the fabrication process shown in Fig. 1a needs to be modified to incorporate a two-step anodization process. First, the sample is etched till the end-of-range and the PS layer is subsequently removed, before a second etching step is used to undercut the structure. After that, a layer of PMMA resist is deposited on top of the sample. Grating structures are then written using direct proton beam writing with a 100 nm beam resolution. The grating pattern is then transferred to the waveguide by reactive ion etching in oxygen and argon atmosphere. Fig. 4 shows the SEM images of a waveguide grating with a period of 1 μm.

2.4. Disk resonators

Microdisk and microring resonators have been an integral part of silicon photonics circuit due to its ultrahigh quality factors and small confinement mode. They are ideal for applications such as filtering, sensing, delay and enhancement of light matter interaction. By implanting erbium into a silicon disk, it is possible to fabricate a silicon microlaser. Previously, Polman et al. [17] fabricated SiO_2 microdisk using lithography and XeF_2 isotropic etching to undercut the silicon pedestal. A Si microdisk has also been fabricated on silicon-on-insulator substrate using a combination of lithography and reactive ion etching [18].

In this case, we demonstrate the versatility of fabricating silicon microdisk resonators by 250 keV proton beam irradiation and electrochemical etching. The isotropic etching process starts to undercut the structure beyond the end-of-range of the ions, resulting in the formation of a silicon microdisk with a thickness of 200 nm (Fig. 5). Characterization of such a device is normally carried out by bringing a tapered optical fiber close to the disk so that light can be coupled evanescently into the disk. However this approach suffers from mechanical vibrations. A more robust method of optical characterization would be to fabricate an integrated waveguide next to the disk.

3. Conclusions

In conclusion we demonstrated the combination of proton beam writing and electrochemical etching for fabricating smooth optical devices in silicon without the need for a mask. Optical isolation is created by undercutting the irradiated structure, to provide a porous silicon cladding. This process eliminates the use of expensive SOI substrates as the fabrication can be carried out directly in silicon. A low loss silicon-on-oxidized porous silicon strip waveguide of 1 dB/cm has been obtained using oxidation smoothening of all sides of the waveguide. Due to the core size dependence on fluence, we are able to produce a 3D waveguide taper by accurate control of the ion fluence, which cannot be easily done with other processes. Characterization of other devices such as waveguide gratings and disk resonators are being investigated and will be reported in future work.

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