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Novel types of silicon waveguides fabricated using proton beam irradiation

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ABSTRACT

In this work, we describe the use of a combination of proton beam irradiation and electrochemical etching to fabricate high index-contrast waveguides directly in silicon without the need for silicon-on-insulator substrate. Various types of waveguides with air or porous silicon cladding have been demonstrated. We show that porous silicon (PS) is a flexible cladding material due to the tunability of its refractive index and thickness. The Si/PS waveguide system also possesses better transmittance in the ranges of 1.2-9 and 23-200 µm, compared to Si/SiO_2 waveguides. This is potentially important for mid and far-IR applications. Since it is compatible with conventional CMOS technology, this process can be used for fabrication of integrated optoelectronics circuits.

Keywords: silicon photonics, waveguides, porous silicon, electrochemical etching, silicon-on-insulator.

1. INTRODUCTION

Silicon photonics is experiencing a dramatic increase in interest due to emerging application areas and several breakthroughs in device and technology development. Most conventional waveguides in silicon photonics are fabricated on silicon-on-insulator (SOI) substrates due to its compatibility with microelectronics technologies and the high index contrast between silicon and silicon dioxide [1]. This means that ultra-compact optical devices with tight bends of a few micrometers can be densely packed and integrated with microelectronic circuits on a single chip.

Conventional SOI substrates are fabricated using separation by implanted oxygen (SIMOX) or the Smart-Cut process [2,3]. A lesser used technique for SOI fabrication is by full isolation by oxidized porous silicon (FIPOS), which was first developed by Imai et. al.[4] for device isolation in microelectronics. The low cost and easy implementation of electrochemical etching has made it an attractive alternative to dry etching. Proton implantation converts p to n-type silicon islands, which are selectively inhibited from porous silicon formation. Compared to SIMOX, this process gives more freedom in controlling the thickness of the overlying silicon layer due to the well defined ion range with energy and higher penetration depth of protons. This means that widely varying thickness of the silicon overlayer can be obtained. The oxide thickness can also be tuned easily with the etching time. There has been much research on the optical properties of structures fabricated using SIMOX [5] and Smart-Cut [6], but not FIPOS.

In this work, we investigate the possibilities of using FIPOS for low-loss waveguide applications. This is carried out either by direct proton beam writing (section 3.1 and 3.2), or broad proton beam irradiation through a mask (section 3.3). The flexibility of using porous silicon or air as cladding eliminates oxide absorption in the mid-IR and far-IR regimes suffered by SOI waveguides [7,8], making these systems viable for operations at such wavelengths.

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2. EXPERIMENTAL

2.1 Fabrication process

Waveguide patterns are irradiated into bulk p-type silicon of medium resistivity of 0.5 ohm.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 then 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 figure 1b, inhibiting the rate of porous silicon formation [9,10]. By prolonged etching beyond the end of the ion-range, the resultant structure becomes completely isolated in porous silicon.

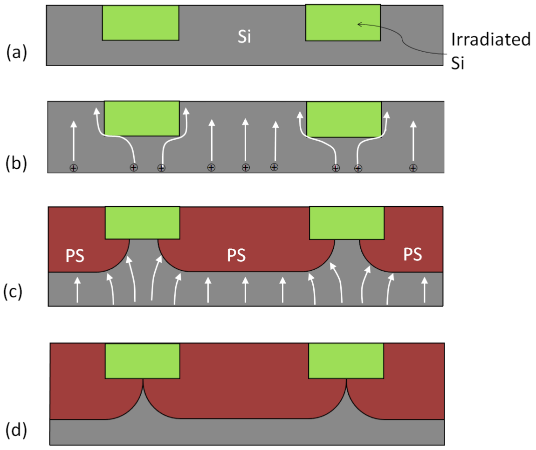


Figure 1. Schematic diagram of the waveguide fabrication process. (a) Proton beam writing in *p*-type silicon followed by (b) electrochemical etching in HF. (c) Prolonged etching results in undercutting of the irradiated region and (d) finally it is surrounded by porous silicon.

2.2 Optical characterization

Optical characterization of the waveguides was carried out in both TE and TM polarizations at 1550 nm. A tunable diode laser is coupled into the waveguide using a 60× objective lens. A polarizing beam splitter and a half-wave plate were inserted into the beam path, enabling discrimination between the TE and TM polarizations. The scattered light from the top of the waveguides was monitored using a highly sensitive InGaAs infrared camera (Xeva-FPA-1.7-320), and the output light from the waveguide is imaged using an IR Vidicon camera (Model 7290A). Precise alignment of a piezoelectric stage is used to optimize the coupling of the laser beam to the waveguide, until the maximum power is detected on a power meter.

3. RESULTS

3.1 Free-standing waveguides

Since energetic ion beams have a well-defined range in materials, it is possible to produce structures with different thickness by changing the energy of the ions [10]. Our first waveguides are free-standing in air, created using double energy irradiation. The waveguide is created using 1 MeV protons, that is supported by longer pillars created using 2 MeV protons. By etching 40 μm into the substrate, just before the penetration depth of 2 MeV protons, the waveguides are fully separated from the substrate and are supported only by the pillars irradiated with higher energy. In this case, the porous silicon has been removed using diluted potassium hydroxide. Such a waveguide has been successfully characterized and shown to have a loss of 13-14 dB/cm in both TE and TM polarizations [11]. The main contribution to loss are the high surface roughness and the proton induced damage in the unannealed waveguides.

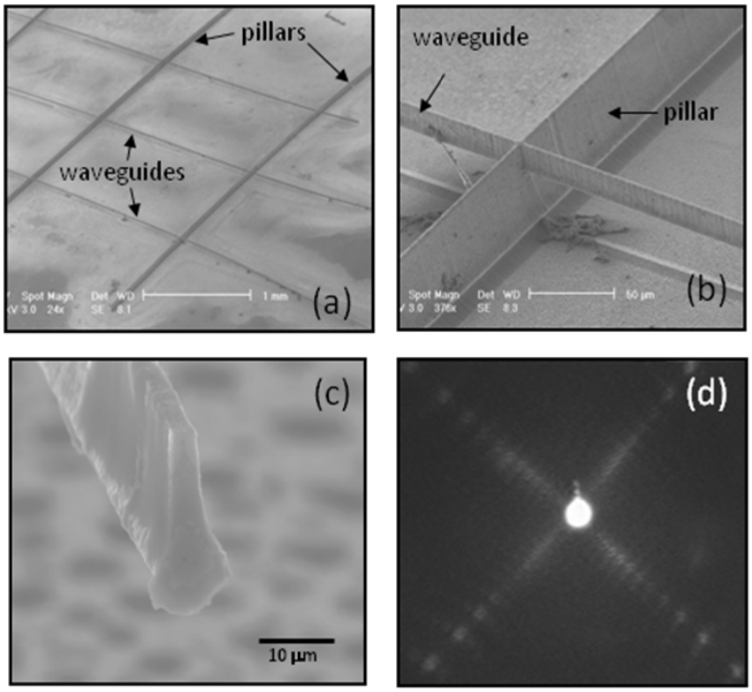


Figure 2 showing an (a) overview and a close-up view of (b) the free-standing waveguide and its (c) facet. Figure 2(d) shows the output image of the light emerging from the waveguide [11].

3.2 Silicon-on-Porous Silicon (SPS) channel and strip waveguide

Figure 3a 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. 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 (see also figure 2(c)). This is because of the sharp increase of 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 μm to 4 μm at the end of range. The core height of the waveguide corresponds to the penetration depth of the ion beam. By removing the porous silicon layer after etching 2.5 μm into the silicon, we are able to produce a surface relief strip waveguide as shown in figure 3b. In order to remove the proton-induced damage, we have annealed the sample at 500ºC for 2 hours in an inert argon atmosphere. According to studies by Day et. al. [12], temperatures of 400ºC-450ºC are sufficient to anneal out more than 90% of the defects caused by proton irradiation in silicon. White light reflectivity measurement shows that the refractive index of the PS cladding is about 1.41, which is lower than 1.45 for conventional SiO_2 cladding [13]. Cutback measurements show that losses of about 6.7 dB/cm in both TE and TM polarizations can be obtained after argon annealing [14]. It is found that the loss can be further reduced down to 1 dB/cm in both TE and TM polarizations by oxidation at 1000°C for 6 hours [15]. Other factors such as the beam fluence and intensity fluctuation also play an important role in affecting the propagation loss [15].

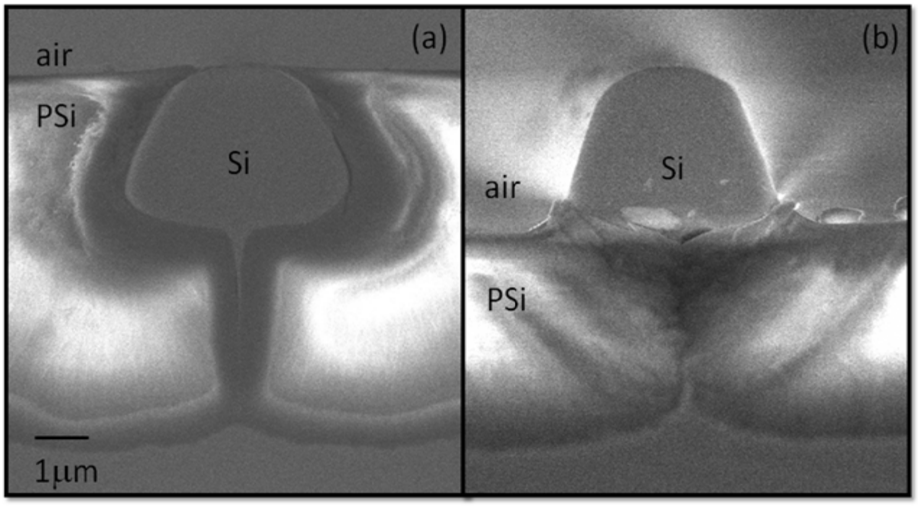


Figure 3 shows a cross-sectional image of SPS (a) buried channel waveguide and (b) strip waveguide.

3.3 Silicon-on-Oxidized Porous Silicon (SOPS) strip waveguide

We have investigated the effects of oxidation on the propagation loss and surface roughness of our waveguides. Figure 4(a) shows an array of waveguides produced using broad proton beam irradiation through a lithographically patterned mask [16]. Although direct writing with a focused beam allows for rapid prototyping, it is time consuming as only one waveguide can be patterned at a time. Simple modifications were made to the microprobe facility to allow for large area patterning of waveguides. The wafer is placed about 50 cm downstream of the focal plane of the proton beam, so that a defocused beam can be distributed uniformly over an area of about 3×3cm^2 onto the lithographically patterned silicon sample.

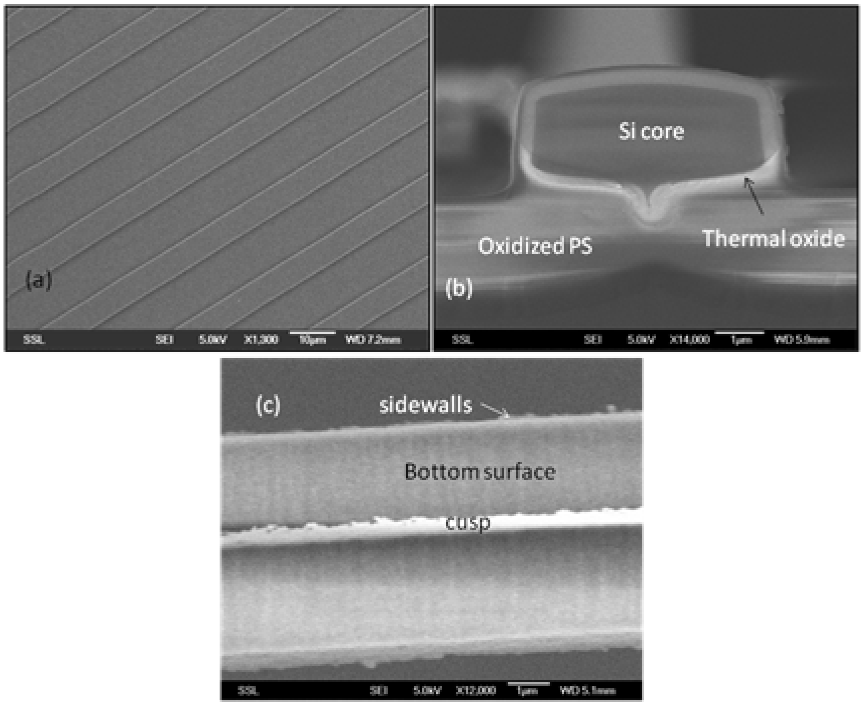
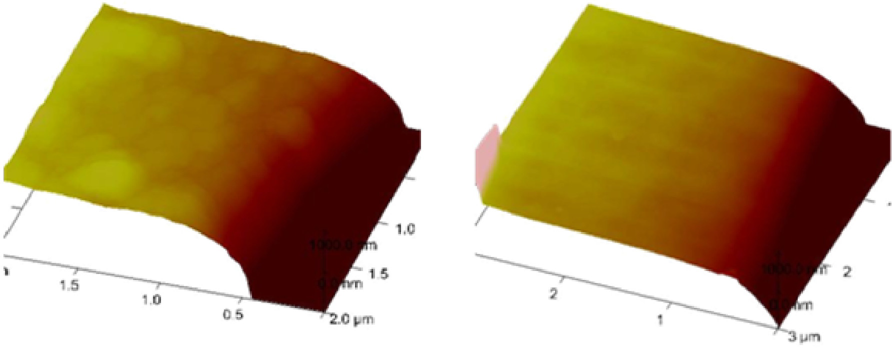


Figure 4(a) shows a large array of waveguides fabricated using broad area irradiation and (b) a cross sectional view of a SOPS waveguide, with the oxide formation around the core. (c) Underside of the waveguide [16].

Due to the high surface area/volume ratio, the oxidation rate of PS is orders of magnitude higher than Si. Oxidation produces a fully oxidized PS layer, while barely growing a thin thermal oxide around the Si core [2]. This enables surface roughness reduction on all sides of the waveguide, including the bottom interface (see figure 4(b)). The oxide also reduces the size of the cusp formed at the point where the core separates from the substrate. Atomic force microscopy (AFM) of the underside of the waveguide shows that the bottom and sidewalls exhibits a 20 nm reduction after oxidation (see figure 5). This improves the loss significantly from 10 dB/cm to 1.4 dB/cm [16].



Before oxidation After oxidation

Figure 5 showing the AFM images of the underside of the waveguide before and after oxidation.

4. CONCLUSIONS

We demonstrated an attractive alternative technique for producing low-loss high index contrast waveguides ($\Delta n \sim 2$) in bulk Si without the need for SOI substrate using a combination of proton beam irradiation and electrochemical etching. We show the possibility of creating novel types of waveguides in the form of channel, strip or free-standing in air. SOPS waveguides show low losses of about 1-2 dB/cm after oxidation due to surface roughness reduction of both the sidewalls and bottom surfaces. This opens up new opportunities of using existing FIPOS technology for photonics applications. For SPS and free-standing waveguides, the lack of oxide cladding make them suitable systems for mid-IR applications.

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