invited Workshop FIB for Photonics, Eindhoven 2008

Iodine enhanced focused ion beam etching of silicon for photonic device modification and prototyping

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Focused-ion-beam etching of silicon has the potential of fast and versatile fabrication of micro- and nanophotonic devices. However, large optical losses due to crystal damage and ion implantation limit the applicability of FIB in devices where the optical mode is confined near the etched region. We demonstrate a reduction of the losses by etching with iodine gas enhancement, followed by baking at 300 °C. This technique was applied for the prototyping of several grating coupler concepts and for the fabrication of slot waveguides and ring resonators.

Introduction

The use of silicon as a platform for passive as well as active photonics has been an exciting research subject in recent years. The primordial advantage of silicon over III–V materials is the large amount of experience that has been built up in electronics over the past decades, the availability of large and reliable manufacturing environments, and the large refractive index contrast between silicon and oxide or air. Most of the micro- or nanophotonic structures in silicon are fabricated by a combination of optical lithography, dry and wet etching processes and layer deposition or growth. These are wafer-scale processes that enable fabrication of many devices in parallel, lowering the cost. However, due to the need for expensive masks, development of devices is costly and slow. Therefore one needs prototyping technologies that enable rapid and flexible fabrication of nanophotonic components. The best example nowadays is electron-beam lithography, which is a serial technique, too slow for the mass fabrication of large devices, but attractive as prototyping technique because of its high resolution compared to standard optical lithography. One of the inconveniences however, is the fact that electrons cannot directly etch a semiconductor. Therefore one has to work with resist layers and etch with the classical tools such as plasma etching. This slows down the optimization process and limits the designs to planar structures.

An interesting alternative is focused-ion-beam (FIB), where a beam of ions is used instead of an electron beam. In current commercial systems the particle optics enables local sputtering with a spot smaller than 10 nm. There is no need for a resist, which enables post processing of devices with a more complex topography such as ridge waveguides. Furthermore, one is no longer limited to etching planar structures, e.g., by tilting the sample one can etch slanted holes or slits. As focused-ion-beam is a serial technique it is not likely to be used for mass fabrication of large area devices. However, it is a suitable technique to make small modifications to structures that were fabricated with other techniques such as optical lithography.

The post processing of III–V devices by means of FIB has been reported [1-3]. In all of the examples the modal volume is big compared to the etched region. A clear deterioration of the optical properties is often observed, but can be overcome by pumping in the undamaged regions. However, in silicon one is often limited to passive devices, and wants to exploit tight confinement and small modal volumes. When a silicon device with its optical mode close to the focused-ion beam etched region is fabricated, large optical losses are observed [4-7], caused by amorphization and ion implantation of the silicon. To enhance the focused-ion-beam etch rate one can use additional gasses in the etch process [8]. In previous work we have reported that the quality of focused-ion-beam etched silicon is improved by iodine enhancement [4, 7, 9]. In this work we summarize these results and present newly fabricated devices: grating couplers and slot waveguides.

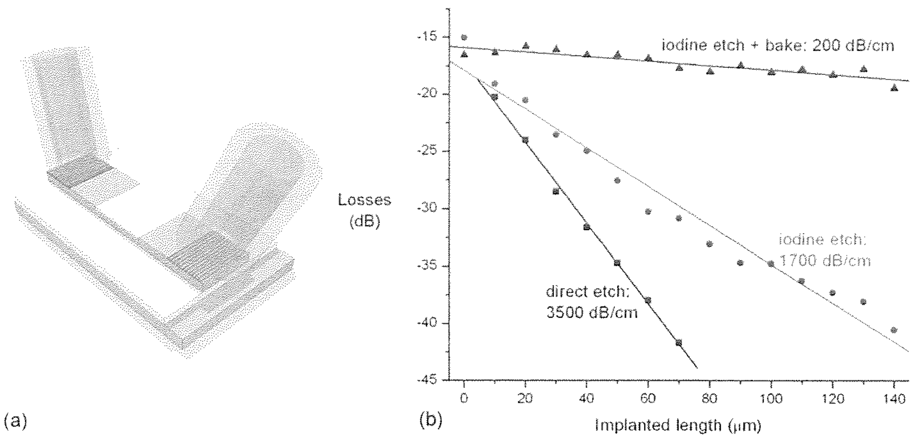

Figure 1: (a) Schematic overview of the loss measurement setup. (b) Iodine enhanced FIB etching of silicon followed by baking results in acceptable optical losses.

Iodine enhanced etching and baking

Fig. 1 shows an experiment that was conducted to determine the influence of iodine etch enhancement on the losses in silicon [7]. Prefabricated waveguides were implanted and etched with FIB over varying length sections with a dose of 5×10^{15} cm^{-2}. It was observed that iodine gas enhancement reduces the losses from 3500 to 1700 dB/cm; a further reduction to 200 dB/cm was obtained after baking for two hours in nitrogen gas at 300°C. We have confirmed by surface analysis techniques that this is caused by desorption of silicon-iodide bonds that stick to the surface. This technique was used to demonstrate several device prototypes. However, because it is difficult to achieve a trench with straight sidewalls and flat bottom using gas enhancement, we have used a 50 nm thick alumina layer as hard etch mask in all the fabricated devices.

Grating couplers

Firstly we have fabricated a copy of an existing grating coupler design, previously made by deep-UV (DUV) lithography. This design consists of 315 nm wide, 70 nm deep slits with a period of 630 nm, on a 10 micron wide waveguide in the top 220 nm thick Si layer of a silicon-on-insulator wafer. The resulting grating (see Fig. 2(c)) has slightly asymmetric trenches because the enhancement gas is fed from the left. Nevertheless, the measured fiber-to-waveguide efficiency is comparable to that of the DUV fabricated original, as depicted in Fig. 2(a) [4].
Higher coupling efficiencies can be achieved by altering the grating grooves. As an example we have fabricated a slanted grating prototype, with 80 nm wide grooves at an off-normal angle of 60° (Fig. 2(b)). The experimentally measured fiber to waveguide coupling efficiency was 46 % [9]. The slits were etched using iodine gas enhancement and an alumina etch mask.
A third grating concept was tested by etching thin slits on the outer radius of a ring resonator (see Fig. 3). The goal of this grating is direct fiber sensing of the power in the optical cavity, without the need for a waveguide and grating coupler. We have achieved slits with a width of less than 50 nm. Fig. 3(b) shows the transmission spectrum measured on the access waveguide of the ring with a Q factor of about 4000 for a grating with period 650 nm. However, the Q factor of this ring is not a good measure to estimate the influence of FIB losses, because it is difficult to separate the power lost by FIB etch losses from the power that is scattered and diffracted out of the optical cavity. The power measured with a fiber positioned on top of the ring grating was increased by a factor of 7 as compared to the case without grating on the ring.

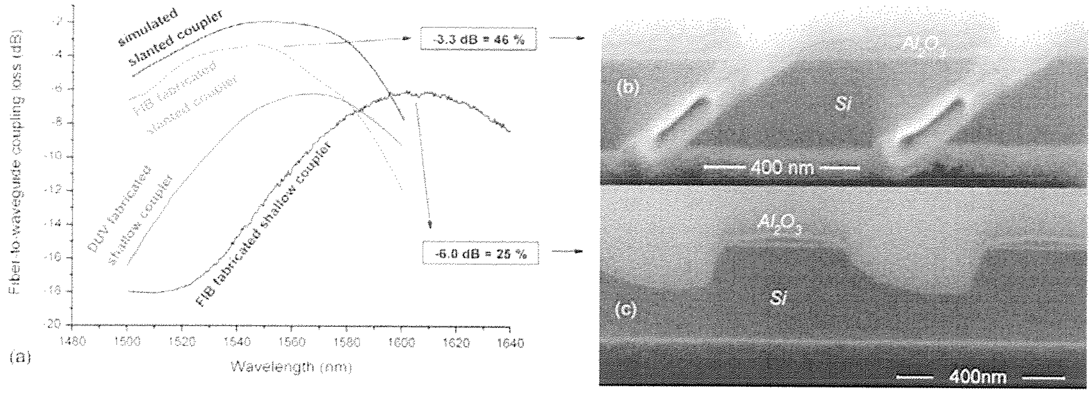

Figure 2: (a) Fiber-to-waveguide coupling spectra for two FIB-fabricated grating couplers: (c) a copy of a DUV fabricated grating coupler and (b) a prototype of a slanted grating coupler.

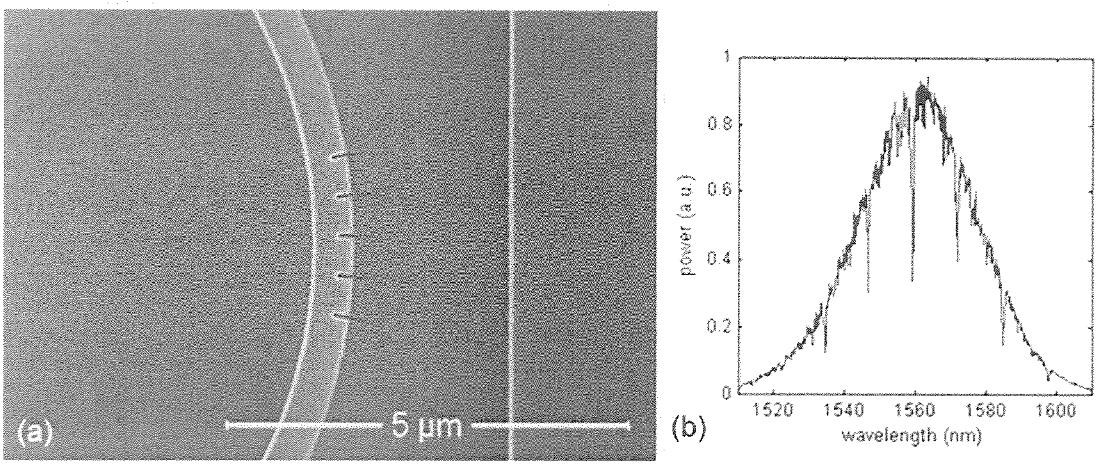

Figure 3: (a) Grating etched in a ring resonator; (b) the spectrum shows Q values of around 4000 for a grating period of 650 nm.

Slot waveguides

A better way to judge the optical losses in etched slits is by etching a slot along the length axis of a waveguide. This was done in DUV fabricated straight waveguides and in ring resonators (width 500nm, height 220 nm), with the purpose of making the effective index of the propagating mode more sensitive to the surrounding environment. The propagation loss in a straight slot waveguide (slot width ~ 100 nm) and coupling loss between regular and slot waveguide were measured by measuring the power transmission through slots with varying length (Fig. 4(a)), resulting in a propagation loss of about 130 dB/cm and a coupling loss of about 1.7 dB. The same slot was fabricated in a ring resonator, of which the spectrum (Fig. 4(b)) shows a cavity Q factor of about 1000. Both measurements demonstrate the relatively low losses in a FIB etched slot.

Conclusions

We have developed a FIB etching technique for prototyping and post-fabrication of silicon photonic components with considerably lower losses than direct FIB etching. The technique was applied to fabricate various grating couplers and slot waveguides and ring resonators.

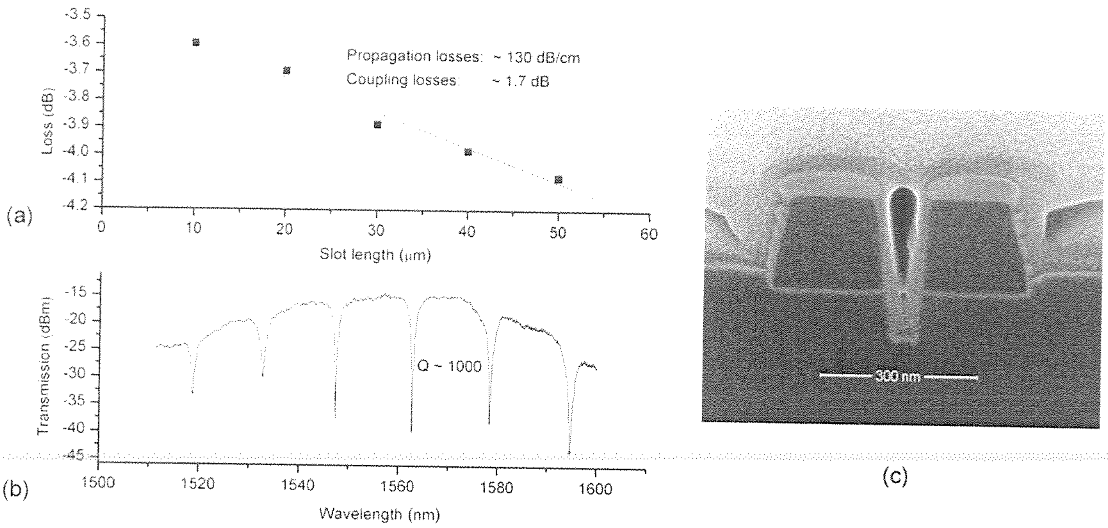

Figure 4: (a) Measurement of the propagation losses in a FIB etched slot in a pre-fabricated waveguide, (b) spectrum of a slot ring resonator and (c) a cross-sectional micrograph of the etched slot.

Acknowledgements

This work was partly supported by the European Network of Excellence ePIXnet and by the Fund for Scientific research (FWO).

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Proceedings of the First International Workshop on

FIB for Photonics

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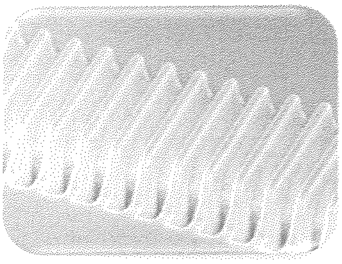
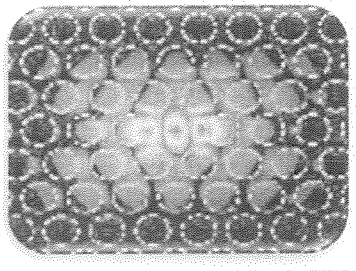
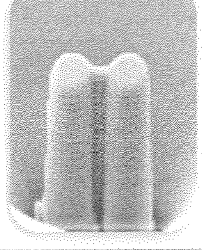
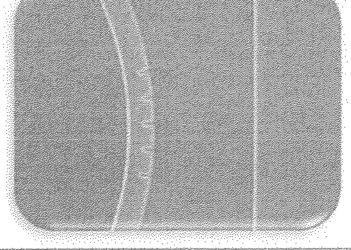

Eindhoven, the Netherlands, 13-14 June 2008

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First International Workshop on

FIB for Photonics

Eindhoven, the Netherlands

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University of Twente
Enschede, The Netherlands
June 2008

ISBN: 978-90-365-2678-4