Focused-ion-beam fabrication of slots in silicon waveguides and ring resonators

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We present the focused-ion-beam fabrication of slots in silicon waveguides and racetrack resonators. The silicon waveguides and resonators were pre-fabricated without slot with deep-UV lithography. The focused-ion-beam etch process was conducted with iodine etch enhancement and alumina hard mask. We demonstrate a propagation loss of 100 dB/cm for slot waveguides and a Q value of 850 for slot racetrack resonators with bend radius of 6 μm.

Introduction

Slot waveguide structures have recently attracted much attention because of their ability to tightly confine light in a material with low refractive index [1]. As opposed to resonant confinement schemes, introducing a slot in a high index waveguide, such as a silicon waveguide, enables broadband confinement in a low index material. Slot structures amplify the interaction between tightly confined optical modes and low index contrast materials, which is of great interest for various devices such as sensors, modulators, etc. The silicon-on-insulator platform is attractive for the fabrication of these devices. A variety of silicon photonic components have been successfully fabricated with deep ultraviolet (UV) optical lithography (248 nm or 193 nm) and dry etching [2], which is compatible with standard processes used for the fabrication of the most advanced electronic circuits and allows for high volume manufacturing. However, the typical size of a slot in a silicon waveguide is of the order of 100 nm, which is a challenge for current optical lithography techniques. Therefore, most of the demonstrated prototype slot structures were fabricated by electron beam lithography and dry etching [1, 3].

An alternative prototyping technology is focused-ion-beam (FIB). This technique offers superior flexibility because of its direct write capability: there is no need for a resist nor dry etching step; and one can easily alter existing devices. On the contrary, similar to electron beam writing, FIB is a serial technique and therefore inherently not adequate for high volume fabrication of devices. However, one can envisage a medium volume production scheme if FIB is used for small modifications to structures that are fabricated with optical lithography, which is the pursued approach in this publication. This fabrication scheme enables the fabrication of angled trenches and slits, and structures with more complex 3D geometries [4]. Furthermore, because the ion beam can be focused in a spot of about 10 nm, features smaller than 50 nm can be fabricated.

FIB etching of silicon is not straightforward because of the optical losses caused by crystal damage and implanted impurities. Several approaches were proposed to alleviate this hurdle. Furnace annealing at temperatures above 800°C reduces the losses due to evaporation and out-diffusion of impurities, and due to crystal regeneration [5]. However, such high temperatures are not compatible with metals, polymers and III-V semiconductors that are potentially present in finished devices. Therefore this approach can not be used for device modifications. An alternative approach is FIB etching in the presence of an etch rate enhancing chemical compound such as iodine [4]. By the presence of a thin layer of non-volatile etch products (mainly silicon-iodide species) the silicon is partly protected from the impinging ions; whereas the etch rate is increased by at least a factor of 10. After removal of the non-volatile etch products by baking at 300°C this process yields structures with relatively low optical losses. Due to the limited maximum temperature of the process it can be applied on most finished devices.

In this paper we first discuss the FIB fabrication of slots by iodine enhanced FIB etching in deep-UV pre-fabricated waveguides and racetrack resonators, then we present a measured propagation loss of 100 dB/cm for a straight slot waveguide and a Q value of 850 for a slot ring resonator with slot widths of respectively 90 and 120 nm.

Fabrication with FIB

The slots were fabricated in a FEI Nova Nanolab 600, with a gallium focused ion beam current of 50 pA and acceleration voltage of 30 keV, corresponding to a beam size of about 30 nm. In previous work we have demonstrated relatively low loss devices with 90 nm slits and vertical sidewalls by using alumina as hard etch mask and iodine as selective etchant [4]. Similarly, an alumina layer of 50 nm was first deposited on the deep-UV fabricated waveguides. Due to the limited penetration depth of gallium ions this thickness is sufficient to protect the sample during ion imaging and alignment procedures. Furthermore the etch rate selectivity is sufficient (more than 10) to guarantee nearly vertical sidewalls of the etched slots. The slits were etched through alumina and silicon in one step using iodine etch enhancement. The width of the slit can be varied by adjusting the etch dose or by using a higher beam current and thus larger beam size. Since the bottom oxide is also etched by this process - albeit slower than silicon - the slot depth is also affected by this variation. After FIB etching the sample was baked on a hotplate in N_2 for 2 h at 300°C to remove the non-volatile silicon-iodide layer [4].

Alignment of the etched slot on the existing waveguides and rings was performed by making ion microscopy images and visually overlaying the slots. The precision of this technique was limited because of the 12 bit digital scan generator in our machine. A higher magnification increases the alignment accuracy; but to be able to etch a slot in a racetrack resonator (with bend radius of 6 μm and straight sections of 3 μm) without stitching, a field of view of 25.6 μm was chosen. The patterns were defined with a digital scan algorithm, with a dwell time of 400 ns and a pitch of 3 nm. To etch straight slots with a length of 30, 40 and 50 μm a single stitch was used.

Figure 1(a) shows a cross-sectional micrograph of a 90 nm slot in a 500 nm wide waveguide (Pt was deposited in situ before cross-sectioning). This slot was etched in the presence of adsorbed iodine on the surface, in 170,000 passes, where each point is etched for 400 ns per pass. 90 nm was the thinnest slot we could obtain with a beam current of 50 pA and beam size of 30 nm. The same process was used to etch a slot in a 600 nm wide racetrack resonator, shown in Figure 1(b). However, in this case the number of passes was 275,000 (total etch time was about 2 min), which resulted in a slot width of about 120 nm.

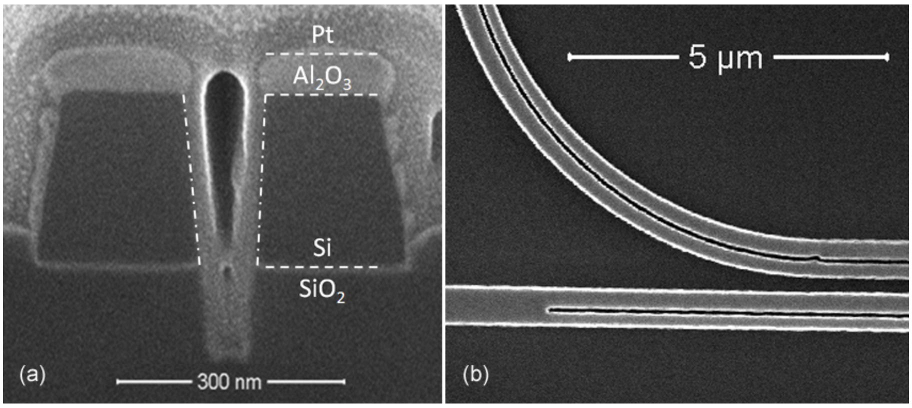

Figure 1: Cross-sectional micrograph (after Pt deposition) (a) and top view (b) of a FIB etched slot in waveguide and racetrack resonator.

Measurement and discussion

The devices were characterized in a fiber-to-fiber transmission measurement. The setup consists of polarization controlled light from a tunable laser that is coupled in and out of tapered broad waveguides by near-vertically positioned fibers and grating couplers. A droplet of water was placed on top of the fabricated devices to provide an aqueous top cladding as the slots were designed for sensing applications in water.

The propagation losses of the straight slot waveguides were calculated by linear regression of the loss through device lengths from 10 μm to 50 μm, as displayed in Figure 2(Top). A distinction between slots up to 20 μm and longer ones can be made: shorter slots were written in one field of view, longer ones were stitched once. The result is a propagation loss of 100 dB/cm, a coupling loss between waveguide and slot waveguide of 1.8 dB, and a stitch loss of 0.1 dB. These losses are not as low as previously reported for electron beam fabricated slot waveguides (about 10 dB/cm [3]). However, since FIB is a serial technique, the length of etched devices for prototyping purposes is not likely to exceed 100 μm. This yields a 1 dB loss per device, which is acceptable. Furthermore, FIB can be used to etch slots in existing waveguides, which is difficult with resist-based methods such as electron beam lithography.

The normalized transmission spectrum of the fabricated slot racetrack resonator is displayed in Figure 2(Bottom). The dips in the spectrum clearly indicate resonance in the racetrack with bend radius of 6 μm. A Q value of about 850 and an extinction ratio of 25 dB were measured around 1560 nm; suggesting that the device is operating near critical coupling. From simulations it can be expected that round trip losses for this ring are dominated by propagation losses, with smaller contributions from bend losses and mode mismatch between straight and bent sections. Although the Q value is likely to increase after high temperature annealing, the current process is attractive as rapid prototyping technique, e.g. for the design verification of high-sensitivity bio-sensors.

Conclusion

We report the direct focused-ion-beam etching of slots in pre-fabricated waveguides and racetrack resonators, with the use of iodine etch enhancement. The experimentally measured propagation loss is 100 dB/cm for a 90 nm wide slot; the measured Q-factor for a

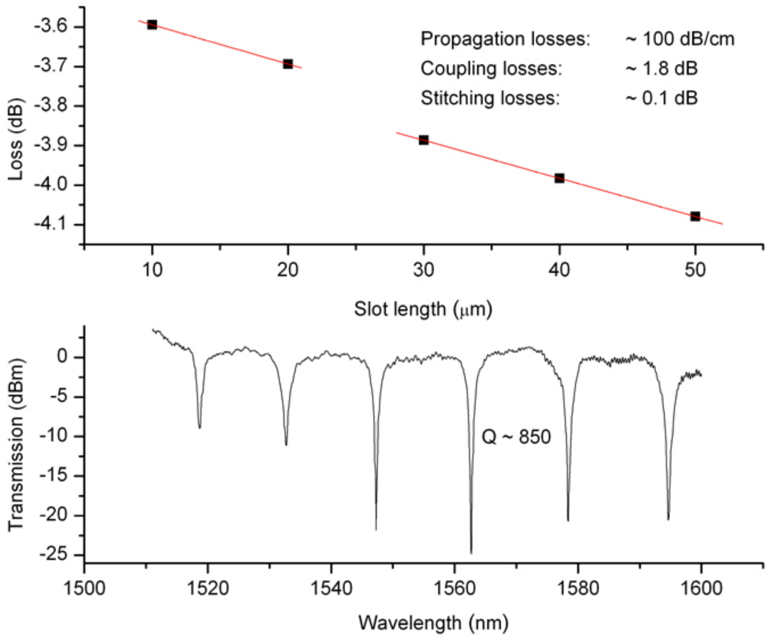

Figure 2: Top: transmission measurements of slots etched in a straight silicon waveguide yield a propagation loss of 100 dB/cm. Bottom: transmission spectrum of slot racetrack resonator. We have measured a Q value of about 850 and an extinction ratio of 25 dB.

resonator with bend radius of only 6 μm is about 850. The developed process is of interest for rapid prototyping and design verification of silicon slot devices.

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