Focused-ion-beam fabricated vertical fiber couplers on silicon-on-insulator waveguides

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Abstract— **We fabricated grating couplers in silicon-on-insulator waveguides with focused-ion-beam. First devices were very lossy, but by using selective etchant and a hard mask we obtained efficiencies comparable to traditional fabrication techniques.**

I. Introduction

Focused-ion-beam (FIB) is known as a very flexible micro-fabrication technique. It has since long been used in micro-electronics for device modification and mask repair. Recently, commercial systems with beam diameters under 10nm have become available, and the ability of FIB to do nanofabrication is being considered [1]. In photonics, FIB would be the ideal tool to do fast prototyping, high resolution device modification, resonant cavity tuning, slanted facet etching, and much more. One of the inherent problems however, is the high acceleration voltage (30kV) needed to focalize the beam. It causes ion implantation, crystal damage and amorphization deep into the processed material. All these effects lead to attenuation of light, which makes the fabrication of low-loss photonic components difficult. FIB has been used to study various phenomena involving light in waveguides [2], [3] and allows the direct fabrication of structures such as photonic crystals [4], [5]. But to our knowledge there are few or no reports in literature about low-loss photonic devices fabricated in silicon-on-insulator by means of FIB. In this work we report on a possible way to circumvent the problem of optical attenuation in devices fabricated with FIB in silicon-on-insulator (SOI). By using I_2 as selective etch gas and Al_2O_3 as protective hard mask we obtained a device that features the same losses as one fabricated with traditional techniques. This proves that FIB can be used to fabricate low-loss photonic devices.

The silicon-on-insulator platform is a good candidate for future ultra-compact photonic integrated circuits due to its compatibility with CMOS technology and the possibility of making low-loss waveguides with compact bends. One inconvenience however, is the large mode-size mismatch with single-mode optical fiber, causing very inefficient fibre-to-chip coupling for butt-coupled devices. This problem can be solved by using tapers or grating couplers. The latter are shallow gratings that diffract the light into a vertically positioned fiber. In previous work we have fabricated these shallow grating couplers with a CMOS compatible process (248nm deep UV lithography and ICP etching) and optimized the parameters for optimal coupling efficiency and 1550nm operation [6]. The optimal design is a grating with about 25 periods, lattice constant of 630nm, slit width of 315nm and etch depth of 70nm. It couples about 25% [7] of the light from the waveguide into a single-mode fiber that is inclined 10 degrees to avoid back diffraction.

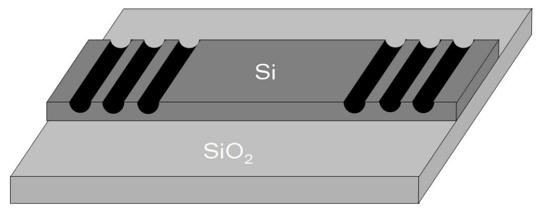

Fig. 1. Two identical fiber couplers fabricated with focused-ion-beam (FIB) on a 10μm wide and 220nm thick Si waveguide.

II. Direct fabrication

A first approach is the direct fabrication of gratings into 10μm wide waveguides. For this process no mask is needed: blanking of the ion beam and correct scanning copy the wanted structure into the substrate. For submicrometer structures however, the gaussian profile of the beam [8] and redeposition cause edges to be rounded and sidewalls to be nonvertical. Due to this effect the gratings we fabricated with FIB have more rounded slits than the ones fabricated with traditional ICP etching. This is shown in the insets of Figure 2. We have performed FDTD calculations to verify whether this has a negative effect on the performance. The result is that if slit width and etch depth are optimized the theoretical efficiency and bandwidth are close to the traditional ones.

To determine the coupling efficiency we use a fibre-to-fibre transmission measurement for TE-polarization. The structure consists of an input coupler, a 10μm wide 220nm thick waveguide and an output coupler. This is shown in Figure 1. We assume that both couplers are identical. Figure 2 shows the measured fibre-to-chip coupling efficiencies for directly fabricated grating couplers. We scanned the ion beam on 25 slits of 200nm wide, with a grating period of 630nm. To vary the etch depth we etched several gratings with different doses, ranging from $4\ 10^{17}$ to $40\ 10^{17}$ Ga^{+}/cm^2. By making FIB cross-sections we verified the etch depths, as shown in the insets of Figure 2. The ion beam at 10keV cannot be focalized as well as the one at 30keV and produces broader and rounder grating slits.

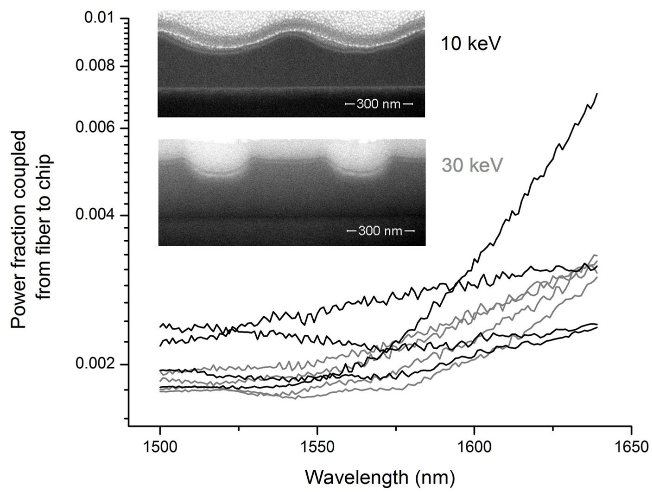

Fig. 2. Very inefficient fiber couplers fabricated directly into Si with 10keV (black) and 30keV (grey) Ga ions. The insets show the cross-sections through two grating periods: the 10keV beam is broader and makes a rounder profile, but still these gratings are the most efficient.

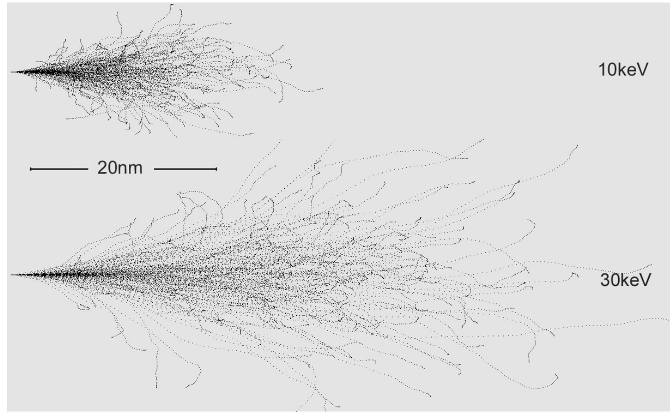

Fig. 3. Trajectories of 250 Ga ions accelerated to 10 and 30keV, perpendicularly projected on a Si target. Etching with 10keV ions produces a shallower damaged layer and less optical losses.

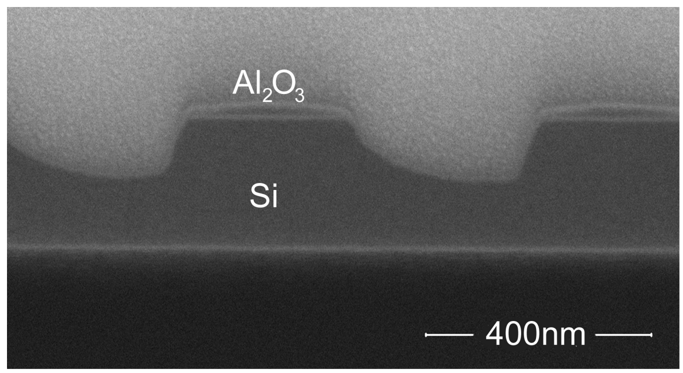

Fig. 4. Profile of a grating etched in Si with I_2 as selective etch gas and Al_2O_3 as hard mask. The profile is asymmetric due to the gas injection system.

The efficiency of the directly etched gratings are all lower than 1%, which is one order of magnitude lower than the values calculated with FDTD. This is most probably due to the damage of the Ga ions in the Si crystal, and was also noticed for gratings in other materials [9]. Figure 3 shows the trajectories of 250 Ga ions accelerated to 10keV and 30keV, and projected perpendicularly on a Si target. They were calculated with SRIM [10], a freely available Monte Carlo simulation tool. The Si atoms that reach the surface after subsequent binary collisions and have enough energy te escape the surface potential are sputtered; the others are displaced and generate vacancies and substitutional Si atoms in addition to the implanted Ga ions. Figure 3 shows that the thickness of this damaged layer is more than 50nm for 30keV Ga ions, whereas for 10keV ions it is about half as thick. This explains the somewhat higher coupling efficiency of gratings fabricated with 10keV. But due to the bad focalization in this case, the dimensions and the sidewall angle of the slits are difficult to control. Even though we did not further optimize the width of the etched slits, we believe that Figure 2 is sufficient proof to say that directly etched gratings in thin Si waveguides are too inefficient for practical use.

III. Etch enhancement and hard mask

It was formerly shown that optically active material is less damaged when chemical etch enhancement gasses are used during FIB etching [11]. I_2 is known as etch enhancement gas for Si: the molecules attach to the Si surface and facilitate the extraction of Si atoms from the collision cascade, resulting in chemical etch enhancement up to a factor of 10. However, the dimensions of an etched hole become difficult to control when chemical enhancement is used, so we need a hard etch mask to controllably make grating couplers. As hard mask one could choose a metal, but thin metal films are often grainy, which makes homogeneous etching with FIB impossible due to the crystal orientation dependence of the etch yield. Therefore we chose Al_2O_3: it is an amorphous material that can homogeneously be etched. In addition to this I_2 reduces the etch yield of Al_2O_3, so the etch selectivity of Si can be enhanced with this etch mask.

A layer of 50nm Al_2O_3 was evaporated on the predefined Si waveguides using electron beam evaporation in a Oxygen rich atmosphere. First the grating was etched into this layer with FIB, using trifluoroacedtamide (TFA) as etch enhancer. The parameters for this etch process were: dose $12.3\ 10^{17}$ Ga^{+}/cm^2, beam energy 30keV, beam current 50pA. The process was optimized for complete mask breakthrough. In principle the second etch step, copying of the grating into the silicon, can be performed with conventional etching techniques, but for process simplicity and speed we chose to perform it also with FIB. The ion beam was scanned on a rectangle covering the entire grating, with I_2 as selective etchant, 30keV acceleration voltage and 50pA beam current. We optimized the etch dose and measured a maximum cou-

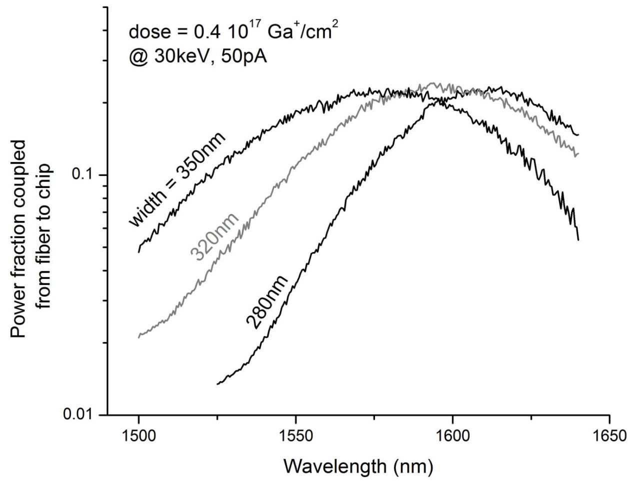

Fig. 5. The coupling efficiency of three gratings fabricated with I_2 and Al_2O_3. The width of the scanned rectangles in the first etch step was varied from 280nm to 350nm to vary the central frequency.

pling efficiency of 24% (by fitting a gaussian to the curve) with an etch dose of $0.4\ 10^{17}$ Ga^+/cm^2 and a slit width of 280nm for the first step. Cross-sections of the fabricated structured showed that the Si is slightly etched in the first etch step. Figure 4 shows that the second etch step produces a somewhat asymmetric slit profile, which could not be changed by changing the way of scanning the ion beam during etching. It is probably caused by the asymmetry in the gas injection system. The original devices were designed to operate at a central wavelength of 1550nm, with the fibers positioned at an angle of 10 degrees. The first devices made with FIB had central wavelengths near 1600nm however. The two step etch process allows for a good control of slit width and depth. The width of the scanned rectangles in the first step determines the final slit width, whereas the dose of the second step determines the etch depth. Figure 5 shows the optimization of the slit width in the first etch step. As expected from simulations the central wavelength shifts to smaller values as the slits become broader. By changing the width of the scanned rectangles from 280nm to 350nm, without changing the areal dose, the central wavelength shifts from 1611nm to 1576nm and the efficiency drops only 1%. The complete etch process for one grating coupler with 25 slits takes about 5 minutes.

IV. Conclusions

We have fabricated a grating coupler in a 10μm wide Si waveguide using focused-ion-beam. The ion induced crystal damage and the resulting optical losses can be minimized by using I_2 as selective etch gas and Al_2O_3 as hard mask. This resulted in a fibre-to-chip coupling efficiency of 24%, which is comparable to devices fabricated with conventional techniques. This proves that the ion induced optical losses can be circumvented, and opens the way to fast FIB prototyping, high resolution device modification, resonant cavity tuning, slanted facet etching, and much more.

V. Aknowledgements

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