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Focused-ion-beam fabrication of slanted fiber couplers in silicon-on-insulator waveguides

J. Schrauwen, F. Van Laere, D. Van Thourhout, R. Baets

Photonics Research Group, Department of Information Technology,
Ghent University - IMEC, 9000 Gent, Belgium

The ability for forming complex three dimensional shapes is one of the prime advantages of focused ion beam based micromachining. We have used this technique to fabricate slanted fiber couplers in silicon on insulator. Simulations show coupling efficiencies of up to 63% for fiber couplers with 167 nm slits under an angle of 59° to the surface normal. We have fabricated these devices with focused-ion-beam. The dimensions of the fabricated structures are similar to the design, but we have not measured efficiencies larger than 20%. The difference with the simulated value is probably caused by ion induced damage in the Si crystal.

Introduction

Microfabrication with focused-ion-beam (FIB) consists of hitting a substrate locally with high energy ions; in most commercial systems these are gallium ions with energies around 30 *keV*. If the substrate is crystalline this process induces lattice damage, makes the top layer amorphous, and implants ions deeper into the substrate [4, 5]. These effects cause optical losses and make the direct fabrication of low-loss photonic devices non-trivial. Nevertheless, FIB remains a promising process due to the flexibility with which we can make photonic devices, e.g. for the fabrication of slanted fiber couplers.

The silicon-on-insulator (SOI) platform is a promising candidate for future ultra-compact photonic integrated circuits because of its compatibility with CMOS technology [1]. The high index contrast in this material system allows for the fabrication of short waveguide bends and thus circuits with a high degree of integration. The SOI wafers we use have a thin top Si layer of 220 *nm* and a bottom oxide thickness of 1 μm. One of the difficulties of a high contrast platform is the coupling of light from optical fibers, due to the large mode-size mismatch. This problem can be solved by using tapers or grating couplers. The latter are shallow gratings in broad waveguides that diffract light out of the waveguides into vertically positioned single-mode fibers. In previous work we have fabricated these shallow grating couplers with a CMOS compatible process (248 *nm* deep UV lithography and Inductively Coupled Plasma etching) and optimized the parameters for optimal coupling efficiency (25% and more [2]) and 1550 *nm* operation [3]. Recently another design was proposed for grating couplers [6], with a theoretical efficiency of over 50%. These structures consist of a series of very narrow slits in the top silicon layer, under an angle of about 60° with the surface normal. Due to this complicated design the structures can't be fabricated with standard CMOS processing, and no fabrication method was proposed so far [6]. In this paper we report on the fabrication of similar structures with FIB. In the first section we detail the design of the slanted fiber couplers with Finite Difference Time Domain (FDTD) methods, and in the second section the fabrication with FIB is evaluated.

In previous work grating couplers were designed with various geometries [3]. In the simplest form, completely CMOS compatible, these are shallow etched gratings. They

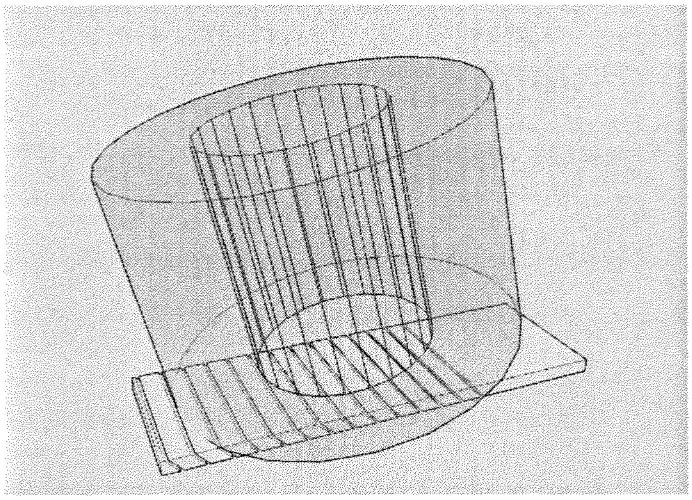

Figure 1: Schematic drawing of the slanted fiber coupler.

have efficiencies of about 25% [2]. When going to more complex fabrication methods, the efficiency of these couplers can be greatly enhanced: by adding a bottom gold mirror by means of bonding, an efficiency of 69% was obtained for the same gratings [7]. All grating couplers from our previous work were designed for coupling of 1550 *nm* infrared light form a waveguide into a fiber positioned at an angle of 10° with respect to the surface normal. This choice was made to reduce reflection by back diffraction into the second order mode. When using slanted gratings, the fraction of light coupled into the second order mode depends on the slant angle of the slits, and can thus be minimized without the necessity of tilting the fiber. However, due to measuring convenience in our setup, we have chosen to design a slanted fiber coupler for coupling to a fiber with 10° tilt, as shown in Figure 1. The advantage of a slanted coupler, as compared to the bottom mirror gratings from [7], is fast fabrication. The slanted couplers can be fabricated with FIB in less than 10 minutes, in situ, anywhere on a wafer.

Simulation

The optimum design has 167 *nm* wide slits, under 59.06° to the surface normal, with a period of 675 *nm*, showed in Figure 2. First we optimized the grating position, then a global scanning of the parameter space and a fine optimization was used to determine slit width, period and angle. This optimization was performed in a simulation environment of 25 μm by 14 μm, with grid cells of 10 *nm* and a PML thickness of 8 cells. A mode was excited in the fiber, and the power coupled to the waveguide mode was calculated, in a two-dimensional approximation and for the polarization with the electric field parallel to the grating slits. The fraction of the measured mode power to the excited power was optimized for 1550 *nm*. For the optimal structure in Figure 2 it is 63.2%.

Fabrication with focused-ion-beam

In previous work we have demonstrated that low-loss fiber couplers can be fabricated with FIB [8]. By using Al_2O_3 as hard mask and I_2 as selective etchant the loss by crystal

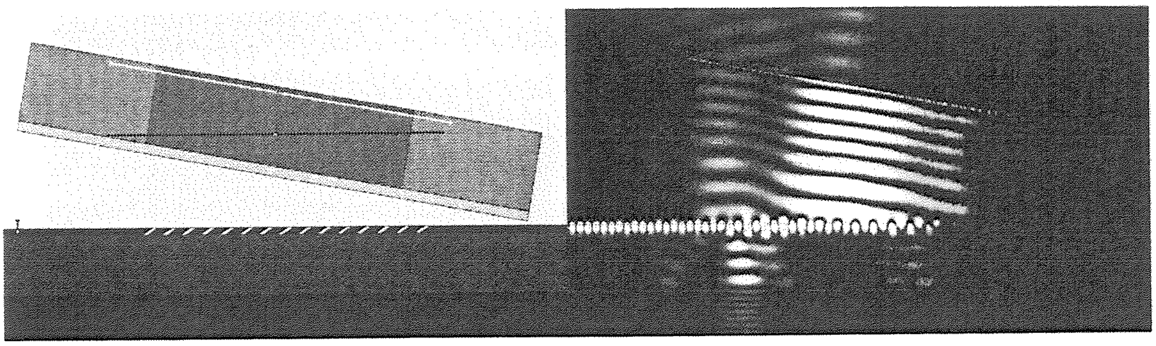

Figure 2: Part of the FDTD simulation environment of the optimal grating with 63.2% efficiency, at the right the magnitude of the electric field parallel to the grating slits is plotted for 1550 *nm* operation.

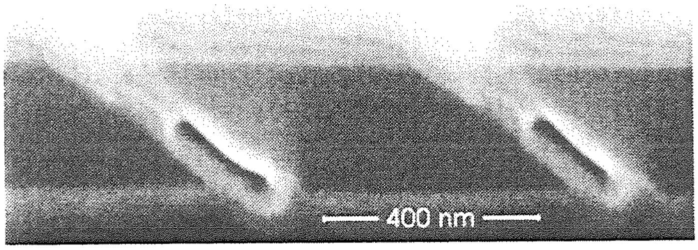

Figure 3: Cross section of two slits of the slanted grating coupler. There is a good agreement with the FDTD designed grating.

damage was minimized. To etch narrow slanted slits we have mounted the sample under 59° relative to the ion beam, and scanned lines under an iodine atmosphere. The etching was performed in an FEI Dualbeam 600. The dose was optimized to etch down to the oxide layer. A cross section of the grating is shown in Figure 3.

Results and discussion

The cross section images of the fabricated gratings are in good agreement with the optimal slanted coupler design. To determine the coupling efficiency we use a fiber-to-fiber transmission measurement for TE polarization. The structure consists of an input coupler, a 10 μm wide waveguide, and an output coupler. We assume that both couplers are identical. We have not measured efficiencies higher than 20%, in contrast to 63% as expected from the simulations. The optical losses are most likely caused by damage to the Si crystal. This result proves that the process proposed in [8] can not straightforward be applied to the etching of slanted grating couplers. We assume that this is caused by the limited iodine etch enhancement due to the difficult placement of the gas injection needle, and due to slow adsorption of iodine on the Si surface in the narrow grooves. Further investigation will show whether slower etching solves this problem.

Conclusions

We have fabricated slanted fiber couplers in silicon-on-insulator with a focused-ion-beam. The etched structures are in good agreement with the FDTD simulated optimal design. However, the measured efficiencies are a factor of three lower than expected. We think that this is caused by a bad penetration of gas molecules in the narrow grooves.

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