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

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Abstract: *We have designed and fabricated an efficient grating coupler for silicon-on-insulator waveguides. The coupler consists of 88nm wide slits, under an angle of 58° to the surface normal. They are defined by direct etching with a focused ion beam, using iodine gas and an alumina hard mask. The measured efficiency was 46%.*

Introduction

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 therefore circuits with a high degree of integration. Due to the large size and shape mismatch between the optical mode in a high index contrast waveguide and in an optical fiber, coupling between both is a problem that has to be addressed. Literature proposes adiabatic tapering and out of plane diffraction as candidates to solve this problem. Three dimensional [2] and inverse [3] taper structures can adiabatically transform the optical mode between a silicon waveguide and a fiber with low loss, but need complicated fabrication strategies and are not compatible with waferscale processing. Alternatively, out of plane diffraction gratings can easily be fabricated with completely CMOS compatible technologies [4]. These gratings are very compact, can be one or two dimensional, and couple light from a waveguide to a fiber with a reasonable efficiency. Grating couplers avoid the necessity of polished facets and enable wafer scale testing of integrated circuits. Although 1D gratings are very polarization sensitive, a polarization insensitive approach can be envisaged when one uses 2D grating couplers [5]. Although the basic process for these gratings is completely CMOS compatible, the different approaches that are proposed in literature to enhance the efficiency are more complicated. One approach is the use of a bottom gold mirror, that can be added by wafer bonding [6]; another approach is the deposition of poly-Silicon overlay which needs Chemical Mechanical Polishing (CMP) and the deposition of low-loss poly-Silicon [7].

These were all fabricated with standard lithography so they do not enable in situ analysis of wafer scale optical circuits. Another approach is the direct etching of grating couplers in predefined silicon waveguides. This is feasible with focused-ion-beam (FIB), a common tool for device analysis and modification in electronics. It was shown that shallow grating couplers can be etched with FIB [8]. However, these couplers require a two step etching process and have a moderate coupling efficiency of 24%.

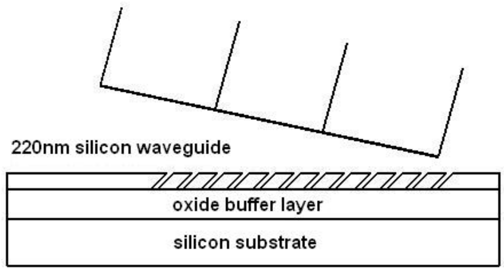

Fig. 1: Schematic drawing of the slanted fiber coupler.

In this paper we discuss the design and fabrication of a slanted grating coupler, combining the flexibility of FIB with a higher efficiency. In the first section we report on the design of a slanted fiber coupler with a theoretical efficiency of 64%. This approach was originally proposed by Ref. [9]. In the next section we discuss the fabrication of the grating with FIB. And in the final section we present the experimental results: a measured fiber-to-chip coupling efficiency of 46%.

Simulation

Regular shallow gratings in SOI have an inherent efficiency limit of around 50% due to diffraction of the first order into the substrate. This limit can be circumvented by a bottom DBR mirror [4], or by a bottom gold mirror [6]. However, these greatly complicate the fabrication of integrated circuits in SOI. Another method to enhance the coupling to the upward first order is the use of slanted facets, in analogy to a blazed grating. Because it is difficult to control the depth of the slanted slits with FIB we have chosen to design a slanted grating with slits through the entire top silicon layer. We use SOI wafers with 220nm top silicon and 2μm oxide buffer. The gratings were simulated in a Finite Difference Time Domain (FDTD) environment. The optimization was done by first scanning the complete parameter space, followed by a local quasi Newton optimization. Although one can in principle couple light upwards by total internal reflection on a single slanted facet, there will be little overlap with the mode in the fiber in that case. To ensure more overlap with the large fiber mode one needs to couple light upwards in a distributed way. This is feasible with - FIB fabricated - sub 100nm slanted slits that allow tunnelling.

The optimum grating for 10° coupling has 87.5nm wide slits under an angle of 58.4°. Our simulations

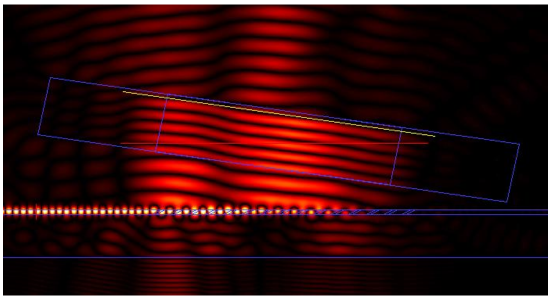

Fig. 2: Part of the FDTD simulation environment of the optimal grating with 64% efficiency. The plot shows the field pattern at 1550nm operation.

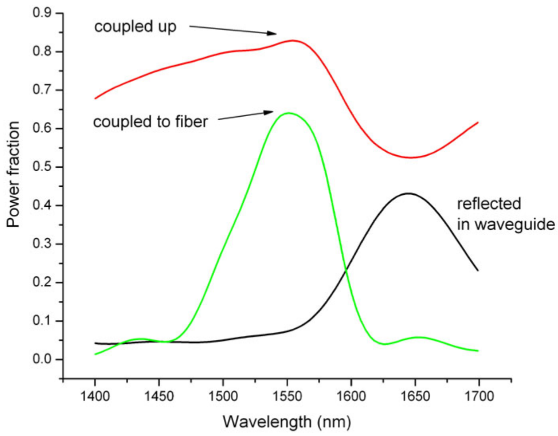

Fig. 3: Result of the slanted coupler optimization with an FDTD simulation. The curves present the power fractions coupled upwards, coupled into the fiber mounted at 10°, and reflected back into the waveguide.

were performed in a 25μm x 14μm base, and converged with a 10nm mesh. A plot of the calculated field pattern for 1550nm operation is shown in Figure 2. The slanted grating coupler has a fiber-to-chip coupling efficiency of 64%, a period of 675nm and a 3dB bandwidth of 100nm. Figure 3 shows the calculated power fractions that are diffracted upwards; coupled into the fiber; and reflected in the waveguide. To ensure a low second order reflection in the waveguide the fiber mounted at 10°. For 1550nm light the back reflection is only 7%. The total amount of power diffracted out of plane is 83% at 1550nm. Although only part of this upward power is coupled into the fiber due to mode mismatch for a periodic grating, the mode mismatch can be decreased by varying slit width. However, due to fabrication complexity of varying slit widths, we have chosen to only design and fabricate periodic slanted gratings.

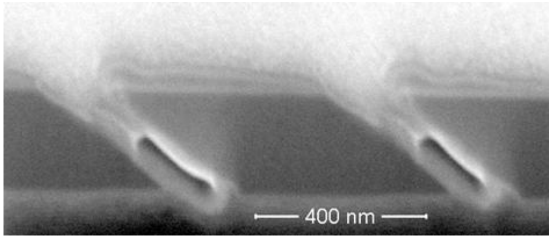

Fig. 4: Cross section of two slits of the slanted grating coupler. There is a good agreement with the FDTD designed grating.

Fabrication with focused-ion-beam

Microfabrication with FIB consists of hitting a substrate locally with high energy ions; in most commercial systems, like our FEI Dualbeam 600, these are gallium ions with energies around 30keV. In crystalline substrates this process induces lattice damage, makes the top layer amorphous, and implants ions deeper into the substrate [10, 11]. Although these effects cause optical losses and make the direct fabrication of low-loss photonic devices non-trivial, there are fabrication strategies to minimize optical losses. When carefully adopting these strategies FIB remains a promising tool due to the flexibility with which we can make photonic devices. In previous work we have for instance 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 damage can be minimized. Al_2O_3 has a very low penetration depth for incident gallium ions and has a very low etch rate under iodine atmosphere.

Therefore 50nm of Al_2O_3 was deposited on predefined SOI waveguides using electron beam evaporation. Simulations and experiments have shown that this thin layer has no influence on the propagation losses of light in the predefined waveguides. That is why we did not incorporate the layer in our simulations. To etch narrow slanted slits we have mounted the sample under 58° relative to the ion beam, and scanned lines under an iodine atmosphere. Both hard mask and silicon are etched in the same run, where narrow slits are formed due to the large etch rate difference between alumina and silicon. The etch dose was optimized to etch down to the oxide buffer layer. We have noticed that the slit width depends strongly on the beam size. The beam current used was 50pA, corresponding to a beam size of about 30nm. A cross section of two grating slits is shown in Figure 4, and a top view is shown in Figure 5. For an etch dose of 1.1 x 10^{13} Ga^+/cm the slits are etched down to the oxide buffer layer and the slit width corresponds to the simulations. The etch time for 15 slits of 10μm wide is about 8 minutes. After fabrication the sample was baked for two hours at 300°C in a nitrogen atmosphere.

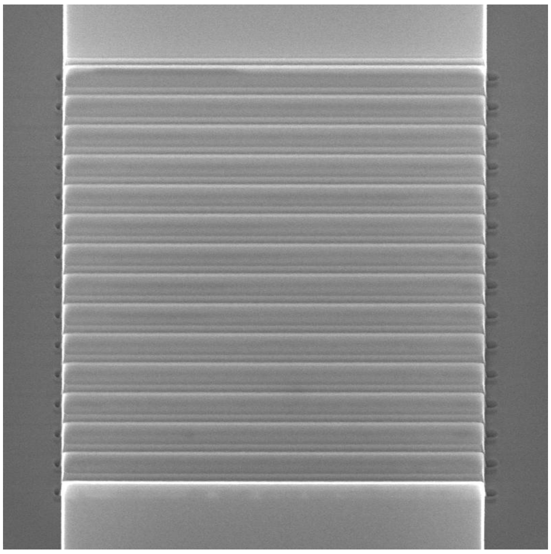

Fig. 5: A top view of the slanted grating coupler.

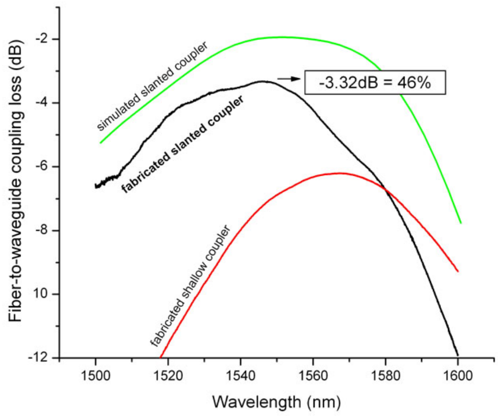

Fig. 6: Coupling spectra of simulated and fabricated slanted fiber coupler, as compared to a shallow grating coupler fabricated with optical lithography.

Measurement and discussion

To determine the coupling efficiency of the fabricated coupling structure we have used a fiber-to-fiber transmission measurement for TE polarized light from a super luminescent LED. The structure consisted of a regular shallow input coupler fabricated with optical lithography, a broad 10μm waveguide, and a slanted output coupler fabricated in situ with FIB. The coupling characteristic of the shallow couplers was measured in a separate setup with identical input and output couplers. The coupling efficiency of the slanted grating coupler is depicted in Figure 6. It is calculated by subtracting - on a logarithmic scale - source spectrum and shallow coupler spectrum from the measured spectrum. We have extracted a maximum fiber-to-waveguide coupling efficiency of 46% and a 3dB bandwidth of about 80nm for the slanted fiber coupler fabricated with FIB.

To evaluate the discrepancy between simulated and measured coupling efficiency we have investigated the fabrication tolerances of the slanted coupler. Period, slant angle, and slot width were varied within the measurement tolerance of the cross section in Figure 4. The observed drop in efficiency was below 5%, therefore bad grating parameters can not fully explain the discrepancy. Instead, we consider the measured loss to be material related. Is is known that FIB etching generates optical losses in silicon [8]. Although the use of alumina as mask and iodine as enhancement gas considerably reduces these losses, we have noticed that an additional baking step at 300°C is necessary to fabricate slanted couplers with efficiencies above 20%. We think that the baking step removes all remaining iodine and silicon iodide from the etched region. However, the damage caused to the silicon crystal remains unaltered after a temperature treatment at 300°C. Therefore we are convinced that silicon crystal damage in the region of the etched slits causes the discrepancy between theory and experiment.

Conclusions

We report on the design and focused-ion-beam fabrication of a slanted grating coupler in a silicon-on-insulator waveguide. The coupler has a maximum coupling efficiency of 46% and can be etched in situ, anywhere on a wafer, in less than 10 minutes.

Acknowledgments

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