High-efficiency Silicon-On-Insulator Fiber-to-Chip Grating Couplers Using a Silicon Overlay

D. Vermeulen, S. Selvaraja, P. Verheyen, G. Lepage, W. Bogaerts, G. Roelkens

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

Process Technology Division, Interuniversity Microelectronics Center (IMEC),
Kapeldreef 75, 3001 Leuven, Belgium

Abstract: We present the realization of a new generation of Silicon-On-Insulator fiber-to-chip grating couplers which use a silicon overlay to enhance the directionality and thereby the coupling efficiency. Devices fabricated in a CMOS pilot line show a coupling efficiency of -1.6dB and a 3dB bandwidth of 80nm.

1. Introduction

In the last decade a lot of research was geared towards silicon photonic integrated circuits, due to the scaling in size that can be accomplished because of the high refractive index contrast available on the SOI material platform. The scaling of the device cross-section complicates the interfacing with a single mode optical fiber however. Several schemes have been proposed to tackle this problem and we focused particularly on fiber-to-chip coupling by means of subwavelength structured surfaces such as line gratings or photonic crystals. With these grating couplers one can couple out-of-plane and thus test photonic circuits on a wafer-scale without the need of any post-processing or cleaving. Furthermore because of a relaxed 1dB alignment sensitivity of 2μm, it is even possible to align several optical fibers at the same time by using fiber arrays for wafer-scale testing or packaging. Despite the fact that these grating couplers are a very good candidate for fiber interfacing for the low cost and high volume oriented silicon photonics framework, they suffer(ed) from low efficiencies, making them only useful for research purposes.

In 2002 we reported an SOI grating coupler with an efficiency of -7dB [1]. Since then, a lot of attempts were made to improve the coupling efficiency significantly. In general there are three factors that contribute to the poor coupling efficiency of standard grating couplers. Most of the light 35%-45% is lost because of diffraction towards the substrate, around 20% is lost because of poor mode-matching to the gaussian shaped mode of the fiber and for perfectly vertical coupling another 30% is reflected back into the waveguide due to second order Bragg diffraction. This last issue can be easily solved by coupling under a small angle which breaks the symmetry and eliminates the reflection [2]. An alternative method is to etch a deep slit in front of the grating which acts together with the grating as a Fabry-Perot cavity [3]. By chirping the grating, back reflections [4] and losses due to mode-mismatch [5] can be minimized. Most attempts to increase the directionality of the grating all involve substrate engineering. This approach is either based on amorphous silicon, which limits the thermal budget [6], or requires a lot of post-processing [7]. Alternatively, one can use exotic gratings with for example slanted facets, in analogy to a blazed grating, to enhance the coupling to the upward first order diffraction [8]. In 2006 however we proposed a rather simple and elegant way to adapt the grating and increase the coupling efficiency drastically, i.e. by defining a silicon overlay prior to etching the grating [9]. Early attempts which involved epitaxial silicon growth were promising and showed efficiencies up to -2.6dB [10]. In this paper we demonstrate high efficiency grating couplers, fabricated in a CMOS pilot line, with -1.6dB coupling efficiency, approaching the coupling efficiencies required in practical applications.

2. Physical Working Principle

The proposed high efficiency grating coupler is schematically illustrated in Figure 1. This structure is theoretically described in [9]. In order to reach high fiber coupling efficiency, a highly directional grating is required while at the same time the grating strength needs to be optimized for maximal overlap with the Gaussian fiber mode. Compared to standard grating structures, where the grating is directly etched into the silicon waveguide layer, the introduction of the overlay gives another degree of freedom to optimize both at the same time. The improvement in directionality with the silicon overlay can be understood as follows. Considering the diffracted field pattern as the superposition of the fields emitted by an array of scattering centers (which have a π phase shift with respect to each other for a perfect vertically coupling grating), constructive interference towards the superstrate (and hence the optical fiber) can be achieved by

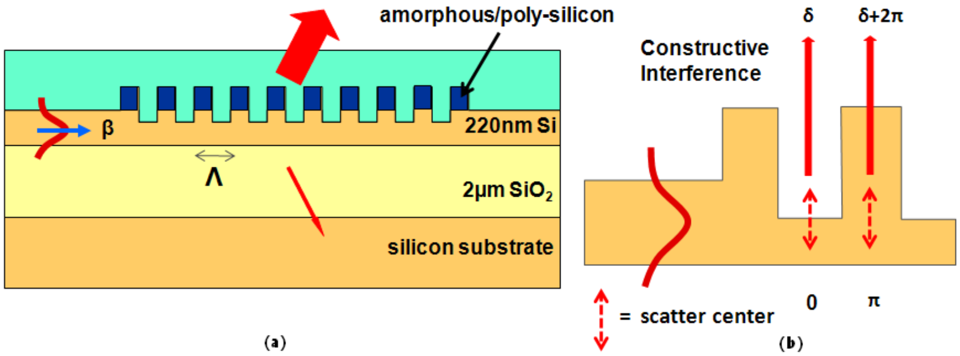

Fig. 1: Cross section of a silicon overlay grating (a) and a schematic illustrating the physical principle of high directionality in these overlay gratings (b).

realizing an additional π phase shift during the propagation towards the superstrate, since light is propagating either in air (in the etched slit) or in silicon (in the grating tooth).

3. Fabrication and Measurements

Devices were fabricated in a CMOS pilot line, on 8 inch silicon wafers. The crystalline silicon waveguide layer is 220nm thick and sits on top of a 2μm buried oxide layer. Simulations show that the thickness of the buried oxide layer is of no importance for the grating directionality, since the grating intrinsically is very directional and doesn't have to rely on the oxide/silicon interface reflection to achieve constructive interference towards the optical fiber, as is the case in a standard grating coupler. On top of the silicon waveguide layer a 160nm thick amorphous silicon layer was deposited, which was then formed into silicon overlay mesas by dry etching. Afterwards the grating was etched in the amorphous silicon/crystalline silicon stack. In Figure 2 a side view image is shown of a fabricated fiber coupler with an amorphous silicon overlay. The grating is etched 70nm into the crystalline silicon waveguide. Notice that the sidewalls of the grating are not straight but under an angle of approximately 10 degrees.
The measurement results are shown in Figure 2. All measurements were performed with a single-mode fiber tilted under an angle of 13 degrees relative to the surface normal of the grating. Index matching fluid was applied between the grating and fiber facet to reduce Fresnel reflections. TE polarized light is used in all experiments, since the gratings behave very polarization dependent. Since amorphous silicon is used, the thermal budget is limited in order to prevent the formation of a poly-crystalline overlay. In graph 2(b) one can see however that there is little difference in terms of maximum coupling efficiency between an amorphous silicon overlay or polysilicon overlay. Due to a difference in refractive index between the two materials, we see a wavelength shift of about 15nm to 20nm. Graph 2(c) shows the central or peak wavelength as a function of the grating period and this for several duty cycles. The central wavelength scales almost linearly with the grating period because the effective refractive index of the grating is weakly dependent upon the wavelength. In the Figure 2(d), the coupling efficiency for different grating periods is plotted versus the duty cycle. It seems that a duty cycle of 35% (refers to the unetched silicon part) is optimal and we measured a maximum efficiency of -1.6dB for a grating period of 690nm and central wavelength of 1530nm. Due to the sidewall angle of the grating slits, the actual fill factor is even lower and approximately 30% for an optimum grating coupler, as is the value predicted by numerical simulations.

4. Conclusion

We have shown experimentally high efficiency grating couplers with a coupling efficiency of -1.6dB for TE polarized ligth and this for both an amorphous and polysilicon overlay. The optimal duty cycle of the grating is found to be 35%. Polarization independent coupling could be achieved by using 2D gratings, which also benefit from the silicon overlay according to 3D FDTD numerical simulations. By chirping the grating, fiber mode-matching could be enhanced and even higher efficiencies could be achieved. Besides the grating couplers, the silicon overlay could also be used in other components on the SOI chip as an extra degree of design freedom.

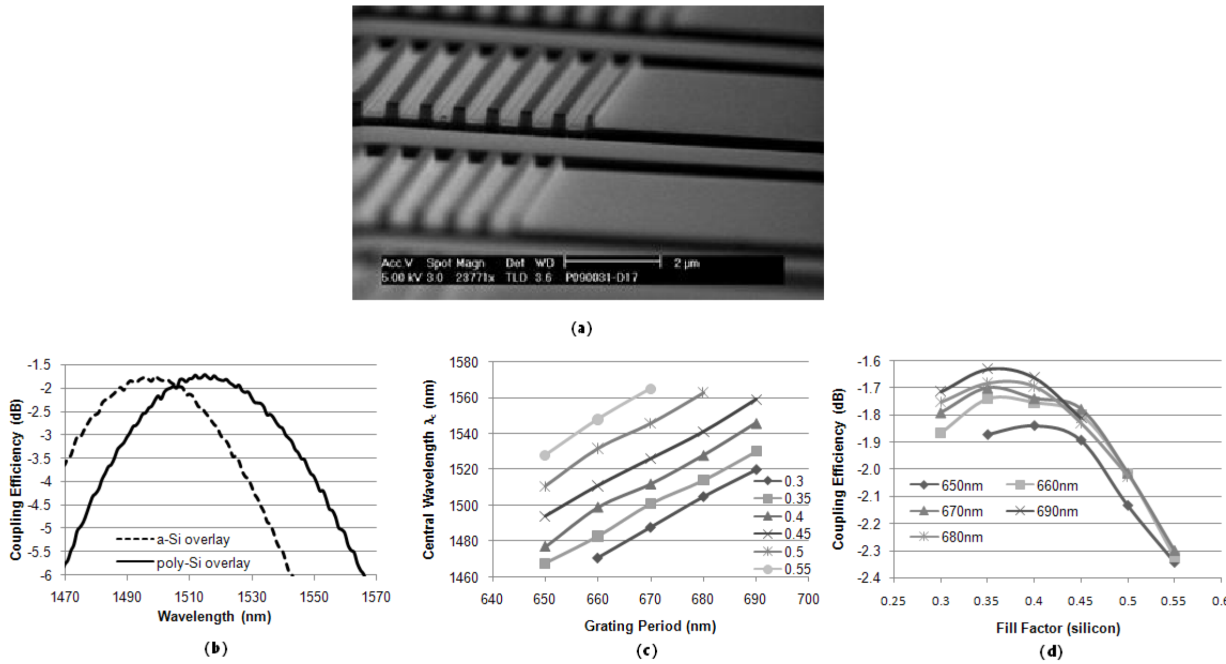

Fig. 2: Side view image of a silicon overlay grating (a). Comparison of the coupling spectrum for an amorphous silicon overlay grating and a polysilicon overlay grating (period=660nm and duty cycle=0.4)(b) Measurement results of a sweep of 1D fiber couplers (a-Si overlay) (c,d).

5. Acknowledgements

Diedrik Vermeulen thanks the Institute for the Promotion of Innovation by Science and Technology in Flanders (IWT) for a grant. W. Bogaerts and G. Roelkens acknowledge the Fund for Scientific Research Vlaanderen (FWO) for a postdoctoral grant. Part of this work was supported by the European Union in the FP7-ICT-HELIOS project.

References and links

1. D. Taillaert, W. Bogaerts, P. Bienstman, T. F. Krauss, P. Van Daele, I. Moerman, S. Verstuyft, K. De Mesel, and R. Baets, “An out-of-plane grating coupler for efficient butt-coupling betweencompact planar waveguides and single-mode fibers,” *IEEE Journal of Quantum Electronics*, vol. 38, no. 7, pp. 949–955, 2002.
2. D. Taillaert, P. Bienstman, and R. Baets, “Compact efficient broadband grating coupler for silicon-on-insulator waveguides,” *Optics letters*, vol. 29, no. 23, pp. 2749–2751, 2004.
3. G. Roelkens, D. V. Thourhout, and R. Baets, “High efficiency grating coupler between silicon-on-insulator waveguides and perfectly vertical optical fibers,” *Optics letters*, vol. 32, no. 11, pp. 1495–1497, 2007.
4. X. Chen, C. Li, and H. K. Tsang, “Fabrication-tolerant waveguide chirped grating coupler for coupling to a perfectly vertical optical fiber,” *IEEE Photonics Technology Letters*, vol. 20, no. 23, pp. 1914–1916, 2008.
5. G. J. Liu, Q. Li, G. L. Jin, and B. M. Liang, “Transfer matrix method analysis of apodized grating couplers,” *Optics communications*, vol. 235, no. 4-6, pp. 319–324, 2004.
6. S. K. Selvaraja, D. Vermeulen, M. Schaekers, E. Sleeckx, W. Bogaerts, G. Roelkens, P. Dumon, D. Van Thourhout, and R. Baets, “Highly efficient grating coupler between optical fiber and silicon photonic circuit.” Lasers and Electro-Optics/International Quantum Electronics Conference, 2009.
7. F. Van Laere, G. Roelkens, M. Ayre, J. Schrauwen, D. Taillaert, D. Van Thourhout, T. F. Krauss, and R. Baets, “Compact and highly efficient grating couplers between optical fiber and nanophotonic waveguides,” *Lightwave Technology, Journal of*, vol. 25, no. 1, pp. 151–156, 2007.
8. J. Schrauwen, F. Van Laere, D. Van Thourhout, and R. Baets, “Focused-ion-beam fabrication of slanted grating couplers in silicon-on-insulator waveguides,” *IEEE Photonics Technology Letters*, vol. 19, no. 11, pp. 816–818, 2007.
9. G. Roelkens, D. Van Thourhout, and R. Baets, “High efficiency silicon-on-insulator grating coupler based on a poly-silicon overlay,” *Optics Express*, vol. 14, no. 24, pp. 11 622–11 630, 2006.
10. G. Roelkens, D. Vermeulen, D. Van Thourhout, R. Baets, S. Brision, P. Lyan, P. Gautier, and J. M. Fdli, “High efficiency diffractive grating couplers for interfacing a single mode optical fiber with a nanophotonic silicon-on-insulator waveguide circuit,” *Applied Physics Letters*, vol. 92, p. 131101, 2008.