

High Efficiency Fiber-to-Waveguide Grating Couplers in Silicon-on-Insulator Waveguide Structures

Günther Roelkens, Jonathan Schrauwen, Dries Van Thourhout, Roel Baets

Photonics Research Group – Ghent University-IMEC

Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium

Gunther.Roelkens@intec.Ugent.be

Abstract: High efficiency fiber-to-waveguide grating couplers were designed in SOI waveguide structures. 66% coupling efficiency can be obtained with a 3dB bandwidth of 85nm. Prototype fabrication reveals 2dB coupling efficiency improvement over standard grating coupler structures.

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1. Introduction

Silicon-on-insulator (SOI) is a promising platform for high density integration of optical functions. This is related to the high refractive index contrast between the silicon waveguide core and the SiO₂ cladding layers ($\Delta n \approx 2$), which allows to fabricate compact optical components. A drawback of the high refractive index contrast is the large mismatch in mode size between the mode of an SOI optical waveguide and the optical fiber mode, making the efficient coupling of light into the integrated optical circuit an important issue. One-dimensional [1] and two-dimensional [2] grating coupler structures were proposed to couple light from an optical fiber into a high refractive index contrast optical waveguide. The standard grating coupler structures proposed in literature only have a moderate fiber coupling efficiency in the range of 20% to 30% however, which is insufficient for practical applications. This low coupling efficiency is intrinsic to the grating structure used in these cases, as an important fraction of the optical power is diffracted towards the silicon substrate and is therefore lost. There are several approaches reported in literature to increase this coupling efficiency. In [3] a gold bottom mirror was added to redirect the downwards diffracted light. In [4], a slanted grating structure was used to increase the directionality of the grating structure. While these approaches result in a high coupling efficiency to fiber, the fabrication process is not CMOS compatible or at least very complex. Therefore, an alternative approach to increase the fiber coupling efficiency is developed here, for which the fabrication only relies on standard CMOS technology.

2. Proposed grating coupler structure

A waveguide layer structure with a 220nm silicon waveguide layer thickness and a 2 μ m buried oxide layer thickness is assumed. This layer stack allows fabricating mono-mode optical waveguides with high omni-directional refractive index contrast. While standard grating coupler structures are defined by etching a grating structure in this waveguide layer [3], the alternative approach we propose in this paper is to locally deposit a silicon layer in the grating coupler region prior to the etching of the grating. This allows more flexibility in the design of the grating coupler structure, leading to a dramatic increase in fiber coupling efficiency as will be discussed later. The addition of this silicon layer can be obtained by epitaxial growth or the local deposition of a poly-crystalline or amorphous silicon layer, which are all standard CMOS processes. The proposed grating coupler structure is schematically depicted in figure 1. The optical fiber is slightly tilted off vertical to avoid a large second order reflection of the grating coupler structure, which significantly reduces the fiber coupling efficiency. The optical fiber is assumed to be AR-coated for 1.55 μ m to avoid reflections at the fiber/air interface. This can also be achieved by adding an index matching glue between the fiber and the grating coupler structure.

3. Device optimization

In order to optimize the grating coupler structure for efficient fiber coupling, the grating directionality (being the ratio of the fraction of optical power that is diffracted towards the optical fiber to the total diffracted power) needs to be maximized while the grating coupling length needs to be optimized. Indeed, when the fundamental waveguide mode is launched in the 220nm waveguide layer, the upwards diffracted field profile can be written as

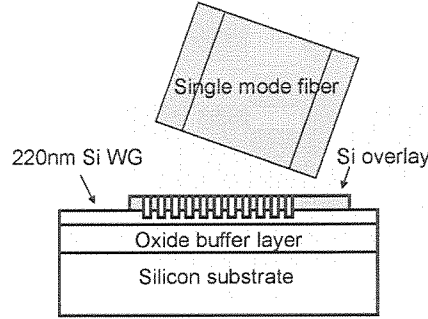


Fig. 1. Proposed grating coupler structure

$$E_{diff} \propto \sqrt{\frac{D}{L_d}} \exp\left(-\frac{z}{2L_d}\right) \quad (1)$$

in which D is the directionality of the grating structure, L_d the grating coupling length and z the distance from the edge of the grating coupler structure. Assuming a Gaussian mode profile of the optical fiber mode

$$E_{fib} \propto \frac{1}{\sqrt{w}} \exp\left(-\frac{(z-\mu)^2}{w^2}\right) \quad (2)$$

the overlap integral between both field profiles can be maximized by optimizing the center position μ of the optical fiber and grating coupling length L_d for an optical fiber with a given width parameter w and a grating with directionality D . For a single mode optical fiber with a width parameter w of $5.2\mu\text{m}$, the overlap integral is maximally $0.81D$ for a grating coupling length L_d of $3.85\mu\text{m}$.

In order to optimize the grating coupler structure, the Bloch mode supported by the periodic grating structure was assessed for various design parameters. A grating duty cycle of 50% was assumed, while the total waveguide layer thickness and the etch depth is varied. Both the directionality and the power attenuation length of the Bloch mode (which is identical to the grating coupling length) are calculated. The results are plotted in figure 2a for a total silicon waveguide thickness of 220nm, 290nm, 370nm and 440nm respectively. A grating period Λ of 610nm, a wavelength of $1.55\mu\text{m}$ and TE polarization is assumed, together with an infinite thickness of SiO_2 bottom cladding and air top cladding. Calculations were performed using a two-dimensional fully vectorial eigenmode expansion tool with PML absorbing boundary conditions. From this figure, the improvement of the grating coupler directionality compared to the standard grating structure (corresponding to the 220nm case in figure 2a) is impressive. An optimal performance is obtained for the 370nm silicon waveguide thickness case with an etch depth of 220nm, for which the optimal attenuation length coincides with the highest directionality of the grating structure. These parameters lead to a diffracted field that is tilted 10 degrees off vertical. While the Bloch mode properties can be optimized for maximum directionality and optimal attenuation length, the excitation of this Bloch mode from a standard waveguide also has to be maximized. As the diffracted field is sufficiently tilted off vertical a large second order reflection can be avoided. In figure 2b the influence of the waveguide height of the exciting waveguide on the fiber coupling efficiency is plotted as calculated by two dimensional FDTD. A maximum coupling efficiency is obtained in the case of a 220nm SOI waveguide thickness exciting the optimized grating structure with total silicon layer thickness of 370nm and an etch depth of 220nm. A fiber-to-waveguide coupling efficiency of 66% can be obtained.

4. Prototype fabrication

A prototype of the optimized fiber coupling structure was fabricated, by local deposition of a 150nm thick amorphous silicon layer on an SOI waveguide substrate with a silicon waveguide layer thickness of 220nm. The silicon was deposited by electron gun evaporation and using a lift-off technique. After deposition of the silicon layer, the grating structure was defined using focused ion beam etching (FIB), etching 220nm deep into the layer stack.

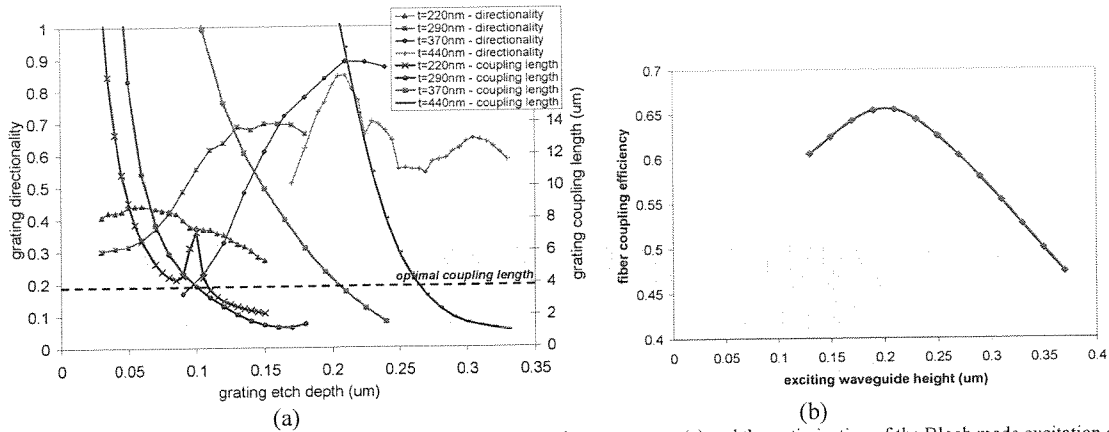


Fig. 2. Investigation of the grating coupler Bloch modes for various design parameters (a) and the optimization of the Bloch mode excitation of the optimal grating coupler structure by varying the exciting waveguide height (b)

A grating period of 610nm and a duty cycle of 50% was used. An SEM image of a grating coupler structure fabricated by FIB is shown in figure 3a, while in figure 3b the obtained fiber coupling efficiency spectrum is plotted, compared to the fiber coupling efficiency spectrum of an optimized grating coupler structure in the 220nm thick silicon waveguide layer, defined using 248nm deep UV lithography and plasma-etching (corresponding to the $t=220\text{nm}$ case in figure 2a). An improvement of 2dB in fiber coupling efficiency can be observed. The shift of the wavelength spectrum is related to the difference in refractive index between the amorphous silicon and the crystalline silicon (which was not taken into account in the design). While an improvement in fiber coupling efficiency of 2dB was observed, this experimentally obtained efficiency is still substantially lower than the theoretically expected coupling efficiency of -1.7dB (66 percent) as predicted above. This discrepancy is probably related to the large optical absorption of the amorphous silicon, the damage induced into the material by the focused ion beam etching and the incorporation of gallium ions in the silicon host, substantially increasing the optical loss and can be avoided by using standard CMOS technology for the fabrication of the structures.

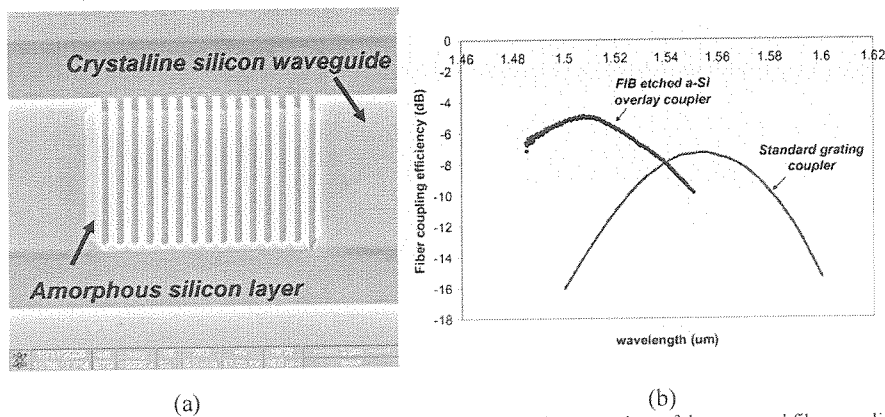


Fig. 3. SEM picture of the fabricated prototype grating coupler structures (a) and a comparison of the measured fiber coupling efficiency spectrum and the measured fiber coupling efficiency spectrum of an optimized grating coupler structure fabricated in the 220nm SOI layer (b)

4. References

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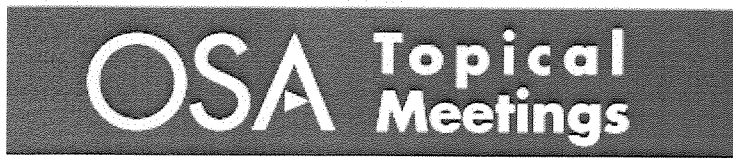
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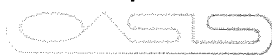
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