SOI grating structure for perfectly vertical fiber coupling

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Abstract: *We present the design of a grating coupler structure allowing efficient coupling to a perfectly vertically positioned single mode fiber. This design no longer implies tilting of the fiber to avoid a large second order reflection, reducing the cost of packaging. By incorporating a slight asymmetry in the grating structure design, a grating fiber coupling efficiency of 50% to single mode fiber and 65% to high numerical aperture fiber can be obtained, with a 3dB bandwidth of 55nm. Constraints in the design are related to the manufacturability using 248nm deep UV lithography. The fabrication tolerance of the device is assessed, which is compatible with the state-of-the-art Silicon processing techniques.*

Introduction

Silicon-on-Insulator (SOI) is emerging as the platform for large scale integration of optical functions due the high omni-directional refractive index contrast between the Silicon core (n_{Si}=3.476) and the SiO_2 cladding (n_{SiO2}=1.447). Moreover, standard CMOS technology can be used to fabricate these photonic integrated circuits, increasing the reproducibility and yield, and lowering the cost of fabrication due to the economy of scale [1]. An inherent drawback of the high omni-directional refractive index contrast is however the large mismatch in mode size between the SOI waveguide and the single mode fiber, making efficient optical coupling to the photonic integrated circuit a non-trivial task. A promising approach is the use of a grating structure to couple the light from a single mode fiber into the photonic integrated circuit. This approach allows wafer scale testing of the integrated circuit as no polished facet is required for coupling [2]. Although one-dimensional grating structures behave very differently for TE and TM polarization, two-dimensional grating structures can be used to tackle this problem by using a polarization diversity approach [3]. Several grating designs are described in literature, both based on vertically etched slits in the Silicon waveguide layer [2] as on slanted grating structures [4]. While the latter directly enable the use of a perfectly vertically oriented optical fiber, the definition of the angled slits is not compatible with standard CMOS processing. Recently, we showed that high coupling efficiency to optical fiber can be obtained using vertically etched slits by optimizing the grating design [5]. A uniform grating structure exhibiting a fiber coupling efficiency of 66% was designed, while using a non-uniform grating structure 78% coupling efficiency could be obtained. The coupling efficiency was in this case dramatically improved by locally adding a Silicon epitaxial layer on top of the 220nm thick single mode Silicon waveguide layer prior to grating etching. However, these designs relied on slightly tilting the optical fiber with respect to the vertical axis (typically 10 degrees off vertical). This was required to avoid a large second order Bragg reflection back into the SOI waveguide in the case of perfectly vertical coupling, which dramatically reduces the fiber coupling efficiency. This can also be understood from symmetry considerations, as equal coupling efficiency in both exit waveguides of the grating structure is obtained when perfectly vertically illuminating a uniform grating structure, resulting in an absolute maximal fiber coupling efficiency of 50%. The requirement of the slight tilting of the optical fiber has important consequences for practical applications, which would require angled polishing of the fiber ferrule and mounting of the ferrule under an angle with respect to the photonic integrated circuit normal direction [6]. In order to avoid this costly complication in the packaging of the photonic integrated circuit, the possibility for perfectly vertical coupling in an efficient way is assessed here, by designing an asymmetric grating structure in order to avoid the large second order Bragg reflection. The grating structure can be made asymmetric by tailoring the width and pitch of the individual grating teeth. This is however not interesting from a fabrication point of view, as the practical realization of these type of structures is hampered by the different etch rate for slits with a different width and optical proximity effects in the lithographic definition of the non-uniform grating structure. In this paper, we will combine the previously mentioned approach of locally adding a Silicon epitaxial layer to improve the fiber coupling efficiency and incorporating an asymmetry in the grating coupler structure to avoid the large second order Bragg reflection, while maintaining a uniform grating structure in which all slits are identical in width and etch depth.

Proposed device structure

The structure we propose to allow efficient vertical fiber coupling is schematically depicted in figure 1. A 220nm Silicon waveguide core layer on top of a 2μm buried SiO_2 layer is assumed. Locally, a Silicon epitaxial layer of thickness *t* is grown in order to in-

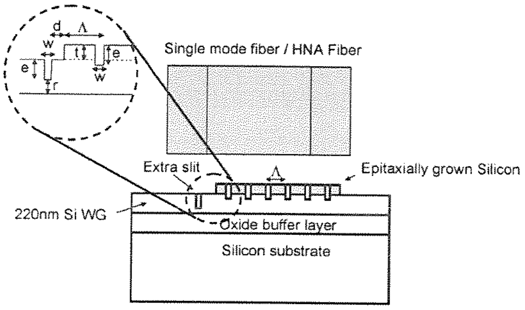

Fig. 1: Layout of the proposed fiber coupler structure together with a definition of the different parameters of the design

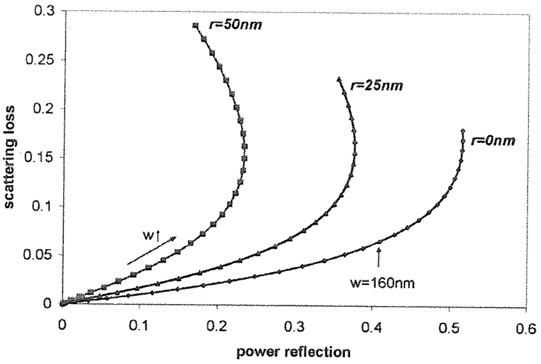

Fig. 2: Scattering loss of a single slit in a 220nm SOI waveguide as a function of the power reflection for various slit widths and etch depths

crease the directionality of the grating (being the ratio of the upwards diffracted optical power to the total diffracted power) as explained in [5]. The asymmetry in the grating structure is created by etching one additional slit in the 220nm thick Silicon waveguide layer instead of in the thicker epitaxial layer stack. This slit will function as a partially reflecting mirror to achieve destructive interference of the second order Bragg reflection from the uniform grating structure.

Optimization of the device structure

The grating structure was optimized using CAMFR [7], a two-dimensional fully vectorial eigenmode expansion tool. A wavelength of 1.55μm and TE polarization is assumed. As mentioned before, these grating structures are very polarization dependent, a problem that can be circumvented using a two-dimensional grating for polarization diversity operation [3]. Therefore, we will only discuss the results for TE polarization here. An analogous approach can be followed for two-dimensional grating structures. The behaviour of the etched slit in the 220nm thick Silicon waveguide layer as a partially reflecting mirror was assessed by calculating power reflection and scattered optical power as a function of the slit etch depth, using the slit width *w* as a parameter. Results are shown in figure 2 for three different etch depths, corresponding to *r*=0 (etched through the Silicon waveguide layer), *r*=25nm and *r*=50nm. From this simulation it is clear that the completely etched through slit offers the largest reflection for a given acceptable scattering loss. Therefore, in the subsequent analysis, the slit is assumed to be etched completely through the 220nm Silicon waveguide layer. This assumption also fixes the slit etch depth in the uniform grating structure to 220nm, for ease of fabrication as explained above. In order to keep the scattering losses low while maintaining a sufficient reflection, the minimum definable slit width using 248nm deep UV lithography of 160nm was chosen for the design. This then also fixes the slit width *w* of the diffractive grating structure in the thick Silicon layer stack to 160nm. In a second step of the optimization, the thickness of the epitaxially grown Silicon *t* and the period of the grating structure Λ were optimized to achieve diffraction in the vertical direction at 1.55μm while maximizing the directionality (the ratio of upwards diffracted optical power to the total diffracted power) of the grating at this wavelength. This can be done by evaluating the Bloch modes at the Γ-point supported by the periodic grating structure and assessing the directionality of these leaky modes. Optimal directionality and vertical coupling at 1.55μm was obtained for a Silicon epitaxial layer thickness *t* of 150nm and a grating period Λ of 560nm. The electric field of this TE Bloch mode is plotted in figure 3. The directionality of the optimized grating structure is higher than 80%. In order to appreciate the influence of the additional slit on the fiber coupling efficiency, the symmetric grating structure without the additional slit was simulated first. The fundamental TE mode at 1.55μm was launched in the SOI waveguide and the scattering by the grating structure was evaluated. In order to obtain the coupling efficiency to a single mode optical fiber, the electric field $\mathbf{E}_{scat}$ at a certain distance above the grating structure was evaluated and the overlap integral of $\mathbf{E}_{scat}$ and a Gaussian beam, with its mode field diameter ($1/e^2$ intensity width) as a parameter, was evaluated. This was done for various center positions of the Gaussian beam profile, thereby obtaining the optimal position of the optical fiber, the optimal mode field diameter and the maximum achievable fiber coupling efficiency. For the uniform grating structure without the additional slit and the parameters mentioned above, a fiber coupling efficiency of 33% and 26% is obtained for a mode field diameter

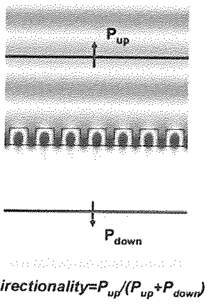

Fig. 3: Electric field of the vertically leaky Bloch mode with optimized directionality

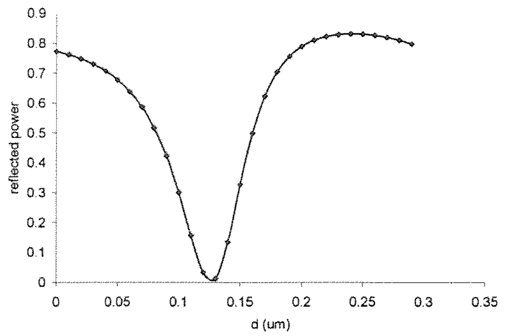

Fig. 4: Influence of the extra slit distance *d* on the power reflection in the SOI waveguide

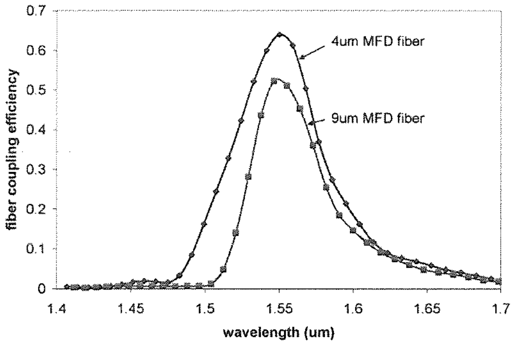

Fig. 5: Optimized fiber coupling efficiency as a function of wavelength for a 4μm and 9μm mode field diameter fiber

of 4μm and 9μm respectively. Reduced mode field-diameters can be obtained by splicing a high numerical aperture fiber to a single mode fiber with low optical loss at the splice [8]. This low coupling efficiency is, as mentioned above, due to the large second order Bragg reflection (55% in this case). In order to achieve destructive interference of this reflection in the proposed design, the distance *d* between the slit and the edge of the thickened layer stack needs to be optimized. The power reflection as a function of the distance *d*, for the parameters mentioned above, is plotted in figure 4. This simulation shows that nearly perfect destructive interference can be obtained by choosing an optimal distance *d* of 0.13μm. Using this optimal set of parameters, the coupling efficiency can be reassessed. The wavelength dependence of the fiber coupling efficiency is plotted in figure 5 for the case of a 4μm and 9μm mode field diameter fiber, showing that a fiber coupling efficiency of 65% and 50% can be obtained respectively, with a 3dB bandwidth of approximately 55nm, while the 1dB bandwidth is about 35nm. This implies a 3dB improvement in coupling efficiency over the symmetric grating structure. A field plot of the optimized structure, when illuminated by the 4μm diameter high numerical aperture fiber is shown in figure 6.

Fabrication tolerance analysis

In order to assess the manufacturability of the device using standard 248nm deep UV lithography, the influence of deviations from the optimized design on the fiber coupling efficiency spectrum was evaluated. To see where deviations can originate from, an overview of the proposed processing scheme for the device is shown in figure 7. After deposition of an SiO_2 hard mask, Silicon is epitaxially grown in an opened window. After epitaxial growth, the grating structure is lithographically patterned in a photoresist layer and etched into the Silicon. By optimizing the exposure dose and applying a proximity correction to the grating structure on the mask, the dimensions of the fabricated slits can approach the optimal values. The epitaxial growth and the etching process are time based processes and a typical deviation of +/- 10nm from the targeted values can be expected. Moreover, the alignment of the grating with respect to the

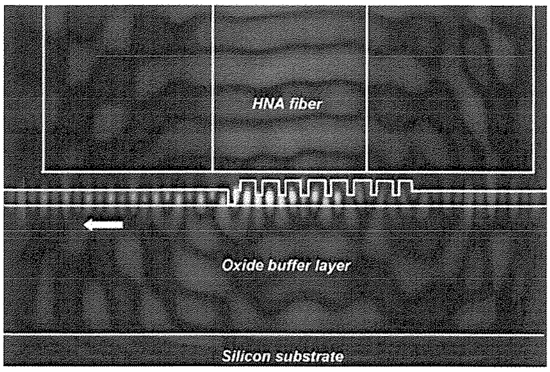

Fig. 6: Electric field plot of the optimized structure for a 4μm mode field diameter fiber

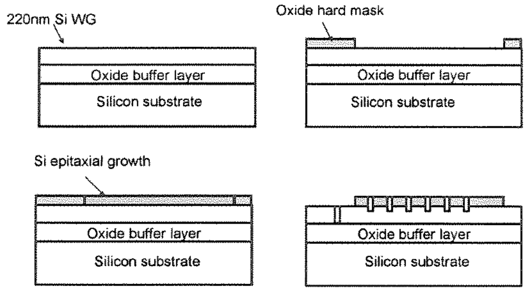

Fig. 7: Proposed processing sequence for the device

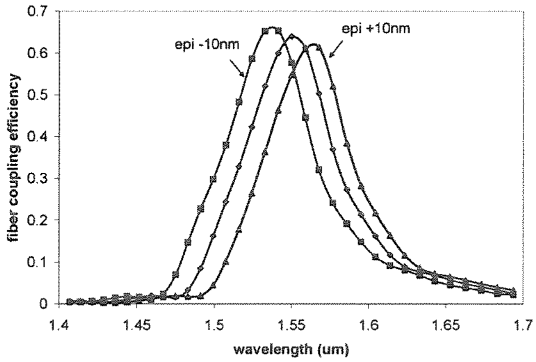

Fig. 8: Influence of a +/-10nm error of the epitaxial layer thickness on the fiber coupling efficiency spectrum (4μm mode field diameter fiber)

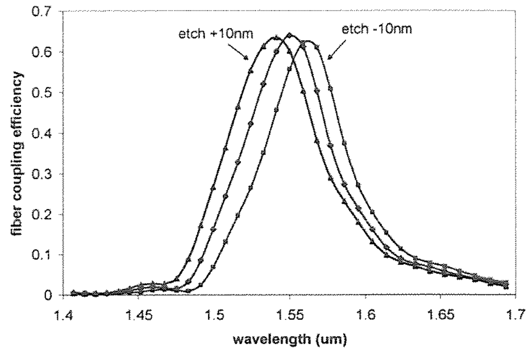

Fig. 9: Influence of a +/-10nm error of the slit etch depth on the fiber coupling efficiency spectrum (4μm mode field diameter fiber)

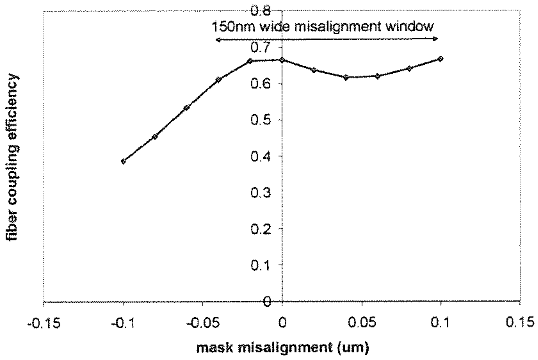

Fig. 10: Influence of the mask misalignment on the obtainable fiber coupling efficiency for a 4μm mode field diameter fiber

window of epitaxially grown Silicon can vary. Typically, an alignment accurary of +/-50nm can be obtained. Finally, a non-optimal position of the optical fiber results in a decrease in fiber coupling efficiency. The influence of a +/- 10nm variation on the epitaxial Silicon thickness *t* and the grating etch depth *e* is plotted in figure 8 and 9 respectively. As the additional slit is etched completely through the Silicon waveguide layer, reaching the SiO_2 etch stop layer, this additional slit cannot be overetched. From these simulations we can conclude that these deviations mainly result in a shift in the wavelength spectrum. In figure 10, the influence of misalignment of the epitaxial Silicon window and the grating structure on the fiber coupling efficiency at 1.55μm is plotted. From this simulation it is clear that there is a sufficiently large window for high efficiency coupling. The influence of the position of the optical fiber on the fiber coupling efficiency is plotted in figure 11. Although a higher coupling efficiency can be obtained for the reduced mode field diameter fiber, alignment tolerances are stricter in this case.

Conclusions

In this paper we developed a Silicon-on-Insulator grating structure for efficient coupling to a vertically positioned optical fiber. A 3dB improvement over a symmetric structure is obtained. While this improvement can decrease the cost of packaging of a photonic integrated SOI circuit, it can also be used for other purposes, for example to efficiently couple light from a flip-chipped VCSEL into an SOI waveguide circuit, using the same grating. While this paper deals with the optimization of a one-dimensional grating structure, the same principle can be used in two-dimensional grating structures for polarization diversity.

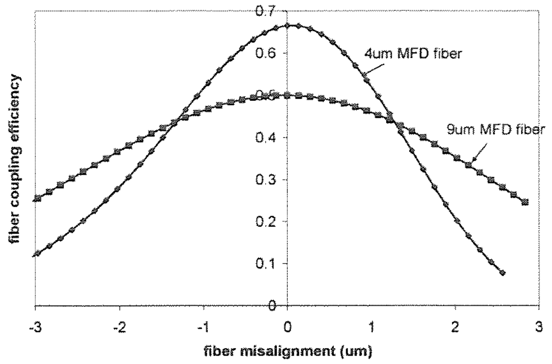

Fig. 11: Influence of a fiber misalignment on the obtainable fiber coupling efficiency for a 4μm and 9μm mode field diameter fiber

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