Efficient grating couplers for Ge-on-Si and Ge-on-SOI platform in the 5μm wavelength range

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We present the design of fiber-to-chip grating couplers on Germanium-on-Silicon (Ge-on-Si) and Germanium on silicon-on-insulator (Ge-on-SOI) waveguides in the 5μm wavelength range. The best TM and TE grating couplers for Ge-on-Si have a coupling efficiency of 40% and 16% respectively with 3dB bandwidths of 180nm and 220nm at a central wavelength around 5.3μm. The best grating couplers for Ge-on-SOI have a coupling efficiency of 70% for the TM mode and 60% for the TE mode. The higher coupling efficiency to Ge-on-SOI waveguides is attributed to the strong reflection at the Si/air interface of the free-standing grating, which can be optimized for maximum coupling efficiency.

Introduction

In the recent years, Ge-on-Si has emerged as a platform of interest for sensing applications beyond 4μm [1, 2]. Ge has reasonable losses for light in 4-12μm range which makes it suitable for realization of mid-infrared (midIR) PIC gas and liquid sensors. The Si substrate makes this platform compatible with CMOS/MEMS processes and therefore low cost when it comes to mass production which is essential for a number of sensing applications. In order to detect different gases, it is necessary to provide wavelength tuning over a wide range of the spectrum. For our application, we have opted for thermal tuning. Since Si has shown to be an excellent heat sink, a buffer layer has to be envisaged to prevent heat losses to the substrate. Ge-on-SOI finds its purpose here as the silicon oxide (SiO_2) layer can be accessed through narrow openings in the Si layer and etched such that the area around the heater is left locally free-standing [3]. The rest of SiO_2 layer serves as support such that the free-standing structures would not collapse (Fig. 1a).
In order to further reduce the cost of these integrated sensors and enable wafer level optical testing, efficient TE and TM grating couplers are needed. In this paper we present efficient grating couplers for the Ge-on-Si and Ge-on-SOI platforms. Couplers are designed for a thick Ge waveguide layer expected to support single-mode operation for 2.2μm wide waveguides around 5.3μm wavelength. All simulations of couplers are done with 2D FDTD.

Coupler Design and Simulations

The main limiting factor of the performance of grating couplers is directionality. This is the portion of the light power scattered towards the optical fiber normalized with respect to the total optical power in the system. The Ge-on-Si platform has low directionality due to the small refractive index contrast between the two materials. A commonly used solution for reflecting a substantial portion of the light towards the fiber is using a metal

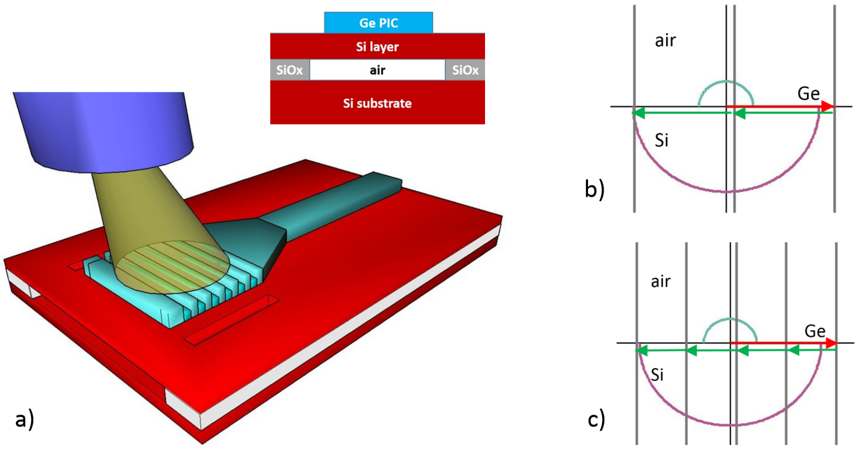

Figure 1: a) Implementation of locally free-standing gratings on the Ge-on-SOI platform b) vector diagram of II order and c) IV order gratings

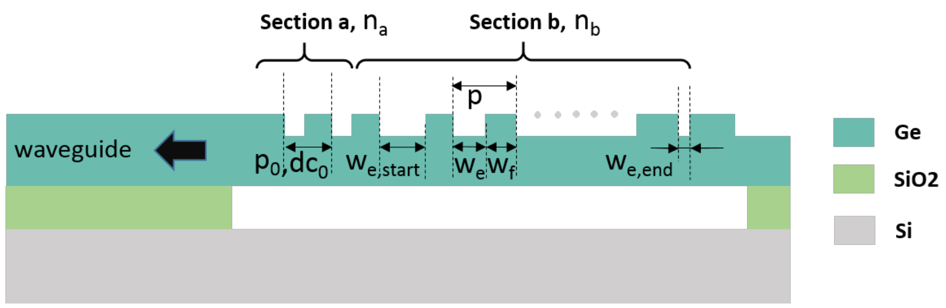

Figure 2: Vertical cross section of a grating coupler - Section a and b represent two parts of the coupler - a section with constant duty cycle and apodized section respectively

mirror under the grating. Although highly efficient, this type of couplers are not CMOS-compatible and furthermore complicate processing. According to our simulations our designs on the Ge on SOI platform achieve efficiencies comparable with the grating couplers with metal reflectors. This is because we can put to use the layered structure of the substrate - light sent downwards is reflected on the interfaces between layers and redirected up towards the fiber. In our design we have fixed the thickness of the SiO_2 layer to 2μm, while the thickness of the Si layer can be optimized. However the thickness of the Si layer in the Ge-on-SOI platform needs to have minimal value such that the waveguide mode does not overlap with the lossy SiO_2. The Si-SiO_2 interface has a reflectance $R_{Si-SiO_2} = (\mathrm{n}_{Si} - n_{SiO_2})^2/(n_{Si} + n_{SiO_2})^2 = 17\%$ while the Si-air interface reflects 30% of light. This implies that under-etched grating couplers on a Si-air-Si substrate have better performance than grating couplers on a Si-SiO_2-Si substrate, hence we opted for a locally free-standing design shown in Fig. 1a.
In our work we focused on II and IV order gratings whose vector representations are shown in Fig. 1b,c respectively. The bottom cladding, Si, supports propagation of several different orders, especially for the IV order gratings. Nevertheless, by carefully designing the coupler and with the use of the layered structure of the Ge-on-SOI platform, we can optimize the excitation of the fundamental waveguide mode.

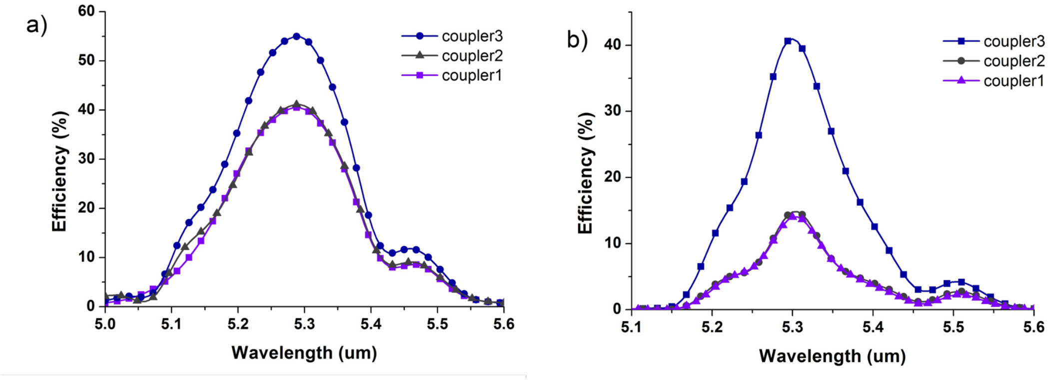

Figure 3: (a) Optimized II order Ge-on-Si grating coupler - coupler 1, Ge-on-SOI coupler - coupler2 and locally free-standing version of coupler2 - coupler 3 for TM polarization and (b) optimized II order Ge-on-Si grating coupler - coupler 1, Ge-on-SOI coupler - coupler2 and locally free-standing version of coupler2 - coupler 3 for TE polarization (b)

When designing a simple grating coupler, we optimized the period of the gratings to ensure that maximal coupling is achieved as close as possible to the central wavelength of interest. We additionally optimized the duty cycle and the etch depth of the gratings to achieve the best directionality of our structure and maximum overlap of the diffracted field profile with the fiber mode. Other parameters taken into consideration are the angle between the fiber and the vertical y-axis, and the position of the fiber on the x-axis parallel to the grating. The number of grooves was kept constant at 30. In order to increase ratio of the part of light coupled to the fiber and the part of light diffracted towards the fiber, we have implemented apodization where etched feature w_e changes in linear manner from $w_{e,start}$ to $w_{e,end}$ and w_f is determined by:

$$0.5 * p = w_e * n_e + w_f * n_f$$

where p is period of corresponding grating coupler with the same etch depth when duty cycle is constant and equal to 0.5, optimized for the corresponding fiber angle. n_e is the index in the etched Ge slab and w_f and n_f are the width and index in the slab of the unetched part of the grating. Another feature that we used in the design of the IV order TM grating is having a few grooves with uniform duty cycle dc_0 and period p_0 in the beginning of the grating which will make the perturbation in the waveguide caused by the grating less abrupt and reduce reflection caused by scattering when coupling from the PIC to the fiber. This section is marked as *Section a* in Fig. 2. The sections a and b are designed in such a manner that the grating is realized in a single etch step.

II order grating couplers

II order gratings can have two orders of diffraction. The second order reflects light back, and the first order scatters light vertically up and down. Working with detuned gratings allows us to minimize, even eliminate the reflected portion of the light by diffracting vertically into the fiber under a small angle. However, this does not prevent the light from diffrancting towards the substrate.

The best simulated TM coupler for Ge-on-Si has a period of 1.48μm and an etch depth of 0.9μm, $w_{e,start} = 0.3\mu$m, $w_{e,end} = 0.5\mu$m with a coupling efficiency of 40% for TM polarization and a 3dB bandwidth of >180nm. The II order grating designed as a Ge-on-SOI coupler (without the locally under-etched SiO_2 layer) does not seem to improve the performance a great deal as the maximum efficiency is 40% for a Si thickness of 3.6μm. It is only by making the grating free-standing that we see significant change in coupling efficiency to 55% (Fig. 3a). This is due to the previously mentioned larger reflection at the Si-air interface as compared to the Si-SiO_2 interface. The optimal angle for the fiber is found to be 6^o.
The optimized TE Ge-on-Si coupler has efficiency of 16% and 80nm 3dB bandwidth, with parameters: 1.42μm period, 0.7 duty cycle and 0.9μm etch depth (Fig. 3b). Here the apodization did not improve the efficiency, hence we opted for simple design. Optimal fiber angle is 3^o. The best Ge-on-SOI coupler has the same parameters with similar coupling results, while with local under-etching we have an efficiency over 40% at the expense of only 130nm 3dB bandwidth. The fiber angle is kept the same with a 3.1μm thick Si layer. According to our simulations, a TE Ge-on-Si coupler with 55% coupling efficiency and 160nm 3dB bandwidth can be achieved by implementing a back metal reflector.

IV order grating couplers

IV order grating couplers give very poor performance for the Ge-on-Si platform, however thanks to the interference in the substrate layers of the Ge-on-SOI platform, they have shown to be highly efficient implemented as Ge-on-SOI and free-standing Ge-on-SOI couplers. As shown in Fig. 1c, the IV order gratings have the possibility to couple light into several diffraction orders when incident from air. When designed carefully, coupling of light to these diffraction orders, can be suppressed in a great deal.
The optimized coupler has a period of $p = 2.88\mu$m, an etch depth of $h = 0.5\mu$m, with $w_{e,start} = 1.4\mu$m, $w_{e,end} = 0.5\mu$m. *Section a* has $n_a = 2$, a period of $p_0 = 1.8\mu$m and a duty cycle of $dc_0 = 0.5$. The thickness of Si layer in this case is 3.2μm. The Ge-on-SOI coupler with these parameters has the coupling efficiency of 36% and a 3dB bandwidth of 210nm, while the free-standing version of the same coupler has a maximum efficiency over 70% and matching 3dB bandwidth (Fig. 4a). The angle of the fiber is 10^o.
The IV order TE grating couples best under a fiber angle of 10^o. This coupler is also apodized with *Section b* parameters $p = 2.92\mu$m, $h = 1.0\mu$m, $w_{e,start} = 1.6\mu$m and $w_{e,end} = 0.8\mu$m. Maximum efficiency for the locally free-standing Ge-on-SOI structure is 62% and for the Ge-on-SOI this value is 47%. The 3dB bandwidth is 160nm in both cases (Fig. 4b).

Conclusion

In this work we have shown optimized Ge-on-Si and efficient Ge-on-SOI grating couplers. We have proposed a new design for improving directionality of grating couplers by locally under-etching the Ge-on-SOI couplers. According to our simulations, the best TM and TE grating couplers for Ge-on-Si have a coupling efficiency of 40% and 16% respectively, with 3dB bandwidths of 180 nm and 220 nm respectively. The best locally free-standing grating couplers for the Ge-on-SOI platform have a coupling efficiency of