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INVITED PAPER

Single etch grating couplers for mass fabrication with DUV lithography

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Abstract Surface grating couplers enable efficient coupling of light between optical fibers and planar waveguide circuits. While traditional grating designs require two etch steps for efficient coupling to silicon-on-insulator waveguides, recently proposed subwavelength structured gratings can achieve the same coupling efficiencies with a single etch step, thereby significantly reducing fabrication complexity. Here we demonstrate that such couplers can be fabricated on a large scale with ultra-violet lithography, achieving a 5 dB coupling efficiency at 1,550 nm. Through both simulations and experiments we give physical insight on how pattern fidelity impacts the performance of these couplers, and propose strategies to deal with inevitable process variations.

Keywords Fiber-to-chip grating coupler · Deep ultraviolet lithography · Single etch process

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1 Introduction

Silicon-on-insulator (SOI) is emerging as a major platform for photonic integrated circuits, with applications expanding from telecommunications to optical interconnects (Asghari and Krishnamoorthy 2011), spectroscopy (Cheben et al. 2007), and high-sensitivity biosensing (Xu et al. 2010), among many others. However, fiber-to-chip coupling is challenging for SOI wire waveguides, because of the large size difference between the cores of silicon waveguides ($\sim$450 nm $\times$ 250 nm) and conventional optical fibers ($\sim$8 μm diameter, SMF-28). Surface grating couplers are an effective coupling solution, extracting light from the waveguide and radiating it towards an optical port (such as an optical fiber) situated over the chip (Taillaert et al. 2004). While grating couplers are polarization and wavelength selective, they can be placed anywhere on the chip surface, thus enabling wafer scale testing, and avoiding the need for facet preparation.

Efficient grating-to-fiber coupling requires matching the grating radiated field profile and the optical fiber mode by controlling the grating strength, i.e. the amount of power extracted from the waveguide per grating period. Traditionally grating couplers in SOI have to be shallowly etched (Taillaert et al. 2004), since a full etch produces a grating that is too strong and thus exhibits poor coupling efficiency. However, this approach requires two etch steps to define the fully etched waveguides and the shallowly etched gratings, thus increasing fabrication complexity. In (Halir 2009) we proposed the use of sub-wavelength gratings (SWG) to design grating couplers in SOI with a single, full etch step. As illustrated schematically in Fig. 1a, the SWGs (periodic structure along the x direction) create effective homogenous media with refractive index between silicon and air (Cheben et al. 2010), thereby allowing the adjustment of diffraction strength. Our concept was recently employed by other groups (Chen and Tsang 2009; Liu et al. 2010), including a proposal of polarization independent couplers based on SWGs (Chen and Tsang 2011). In Halir et al. (2010) we experimentally demonstrated that continuously apodized couplers, fabricated with e-beam lithography, yield higher coupling efficiency and lower back reflections compared to uniform couplers, but their fabrication is more challenging. However, SWG based grating couplers have not yet been systematically advanced from exploratory e-beam realizations to CMOS compatible, large scale fabrication. While the feature sizes of such couplers are within the reach of large-scale deep-ultraviolet (DUV) lithography processes, it is so far not understood how the tolerances of these processes affect SWG coupler performance.

Here we give, for the first time, physical insight into the fabrication sensitivity of SWG based fiber-to-chip grating couplers, both in terms of maximum coupling efficiency (η) and peak coupling wavelength (λ_c), showing that large scale fabrication of such couplers is indeed feasible. Based on this we demonstrate a fully etched, SWG based grating coupler for TM polarized light, fabricated with 193 nm DUV lithography with a 5 dB coupling efficiency and a 3 dB bandwidth of 55 nm centered at 1,550 nm.

This paper is organized as follows. In Sect. 2, the specific application of our coupler as well as its structure are briefly described. Section 3 is devoted to numerical simulations of the coupler behavior when its geometrical parameters change. Experimental results are given in Sect. 4, and finally conclusions are drawn in Sect. 5.

2 Application and device dimensions

Fiber-to-chip grating couplers provide an almost universal coupling solution. At the same time, they have a limited bandwidth and are sensitive to the input polarization. Key objectives

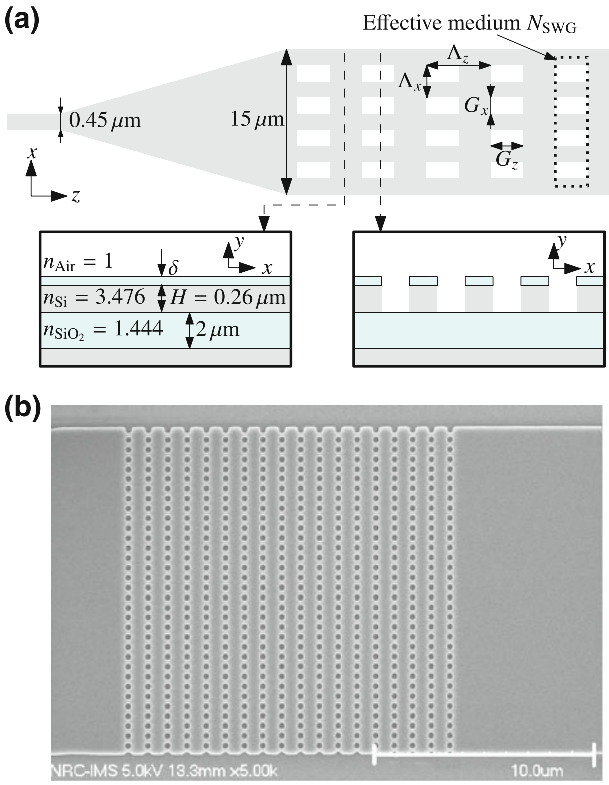


Fig. 1 **a** Schematic illustration of a fully etched SWG based grating coupler, with cross-sectional views of the waveguide and SWG region. Refractive indices are given at $\lambda = 1.55\,\mu$m. A residue layer of oxide etch mask is present on the top. **b** Scanning electron microscope image of one of the couplers fabricated with DUV lithography

for optimization are to maximize the coupling efficiency for the given operating wavelength range and polarization. Here we consider their application for photonic biosensors. Such sensors operate with TM polarization to maximize their sensitivity (Xu et al. 2010), and require efficient coupling around 1,550 nm. Furthermore bio-sensing chips need to be fabricated on a large scale to reduce chip cost. Our study focuses on the DUV based fabrication of the uniform SWG fiber-to-chip grating coupler for TM polarization shown in Fig. 1a. A scanning electron microscope (SEM) image of one of the fabricated couplers is shown in Fig. 1b. The nominal dimensions of the diffractive grating are $\Lambda_z = 840$ nm, and $G_z = 250$ nm, corresponding to a duty cycle of $DC_z = (\Lambda_z - G_z)/\Lambda_z = 70\%$. The SWG structure has a pitch of $\Lambda_x = 300$ nm, and a gap width of $G_x = 150$ nm ($DC_x = 50\%$), which synthesizes an effective refractive index of 2.73. The silicon layer is $H = 260$ nm thick. The grating has 17 periods in the longitudinal (z) direction, and its nominal radiation angle is $11°$ with respect to the grating normal. For the DUV pattern transfer process, we use an oxide layer as the etch mask, of which a residual layer of thickness δ may be left after the etch process. In the following sections we study, by simulation and experiment, how variations in G_x, G_z, H and δ affect the device's coupling efficiency (η) and peak coupling wavelength (λ_c).

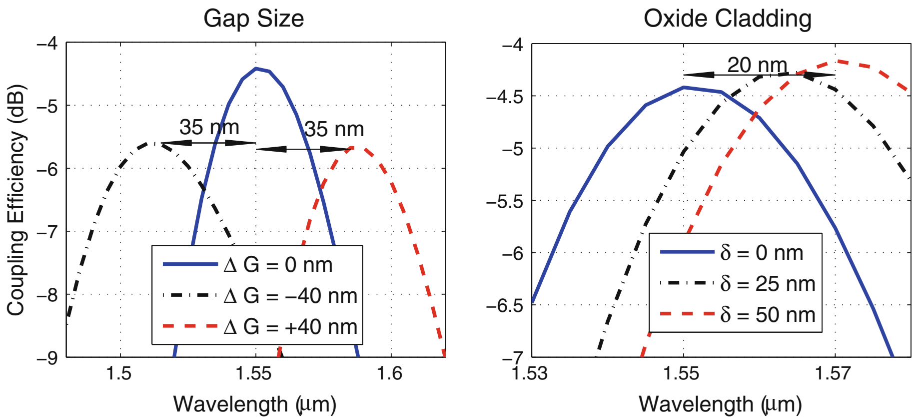


Fig. 2 Simulated effect of variations in **a** the gap size ($\Delta G = \Delta G_x = \Delta G_z$), and **b** residual top SiO_2 thickness (δ) on grating coupling efficiency

3 Simulations

For the theoretical tolerance analysis the 3D grating structure is decomposed into two decoupled 2D models. First, the SWG patterned area enclosed by the dotted rectangle in Fig. 1 is simulated in the xz plane, and the effective medium index, N_{SWG}, is obtained. This index is then used to simulate the grating coupler structure in the yz plane. All simulations were carried out with an in-house tool based on the Fourier eigenmode expansion method (Zavargo-Peche et al. 2012). In (Halir 2009) we validated this approach with 3D finite difference time domain simulations. For all coupling efficiency calculations the optical fiber is aligned with the nominal radiation angle of the grating (11°).

We start our analysis assuming there is no oxide residue on the device, i.e. $\delta = 0$. Figure 2a shows the simulated coupling efficiency of the grating coupler as a function of wavelength, as the size of the air holes in the SWG region is varied ($\Delta G_x = \Delta G_z = \Delta G$). For a $\Delta G = \pm 40$ nm deviation from the nominal dimensions of the air gaps, the coupling efficiency is decreased by $\sim$1.2 dB, and the peak coupling wavelength shifts by approximately $\Delta\lambda = \mp 35$ nm. This yields a sensitivity of $\Delta\lambda/\Delta G \sim -0.87$ nm/nm.

As shown in Fig. 2b, the presence of a residual SiO_2 top layer produces only small variations in coupling efficiency ($\sim$0.2 dB for $\delta = 50$ nm), but it induces an appreciable shift of the peak coupling wavelength. The peak coupling wavelength is red-shifted by $\Delta\lambda = 20$ nm for an oxide thickness of $\delta = 50$ nm, giving a sensitivity of $\Delta\lambda/\delta = 0.4$ nm/nm. Partial removal of this layer can thus be used to adjust the peak coupling wavelength of the device.

Commercial SOI wafers exhibit wafer-to-wafer variations in the silicon layer thickness of the order of $\Delta H = \pm 10$ nm, while variations within a single wafer are usually smaller (Dumon 2007). According to our simulations (not shown in Fig. 2), variations in silicon layer thickness produce significant peak coupling wavelength changes of $\Delta\lambda/\Delta H = 2.5$ nm/nm. However, the coupling efficiency was found to vary only moderately by ± 0.3 dB in the $\Delta H = \pm 10$ nm range. Thus, if the silicon thickness is measured before fabrication, the exposure dose or the silicon oxide residue layer may be used to adjust the peak coupling wavelength.

4 Experiments

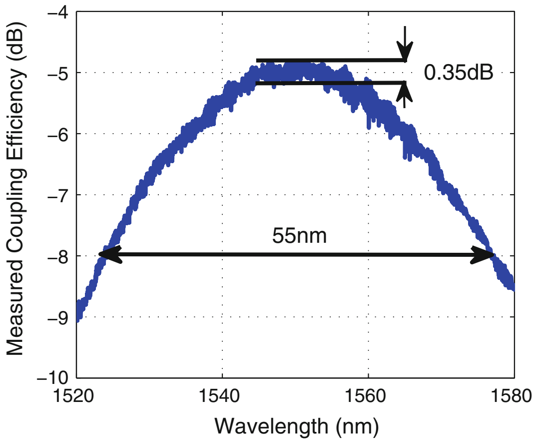
The uniform grating couplers were fabricated by LETI (http://www.epixfab.eu/) using 193 nm DUV lithography, on a $H = 260$ nm thick silicon layer, with a 2 μm bottom oxide. An oxide layer was used as etch mask. The devices were replicated in 40 columns on a 8 inch wafer, and the lithographic exposure dose, E, was swept from 17 to 23 mJ across the wafer, thereby varying the size (G_z and G_x) of the air gaps in the SWG structure in a range of approximately ±40 nm. The gratings were 15 μm wide and 14.5 μm long, and were coupled to the interconnecting single-mode waveguides by a 500 μm long tapered section.

The efficiency of the grating couplers was measured as follows. Two identical grating couplers were arranged in back-to-back configuration, and light was injected with a single mode cleaved optical fiber into one of the couplers and extracted through the other coupler by the output fiber. Both fibers were tilted at 11°. The fiber-to-fiber insertion loss, L, which comprises the coupling losses of the two couplers and the propagation losses of the interconnecting waveguide, L_{Wg}, was recorded as the input wavelength was scanned. The coupling efficiency was then computed as $(L - L_{Wg})/2$, with all quantities expressed in dB. The waveguide losses were determined to be 3 dB/cm, by measuring several identical pairs of couplers with interconnecting waveguides of different lengths. The couplers used for the tolerance analysis had 0.4 cm long waveguides, so that $L_{Wg} = 1.2$ dB.

By measuring the coupling efficiency of gratings with different exposure doses we found the peak coupling wavelength to vary by $\Delta\lambda/\Delta E = -9$ nm/mJ. The size variations of the holes was determined by SEM inspection to be $\Delta G/\Delta E = 13$ nm/mJ. This yields a variation of peak coupling wavelength with hole size of $\Delta\lambda/\Delta G \sim -0.7$ nm/nm, in good agreement with the simulated value of $\Delta\lambda/\Delta G \sim -0.87$ nm/nm. The small discrepancy is attributed to the fact that the length and the width of the gaps does not necessarily change in exactly the same amount as exposure dose is swept.

The fabricated devices were covered with a $\delta \sim 50$ nm thick residual top oxide layer, as measured using ellipsometry. Removal of this layer blue-shifted the peak coupling wavelength by $\Delta\lambda = 20$ nm, indicating a sensitivity of $\Delta\lambda/\delta \sim 0.4$ nm/nm, while reducing coupling efficiency by only ∼0.4 dB. This is in very good agreement with the simulated results. As already shown, the peak coupling wavelength (λ_c) is more strongly affected than

Fig. 3 Measured coupling efficiency of a uniform SWG based grating coupler fabricated with 193 nm DUV lithography. The coupler is from wafer column 5, with an exposure dose of ∼20.7 mJ. A residue oxide layer of ∼50 nm thickness is present



the maximum coupling efficiency (η), particularly by the silicon thickness, H. Therefore the top oxide layer can be used to trim the peak coupling wavelength of the couplers.

Finally, Fig. 3 shows the measured coupling efficiency of a grating coupler with the appropriate exposure dose of ~20.7 mJ. The peak coupling efficiency is 5 dB, close to the simulated efficiency of 4.4 dB (see Fig. 2), and the peak coupling wavelength is 1,550 nm. The coupler exhibits a 3 dB bandwidth of 55 nm. The small ripple (0.35 dB) in the measurements arises from back-reflections between the back-to-back grating couplers, and indicates back-reflections from each coupler well below 3%. This shows that albeit fabrication tolerances of the SWG based coupler are stringent, efficient couplers can be fabricated in high volumes by proper process calibration. Indeed, a nominally identical coupler fabricated with e-beam lithography, yielded a similar performance: a coupling efficiency of ~4.4 dB with back-reflections of 1.5%.

5 Conclusions

We have both experimentally and theoretically analyzed the fabrication tolerances of single etch, SWG based grating couplers. The peak coupling wavelength (λ_c) is more strongly affected than the maximum coupling efficiency (η) by dimensional variations. For a 40 nm variation in the air hole size, λ_c is shifted by 35 nm, while the penalty in η is only 1.2 dB. The thickness of the silicon layer has a strong impact on the peak coupling wavelength, which can, however, be tuned with exposure dose or a residue top oxide layer. We have furthermore shown that by calibration of the lithographic exposure dose, fully etched, SWG based grating couplers with a 5 dB coupling efficiency at 1,550 nm can be fabricated on a large scale with 193 nm DUV lithography.

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