AN APODIZED SURFACE GRATING COUPLER ENABLING THE FABRICATION OF SILICON PHOTONIC NANOWIRE SENSOR CIRCUITS IN ONE LITHOGRAPHY STEP

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ABSTRACT

We present the design, fabrication, and experimental characterization of a silicon surface grating coupler that enables the creation of complete photonic nanowire sensor circuits in a single lithography step on a standard SOI wafer. This advance is achieved without sacrifices in the coupling efficiency through the use of an apodization algorithm that tunes the width of each gap and bar in the grating. This design optimization provides a high light coupling efficiency and a low back reflection with a grating etched fully through the SOI device layer. We experimentally demonstrate a coupling efficiency of 35% on a standard SOI substrate at a wavelength of 1536 nm, and show that with an optimized buried oxide (BOX) thickness, a coupling efficiency of 72% could be achieved.

KEYWORDS

Apodized grating coupler, silicon photonics, photonic nanowire sensor.

INTRODUCTION

Silicon photonic nanowire sensors based on ring resonators [1] and interferometers [2] etched into silicon on insulator (SOI) substrates have shown great utility for the sensing of biomarkers, for example for rapid cancer detection [3]. However, because of the large refractive index contrast between silicon and silicon dioxide, the photonic wire cross-section must have nanoscale dimensions to guarantee single-mode propagation. Thus, because of the mismatch between the size of the propagating mode in the nanowire and the beam diameter of a typical light source, such as cleaved optical fiber, it is challenging to couple light with high efficiency to photonic nanowires.

Figure 1: a) With conventional end-face coupling, the alignment tolerance between a photonic silicon nanowire and a cleaved optical fiber is in the sub-micron range. b) By expanding the nanowire in the plane of the substrate with an adiabatic taper, and etching a grating into the expanded section, the fiber can be placed vertically above the surface, with an alignment tolerance in the micron range.

Surface grating couplers present a promising solution to this problem. Instead of illuminating the nanowire end-face with a cleaved optical fiber (Fig. 1 a), as commonly done with photonic waveguides of larger cross sections, the nanowire is widened by an adiabatic waveguide taper, and a grating etched into the expanded section. The grating diffracts the incoming beam such that the coupling fiber can be placed perpendicular to the surface (Fig. 1 b). By proper design of the taper and the grating, a good overlap between the fiber and waveguide modes can be achieved. Silicon grating couplers have shown coupling efficiency to single-mode optical fibers of up to 70% [4]. However, the inclusion of high performance gratings in a trough-etched silicon photonic sensor circuit has added significant fabrication complexity, e.g. 8 process steps in [4]. Such added complexity increases fabrication cost and thus hinders the application of single-use silicon photonic sensors in health-care applications.

Here, we present a grating coupler that is etched fully through the silicon device layer, thus adding no complexity to the sensor circuit fabrication. To increase the coupling efficiency and to avoid the large back reflections that plague conventional periodic trough-etched gratings, the fill factor of the grating is apodized by algorithmic design optimization.

DESIGN AND FABRICATION

As illustrated in Fig. 2, we calculated the efficiency of coupling from a single-mode silicon photonic nanowire entering the image from the left to a single mode silica fiber placed at a 10° angle to the wafer surface normal. The calculation was performed using the eigenmode expansion technique [5].

First, we designed a conventional periodic grating with an optimal fill factor and etched fully through the 220 nm thick silicon device layer. The fill factor was optimized by an exhaustive search in the (grating period, fill factor) space, at a wavelength of 1550 nm. Fig. 2 a) shows the calculated optical field (E_z) in a cross section of the periodic grating. The picture shows that much light is lost to the left and right of the fiber. Furthermore, the reflection back into the nanowire is 21% in this design. The coupling efficiency from nanowire to fiber was 51%.

Fig. 2 b) shows the same cross section of the optimally apodized grating coupler. The figure shows how the apodization matches the radiated field from the silicon grating to the Gaussian mode profile of the fiber. The apodization increased the coupling efficiency to 72% and reduced the reflection back into the nanowire to 0.1%. A more detailed description of the simulation and design optimization can be found in [6].

Figure 2: a) A cross-sectional view of a conventional periodic through-etched grating with an optimal fill factor. The gray-scale shows the simulated optical field (E_y) when coupling from the photonic nanowire on the left to an optical fiber above the surface. b) The same view of the apodized grating shows how the apodization matches the radiated field to the Gaussian mode profile of the fiber.

Because of interference with the wave reflected back from the BOX/substrate interface, the coupling efficiency depends strongly on the thickness of the BOX. Thus, we designed two apodized devices: one on an optimal BOX of 2.2 μm thickness, and one on a 2 μm BOX, the standard used at the European ePIXfab silicon photonics foundries. As shown in Fig. 3, the coupling efficiency has a strong periodic dependence on the BOX thickness, and the standard BOX of 2 μm is close to the worst-case thickness. The period of the BOX thickness dependence is about 550 nm, as expected for a 1550 nm wave propagating the distance twice in silicon dioxide (refractive index 1.44).

Fig. 4 a) shows a top view of the photonic circuit layout used to evaluate the performance of the grating coupler. It consists of two grating couplers back-to-back, with a photonic nanowire sensor circuit between them. The sensor is a ring resonator.

The photonic circuit was fabricated on an SOI wafer with a 220 nm thick device layer and a standard 2 μm BOX. The circuit was patterned by electron beam lithography, using a Raith 150 system.

Figure 3: The calculated dependence of the coupling efficiency from nanowire to fiber on the BOX thickness for the apodized grating designed for the optimal 2.2 μm BOX thickness.

The negative tone electron beam resist hydrogen silsesquioxane (HSQ) (Dow Corning XR-1541 2%) was exposed with a dose of 270 pC/cm² at a 25 kV acceleration voltage using a 10 μm aperture. Prebake was 2 min at 150°C, followed by 2 min at 220°C. No post-exposure bake was applied. The pattern was developed in 2% concentration TMAH developer for 2 min. To improve etch resistance, the resist was hard baked at 400°C for 40 minutes on a hotplate. Finally, the pattern was transferred into the silicon device layer by dry etching in a Cl₂/HBr/HeO₂ plasma. Fig. 4 b) shows an SEM image of the fabricated device.

Figure 4: a) A top view of the layout used to evaluate the performance of the grating coupler. The ring resonator is included to demonstrate coupling to a sensor. b) An angled SEM close-up view of the apodized through-etched grating coupler. The device was patterned in HSQ by electron-beam lithography and transferred into the silicon layer by etching in a Cl₂/HBr/HeO₂ plasma. The width of each gap and bar is algorithmically optimized in the design process.

EXPERIMENTAL RESULTS

The transmission loss of a SMF-28 fiber patch cord was determined, and the fiber subsequently cleaved. The coupling loss of each grating coupler is then half of the excess loss when coupling in and out the chip using the cleaved fiber. Fig. 5 shows the resulting power transmission through the test structure. The solid curve is the measured transmission spectrum. The dips correspond to resonance frequencies of the ring resonator, and show that light is successfully coupled to the photonic nanowire circuit. A maximum coupling efficiency of 33% is obtained at a wavelength of 1536 nm. The dot-dashed curve shows the simulated spectrum of the apodized design on a 2 μm BOX and the dashed curve shows the simulated spectrum for the grating dimensions obtained in fabrication. The dotted curve shows the simulated spectrum of the apodized design on an optimal 2.2 μm BOX with a maximum transmission of 72% at 1553 nm.

Figure 5: The power transmission through the back-to-back grating coupler structure shown in Fig. 4 a). The solid curve is the measured transmission spectrum of the apodized grating on a standard 2 μm BOX. The dips correspond to resonance frequencies of the ring resonator. A maximum coupling efficiency of 35% per grating is obtained at a wavelength of 1536 nm. The dot-dashed curve shows a simulated transmission of the apodized design on a 2 μm BOX with a maximum efficiency of 33% at 1549 nm, and the dashed curve shows a simulated spectrum for the grating dimensions obtained in fabrication, as measured from an SEM image. The dotted curve shows the simulated transmission curve of the apodized design on a 2.2 μm BOX with a maximum efficiency of 72% at 1553 nm.

Fig. 6 shows an enlarged view on a linear scale of the transmission around the ring resonance at 1542.43 nm, measured with a wavelength resolution of 0.4 pm. By fitting a Lorentzian model to the transmission spectrum, we find that the full width at half maximum is 63 pm, and thus that the loaded Q of the sensing resonator is 25000. Single mode silicon ring resonators with similar Q have recently been demonstrated to have a refractive index detection limit of 7.6×10^{-7} refractive index units [7].

Figure 6: An enlarged view on a linear scale of the transmission around the ring resonance at 1542.43 nm measured with 0.4 pm wavelength resolution. The Lorentzian fit yields a loaded resonator Q of 25000.

CONCLUSIONS

We have demonstrated a high efficiency silicon surface grating coupler design that permits the fabrication of complete photonic silicon nanowire sensor circuits in a single lithography step.

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