Grating couplers for Si_3N_4 waveguides at 900 nm

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***Abstract*— We demonstrate a 1-D grating coupler for silicon nitride wires with an average efficiency of 7 dB in the 890-910 nm wavelength range. The effect of etch depth on the grating efficiency is presented and compared with the theoretical results.**

Keywords-Grating coupler, Silicon nitride ,Silicon photonics, Integrated optics, Fiber coupler

I. Introduction

Grating couplers (GCs) enable efficient coupling from optical fibres to photonic integrated components (PICs) without the need of using lenses or inverted tapers [1]. They avoid expensive methods such as end-polishing and the use of lens fibre to couple light into the waveguides, and also allows wafer level testing of PICs. GCs with high efficiency have been successfully demonstrated for telecom wavelengths and have become a standard practice for coupling light in and out of PICs in silicon photonics [2-3]. However, GCs for a high index contrast (HIC) platform at visible or near-visible IR wavelengths have not been investigated in detail. The visible and near-visible IR bands are important for several applications such as sensing and spectroscopy [4], especially in a biological context given the high penetration depth of light in tissue in these bands. Visible wavelengths also avoid water absorption band which helps in preventing cell damage at high powers. GC-based PICs will help in realizing efficient and easy-to-use integrated spectrometers and sensors. Silicon nitride (Si_3N_4) is a versatile HIC platform for its transparency in both visible and infrared spectrum. Besides it is compatible with the well established CMOS process technology therefore enabling low-cost photonic devices much like in silicon photonics.

In this paper, we present the design, fabrication and theoretical calculations for the GC for Si_3N_4 based PICs in the 890-910 nm band. Finally we report the experimental results on the coupling efficiency and its dependence on the wavelength, coupling angle, and etch depth of the grating.

II. Grating Coupler Design

Design and fabrication of silicon based PICs for telecommunication is well established and standardized. However, silicon cannot be used for visible wavelengths owing to strong absorption below 1.1 µm. Si_3N_4 (n~2.0) is transparent in the visible region and at 900 nm the effective wavelength inside the medium is approximately equal to that of silicon (n~3.5) at 1550 nm. This equivalence makes available the existing standard silicon PIC design and masks (at 1550 nm) to be used for Si_3N_4 applications at 900 nm.

For designing GCs, a cross-section of 220 nm × 450 nm was used to define the core of Si_3N_4 waveguide. For this dimension, Si_3N_4 waveguide was single mode at 900 nm. The two GCs were connected together by 4 mm long waveguide 10 µm wide (at the start and end) and tapered down to 450 nm. The GC period and fill factor (pitch/period) was fixed at 630 nm and 0.55 respectively. The etch depth of GCs (65-220 nm), coupling angle (8^o-12^o) and the wavelength (890-910 nm) were left as free parameters to maximize the coupling efficiency. The gratings were designed for TE polarisation, using CAMFR, an eigenmode expansion tool [5]. The underlying oxide thickness has a major influence on the coupling efficiency. Its value is chosen in such a way that the downward radiated light which gets reflected at the oxide/substrate interface interferes constructively with the direct upward radiated light. This effect is depicted in Fig. 1 for the central wavelength (900 nm) of the coupler. Based on this result the oxide thickness was fixed at 2.5 µm.

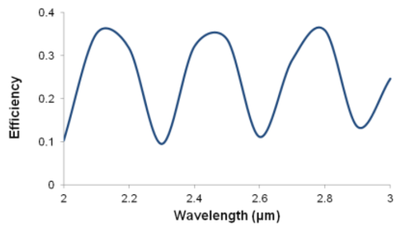

Figure 1. Effect of buried oxide thickness on the coupler efficiency

III. Fabrication and Characterisation

A. *Si_3N_4 deposition and grating fabrication*

For the fabrication, 200 mm bare Si wafer is used as the substrate. Plasma enhanced chemical vapor deposition is used to first deposit 2.5 µm of silicon dioxide (SiO_2) followed by 220 nm of Si_3N_4. The SiH_4, N_2 and NH_3 gas flow was optimized for Si_3N_4 deposition at 400^oC, which ensured CMOS back-end compatibility. After layer deposition, the waveguide and the GCs were patterned by using 193 nm optical lithography and reactive ion etch process. The waveguide was 220 nm deep etched, and GCs were patterned with different etch depths by controlling the etch duration. Photoresist is used as an etch mask for both the etch processes. After dry etching, the wafers were cleaned by using oxygen plasma and a wet chemical process. Finally, after pattering wafers some of the wafers were covered with 1.5 µm of SiO_2.

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Lastly, the dies were cleaved from the wafer for optical characterization.

B. Optical characterisation of waveguide and GCs

All measurements were performed by coupling light from a tunable laser source (890-910 nm) using single mode fibre into the Si_3N_4 waveguides. Another similar fibre is positioned above the output GC to collect the light and connected to the power meter. Both the fibres were mounted on a goniometer controlled stage to change the tilt angle. The coupling efficiency is determined from the fibre-to-fibre transmission for the TE polarisation. The position of the fibre is optimized for the maximum transmission. The waveguide loss was measured by measuring the change in fibre-to-fibre transmission through spirals of different length (1-7 cm, with bend radius 10 µm).

IV. RESULTS AND DISCUSSION

The average propagation loss in the uncladded and cladded Si_3N_4 wire was measured to be 3.75 dB/cm and 1.9 dB/cm over the wavelength range of 890-910 nm. The GC efficiency was extracted by subtracting the waveguide loss contribution from the total fiber-to-fiber transmission loss. The efficiency was measured for uncladded samples for four different GC etch depths- 65 nm, 95 nm, 145 nm, and 220 nm and each of those was measured at different tilt angles- 8^o, 10^o and 12^o. Fig. 2 shows the GC efficiency variation with respect to the grating etch depth at 909 nm for 10^o tilt angle. There is good correspondence between the theory and experimental results except for the 220 nm etched GC. This discrepancy can be attributed to the high reflection loss for fully etched structures as shown by the calculated reflection loss in fig.2 below.

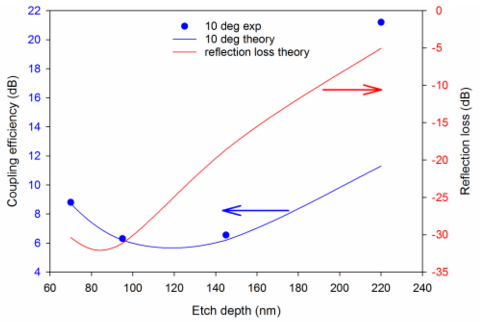

Figure 2. Experimental (blue circle) and theoretical (blue line) coupler efficiency, and reflection loss (red line) vs. etch depth at 909 nm at 10^o angle

The best efficiency was recorded for 100 and 145 nm etch GCs at 12^o and 8^o tilt angle. Fig. 3 shows the GC bandwidth over a 80 nm wavelength span and compares it with the experimental results (890-910 nm) for the variation of GC efficiency at different tilt angles for 100 nm and 145 nm etch depths. Theoretically the best efficiency (4-5 dB) is observed at longer wavelengths (920-930 nm) than used in the experiments. The period of the grating can be optimised to shift the efficiency peak to the desired wavelength range as for the current work the standard SOI GC design was used for the Si_3N_4 GCs as well.The discrepancy between the theory and the experiment (890-910 nm) is attributed to the variation (~250 nm) in the absolute value of the buried oxide thickness leading to reduced efficiency than predicted by the theoretical model. It is equally important to mention here that these experiments were performed without using index matching fluid (IMF) and it is expected that using IMF would reduce the reflection losses and further improve the efficiency. Nevertheless, an efficiency in the range of of 6-8 dB was achieved in the 890-910 nm wavelength range with 145 nm etched GC at 8^o launch angle. It is worthwhile to mention here that Si_3N_4 is a deposited material therefore it is possible to further boost the efficiency to <1.5 dB by depositing a mirror underneath the grating to 100% reflect the downward radiated light [4-5].

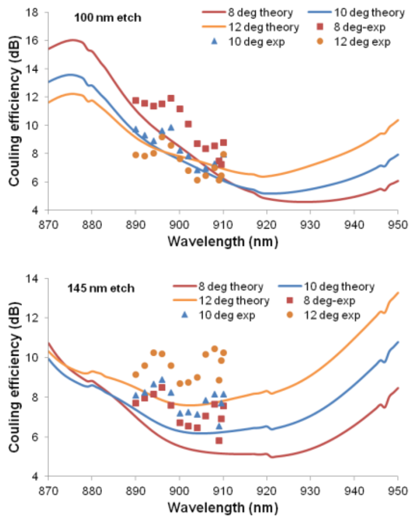

Figure 3. Coupler efficiency vs. wavelength at different tilt angles for 100 nm (top) and 145 nm etched (bottom) GC.

In conclusion, to our knowledge a GC at near-visible wavelengths has been demonstrated for the first time using Si_3N_4 waveguide with an average coupling efficiency of 7 dB.

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