Efficient and Broad Band Coupling between Silicon and Ultra-Low-Loss Silicon Nitride Waveguides

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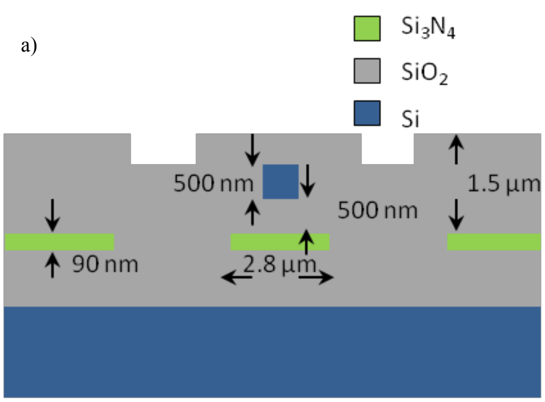
Abstract: We demonstrate a very low loss coupler between a silicon nanowire waveguide and ultra-low loss (less than 2 dB/m) silicon nitride waveguide. Coupling between layers is achieved loss below 0.1 dB per transition over 50 nm of bandwidth.

1. Introduction

The silicon (Si) photonics platform has emerged as a promising candidate to fulfill the rising demand for low-cost and high-volume photonic integrated circuits through utilization of existing mature CMOS manufacturing capabilities. Si is transparent at wavelengths of interest for data transmission, and can be used to produce a wide range of photonic devices [1]. Addition of III-V semiconductors such as indium phosphide (InP) for light emitting devices and advanced photodetectors and modulators is possible by heterogeneous integration via wafer bonding or hybrid integration via co-packaging with completed InP devices [2]. Si is an outstanding material for the production of compact waveguides, owing to its high index contrast. This causes the Si waveguide to be sensitive to surface and sidewall roughness, and decreases its tolerance to waveguide dimensional variations.

Silicon nitride (Si_3N_4) is an alternative waveguide core material that has much lower index contrast than Si, with $\Delta n = 0.6$ compared to silicon dioxide (SiO_2), versus $\Delta n = 2$ for Si. This allows fabrication of waveguides with extremely low propagation loss, below 0.1 dB/m [3]. This makes these waveguides an excellent choice for the production of optical devices which depend on low propagation loss, such as narrow bandwidth spectral filters. However, these devices occupy a much larger footprint due to the drastically increased minimum bend radius compared to Si, and it is currently impossible to produce devices that emit or absorb light in wavelengths of interest for fiber optical communication. In order to fully realize the advantages available from the Si_3N_4 waveguide system, integration with a semiconductor-based photonic platform is necessary.

Addition of dielectric waveguides can be completed by deposition of the waveguide core and cladding material onto a completed Si integrated circuit [4], but low-temperature deposited SiO_2 and Si_3N_4, typically by plasma-enhanced chemical vapor deposition (PECVD), is contaminated due to the presence of hydrogen in the Si precursor gas. The hydrogen creates absorption due to the N-H and Si-H bond resonances [3], and can be mostly removed from the film by high-temperature thermal annealing, typically above 1000°C. This is impossible if the dielectric waveguide is deposited after the production of the Si photonics, as it will cause diffusion of the dopants and metal layers.



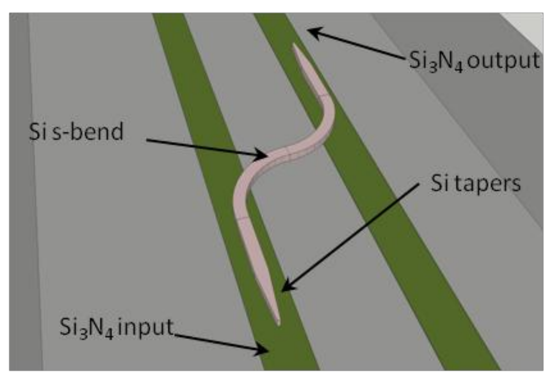


Figure 1: a) Cross section of the coupler region of the device. b) Overview of the taper test structure.

For integration with an ultra-low loss waveguide, the dielectric waveguide must be fabricated first. This allows for deposition of the Si_3N_4 at higher temperature using the low-pressure chemical vapor deposition technique (LPCVD), which produces smoother and more stoichiometric films, and for post-deposition annealing of the Si_3N_4 and SiO_2 films to remove hydrogen. The crystalline Si layer may then be attached to the completed Si_3N_4 circuit by wafer bonding. The wafer is then in principle a silicon-on-insulator (SOI) wafer, and may be processed to produce

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the Si devices using high-volume manufacturing processes. The cross section of the device is shown in **Error! Reference source not found.**a.

2. Experiment

Coupling between the layers may be achieved through a variety of means, but to ensure broad spectral bandwidth operation, the best approach is through a lateral taper of the Si waveguide. This approach has been demonstrated previously [5][6], but restraints on the feature size of the taper tip limited the performance of the device. Specifically, the taper tip was 400 nm wide, causing coupling to higher order modes in the silicon waveguide. This limited the usefulness of the coupler to photodetector devices, as a laser emitting into a single mode would not have efficient operation.

In this work, the taper tip size was reduced to below 100 nm through the use of 248 nm deep-UV lithography, allowing coupling between the fundamental TE modes in the waveguides. The device is comprised of a single linear lateral taper of the Si waveguide. The loss was measured by injecting light into a Si3N4 waveguide, which then coupled into the Si layer and was guided through an s-bend and a second taper to couple into an adjacent Si3N4 waveguide. The two Si3N4 waveguides were separated by 100 µm so that light which was transmitted through the taper in the Si3N4 waveguide would not be collected.

The result of this measurement is shown in Figure 2. The transmission loss was below 0.1 dB for the entire wavelength range of the tunable laser used during testing. In addition, an optical backscatter reflectometer trace of a 0.75 m Si3N4 waveguide spiral using the same 90 nm thick and 2.8 µm wide geometry at 1580um showing 1.5 dB of propagation loss is shown in Figure 3 to demonstrate that the Si3N4 waveguide is truly ultra-low loss.

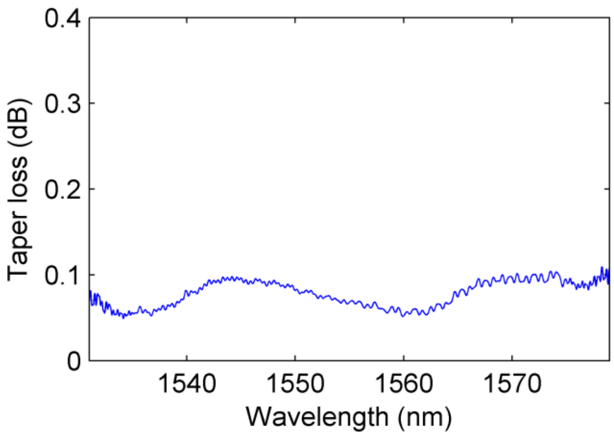

Figure 2: Transmission loss for a single taper versus wavelength.

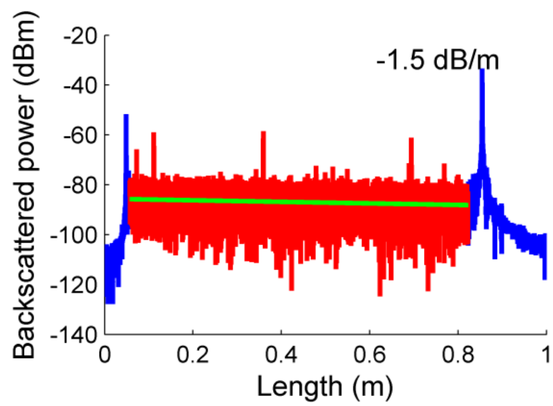

Figure 3: Optical backscatter reflectometer measurement of the ultra-low loss waveguide

3. Conclusion

We have demonstrated coupling between a Si nanowire waveguide and an ultra-low loss Si3N4 nanostrip waveguide with below 0.1 dB of propagation loss over 50 nm of optical bandwidth. This allows, in principle, the integration of any silicon photonic device with Si3N4 waveguides with ultra-low propagation loss. Using this capability, a wide range of high performance photonic integrated circuits may be demonstrated, such as optical rotation sensors utilizing long delay lines, tunable lasers with narrow linewidth, and low-loss wavelength multiplexers and demultiplexers.

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