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Efficient Nanotaper Edge Couplers in PECVD Amorphous Silicon Carbide for Integrated Photonics Applications

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The field of integrated photonics has experienced remarkable growth, supported by significant advancements in nanofabrication techniques. This growth has accelerated the development of applications in areas such as telecommunications, optical sensing, and quantum information processing, etc. A diverse range of materials has been studied for photonic applications, such as silicon (Si), silicon nitride (Si_3N_4), lithium niobate ($LiNbO_3$), aluminum nitride (AlN), aluminum gallium arsenide (AlGaAs), and silicon carbide (SiC). SiC, in particular, has emerged as an exceptionally promising candidate for integrated photonics, owing to its wide bandgap, high refractive index, strong nonlinearity, and resistance to harsh environments [1]. Out of the high number of polytypes of SiC, 3C-, 4H-, and 6H-SiC have been the primary focus of research. In addition to crystalline SiC, amorphous SiC (a-SiC) has also attracted attention in recent years due to its superior third-order nonlinearity and higher thermo-optic coefficient [2-4]. Plasma-enhanced chemical vapor deposition (PECVD) is the primary method for the formation of a-SiC thin films and integrating them into the field of integrated photonics [5]. By depositing a-SiC directly onto a SiO_2-on-Si substrate, silicon carbide on insulator (SiCOI) can be easily synthesized, rendering a-SiC photonic devices amenable to large-scale fabrication using complementary metal-oxide-semiconductor (CMOS)-compatible processes while maintaining cost-effectiveness.

In integrated photonics, efficient coupling of light from fibers to on-chip waveguides is necessary. Losses incurred during the coupling process can significantly impact the overall system performance, i.e., leading to reduced signal-to-noise ratios and requirement of high injected power. Therefore, it is crucial to study couplers with low insertion losses to facilitate effective light transmission between integrated photonic devices and optical fibers. Inverse taper edge couplers, which use a narrow nanotaper to guide light coupled from the fiber, are commonly employed to match the mode profile of lensed fibers [6]. The nanotaper width increases gradually along the direction of light propagation, transitioning from a small cross-section to the dimensions of a standard waveguide. This abstract focuses on the design, fabrication and characterization of inverse taper edge coupler in a-SiCOI platform, and study the fabrication tolerance of the nanotapers. The transverse electric (TE) mode is studied in this work. The schematic diagram of inverse taper edge coupler is shown in Fig. 1(a), and the supported mode of a nanotaper is shown in Fig. 1(b). Consequently, the energy shifts from the surrounding medium to the core medium gradually.

To design a high coupling efficiency edge coupler, the taper width is the most critical parameter to study, as it determines the mode distribution of the nanotaper and subsequently influences the coupling loss. We performed a sweep of the nanotaper width while keeping the waveguide height fixed at 480 nm. Lumerical Finite-difference time-domain (FDTD) software is used to simulate the coupling loss from a lensed fiber (core diameter of 2.5 μm) to the edge coupler by calculating the overlap of the studied modes of the edge coupler and the fiber. The results are illustrated in Figure 1(c). The optimal width is found to be 190 nm, yielding a coupling loss of -0.28 dB per facet. The power density of TE mode with a nanotaper width of 190 nm, is depicted in Figure 1(b).

In fabrication process, a-SiC is deposited on thermally oxidized Si wafer through PECVD, resulting in a thickness of 480 nm. The refractive index is measured 2.49 using Ellipsometer VASE. Next, we fabricate the nanotaper with a sweep of the edge coupler width to investigate fabrication tolerance. Electron-beam lithography is employed to define the designed pattern on the e-beam resist coated on the chip, while inductively coupled plasma reactive-ion etching (ICP-RIE) is utilized to transfer the pattern to the a-SiC thin film. After removing residual resist and applying the cladding layer (SiO_2), the a-SiC nanotaper edge coupler is fabricated. The final step involves cleaving the edge coupler to expose the facets.

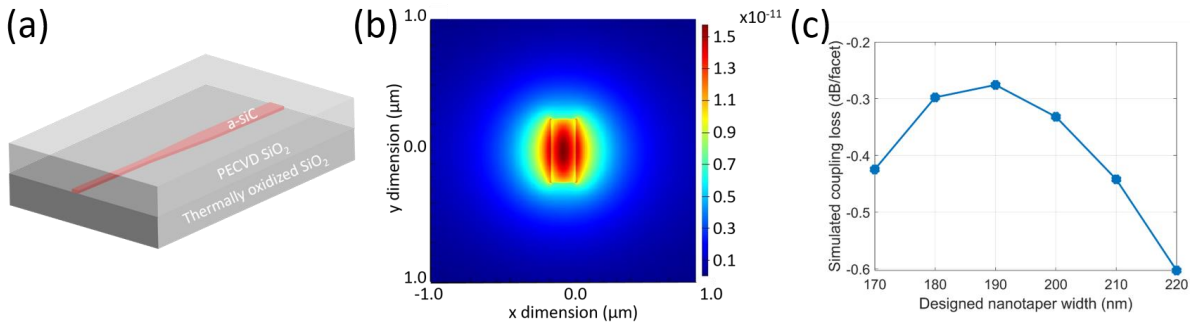

Fig. 1 (a) Perspective view of the sketch of nanotaper edge coupler. (b) Mode profiles (Energy density) of TE mode with nanotaper width = 190 nm. (c) Simulation results depicting the coupling efficiency of the nanotaper edge coupler.

To study the fabrication tolerance, we prepared six nanotaper widths based on the optimal value (190 nm), which included -20, -10, 0, +10, +20 and +30 nm variations. Following the completion of all process steps, we cleaved the chip to expose the edge couplers, and the cross-sections were characterized using scanning electron microscopy (SEM), as shown in Figure 2(a). The measured width is 190.0 nm for a corresponding design width of 210 nm. The silicon dioxide below the bottom of the nanotaper is thermally oxidized, while the surrounding material is formed by PECVD SiO_2.

After fabrication, the fabricated nanotaper widths were inspected using SEM, and the results are presented in Figure 2(b). The fabricated width consistently appears narrower compared to our design, with the linewidth reduction averaging around 16.7 nm. Figure 2(c) shows the coupling loss which was obtained by deducting the transmission loss from the total intersection loss.

The highest coupling efficiency is achieved at the designed value of 200 nm. However, due to linewidth reduction, the actual width is 184 nm, which is close to our design result. For the width of 184 nm, we observed an optimal coupling efficiency of -3.17 dB/facet, larger than the optimal simulated value. Cracks in the cladding layer, resulting from PECVD on surfaces with large height variations, can increase the light scattering when it is propagating in the waveguide. Moreover, the cross section of nanotaper is not perfectly smooth which will increase the coupling loss as well. The experiment reveals that within 20 nm range, the tolerance at smaller widths is better than at larger widths, aligned with the simulated results. However, as the nanotaper width narrows further, the experimental coupling efficiency drops significantly. This phenomenon can be attributed to the fact that, with a smaller width, the modes are distributed over a larger area in the surrounding material, leading to increased scattering loss from defects in the SiO2 layer.

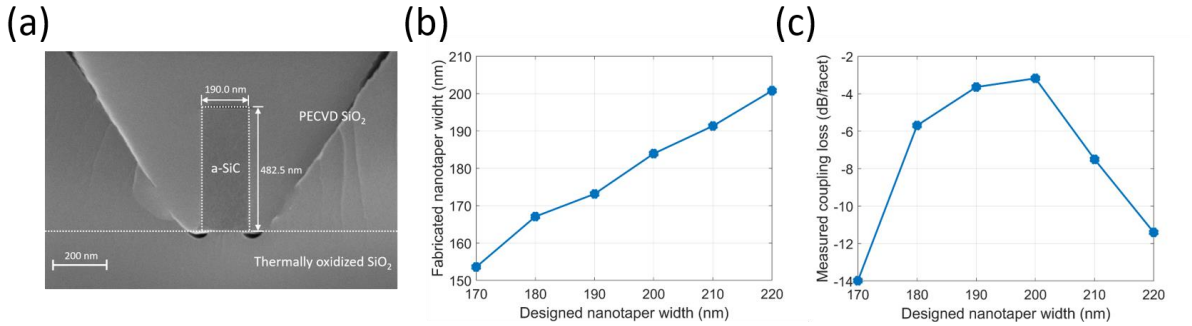

Fig. 2 (a) Scanning electron microscopy (SEM) image of the fabricated nanotaper's cross section. (b) Linewidth reduction comparison between the fabricated and designed nanotaper widths. (c) Measured coupling loss of the nanotaper edge coupler at each facet.

In conclusion, we have simulated, designed, and fabricated a-SiCOI nanotaper edge couplers and characterized the optimal design, which exhibits a 3.17 dB/facet loss for TE mode with a practical nanotaper width of 186 nm. To the best of our knowledge, this is the lowest coupling loss mentioned in papers to date in a-SiCOI platform. Furthermore, we observed that the fabrication tolerance is higher when the fabricated width is smaller than the optimal design in the experiment.

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