Low-loss Hybrid Optical Waveguides in Amorphous Silicon Carbide Enabled by Weak Modes

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Abstract: *Exploiting the interaction of weak optical modes, we demonstrate low-loss and compact hybrid optical waveguides in amorphous silicon carbide (a-SiC). The waveguide is comprised of a low-index polymer and a thin layer of high-quality a-SiC, which is deposited using an optimized recipe. Only the polymer layer is patterned; the a-SiC layer is not processed. The waveguides are defined directly on the polymer layer using the electron beam writing method with a non-standard writing approach. For this material combination, a minimum bending radius of 150 µm (for a bending loss of 0.005 dB/90°) and propagation loss of 1.3 dB/cm is achieved. Using this waveguide technology, we successfully demonstrate two of the most often used integrated optical components; racetrack resonators and Mach Zehnder interferometers. For a racetrack resonator with a bending radius of 150 µm, an intrinsic quality factor of* $Q_{int} = 2.24\times10^5$ *is achieved. After the polymer layer is thermally hard-baked for an hour at 170°, the* Q_{int} *value is enhanced by ~21%, to* $Q_{int} = 2.7\times10^5$*. Surprisingly, we discovered that our waveguide structure functions as a perfect transverse electric (TE)-pass polarizer, suppressing the transverse magnetic (TM) mode by 62 dB at 1550 nm. This hybrid platform offers an unconventional and simple way of realizing compact and low-loss SiC-based integrated optical components, leveraging the exciting applications of SiC in integrated photonics, optomechanics and quantum fields.*

1. Introduction

Silicon carbide (SiC) is a well-known complementary metal-oxide-semiconductor (CMOS) compatible material that has been extensively explored for use in electronic devices. In recent years, its potential for integrated photonic devices also has garnered significant attention[1-3] due to its outstanding optical properties such as wide transparency window[4], the high second-order[5], third-order nonlinearity[6], and a high refractive index[7]. For integrated optics applications of SiC,

Here, we present a hybrid a-SiC optical waveguide platform, which is low loss, etch-free, and allows for realizing compact integrated photonic components. The waveguide is formed by combining a low refractive index polymer layer (SU8) with a thin film of high-quality ICPCVD-deposited a-SiC. In essence, our approach couples two vertically weakly guiding regions, with near-cutoff optical modes, into an optical waveguide with strong mode confinement. The unique aspect of this approach is that strong mode confinement can be achieved in low-index-contrast material systems, which is usually a big challenge. Figure 1a&b illustrates the concept. The working principle is explained in detail in Ref. [25]. we discovered that our hybrid waveguide structure functions as a perfect transverse electric (TE)-pass polarizer, suppressing the transverse magnetic (TM) mode by 62 dB. Our platform offers a new way of realizing low-loss, compact, and easy-to-fabricate SiC-based optical waveguides with new functionalities,

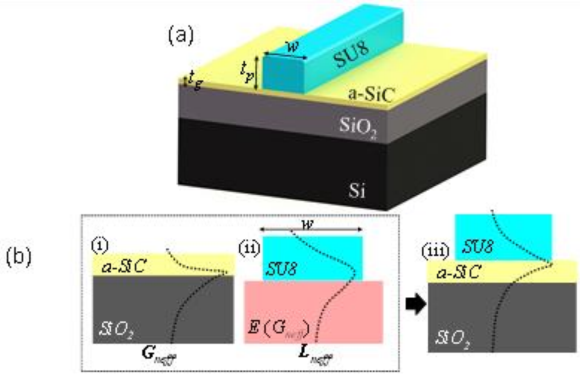

Figure 1. (a) Schematic of the hybrid a-SiC optical waveguide. **(b)** The vertical mode profiles in the (i) guiding (a-SiC) (ii) loading (SU8) layers of the hybrid waveguide.

2. Methods

2.1. Fabrication

A thin layer of a-SiC was deposited on an 8-µm-thick thermally-oxidized silicon wafer using the ICPCVD method with an optimized recipe described in Ref. [7]. The propagation loss of a SiC racetrack resonator based on this recipe was reported as 0.73 dB/cm. We measured the material absorption of the SU8 layer as ~3 dB/cm at 1550 nm wavelength. The refractive index of the thermal oxide, polymer layer, and a-SiC layer are 1.45, 1.58, and 2.57 at λ=1550 nm, respectively. The width was chosen as *w*=1.5 µm to guide only the fundamental mode. An air cladding was used, which helps reduce the optical loss caused by the SU8 absorption. The devices were fabricated using e-beam writing. We did not use any conductive polymers to define the structures in contrast to common practice and we directly exposed the SU8 layer,

3. Design and Experimental Results of PIC Components

3.1. Measurement setup

The optical loss value of the hybrid a-SiC waveguides was extracted from the racetrack resonator measurement results. We developed a new measurement method, the so-called sweeping optical heterodyne method[8], to measure the full width at half maximum (FWHM) of the fabricated resonators. When the frequency difference of the sample and the reference lasers are within the bandwidth of the photodetector, a beat frequency equal to the difference between the frequencies of the two lasers is detected on the balanced photodetector and measured with the ESA.

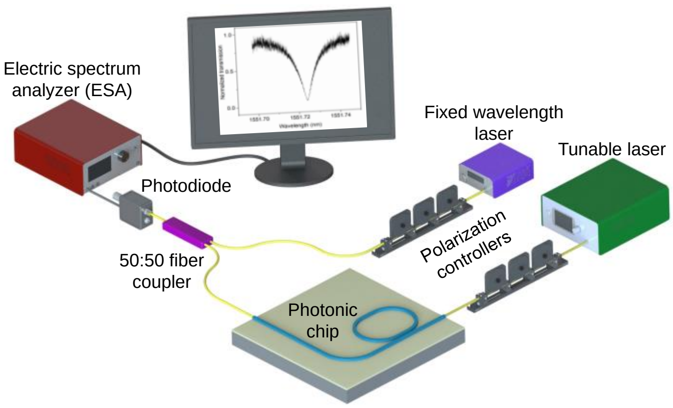

Figure 2. Measurement setup.

3.2 Racetrack resonator design and optical loss measurements

We designed several racetrack resonators with varying coupling lengths and R= 150 µm. The best coupling length that provides close to critical coupling was found to be L_c= 50 µm. The FWHM value of the resonance peak at λ = 1550 nm was measured as 11 pm, which corresponds to $Q_{int} = 2.24\times10^5$ (**Figure 3a**). We post-baked the fabricated devices at 170 °C for an hour using a hot plate and the FWHM of the same racetrack resonator decreased to 9.5 pm, corresponding to $Q_{int} = 2.7\times10^5$ (i.e. 21% improvement in the optical loss). The scanning electron microscope (SEM) images of the waveguide cross-section before and after the thermal hard bake step are provided in **Figures 3a** and **b**, respectively.

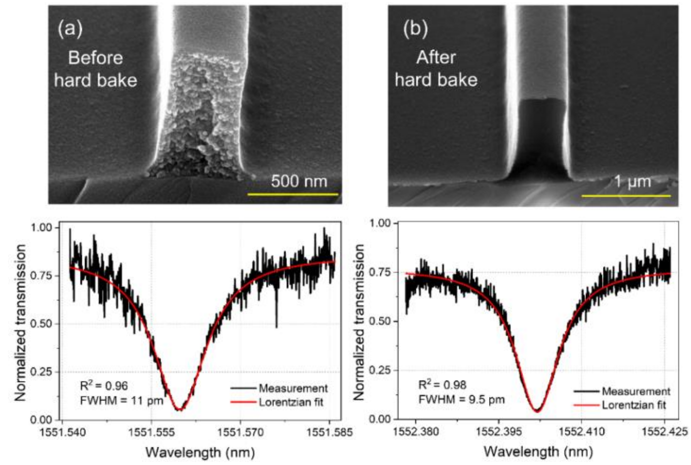

Figure 3. The scanning electron microscope images of the waveguide cross-sections of the racetrack resonators **(a)** before and **(b)** after the hard bake at 170° for an hour.

3.3 Eliminating Fabry Perot oscillations in the resonance spectrum

The Fabry-Perot (FP) oscillations induced by the reflections coming from waveguide facets interfere with the precise measurement of the resonator's FWHM. To overcome this problem, we designed the input and output waveguides of the racetrack resonators with an angle of θ = 15°, which eliminated the FP oscillations by almost 100% as shown in **Figure 4b.** For the purpose of comparison, we also fabricated a racetrack resonator with regular input and output waveguides (θ = 0) and observed strong FP oscillations in the spectrum as shown in **Fig. 4a**.

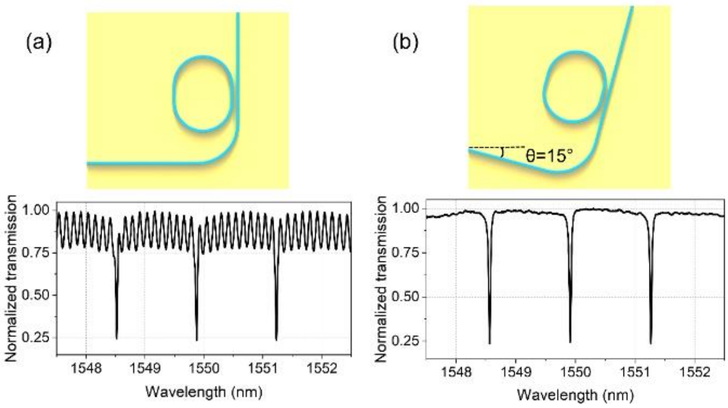

Figure 4. (a) Racetrack resonator with the in and out parts of the waveguide having an angle of **(a)** θ = 0° and **(b)** θ = 15° The bottom row shows the experimental results obtained from each configuration.

3.4 Transverse electric (TE)-pass polarizer

Controlling and manipulating the polarization state of light in integrated photonic circuits is crucial in applications ranging from optical sensing to optical communications. Surprisingly, we discovered that the hybrid waveguide structure can function as a perfect

TE-pass polarizer with a very high polarization extinction ratio. The schematic of the measurement setup is given in **Figure 7a**. We simulated the coupling loss of the waveguide for TE and TM polarized light for different waveguide widths as shown in **Figure 7b.** As can be seen, the coupling loss is significantly larger for the TM mode and there is an inverse relation between the coupling loss of the TE and TM modes for increasing waveguide widths.

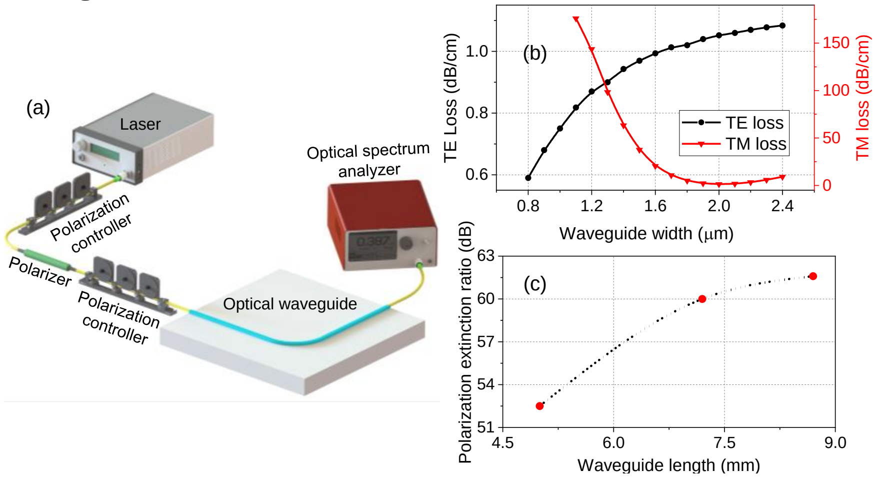

Figure 7. **(a)** Polarization measurement setup. **(b)** Simulation results of the loss for the TE and TM modes for different waveguide widths**. (c)** Measured TM suppression ratio for three waveguide lengths; 5 mm, 7.2 mm, and 8.7 mm. A polarization extinction ratio of 62 dB was achieved for the waveguide length of 8.7 mm.

4. Conclusion

In conclusion, we demonstrated a new hybrid waveguide platform in a-SiC based on the interaction of weak optical modes. SU8 was used as the loading layer to confine the light in the horizontal direction. A high-quality a-SiC layer was deposited using an optimized ICPCVD recipe. Here the choice of layer thickness for both guiding and loading layers turns out to be of critical importance. Compact and low-loss waveguides, with a minimum bend radius of 150 µm, for acceptable/negligible bend losses of 0.005 dB/90°, and optical losses of 1.3 dB/cm have been realized. Thanks to the flexible nature of polymers, we reduced the scattering losses by 21% through thermal annealing. A quality factor of $Q_{int} = 2.7\times10^5$ was achieved. We expect that the loss can be further reduced by using different polymers with lower absorption losses. We characterized fabricated resonators using a custom-built sweeping optical heterodyne detection method, which exceeds the figure of merits of conventional methods in terms of resolution, speed, and sensitivity. Surprisingly, this hybrid waveguide structure functions as a perfect transverse electric (TE)-pass polarizer, suppressing the transverse magnetic (TM) mode by 62 dB.

References

[1] Y. Zheng, M. Pu, A. Yi, X. Ou, and H. Ou, Opt. Lett. 44, 5784 (2019).

[2] T. Fan, X. Wu, S.R.M. Vangapandu, A.H. Hosseinnia, A.A. Eftekhar, and A. Adibi, Opt. Lett. 46, 2135 (2021).

[3] C. Wang, Z. Fang, A. Yi, B. Yang, Z. Wang, L. Zhou, C. Shen, Y. Zhu, Y. Zhou, R. Bao, Z. Li, Y. Chen, K. Huang, J. Zhang, Y. Cheng, and X. Ou, Light-Sci. Appl. 10, 139 (2021)

[4] S. Wang, M. Zhan, G. Wang, H. Xuan, W. Zhang, C. Liu, C. Xu, Y. Liu, Z. Wei, and X. Chen, Laser. Photonics. Rev 7, 831 (2013).

[5] I.J. Wu and G.Y. Guo, Phys. Rev. B 78, 035447 (2008).

[6] R. Adair, L.L. Chase, and S.A. Payne, Phys. Rev. B 39, 3337 (1989).

[7] B. Lopez-Rodriguez, R. van der Kolk, S. Aggarwal, N. Sharma, Z. Li, D. van der Plaats, T. Scholte, J. Chang, S. Gröblacher, S. F. Pereira, H. Bhaskaran, and I. E. Zadeh, "High-Quality Amorphous Silicon Carbide for Hybrid Photonic Integration Deposited at a Low Temperature," ACS Photonics, (2023)

[8] Dashtabi M. and Akca B. I. September 25, 2023. High throughput measurement and characterization system for integrated photonics-based bio-sensors. European patent application No. 23199844.4