

Tunable Silicon Carbide Nanophotonics for Defect-Enhanced Optical Readout and Optically Detected Magnetic Resonance

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Abstract:

Silicon carbide-on-insulator (SiCOI) combines optically addressable spin defects with high-index-contrast photonics. We establish a fabrication process for microring-waveguide-grating devices, obtain room-temperature resonances with quality factor $Q \approx 6,500$, and extend the platform to implanted silicon-vacancy ensembles. At 77 K, V1, V1', and V2 emission was routed through the integrated photonics. By sweeping the radius and ring-waveguide gap, we tune cavity alignment and external coupling, producing strong, reproducible changes in the V1/V1' photoluminescence ratio and enhancement of V1. We also demonstrate the continuous-wave optically detected magnetic resonance (ODMR) of V2 ensembles at room temperature with magnetic-field and optical-power dependence. These results connect to cavity-assisted spin readout for chip-scale sensing.

Summary of Research:

Silicon carbide hosts color centers with optically addressable spins and near-infrared transitions, but bulk collection is limited by the material's high refractive index and weak zero-phonon-line emission [1–3]. SiCOI provides a route to increase useful photon collection by combining defect ensembles with optical resonators, waveguides, and grating couplers. Our work progress from fabrication development to defect-cavity coupling and spin-resonance measurements.

Our SiCOI devices are fabricated from a 540 nm 4H-SiC layer on 3.044 μm SiO_2 on Si substrate [4]. The PMMA495/PMMA950 bilayer resist is patterned by electron-beam lithography, followed by duty-cycled deposition and lift-off of a 100 nm Ni hard mask. The pattern is transferred to SiC by SF_6/O_2 reactive-ion etching, the Ni is removed, and approximately 2.5 μm SiO_2 is deposited as upper cladding (Fig. 1). Our etch

studies balanced sidewall taper against micromasking by tuning the SF_6/O_2 ratio, pressure and power. The optimized devices contain around 10 μm -radius rings, bus waveguides, and grating couplers with systematic radius, gap, and pitch variations.

The devices were characterized through two sets of fast-steering mirrors (FSM 4f-1 and FSM 4f-2) to control the excitation and collection paths (Fig. 2a). The confocal scan verifies the devices, and the strong PL at grating couplers suggests the efficient optical coupling into and out of the device. The non-confocal geometry excites one grating and collected from another to probe the T13 transmission of the waveguide-ring-waveguide structure. A representative optical ring TM₀₀ mode at 915.44 nm has 0.14 nm linewidth and $Q \approx 6,500$ (Fig. 2e).

To couple the ring modes with spin defects, we sweep the devices parameters. We change the ring radius R from 9.94 to 10.06 μm to shift the mode wavelength for spectral alignment with V1 near 861 nm and V2 near 916 nm; the ring-waveguide gap g from 0.14 to 0.10 μm to change the coupling condition of those ring modes and the bus waveguide from under-coupled and near-critical-coupled operation; and grating pitch from 0.39 to 0.62 μm to move the detection window and alter the relative TE and TM contributions.

For defect integration, the SiCOI chips are annealed, implanted with 50 keV He ions at $1 \times 10^{13} \text{ cm}^{-2}$, and post-annealed. At 77 K, V1', V1, and V2 emission are observed from the fabricated device [7]. Figure 3 gives V1 defect-cavity coupling. At fixed grating pitch, changing the ring radius shifts the ring resonance by about 1 nm for each 0.01 μm radius step. The V1/V1' peak ratio increases from 1.52 off resonance at $R = 9.99 \mu\text{m}$ to 14.6 on resonance at $R = 10.06 \mu\text{m}$. The normalized radius-wavelength map shows this systematic mode translation. At $R = 10.06 \mu\text{m}$, decreasing the ring-

waveguide gap g from 0.14 to 0.11 μm increases the V1/V1' ratio from 3.25 to 14.6 as the device moves toward critical coupling. Together, the radius and gap sweeps show that spectral alignment and waveguide–ring coupling independently control the routed V1 signal. These spectra demonstrate resonant spectral enhancement and integrated routing, complementing

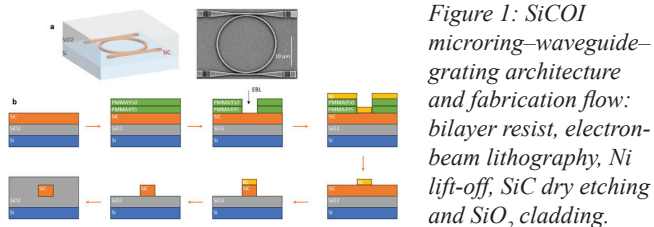
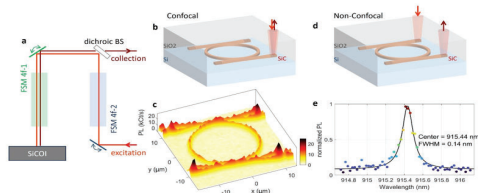


Figure 1: SiCOI microring-waveguide-grating architecture and fabrication flow: bilayer resist, electron-beam lithography, Ni lift-off, SiC dry etching and SiO₂ cladding.

Figure 2: Room-temperature optical characterization. (a) Optical setup. The light red excitation beam is controlled



by both fast-steering mirrors (FSM 4f-1 and FSM 4f-2) and the dark red collection beam is only controlled by FSM 4f-2. (b)-(c) The confocal scan map of the device shows that the ring and two coupling waveguides, equipped with four grating couplers, align precisely with the designed geometry. (d)-(e) The non-confocal emission from the SiCOI device shows the TM₀₀ ring resonance with a narrow linewidth and high Q -factor of 6500.

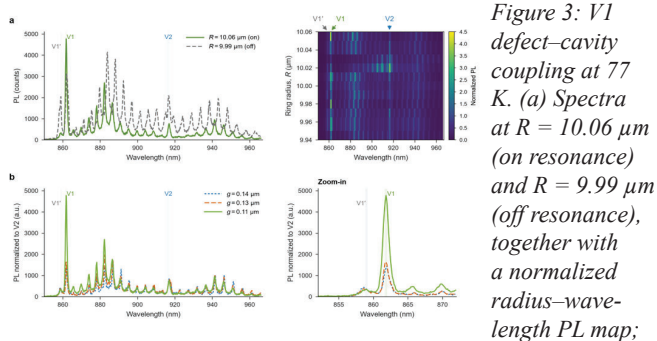
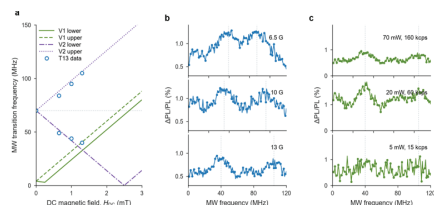


Figure 3: V1 defect-cavity coupling at 77 K. (a) Spectra at $R = 10.06 \mu\text{m}$ (on resonance) and $R = 9.99 \mu\text{m}$ (off resonance), together with a normalized radius-wave-length PL map;

the reported V1/V1' ratio changes from 1.52 off resonance to 14.6 on resonance. (b) Gap-dependent spectra at $R = 10.06 \mu\text{m}$ for ring-waveguide gaps of 0.11, 0.13, and 0.14 μm , shown over the full collection band and the V1 region. Increasing the gap moves the ring toward under-coupling and reduces the reported V1/V1' ratio from 14.6 to 3.25.

Figure 4: Continuous-wave ODMR of the V2 ensemble measured through T13 at room temperature. (a) Calculated V1 and V2 transition branches versus DC magnetic field HDC, with measured V2 resonances through T13. (b) Measured $\Delta\text{PL}/\text{PL}$ spectra at HDC = 6.5, 10, and 13 Gs; dashed guides mark the V2 branches. (c) $\Delta\text{PL}/\text{PL}$ spectra at HDC = 13 Gs for 70, 20, and 5 mW optical power, corresponding to 160, 60, and 15 kcps.



prior cavity-enhanced SiC color-center studies (5, 6). A lifetime measurement is still required to separate Purcell enhancement from changes in excitation and collection efficiency.

We next measure continuous-wave ODMR of V2 at room temperature in Figure 4, following established room-temperature V2 spin control.[8] The zero-field splitting at 70 MHz splits into two field-dependent branches with the DC magnetic field HDC; measured resonances from HDC = 6.5–13 Gs follow the expected V2 transition trend (Fig. 4b). Optical-power sweeps from 5 to 70 mW increase the detected rate from approximately 15 to 160 kcps and made the resonance structure progressively clearer (Fig. 4c). These data establish spin addressability although background from V1 and cavity/waveguide modes and a technical-noise floor currently limit contrast for magnetic-field sensitivity application.

Conclusions and Future Steps:

We develop a tunable SiCOI photonic platform, coupled implanted V1 ensembles to the optical resonances, and observed V2 ODMR. The combined results move from optimizing fabrication process, to control optical modes, route defect emission, and support spin readout. Next steps are spatially PMMA-masked He implantation, lower-damage etching and annealing, resonant V1 excitation at 4 K, lifetime measurements, and pulsed ODMR to determine T_2^* and T_2 .

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