

Silicon Carbide Nanophotonic Cavities for Integration with Color Centers

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Principal Investigator(s): Greg Fuchs

User(s): Ying Yang

Affiliation(s): School of Applied and Engineering Physics, Cornell University

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Contact: gdf9@cornell.edu

Primary CNF Tools Used: Oxford COBRA, Oxford 81 Etcher, JEOL 6300, Nabity, Dicing saw -- Disco, Glen 100, CVC SC4500 Odd hour Evaporator, Zeiss Supra SEM, Zeiss Ultra SEM, LPCVD HTO & LTO

Abstract:

Silicon carbide (SiC) has emerged as a promising platform for quantum photonics due to its excellent material properties and intrinsic color centers. We demonstrate the fabrication of two complementary cavity architectures in SiC: plasmonic silver nanopan cavities and dielectric ring-waveguide resonators on SiC-on-insulator (SiCOI). These structures are designed to provide cavity modes with field confinement and high-quality factor. The cavity modes are coupled with SiC color centers to enhance collection efficiency and emission rate through the Purcell effect. We report significant advances in addressing fabrication challenges including sidewall tapering through optimized e-beam lithography using dual PMMA layers and refined etching recipes.

Summary of Research:

Silicon carbide hosts optically addressable spin defects that exhibit excellent quantum properties, including long spin coherence times (>1 ms) and near-infrared emission compatible with telecommunication infrastructure (1,2). However, the collection efficiency of photons from these color centers is limited by their low Debye-Waller factor (5% for divacancies) and the high refractive index of SiC ($n = 2.6$), which causes most emitted light to undergo total internal reflection. Photonic cavities can overcome these limitations through Purcell enhancement, increasing both the emission rate and the fraction of photons collected into desired optical modes (3,4). Here, we develop two cavity platforms that leverage different enhancement mechanisms: plasmonic nanopan cavities offering ultrasmall mode volumes and dielectric ring resonators on insulator providing high quality factors.

For the plasmonic nanopan cavity fabrication in Figure 1, we begin with 8×8 mm pieces of 4H-SiC. Prior to any fabrication steps, samples undergo thermal annealing at

650°C in vacuum for 1 hour to remove inherent defects and damage. The process is given in Figure 1. It first employs electron beam lithography with a bilayer resist structure consisting of 220 nm PMMA 495 A4 (spun at 1600 rpm) and 120 nm PMMA 950 A4 (spun at 6000 rpm) to create undercut profiles that mitigate sidewall angles, and each baked at 170°C for 15 minutes. An e-spacer layer (~ 25 nm) is applied without baking to prevent charging. Circular patterns with diameters ranging from 200-800 nm are exposed using a Nabity at 10kV with doses of $400\text{--}850 \mu\text{C}/\text{cm}^2$. After development in 1:3 MIBK:IPA for 60s, we deposit 100 nm of nickel using the CVC SC4500 evaporator at $1.3 \text{ \AA}/\text{s}$ with intermittent cooling (20 nm deposition followed by 77s pause). Lift-off is performed in acetone overnight, followed by 5s brief ultrasonication.

The etching process utilizes Oxford COBRA ICP-RIE with an SF_6/O_2 chemistry (30:15 sccm) at 2000W/40W and 8 mTorr pressure, achieving an etch rate of ~ 5.5 nm/s. We address the sidewall taper issue by utilizing the undercut profile from the PMMA495/PMMA950 bilayer, which provides better pattern transfer fidelity compared to MMA/PMMA495 bilayer in our previous recipe. After etching to depths of 400 nm, the nickel mask is removed using Type 1 nickel etchant at 40°C for 10s. The SiC nanopillars are then encapsulated with 500 nm of silver deposited by CVC SC4500 evaporator, creating the plasmonic cavity structure. The devices (Figure 2a-d) demonstrate strong out-of-plane field confinement in FDTD simulations in Figure 2e, enabling the efficient coupling to c-axis oriented VSi dipoles and realizing photoluminescence enhancement (5).

For the SiCOI ring-waveguide resonators in Figure 3, we use commercially available 4H-SiCOI pieces with 540 nm SiC, 3044 μm SiO₂ and 680 μm Si layers (6). The fabrication is given in Figure 3. It first employs the same dual PMMA resist approach. To remove the edge

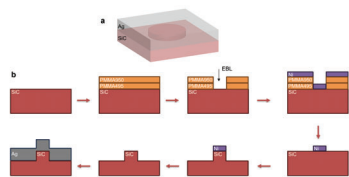


Figure 1: (a) Schematic of the SiC nanopan cavities. (b) Fabrication process flow for SiC nanopan cavities showing resist deposition, e-beam lithography, metal deposition, etching, and silver encapsulation steps.

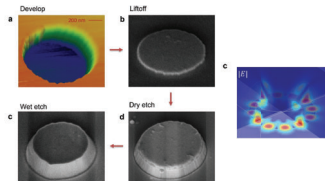


Figure 2: (a) AFM and SEM image of the fabricated SiC nanopan cavities of developing the resist, liftoff Ni mask, dry etching the SiC, wet etching the Ni mask. (b) FDTD simulation of SiC nanopan cavity's E field profile showing the whispering gallery mode $TM_{12,0,0}$ the field concentration at SiC-silver interface. (c) Photoluminescence spectrum from silver nanopan cavity (red) compared to bare SiC substrate (black), showing enhancement of V1 and V1' emission lines around 860 nm.

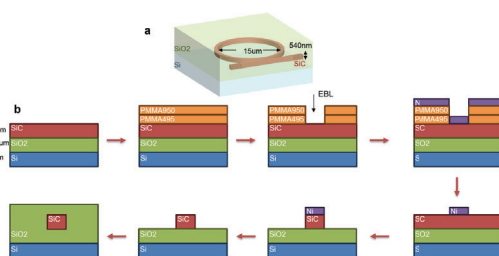


Figure 3: (a) Schematic of the SiCOI ring-waveguide-grating devices. (b) Fabrication process flow for SiCOI ring-waveguide-grating devices showing resist deposition, e-beam lithography, metal deposition, etching, and silica cladding steps.

beads on the 5×5 mm SiCOI pieces, the sample piece is bond to the center of a dummy wafer and a dummy piece is bond side by side. Ring resonators with radii of 10-20 μm , waveguide width of 300-500 nm and grating couplers with of 2 μm width, 50% duty cycle and 420 nm pitch (7,8), are patterned by JEOL 6300 system in 10nA 60nm aperture with doses of 300-500 $\mu\text{C}/\text{cm}^2$. We deposit 100 nm nickel masks with the same duty-cycled evaporation to minimize thermal stress. The etching recipe was optimized to reduce the taper by adjusting SF_6/O_2 to 30:10 sccm.

The fabricated ring resonators exhibit smooth sidewalls. Coupling gaps of 300-700 nm between the ring and bus waveguides are achieved with good uniformity, to guarantee the critical coupling. After nickel mask removal, we deposit a SiO₂ cladding layer using a two-step LPCVD process: first, 600 nm of high-temperature

oxide (HTO) deposited at 1.5 nm/min to conformally cover the etched structures and fill narrow gaps, followed by 2 μm of low-temperature oxide (LTO) at 10 nm/min to provide a thick upper cladding for mode confinement and environmental protection. In Figure 4, preliminary transmission simulations show whispering gallery modes $TM_{m,0,0}$ with high quality factors due to the large refractive index mismatch of SiC and SiO₂ layers. The grating coupler's simulated transmission gives a broad stop band centered at 860 nm close to V1 centers in SiC, which can provide good injection and reading of laser beam into the device.

Conclusions and Future Steps:

We have demonstrated two complementary approaches for creating photonic cavities in silicon carbide: plasmonic nanopan structures and SiCOI ring resonators for maximum field enhancement and high-Q operation. The optimized dual PMMA resist system and refined etching processes effectively address the sidewall taper challenges for us to tune the device performance. Future work will focus on precise spectral and spatial alignment of color centers with cavity modes through controlled ion implantation after cavity fabrication. We plan to perform detailed Purcell factor measurements using time-resolved photoluminescence and explore coherent control of cavity-coupled spins. Additionally, we will investigate hybrid integration approaches combining the high field enhancement of plasmonic structures with the low loss of dielectric cavities to approach the strong coupling regime necessary for deterministic quantum gates.

References:

- [1] Castelletto, S. et al. Nat. Mater. 21, 67-73 (2022)
- [2] Lukin, D. et al. Nat. Photonics 14, 330-334 (2020)
- [3] Castelletto, S. et al. ACS Photonics, 9, 1434-1457 (2022)
- [4] Ou, H. et al. Materials, 16, 1014 (2023)
- [5] So, J. P. et al. Nano Letters, 24, 11669-11675 (2024).
- [6] Yi, A. et al. Optical Materials, 107, 109990 (2020).
- [7] Lukin, D. et al. arXiv preprint, 2504, 09324, (2025).
- [8] Afridi, A. A. et al. Applied Physics Letters, 124 (2024).