Nanostructure Integrated Silicon Vacancy in 4H-Silicon Carbide

CNF Project Number: 2126-12
Principal Investigator(s): Gregory David Fuchs
User(s): Jae-Pil So

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

Primary Source(s) of Research Funding: National Science Foundation, OMA.2137828

Contact: gdf9@cornell.edu, js3338@cornell.edu

Primary CNF Tools Used: Oxford COBRA, Oxford 81 Etcher, 5X g-line stepper, Dicing saw - DISCO, SC4500 Odd hour Evaporator, AJA Sputter, Zeiss Supra SEM, Zeiss Ultra SEM, Nabity

Abstract:

Silicon vacancy (V_{si}) centers in 4H-silicon carbide (4H-SiC) has emerged as a candidate for quantum networking applications owing to its outstanding physical properties including a long spin coherence time, a high Debye-Waller factor, and its status in a mature semiconductor with established fabrication recipes. However, the out-of-plane orientation of optical dipole of VSi introduces a challenge for optically exciting it with a free-space laser, and coupling it external optical structures. Here we demonstrate fabrication of SiC nanowires using metal-assisted chemical etching (MACE) that can be cleaved mechanically and transferred on the other substrates. Also, we demonstrate combining V_{si} with a plasmonic cavity that enhances the emission rate.

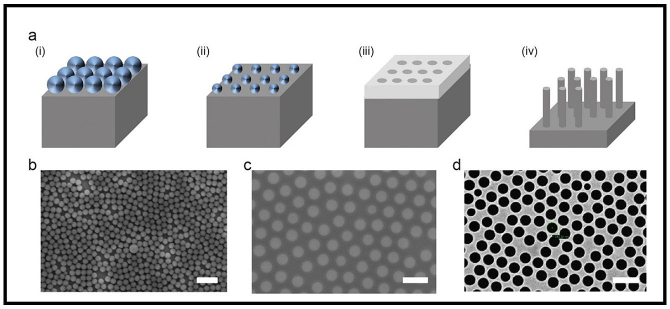

Figure 1: (a) Schematic of the fabrication procedures to create SiC nanowire. (b,c) SEM images of the polystyrene beads array on SiC substrate (b) before and (c) after reducing the diameter via RIE. Scale bar, 3 mm and 500 nm, respectively. (d) SEM image of the Pt mesh. Scale bar, 500 nm.

Summary of Research:

Optically accessible spin states in solids are a promising basis for establishing a quantum networking platform. 4H-SiC offers a unique opportunity for on-chip quantum photonics, as it hosts a variety of optically accessible defects [1,2]. V_{si} in 4H-SiC has shown excellent optical coherence at cryogenic temperatures with millisecond spin-coherence time, and coherent coupling to nuclear spins [3-5]. However, the out-of-plane orientation of its optical dipole prevents it from being excited by a free-space pump laser that produces only in-plane electric field oscillation. Here, we demonstrate the fabrication of SiC nanowires using a top-down method, allowing nanowires that can be cleaved mechanically and transferred on the other substrates [6]. This approach enables the excitation of the optical dipole, which is now elongated along the in-plane direction. Also, we demonstrate combining V_{si} with a plasmonic silver nanopan cavity which has both transverse electric (TE) and magnetic (TM) modes [7].

To demonstrate SiC nanowires with embedded V_{si}, we use a metal-assisted chemical etching (MACE) technique (Figure 1a) [6]. First, a monolayer polystyrene bead array is dispersed on entire SiC chip using DI-water batch (Figure 1b). Next, the diameter of the beads are reduced to 260 nm to free up space between the beads via reactive ion etching (RIE) as shown in Figure 1c. Then we obtain Pt mesh via typical metal deposition method using e-beam evaporation (Figure 2d). The hole diameter of the Pt mesh determines the diameter of the SiC nanowire to be fabricated. Lastly, the SiC substrate with the PT mesh is immersed in etching solutions of $HF:H_2O_2:H_2O$ (volume ratio = 5:1:6) at room temperature while Pt mesh act as an etching catalyst. The etching front of the SiC substrate moves downward vertically, which results in the formation of vertical SiC nanowire arrays.

After being cleaved and transferred onto the Si/SiO_2 substrate, we perform optical measurements of the single nanowires using confocal laser microscope setup with continuous-wave 785 nm laser and two scanning mirrors at 10 K. The light emission from the nanowire is collected by objective lens and sent to avalanche photodiodes or monochromator/charge-coupled device via optical fibers. Figure 2a shows the measured photoluminescence (PL) intensity map of the SiC nanowire at 10 K. Bright emission spots are observed at the end of the nanowire probably due to scattered emission at the end facet of it. Additionally, the PL spectrum measured at the brightest spot exhibit three emission peaks at 859.1 nm, 861.6 nm,

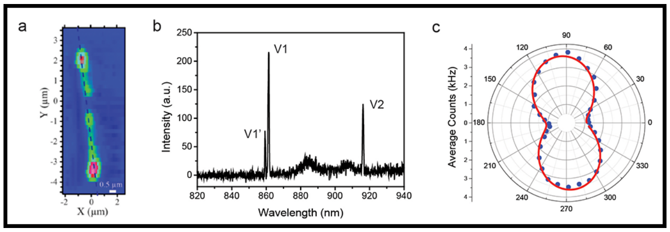

Figure 2: (a) Measured PL intensity map for the SiC nanowire on the Si/SiO_2 substrate. The pump power was 105 mW. Scale bar, 500 nm. (b) PL spectrum measured at the brightest spot in (a). (c) Polar plot of the emission as a function of the polarization angle. The line indicates the fitted curve.

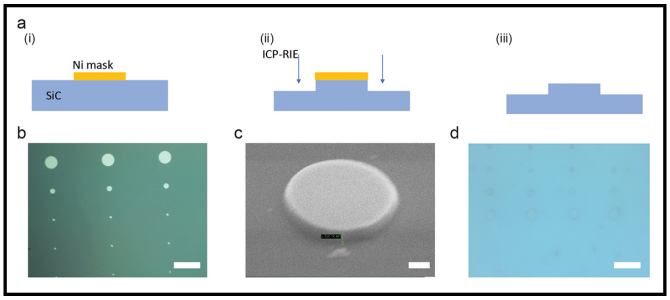

Figure 3: (a) Schematic of the fabrication procedures for SiC-Ag nanopan structure. (b) Optical microscope image of Ni masks on SiC substrate. Scale bar, 20 mm. (c) SEM image of the SiC disk prior to silver encapsulation. Scale bar, 500 nm. (d) Optical microscope image of the SiC-Ag nanopan structure from the back side of the wafer. Scale bar, 20 mm.

and 914.1 nm, which corresponds to the V1', V1, and V2 emission, respectively. This means that elongation of optical dipole along the in-plane direction enables observation of all emission lines under free-space laser pumping. To verify the optical dipole orientation of the emission, we performed emission polarization measurements. Figure 2c shows the emission polarization data obtained from the same spot used in Figure 2b and the corresponding fitting curve obtained using a cos2(q) fitting function. The emission polarization visibility is calculated to be 76% elongated along axial direction of the nanowire as expected.

Next, to demonstrate a plasmonic cavity coupled V_{si} in 4H-SiC, we employ silver nanopan resonator encapsulating the SiC microdisk structure. Figure 3a shows the fabrication procedure. First, a circular shape Ni mask with a thickness of 100 nm is deposited on 4H-SiC wafer which contains V_{si} using e-beam lithography and metal evaporation technique (Figure 3b). Next, inductively coupled plasma-reactive ion etching (ICP-RIE) is performed to etch the SiC layer (Figure 3c), and subsequently the Ni mask is removed using a Ni etchant (Figure 3d). After removing the Ni mask, 400.nm-thick silver layer is coated on the whole surface of the SiC disk substrate using an e-beam evaporator.

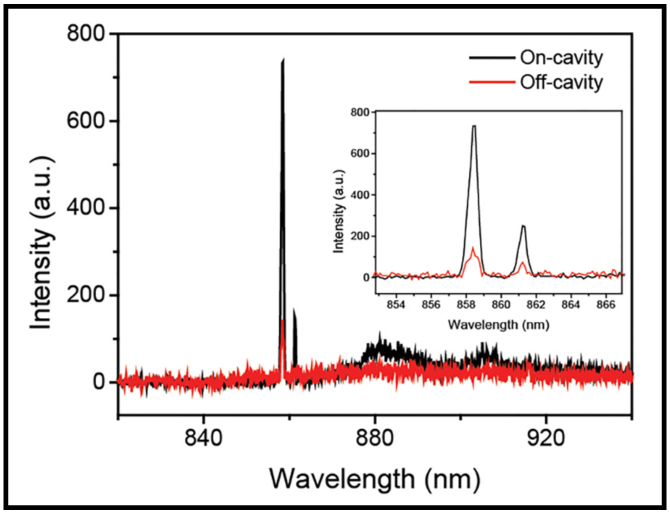

Figure 4: PL spectra measured at the nanopan (black) and the flat substrate (red). Inset shows the close-up of the emission peaks.

To access initially the characteristics of the nanopan combined V_{si}, we optically pump the nanopan region using a 785 nm continuous-wave laser and compare the emission spectrum to that from the flat surface at 10 K. We observe a 4-fold enhancement of V1' emission and 5-folds enhancement of V1 emission at the same time (Figure 4). The V1' emission is polarized along in-plane direction is predicted to couple to the TE whispery gallery mode (WGM), whereas V1 emission is probably coupled to the TM WGM.

Conclusions and Future Steps:

In this work, we demonstrate the integration of V_{si} in 4H-SiC with two types of nanostructures that enable us to excite the V1 emission via free-space laser pumping. In the future, we plan to perform the time-resolved PL measurements to extract the Purcell factor of this cavity-coupled emitter system. Also, it might be possible to apply microwave excitation to the emitter to mix the ground spin states, which will enable us to observe photoluminescence excitation (PLE) under resonant excitation.

References:

[1] Lukin, D., et al., Nat. Photonics 14, 330-334 (2020).
[2] Crook, A., et al., Nano Lett. 20, 3427-3434 (2020).
[3] Nagy, R., et al., Nat. Commun. 10, 1954 (2019).
[4] Widmann, M., et al., Nat. Mater. 14, 164-168 (2015).
[5] Babin, C., et al., Nat. Mater. 21, 67-73 (2022).
[6] Kim, J., et al., Nat. Nanotechnol. 12, 963-968 (2017).
[7] Kwon, S., et al., Nano Lett. 10, 3679-3683 (2010).