Purcell Enhancement of a Single Silicon Carbide Color Center with Coherent Spin Control

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ABSTRACT: Silicon carbide has recently been developed as a platform for optically addressable spin defects. In particular, the neutral divacancy in the 4H polytype displays an optically addressable spin-1 ground state and near-infrared optical emission. Here, we present the Purcell enhancement of a single neutral divacancy coupled to a photonic crystal cavity. We utilize a combination of nanolithographic techniques and a dopant-selective photoelectrochemical etch to produce suspended cavities with quality factors exceeding 5000. Subsequent coupling to a single divacancy leads to a Purcell factor of \( \sim 50 \), which manifests as increased photoluminescence into the zero-phonon line and a shortened excited-state lifetime. Additionally, we measure coherent control of the divacancy ground-state spin inside the cavity nanostructure and demonstrate extended coherence through dynamical decoupling. This spin-cavity system represents an advance toward scalable long-distance entanglement protocols using silicon carbide that require the interference of indistinguishable photons from spatially separated single qubits.

KEYWORDS: Silicon carbide, divacancy, single spin defect, Purcell enhancement, coherent spin control, photonic crystal cavity
Purcell factor, which quantifies an excited state’s lifetime reduction as a ratio of emission rates\(^{22}\):
\[
F \equiv \frac{\Gamma_{\text{cavity}}}{\Gamma_{\text{bulk}}} = F_1 \cdot F_2 \cdot \frac{3Q}{4\pi^2 V} \left( \frac{\lambda_{\text{cavity}}}{n} \right)^3 + 1
\]

where \(\Gamma_{\text{cavity}}\) and \(\Gamma_{\text{bulk}}\) are the cavity-enhanced and unmodified emission rates, with \(F = 1\) defining no enhancement. For the photonic cavity, \(Q\) is the quality factor, \(V\) is the mode volume, \(\lambda_{\text{cavity}}\) is the resonant wavelength, and \(n\) is the index of refraction. The terms \(F_1\) and \(F_2\) represent spatial overlap and spectral matching between the emitter and cavity mode, respectively, and are both equal to 1 in the case of perfect coupling (see Supporting Information). In recent work, cavity-defect systems in both diamond and silicon carbide have featured photonic crystal cavities with high quality factors (\(\sim 10^3 - 10^4\)) and small mode volumes (\(\sim (\lambda/n)^3\)).\(^{25-30}\) For silicon carbide, in particular, its high-Q nanophotonic capabilities,\(^{31,32}\) intrinsic spin-defect emitters, and wafer-scale doping control situates it to be a highly promising platform for integrated spin-photonic systems. However, despite SiC’s potential, photonic integration with single \(\text{VV}^0\)’s remained unexplored.

In this Communication, we fabricate nanobeam photonic crystal cavities in 4H-SiC and couple them to single \(\text{VV}^0\)’s. We start with a description of the photonic cavity design and fabrication process. We then characterize a single \(\text{VV}^0\) within the cavity structure at cryogenic temperatures. When the cavity is tuned into resonance with the \(\text{VV}^0\), we observe a Purcell enhancement of \(\sim 50\) and an improvement of the Debye–Waller (DW) factor from \(\sim 5\%\) to \(\sim 70\% - 75\%\). Lastly, we demonstrate microwave control of the ground-state spin and measure spin coherence times. This union between single defect control and cavity-emitter interactions results in significant increases in the \(\text{VV}^0\)’s ZPL emission with coherent electron spin states, establishing important groundwork for single-shot readout and scalable remote spin entanglement using defect spins.

**Cavity Fabrication and Characterization.** To create a photonic nanocavity, light must be confined in all three dimensions. Archetypal structures employ a submicron thin slab of dielectric material to provide out-of-plane confinement through total internal reflection and a patterning of Bragg mirrors to provide in-plane confinement. This results in either a one-dimensional (1D) or two-dimensional (2D) photonic crystal design, with both systems demonstrating high quality factors with small mode volumes.\(^ {33,34}\) For this work, we select a 1D nanobeam structure due to its more compact size and successful demonstration in previous work.\(^ {26,27}\) We use the general design outline in work by Bracher et al.,\(^ {27}\) where circular holes are tapered to ellipses at the center of the nanobeam. This forms a photonic cavity, with a simulation of the resonant mode shown in Figure 1a and simulated quality factors typically in the range of \(\sim 10^3 - 10^4\).
To form the nanobeam cavities, we utilize electron beam lithography for in-plane patterning and photoelectrochemical (PEC) etching for creating an undercut structure.\textsuperscript{35,36} The fabrication procedure, outlined in Figure 1b, begins with electron beam lithography to define a thin nickel mask with evaporation and lift-off. Next, a SF$_6$-based inductively coupled plasma (ICP) etches through the silicon carbide in the regions not protected by the nickel. After an acid clean to remove the metal, a PEC etch and subsequent HF clean selectively etches the layer of p-type 4H-SiC 400 nm below the top surface, suspending the nanobeams. A scanning electron microscopy (SEM) image of a representative device is shown in Figure 1c. The nanobeams appear smooth both on the topside and sidewalls of the beams, with relatively smooth and vertical etched holes. We employed a variety of cavity dimensions to create cavity resonances that include ZPLs for each of the (\(hh\)), (\(kk\)), and (\(kh\))\textsuperscript{VV0}s (see Supporting Information for nomenclature). Several resulting cavities were then characterized for optical resonances with photoluminescence spectra collected using 905 nm excitation. For one such nanobeam, we measured a quality factor of \(\sim 5 \times 10^3\) (Figure 1d) that was typical for photonic cavities in this sample.

**Single VV0 Characterization.** After creating defects with an electron irradiation procedure (see Supporting Information), we characterize a single VV0 coupled to the cavity in Figure 1d. Figure 2a shows a spatial PL scan taken at 5 K with off-resonant (905 nm) excitation and the cavity off/on resonance with an \(\sim 1078\) nm VV0 transition. Subsequent photoluminescence excitation (PLE) measurements reveal two peaks at frequencies of 277.984 and 278.027 THz (Figure 2b). We then perform pulsed optically detected magnetic resonance (ODMR) with resonant optical excitation and a nearby wire-bond to drive microwave spin transitions. This results in an ODMR peak centered at 1.328 GHz (Figure 2c, center), which is closest to the (\(hh\))\textsuperscript{VV0} transition at 1.336 GHz.\textsuperscript{37} As we vary the strength of an applied c-axis oriented magnetic field, this resonance separates into two lines due to a Zeeman splitting (Figure 2c). The observed shifts at \(\sim 2.76\) MHz/G match closely with the electron gyromagnetic ratio of 2.8 MHz/G found in the c-axis (\(hh\)) and (\(kk\)) defects.\textsuperscript{37} The presence of only one ODMR peak under zero magnetic field indicates that the transverse zero-field splitting (\(E_i\)) is approximately zero in the VV0 spin Hamiltonian,\textsuperscript{5} which is also consistent with a c-axis oriented VV0. If we instead apply off-resonant optical excitation, we observe ODMR with a negative contrast that matches previous work with (\(hh\))\textsuperscript{VV0}s.\textsuperscript{37} Thus, while the ZPL of this defect matches the (\(kh\))\textsuperscript{VV0} wavelength (\(\sim 1078\) nm), the c-axis spin orientation and the off-resonant ODMR contrast sign indicate the presence of an (\(hh\))\textsuperscript{VV0}. We attribute this behavior to a highly strained environment (see Supporting Information), likely due to the high doping levels used during growth.\textsuperscript{38–41}
Additionally, we confirm the presence of a single optical emitter with a second-order correlation measurement under resonant excitation (Figure 2d). The antibunching dip \( g^{(2)}(0) \leq 0.5 \) indicates the presence of a single emitter, and the value \( g^{(2)}(0) = 0.096 \) indicates that this \( \text{VV}^0 \) is an excellent single-photon source. Meanwhile, the observed bunching behavior is indicative of nonradiative transitions from the excited state. Solving the rate equations for this system (see Supporting Information) and fitting it to the observed \( g^{(2)} \) gives an effective dark state lifetime of \( \tau_{\text{dark}} \approx 60.7 \text{ ns} \). The nonradiative transitions are likely a combination of intersystem crossing (ISC) decays and \( \text{VV}^0 \) ionization. Although the ISC rates have not been explored in 4H-SiC \( \text{VV}^0 \), in the 3C \( \text{VV}^0 \) they were estimated to be on a similar time scale of \( \sim 50-100 \text{ ns} \). Additionally, \( \text{VV}^0 \) ionization can be observed in our experiment under lower laser powers as a blinking behavior. Without a sufficiently strong 905 nm charge reset pulse, the \( \text{VV}^0 \) may be trapped in a nonradiative charge state for long periods of time, as has been observed in other work.\(^{42,43}\)

**Purcell Enhancement.** With a tunable photonic nanocavity and a \( \text{VV}^0 \) emitter within its mode volume, we are able to observe Purcell enhancement of the \( \text{VV}^0 \)'s optical emission. When the cavity is off resonance with the \( \text{VV}^0 \) and addressed with an off-resonant 905 nm laser, two peaks at \( \sim 1078 \text{ nm} \) can be observed in a PL spectrum (Figure 3a, top inset). These peak locations and their \( \sim 40 \text{ GHz} \) splitting correspond to the PLE peaks observed under resonant excitation (Figure 2b). We will label the lower/higher energy transitions as the lower/upper branches of the orbital fine structure, respectively.\(^{17}\) When the cavity is then tuned into resonance with the defect, a significant increase in emission is observed, with selective enhancement of the lower branch shown in Figure 3a. This count rate increase correlates closely with the Purcell factor, which in this case is given by

\[
F = \frac{I_{\text{ZPL on}}}{I_{\text{ZPL off}}}
\]

where \( I_{\text{ZPL on}} \) and \( I_{\text{ZPL off}} \) represent the ZPL intensity when the cavity is on resonance and blueshifted off resonance, respectively. This equation matches the form of eq 1, with ZPL intensities acting as measures of emission rates. Integrating the counts under the two peaks when off and on cavity resonance gives Purcell factors of \( \sim 53 \) (Figure 3a) and \( \sim 16 \) (see Supporting Information) for the lower and upper branches, respectively. This difference could be explained by differing optical dipole orientations of the two branches, which would give varied matching to the cavity mode. A similar effect was observed for cavity enhancement of \( \text{V}_{\text{Si}} \) defects in silicon carbide, which also displays two rotated optical dipoles.\(^{27}\)

To corroborate the presence of Purcell enhancement, we directly measured excited-state lifetimes with the cavity on and off resonance with the \( \text{VV}^0 \). Using resonant excitation pulses from an electro-optic modulator, we observe an off-resonance lifetime of \( \tau_{\text{off}} = 15.7 \pm 0.3 \text{ ns} \) (consistent with bulk measurements\(^{17}\)) and an on-resonance lifetime of \( \tau_{\text{on}} = 5.3 \pm 0.1 \text{ ns} \) (Figure 3b). The relationship between measurable lifetimes and the Purcell factor is given by

\[
F = \frac{\tau_{\text{dark}}(\tau_{\text{off}} - \tau_{\text{on}})}{\alpha \tau_{\text{on}}(\tau_{\text{dark}} - \tau_{\text{off}})} + 1
\]

where, for the \( \text{VV}^0 \), \( \tau_{\text{dark}} \) is the combined lifetime of all nonradiative decays, \( \tau_{\text{off}} \) is the lifetime off cavity resonance, \( \tau_{\text{on}} \) is the lifetime on cavity resonance, and \( \alpha \) is the intrinsic DW factor (see Supporting Information). Combining our measurements with a previously measured \( \sim 5.3 \text{ %} \) DW factor\(^{17}\) gives a Purcell factor of \( F \approx 51 \), which is in good agreement with the value of \( F \approx 53 \) from spectral measurements.

One of the direct consequences of a Purcell enhancement is an increased Debye–Waller factor, which follows the relation

\[
F = \frac{\beta(\alpha - 1)}{\alpha(\beta - 1)}
\]

where \( \alpha \) and \( \beta \) represent the \( \text{VV}^0 \)'s DW factor off and on cavity resonance, respectively (see Supporting Information). For our sample, spatially varying background luminescence from nitrogen vacancy (NV) centers in the n-doped silicon carbide\(^{6,7,16,44}\) makes it difficult to directly integrate spectrometer counts to obtain \( \alpha \) and \( \beta \). However, we do observe background-subtracted count rates of 120 and 460 kcts/s when off and on cavity resonance, which allows us to estimate an on-resonance DW factor of \( \beta \approx 75 \% \) and a Purcell factor of \( F \approx 54 \) (see Supporting Information). These numbers match well with the Purcell factors of \( \sim 53 \) and \( \sim 51 \) obtained from Figure 3 and the corresponding 74% DW factor from eq...
the cavity is on resonance. This is a selective but still display a spectral overlap from the individual optical spin transitions are moderately observed for o

Rabi oscillations with a readout contrast of 15% achieved for SiC spin defects. Combined with the lifetime enhancement 460 kCts/s is among the highest count rates ± 0.2, ∼ 40% (Figure 4a). It should be possible to achieve higher contrast with a slight narrowing of line widths.

Coherent Spin Control. While addressing the cavity VV⁰ with resonant microwave pulses and resonant optical excitation, we drive coherent Rabi oscillations between the spin sublevels. To address a single microwave transition, we apply a small magnetic field of ∼6 G parallel to the c-axis to Zeeman split the spin resonances and then focus on the ||0) to ||+1) transition at 5 K. Under these conditions, we observe Rabi oscillations with a readout contrast of ∼40% (Figure 4a). This contrast level is significantly higher than the typical 10−15% observed for off-resonant Rabi oscillations but below the ∼94−98% levels observed with resonant excitation. This indicates that individual optical spin transitions are moderately selective but still display a spectral overlap from the ∼4−5 GHz PLE optical line widths broadened from spectral diffusion. Given that individual spin transitions for c-axis VV⁰’s are typically separated by a few gigahertz, it should be possible to achieve higher contrast with a slight narrowing of line widths.

We then apply Ramsey interferometry and Hahn echo pulse sequences on the same ||0) → ||+1) transition to determine the spin dephasing and spin coherence times. Under a c-axis magnetic field of ∼218 G, we obtain a dephasing time of T₂ = 592 ± 18 ns (Figure 4b) and a decoherence time of T₂ = 9.3 ± 2.0 μs (Figure 4c). Under a lower magnetic field of ∼6 G, we obtain similar times of T₂ = 605 ± 33 ns and T₂ = 7.4 ± 0.6 μs (see Supporting Information), indicating that coherence in this sample is not primarily limited by the SiC nuclear spin bath. Collectively these times are shorter than previous reports of T₂ ≈ 1−2 μs and T₂ ≈ 1.2 ms in bulk SiC c-axis VV⁰’s with the discrepancy likely arising from magnetic dipole interactions with electron spins from n-type dopants and surface charge traps. It is worth noting that, for a VV⁰ located in an unfabricated NIX epilayer, we measure an improved T₂ = 4.01 ± 0.38 μs and T₂ = 200 ± 27 μs under ∼218 G (see Supporting Information). Therefore, it appears the fabrication process introduces additional decoherence sources, potentially from increased surfaces or crystal damage. However, there is a variety of approaches to offset these effects. The PEC undercut could likely be performed at lower doping levels, and postfabrication surface treatments could potentially be used to limit the presence of surface charge traps.

In the regime where T₂ is significantly longer than T₂, it is possible to extend spin coherence through dynamical decoupling sequences. For the cavity VV⁰, in two separate
measurements we observe spin relaxation times of $T_1 = 1.02 \pm 0.47$ ms and $T_1 = 2.43 \pm 1.58$ ms, placing a lower bound of $T_1 \geq 500 \mu s$ (see Supporting Information) and indicating that $T_2$ is not $T_1$ limited. This is expected for the VV0 at cryogenic temperatures, where $T_1$ has been measured to be 8–24 ms at 20 K.37 As a proof of principle, we then employ a Carr–Purcell–Meiboom–Gill (CPMG) sequence51 at low field with one, two, and four $\pi$ pulses (Figure 4d). Strretched exponential fits give $T_2$ values of $6.8 \pm 0.7$, $11.0 \pm 1.9$, and $19.5 \pm 6.1 \mu s$, indicating the viability to extend spin coherence in SiC nanostructures with dynamical decoupling up to the $T_1$ limit.

## DISCUSSION

Experimentally, increases in both the Debye–Waller factor and PL count rate have significant implications for enhancing the entanglement generation rate between VV0 spins. In the Barrett-Kok protocol,52,53 for example, the entanglement could be achievable in future studies.

Photonic structure and photonically enhanced entanglement could be from nearby doped regions, other nearby defects and impurities, or surface charge traps. It is worth noting that the fabricated process or fabrication details, VV0 nomenclature conventions, and cavity tuning procedure. Additional cavity VV0 spin coherence measurements and measurements with off-resonant optical excitation. Characterization of bulk defects in the NINPN material. Observation of Purcell enhancement of upper branch of the cavity VV0. Discussion of modeled cavity mode with relevant dimensions. Details on photoelectrochemical etching. Details on rate equations used to model the system. Derivations of Purcell factor expressions. Discussion of the effect of strain on the cavity VV0 (PDF)

## ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.nanolett.0c00339.

Details on VV0 creation procedure, SiC doping, fabrication details, VV0 nomenclature conventions, and cavity tuning procedure. Additional cavity VV0 spin coherence measurements and measurements with off-resonant optical excitation. Characterization of bulk defects in the NINPN material. Observation of Purcell enhancement of upper branch of the cavity VV0. Discussion of modeled cavity mode with relevant dimensions. Details on photoelectrochemical etching. Details on rate equations used to model the system. Derivations of Purcell factor expressions. Discussion of the effect of strain on the cavity VV0 (PDF)

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Author Contributions
A.C. developed, fabricated, and measured the photonic crystal devices. C.A. and H.L. aided with fabrication procedures. C.A., K.M., and A.B. aided with optical characterization, cryogenic spin measurements, and analysis of data. S.B. assisted with resonant lifetime measurements and development of the three-level $\chi^{(3)}$ model. D.B., X.Z., and E.H. were instrumental in the resonant lifetime measurements and development of the three-level $\chi^{(3)}$ model. D.B., X.Z., and E.H. were instrumental in the development of both the PEC etch of SiC and SiC photonic devices. H.A. and T.O. performed electron irradiation of SiC samples to create divacancies. D.A. oversaw and directed the project. A.C., C.A., K.M., A.B., H.L., and S.B. all contributed with the drafting of the manuscript.

Notes
The authors declare no competing financial interest.

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REFERENCES