

Quantum magnetometer chip based on industrially scalable 4H-SiC technology

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This work presents an industrially scalable, power-efficient quantum magnetometer chip based on 4H-silicon carbide (SiC) technology, leveraging wafer-scale fabrication techniques to optimize V2 silicon-vacancy color centers for reproducible fabrication. The integration of these color center ensembles into a planar silicon carbide waveguide enables efficient excitation of a large ensemble and simplifies fluorescence extraction compared with standard confocal methods. We report continuous wave (cw) optically detected magnetic resonance measurements, complemented by Rabi, Ramsey, and Hahn-echo sequences, which demonstrate the coherent capabilities of the large embedded ensemble of V2 centers. Based on the data, our device exhibits sensor shot-noise-limited sensitivities of around $30 \text{ nT}/\sqrt{\text{Hz}}$, 2–3 orders of magnitude lower compared with more complex confocal techniques. This concept simplifies the quantum sensor architecture, enhances sensitivity, and streamlines optical excitation and collection, thereby paving the way for the development of next-generation SiC-quantum sensing technologies.

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I. INTRODUCTION

Spin-based quantum sensing based on N-V-centers in diamond [1,2] has been developed for more than 10 years and has already found its way into commercialization in the form of a multitude of companies and startups employing its physical principles in areas ranging from biotech to material analysis [3]. However, there are major obstacles for diamond-based quantum technologies. Besides being a much more expensive material than silicon carbide (SiC), it does not fare well within the semiconductor manufacturing ecosystem, as it cannot leverage existing scalable wafer-based processes that come with high-volume SiC fabrication [1,4–7]. Silicon carbide has a wide band gap and hosts stable crystal defects that give rise to solid-state spin quantum systems with advantageous quantum properties [8–14]. In this work, the negatively charged V2 color center is used [15,16], which is formed by the absence of a silicon atom within a cubic lattice site and a subsequent

capture of a single electron. Its crystal structure is shown in Fig. 1. The system can be optically excited off-resonantly via 785 nm, resulting in a zero-phonon line at a wavelength of 917 nm and a phononic sideband extending up to 1100 nm [17].

Even though silicon carbide is a younger quantum technology platform compared with diamond, recent demonstrations of defect systems show quantum properties on par with diamond, making SiC a very promising candidate for high-volume quantum devices [18]. Quantum sensing can be implemented for different sensing parameters such as magnetic and electric fields, temperature, pressure, and rotation [19–24], each requiring slightly different implementations but fundamentally relying on the same physical principle: detection of spin-dependent transitions. Here, in order to achieve high sensitivity, one requires a strong fluorescence signal contrast, narrow linewidth, and a large number of fluorescence photons [6,25,26]. One method in order to increase the number of fluorescence photons is to expand ensemble density. However, higher ensemble densities lead to higher crystal damage, in turn causing severe deterioration of quantum properties, leading, for example, to increased linewidth and reduced contrast.

Another strategy is to increase the active volume while keeping the ensemble density constant. However, this requires an optical waveguide [27–30] in order to

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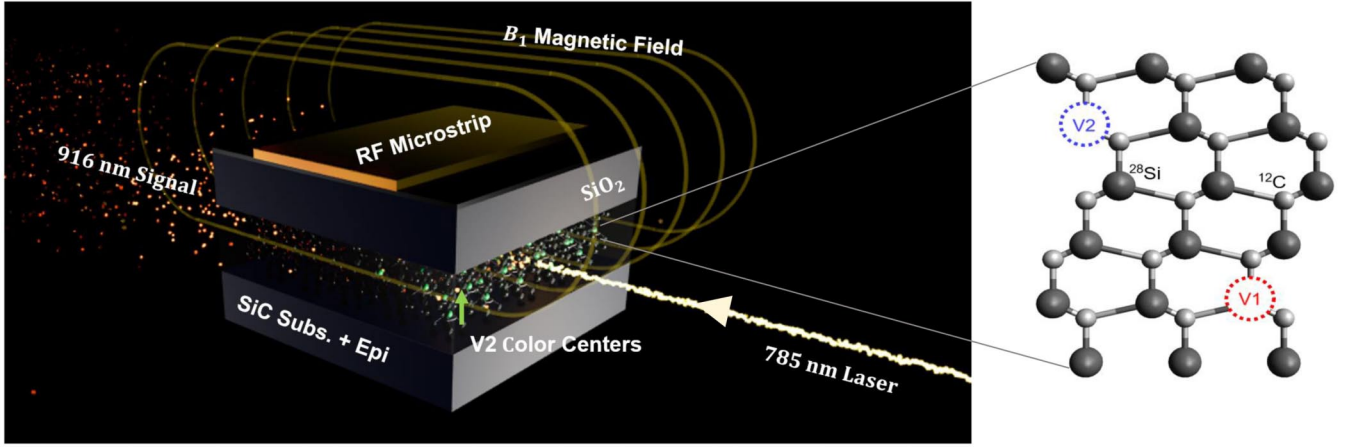


FIG. 1. Illustration of the sensor concept: The planar monolithic 4H-SiC waveguide is formed as a sandwich structure consisting of a n^{++} doped substrate, an intrinsically doped core, and a very thin layer of SiO_2 on top. The V2 C3_v -symmetry axis points perpendicular to the sensor plane, enabling efficient rf-excitation by a simple microstrip design as shown above or alternatively by a coil. On the right, a schematic of the 4H-SiC crystal structure is shown, with corresponding silicon-vacancy color centers, V1 and V2.

efficiently excite the color centers and extract their signal, which poses a technological challenge on its own. In the absence of a photonic waveguide, the required optical excitation power over a large volume increases, affecting the overall energy consumption and therefore competitiveness of the sensor system. Furthermore, the unconfined emission of photons reduces collection efficiency, in turn leading to lower sensitivity. In order to circumvent those problems, the principle in this work incorporates a monolithic SiC waveguide, as shown in Fig. 1(a). This photonic concept [31] is based on exploiting the change in the refractive index of SiC when changing the doping level of the semiconductor. By using a n^{++} doped substrate as bottom cladding, a lowering of the refractive index is achieved. On top, a very thin layer of SiO_2 is deposited, causing a strong change in the refractive index compared with the intrinsically doped core, leading to asymmetric modes along the vertical stack. The number of waveguide modes is dependent on the thickness of the core layer [31]. Additionally, the strong jump in the refractive index between the core and upper layer has the effect of strongly confining the evanescent portion of the wave propagating in the upper cladding, avoiding coupling to conductive structures on top of the SiO_2 . The photonic waveguide shows near-identical behavior for wavelengths from around 780 up to 1200 nm, guiding both the excitation and the fluorescence light of the V2 color centers efficiently with low loss.

While the photonic performance of such devices was already demonstrated [28,31], the work was limited to optical characterization of planar SiC waveguides. No quantum measurements were shown in this regard. In the following, we demonstrate both types of measurements: continuous wave (cw) and coherent pulsed quantum protocols on a large spin ensemble integrated within such a waveguide.

II. METHODOLOGY

Bulk samples were prepared by chemical vapor deposition (CVD) of a 10- μm -thin and low-nitrogen-doped [31] SiC epitaxial layers on n^{++} 4H-SiC substrates. Proton implantation was employed to generate depth-controlled vacancy distributions, with parameters selected using Stopping and Range of Ions in Matter (SRIM) simulations [32]. The simulated peak of the crystal damage profile is positioned at target depths of approximately 3 and 5 μm inside the epitaxy layer.

The simulations were performed for H^+ incident for different implantation angles between 5° and 10° from the surface normal into stoichiometric SiC (50% Si and 50% C; density 3.21 g cm^{-3}), using damage parameters $E_{d,\text{Si}} = 21$ eV and $E_{d,\text{C}} = 35$ eV, lattice binding $U_1 = 2\text{--}3$ eV, and surface binding energies $U_{s,\text{Si}} = 4.7$ eV and $U_{s,\text{C}} = 7.4$ eV. While standard SRIM defaults were used for baseline consistency, they potentially underestimate carbon displacement compared with experimental observations of higher carbon-vacancy concentrations [33]. The dose of the proton implantation was chosen between $1 \times 10^{12}\text{--}1 \times 10^{14}$ cm^{-2} and an energy of 400 keV for the generation of V2 ensembles. For comparison, electron irradiation was performed on other samples to realize a homogeneous depth distribution of defects across the wafer, leveraging the comparatively long mean free path of electrons in SiC. The energy for the electron implantation was chosen to be 10 MeV, while the dose was chosen to be 1×10^{16} cm^{-2} in order to yield a dense ensemble of V2 vacancies.

All irradiated samples underwent high-temperature annealing at 600 $^\circ\text{C}$ for 30 min to activate vacancies and mitigate residual lattice damage. Depth-resolved mapping of generated V2 profiles was conducted by confocal microscopy, including side-scans using an immersion

objective to reconstruct emitter distributions along the implantation axis; continuous wave optically detected magnetic resonance (cw-ODMR) measurements were performed at the centers of the implanted regions using a confocal setup where the rf-power was delivered through an impedance-unmatched wire, as in Ref. [9]. Low-temperature photoluminescence spectroscopy was carried out on both proton- and electron-irradiated samples to probe the zero-phonon line near 917 nm and the associated phonon sideband. Charge-state considerations for the V2 center in low n-doped epitaxial material [11] were investigated by correlating the residual nitrogen-doping profile with the zero-phonon-line (ZPL) strength. This was done by spectrally resolving V2 photoluminescence excited by a 730 nm laser at 0.5 mW, measured at low temperature (8 K) under vacuum (1.4×10^{-5} mbar). A statistical sampling of points along the depth of the epitaxial layer was acquired; for each point, the spectrum was analyzed and the ZPL signal at 917 nm was extracted.

SiC chips with integrated planar waveguides were fabricated in a high-volume 6-inch wafer process. The photonic SiC epitaxy was grown to a thickness of 9 μm , considering a nitrogen background concentration at the target depth suitable for stabilizing the V2 color centers. A thin plasma-enhanced CVD oxide layer was deposited on top of the active layer to form the upper cladding, resulting in a dual-mode waveguide stack, as shown previously in Ref. [31]. A proton implantation energy of 600 keV was chosen to guarantee that the position of the guided optical mode maxima is consistent with the depth of the generated V2 color centers. Postimplantation annealing was performed with the same recipe as for the bulk samples to reduce residual implantation damage. The wafers were finally diced into $3 \times 3 \text{ mm}^2$ chips using an optimized process engineered to achieve low optical surface roughness and thus minimal coupling losses, as shown in Ref. [31].

For the characterization of those samples, a custom-built transmission fluorescence setup was used, as shown in Fig. 3(b). A 785 nm single-mode signal generated from a fiber laser (pigtailed Hübner Photonics Cobolt 06-01) was coupled into a single-mode polarization-maintaining fiber, which was then edge-coupled into the SiC waveguide containing the V2 color center ensemble. On the opposite side of the SiC die, an objective (Nikon OFN25, 0.3 NA) was used to collect the emitted light. Next in the beam path, an optical long-pass filter with a cutoff wavelength of 850 nm (Thorlabs FELH0850) was used to filter out any unwanted excitation light. The V2 fluorescence light passed through a beamsplitter, where one arm was focused onto a standard CMOS camera (IDS uEye), while the other was focused onto an avalanche photodiode (APD440A) with an integrated transimpedance amplifier (TIA) and variable gain. Because of the vertical photonic confinement but lateral free evolution [31], the CMOS camera shows a quasi-elliptical profile of the emitted light. The

output voltage of the TIA was measured via a lock-in amplifier (Stanford Research Systems SR865A) (configuration 1, solid line) or a standard microcontroller (Arduino Uno Minima) (configuration 2, dashed line). On the transmitter side, we either controlled the signal generator (Rigol DG 2000) via serial connection with the lab-computer for cw measurements, which are not time-critical in terms of synchronization, or we used a programmable pulse generator, as in Ref. [34], depending on the configuration. The pulse generator synchronizes the lock-in frequency, which demodulates the resulting voltage signal coming from the avalanche photo-diode (APD). In each pulse sequence, five identical sequences were performed due to the low bandwidth of the APD (APD440), requiring time-averaging. This would not be necessary with a high-speed detector, fully capable of time-resolving the fluorescence response. In the low phase of the rectangular modulation (compare Fig. 4), just the laser was switched on, whereas in the high phase, also the rf-switch (Mini-Circuits ZASWA-2-50DR+) gets triggered, effectively modulating the signal.

The rf-signal was amplified by a 43 dB amplifier (Mini-Circuits LZY-22+) and passed through the microstrip before being dissipated in an attenuator (Microlab TB-80 MN) in order to avoid rf-reflections. Besides efficient photonic excitation and collection, a V2 spin-based quantum sensor additionally needs a radio-frequency (rf) field, termed B_1 , to drive spin transitions [35–37]. The strength of the excitation of the spin system in first-order perturbation is given by [25]:

$$P = \langle \Psi_b | B_1 S | \Psi_a \rangle, \quad (1)$$

where B_1 is the amplitude vector of the driving rf field and S is the tensor of spin matrices for the silicon-vacancy spin system, while Ψ_a and Ψ_b are the corresponding quantum states involved in the transition. This matrix element is maximized for a B_1 coupling orthogonal to the spin-system symmetry axis [25]. Accordingly, in our design, the crystal axis and therefore the C_{3V} -symmetry axis of the silicon vacancies point perpendicular to the sensor plane. This simplifies the task of designing an rf-microstrip with high B_1 homogeneity across most of the active region. One possibility is to deposit a metallization with a thickness of 3 μm on top of the SiO_2 , which generates a homogeneous field parallel to the sensor plane when current is applied. The B_1 fields at the center of the microstrip are calculated via Ansys finite-element simulations for an exemplary current of 200 mA at a frequency of 70 MHz at a distance of 3 μm with respect to the microstrip, and results are shown in Fig. 2(a). It is noted that homogeneity diminishes toward chip edges for V2 centers, causing effective ensemble dephasing; nonetheless, averaging over predominantly homogeneous regions supports robust pulsed control, and future designs can localize centers via implantation masks to high-homogeneity zones to mitigate

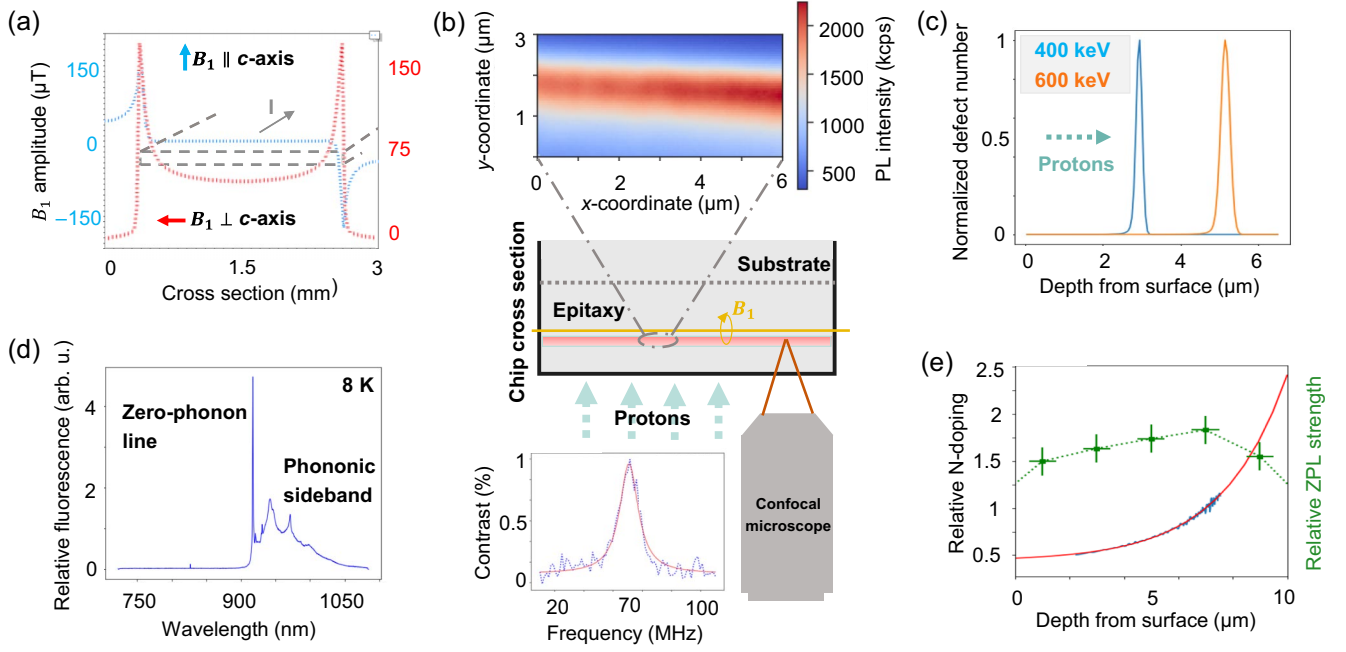


FIG. 2. (a) Calculated B_1 field distributions induced by a 70 MHz current parallel and orthogonal to the color center symmetry axis at a distance of 3 μm from the microstrip. (b) Confocal scan of the chip cross section, revealing a ribbon of V2 emerging from the proton implantation peak and a corresponding cw-ODMR measurement, fitted with a Lorentzian. (c) Simulated defect density distribution induced by protons implanted into 4H-SiC with 400 and 600 keV. (d) 8 K low-temperature spectrum of the V2 ensemble clearly showing the ZPL at 917 nm and its phononic sideband. (e) ZPL signal versus nitrogen-doping concentration of an electron-irradiated sample: for the nitrogen doping, 1 corresponds to $1 \times 10^{15} \text{ cm}^{-3}$, while the variation of the ZPL strength is around 20% from the maximum within the epitaxy.

this effect. In addition to this method, efficient coils within the range of V2 frequencies around the zero-field splitting can be designed for excitation, as well as for future iterations. These have the advantage of lower current consumption for the same B_1 amplitudes, however, require more complex packaging than the above-presented structure. The V2 itself was modeled using the Lindblad equation [38]

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H, \rho] + \sum_i \left(L_i \rho L_i^\dagger - \frac{1}{2} \{ \rho, L_i^\dagger L_i \} \right), \quad (2)$$

where ρ is the density matrix and $L_i, L_i^\dagger$ are an infinite set of jump operators acting on the Hilbert space. The mathematical form of the Lindblad interaction ensures that the trace of the density matrix stays constant. The full physical model is shown in Fig. 3(a). Here, only the ground state is modeled (first four levels) as a coherent quantum system, described via the Von-Neumann equation, and the excited and metastable states are modeled as a noncoherent rate model, in total using a 10-dimensional Hilbert space to account for all levels. The form of the Lindblad jump operator for the diagonal states is [38]:

$$L_i = \sqrt{R_i} |u_i\rangle \langle v_i|,$$

where $|u_i\rangle$ and $|v_i\rangle$ are the final and initial states of the transition and R_i the transition rate (1/s), where the values are extracted from Ref. [39]. Here, we note that those rates were measured at cryogenic temperatures and might deviate from room temperature. The Hamiltonian H in Eq. (2) is the standard V2 four-level ground state Hamiltonian [4], taking into account both the applied magnetic field B_0 and B_1 driving fields. The spin-lattice relaxation and the dephasing of the ground state are modeled with the following Lindblad operators, taken from Ref. [38]:

$$L_\alpha = \sqrt{2\alpha} S_x \quad L_\beta = \sqrt{2\beta} S_z.$$

The connection between those relaxation parameters and experimental quantities can be established by analyzing the corresponding dissipation matrices, yielding $\alpha = \frac{1}{3T_1}$ and $\beta = T_2^{-1} - \frac{5}{2}\alpha$. Combining T_1 data from Fig. 3(d) alongside the extracted T_2 value in Fig. 4(d), in the results section of this work, we estimate $\alpha = 2123 \text{ 1/s}$ and $\beta = 3.54 \times 10^5 \text{ 1/s}$.

III. RESULTS

Based on proton and electron implantation techniques, we conducted a comparative study in order to identify the

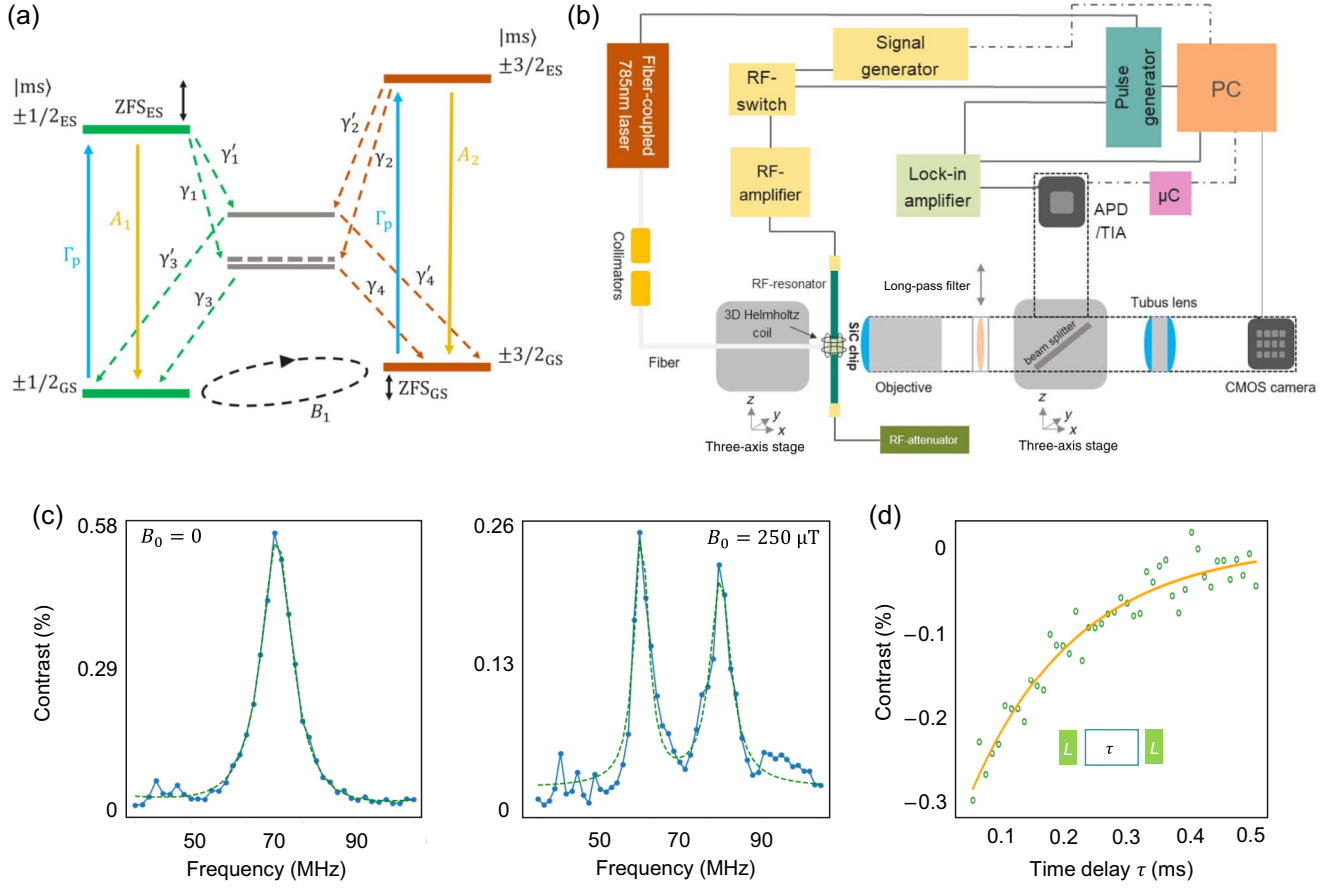


FIG. 3. (a) Hybrid quantum model for describing both the ground state coherently and the fluorescence dynamics of the V2. (b) Block diagram of the characterization setup for both continuous wave and pulsed measurements. (c) CW-ODMR measurements performed on the V2 ensemble embedded into the planar waveguide for the case of $B_0 = 0$ and $B_0 = 250 \mu T$, fitted with a single and double Lorentzian, respectively. (d) T1 measurement on the V2 ensemble in the waveguide by initializing the system with a first laser pulse and then reading out the fluorescence with a second laser pulse separated by a time-delay τ .

most effective method to generate V2 silicon vacancies. Proton implantation was performed on CVD-grown bulk epitaxies on n_{++} 4H-SiC substrates with different implantation energies and doses, followed by annealing as explained in the methodology section. The use of protons enables precise depth control, as they are completely stopped within the SiC bulk, with the applied energy determining the depth profile. Simulation results using the SRIM model [32] are presented in Fig. 2(c), illustrating the depth profiles for 400 and 600 keV protons, with peak depths of approximately 3 and 5 μm , respectively. Experimental verification of these results is provided in Fig. 2(b), which shows a chip irradiated with an energy of 400 keV, scanned from the side using a confocal setup with an immersion lens. The resulting depth profile of the generated V2 color centers reveals a peak located around 3 μm from the bottom edge, which confirms the simulation results. CW-ODMR measurements were performed at the center of the implantation ribbon with confocal microscopy at around 0.7 mW laser power and around 22 dBm rf-power through an impedance-unmatched wire, as in

Ref. [9]. This measurement yields an ODMR contrast of approximately 1% between the resonance peak and background of the plot. This result confirms the successful generation of a dense V2 ensemble. By analyzing the count rate, a peak ensemble density of around $350 \pm 80 \mu m^{-3}$ color centers can be inferred. In addition to proton implantation, electron implantation was performed. On both proton- and electron-irradiated samples, low-temperature spectra were measured, revealing a distinct ZPL at 917 nm, as well as the phononic sideband still visible at 8 K, as shown in Fig. 2(d). Because of the significantly smaller mass of electrons compared with protons, their comparatively long mean free path length allows them to pass through the entire wafer. It can thus be assumed that no implantation peak is present, resulting in a homogeneous depth distribution. This means that the strongest limiting factor is the local nitrogen doping and therefore the Fermi energy, affecting the formation energy of the silicon-vacancy charge state [11], where V2s are single-negatively charged (-1). By correlating the N-doping concentration (measured by standard capacitance-voltage measurement)

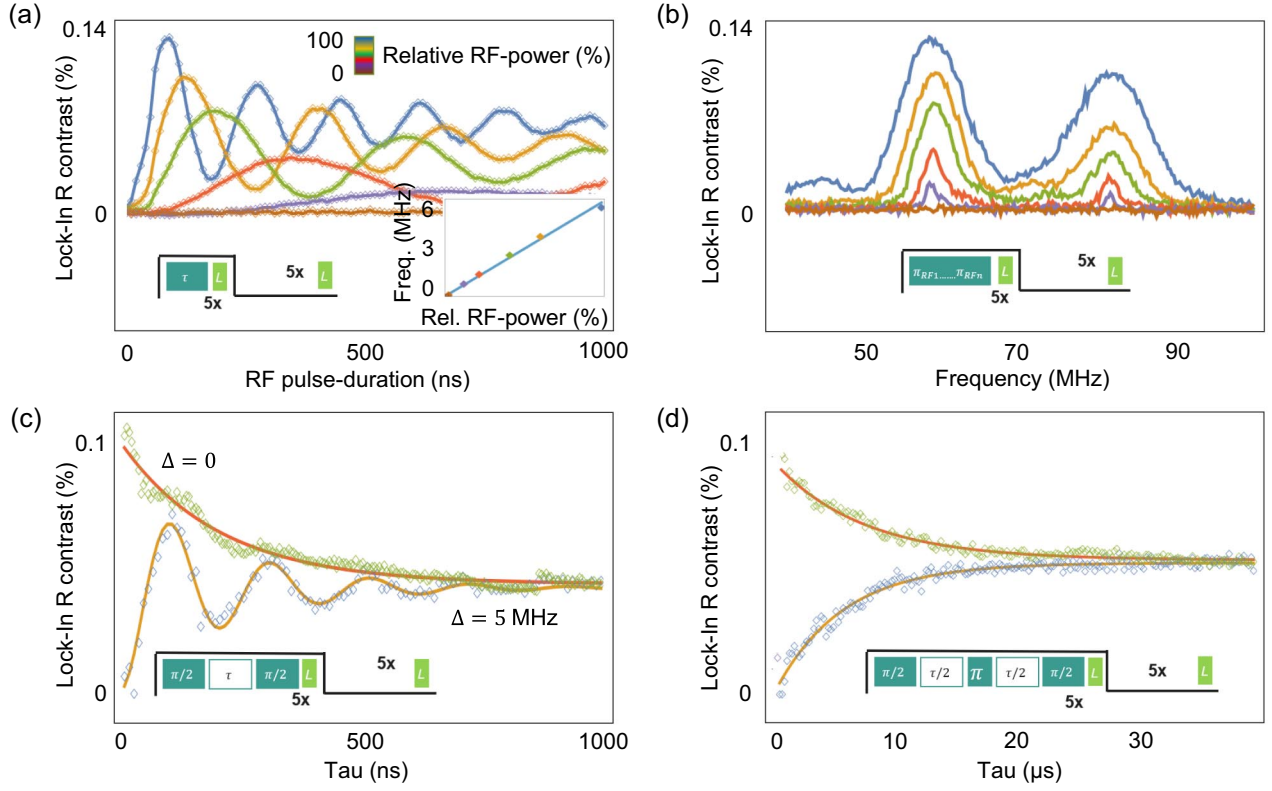


FIG. 4. Pulsed measurements performed on the V2 ensemble in the planar waveguide, consisting of $\pi/2$ or π rf-pulses, free evolution times τ , and laser initialization and readout pulses L : (a) Rabi oscillations for different B_1 amplitudes fitted with exponentially decaying harmonic, (b) Pulsed ODMR measurement for different amplitudes of B_1 , (c) Ramsey sequence for a detuning of 0 and 5 MHz fitted with a decaying exponential and an exponentially decaying harmonic for the case of detuning respectively, and (d) Hahn-echo sequence performed for two different phases of the $\pi/2$ pulse (x and y) fitted with a decaying exponential.

with the spectrally resolved low-temperature ZPL fluorescence as explained in the methodology section, an optimal N-doping concentration of around 10^{15} cm^{-3} can be inferred, as shown in Fig. 2(e). It should be noted that the experiment was repeated at the same electron energy with 1/10 of the implantation dose; no statistically significant shift in the optimum was observed. This could indicate that the silicon-vacancy concentration is too low, as an acceptor, to compensate the residual nitrogen donors and thereby lower the Fermi level.

Moving to the samples with integrated planar waveguide, first cw-ODMR measurements are performed for $B_0 = 0 \text{ } \mu\text{T}$ and $B_0 = 250 \text{ } \mu\text{T}$ for the $9 \text{ } \mu\text{m}$ waveguide by use of a custom-built 3D-Helmholtz coil, applying the magnetic field parallel to the symmetry axis, as shown in Fig. 3(c), at a laser power of 36 mW in the waveguide. To this end, the SiC chips are placed on a broadband printed circuit board-based microstrip manufactured on a Rogers 4003 C substrate, as shown in Fig. 3(b), with 3 mm width, which creates a very similar field structure as shown in the simulation, but with a different amplitude. The resulting contrast without a magnetic field is around 0.6% at zero field and 0.26% when a Zeeman splitting is induced. The shot-noise-limited sensitivity for cw-ODMR is given [6] by:

$$\eta_{\text{cw}} = \frac{4}{3\sqrt{3}} \frac{h}{g_e \mu_B} \frac{\Delta v}{C_{\text{cw}} \sqrt{R}}, \quad (3)$$

where h is the Planck constant, g_e is the Landé-factor for the system, μ_B is the Bohr magneton, Δv is the FWHM linewidth, C_{cw} is the cw-ODMR contrast, and R is the fluorescence photon number. We estimate a sensitivity below $270 \text{ nT}/\sqrt{\text{Hz}}$. In comparison, the confocal cw-ODMR (Fig. 2) delivers a sensitivity of around $40 \text{ } \mu\text{T}/\sqrt{\text{Hz}}$. The main driver of this increase is the increase in participating V2s due to the higher active volume. The lower contrast compared with the confocal study hints at the fact that the ensemble might not be optically saturated yet.

Subsequently, pulsed measurements are performed. To this end, the microstrip is changed to a home-built coil with 10 windings and a 3D-printed frame, which equally creates a magnetic field in the center of the coil but requires less current for the same B_1 compared with the sheet conductor in Fig. 2. This configuration provides greater power headroom, enabling faster coherent pulses that broaden the frequency response of the spin driving and reduce off-resonant pulse errors. While the coil geometry

was not simulated and thus lacks optimized homogeneity, it served as a successful feasibility demonstration that can be refined in future iterations through rigorous electromagnetic design. The laser initialization and readout times t_I and t_R are chosen to be 12 μs . Figure 4(a) shows Rabi oscillations using different B_1 -field amplitudes. Here we observe clear coherent oscillations in fluorescence and thus population in the respective spin states, demonstrating that a large ensemble of an estimated $6.4 \cdot 10^7$ V2 centers can be driven coherently embedded in a planar waveguide. The Rabi frequency increases linearly with the B_1 amplitude as expected theoretically. Next, pulsed ODMR measurements are performed, as shown in Fig. 4(b), for different B_1 amplitudes. The shot-noise sensitivity [6] is given by:

$$\eta_{\text{pulsed}} = \frac{8}{3\sqrt{3}} \frac{\hbar}{g_e \mu_B} \frac{1}{C_{\text{pulsed}} \sqrt{N}} \frac{\sqrt{t_I + T_2^* + t_R}}{T_2^*}, \quad (4)$$

where N is the number of counts collected for each readout and T_2^* is the decoherence time. Using this metric, a sensitivity of below 30 nT/ $\sqrt{\text{Hz}}$ is estimated. Subsequently, the Ramsey protocol is tested successfully, as seen in Fig. 4(c), for the case that the detuning between the microwave and the resonance Δ is 0 and 5 MHz, where the first case does not and the second case does show oscillations of 5 MHz as expected from theory [6]. Moreover, a T_2^* coherence time of around 230 ns is extracted from the measurement. This might be improved in future since B_1 homogeneity was not optimized in this measurement, which causes effective dephasing across the ensemble deviating from the intrinsic T_2^* . We estimate the sensitivity for the Ramsey protocol, which relies on measuring the phase of the resulting detuned oscillation in order to extract the B_0 amplitude, which is given by [6]:

$$\eta_{\text{Ramsey}} = \frac{\hbar}{\Delta m_s g_e \mu_B} \frac{1}{C e^{-(\tau/T_2^*)^p} \sqrt{N}} \frac{\sqrt{t_I + \tau + t_R}}{\tau}, \quad (5)$$

where Δm_s is the spin difference between the two states and $p = 1$ for Lorentzian peaks and τ is the free-precession time on the equator of the Bloch sphere. A shot-noise-limited sensitivity below 50 nT/ $\sqrt{\text{Hz}}$ is estimated. Finally, Fig. 4(d) shows a demonstration of Hahn-echo for two different phases of the refocusing $\pi/2$ pulse. It gives a T_2 coherence time of around 2.8 μs . In scenarios where one knows the frequency of ac- B_0 magnetic field to be measured, the Hahn-echo can be used to precisely measure it with the advantage of inherently suppressing low-frequency stray fields, especially dc, which is invisible for Hahn-echo. Sensitivity is highest for fields with periods close to τ , which is limited fundamentally by T_2 . In this case, a B_0 field with around 300 kHz could be resolved with below 10 nT/ $\sqrt{\text{Hz}}$,

improving the Ramsey sensitivity by extending T_2^* to T_2 [6]. It should be mentioned that those sensitivities are assuming shot-noise as the main sensor noise source and do not consider electronic noise sources in the laser and readout circuits.

IV. CONCLUSION

This study presents an approach that enhances and simplifies the sensitivity of SiC-based quantum sensors. We demonstrate the feasibility of the implementation of coherent quantum protocols on a large ensemble of V2 color centers, in turn yielding an improvement in sensitivity, exceeding conventional confocal measurements by at least 2 orders of magnitude. The concept employed is broadband, thereby offering the potential for expansion to other vacancy types. Furthermore, the underlying architecture of this approach enables a reduction in optical power consumption, rendering it a more energy-efficient solution compared with traditional methods and simplifying the sensor concept. Additionally, the SiC-based technology is fully CMOS compatible, in stark contrast to diamond-based systems, which are often limited by their material properties and fabrication constraints. Despite the advancements achieved, there remains room for further improvement, such as optimizing the pulse sequences to achieve the highest sensitivity, integrating the chip into a miniaturized module, and further optimizing power density. Besides this, further improvements in sensitivity could be achieved by optimizing annealing parameters, potentially improving count rate and contrast (even though the theoretical maximum is capped by the system transition rates determining spin polarization), and finally the integration of brighter and higher-contrast spin-color centers, such as PL6. Even though the larger sensing volume due to the photonic structure reduces spatial resolution, the focus of the presented investigation was high absolute sensitivity and a wide dynamic range for robust operation in unshielded environments and to support monolithic vector magnetometry. This development may enable SiC-based quantum sensors to close the gap in performance compared with diamond-based systems in the future and provides a clear path toward mass production of quantum sensing technology.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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