Coherent control of nitrogen-vacancy center spins in silicon carbide at room temperature

Jun-Feng Wang\textsuperscript{1,2}, Fei-Fei Yan\textsuperscript{1,2}, Qiang Li\textsuperscript{1,2}, Zheng-Hao Liu\textsuperscript{1,2}, He Liu\textsuperscript{1,2}, Guo-Ping Guo\textsuperscript{1,2}, Li-Ping Guo\textsuperscript{3}, Xiong Zhou\textsuperscript{3}, Jin-Ming Cui\textsuperscript{1,2}, Jian Wang\textsuperscript{1,2}, Zong-Quan Zhou\textsuperscript{1,2}, Xiao-Ye Xu\textsuperscript{1,2}, Jin-Shi Xu\textsuperscript{1,2,*}, Chuan-Feng Li\textsuperscript{1,2,*} and Guang-Can Guo\textsuperscript{1,2}

\textsuperscript{1}CAS Key Laboratory of Quantum Information, University of Science and Technology of China, Hefei, Anhui 230026, People’s Republic of China
\textsuperscript{2}CAS Center for Excellence in Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui 230026, People’s Republic of China
\textsuperscript{3}Accelerator Laboratory, School of Physics and Technology, Wuhan University, Wuhan, Hubei 430072, People’s Republic of China

*Corresponding author: jsxu@ustc.edu.cn, cfli@ustc.edu.cn

Abstract

Solid-state color centers with manipulable spin qubits and telecom-ranged fluorescence are ideal platforms for quantum communications and distributed quantum computations. In this work, we coherently control the nitrogen-vacancy (NV) center spins in silicon carbide at room temperature, in which the telecom-wavelength emission is detected. Through carefully optimizing the implanted conditions, we improve the concentration of NV centers for about 4 times. Based on this, the coherent control of NV center spins is achieved at room temperature and the coherence time \(T_2^*\) can be reached around 1 \(\mu\)s. Furthermore, the investigation of fluorescence properties of single NV centers shows that they are room temperature photostable single photon sources at telecom range. Taking the advantages of the technological mature materials, the experiment demonstrates that the NV centers in silicon carbide are promising systems for large-scale integrated quantum photonics and long-distance quantum networks.
Identification and coherent control of novel spin defects are important for extending the scope of solid-state quantum information science [1-3]. Optically active defect spins in solid–state systems have been widely used in quantum photonics, quantum communications, quantum computation and quantum metrology [1-22]. Nitrogen-vacancy (NV) centers in diamond have become the most leading candidates due to their excellent properties, including photostability and long spin coherence times even at room temperature [4,5]. However, the drawbacks of visible-wavelength emission and lack of mature nanofabrication of diamond limit their application in long-distance quantum communications and wafer-scale quantum technology [1-6]. In order to overcome these drawbacks, in recent years, defects in silicon carbide (SiC) have been developed as promising platforms for the quantum information science [6-22].

SiC has been widely used in power electronic devices which has commercial available inch-scale growth and matured nano-fabrication protocols [6-13]. Several bright (about Mcps) visible and telecom range single photon emitters have been found in different polytypes of SiC, which can be used for quantum photonics and quantum communications [7-10]. Besides, similar with NV centers in diamond, there are also optically active spin defects: silicon vacancy and divacancy defects in SiC, which can be polarized by laser and controlled by microwave [6,11-22]. These two kinds of defects have realized the single spin manipulation with long coherence times (about 1 ms) [11-16], high-fidelity near infrared spin-to-photon interface [16,17], high-sensitivity quantum metrologies for such as magnetic fields [18], electric fields [19], local strain fields [20] and temperature [21,22] etc. However, their emission spectra are only in the near infrared [6,11-16]. Efficient generation and coherent control of optically active spin defects with telecom-range emissions in SiC are still great challenges.

Most recently, NV centers in 4H-SiC and 3C-SiC have been demonstrated as electron paramagnetic defects with the emission at telecom wavelengths [23-29]. The NV center in SiC is consist of a nitrogen impurity substituting the carbon atom (N_C) and a silicon vacancy (V_Si) being adjacent to it [23-29]. However, most of the previous experiments are focused on the properties of low temperature photoluminescence (PL) spectra and electron paramagnetic resonance (EPR) of the NV centers [23-29]. Little is
known about the optically-detected-magnetic-resonance (ODMR) spectrum and spin coherence property. Moreover, there are still no reports on the scalable generation of single NV centers in SiC, which is vital to construct on-chip quantum processors [6,11-17].

In this work, we realize the coherent control of the NV center spins at room temperature and scalable generation of the single NV centers in 4H-SiC. Through optimizing the implanted conditions, the concentration of NV centers increases about 4 times. The PL spectra of NV centers show that the wavelengths are in the telecom range. We then implement the ODMR measurement and realize the coherent control of the NV center spins at room temperature with the Ramsey coherence time $T_2^*$ obtaining to be around 1 μs. Moreover, we find that the $T_2^*$ decreases as the nitrogen implanted dose increases from $1\times10^{13}$ cm$^{-2}$ to $1\times10^{16}$ cm$^{-2}$. Finally, we present the implanted single NV center and characterize the fluorescence property. The experiments pave the way for using the NV centers in SiC for quantum photonics and quantum information processing.

In the experiment, a bulk high-purity 4H-SiC epitaxy layer sample is used [30,31]. In order to generate the NV centers in 4H-SiC, 30 keV nitrogen ions are implanted on the surface of the sample. The experiments are performed in a homebuilt confocal setup combined with a microwave and magnetic system. A 980 nm laser is used to excite the NV centers since this pumping wavelength has a better exciting effect for NV centers and reduces the emission from the divacancy defects at the same time [24,27]. For the room temperature confocal setup, an oil objective with 1.3 N.A. is used to excite the NV centers. The fluorescence is collected by a multimode fiber to a photoreceiver (Femto, OE-200-Si) after a 1150 nm long pass filter for the spin control experiment of the NV center ensemble [21]. And the spin signal is detected by the lock-in methods [21,31]. While for the investigation of the single NV defect, the fluorescence is collected by a single-mode fiber to a superconducting single-photon detector (Scontel) [22]. A Montana cryostation combined with a confocal setup is used for the low temperature experiment [21,31].
Since the PL and ODMR spectra of the NV centers in 4H-SiC are very close to that of the divacancy defects, it is critical to optimize the implanted conditions to efficiently generate the NV centers. In the experiment, the samples implanted by the nitrogen ions with the influence of $1 \times 10^{14}$ cm$^{-2}$ are annealing at different temperature for the same time (1 hour). Figure 1a shows the low temperature (LT, 20K) PL spectra of the implanted samples at different annealing temperature with a 1000 nm long pass filter. The results show that the PL intensities of the zero phonon lines (ZPLs) of NV centers obviously increase as the annealing temperature increases from 800 °C to 1050 °C; while the PL intensities of the divacancy defects decrease at the same time (The inset in Fig. 1a). When the annealing temperature increases to 1100 °C, the PL intensities of the NV centers decrease. The corresponding scanning images of $10 \times 10$ μm$^2$ areas using
The 1150 nm long pass filter with a laser power of 1 mW are shown in the Supplemental Material (SM, Fig. S1). The mean counts of the scanning images are presented in Fig. 1b. We can find that the mean counts increase about 4 times for annealing temperature increases from 800 °C to 1050 °C; then decrease to about 1.3 times at 1100 °C.

The LT (20 K) PL spectra of NV centers after annealing at 1050 °C for different doses are shown in Fig. 1c, which range from 1150 nm to 1350 nm telecom wavelengths. Besides four sharp ZPL peaks (denoted by the green dotted lines), there are also evident broad phonon sidebands, which are similar with the silicon vacancy and divacancy defects in 4H-SiC [6,11,30,31]. The ZPL intensities increase as the implanted influence increases from $1 \times 10^{13}$ cm$^{-2}$ to $1 \times 10^{14}$ cm$^{-2}$, and decrease when the dose increases to $1 \times 10^{16}$ cm$^{-2}$. Furthermore, in Fig. 1d, we also study the PL spectra of the sample implanted with $1 \times 10^{14}$ cm$^{-2}$ as a function of the sample temperature increasing from 20 K to 300 K. We can see that the ZPL peaks of the NV centers decrease as the sample temperature increases and they can still be observed when the temperature increases to 150 K (See Fig. S3 in SM). At room temperature, the PL spectra range from 1100 nm to about 1400 nm, which are in the telecom range.

The electronic ground state of the negative nitrogen-vacancy (NV$^-$) center in 4H-SiC is a spin-1 state [23-29]. There are two types of bond directions for NV centers. One is the c-axis defects (hh and kk, $C_{3v}$ symmetry), and another is the basal defects (hk and kh, $C_{1h}$ symmetry) [28]. The spin Hamiltonian is:

$$H = D(S_x^2 - S_y^2 - S_z^2/3) + E(S_x^2 - S_y^2) + g \mu_B B S_z,$$

(1)

where the $D$ and $E$ are the axially symmetric and anisotropic components of the zero-field-splitting (ZFS) parameter, $g = 2$ is the electron g-factor, $\mu_B$ is the Bohr magneton and $B$ is the applied axial static magnetic field. Moreover, they also have $^{14}$N nuclear ($I = 1$) hyperfine interactions, which is around 1.2 MHz. Figure 2a presents the ODMR measurement of the sample (implanted by $1 \times 10^{13}$ cm$^{-2}$ and annealing at 1050 °C) without magnetic (bottom part) and with magnetic field (50.5 G, upper part), respectively. In order to isolate the ODMR signals of the NV defect ensemble at zero magnetic field, we use a low power microwave and laser to measure the ODMR signal.
in the experiment. Inferred from the fit, there are six transition frequencies (denoted by the green dotted lines). Besides some known ZFS peaks of divacancy defects PL7 (1333 MHz), PL5 (1343.8 and 1374.2 MHz), PL6 (1350.9 MHz), there are also two ZFS peaks at 1316.5 MHz and 1328.6 MHz, respectively.

**Figure 2.** ODMR signals and coherent control of NV center spins at room temperature. 

- **a** The ODMR measurement of the sample without (bottom part) and with (upper part) magnetic field. The red line in the bottom is the fitting of the data using the Lorentzian function. Respective resonant frequencies are denoted by the green dotted lines. 
- **b** The resonant frequencies of the ODMR signal as a function of the axial magnetic field from 21.5 G to 60.5 G. The red and blue lines are the linear fits to the data. 
- **c** The spin Rabi oscillation between \( |0\rangle \) and \( |-1\rangle \) states for the c-axis NV centers (hh) at room temperature. 
- **d** The free induction decay of the NV center spins at room temperature. The red lines in **c** and **d** are the fits of the data using the decayed sinusoidal function.

In order to further identify the types of the two spin resonant lines, we measure the ODMR signals as a function of the c-axis magnetic field [11,21,22]. Under a representative magnetic field of 50.5 G, the degenerated states are split. There are eight transition frequencies for the ODMR measurement. The corresponding types of the
defects are denoted in Fig. 2a. The summary of the resonant frequencies of the ODMR signals as a function of the axial magnetic field from 21.5 G to 60.5 G is shown in Fig. 2b. The red and blue lines are the linear fits to the data with the slope of 2.8 MHz/G, which imply the corresponding spin defects are c-axis electron spin defects. Inferred from the fittings, the ZFS values of the transitions with red and blue colors are 1317.2 MHz and 1350.3 MHz, respectively. The ZFS value of 1350.3 MHz has been identified to be the PL6 divacancy [6,11,14,21,22]. The calculated ZFS value of 1317.2 MHz is consistent with the measured ZFS values of the zero magnetic field (1316.5 MHz). The ZFS value of 1316.5 MHz (c-axis) at room temperature is coincide with the value of 1331 MHz at 20 K of the c-axis NV center (hh) in 4H-SiC [28]. Moreover, the ZFS peak of 1328.6 MHz mixes with the PL7 defects (purple points), which corresponds to the basal defects. The room temperature resonant peak (1328.6 MHz) is also consistent with the value of 1343 MHz at 20 K for the basal NV center (kh) [28]. The experiment confirms that the ODMR signals of NV centers (hh, kh) in 4H-SiC are observed at room temperature. Coherent control of the spin state at room temperature is the cornerstone for the applications of NV centers in quantum information processing [6,11-14]. In view of this, we measure the Rabi oscillation using the resonant microwave frequency between |0⟩ and |−1⟩ states transition (c-axis NV centers (hh)) with variable pulse lengths. The initialization and readout laser pulses are both set to be 5 μs [6,11,21,31]. The corresponding coherent Rabi oscillation of the NV centers (hh) at room temperature is shown in Fig. 2c. Inferred from the fit, the Rabi frequency is about 6.7 MHz. The obvious oscillation signals demonstrate the coherent control of the NV center spins at room temperature [6,11,12,14]. The spin coherence properties of the NV centers in SiC are important for quantum computation and high sensitivity quantum sensing [6,11,15,18-22,32,33]. We then measure the free induction decay of the NV centers at room temperature with the magnetic field of 350 G. The Ramsey fringe is shown in Fig. 2d and the corresponding microwave frequency detunes for about 5 MHz. The inferred coherence time T2* is 1.1 ± 0.1 μs, which is comparable with the silicon vacancy [34].
and divacancy [14,16] in SiC.

**Figure 3.** Coherent control of NV center spins with different implanted doses. a The mean counts of the NV centers on samples with different implanted doses. b The widths of ZPL of the NV center (hh) as the function of the implanted dose. c Comparison of the coherence time $T_2^*$ for samples with four different implanted doses.

We further investigate the influence of the implanted doses on the coherence properties [11,33]. Fig. 3a shows mean counts of the NV centers as a functions of the dose, where the mean counts are calculated as the average counts of $10 \times 10 \, \mu\text{m}^2$ areas. The counts increase with the dose increases from $1 \times 10^{12} \, \text{cm}^{-2}$ to $1 \times 10^{15} \, \text{cm}^{-2}$, while slightly decrease when the dose increases to $1 \times 10^{16} \, \text{cm}^{-2}$. The saturation of the counts might be due to the nitrogen ion implanted damage of the crystal lattices, which leads to the amorphization of the SiC [31,35]. We also study the changes of the width of NV centers (hh) ZPL as the increase of the dose. As shown in Fig. 3b, the ZPL width slowly increases from 1.2 nm to 1.3 nm as the dose increases from $1 \times 10^{13} \, \text{cm}^{-2}$ to $1 \times 10^{14} \, \text{cm}^{-2}$, then it rapidly increases to 3.0 nm as the dose increases to $1 \times 10^{16} \, \text{cm}^{-2}$. Moreover, we compare the free induction decay of the sample with the different implanted dose. The coherence time $T_2^*$ as a function of implanted dose is presented in Fig. 3c. The $T_2^*$ decreases a bit as the dose increases from $1 \times 10^{13} \, \text{cm}^{-2}$ to $1 \times 10^{15} \, \text{cm}^{-2}$, then it quickly decreases to 0.45 $\mu$s as the dose increases to $1 \times 10^{16} \, \text{cm}^{-2}$. The decrease of the $T_2^*$ might be due to the increase of the defects densities and damage of the lattice of the SiC, which is similar with that of the divacancy in SiC [11].

Generating and isolating single NV centers in SiC is vital to various quantum
technologies, including quantum photonics, quantum networks and nanoscale quantum sensing, etc [5,12-14,16,17,30,31,36]. In our experiment, a 200 nm thickness polymethyl methacrylate (PMMA) layer are deposited on the SiC surface. Then 70 ± 10 nm diameter nano-aperture arrays (2 × 2 μm²) are generated using the electron-beam lithography technology [30,31]. 30 keV nitrogen ions with the dose of 2.5 × 10¹¹ cm⁻² are implanted through the nano-apertures to generate single NV center array in 4H-SiC.

We then characterize the fluorescence properties of the generated single NV centers. A representative 20 × 20 μm² confocal image of the single defect arrays is displayed in Fig. 4a. To identify the number of NV center, we perform the Hanbury-Brown and Twiss (HBT) measurement and obtain the corresponding second-order photon correlation function. Figure 4b presents the result of the circled defects in Fig. 4a. Since the signal-to-noise ratio of the defects is small, the raw g²_raw(t) is corrected using the function g²(t) = [g²_raw(t)− (1−ρ²)]/ρ², where ρ = s/(s+b). The s and b represent signal and background counts, respectively [9,12-14]. Then we fit the g²(τ) using the function g²(τ) = 1−a*exp(-|τ|/τ₁)+b*exp(-|τ|/τ₂), where a and b are fitting parameters, τ₁ and τ₂ are related to the excited state and metastable state lifetimes, respectively. The obtained g²(0) is around 0.03, which demonstrates that it is a single defect. Inferred from the fit, the τ₁ and τ₂ are about 2.4 ns and 12.1 ns, respectively. In order to further certify this, we measure the fluorescence lifetime of the NV centers in the same sample using a 1040 nm femtosecond pulse laser at both room temperature and low temperature. Figure 4c shows the lifetime of the NV center ensemble at room temperature. The red line is the fit of the data using double-exponential decay function. The fluorescence lifetime is about 2.1 ± 0.1 ns which is almost the same with the short excited state lifetimes τ₁ [37,38]. The lifetime is much smaller than that of the divacancy in 4H-SiC [14,16,20,39], which is also consistent with the narrower gap of the g²(τ) function in Fig. 4b. The result of the low temperature lifetime is shown in SM (Fig. S4) with the value fitting to be 2.7 ± 0.1 ns, which is consistent with that at room temperature.

The saturation curve of the single NV center is shown in Fig. 4d. The red line is the fitting using the power dependence model I(P) = I_s/(1 + P₀/P), where I_s is the maximal emission counts and P₀ is the saturation power. The fit indicates that the saturation
**Figure 4.** Characterizing fluorescence property of the single NV center in 4H-SiC. **a** A confocal scan image (20×20 μm²) of the single NV center arrays in 4H-SiC with a laser power of 4 mW. The circled one is the investigated single NV center. The scale bar is 2 μm. **b** The correlation function measurement of the circled single NV center in **a**. The red line is the fit of the data. **c** The lifetime of the NV centers ensemble at room temperature. **d** The counts of the single NV centers as a function of the laser power. **e** The photostability of the single NV center at two different pump laser powers with the time bin is 100 ms time bin.

Counts $I_s$ is around $17.4 \pm 0.2$ kcps and the saturation power $P_0$ is around $1.7 \pm 0.1$ mW, respectively. The photostability of the single photon source is important for quantum photonics [8,9,36] and quantum information technologies [12,16,17]. Figure 4e exhibits time trace of counts of the single NV centers for about 6 minutes with 100 ms time bin for two different pump laser powers. The stable fluorescence emission demonstrates that the NV center is a stable telecom-wavelength single photon source at room temperature. Moreover, we randomly measure 8 defects and all the correlation functions $g^2(\tau)$ are similar with each other. Combined the PL spectra in Fig. 1 and the $g^2(\tau)$ measurement, we deduce that most of defects in the array are NV centers.

In conclusion, we coherently control the NV center spins and characterize the fluorescence properties of the single NV centers in 4H-SiC at room temperature. Through optimizing the annealing condition, the concentration of the NV centers increases about four times. Moreover, the PL spectra show that the wavelengths of NV
centers are at the telecom range. After measuring the ODMR spectra as a function of the c axis magnetic field at room temperature, we identify the spin resonant frequency of the $C_{3v}$ NV centers (hh). Furthermore, we coherently control the spin states of the NV centers at room temperature and obtain the coherence time $T_2^*$ of around 1 µs, which is comparable with that of the divacancy defects in SiC [6,10]. The coherence time $T_2^*$ is shown to decrease as the implanted dose increases. The single NV centers are demonstrated to be room temperature photostable with a saturation counts about 17.4 kcps, which are also comparable with that of the single divacancy [14,16] and silicon vacancy defects [12,13,30,31] in 4H-SiC. The experiment paves the way for using the NV centers with telecom-wavelength emission in technologically friendly SiC materials in quantum photonics, quantum information processing and scalable quantum networks.

**Acknowledge**

We thank Prof. J. Wrachtrup for the helpful discussion. We also thank Yongxiang Zheng, Jun Hu for their help in the experiment. This work was supported by the National Key Research and Development Program of China (Grant No. 2016YFA0302700 and 2017YFA0304100), the National Natural Science Foundation of China (Grants No. 61725504, 61905233, 11975221, 11804330, 11821404 and 11774335), the Key Research Program of Frontier Sciences, Chinese Academy of Sciences (CAS) (Grant No. QYZDY-SSW-SLH003), Science Foundation of the CAS (No. ZDRW-XH-2019-1), Anhui Initiative in Quantum Information Technologies (AHY060300 and AHY020100), the Fundamental Research Funds for the Central Universities (Grant No. WK2030380017 and WK2470000026).

**References**

1. J. R. Weber, W. F. Koehl, J. B. Varley, A. Janotti, B. B. Buckley, C. G. Van de Walle, and D. D. Awschalom, Proc. Natl Acad. Sci. USA **107**, 8513–8518 (2010).
2. D. D. Awschalom, R. Hanson, J. Wrachtrup, and B. B. Zhou, Nat. Photon. **12**, 516–
3. M. Atatüre, D. Englund, N. Vamivakas, S.-Y. Lee, and J. Wrachtrup, Nat. Rev. Mater. 3, 38–51 (2018).

4. A. Gruber, A. Dräbenstedt, C. Tietz, L. Fleury, J. Wrachtrup, and C. von Borczyskowski, Science 276, 2012–2014 (1997).

5. B. Hensen, H. Bernien, A. E. Dréau, A. Reiserer, N. Kalb, M. S. Blok, J. Ruitenberg, R. F. L. Vermeulen, R. N. Schouten, C. Abellán, W. Amaya, V. Pruneri, M. W. Mitchell, M. Markham, D. J. Twitchen, D. Elkouss, S. Wehner, T. H. Taminiau, and R. Hanson, Nature 526, 682–686 (2015).

6. W. F. Koehl, B. B. Buckley, F. J. Heremans, G. Calusine, and D. D. Awschalom, Nature, 479, 84 (2011).

7. S. Castelletto, B. C. Johnson, V. Ivády, N. Stavrias, T. Umeda, A. Gali, and T. Ohshima, Nat. Mater. 13, 151–156 (2014).

8. A. Lohrmann, B. C. Johnson, J. C. McCallum, and S. Castelletto, Rep. Prog. Phys. 80, 034502 (2017).

9. J. F. Wang, Y. Zhou, Z. Y. Wang, A. Rasmita, J. Q. Yang, X. J. Li, H. J. von Bardeleben, and W. B. Gao, Nat. Commun. 9, 4106 (2018).

10. Q. Li, J. Y. Zhou, Z. H Liu, J. S. Xu, C. F. Li; G.C. Guo J. Semicond. 40, 072902 (2019).

11. A. L. Falk, B. B. Buckley, G. Calusine, W. F. Koehl, V. V. Dobrovitski, A. Politi, C. A. Zorman, P. X.-L. Feng, and D. D. Awschalom, Nat. Commun. 4, 1819 (2013).

12. M. Widmann, S.-Y. Lee, T. Rendler, N. T. Son, H. Fedder, S. Paik, L.-P. Yang, N. Zhao, S. Yang, I. Booker, A. Denisenko, M. Jamali, S. A. Momenzadeh, I. Gerhardt, T. Ohshima, A. Gali, E. Janzén, and J. Wrachtrup, Nat. Mater. 14, 164–168 (2015).

13. F. Fuchs, B. Stender, M. Trupke, D. Simin, J. Pflaum, V. Dyakonov, and G. V. Astakhov, Nat. Commun. 6, 7578 (2015).

14. D. J. Christle, A. L. Falk, P. Andrich, P. V. Klimov, J. Ul Hassan, N. T. Son, E. Janzén, T. Ohshima, and D. D. Awschalom, Nat. Mater. 14, 160–163 (2015).

15. P. V. Klimov, A. L. Falk, D. J. Christle, V. V. Dobrovitski, and D. D. Awschalom, Sci. Adv. 1, e1501015 (2015).
16. D. J. Christle, P. V. Klimov, F. Charles, K. Szász, V. Ivády, V. Jokubavicius, J. Ul Hassan, M. Syväjärvi, W. F. Koehl, and T. Ohshima, E. Janzén, Á, Gali, and D. D. Awschalom, Phys. Rev. X 7, 021046 (2017).
17. R. Nagy, M. Niethammer, M. Widmann, Y.-C. Chen, P. Udvarhelyi, C. Bonato, J. Ul Hassan, R. Karhu, I. G. Ivanov, N. Tien Son, J. R. Maze, T. Ohshima, Ö. O. Soykal, Á. Gali, S.-Y. Lee, F. Kaiser, and Jörg Wrachtrup, Nat. Commun. 10, 1954 (2019).
18. D. Simin, V. A. Soltamov, A. V. Poshakinskiy, A. N. Anisimov, R. A. Babunts, D. O. Tolmachev, E. N. Mokhov, M. Trupke, S. A. Tarasenko, A. Sperlich, P. G. Baranov, V. Dyakonov, and G. V. Astakhov, Phys. Rev. X 6, 031014 (2016).
19. G. Wolfowicz, S. J. Whiteley, and D. D. Awschalom, Proc. Natl. Acad. Sci., 115, 7879–7883 (2018).
20. A. L. Falk, P. V. Klimov, B. B. Buckley, V. Ivády, I. A. Abrikosov, G. Calusine, W. F. Koehl, Á Gali, and D. D. Awschalom, Phys. Rev. Lett. 112, 187601 (2014).
21. Y. Zhou, J. F. Wang, X. M. Zhang, K. Li, J. M. Cai, and W. B. Gao, Phys. Rev. Appl. 8, 044015 (2017).
22. F. F. Yan, J. F. Wang, Q. Li, Z. D. Cheng, J. M. Cui, W. Z. Liu, J. S. Xu, C. F. Li, and G. C. Guo, Phys. Rev. Appl. 10, 044042 (2018).
23. H. J. Von. Bardeleben, J. L. Cantin, E. Rauls, and U. Gerstmann, Phys. Rev. B 92, 064104 (2015).
24. S. A. Zargaleh, B. Eble, S. Hameau, J.-L. Cantin, L. Legrand, M. Bernard, F. Margaillan, J.-S. Lauret, J.-F. Roch, H. J. von Bardeleben, E. Rauls, U. Gerstmann, and F. Treussart, Phys. Rev. B 94, 060102 (2016).
25. H. J. Von Bardeleben, J. L. Cantin, A. Csóré, A. Gali, E. Rauls, and U. Gerstmann, Phys. Rev. B 94, 121202 (2016).
26. A. Csóré, H. J. Von. Bardeleben, J. L. Cantin, and A. Gali, Phys. Rev. B 96, 085204 (2017).
27. B. Magnusson, N. T. Son, A. Csóré, A. Gällström, T. Ohshima, A. Gali, and I. G. Ivanov, Phys. Rev. B 98, 195202 (2018).
28. S. A. Zargaleh, H. J. von Bardeleben, J. L. Cantin, U. Gerstmann, S. Hameau, B. Eblé, and W. B. Gao, Phys. Rev. B 98, 214113 (2018).
29. S. A. Zargaleh, S. Hameau, B. Eble, F. Margaillan, H. J. von Bardeleben, J. L. Cantin, and W. B. Gao, Phys. Rev. B 98, 165203 (2018).
30. J. F. Wang, Y. Zhou, X. M. Zhang, F. C. Liu, Y. Li, K. Li, Z. Liu, G. Z. Wang, and W. B. Gao, Phys. Rev. Appl. 7, 064021 (2017).
31. J. F. Wang, Q. Li, F. F. Yan, H. Liu, G. P. Guo, W. P. Zhang, X. Zhou, L. P. Guo, Z. H. Lin, J. M. Cui, X. Y. Xu, J. S. Xu, C. F. Li and G. C. Guo, ACS Photon. 6, 1736-1743 (2019).
32. H. Seo, A. L. Falk, P. V. Klimov, K. C. Miao, G. Galli and D. D. Awschalom, Nat. Commun. 7, 12935 (2016).
33. J.-P. Tetienne, R. W. de Gille, D. A. Broadway, T. Teraji, S. E. Lillie, J. M. McCoey, N. Dotschuk, L. T. Hall, A. Stacey, D. A. Simpson, and L. C. L. Hollenberg, Phys. Rev. B 97, 085402 (2018).
34. R. Nagy, M. Widmann, M. Niethammer, D. B. R. Dasari, I. Gerhardt, O. O. Soykal, M. Radulaski, T. Ohshima, J. Vučković, N. T. Son, I. G. Ivanov, S. E. Economou, C. Bonato, S.-Y. Lee, and J. Wrachtrup, Phys. Rev. Appl. 9, 034022 (2018).
35. T. Schröder, M. E. Trusheim, M. Walsh, L. Li, J. Zheng, M. Schukraft, A. Sipahigil, R. E. Evans, D. D. Sukachev, C. T. Nguyen, J. L. Pacheco, R. M. Camacho, E. S. Bielejec, M. D. Lukin, and D. Englund, Nat. Commun. 8, 15376 (2017).
36. M. Radulaski, M. Widmann, M. Niethammer, J. L. Zhang, S. Y. Lee, T. Rendler, K. G. Lagoudakis, N. T. Son, E. Janzen, T. Ohshima, J. Wrachtrup, and J. Vučković, Nano Lett. 17, 1782-1786 (2017).
37. A. M. Berhane, K.-Y. Jeong, C. Bradac, M. Walsh, D. Englund, M. Toth, and I. Aharonovich, Phys. Rev. B 97, 165202 (2018).
38. G. Wolfowicz, C. P. Anderson, B. Diler, O. G. Poluektov, F. Joseph Heremans, and D. D. Awschalom, arXiv, 1908, 09817 (2019).
39. C. P. Anderson, A. Bourassa, K. C. Miao, G. Wolfowicz, P. J. Mintun, A. L. Crook, H. Abe, J. Ul Hassan, N. T. Son, T. Ohshima, and D. D. Awschalom, arXiv, 1906, 08328 (2019).