

Coherent Control of Defect Spins in Silicon Carbide above 550 K

Fei-Fei Yan,^{1,2} Jun-Feng Wang,^{1,2} Qiang Li,^{1,2} Ze-Di Cheng,^{1,2} Jin-Ming Cui,^{1,2} Wen-Zheng Liu,¹
Jin-Shi Xu,^{1,2,*} Chuan-Feng Li,^{1,2,†} and Guang-Can Guo^{1,2}

¹*CAS Key Laboratory of Quantum Information, University of Science and Technology of China, Hefei 230026, People's Republic of China*

²*Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei 230026, People's Republic of China*



(Received 17 May 2018; revised manuscript received 9 July 2018; published 17 October 2018)

Great efforts have been made in the investigation of defects in silicon carbide for their attractive optical and spin properties. However, most research is done at low and room temperature. Little is known about the spin-coherence property at high temperature. Here we experimentally demonstrate coherent control of divacancy defect spins in silicon carbide above 550 K. The spin properties of defects from room temperature to 600 K are investigated, and the zero-field splitting is found to have a polynomial temperature dependence and the spin-coherence time decreases as the temperature increases. Moreover, as an example of an application, we demonstrate thermal sensing using the Ramsey method at about 450 K. Our experimental results would be useful for the investigation of high-temperature properties of defect spins and silicon carbide-based broad-temperature-range quantum sensing.

DOI: [10.1103/PhysRevApplied.10.044042](https://doi.org/10.1103/PhysRevApplied.10.044042)

I. INTRODUCTION

Most recently, defects in silicon carbide (SiC) have attracted much attention for their appealing optical and spin properties [1–14]. Since SiC is a widely used semiconductor material in electronic devices with outstanding features such as various mature fabrication technologies and large-scale high-quality single-crystal growth, defect-based control and manipulation in SiC would lead to practical wafer-scale quantum-information processing [1–5]. Besides some types of very bright single-photon sources [6,7], there are two types of spin qubit in SiC: the silicon-vacancy defect [3,4,8] and the divacancy defect consisting of a carbon vacancy adjacent to a silicon vacancy [1–3,9]. Similarly to nitrogen-vacancy (NV) centers in diamond [15], the defect spins in SiC can be polarized and read out by a laser and controlled by microwaves. Because of the outstanding properties of infrared (IR) fluorescence wavelength and a long coherence time (on the order of milliseconds), the divacancy defects with spin $S = 1$ in SiC have enabled applications in quantum metrology, including magnetic sensing [16–18], electric sensing [13,19], and temperature sensing [14], and etc. Unlike other thermometers such as fluorescence-based organic dyes and Raman spectroscopy with the drawbacks of local environmental disturbance and low sensitivity [20], SiC-based quantum sensors have the advantages of photostable fluorescence,

chemical inertness, no toxicity, and high sensitivity [3, 9,11,14]. Moreover, the IR range of fluorescence may be more suitable for biological systems than that of NV centers in diamond [14,21].

However, most of the previous experiments were performed at low and room temperature. Little is known about the spin-coherence property at high temperature. Understanding such a property is important for manipulating defect spins in SiC at high temperature, which would be useful for making a broad-temperature-range high-sensitivity quantum sensor.

In this work, we study the coherence of divacancy defect spins in 4H-SiC with the temperature ranging from 300 to 600 K. In particular, we focus on the PL5 divacancy defects with a basal C_{1h} symmetry. By measuring the optically-detected-magnetic-resonance (ODMR) spectrum, we find that the zero-field splitting (ZFS) has a polynomial temperature dependence and the contrast of the ODMR signal decreases with the increase of temperature, and almost vanishes at about 600 K. The spin-coherence time is also found to decrease as the temperature increases. Infrared high-temperature thermometry based on Ramsey methods is also demonstrated. The results pave the way for SiC-based broad-temperature-range quantum sensing such as magnetic and temperature sensing.

II. EXPERIMENTAL SETUP AND RESULTS

We use a homebuilt confocal microscopy system and a microwave system to excite and control the defect spins in

*jsxu@ustc.edu.cn

†cfli@ustc.edu.cn

a commercial high-purity semi-insulating 4H-SiC sample purchased from Cree. As shown in Fig. 1(a), an IR laser with a center wavelength at 920 nm modulated by an acousto-optic modulator is used to excite the defects. After reflection by a dichroic mirror (980-nm long-pass mirror), the laser is focused on the SiC sample by a near-infrared objective (NA = 0.7) with a long working distance. The fluorescence is collected by the same objective and detected by a superconducting single-photon detector (Scontel) after a 1064-nm long-pass interference filter. A ring-shaped microwave antenna is fabricated on the sample for transmission of microwaves to manipulate defect spins [Fig. 1(b)]. The electrical pulse sequences for manipulating the laser and microwaves are generated by a pulse generator (PBESR-PRO-500, Spincore) in a personal computer. To control the sample's temperature, the sample is mounted on a metal ceramic heater (HT24S, Thorlabs) with a resistive temperature detector (TH100PT, Thorlabs) fixed on it. The heater and the resistive temperature detector are controlled by a temperature controller to achieve stability within ± 100 mK up to 600 K in an atmospheric environment.

To identify defects in the 4H-SiC sample, we scan the ODMR spectrum as a function of the applied magnetic

field along the c axis of the sample, which is shown in the upper part of Fig. 2(a) and agrees with the previous results [2]. Four distinct divacancy defects are detectable at room temperature, which are labeled as PL3, PL5 and PL7 with basal symmetry and PL6 with c -axis symmetry. The two transitions of PL6 defects are measured to split at a slope of 2.8 MHz/G with the c -axis magnetic field [1,2]. The lower part of Fig. 2(a) shows the ODMR spectrum at zero magnetic field. The ZFS parameter (D) of the right branch of PL5 is measured to be 1374.5 MHz, which further confirms the type of divacancy defects. Since it is easily distinguishable and has a higher contrast and long Ramsey coherence time, we focus on the right branch of PL5 defects to investigate spin dynamics at high temperature with zero magnetic field.

Coherent control of spins at room temperature including the implementation of Rabi-oscillation, Ramsey, and thermal-echo [14,21] measurements is shown in Figs. 2(b)–2(d), respectively. In the experiment, the length of the initialized and read-out laser pulses are both set to be $3 \mu\text{s}$ [1,2,14]. The Rabi oscillation is measured as a function of the microwave pulse duration, as shown in Fig. 2(b). The microwave pulse sequences for Ramsey and thermal-echo oscillations are shown in the insets in Figs. 2(c) and 2(d), respectively. Blue lines are the theoretical fits. An exponentially decaying sine function is used to fit the Rabi oscillation, while the Ramsey and thermal-echo oscillations are fitted with the function

$$I_{\text{PL}} = a \exp \left[- \left(\frac{t}{T_d} \right)^n \right] \cos (2\pi f t + \varphi) + b, \quad (1)$$

where a , n , b , and φ are free parameters, and T_d represents the dephasing time [1,2,14]. The oscillating frequency f corresponds to the detuning frequency from the ZFS parameter, which is set to be 1.7 MHz. The Ramsey dephasing time (T_2^*) and the thermal-echo dephasing time (T_{TE}) are both obtained to be about $1.9 \mu\text{s}$, which are consistent with previous results [1,14]. This is because PL5 has a large transverse strain E (about 13.5 MHz), which has a self-protecting effect for the local slowly varying magnetic field in the Ramsey measurement, and the coherence time is not expected to increase with thermal echo in our experiment [14]. The coherence time (T_2) is measured to be about $48.9 \mu\text{s}$.

We then detect the ODMR spectrum at temperatures ranging from 300 to 600 K. Fig. 3(a) shows four representative ODMR signals at 300, 400, 500, and 550 K, respectively, which are fitted with Lorentzian functions (blue lines). Both the ZFS parameter D and the ODMR contrast decrease as the temperature increases. The details of the dependence of D on temperature are shown in Fig. 3(b). The change of D is about -32 MHz from 300 to 600 K. We use a three-order polynomial function to fit the data, which reads as $D(T) = a_0 + a_1(T - 300) + a_2(T -$

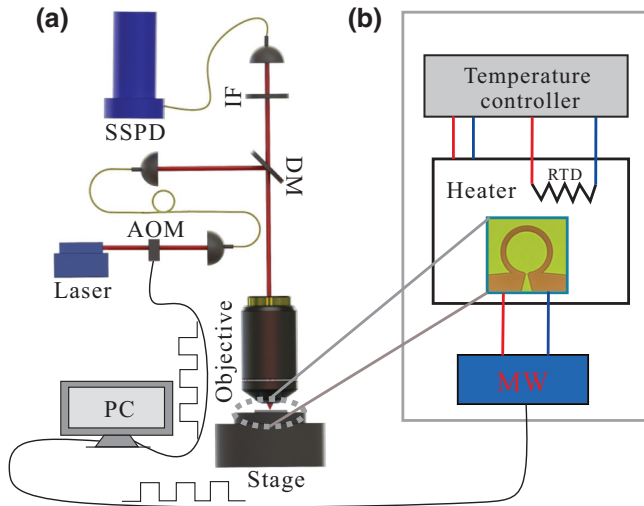


FIG. 1. Experimental setup. (a) The homebuilt confocal microscope system. A laser with a wavelength of 920 nm is modulated by an acousto-optic modulator (AOM). After reflection by a dichroic mirror (DM), laser pulses are focused by an objective to pump the sample. The fluorescence is collected by the same objective and filtered by an interference filter (IF), which is finally detected by a superconducting single photon detector (SSPD). (b) The sample is fixed on a metal ceramic heater and the temperature is detected by a resistive temperature detector (RTD); these are connected to a temperature controller. A ring-shaped antenna is mounted on the sample to implement microwave (MW) pulses. The electrical pulse sequences on the AOM and MW system are controlled by a personal computer (PC).

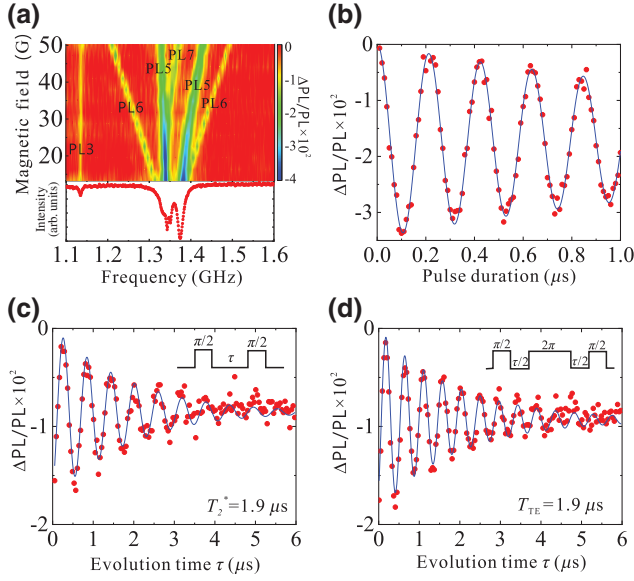


FIG. 2. Coherent control of spins at room temperature. (a) The ODMR spectrum of divacancy defect spins in 4H-SiC with the increase of magnetic field (upper part) and zero magnetic field (lower part). PL3, PL5, PL6, and PL7 are four types of divacancies. (b) Rabi oscillation of PL5. The blue line represents the theoretical fit with an exponentially decaying sine function. (c) Ramsey fringe of PL5. The decay time shows that the dephasing time T_2^* is about $1.9 \mu s$. (d) Thermal-echo oscillation of PL5. The thermal-echo dephasing time T_{TE} is also about $1.9 \mu s$. The blue lines and insets in (c),(d) are the fits obtained with Eq. (1) and the microwave pulse sequences, respectively.

$300)^2 + a_3(T - 300)^3$, with parameters $a_0 = 1374.5 \pm 0.1$ MHz, $a_1 = -0.096 \pm 0.003$ MHz/K, $a_2 = (-8.1 \pm 3.3) \times 10^{-5}$ MHz/K², and $a_3 = (1.4 \pm 0.9) \times 10^{-7}$ MHz/K³ [22–24]. Compared with the case of NV centers [22], we obtain a better linear relationship, which should pave the way to construct an ODMR-signal-based broad-temperature-range thermal sensor. The dependence between the ODMR contrast and temperature is shown in Fig. 3(c). The decrease of the ODMR contrast might also be caused by the thermally activated nonradiative processes, which would diminish the fluorescence-based spin read-out [22].

Ramsey and thermal-echo oscillations are widely used in quantum sensing [14,21,25–29]. We further investigate the temperature dependence of Ramsey and thermal-echo oscillations. Fig. 4(a) shows three Ramsey measurements at different temperatures and Fig. 4(b) shows the dephasing time T_2^* varying with temperature ranging from 300 to 520 K. Similarly to the temperature dependence of D , both the contrast of the Ramsey oscillation and T_2^* decrease as the temperature increases. In particular, T_2^* reduces to only about $0.4 \mu s$ at 520 K. Unlike the behavior of T_2^* of NV spins in diamond, which remains almost the same from

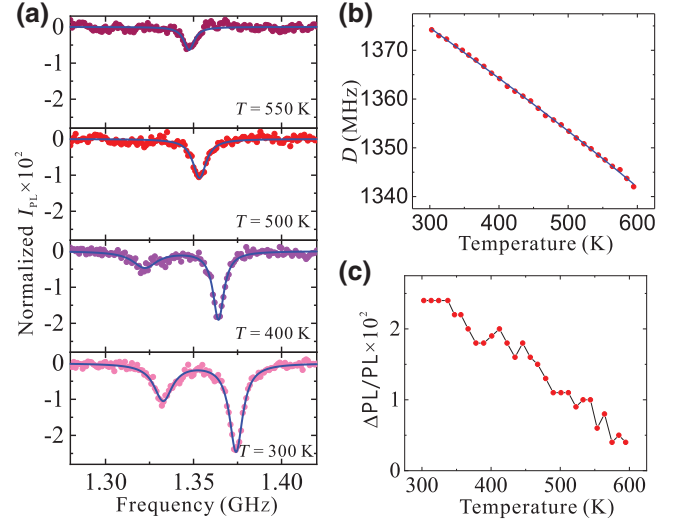


FIG. 3. Temperature dependence of ODMR signals for PL5. (a) The ODMR spectrum at four representative temperatures. The blue lines are the theoretical Lorentzian fits. (b) The ZFS parameter D as a function of the temperature from 300 to 600 K. The blue line is the theoretical fit with a third-order polynomial. The error bar of every point deduced from the ODMR fitting error is smaller than the corresponding symbol size. (c) The corresponding ODMR contrasts of the right branch of PL5 as a function of the temperature from 300 to 600 K.

300 to 620 K [22], T_2^* of PL5 divacancy defects in 4H-SiC first decreases slowly when the temperature is below 400 K, and then decreases quickly when the temperature is increased to about 520 K. Further investigations are needed to exactly understand the origin of the difference. Moreover, the coherence time of the thermal-echo oscillation T_{TE} varying as a function of temperature is shown in Fig. 4(c). T_{TE} decreases as the temperature increases, which is similar to the results for T_2^* . T_{TE} decreases to only about $0.6 \mu s$ at 520 K.

The PL5 spin dynamics in 4H-SiC can be used for high-temperature quantum sensing [22,29,30]. We investigate a thermal sensing at about 450 K using the Ramsey method. As shown in Fig. 5(a), the ZFS parameter D deduced from the ODMR spectrum ranging from 440 to 460 K is shown to linearly decrease with increase of temperature with a slope of -107 ± 4 kHz/K. We then measure the frequencies of Ramsey oscillations at five different temperatures; see Fig. 5(b). The microwave frequency is kept constant for all further measurements after it is set to 1.7-MHz detuning at 442.4 K. There is a linear relation between the oscillation frequency and temperature. The slope is measured to be 105 ± 3 kHz/K, which is consistent with that in Fig. 5(a). Two Ramsey oscillations, at 442.4 and 447 K, are shown in Figs. 5(c) and 5(d), with the oscillation frequencies being $f = 1695 \pm 17$ kHz and $f = 2204 \pm 15$ kHz, respectively. The dephasing time T_2^* is deduced to be about

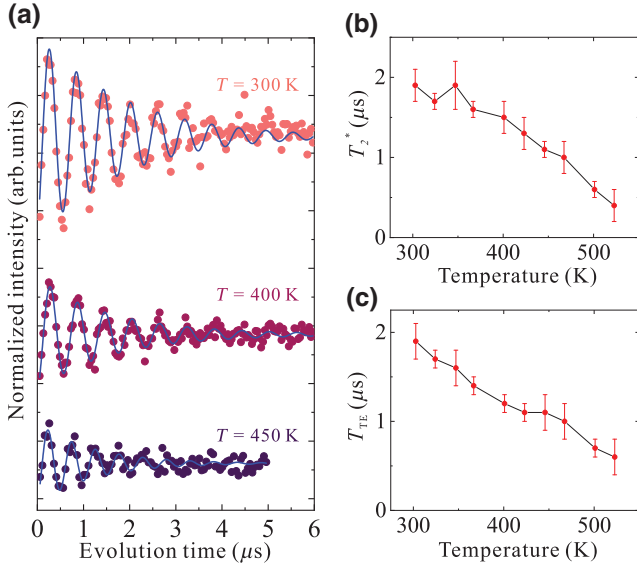


FIG. 4. Temperature dependence of coherence-time measurement. (a) The Ramsey oscillations at three different temperatures. (b) The dephasing time T_2^* versus temperature. (c) The thermal-echo dephasing time T_{TE} versus temperature.

1.1 μs . Using the standard error derived from the fitting, we estimate that the precision of the measured temperature is about 160 mK. The sensitivity is a significant physical quantity to measure the quality of a thermometer. We can

get the sensitivity using the equation

$$\eta = \sqrt{\frac{2(p_0 + p_1)}{(p_0 - p_1)^2}} \frac{1}{2\pi \frac{dD}{dT} \exp\left[-\left(\frac{t}{T_d}\right)^n\right] \sqrt{t}}, \quad (2)$$

with p_0 and p_1 being the photon counts per measurement shot for the bright and dark spin states, respectively. The sensitivity η corresponds to the maximum value of $\exp[-(t/T_d)^n] \sqrt{t}$ [14,25]. In our experiment, the sensitivity is about 274 mK/Hz^{1/2} at room temperature and about 880 mK/Hz^{1/2} at 450 K. The sensitivity should be greater with a higher collection efficiency. In our experiment, the count rate is about 570 000 per second for a 4-mW laser pump at room temperature and is stable during the measurement. The reduced sensitivity at higher temperature is due to the decrease of photon counts, contrast of ODMR signal, and T_2^* as the temperature increases.

III. CONCLUSIONS

In summary, we investigate the ODMR spectrum and Ramsey oscillation of the PL5 divacancy defect spins in 4H-SiC from 300 to 600 K. The results show that coherent control of defect spins in 4H-SiC can be achieved even at high temperature up to 600 K. As an application, high-temperature thermal sensing at 450 K is demonstrated with the PL5 divacancy defect spins, which are shown to be useful for the construction of a robust broad-temperature-range thermometer with high sensitivity. Temperature sensitivity can be further increased by use of high-order thermal Carr-Purcell-Meiboom-Gill measurements [25,29], and higher photon collection efficiency [5,31]. A broad-range, high-sensitivity, and nanoscale-resolution thermometer can be constructed by use of nano-SiC particles, which would be used in a wide variety of systems, including living-cell and microelectronics systems [21]. Our results are helpful in understanding the spin dynamics in SiC at high temperature and should stimulate further research in this area.

ACKNOWLEDGMENTS

We thank Haiou Li for his help in the experiment. This work was supported by the National Key Research and Development Program of China (Grants No. 2016YFA0302700 and No. 2017YFA0304100), the National Natural Science Foundation of China (Grants No. 61725504, No. 61327901, No. 61490711, and No. 11774335), the Key Research Program of Frontier Sciences, Chinese Academy of Sciences (Grant No. QYZDY-SSW-SLH003), the Anhui Initiative in Quantum Information Technologies (Grants No. AHY060300 and No. AHY020100), and the Fundamental Research Funds for the Central Universities (Grants No. WK2470000020).

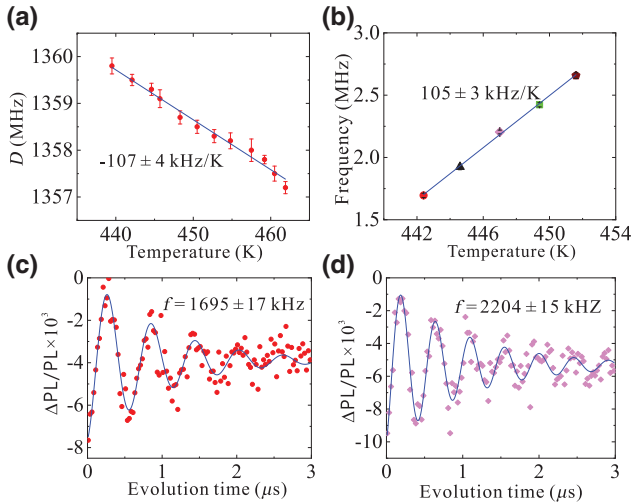


FIG. 5. Thermal-sensing properties at about 450 K. (a) The ZFS parameter D , inferred from the Lorentzian fit to the ODMR data, at about 450 K. The blue line shows the linear fitting. (b) Ramsey oscillation frequency as a function of temperature. The blue line is a linear fitting. The slope of the Ramsey oscillation frequency is consistent with the slope of D as a function of temperature. (c),(d) Ramsey oscillations at two different temperatures show different frequencies. Blue lines are the fittings obtained with Eq. (1). The corresponding oscillation frequencies are shown in (b) as a red circle and a pink rhombus, respectively.

and No. WK2470000026). This work was partially performed at the University of Science and Technology of China Center for Micro and Nanoscale Research and Fabrication.

F.-F.Y. and J.-F.W. contributed equally to this work.

-
- [1] W. F. Koehl, B. B. Buckley, F. J. Heremans, G. Calusine, and D. D. Awschalom, Room temperature coherent control of defect spin qubits in silicon carbide, *Nature* **479**, 84 (2011).
 - [2] 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, Polytype control of spin qubits in silicon carbide, *Nat. Commun.* **4**, 1819 (2013).
 - [3] D. J. Christle, A. L. Falk, P. Andrich, P. V. Klimov, J. U. Hassan, N. T. Son, E. Janzén, T. Ohshima, and D. D. Awschalom, Isolated electron spins in silicon carbide with millisecond coherence times, *Nat. Mater.* **14**, 160 (2015).
 - [4] F. Fuchs, B. Stender, M. Trupke, D. Simin, J. Pflaum, V. Dyakonov, and G. Astakhov, Engineering near-infrared single-photon emitters with optically active spins in ultra-pure silicon carbide, *Nat. Commun.* **6**, 7578 (2015).
 - [5] M. Widmann, S. Y. Lee, T. Rendler, N. T. Son, H. Fedder, S. Paik, L. P. Yang, N. Zhao, S. Yang, and I. Booker *et al.*, Coherent control of single spins in silicon carbide at room temperature, *Nat. Mater.* **14**, 164 (2015).
 - [6] S. Castelletto, B. Johnson, V. Ivády, N. Stavrias, T. Umeda, A. Gali, and T. Ohshima, A silicon carbide room-temperature single-photon source, *Nat. Mater.* **13**, 151 (2014).
 - [7] B. Lienhard, T. Schröder, S. Mouradian, F. Dolde, T. T. Tran, I. Aharonovich, and D. Englund, Bright and photostable single-photon emitter in silicon carbide, *Optica* **3**, 768 (2016).
 - [8] J. F. Wang, Y. Zhou, X. M. Zhang, F. C. Liu, Y. Li, K. Li, Z. Liu, G. Z. Wang, and W. B. Gao, Efficient Generation of an Array of Single Silicon-Vacancy Defects in Silicon Carbide, *Phys. Rev. Appl.* **7**, 064021 (2017).
 - [9] D. J. Christle, P. V. Klimov, F. Charles, K. Szász, V. Ivády, Valdas Jokubavicius, Jawad Ul Hassan, Mikael Syv"aj"arvi, W. F. Koehl, and T. Ohshima *et al.*, Isolated Spin Qubits in Sic with a High-Fidelity Infrared Spin-to-Photon Interface, *Phys. Rev. X* **7**, 021046 (2017).
 - [10] P. V. Klimov, A. L. Falk, D. J. Christle, V. V. Dobrovitski, and D. D. Awschalom, Quantum entanglement at ambient conditions in a macroscopic solid-state spin ensemble, *Sci. Adv.* **1**, e1501015 (2015).
 - [11] H. Seo, A. L. Falk, P. V. Klimov, K. C. Miao, G. Galli, and D. D. Awschalom, Quantum decoherence dynamics of divacancy spins in silicon carbide, *Nat. Commun.* **7**, 12935 (2016).
 - [12] P. V. Klimov, A. L. Falk, B. B. Buckley, and D. D. Awschalom, Electrically Driven Spin Resonance in Silicon Carbide Color Centers, *Phys. Rev. Lett.* **112**, 087601 (2014).
 - [13] 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, Electrically and Mechanically Tunable Electron Spins in Silicon Carbide Color Centers, *Phys. Rev. Lett.* **112**, 187601 (2014).
 - [14] Y. Zhou, J. F. Wang, X. M. Zhang, K. Li, J. M. Cai, and W. B. Gao, Self-Protected Thermometry with Infrared Photons and Defect Spins in Silicon Carbide, *Phys. Rev. Appl.* **8**, 044015 (2017).
 - [15] J. R. Maze, P. L. Stanwix, J. S. Hodges, S. Hong, J. M. Taylor, P. Cappellaro, L. Jiang, M. V. Gurudev Dutt, E. Togan, and A. S. Zibrov *et al.*, Nanoscale magnetic sensing with an individual electronic spin in diamond, *Nature* **455**, 644 (2008).
 - [16] M. Niethammer, M. Widmann, S. Y. Lee, P. Stenberg, O. Kordina, T. Ohshima, N. T. Son, E. Janzén, and J. Wrachtrup, Vector Magnetometry Using Silicon Vacancies in 4H-SiC Under Ambient Conditions, *Phys. Rev. Appl.* **6**, 034001 (2016).
 - [17] 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, and A. Sperlich *et al.*, All-Optical dc Nanotesla Magnetometry using Silicon Vacancy Fine Structure in Isotopically Purified Silicon Carbide, *Phys. Rev. X* **6**, 031014 (2016).
 - [18] D. Simin, F. Fuchs, H. Kraus, A. Sperlich, P. G. Baranov, G. V. Astakhov, and V. Dyakonov, High-Precision Angle-Resolved Magnetometry with Uniaxial Quantum Centers in Silicon Carbide, *Phys. Rev. Appl.* **4**, 014009 (2015).
 - [19] G. Wolfowicz, S. J. Whiteley, and D. D. Awschalom, Electrometry by optical charge conversion of deep defects in 4H-SiC, arXiv:1803.05956 (2018).
 - [20] C. D. Brites, P. P. Lima, N. J. Silva, A. Millán, V. S. Amaral, F. Palacio, and L. D. Carlos, Thermometry at the nanoscale, *Nanoscale* **4**, 4799 (2012).
 - [21] G. Kucsko, P. C. Maurer, N. Y. Yao, M. Kubo, H. J. Noh, P. K. Lo, H. Park, and M. D. Lukin, Nanometre-scale thermometry in a living cell, *Nature* **500**, 54 (2013).
 - [22] D. M. Toyli, D. J. Christle, A. Alkauskas, B. B. Buckley, C. G. Van de Walle, and D. D. Awschalom, Measurement and Control of Single Nitrogen-Vacancy Center Spins above 600 K, *Phys. Rev. X* **2**, 031001 (2012).
 - [23] T. Plakhotnik, M. W. Doherty, J. H. Cole, R. Chapman, and N. B. Manson, All-optical thermometry and thermal properties of the optically detected spin resonances of the nv-center in nanodiamond, *Nano Lett.* **14**, 4989 (2014).
 - [24] C. C. Li, M. Gong, X. D. Chen, S. Li, B. W. Zhao, Y. Dong, G. C. Guo, and F. W. Sun, Temperature dependent energy gap shifts of single color center in diamond based on modified varshni equation, *Diam. Relat. Mater.* **74**, 119 (2017).
 - [25] J. F. Wang, F. P. Feng, J. Zhang, J. H. Chen, Z. C. Zheng, L. P. Guo, W. L. Zhang, X. R. Song, G. P. Guo, and L. L. Fan *et al.*, High-sensitivity temperature sensing using an implanted single nitrogen-vacancy center array in diamond, *Phys. Rev. B* **91**, 155404 (2015).
 - [26] J. M. Taylor, P. Cappellaro, L. Childress, L. Jiang, D. Budker, P. R. Hemmer, A. Yacoby, R. Walsworth, and M. D. Lukin, High-sensitivity diamond magnetometer with nanoscale resolution, *Nat. Phys.* **4**, 810 (2008).
 - [27] P. Neumann, I. Jakobi, F. Dolde, C. Burk, R. Reuter, G. Waldherr, J. Honert, T. Wolf, A. Brunner, and J. H. Shim *et al.*, High-precision nanoscale temperature sensing using single defects in diamond, *Nano Lett.* **13**, 2738 (2013).

- [28] R. Schirhagl, K. Chang, M. Loretz, and C. L. Degen, Nitrogen-vacancy centers in diamond: nanoscale sensors for physics and biology, [Annu. Rev. Phys. Chem. **65**, 83 \(2014\)](#).
- [29] D. M. Toyli, F. Charles, D. J. Christle, V. V. Dobrovitski, and D. D. Awschalom, Fluorescence thermometry enhanced by the quantum coherence of single spins in diamond, [Proc. Natl. Acad. Sci. USA **110**, 8417 \(2013\)](#).
- [30] A. N. Anisimov, D. Simin, V. A. Soltamov, S. P. Lebedev, P. G. Baranov, G. V. Astakhov, and V. Dyakonov, Optical thermometry based on level anticrossing in silicon carbide, [Sci. Rep. **6**, 33301 \(2016\)](#).
- [31] M. Radulaski, M. Widmann, M. Niethammer, J. L. Zhang, S. Y. Lee, T. Rendler, K. G. Lagoudakis, N. T. Son, E. Janzen, and T. Ohshima *et al.*, Scalable quantum photonics with single color centers in silicon carbide, [Nano Lett. **17**, 1782 \(2017\)](#).