# Title of my Dissertation

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MSc in Theoretical Physics

The University of Edinburgh

2023

**Abstract**

This is where you summarise the contents of your dissertation. It should be at least 100 words, but not more than 250 words.

## Declaration

I declare that this dissertation was composed entirely by myself.

## Personal Statement

*You* **must** *include a Personal Statement in your dissertation. This should describe what you did during the project, and when you did it. Give an account of problems you faced and how you attempted to overcome them. The examples below are based on personal statements from MSc and MPhys projects in previous years, with (mostly-obvious) changes to make them anonymous.*

# Acknowledgements

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# Chapter 1

# Introduction

## 1.1 Defect Orientation

Colour centres or defects in general are part of the crystal lattice and thus have an associated orientation and direction within the lattice. This allows the definition of a **defect axis**. For example, in diamond the NV axis is defined as the vector from the vacancy towards the Nitrogen atom when the vacancy is taken as the origin of your co-ordinate system.

In a tetragonal crystal, due to symmetry there are four possible orientations of a defect within the lattice: 111, $1\overline{1}\overline{1}$, $\overline{1}1\overline{1}$ and $\overline{1}\overline{1}1$ directions.

## 1.2 Miller Indices

The notation for defect orientation above is known as a Miller Index, and we consider the 111 direction to be aligned with the defect axis.

This means that if we know the orientation of our crystal then we can establish the orientations of the defect axis inside. For example, using a crystal for which all surfaces belong to the $\{001\}$ lattice planes, each surface normal is aligned with a Cartesian axis. Thus, by fixing the crystal in place, there remain just **four** possible angles which a defect axis can have with respect to the crystal surface.

Calculating the scalar product of any of the surface planar directions in the family of $\{001\}$ and the four possible orientations of the defect within the lattice we find $\cos\theta = \pm 0.6$. Then, considering the physical solutions (from $0, 2\pi$) gives four possible angles that the (directed) defect axis may make with the surface of the crystal: 53.13°, 306.87°, 126.9° and 233.13° (0.927, 5.355, 2.214 and 4.069 radians respectively).

## 1.3 Spintronic Magnetometry

The Hamiltonian, and thus the energy, of a spin is sensitive to the magnetic field because of the Zeeman interaction.

How the electron Zeeman energy varies with magnetic field is known to a very large precision. Therefore, by measuring the energy difference we may determine the magnetic field. This is the mechanism which enables us to use the spin of an electron as a magnetic-field sensor.

In practice, for example with diamond a fluorescence microscope to measure the electron spin resonances of an ensemble of NV centres. This allows the determination of both magnitude and direction of an external magnetic field.

### 1.3.1 Applied Magnetic Field

To use defects as magnetometers, we must understand the nature of their spin states when an external magnetic field is applied. From this we may determine both the amplitude and direction of the external magnetic field from the electron spin resonance frequencies of the defect.

### 1.3.2 Spin-1 Defect

A spin-1 defect has $S = 1$ electron spin. Therefore, it has 3 possible spin states, $m_S = 0, 1, +1$.

With no external applied magnetic field, in general, the $m_S = \pm 1$ states are degenerate, that is they have the same energy. Applying a magnetic field lifts the degeneracy and the $m_S = \pm 1$ states will have different energies, $E_u$ and $E_l$ (subscripts refer to "upper" and "lower"). These are equivalent to transition frequencies by $E = hf$, which we denote $f_u$ and $f_l$.

The exact values of these frequencies are functions of both amplitude and direction of the magnetic field, specifically the cosine of the angle between the applied magnetic field and the defect axis $\theta$.

Thus, by experimentally determining the transition frequencies, the magnitude and relative angle of the applied magnetic field may be determined. Details of the derivation are included in 4.2.2 and we find we may determine

$$\gamma B = \frac{1}{3}\sqrt{f_u^2 + f_l^2 - f_u f_l - D^2} \tag{1.1}$$

$$\cos^2\theta = \frac{-(f_u + f_l)^3 + 3f_u^3 + 3f_l^3}{27D(\gamma B)^2} + \frac{2D^2}{27(\gamma B)^2} + \frac{1}{3} \tag{1.2}$$

Here $\gamma = 28$GHz/T is the gyromagnetic ratio of the electron. $D = 2.87$GHz is the zero-field splitting of the defect ground state, that is the energy difference between $m_S = 0$ and $m_S = \pm 1$ with no external field applied.

The simplest possible case is when the defect axis aligns with the applied field for which we get a linear relationship

$$f_u = D + \gamma B \qquad f_l = D - \gamma B. \tag{1.3}$$


Include plot of the electron spin resonances vs applied magnetic field.

# Chapter 2

# Background Theory

## 2.1 Spintronics

Spintronics, a portmantau of **spin** and elec**tronics** is a technology which exploits the characteristics of spin akin to how charge is manipulated in electronics. Fundamentally, the smallest stable magnetic moment available in nature is generated by the spin of a single electron. Careful construction of an appropriate system allows for this magnetic moment to be initialised, manipulated and measured to infer the physical properties of the environment surrounding the system.

## 2.2 Quantum Sensing

Quantum sensing involves using a qubit system acting as a quantum sensor that interacts with an external variable of interest, such as a magnetic field, electric field, strain or acoustic wave, or temperature [1].

Quantum sensors have a higher sensitivity within a nanoscale or microscale sampling volume compared to a fully classical counterpart which would require higher field densities or higher volume interrogation to be effective.

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### 2.2.1 DiVincenzo Criteria

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### 2.2.2 Crystal Defects

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#### Quantisation

#### Polarisation

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#### Coherent Manipulation

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#### Efficient Readout

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#### Spin Relaxation

#### Dephasing

#### Hahn Echo

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#### Example: NV Diamond

### 2.2.4 Sensitivity

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### 2.2.5 ODMR

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### 2.2.6 Multimodal Sensors

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## 2.3 Silicon Carbide

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### 2.3.1 Production of SiC

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### 2.3.2 Colour Defects in SiC

#### Electronic Structure

#### Charge State

#### Spin System

### 2.3.3 Wider Scientific Context

[60]

# Chapter 3

# To Sort

## 3.1 Spin

The magnetic moment of elementary particles is called spin.

## 3.2 Defect Orientation

Colour centres or defects in general are part of the crystal lattice and thus have an associated orientation and direction within the lattice. This allows the definition of a **defect axis**. For example, in diamond the NV axis is defined as the vector from the vacancy towards the Nitrogen atom when the vacancy is taken as the origin of your co-ordinate system.

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## 3.4 Lattice Symmetry

Tetragonal lattice has the

# Chapter 4

# Task

## 4.1 Brief

I think, as a start can go through section 3.2.4 in the attached PhD thesis? In particular check in details how to diagonalise the NV centre spin S=1 Hamiltonian to get Eq. 3.31? You could also do some python simulations to plot how the spin levels (i.e. the eigenvalues of the spin Hamiltonian) change with applied magnetic field.

Once we've learned this, we can apply it to other spin defects in SiC.

## 4.2 Work

### 4.2.1 Concepts and Nomenclature

#### Spin-Spin Interactions

#### Zeeman Splitting

#### Hyperfine Interaction

### 4.2.2 System Hamiltonian

The ground state of the NV$^-$ spin system in diamond is a triplet state, thus a $S = 1$ system.

The corresponding Hamiltonian, which it seems can be generalised to an electron spin system of a defect, can be expressed as:

$$H_{\mathrm{NV}} = H_{\mathrm{D}} + H_{\mathrm{Zeeman}} + H_{\mathrm{HF}} \tag{4.1}$$

Here the labels D, Z and HF describe the electron spin-spin interactions, the Zeeman interaction with an external magnetic field and the hyperfine interaction between the nuclparallel spin $I$ and the electron spin $S$ of the NV.

They have the following forms:

$$
\begin{aligned}
H_{\mathrm{D}} &= DS_z^2 + E(S_x^2 + S_y^2) && (4.2)\\
H_{\mathrm{Z}} &= g\mu_B \sum_j^{x,y,z} B_j \cdot S_j && (4.3)\\
H_{\mathrm{HF}} &= \vec{S} \cdot A \cdot \vec{I}. && (4.4)
\end{aligned}
$$

### Spin-Spin Interaction

The $E$ and $D$ in equation 4.2 the fine structure constants of the spin system, describing the spin-spin interaction and $S_j$ the corresponding spin operators in x,y and z-direction.

D is non-zero in system with axis of threefold (or other manifold) symmetry. The symmetry or spin quantization axis points along the connection of the nitrogen atom and vacancy forming the defect. In bulk diamond $D$ is around 2.87 GHz at room temperature.

The definiteness, orientation and magnitude of $D$ is thus dependent on the specific spin system being studied.

E occurs when there is a distortion of the point group symmetry, for example strain or an electrical field. In bulk diamond $E$ is typically negligibly small but especially in NDs, $E$ can be of the order of several MHz.

Thus, similarly, the value of $E$ is a characteristic of the nature of the distortion and the specifics of the spin system being studied.

### Zeeman Interaction

$B_j$ in equation 4.3 is the magnetic field along the $x$, $y$ and $z$ direction, $g$ is the $g$-factor of the vacancy and $\mu_B$ the Bohr-Magneton, a constant.

It seems often the scaled parameter $g\mu_B$ is considered, for the $NV^-$ system this is around 28 $\mathrm{GHz\,T^{-1}}$, but again, will be a characteristic of the system being studied.

### Hyperfine Interaction

Equation 4.4 related the nuclear spin to the electron spin via the hyperfine tensor $A$ which has the form

$$
A = \begin{pmatrix} A_\perp & 0 & 0 \\ 0 & A_\perp & 0 \\ 0 & 0 & A_\parallel \end{pmatrix}. \tag{4.5}
$$

$A_\parallel$ and $A_\perp$ are the axial and non-axial hyperfine parameters which encode two different interactions.

**Fermi Contact Interaction.** This interaction is calculated by

$$
f_A = \frac{A_\parallel + 2A_\perp}{3}. \tag{4.6}
$$

**Anisotropic Interaction.** This interaction is found by considering both spins as magnetic dipoles is calculated by

$$d_A = \frac{A_{\parallel} - A_{\perp}}{3}. \tag{4.7}$$

For the NV$^-$ system in diamond specifically, using the values for $A_{\parallel}$ and $A_{\perp}$ we calculate that $f_A$ is an order of magnitude stronger than $d_A$ for both N$^{14}$ and N$^{15}$.

### Reduced Hamiltonian

By combining $H_{\mathrm{D}}$ and $H_{\mathrm{Z}}$ and neglecting $H_{\mathrm{HF}}$ we find

why (specifically) do we get to neglect this? Can we generalise?

$$H_{\mathrm{NV}} = DS_z^2 + E(S_x^2 + S_y^2) + g\mu_B \sum_j^{x,y,z} B_j \cdot S_j \tag{4.8}$$

The spin operators $S_j$ in matrix representation are

$$S_x = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, S_y = \frac{i}{\sqrt{2}} \begin{pmatrix} 0 & -1 & 0 \\ 1 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix}, S_z = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}. \tag{4.9}$$

Then, aligning the magnetic field (with strength $B_0$) along the $z$-axis (the quantisation axis), the reduced Hamiltonian will have the form

$$H_{\mathrm{NV}} = \begin{pmatrix} D + B_0 & 0 & E \\ 0 & 0 & 0 \\ E & 0 & D - B_0 \end{pmatrix}, \tag{4.10}$$

with Eigenvalues

$$E_x = E_y = D \pm \sqrt{B_0^2 + E^2},\ E_z = 0. \tag{4.11}$$

The corresponding non-normalised Eigenvectors are then

$$|X\rangle = \frac{1}{E}\left(B_0 + \sqrt{B_0^2 + E^2}\right)|{+1}\rangle + |{-1}\rangle \tag{4.12}$$

$$|Y\rangle = \frac{1}{E}\left(B_0 - \sqrt{B_0^2 + E^2}\right)|{+1}\rangle + |{-1}\rangle \tag{4.13}$$

$$|Z\rangle = |0\rangle, \tag{4.14}$$

with

$$|1\rangle = \begin{pmatrix} 1 & 0 & 0 \end{pmatrix}, |0\rangle = \begin{pmatrix} 0 & 1 & 0 \end{pmatrix}, |{-1}\rangle = \begin{pmatrix} 0 & 0 & 1 \end{pmatrix}, \tag{4.15}$$

the Eigenvectors for $H_{\mathrm{NV}}$ with $E = 0 \ldots$

In the case where $E \ll B_0$ the Eigenvectors are well described by the bases $|0\rangle$ and $|\pm 1\rangle$.

For $E \gg B_0$, when transforming the spin operators $S_j$ into the diagonalised system with Hamiltonian $H_{\mathrm{NV}}$ they read

$$\hat{S}_x^{\parallel} \propto \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \hat{S}_y^{\parallel} \propto \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}, \hat{S}_z \propto \begin{pmatrix} 0 & 0 & -1 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{pmatrix}, \tag{4.16}$$

and

$$\hat{H}_{\mathrm{NV}} = \begin{pmatrix} D + \sqrt{B_0^2 + E^2} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & D - \sqrt{B_0^2 - E^2}. \end{pmatrix} \tag{4.17}$$

Another solution for a $\pi/2$ shifted, modulating magnetic field leads to

$$\hat{S}_x^{\perp} \propto \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \hat{S}_y^{\perp} \propto \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \hat{S}_z \propto \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}, \tag{4.18}$$

a physical interpretation of which is that a linear modulating B-field aligned along the $x$-axis where strain is applied only allows transitions between the state $|X\rangle$ and $|0\rangle$, whereas fields perpendicular to the strain and the NV quantization axis only allow coupling between $|Y\rangle$ and $|0\rangle$.

For an arbitrary external magnetic field, $H_{\mathrm{NV}}$ can be expressed using spherical coordinates:

$$H_{\mathrm{NV}} = \begin{pmatrix} D + B_0 \cdot \cos\theta & \frac{B_0}{\sqrt{2}} \cdot e^{-i\cdot\varphi} \cdot \sin\theta & E \\ \frac{B_0}{\sqrt{2}} \cdot e^{i\cdot\varphi} \cdot \sin\theta & 0 & \frac{B_0}{\sqrt{2}} e^{-i\cdot\varphi} \cdot \sin\theta \\ E & \frac{B_0}{\sqrt{2}} \cdot e^{i\cdot\varphi} \cdot \sin\theta & D - B_0 \cdot \cos\theta \end{pmatrix} \tag{4.19}$$

Here, we transformed the magnitude of the arbitrary magnetic field into spherical coordinates as

$$B_x = B_0 \cos\varphi \sin\theta \tag{4.20}$$
$$B_y = B_0 \sin\varphi \sin\theta \tag{4.21}$$
$$B_z = B_0 \cos\theta \tag{4.22}$$

with $\theta$ the azimuthal and $\varphi$ the polar angle. Then using equations 4.8 and 4.9 we compute 4.19.

It immediately follows from the characteristic equation that Eigenvalues $\lambda$ satisfy

$$0 = \lambda^3 - 2\cdot\lambda^2\cdot D + \frac{D \cdot B_0^2}{2} + \lambda(D^2 - E^2 - B_0^2) - \frac{1}{2}B_0^2 \underbrace{\left(D \cdot \cos(2\theta) - 2 \cdot E\cos(2\varphi) \cdot \sin(\theta)^2\right)}_{\Delta_{\varphi\theta}} \tag{4.23}$$

# Chapter 5

# Design

# Chapter 6

# Results and Analysis

# Chapter 7

# Conclusions

# Chapter 8

# Test

Does adding this chapter and pushing to GitHub make it to Overleaf?

# Bibliography


[1] S Castelletto, C T-K Lew, Wu-Xi Lin, and Jin-Shi Xu. Quantum systems in silicon carbide for sensing applications. *Reports on Progress in Physics*, 87(1):014501, dec 2023.

[2] Gary Wolfowicz, F. Joseph Heremans, Christopher P. Anderson, Shun Kanai, Hosung Seo, Adam Gali, Giulia Galli, and David D. Awschalom. Quantum guidelines for solid-state spin defects. *Nature Reviews Materials*, 6(10):906–925, April 2021.

[3] Yiu Yung Pang Wai Kuen Leung Nan Zhao Kin On Ho, Yang Shen and Sen Yang. Diamond quantum sensors: from physics to applications on condensed matter research. *Functional Diamond*, 1(1):160–173, 2021.

[4] Corey J. Cochrane, Jordana Blacksberg, Mark A. Anders, and Patrick M. Lenahan. Vectorized magnetometer for space applications using electrical readout of atomic scale defects in silicon carbide. *Scientific Reports*, 6(1), November 2016.

[5] Tianyu Xie, Zhiyuan Zhao, Xi Kong, Wenchao Ma, Mengqi Wang, Xiangyu Ye, Pei Yu, Zhiping Yang, Shaoyi Xu, Pengfei Wang, Ya Wang, Fazhan Shi, and Jiangfeng Du. Beating the standard quantum limit under ambient conditions with solid-state spins. *Science Advances*, 7(32), August 2021.

[6] C. L. Degen, F. Reinhard, and P. Cappellaro. Quantum sensing. *Rev. Mod. Phys.*, 89:035002, Jul 2017.

[7] Scott E. Crawford, Roman A. Shugayev, Hari P. Paudel, Ping Lu, Madhava Syamlal, Paul R. Ohodnicki, Benjamin Chorpening, Randall Gentry, and Yuhua Duan. Quantum sensing for energy applications: Review and perspective. *Advanced Quantum Technologies*, 4(8), June 2021.

[8] H. Kraus, V. A. Soltamov, F. Fuchs, D. Simin, A. Sperlich, P. G. Baranov, G. V. Astakhov, and V. Dyakonov. Magnetic field and temperature sensing with atomic-scale spin defects in silicon carbide. *Scientific Reports*, 4(1), July 2014.

[9] Shun Kanai, F. Joseph Heremans, Hosung Seo, Gary Wolfowicz, Christopher P. Anderson, Sean E. Sullivan, Mykyta Onizhuk, Giulia Galli, David D. Awschalom, and Hideo Ohno. Generalized scaling of spin qubit coherence in over 12, 000 host materials. *Proceedings of the National Academy of Sciences*, 119(15), April 2022.

[10] 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, Feb 2014.

[11] Matthias Widmann, Sang-Yun Lee, Torsten Rendler, Nguyen Tien Son, Helmut Fedder, Seoyoung Paik, Li-Ping Yang, Nan Zhao, Sen Yang, Ian Booker, Andrej Denisenko, Mohammad Jamali, S. Ali Momenzadeh, Ilja Gerhardt, Takeshi Ohshima, Adam Gali, Erik Janzén, and J¨ org Wrachtrup. Coherent control of single spins in silicon carbide at room temperature. *Nature Materials*, 14(2):164–168, December 2014.

[12] A. Csóré, I. G. Ivanov, N. T. Son, and A. Gali. Fluorescence spectrum and charge state control of divacancy qubits via illumination at elevated temperatures in $4h$ silicon carbide. *Phys. Rev. B*, 105:165108, Apr 2022.

[13] Fei-Fei Yan, Ai-Lun Yi, Jun-Feng Wang, Qiang Li, Pei Yu, Jia-Xiang Zhang, Adam Gali, Ya Wang, Jin-Shi Xu, Xin Ou, Chuan-Feng Li, and Guang-Can Guo. Room-temperature coherent control of implanted defect spins in silicon carbide. *npj Quantum Information*, 6(1), May 2020.

[14] William F. Koehl, Bob B. Buckley, F. Joseph Heremans, Greg Calusine, and David D. Awschalom. Room temperature coherent control of defect spin qubits in silicon carbide. *Nature*, 479(7371):84–87, November 2011.

[15] Zhao Mu, Soroush Abbasi Zargaleh, Hans Jürgen von Bardeleben, Johannes E. Fröch, Milad Nonahal, Hongbing Cai, Xinge Yang, Jianqun Yang, Xingji Li, Igor Aharonovich, and Weibo Gao. Coherent manipulation with resonant excitation and single emitter creation of nitrogen vacancy centers in 4h silicon carbide. *Nano Letters*, 20(8):6142–6147, July 2020.

[16] Jun-Feng Wang, Fei-Fei Yan, Qiang Li, Zheng-Hao Liu, He Liu, Guo-Ping Guo, Li-Ping Guo, Xiong Zhou, Jin-Ming Cui, Jian Wang, Zong-Quan Zhou, Xiao-Ye Xu, Jin-Shi Xu, Chuan-Feng Li, and Guang-Can Guo. Coherent control of nitrogen-vacancy center spins in silicon carbide at room temperature. *Phys. Rev. Lett.*, 124:223601, Jun 2020.

[17] Erik R. Eisenach, John F. Barry, Michael F. O'Keeffe, Jennifer M. Schloss, Matthew H. Steinecker, Dirk R. Englund, and Danielle A. Braje. Cavity-enhanced microwave readout of a solid-state spin sensor. *Nature Communications*, 12(1), March 2021.

[18] Christopher P Anderson, Elena O Glen, Cyrus Zeledon, Alexandre Bourassa, Yu Jin, Yizhi Zhu, Christian Vorwerk, Alexander L Crook, Hiroshi Abe, Jawad Ul-Hassan, Takeshi Ohshima, Nguyen T Son, Giulia Galli, and David D Awschalom. Five-second coherence of a single spin with single-shot readout in silicon carbide. *Sci. Adv.*, 8(5):eabm5912, February 2022.

[19] Matthias Niethammer, Matthias Widmann, Torsten Rendler, Naoya Morioka, Yu-Chen Chen, Rainer Stöhr, Jawad Ul Hassan, Shinobu Onoda, Takeshi Ohshima, Sang-Yun Lee, Amlan Mukherjee, Junichi Isoya, Nguyen Tien Son, and Jörg Wrachtrup. Coherent electrical readout of defect spins in silicon carbide by photo-ionization at ambient conditions. *Nature Communications*, 10(1), December 2019.

[20] Andrea Morello, Jarryd J. Pla, Floris A. Zwanenburg, Kok W. Chan, Kuan Y. Tan, Hans Huebl, Mikko Möttönen, Christopher D. Nugroho, Changyi Yang, Jessica A.

van Donkelaar, Andrew D. C. Alves, David N. Jamieson, Christopher C. Escott, Lloyd C. L. Hollenberg, Robert G. Clark, and Andrew S. Dzurak. Single-shot readout of an electron spin in silicon. *Nature*, 467(7316):687–691, September 2010.

[21] Yu-Wei Liao, Qiang Li, Mu Yang, Zheng-Hao Liu, Fei-Fei Yan, Jun-Feng Wang, Ji-Yang Zhou, Wu-Xi Lin, Yi-Dan Tang, Jin-Shi Xu, Chuan-Feng Li, and Guang-Can Guo. Deep-learning-enhanced single-spin readout in silicon carbide at room temperature. *Phys. Rev. Appl.*, 17:034046, Mar 2022.

[22] David J. Christle, Abram L. Falk, Paolo Andrich, Paul V. Klimov, Jawad Ul Hassan, Nguyen T. Son, Erik Janzén, Takeshi Ohshima, and David D. Awschalom. Isolated electron spins in silicon carbide with millisecond coherence times. *Nature Materials*, 14(2):160–163, December 2014.

[23] V. A. Soltamov, C. Kasper, A. V. Poshakinskiy, A. N. Anisimov, E. N. Mokhov, A. Sperlich, S. A. Tarasenko, P. G. Baranov, G. V. Astakhov, and V. Dyakonov. Excitation and coherent control of spin qudit modes in silicon carbide at room temperature. *Nature Communications*, 10(1), April 2019.

[24] Carmem M Gilardoni, Tom Bosma, Danny van Hien, Freddie Hendriks, Björn Magnusson, Alexandre Ellison, Ivan G Ivanov, N T Son, and Caspar H van der Wal. Spin-relaxation times exceeding seconds for color centers with strong spin–orbit coupling in sic. *New Journal of Physics*, 22(10):103051, October 2020.

[25] Oscar Bulancea-Lindvall, Nguyen T. Son, Igor A. Abrikosov, and Viktor Ivády. Dipolar spin relaxation of divacancy qubits in silicon carbide. *npj Computational Materials*, 7(1), December 2021.

[26] T. Astner, P. Koller, C. M. Gilardoni, J. Hendriks, N. T. Son, I. G. Ivanov, J. U. Hassan, C. H. van der Wal, and M. Trupke. Vanadium in silicon carbide: Telecom-ready spin centres with long relaxation lifetimes and hyperfine-resolved optical transitions, 2022.

[27] Hosung Seo, Abram L Falk, Paul V Klimov, Kevin C Miao, Giulia Galli, and David D Awschalom. Quantum decoherence dynamics of divacancy spins in silicon carbide. *Nat. Commun.*, 7(1):12935, September 2016.

[28] Yuzhou Wu, Fedor Jelezko, Martin B Plenio, and Tanja Weil. Diamond quantum devices in biology. *Angewandte Chemie International Edition*, 55(23):6586–6598, April 2016.

[29] John F. Barry, Jennifer M. Schloss, Erik Bauch, Matthew J. Turner, Connor A. Hart, Linh M. Pham, and Ronald L. Walsworth. Sensitivity optimization for nv-diamond magnetometry. *Rev. Mod. Phys.*, 92:015004, Mar 2020.

[30] 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, Jul 2015.

[31] John B. S. Abraham, Cameron Gutgsell, Dalibor Todorovski, Scott Sperling, Jacob E. Epstein, Brian S. Tien-Street, Timothy M. Sweeney, Jeremiah J. Wathen, Elizabeth A. Pogue, Peter G. Brereton, Tyrel M. McQueen, Wesley Frey, B. D.

Clader, and Robert Osiander. Nanotesla magnetometry with the silicon vacancy in silicon carbide. *Phys. Rev. Appl.*, 15:064022, Jun 2021.

[32] Ilja Fescenko, Andrey Jarmola, Igor Savukov, Pauli Kehayias, Janis Smits, Joshua Damron, Nathaniel Ristoff, Nazanin Mosavian, and Victor M. Acosta. Diamond magnetometer enhanced by ferrite flux concentrators. *Phys. Rev. Res.*, 2:023394, Jun 2020.

[33] Stefania Castelletto, Abdul Salam Al Atem, Faraz Ahmed Inam, Hans Jürgen von Bardeleben, Sophie Hameau, Ahmed Fahad Almutairi, Gérard Guillot, Shin-ichiro Sato, Alberto Boretti, and Jean Marie Bluet. Deterministic placement of ultra-bright near-infrared color centers in arrays of silicon carbide micropillars. *Beilstein Journal of Nanotechnology*, 10:2383–2395, December 2019.

[34] Ji-Yang Zhou, Qiang Li, Zhi-He Hao, Wu-Xi Lin, Zhen-Xuan He, Rui-Jian Liang, Liping Guo, Hao Li, Lixing You, Jian-Shun Tang, Jin-Shi Xu, Chuan-Feng Li, and Guang-Can Guo. Plasmonic-enhanced bright single spin defects in silicon carbide membranes. *Nano Letters*, 23(10):4334–4343, May 2023.

[35] Jun-Feng Wang, Jin-Ming Cui, Fei-Fei Yan, Qiang Li, Ze-Di Cheng, Zheng-Hao Liu, Zhi-Hai Lin, Jin-Shi Xu, Chuan-Feng Li, and Guang-Can Guo. Optimization of power broadening in optically detected magnetic resonance of defect spins in silicon carbide. *Phys. Rev. B*, 101:064102, Feb 2020.

[36] Gary Wolfowicz, Christopher P. Anderson, Andrew L. Yeats, Samuel J. Whiteley, Jens Niklas, Oleg G. Poluektov, F. Joseph Heremans, and David D. Awschalom. Optical charge state control of spin defects in 4h-sic. *Nature Communications*, 8(1), November 2017.

[37] 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. *Scientific Reports*, 6(1), September 2016.

[38] A. V. Poshakinskiy and G. V. Astakhov. Optically detected spin-mechanical resonance in silicon carbide membranes. *Phys. Rev. B*, 100:094104, Sep 2019.

[39] Lin Liu, Jun-Feng Wang, Xiao-Di Liu, Hai-An Xu, Jin-Ming Cui, Qiang Li, Ji-Yang Zhou, Wu-Xi Lin, Zhen-Xuan He, Wan Xu, Yu Wei, Zheng-Hao Liu, Pu Wang, Zhi-He Hao, Jun-Feng Ding, Hai-Ou Li, Wen Liu, Hao Li, Lixing You, Jin-Shi Xu, Eugene Gregoryanz, Chuan-Feng Li, and Guang-Can Guo. Coherent control and magnetic detection of divacancy spins in silicon carbide at high pressures. *Nano Letters*, 22(24):9943–9950, December 2022.

[40] Yu Zhou, Junfeng Wang, Xiaoming Zhang, Ke Li, Jianming Cai, and Weibo Gao. Self-protected thermometry with infrared photons and defect spins in silicon carbide. *Phys. Rev. Appl.*, 8:044015, Oct 2017.

[41] G. Wolfowicz, S. J. Whiteley, and D. D. Awschalom. Electrometry by optical charge conversion of deep defects in 4h-sic. *Proceedings of the National Academy of Sciences*, 115(31):7879–7883, July 2018.

[42] Ö. O. Soykal, Pratibha Dev, and Sophia E. Economou. Silicon vacancy center in $4h$-sic: Electronic structure and spin-photon interfaces. *Phys. Rev. B*, 93:081207, Feb 2016.

[43] S. A. Tarasenko, A. V. Poshakinskiy, D. Simin, V. A. Soltamov, E. N. Mokhov, P. G. Baranov, V. Dyakonov, and G. V. Astakhov. Spin and optical properties of silicon vacancies in silicon carbide  a review. *physica status solidi (b)*, 255(1), September 2017.

[44] Fei-Fei Yan, Jun-Feng Wang, Qiang Li, Ze-Di Cheng, Jin-Ming Cui, Wen-Zheng Liu, Jin-Shi Xu, Chuan-Feng Li, and Guang-Can Guo. Coherent control of defect spins in silicon carbide above 550 k. *Phys. Rev. Appl.*, 10:044042, Oct 2018.

[45] Qin-Yue Luo, Shuang Zhao, Qi-Cheng Hu, Wei-Ke Quan, Zi-Qi Zhu, Jia-Jun Li, and Jun-Feng Wang. High-sensitivity silicon carbide divacancy-based temperature sensing. *Nanoscale*, 15:8432–8436, 2023.

[46] Junfeng Wang, Fupan Feng, Jian Zhang, Jihong Chen, Zhongcheng Zheng, Liping Guo, Wenlong Zhang, Xuerui Song, Guoping Guo, Lele Fan, Chongwen Zou, Liren Lou, Wei Zhu, and Guanzhong Wang. High-sensitivity temperature sensing using an implanted single nitrogen-vacancy center array in diamond. *Phys. Rev. B*, 91:155404, Apr 2015.

[47] Wei-Ke Quan, Lin Liu, Qin-Yue Luo, Xiao-Di Liu, and Jun-Feng Wang. Fiber-coupled silicon carbide divacancy magnetometer and thermometer. *Opt. Express*, 31(10):15592–15598, May 2023.

[48] C. R. Eddy and D. K. Gaskill. Silicon carbide as a platform for power electronics. *Science*, 324(5933):1398–1400, June 2009.

[49] J.B. Casady and R.W. Johnson. Status of silicon carbide (sic) as a wide-bandgap semiconductor for high-temperature applications: A review. *Solid-State Electronics*, 39(10):1409–1422, 1996.

[50] Qiang Li, Jun-Feng Wang, Fei-Fei Yan, Ji-Yang Zhou, Han-Feng Wang, He Liu, Li-Ping Guo, Xiong Zhou, Adam Gali, Zheng-Hao Liu, Zu-Qing Wang, Kai Sun, Guo-Ping Guo, Jian-Shun Tang, Hao Li, Li-Xing You, Jin-Shi Xu, Chuan-Feng Li, and Guang-Can Guo. Room-temperature coherent manipulation of single-spin qubits in silicon carbide with a high readout contrast. *National Science Review*, 9(5):nwab122, 07 2021.

[51] Nguyen T. Son and Ivan G. Ivanov. Charge state control of the silicon vacancy and divacancy in silicon carbide. *Journal of Applied Physics*, 129(21), June 2021.

[52] Matthias Niethammer, Matthias Widmann, Sang-Yun Lee, Pontus Stenberg, Olof Kordina, Takeshi Ohshima, Nguyen Tien Son, Erik Janzén, and Jörg Wrachtrup. Vector magnetometry using silicon vacancies in $4h$-sic under ambient conditions. *Phys. Rev. Appl.*, 6:034001, Sep 2016.

[53] Zhengzhi Jiang, Hongbing Cai, Robert Cernansky, Xiaogang Liu, and Weibo Gao. Quantum sensing of radio-frequency signal with nv centers in sic. *Science Advances*, 9(20), May 2023.

[54] Stefania Castelletto, Alberto Peruzzo, Cristian Bonato, Brett C. Johnson, Marina Radulaski, Haiyan Ou, Florian Kaiser, and Joerg Wrachtrup. Silicon carbide photonics bridging quantum technology. *ACS Photonics*, 9(5):1434–1457, April 2022.

[55] Stefania Castelletto and Alberto Boretti. Silicon carbide color centers for quantum applications. *JPhys Photonics*, 2(2):022001, April 2020.

[56] F. Fuchs, B. Stender, M. Trupke, D. Simin, J. Pflaum, V. Dyakonov, and G. V. Astakhov. Engineering near-infrared single-photon emitters with optically active spins in ultrapure silicon carbide. *Nature Communications*, 6(1), July 2015.

[57] Takeshi Ohshima, Takahiro Satoh, Hannes Kraus, Georgy V Astakhov, Vladimir Dyakonov, and Pavel G Baranov. Creation of silicon vacancy in silicon carbide by proton beam writing toward quantum sensing applications. *Journal of Physics D: Applied Physics*, 51(33):333002, July 2018.

[58] Jun-Feng Wang, Qiang Li, Fei-Fei Yan, He Liu, Guo-Ping Guo, Wei-Ping Zhang, Xiong Zhou, Li-Ping Guo, Zhi-Hai Lin, Jin-Ming Cui, Xiao-Ye Xu, Jin-Shi Xu, Chuan-Feng Li, and Guang-Can Guo. On-demand generation of single silicon vacancy defects in silicon carbide. *ACS Photonics*, 6(7):1736–1743, May 2019.

[59] F. Sardi, T. Kornher, M. Widmann, R. Kolesov, F. Schiller, T. Reindl, M. Hagel, and J. Wrachtrup. Scalable production of solid-immersion lenses for quantum emitters in silicon carbide. *Applied Physics Letters*, 117(2), July 2020.

[60] H. Kraus, V. A. Soltamov, D. Riedel, S. Väth, F. Fuchs, A. Sperlich, P. G. Baranov, V. Dyakonov, and G. V. Astakhov. Room-temperature quantum microwave emitters based on spin defects in silicon carbide. *Nature Physics*, 10(2):157–162, December 2013.

[61] Edlyn V. Levine, Matthew J. Turner, Pauli Kehayias, Connor A. Hart, Nicholas Langellier, Raisa Trubko, David R. Glenn, Roger R. Fu, and Ronald L. Walsworth. Principles and techniques of the quantum diamond microscope. *Nanophotonics*, 8(11):1945–1973, 2019.

[62] Abram L. Falk, Paul V. Klimov, Bob B. Buckley, Viktor Ivády, Igor A. Abrikosov, Greg Calusine, William F. Koehl, Ádám Gali, and David D. Awschalom. Electrically and mechanically tunable electron spins in silicon carbide color centers. *Phys. Rev. Lett.*, 112:187601, May 2014.

[63] Gopalakrishnan Balasubramanian, Philipp Neumann, Daniel Twitchen, Matthew Markham, Roman Kolesov, Norikazu Mizuochi, Junichi Isoya, Jocelyn Achard, Johannes Beck, Julia Tissler, Vincent Jacques, Philip R. Hemmer, Fedor Jelezko, and Jörg Wrachtrup. Ultralong spin coherence time in isotopically engineered diamond. *Nature Materials*, 8(5):383–387, April 2009.