Magnetic detection under high pressures using designed silicon vacancy centres in silicon carbide

Jun-Feng Wang1,9,10, Lin Liu1,2,10, Xiao-Di Liu1,2,10, Qiang Li1,3, Jin-Ming Cui1,3,4, Di-Fan Zhou5, Ji-Yang Zhou1,3, Yu Wei6, Hai-An Xu2, Wan Xu2, Wu-Xi Lin1,3,4, Jin-Wei Yan2, Zhen-Xuan He1,3, Zheng-Hao Liu1,2, Zhi-He Hao1,3, Hai-Ou Li1,2,10, Wen Liu6, Jin-Shi Xu1,3,4, Eugene Gregoryanz2,7,8, Chuan-Feng Li1,3,4, & Guang-Can Guo1,3,4

Pressure-induced magnetic phase transitions are attracting interest as a means to detect superconducting behaviour at high pressures in diamond anvil cells, but determining the local magnetic properties of samples is a challenge due to the small volumes of sample chambers. Optically detected magnetic resonance of nitrogen vacancy centres in diamond has recently been used for the in situ detection of pressure-induced phase transitions. However, owing to their four orientation axes and temperature-dependent zero-field splitting, interpreting these optically detected magnetic resonance spectra remains challenging. Here we study the optical and spin properties of implanted silicon vacancy defects in 4H-silicon carbide that exhibit single-axis and temperature-independent zero-field splitting. Using this technique, we observe the magnetic phase transition of Nd2Fe14B at about 7 GPa and map the critical temperature–pressure phase diagram of the superconductor YBa2Cu3O6.6. These results highlight the potential of silicon vacancy-based quantum sensors for in situ magnetic detection at high pressures.

The ability of pressure to alter the electronic, magnetic and structural properties of matter is a vital feature widely used in fundamental and applied sciences studies1–8. High-pressure techniques have been applied in many fields, including physics, material sciences, geophysics and chemistry, revealing many unusual and important phenomena observed under pressure9–10. In particular, claims of pressure-induced high-critical-temperature (Tc) superconductivity have attracted serious attention and excitement in recent years6–8. For example, lanthanum hydride has been inferred to be a superconductor with a Tc of ~250 K at around 170 GPa (refs. 7,8). One of the great challenges in high-pressure research is the measurement of magnetic properties and their evolution. Conventional methods such as using superconducting quantum...
interference devices or a.c. susceptibility cannot directly detect weak magnetic signals of micrometre-sized samples in diamond anvil cells (DACs)\(^{20–22}\). It is therefore important to explore new methods for magnetic detection.

The high sensitivity and high resolution of in situ magnetic detections in DAC chambers were achieved using nitrogen vacancy (NV) centres in diamond\(^{23–32}\). Diamond NV centres are versatile solid-state spin quantum sensors that have been used to detect a wide variety of physical parameters, such as magnetic and electric fields, temperature, strain, spins, pressure and electrical currents\(^{23–35}\). The zero-field-splitting parameter \(D\) of the NV centre ground spin state was shown to increase linearly with pressure with a slope of 14.6 MHz GPa\(^{-1}\) up to 60 GPa (ref. \(^{26}\)). On this basis, an in situ magnetic detection method based on NV centres using optically detected magnetic resonance (ODMR) technologies has recently been developed at high pressure\(^{27–31}\). Micrometre-sized diamond particles with ensemble NV centres have been placed inside DAC chambers to measure the \(T_2\)–pressure phase diagram of a superconductor\(^{32}\) and detect the pressure-induced magnetic phase transition of a magnet\(^{33}\). The shallow implanted NV centres on the surface of the diamonds were also used to probe the magnetization of Fe particles and the Meissner effect of a superconductor, and to construct the full stress tensor on the culet surface\(^{34,35}\).

Defects in silicon carbide (SiC) could also be used to measure magnetic properties under extreme conditions. SiC is a widely used semiconductor owing to its unique properties, such as mature inch-scale growth and micro/nanofabrication\(^{30–32}\). Several spin qubits and bright single-photon emitters in SiC have also attracted considerable attention in the quantum community\(^{36–38}\). In particular, the silicon vacancy (V\(_{\text{Si}}\)) defect in 4H-SiC with a negative charge has been extensively used in spin–photon interfaces\(^{23}\), quantum photonics\(^{26}\), quantum information processing\(^{39}\) and quantum sensing of properties such as magnetic fields\(^{40}\) and temperatures\(^{41,42}\) owing to its outstanding properties (an \(S = 3/2\) spin quartet and ground state \(D \approx 0.31\) MHz GPa\(^{-1}\)) (refs. \(^{26,27}\)). It has only one axis (along the c axis of 4H-SiC), and the corresponding ODMR spectrum has two resonant peaks under an external magnetic field, which is convenient for determining the resonant frequencies and enhancing the scalability of SiC devices\(^{43}\). Moreover, its \(D\) value is also almost temperature independent from 20 K to 500 K at ambient pressure, which is beneficial for temperature–pressure research\(^{41,42}\). However, most of the previous investigations on the V\(_{\text{Si}}\) defect were performed under ambient pressure\(^{23–26}\). The study of the optical and spin properties at high pressure is important for V\(_{\text{Si}}\) defect-based quantum sensing at extreme conditions. In comparison with traditional high-pressure magnetometry techniques, the spatial resolution of V\(_{\text{Si}}\) defect detection is only around a few micrometres.

Here we investigate and characterize the optical and spin properties of the implanted silicon vacancy defects at the culets of a 4H-SiC anvil, which exhibit single-axis and temperature-independent...
The experimental results show that the photoluminescence spectrum blueshifts and $D$ increases with pressure at a rate of $0.31 \text{ MHz GPa}^{-1}$. We probe the pressure-induced magnetic phase transition of a Nd$_2$Fe$_{14}$B magnet at around 7 GPa at room temperature. Finally, we observed the Meissner effect of a YBa$_2$Cu$_3$O$_{6.6}$ superconductor at different pressures, yielding its $T_c$–pressure ($P$) phase diagram. These experiments demonstrate the feasibility of using V$_{Si}$ defects in SiC as quantum sensors and open up the possibility of studying superconducting phenomena under extreme conditions.

**Optical properties of silicon vacancies under high pressure**

The experimental configuration used in our experiments is shown in Fig. 1a (see the Methods and Supplementary Text 1 for details). First, we describe the optical and spin properties of the V$_{Si}$ defects at high pressures. The energy levels of the defects at high pressures are shown in Fig. 1b. The 720 nm laser pumped the electrons from the ground state to the phonon sideband, and the zero-phonon line (ZPL) at ambient pressure was 916 nm. Both the ZPL and the ground spin state $D$ changed under high pressure. The room temperature photoluminescence spectra of the defects at three different compressions are shown in Fig. 1c. The photoluminescence spectra of the V$_{Si}$ defects are blueshifted with pressure. We then investigate the mean counts of the V$_{Si}$ defects as a function of compression. The counts increased as the pressure increased from ambient pressure to 8 GPa due to the higher detection efficiency at shorter wavelengths of the single-photon counting module (Fig. 1d). The counts then decreased as the pressure increased to approximately 25 GPa (see Supplementary Text 1 for more details). At the same time, we observed a decrease in the ODMR contrast with increasing pressure (Fig. 2a). We speculate that the decrease in the photon counts and ODMR contrast are both related to, and driven by, the lattice distortion of the 4H-SiC, caused by the inhomogeneity and deviation of compression at high pressures. The altered probability density and the electronic structure of the silicon vacancy due to compression may also contribute to the decrease in the photon counts and ODMR contrast.

**Spin properties of silicon vacancies under high pressure**

We then study the spin properties of V$_{Si}$ defects at high pressures. The ODMR spectra at zero external magnetic field are shown in Fig. 2a. The zero-pressure ODMR peak of 72.4 ± 0.3 MHz may be due to the strain during the preparation of the SiC anvil, and the effect has been observed before. The resonant frequency shifts to higher frequencies as the pressure increased, in line with the ODMR signal of NV centres in diamond. The local structural distortions and the decreasing distance between V$_{Si}$ spin in the macroscopic compression in the SiC crystal drive the resonant frequency shifts to higher values as the pressure increases. As shown in Fig. 2b, the mean $D$ increased linearly with the pressure with a coefficient of

![Fig. 3](https://doi.org/10.1038/s41563-023-01477-5)
0.31 ± 0.01 MHz GPa⁻¹, which is considerably smaller than the coefficient of 14.6 MHz GPa⁻¹ for NV centres in diamond⁹,¹³,¹⁴. The smaller slope is beneficial for directly observing the shift of the ODMR signal over a large pressure range. The reason for the small slope is the degeneracy of half-integer VSi defects (\(S = \frac{3}{2}\)), which make it relatively insensitive to strain fluctuations³⁹.

Through coherent control of VSi defects, one can detect the noise spectroscopy of magnetic materials⁵⁰. Figure 2c shows the measurement of Rabi oscillations at ambient pressure using a standard pulse sequence⁵²,⁵³. The Rabi frequency inferred from the fit is 9 MHz. Figure 2d,e present the spin echo inferred the ODMR splitting during the superconducting phase transition of the sample at 9.0 GPa. The red line is the fit to the data, used to obtain \(T_c = 95.2 ± 0.2\) K.

Fig. 4 | Measurement of the temperature–pressure phase diagram of the superconductor YBa₂Cu₃O₆.₆ using implanted VSi defects. a, Confocal scanning microscopy image of the YBa₂Cu₃O₆.₆ sample and VSi defects in the culet surface. The region enclosed by the black dashed line is the investigated YBa₂Cu₃O₆.₆ sample, and the black cross marks the corresponding detected position. b, ODMR spectra with superconductivity diamagnetism in the detected position at different temperatures at 9.0 GPa. The dashed lines are guides to an eye only. c, The inferred ODMR splitting as a function of temperature under different pressures. The labelled coefficients are the ODMR splitting magnification times to normalize the data at 12.3 GPa. The error bars in c and d are the standard deviation of the left branch of ODMR spectra. e, The YBa₂Cu₃O₆.₆ \(T_c\)–pressure phase diagram. The \(T_c\) at ambient pressure (blue dot) is measured through a magnetic property measurement system (see Supplementary Text 2 for more details). The \(T_c\) under pressure (red dots) is inferred from the ODMR splittings. The orange shaded area represents the superconducting state, and the white area is the normal state for YBa₂Cu₃O₆.₆. The error bars obtained from the fitting standard deviations are smaller than the symbol sizes.

Magnetic detection using silicon vacancies under high pressures

SiC anvils with VSi defects could be used to study magnetic and superconducting properties of materials under compression. Using the ODMR spectrum, we studied the pressure-induced magnetic phase transitions of the common magnet Nd₂Fe₁₄B. A small sample of Nd₂Fe₁₄B was placed on the surface of the culet. The confocal scanning microscopy images of the implanted shallow VSi defects and Nd₂Fe₁₄B sample on the culet surface are presented in Fig. 3a. To efficiently detect the magnetic field of the sample, a location close to the sample (the region outlined by a black dashed line) was
chosen as the detection position, denoted by a black cross. As a comparison, a remote location (denoted by a blue cross) was the reference position. In the experiment, we applied a c-axis (perpendicular to the culet) magnetic field \(B_c\) with a strength of 198 G. Three schematics of local magnetic field vectors at the detected position under different pressures are shown in Fig. 3b. \(B_{\text{NaO}}\) and \(B_{\text{r.m.s.}}\) represent the magnetic field of the NdFeB sample and the total magnetic field on the V\(_S\) defects, respectively. Standard lock-in technique was used to detect the ODMR signals\(^{3,45}\). The integration time for each frequency was around 5 s, and the total measurement time was \(\approx\)80 s. The representative ODMR signals at the detected positions and reference during the compression process are presented in Fig. 3c. The ODMR signals at the reference position, reflecting the strength of \(B_c\), were also measured at each pressure. The ODMR resonant frequencies at the detected position did not change up to 5.1 GPa, but then abruptly shifted to a higher frequency at 6.7 GPa. Since both \(B_{\text{NaO}}\) and \(B_{\text{r.m.s.}}\) could be deduced from the measured ODMR spectra at each pressure, we calculate the magnetic field of the NdFeB sample as \(B_{\text{NaO}} - B_{\text{r.m.s.}}\) and plot it in Fig. 3d. The magnetic field of the sample during the compression (blue squares) and decompression (red dots) processes are shown in Fig. 3d. The sample magnetic field, as seen with the ODMR Frequencies, remained unchanged as the pressure increased to approximately 6 GPa, but then had a sharp reduction at around 7 GPa. This phenomenon demonstrates that the NdFeB sample reversibly changed from the diamagnetic state associated with the superconductivity of \(\text{NdFeB}\) to the paramagnetic state at \(7\) GPa, in good agreement with the literature\(^{1,12,13}\).

Extreme conditions have recently been applied to synthesize and study novel superconducting materials, with critical temperatures well above 200 K reported (refs. 6–9). As a proof-of-concept experiment, we detected the superconducting phase transition of the well-known superconductor \(\text{YBa}_2\text{Cu}_3\text{O}_7\) (refs. 14,15) at different pressures and low temperatures using our SiC anvils with V\(_S\) defects. \(\text{YBa}_2\text{Cu}_3\text{O}_7\) is a type-II high-\(T_c\) superconductor with different concentrations of oxygen (x). \(\text{YBa}_2\text{Cu}_3\text{O}_{7-x}\) was chosen due to its high \(T_c\) and dramatic \(T_c\)-pressure curve\(^{16}\). The \(\text{YBa}_2\text{Cu}_3\text{O}_{7-x}\) sample was synthesized in-house by conventional heat treatment methods (see Supplementary Text 2 for more details). The confocal scanning microscopy image of V\(_S\) defects and the \(\text{YBa}_2\text{Cu}_3\text{O}_{7-x}\) sample on the culet is shown in Fig. 4a. To measure the superconductor magnetic moment, we first cooled the superconductor below its \(T_c\) in a zero magnetic field, and then a small c-axis magnetic field (7.7 G) was applied to generate a Zeeman splitting of the V\(_S\) defects\(^{17,18}\). The ODMR measurements were performed as the temperature increased. The raw ODMR spectra versus temperature at one pressure point (9 GPa) are shown in Fig. 4b. At 9 GPa, the splitting underwent a sudden step-like change at 95 K (Fig. 4c). This is the manifestation of the Meissner effect and the indication that the sample entered the diamagnetic state associated with the superconductivity of the sample. The red line represents the fitting of the data points using a sigmoid function: \(S(T) = a + b/(1 + \exp(-(T - T_c)/\delta T))\), where \(a, b, T_c\) and \(\delta T\) are fitting parameters\(^{19,20}\). The fitted \(T_c\) at 9 GPa yielded 95.2 ± 0.2 K, which is in excellent agreement with the previous results\(^{17,18}\).

We also investigated \(T_c\) at different pressures. Figure 4d shows the measured ODMR splitting as a function of temperature at different pressures. The \(T_c\) increased with pressure, changing slope at around 12 GPa, but continuing to increase (see Fig. 4c). Our mapping of the \(T_{\text{c}}\)-pressure phase diagram is in excellent agreement with the previous data obtained by a.c. susceptibility methods in the DAC\(^{11}\). The pressure dependence of \(T_c\) is because high pressure leads to a change in the charge carrier concentration in the CuO\(_2\) planes within the unit cell\(^{12}\).

**Outlook**

Silicon-defect-based in situ magnetic detection technologies could provide several immediate research opportunities in materials science. First, by using a higher NA objective, better detectors\(^{11}\) and optimized samples, both the sensitivity and spatial resolution can be improved several times. The ideal spatial resolution could reach approximately 1 μm. As the size of the vortex/domains is approximately micrometre scale, the technique could be used to detect the magnetic vortices/domains walls of ferromagnetic materials\(^{1,16,47}\), magnetic two-dimensional materials\(^{48,49}\) and geochemistry at high pressure. Second, we could apply the magnetic sensor to investigate the \(T_c\)-pressure phase diagram, lower critical magnetic field and London penetration depth of new types of superconductor, such as kagome superconductors at high pressures\(^{41,50}\). Micrometre-sized particles of 4H–SiC with V\(_S\) defects\(^2\) and other types of spin quibits, including divacancies\(^{30,31}\), NV centres\(^{27,28}\) and even transition metal ions in 4H, 6H and 3C polytypes of SiC, could also be applied to local magnetic detection at high pressure. Some types of novel spin readout technologies, such as photocurrent-detected magnetic resonance\(^{131}\) and anti-Stokes excited ODMR technology\(^3\) could also be used for V\(_S\) defect-based magnetic sensing under high pressure. These experiments form a framework for using SiC V\(_S\) defects for local, in situ magnetic detection under high pressure.

In conclusion, we realized in situ magnetic detection of magnetic materials using an implanted V\(_S\) defect ensemble in SiC-based anvil cells under high pressure. By studying the optical and spin properties of the implanted V\(_S\) defects, we showed that the photoluminescence spectrum has a blueshift and that the mean counts decrease under high pressure. At the same time, \(T_c\) increases with pressure with a small coefficient of 0.31 MHz GPa\(^{-1}\), which is much less than that of the NV centres in diamond. Moreover, the spin coherence time does not vary with pressure, which is vital for probing the noise spectroscopy of magnetic materials at high pressure without a direct magnetic signal. Using these results, the pressure-induced magnetic phase transitions of the magnet \(\text{NdFeB}\) sample were detected in the range of 6–10 GPa using ODMR methods at room temperature. Finally, we mapped the \(T_c\)-pressure phase diagram of superconductor \(\text{YBa}_2\text{Cu}_3\text{O}_{7-x}\) by ODMR technology at low temperatures.

**Online content**

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41563-023-01477-5.

**References**

1. Dalladay-Simpson, P., Howie, R. T. & Gregoryanz, E. Evidence for a new phase of dense hydrogen above 325 gigapascals. Nature 529, 63–67 (2016).
2. Hanfland, M. et al. New high-pressure phases of lithium. Nature 408, 174–178 (2000).
3. Liu, X. D. et al. High-pressure behavior of hydrogen and deuterium at low temperatures. Phys. Rev. Lett. 119, 065301 (2017).
4. Babaev, E., Sudbø, A. & Ashcroft, N. W. A superconductor to superfluid phase transition in liquid metallic hydrogen. Nature 431, 666–668 (2004).
5. Gregoryanz, E. et al. Synthesis and characterization of a binary noble metal nitride. Nat. Mater. 3, 294–297 (2004).
6. Drozdov, A. P. et al. Conventional superconductivity at 203 kelvin at high pressures in the sulfur hydride system. Nature 525, 73–76 (2015).
7. Somayazulu, M. et al. Evidence for superconductivity above 260 K in lanthanum superhydride at megabar pressures. Phys. Rev. Lett. 122, 027001 (2019).
8. Drozdov, A. P. et al. Superconductivity at 250 K in lanthanum hydride under high pressures. Nature 569, 528–531 (2019).
9. Doherty, M. W. et al. Electronic properties and metrology applications of the diamond NV center under pressure. Phys. Rev. Lett. 112, 047601 (2014).
10. Yip, K. Y. et al. Measuring magnetic field texture in correlated electron systems under extreme conditions. Science 366, 1355–1359 (2019).

11. Lesik, M. et al. Magnetic measurements on micrometer-sized samples under high pressure using designed NV centers. Science 366, 1359–1362 (2019).

12. Hsieh, S. et al. Imaging stress and magnetism at high pressures using a nanoscale quantum sensor. Science 366, 1349–1354 (2019).

13. Shang, Y. X. et al. Magnetic sensing inside a diamond anvil cell via nitrogen-vacancy center spins. Chin. Phys. Lett. 36, 086201 (2019).

14. Ho, K. O. et al. Probing local pressure environment in anvil cells with nitrogen-vacancy (N-V−) centres in diamond. Phys. Rev. Appl. 13, 024041 (2020).

15. Schirhagl, R. et al. Nitrogen-vacancy centers in diamond: nanoscale sensors for physics and biology. Annu. Rev. Phys. Chem. 65, 83–105 (2014).

16. Oliver, S. M. et al. Vector magnetic current imaging of an 8 nm process node chip and 3D current distributions using the quantum diamond microscope. ISTFA ista2021p0096, 96–107 (2021).

17. Gars, M. et al. Non-invasive imaging of three-dimensional integrated circuit activity using quantum defects in diamond. Preprint at https://arxiv.org/abs/2112.12242 (2021).

18. Chen, X. D. et al. Temperature dependent energy level shifts of nitrogen-vacancy centers in diamond. Appl. Phys. Lett. 99, 161903 (2011).

19. Toyli, D. M. et al. Measurement and control of single nitrogen-vacancy center spins above 600 K. Phys. Rev. X 2, 031001 (2012).

20. Koehl, W. F. et al. Room temperature coherent control of defect spin qubits in silicon carbide. Nature 479, 84–87 (2011).

21. Christie, D. J. et al. Isolated electron spins in silicon carbide with millisecond coherence times. Nat. Mater. 14, 160–163 (2015).

22. Widmann, M. et al. Coherent control of single spins in silicon carbide at room temperature. Nat. Mater. 14, 164–168 (2015).

23. Nagy, R. et al. High-fidelity spin and optical control of single silicon-vacancy centres in silicon carbide. Nat. Commun. 10, 1954 (2019).

24. Wang, J. F. et al. Bright room temperature single photon source at telecom range in cubic silicon carbide. Nat. Commun. 9, 4106 (2018).

25. Lohmann, A., Johnson, B. C., McCallum, J. C. & Castelletto, S. A review on single photon sources in silicon carbide. Rep. Prog. Phys. 80, 034502 (2017).

26. Lukin, D. M. et al. 4H-silicon-carbide-on-insulator for integrated quantum and nonlinear photonics. Nat. Photon. 14, 330–334 (2020).

27. Zargaleh, S. A. et al. Nitrogen vacancy center in cubic silicon carbide: a promising qubit in the 1.5 μm spectral range for photonic quantum networks. Phys. Rev. B 98, 165203 (2018).

28. Wang, J. F. et al. Coherent control of nitrogen-vacancy center spins in silicon carbide at room temperature. Phys. Rev. Lett. 124, 223601 (2020).

29. Mu, Z. et al. Coherent manipulation with resonant excitation and single emitter creation of nitrogen vacancy centers in 4H silicon carbide. Nano Lett. 20, 6142–6147 (2020).

30. Simin, D. et al. All-optical dc nanotesla magnetometry using silicon vacancy fine structure in isotopically purified silicon carbide. Phys. Rev. X 6, 031014 (2016).

31. Anisimov, A. N. et al. Optical thermometry based on level anticrossing in silicon carbide. Sci. Rep. 6, 33301 (2016).

32. Wang, J. F. Robust coherent control of solid-state spin qubits using anti-Stokes excitation. Nat. Commun. 12, 3223 (2021).

33. Steele, L. G. et al. Optically detected magnetic resonance of nitrogen vacancies in a diamond anvil cell using designer diamond anvils. Appl. Phys. Lett. 111, 221903 (2017).

34. Ivády, V. et al. Pressure and temperature dependence of the zero-field splitting in the ground state of NV centers in diamond: a first-principles study. Phys. Rev. B 90, 235205 (2014).

35. Dai, J.-H. et al. Optimally detected magnetic resonance of diamond-nitrogen-vacancy centers under megabar pressures. Chin. Phys. Lett. 39, 117601 (2022).

36. Fuchs, F. et al. Engineering near-infrared single-photon emitters with optically active spins in ultrapure silicon carbide. Nat. Commun. 6, 7578 (2015).

37. Niethammer, M. et al. Coherent electrical readout of defect spins in silicon carbide by photo-ionization at ambient conditions. Nat. Commun. 10, 5569 (2019).

38. Wang, J. F. et al. Efficient generation of an array of single silicon-vacancy defects in silicon carbide. Phys. Rev. Appl. 7, 084021 (2017).

39. Nagy, R. et al. Quantum properties of dichroic silicon vacancies in silicon carbide. Phys. Rev. Appl. 9, 034022 (2018).

40. Kamarád, J., Arnold, Z. & Schneider, J. Effect of pressure on the curie and spin reorientation temperatures of polycrystalline Nd2Fe14B compound. J. Magn. Magn. Mater. 67, 29–32 (1987).

41. Sadewasser, S., Schilling, J. S., Paulikas, A. P. & Veal, B. W. Pressure dependence of Tc to 17 GPa with and without relaxation effects in superconducting YBa2Cu3O7. Phys. Rev. B 61, 741 (2000).

42. Chen, X. J., Lin, H. Q. & Gong, C. D. Pressure dependence of Tc in Y-Ba-Cu-O superconductors. Phys. Rev. Lett. 85, 2180 (2000).

43. Waxman, A. et al. Diamond magnetometry of superconducting thin films. Phys. Rev. B 89, 054509 (2014).

44. Joshi, K. R. et al. Measuring the lower critical field of superconductors using nitrogen-vacancy centers in diamond optical magnetometry. Phys. Rev. Appl. 11, 014035 (2019).

45. Husn, N. M. et al. Spatially resolved study of the Meissner effect in superconductors using NV-centers-in-diamond optical magnetometry. New J. Phys. 20, 043010 (2018).

46. Rondin, L. et al. Stray-field imaging of magnetic vortices with magnetometry based on nitrogen-vacancy centres in diamond. Nat. Rev. Mater. 4, 2279 (2013).

47. Casola, F. et al. Probing condensed matter physics with magnetometry based on nitrogen-vacancy centres in diamond. Nat. Rev. Mater. 13, 17088 (2018).

48. Li, T. X. et al. Pressure-controlled interlayer magnetism in atomically thin CrI3. Nat. Mater. 18, 1303–1308 (2019).

49. Zhang, L. L. et al. 2D materials and heterostructures at extreme pressure. Adv. Sci. 7, 2002697 (2020).

50. Nie, L. P. et al. Charge-density-wave-driven electronic nematicity in a kagome superconductor. Nature 604, 59–64 (2022).

51. Castelletto, S. et al. Fluorescent color centers in laser ablated 4H-SiC nanoparticles. Opt. Lett. 42, 1297–1300 (2017).

52. Falk, A. L. et al. Polytetrafluorethylene. Nat. Commun. 4, 1819 (2013).

53. Wolfowicz, G. et al. Vanadium spin qubits as telecom quantum emitters in silicon carbide. Sci. Adv. 6, eaaz1192 (2020).

54. Ho, K. O. et al. Recent developments of quantum sensing under pressurized environment using the nitrogen vacancy (NV) center in diamond. J. Appl. Phys. 129, 241101 (2021).
Methods

SiC anvil preparation and silicon vacancy generation
In the experiments, two high-quality single-crystal 4H-SiC cubes were used to fabricate SiC anvils with 200-μm-diameter culets. As shown in Fig. 1a, high-density shallow V_{Si} defects in a 100-nm-deep layer were perpendicularly implanted into the culets to generate high-density V_{Si} defects. The corresponded density was estimated to be approximately 7,500 μm^{-2}. Two 650 nm and 850 nm longpass filters were used to collect the ruby and V_{Si} defect fluorescence. The surface V_{Si} density of the defects was estimated to be approximately 7,500 μm^{-2} (see Supplementary Text 1 for more details).

Experimental set-up
Our set-up consisted of a custom-built confocal scanning microscope equipped with a radiofrequency system. Two lasers with wavelengths of 532 nm and 720 nm were used to excite the ruby and V_{Si} defects, respectively. Two 650 nm and 850 nm longpass filters were used to collect the ruby and V_{Si} defect fluorescence. We adopted a long-working-distance (20 mm) infrared objective (0.4 numerical aperture, Mitutoyo) to excite the samples and collect the fluorescence. A single-photon counting module (SPCM-AQRH-14-FC) was applied to detect the fluorescence of V_{Si} defects to determine the average photon counts. A liquid nitrogen temperature range optical cryostat (Oxford Instruments) combined with a confocal system was used for the low-temperature experiments. Standard lock-in technology was used to measure the ODMR and coherence control signals using a photoreceiver (Femto, OE-200-Si). A B_{0} field was applied to adjust the energy levels of the spin states. To eliminate heating by the laser and radiofrequency in the measurements, we used a small laser power (8 mW) and radiofrequency power (25 dBm for RdFeB experiments and 15 dBm for YBCO experiments).

Data availability
The data that support the findings of this study are presented in the article and the Supplementary Information, and are available from the corresponding authors upon reasonable request. Source data are provided with this paper.

References
55. Wang, J. F. et al. On-demand generation of single silicon vacancy defects in silicon carbide. *ACS Photon.* 6, 1736–1743 (2019).
56. Liu, X. D. et al. Counterintuitive effects of isotopic doping on the phase diagram of H2–HD–D2 molecular alloy. *Proc. Natl Acad. Sci. USA* 117, 13374–13378 (2020).

Acknowledgements
We thank G.-Q. Liu, E.-K. Liu and T. Wu for helpful discussions. This work was supported by the Innovation Program for Quantum Science and Technology (grant numbers 2021ZD0301400 and 2021ZD0301200), the National Natural Science Foundation of China (grant numbers U19A2075, 11975221, 11874361, 51672279, 51727806, 11774354, 61905233, 61725504, 11804330 and 11821404), the Science Challenge Project (grant number ZZ2016001), the CAS Innovation Grant (grant number CXJJ-19-008), the CAS HFiPS Director’s Fund (grant numbers YZJJ202102 and 2021YZGH15), the Anhui initiative in Quantum Information Technologies (grant number AHY060300) and the Fundamental Research Funds for the Central Universities (grant number WK2030380017). X.-D.L. is grateful for support from the Youth Innovation Promotion Association of CAS (grant number 2021446) and the Anhui key research and development programme (grant number 2022hh11020007) and J.-F.W. acknowledges financial support from the Science Specialty Program of Sichuan University (grant number 2020SCUNL210). This work was partially carried out at the USTC Center for Micro and Nanoscale Research and Fabrication. We thank Hefei advanced crystal technologies LTD for the sample preparation.

Author contributions
J.-F.W., X.-D.L. and J.-S.X. conceived the experiments. J.-F.W. and L.L. built the experimental set-up and performed the measurements with the help of X.-D.L., Q.L., J.-Y.Z., J.-M.C., H.-A.X., W.X., J.-W.Y., W.-X.L., Z.-X.H., Z.-H.L., Z.-H.H. and H.-O.L. L.L., J.-F.W. and X.-D.L. prepared the samples in the SiC-based high-pressure chamber. D.-F.Z. prepared the YBCuO sample. Y.W. and W.L. performed the implantation of the V_{Si} defects. J.-F.W., J.-S.X., L.L. and X.-D.L. performed the data analysis with contributions from all co-authors. J.-F.W., J.-S.X., X.-D.L. and E.G. wrote the paper with contributions from all co-authors. J.-S.X., X.-D.L., E.G., C.-F.L. and G.-C.G. supervised the project. All authors contributed to the discussion of the results.

Competing interests
The authors declare no competing interests.

Additional information

Correspondence and requests for materials

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41563-023-01477-5.

Peer review information
Nature Materials thanks Norman Yao and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.