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

Jun-Feng Wang

University of Science and Technology of China <https://orcid.org/0000-0002-5720-056X>

Lin Liu

Institute of Solid State Physics, HFIPS, Chinese Academy of Sciences

Xiao-Di Liu

Institute of Solid State Physics

Qiang Li

University of Science and Technology of China

Jin-Ming Cui

University of Science and Technology of China

Di-Fan Zhou

Shanghai University

Ji-Yang Zhou

University of Science and Technology of China

Yu Wei

University of Science and Technology of China

Hai-An Xu

Institute of Solid State Physics, HFIPS, Chinese Academy of Sciences

Wan Xu

Institute of Solid State Physics, HFIPS, Chinese Academy of Sciences,

Wu-Xi Lin

University of Science and Technology of China

Jin-Wei Yan

Institute of Solid State Physics, HFIPS, Chinese Academy of Sciences

Zhen-Xuan He

University of Science and Technology of China

Zheng-Hao Liu

University of Science and Technology of China <https://orcid.org/0000-0001-8067-1477>

Zhi-He Hao

University of Science and Technology of China

Hai-Ou Li

University of Science and Technology of China

Wen Liu

University of Science and Technology of China

Jin-Shi Xu

University of Science and Technology of China <https://orcid.org/0000-0003-0528-1000>

Eugene Gregoryanz

School of Physics and Centre for Science at Extreme Conditions <https://orcid.org/0000-0001-9080-8756>

Chuan-Feng Li (✉ cfl@ustc.edu.cn)

University of Science and Technology of China <https://orcid.org/0000-0001-6815-8929>

Guangcan Guo

University of Science and Technology of China

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Abstract

Pressure is a significant parameter to investigate the properties of matter. The phenomenon of pressure-induced magnetic phase transition has attracted great interest due to its ability to detect superconducting behaviour at high pressures in diamond anvil cell. However, detection of the local sample magnetic properties is a great challenge due to the small sample chamber volume. Recently, *in situ* pressure-induced phase transition has been detected using optically detected magnetic resonance (ODMR) method of the nitrogen vacancies (NV) centers in diamond. However, the NV centers with four orientation axes and temperature-dependent zero-field-splitting present some difficulty to interpret the observed ODMR spectra. Here, we investigate and characterize the optical and spin properties of the implanted silicon vacancy defects in 4H-SiC, which is single-axis and temperature-independent zero-field-splitting. Using this technique, we observe the magnetic phase transition of a magnetic $\text{Nd}_2\text{Fe}_{14}\text{B}$ sample at about 7 GPa. Finally, the critical temperature-pressure phase diagram of the superconductor $\text{YBa}_2\text{Cu}_3\text{O}_{6.66}$ is mapped and refined. These experiments pave the way for the silicon vacancy-based quantum sensor being used *in situ* magnetic detection at high pressures.

Introduction

Pressure can alter electronic, magnetic and lattice properties of matter, which is vital both in fundamental and applied sciences^{1–4}. The high pressure techniques can be applied in many fields including physics, material science, geophysics and chemistry¹. Plethora of exciting and important phenomena were observed under pressure^{1–4}. Particularly, pressure-induced high critical temperature (T_c) superconductivity has drawn much attention in recently^{1–4}. For example, lanthanum hydride has been demonstrated to be a superconductor with a critical temperature of around 250 K at pressures of about 170 GPa⁴. One of the great challenges of superconducting studies at high pressure is the measurement of magnetic properties and their evolution. However, conventional methods such as using superconducting quantum interference devices (SQUID) or the AC susceptibility cannot directly detect weak magnetic signals at microscale inside the diamond anvil cell (DAC) sample chamber^{5–11}. Therefore, it is urgent to explore new methods for the magnetic detection.

Recently, the high sensitivity and high resolution of the *in situ* magnetic detections in the DAC chamber was achieved by utilising the nitrogen-vacancy (NV) centres^{7–9}. Diamond NV centers are versatile solid-state spin quantum sensors, which have been used to detect a wide variety of physical parameters such as magnetic field, electric field, temperature, strain, spins, and so on¹². The zero-field-splitting (ZFS) parameter D of the NV centre ground spin state was shown to linearly increased as the pressure with a slope of 14.6 MHz/GPa up to 60 GPa⁶. On this basis, *in situ* magnetic detection method based on NV centers through the optically detected magnetic resonance (ODMR) technologies had been developed at high-pressure recently^{7–10}. Micron-sized diamonds with ensemble NV centers have been placed inside the DAC chamber to measure T_c -pressure phase diagram of a superconductor⁷ and detect the pressure-induced magnetic phase transition of a magnet¹⁰. On the other hand, shallow implanted NV centers in the surface of the DAC culet are also used to probe the magnetization of a Fe particle and the Meissner effect of a superconductor, and construct the full stress-tensor on the culet surface^{8,9}. Besides the ODMR methods, the noise spectroscopy method has been used to probe the phase transition of a gadolinium⁹.

However, NV centers have four different orientation axes in the diamond crystal, and the corresponding ODMR signals have eight resonate peaks, making it difficult to analyse the ODMR spectrum of the specific axis under a magnetic field^{7–10}. It will be especially intractable for using diamond particles in the DAC chamber due to the unknown and different orientations of the NV centers^{7,10}. Additionally, the ZFS parameter D decreases with the temperature from around 50 K to 600 K^{13,14}, meanwhile, it also increases with the pressure at the same time, the convolution in P-T space present some difficulty to interpret the observed spectra. Defects in silicon carbide (SiC) is another promising candidate to measure magnetic properties under extreme conditions. We then use a similar solid quantum sensor based on silicon vacancy (V_{Si}) defects in 4H-SiC to realize the *in situ* magnetic measurement under high pressure.

SiC is a widely used semiconductor due to its unique properties, such as mature inch-scale growth and micro-nano fabrication^{15–17}. In recent years, several spin qubits and bright single-photon-emitters in SiC attracted great attentions in the quantum community^{15–26}. Particularly, the V_{Si} (V2) defect has been extensively used in spin-photon interface¹⁸, quantum photonics²¹, quantum information processing¹⁷, quantum sensing such as magnetic field²⁷ and temperature^{28,29} due to its outstanding properties. its spin state is $S = 3/2$ spin quartet and the ground state ZFS parameter D is 70 MHz^{17,18}. In contrast to NV centers in diamond, it only has one axis (along the

c-axis of the 4H-SiC), and the corresponding ODMR spectrum only has two resonate peaks under an external magnetic field, which is convenient to readout the resonate frequencies and enhance the scalability in SiC devices^{17,29}. Moreover, the ZFS parameter D is also almost temperature independent from 20 K to 500 K, which is beneficial to temperature-pressure research^{28,29}. Besides, comparison with the traditional high-pressure magnetometry techniques, the V_{Si} defects detected spatial resolution is only about a few microns.

Here, we investigate and characterize the optical and spin properties of the implanted silicon vacancy defects in 4H-SiC, which is single-axis and with temperature-independent zero-field-splitting. The experimental results show that the PL spectrum has a blue shift and the ZFS parameter D increases with pressure at the rate 0.31 MHz/GPa under the pressure. Based on this, we have probed the pressure-induced magnetic phase transition of a $Nd_2Fe_{14}B$ magnet at about 7 GPa at room temperature. Finally, Meissner effect of the superconductor $YBa_2Cu_3O_{6.66}$ at different pressures is observed and we map and refine the T_c -P phase diagram. These experiments demonstrate the feasibility of using V_{Si} defects in SiC as novel quantum sensors and open up the applications to study superconducting phenomena under extreme conditions

Results

Two high-quality single crystal 4H-SiC cubes are used to fabricate SiC anvil cells using the standard design with 200 μm diameter culets. As shown in Fig. 1a, high-density shallow V_{Si} defects in a 100 nm depth layer are used for magnetic detection³⁰ (see details in Methods). A non-magnetic rhenium gasket is used to confine the sample between the two anvils⁸. The NaCl is applied as the pressure transmitting medium in all the experiments. The *in situ* pressure is monitored by measuring the PL spectrum of the ruby (about 10 μm) in the pressure chamber. A 10 μm platinum wire is placed across the culet surface, which is used to transmit microwave to control V_{Si} defects spin states.

The energy levels of V_{Si} defects at high pressures are shown in Fig. 1b. The 720 nm laser pumps the electron from the ground state to the phonon sideband, and the ZPL at ambient pressure is 916 nm. Both the ZPL and the ground spin state ZFS parameter D change under high pressure. We first investigate the optical properties of the V_{Si} defects at high pressures. The details of experimental setup can be found in Methods. The room temperature PL spectra of V_{Si} defects and the corresponding ruby PL spectra at three different pressures are presented in Fig. 1c. The PL spectra of the ruby are used to monitor the local pressure. While, the PL spectra of V_{Si} defects shift towards a shorter wavelength with the pressure, which is similar to that of NV center in diamond⁶. We then study mean counts of the V_{Si} defects as a function of pressure. As shown in Fig. 1d, the counts increase as the pressure increases from the ambient pressure to around 8 GPa, which is due to the higher detect efficiency at the shorter wavelength of the single-photon counting module. Then the counts decrease as the pressure increase to around 25 GPa (see Supplementary Note 1 for more details). The decrease of the photon counts may due to the lattice distortion of the 4H-SiC caused by compression.

The characterization of V_{Si} defect spin properties at high pressures is the foundation for high-pressure magnetic field sensing. Three respectively ODMR spectra at zero external magnetic field are presented in Fig. 2a. The resonant frequency shifts to higher frequencies as the pressure increases, which is similar to the ODMR signal of NV centers in diamond^{6-11,31,32}. The reason might due to the local structural distortions and the decreasing distance between V_{Si} spins in the macroscopic compression at the corresponding SiC lattices^{6,31,32}. As shown in Fig. 2b, the mean ZFS parameter D increases linearly with the pressure with the coefficient of 0.31 ± 0.01 MHz/GPa, which is much less than the 14.6 MHz/GPa of the NV centers in diamond^{6,10,11}. The smaller slope is beneficial for directly observing the shift of the ODMR signal with a large pressure range. The reason for the small slope might be due to the degeneracy of half-integer V_{Si} defects ($S = 3/2$), which makes it rather insensitive to fluctuations in strain³³. Through the coherent control of V_{Si} defects, the dynamic magnetic properties of the magnetic materials without a direct magnetic signal could be detected^{9,10}. Figure 2c shows the measurement of the Rabi oscillation at ambient pressure using a standard pulse sequence²⁹. Inferred from the fitting, the Rabi frequency is about 9 MHz. Then the coherence time under high pressures are studied. Figures 2d and 2e present the spin echo measurement of V_{Si} defects at

Fig. 2 The spin properties of V_{Si} defects at high pressures. **a**, The ODMR spectra at three different pressures with zero external magnetic field. The solid lines represent Lorentzian fittings. **b**, The mean ZFS parameter D linearly increases with the pressure up to 27 GPa. Error bars represent the standard deviations of the measured results. **c**, Rabi oscillation at 31 Gauss at ambient pressure. The red line is fitted using an exponential decaying sine function. **d and e**, The spin echo results at ambient pressure and 15.1 GPa, respectively.

Red lines represent the exponentially decay fittings to the data. **f**, The coherence time T_2 as a function of the pressure. Error bars are the data fitting standard deviations.

ambient pressure and 15.1 GPa, respectively. The corresponding coherence time T_2 are $7.8 \pm 0.9 \mu\text{s}$ and $7.8 \pm 0.8 \mu\text{s}$, respectively. Both the values are consistent with previous results²⁹. The coherence time T_2 as a function of pressure up to 25 GPa are summarized in Fig. 2f. The coherence time remains invariable up to 25 GPa, which is similar to that of NV centers in diamond¹⁰. The robustness V_{Si} defects coherence time under pressure helps detect phase transitions of magnetic samples at high pressures without an obvious static magnetic signals^{9,10}.

Pressure-induced magnetic phase transitions of a common magnet $\text{Nd}_2\text{Fe}_{14}\text{B}$ sample at room temperature are detected here using the ODMR methods of the V_{Si} defects. A small piece of $\text{Nd}_2\text{Fe}_{14}\text{B}$ sample is placed on the surface of the culets. The PL image of the implanted shallow V_{Si} defects and $\text{Nd}_2\text{Fe}_{14}\text{B}$ sample on the culet surface are presented in Fig. 3a. In order to efficiently detect the magnetic field of the sample, a location close to the sample (black dashed line region) is chosen as the detect position, which is denoted as a black cross. As a comparison, a remote location is the reference position (denoted as a red cross). In the experiment, we apply a c-axis (perpendicular to the culet) magnetic field B_c with the strength of 198 Gauss. Three schematics of local magnetic field vectors at the detected position under different pressures are shown in Fig. 3b. The B_c , B_{NdFeB} and B_{tot} represent the c-axis external magnetic field, magnetic field of the $\text{Nd}_2\text{Fe}_{14}\text{B}$ sample and total magnetic field on the V_{Si} defects, respectively. The strength of B_{NdFeB} decreases with pressure in the compression processes and it recovers in the decompression processes. It leads to the corresponding changes of the ODMR spectra signal as the pressure. We calculate the magnetic field of the $\text{Nd}_2\text{Fe}_{14}\text{B}$ sample by the $|B_{\text{tot}} - B_c|$. Both of the B_{tot} and B_c can be deduced from the measured ODMR spectra at each pressure. The representative several ODMR signals at the detected positions during the compression process are presented in Fig. 3c. The ODMR signals at the reference position reflecting the strength of external magnetic field are also measured at each pressure. One of representative ones at the pressure 0.3 GPa is shown in Fig. 3c. The ODMR resonant frequencies at the detected position do not change up to 5.1 GPa, and then they increase quickly up to 6.7 GPa. Finally, they again slightly change as the pressure further increases. The summary of the magnetic field of the sample measured by V_{Si} defects during the compression (blue squares) and decompression (red dots) processes are shown in Fig. 4d, respectively. In the compression process, the sample magnetic field decreases slowly as the pressure increases to about 6 GPa, then it has a sharp reduction in the range of about 6–8 GPa. Finally, it slightly decreases as the pressure increases to around 9.5 GPa. This phenomenon demonstrates that the $\text{Nd}_2\text{Fe}_{14}\text{B}$ sample changes from ferromagnetic phase to paramagnetic phase at around 7 GPa, which is consistent with previous results¹⁰. Furthermore, we also measure the sample magnetic field during the decompression process, which is almost the same as that in the compression process. It is due to the robust magnetic property of the used $\text{Nd}_2\text{Fe}_{14}\text{B}$ sample. The magnetic field-pressure data demonstrate the pressure-induced ferromagnetic-paramagnetic phase transitions of the $\text{Nd}_2\text{Fe}_{14}\text{B}$ sample in the range of 6 to 10 GPa, which is also consistent with previous results^{10,34}.

Figure 3 The detection of pressure-induced magnetic phase transition of a $\text{Nd}_2\text{Fe}_{14}\text{B}$ magnet using the shallow V_{Si} defects. **a**, The PL image of the V_{Si} defects and $\text{Nd}_2\text{Fe}_{14}\text{B}$ sample in the culet surface. The black and red crosses are the detected and reference positions, respectively. The black dashed line region indicates the $\text{Nd}_2\text{Fe}_{14}\text{B}$ sample. The scale bar is 20 μm . **b**, Three typically local magnetic fields vectors during the pressure-induced magnetic phase transition in the compression and decompression processes. The external magnetic field B_c is along the c-axis of the 4H-SiC. The magnetic field of the $\text{Nd}_2\text{Fe}_{14}\text{B}$ sample and the total magnetic field are labelled as B_{NdFeB} and B_{tot} , respectively. **c**, The shallow V_{Si} defects ODMR spectra in the detected and reference positions in the culet surface during the compression process. **d**, The inferred magnetic fields of the $\text{Nd}_2\text{Fe}_{14}\text{B}$ sample measured by V_{Si} defects during the compression (blue squares) and decompression (red circles) processes, respectively.

In the past decades, extreme conditions were applied to synthesize and study the novel superconducting materials^{1–4,7–9}. It has been used to provide new insights to the mechanism of superconducting and explore higher T_c superconductors^{1–4,7–9}. As a proof-of-principle experiment, we detect the superconducting phase transition of the well-known superconductor $\text{YBa}_2\text{Cu}_3\text{O}_x$ ^{35–38} using the implanted V_{Si} defects at different pressures and low temperature. $\text{YBa}_2\text{Cu}_3\text{O}_x$ is a type II high- T_c (liquid nitrogen temperature range) superconductor, with different concentration of oxygen x. The $\text{YBa}_2\text{Cu}_3\text{O}_{6.6}$ are used in the experiment due to its high T_c and dramatically T_c -pressure curve³⁵. The $\text{YBa}_2\text{Cu}_3\text{O}_{6.6}$ sample is made by conventional heat treatment methods (see Supplementary Note 2 for more details). In the experiment, we put a tiny flake of $\text{YBa}_2\text{Cu}_3\text{O}_{6.6}$ on the surface of the culet. Then the SiC-based pressure

chamber is set in the cryostat³¹. The confocal scanning image of V_{Si} defects and $YBa_2Cu_3O_{6.66}$ sample on the culet is delineated in Fig.4a. We detected the Meissner effect of the sample (black dashed line region) through the ODMR spectra at the detected position (black cross) under the pressure of 9.0 GPa^{6–8}. In order to measure superconductor magnetic moment, we first cool the superconductor below its T_c in zero magnetic field, then a small c-axis magnetic field (7.7 Gauss) is applied to generate a Zeeman splitting of the V_{Si} defects^{37–39}. The ODMR measurements are performed as the temperature increases. The ODMR spectra with respect to temperatures are shown in Fig.4b, which have different splittings at different temperatures. This phenomenon indicates the diamagnetism associated with superconductivity Meissner effect. The summary of the ODMR splitting as a function of temperature are presented in Fig.4c. The splitting almost does not change as the temperature increases from 82.4 K to 94.7 K, but then it has a step-like jump at around 95 K. Then the splitting remains nearly invariable as the temperature further increases to 108 K. The red line represents the fitting of the data using a sigmoid function: $S(T)=a+b/(1+\exp[-(T-T_c)/\delta T_c])$, where a , b , δT_c are fitting parameters and T_c is the critical temperature^{37,38}. The fitted critical temperature T_c at 9 GPa is 95.3 ± 0.2 K, which is consistent with the previous results³⁵. The small change of the ODMR splitting is consistent with the result measured by implanted NV centers in diamond, which may due to the large distance between the quantum sensors and the samples⁸.

Figure 4 The measurement of temperature-pressure phase diagram of the superconductor $YBa_2Cu_3O_{6.66}$ using implanted V_{Si} defects.

a, The confocal scanning image of $YBa_2Cu_3O_{6.66}$ sample and V_{Si} defects in the culet surface. The black dashed line region marks the investigated $YBa_2Cu_3O_{6.66}$ sample and the black cross marks the corresponding detected position. The size scale bar is 20 μm . **b**, The ODMR spectra with the 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 during the sample superconducting phase transition at 9.0 GPa. The red line is the fitting of the data. The superconducting transition temperature T_c is deduced to be 95.2 ± 0.2 K. **d**, The inferred ODMR splittings as a function of the temperature under different pressures. The labeled coefficients are the ODMR splitting magnification times in order to normalization the data. **e**, The $YBa_2Cu_3O_{6.66}$ T_c -pressure phase diagram. The T_c under ambient pressure (blue dot) is measured through a magnetic property measurement system (see Supplementary Note 2 for more details). The T_c under pressures (red dots) are inferred from the ODMR splittings. The shadow area represents the superconducting state and the transparent area is the normal state for the $YBa_2Cu_3O_{6.66}$. The error bars are obtained from the fitting standard deviations are smaller than the symbol sizes.

We further investigate the critical temperatures at different pressures. Figure 4d shows the measured ODMR splitting as a function of the temperature at different pressures, from which we can infer the pressure-dependent T_c . The critical temperature T_c increases as the pressure increases. As presented in Fig. 4e, the $YBa_2Cu_3O_{6.66}$ T_c -pressure phase diagram is mapped by the ODMR method. T_c increases quickly as the pressure increases from ambient pressure to about 12.3 GPa, then it increases slowly up to around 17.1 GPa, which are consistent with previous results³⁵. The pressure dependence of T_c is due to that high pressure leads to the change of charge carrier concentration in the CuO_2 planes within the unit cell³⁶. The shadow and transparent areas represent the superconducting state and normal state for the $YBa_2Cu_3O_{6.66}$, respectively, which is in agreement with the previous results³⁵. Furthermore, the V_{Si} defects-based ODMR methods can be used to study the T_c -pressure phase diagram of $YBa_2Cu_3O_x$ with different concentration of oxygen x and its intrinsic properties, including the lower critical field and London penetration depth under high pressure^{38,39}.

Discussion

In conclusion, we realize *in situ* magnetic detection of the magnetic materials using implanted V_{Si} defects ensemble in SiC-based anvil cells under high pressures. Through studying the optical and spin properties of the implanted V_{Si} defects, the experiments show that the PL spectrum has a blue shift and the mean counts decrease under high pressure. At the same time, the ZFS parameter D increases as the pressure with a small coefficient of 0.31 MHz/GPa, which is much less than that of the NV centers in diamond. Moreover, the spin coherence time keeps invariable as the pressure which is vital to probe phase transitions of samples at high pressure without a direct magnetic signal. Besides, the ODMR contrast can further increase several times using optimized anneal parameters, which can improve the ODMR signal detecting efficiency⁴⁰. Based on these, the pressure-induced magnetic phase transitions of magnet $Nd_2Fe_{14}B$ sample are detected in the range of 6–10 GPa using the ODMR methods at room temperature. Finally, we map and refine the superconductor $YBa_2Cu_3O_{6.66}$ T_c -pressure phase diagram by the ODMR technology at low temperatures.

It can further realize the directly magnetic field image of the sample using a CMOS camera detector⁸. The 4H-SiC micrometer particle with V_{Si} defects⁴¹ and other types of spin qubit including divacancy^{15,16,42}, NV center^{24–26} and even transition metal ions⁴³ in 4H, 6H

and 3C polytypes of SiC may also be applied to local magnetic detection at high pressure. Some types of novel spin readout technologies such as photocurrent detected magnetic resonance^{44,45} and anti-Stokes excited ODMR technology²⁹ can also be used for V_{Si} defects-based magnetic sensing under high pressure. The experiments form a framework for using SiC V_{Si} defects in the local *in situ* magnetic detection under high pressure.

Methods

Silicon vacancy generation. In the experiments, two high-quality single crystal 4H-SiC cubes are used to fabricate SiC anvil cells using the standard design. The culet diameter is 200 μm and the crystalline orientation with the 1000 (c-axis). 20 keV helium ions (He^+) with a dose of $1 \times 10^{13}/\text{cm}^2$ are perpendicularly implanted to the culets to generate high-density shallow V_{Si} defects and the corresponding depth is around 100 nm through the stopping and range of ions in matter (SRIM) simulation³⁰. We then anneal the SiC anvil cells at 500 °C for 2 hours to further increase the V_{Si} defects density by around 3 times³⁰.

Experimental set-up. The measurement setup is a homebuilt confocal scan microscope equipped with a microwave system^{29,30}. Two lasers with the wavelengths of 532 nm and 720 nm are used to excite the ruby and V_{Si} defects, respectively. Two 650 nm and 850 nm long-pass filters are used for the collection of ruby and V_{Si} defects fluorescence, respectively. We adopt a long-working distance (20 mm) infrared objective (0.4 N.A., Mitutoyo) to excite the samples and collect the fluorescence. A single-photon counting module (SPCM-AQRH-14) is applied to 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 is applied in the low-temperature experiments⁴⁶. The standard lock-in technology is used to detect the ODMR and the coherence control signals using a photoreceiver (Femto, OE-200-Si)^{15,29}. A c-axis (perpendicular to the culet surface) magnetic field B_c is added to adjust the spin state energy levels.

Declarations

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Author contributions

J.-F.W., X.-D. L. and J.-S.X. designed the experiments. J.-F.W. and L.L. built the experiment 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 manuscript 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.

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Figures

Figure 1

The SiC anvil cell and V_{Si} defects optical properties with pressure. **a**, The schematic of SiC anvil cell. The samples are placed on the surface of the culet, and the local shallow (100 nm) V_{Si} defects are used for the *in situ* magnetic detection. A 10 μm ruby is put close to the samples to measure the pressure. **b**, Energy levels of V_{Si} defects at high pressure. The red line indicates the 720 nm excitation laser. The pressure changes the ZPL emission and shifts the ground state ZFS parameter D with Δ . **c**, Room temperature PL spectra of the V_{Si} defects at three representative pressures. The inset is the corresponding PL spectra of the ruby. **d**, The mean counts of V_{Si} defects with 10 mW laser excitation as a function of the pressure. Error bars are due to the standard deviations of counts in an $8 \times 8 \mu\text{m}^2$ area.

Figure 2

The spin properties of V_{Si} defects at high pressures. **a**, The ODMR spectra at three different pressures with zero external magnetic field. The solid lines represent Lorentzian fittings. **b**, The mean ZFS parameter D linearly increases with the pressure up to 27 GPa. Error bars represent the standard deviations of the measured results. **c**, Rabi oscillation at 31 Gauss at ambient pressure. The red line is fitted using an exponential decaying sine function. **d** and **e**, The spin echo results at ambient pressure and 15.1 GPa, respectively. Red lines represent the exponentially decay fittings to the data. **f**, The coherence time T_2 as a function of the pressure. Error bars are the data fitting standard deviations.

Figure 3

The detection of pressure-induced magnetic phase transition of a $\text{Nd}_2\text{Fe}_{14}\text{B}$ magnet using the shallow V_{Si} defects. **a**, The PL image of the V_{Si} defects and $\text{Nd}_2\text{Fe}_{14}\text{B}$ sample in the culet surface. The black and red crosses are the detected and reference positions, respectively. The black dashed line region indicates the $\text{Nd}_2\text{Fe}_{14}\text{B}$ sample. The scale bar is 20 μm . **b**, Three typically local magnetic fields vectors during the pressure-induced magnetic phase transition in the compression and decompression processes. The external magnetic field B_c is along the c-axis of the 4H-SiC. The magnetic field of the $\text{Nd}_2\text{Fe}_{14}\text{B}$ sample and the total magnetic field are labelled as B_{NdFeB} and B_{tot} , respectively. **c**, The shallow V_{Si} defects ODMR spectra in the detected and reference positions in the culet surface during the compression process. **d**, The inferred magnetic fields of the $\text{Nd}_2\text{Fe}_{14}\text{B}$ sample measured by V_{Si} defects during the compression (blue squares) and decompression (red circles) processes, respectively.

Figure 4

The measurement of temperature-pressure phase diagram of the superconductor $\text{YBa}_2\text{Cu}_3\text{O}_{6.66}$ using implanted V_{Si} defects. **a**, The confocal scanning image of $\text{YBa}_2\text{Cu}_3\text{O}_{6.66}$ sample and V_{Si} defects in the culet surface. The black dashed line region marks the investigated $\text{YBa}_2\text{Cu}_3\text{O}_{6.66}$ sample and the black cross marks the corresponding detected position. The size scale bar is 20 μm . **b**, The ODMR spectra with the 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 during the sample superconducting phase transition at 9.0 GPa. The red line is the fitting of the data. The superconducting transition temperature T_c is deduced to be 95.2 ± 0.2 K. **d**, The inferred ODMR splittings as a function of the temperature under different pressures. The labeled coefficients are the ODMR splitting magnification times in order to normalization the data. **e**, The $\text{YBa}_2\text{Cu}_3\text{O}_{6.66}$ T_c -pressure phase diagram. The T_c under ambient pressure (blue dot) is measured through a magnetic property measurement system (see Supplementary Note 2 for more details). The T_c under pressures (red dots) are inferred from the ODMR splittings. The shadow area represents the superconducting state and the transparent area is the normal state for the $\text{YBa}_2\text{Cu}_3\text{O}_{6.66}$. The error bars are obtained from the fitting standard deviations are smaller than the symbol sizes.

Supplementary Files

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