Anisotropic Spin-Acoustic Resonance in Silicon Carbide at Room Temperature

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We report on acoustically driven spin resonances in atomic-scale centers in silicon carbide at room temperature. Specifically, we use a surface acoustic wave cavity to selectively address spin transitions with magnetic quantum number differences of $\pm 1$ and $\pm 2$ in the absence of external microwave electromagnetic fields. These spin-acoustic resonances reveal a nontrivial dependence on the static magnetic field orientation, which is attributed to the intrinsic symmetry of the acoustic fields combined with the peculiar properties of a half-integer spin system. We develop a microscopic model of the spin-acoustic interaction, which describes our experimental data without fitting parameters. Furthermore, we predict that traveling surface waves lead to a chiral spin-acoustic resonance that changes upon magnetic field inversion. These results establish silicon carbide as a highly promising hybrid platform for on-chip spin-optomechanical quantum control enabling engineered interactions at room temperature.

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Hybrid spin-mechanical systems are considered as a promising platform for the implementation of universal quantum transducers [1] and ultrasensitive quantum sensors [2]. Spin states can be coupled by the strain fields of phonons and mechanical vibrations. Coherent sensing of mechanical resonators [3], acoustic control of single spins [4], and electromechanical stabilization of spin color centers [5] based on spin-optomechanical coupling have been demonstrated. Similarly to a magnetic field, the application of a static strain field leads to a shift of the spin levels, while a resonantly oscillating strain field induces interlevel spin transitions. Their selection rules are imprinted by the crystal symmetry or device geometry, which provide a high degree of flexibility for on-chip coherent spin manipulation [6–8] and may support chiral spin-phonon coupling [9].

Most of the systems coupling atomic-scale spins to vibrations studied so far are based on color centers in diamond [3–5,10–14]. Two characteristics of silicon carbide (SiC) make it a natural material choice for hybrid spin optomechanics. As diamond, SiC hosts highly coherent optically active spin centers such as negatively charged silicon vacancies ($V_{Si}$) [15] and divacancies (VV) [16]. In addition, SiC is already used in commercial nano-electromechanical systems with robust performance and ultrahigh sensitivity to vibrations [17]. Recently, the mechanical tuning [18] and acoustic coherent control [19] of the VV spin $S = 1$ centers in SiC have been demonstrated at cryogenic temperatures. However, symmetry-dependent spin-acoustic interactions are still largely unexplored, and SiC-based hybrid spin-mechanical systems under ambient conditions remain elusive.

In this Letter, we demonstrate room-temperature spin-acoustic resonance (SAR) in 4H-SiC. We exploit the intrinsic properties of the half-integer spin $S = 3/2$ system [20], the so-called V$_{Si}$ qudit [21], to realize full control of the spin states using high-frequency vibrations. This is fulfilled by acoustically coupling spin sublevels with magnetic quantum numbers ($m_S$) differing by both $\Delta m_S = \pm 1$ and $\Delta m_S = \pm 2$. The previous SAR studies were mostly restricted to $S = 1$ atomic-scale spins [3,5,10–14,18,19], which usually require the application of microwave electromagnetic fields for the optical readout. Very recently, microwave-free SAR resonance has been demonstrated in a spin $S = 1/2$ system with strong spin-orbit coupling at cryogenic temperature [4]. We show that the spin $S = 3/2$ system enables all-optical readout without external microwave electromagnetic fields even at room temperature.

The mechanical vibrations are applied via a surface acoustic wave (SAW) resonator patterned on the surface of a 4H-SiC wafer perpendicular to the $c$ hexagonal axis (see Fig. 1). The superposition of axial and shear strain components with different amplitudes and phases makes the SARs dependent on the quantization direction of the spin states relative to the SAW propagation direction. Here, this anisotropy manifests itself as a complex angular dependence of the $\Delta m_S = \pm 1$ and $\Delta m_S = \pm 2$ transitions.
and detection of SAWs with a wavelength our acoustic SAW resonator[27]. It consists of a pair of [25]. As shown in the SM[27], the observed zero-field which has a mean depth of 250 nm below the SiC surface in atomic-scale spin systems.

Figure 1(a) displays the 4H-SiC lattice with a single V_{Si} center [23]. These centers are created in a semi-insulating 4H-SiC substrate by proton irradiation [24]. Figure 2(d) shows the calculated depth distribution of the SiC crystal field. The zero-field splitting between the m_{S} = \pm 1/2 and m_{S} = \pm 3/2 doublets in the ground state (GS) is equal to 70 MHz, with the spin quantized along the c axis. Optical excitation into the excited state, followed by spin-dependent recombination via the metastable state, leads to a preferential population of the m_{S} = \pm 1/2 spin sublevels in the ground state, as indicated by the green dots in Fig. 1(d). For the optical excitation along the c axis (as in our experiments), no dependence on the excitation polarization is observed at room temperature. As the photoluminescence intensity is stronger for optical transitions between the m_{S} = \pm 3/2 states, it becomes sensitive to the resonant spin transitions between the m_{S} = \pm 1/2 and m_{S} = \pm 3/2 GS sublevels (see SM [27]) [31].

The optically detected SAR experiments are performed in a confocal microphotoluminescence setup in which the sample is excited by a 780-nm-wavelength laser focused onto a spot size of 10 \mu m at the center of the SAW resonator. The GS spin transition frequencies are tuned to the SAW resonance frequency by applying the in-plane magnetic field B [27]. To describe the spin-acoustic interaction of the V_{Si} center in the presence of B, we consider an effective spin-3/2 Hamiltonian

\[ H = H_{B} + H_{\text{def}}, \]  
\[ H_{B} = g \mu_{B} S \cdot B + D \left( S_{z}^{2} - \frac{5}{4} \right). \]  

Here, S=(S_x, S_y, S_z) is the spin-3/2 operator, \mu_{B} the Bohr magneton, g \approx 2 the in-plane g factor, and D = 35 MHz the zero-field splitting constant. H_{\text{def}} describes the Zeeman splitting. For B = 0, this Hamiltonian yields the GS eigenstates displayed in Fig. 1(d). As discussed below, H_{\text{def}} describes the coupling between the V_{Si} spin and elastic deformations [2,22].

Figure 2(a) shows the Zeeman shift of the GS spin sublevels calculated from H_{B}. In what follows, we consider magnetic fields much larger than the GS zero-field splitting 2D/g \mu_{B} \sim 2.5 mT. In this case, the spin quantization axis aligns along the B direction and the spin sublevels shift linearly with the magnetic field. The mixing of the states quantized along B is on the order of D/(g \mu_{B} B) and can be neglected. We note that for in-plane magnetic fields, the states with spin projection on magnetic field direction m_{S} = \pm 3/2 are preferentially populated under optical pumping (as indicated by the green dots). In contrast to the B = 0 case illustrated in Fig. 1(d), the photoluminescence is now stronger for transitions between the excited state and GS involving the m_{S} = \pm 1/2 states (see the light bulbs next to each energy level).
The optically detected SAR as a function of $B$ is presented in Fig. 2(b). We observe two resonances at $B = 16.7$ mT and $B = 33.3$ mT, which are ascribed to the acoustically driven $\Delta m_5 = \pm 2$ and $\Delta m_5 = \pm 1$ spin transitions, respectively. They agree well with the magnetic field strengths calculated from Eq. (1) for the resonance frequency $f_{\text{SAW}} = 916$ MHz [cf. double vertical arrows in Fig. 2(a)]. Both resonances are well fitted by a Lorentzian function [solid curves in Fig. 2(b)] with an FWHM of 2.2 mT and 6.0 mT, respectively. Due to the zero-field splitting [cf. Eq. (2)], these resonances are actually doublets. With the zero-field spin splitting of 70 MHz, they should be split by approximately 1 mT and 2 mT for the $\Delta m_5 = \pm 2$ and $\Delta m_5 = \pm 1$ spin transitions, respectively. These splittings are not resolved due to a relatively large broadening partially caused by a reduction of the spin coherence in proton-irradiated samples with high irradiation fluences [35].

A remarkable property of the SAR interaction illustrated in Fig. 2(b) is the ability to selectively couple all spin states within the $V_{\text{Si}}$ qudit [36]. In particular, the $\Delta m_5 = \pm 2$ transitions are normally forbidden for microwave-driven spin resonance. Therefore, their excitation in Fig. 2(b) represents a clear evidence of the acoustic nature of the observed resonances. To further corroborate this acoustic nature, we display in Fig. 2(c) the intensity of the optically detected $\Delta m_5 = \pm 2$ SAR as a function of the magnetic field strength (vertical axis) and the rf frequency applied to the SAW resonator (horizontal axis). The SAR signal vanishes as soon as either $B$ is changed or $f_{\text{SAW}}$ is detuned (cf. $S_{11}$ in the same panel), thus confirming that the spin transitions are caused by the dynamic fields of the SAW. Additional evidences for the acoustic nature are summarized in the SM [27].

We now discuss the anisotropic nature of the SAR. Figure 2(b) compares the optically detected SAR signal for two angles $\Phi_B$ between the SAW propagation direction [x-axis, cf. Fig. 1(b)] and the in-plane magnetic field. While the magnetic field strengths at which the SARs take place are independent of the in-plane orientation of $B$, the SAR intensities do clearly depend on $\Phi_B$. Circles present the experimental data, the dashed lines are guides to the eye. The thick lines show the calculation after Eq. (4) with $\eta = 0$.
spin-acoustic interaction. In the spherical approximation, the effect of a lattice deformation on a spin center is described by the interaction term

\[ \mathcal{H}_{\text{def}} = \sum_{\alpha\beta} u_{\alpha\beta} S_{\alpha} S_{\beta}, \]  

where \( \Xi \) is the interaction constant [2]. Being quadratic in the spin operators, such an interaction can induce spin transitions with \( \Delta m_S = \pm 1 \) as well as with \( \Delta m_S = \pm 2 \). For \( B \| x \), the spin transitions with \( \Delta m_S = \pm 1 \) are induced by the strain tensor components \( u_{xx} \) and \( u_{zz} \), while those with \( \Delta m_S = \pm 2 \) are induced by the other linear-independent components \( u_{yx}, u_{zz}, \) and \( u_{yx} \). The strain components responsible for the spin transitions for other \( B \) directions can be obtained by the corresponding rotation of the strain tensor.

A plane Rayleigh SAW propagating along \( x \) [cf. Fig. 1(b)] is described by the strain tensor \( u_{\alpha\beta}(t, x, z) = u_{\alpha\beta}(z)e^{\mathbf{k}x \cdot \mathbf{t}} + \text{c.c.} \) with nonvanishing components \( u_{xx}, u_{zz}, \) and \( u_{xz} = \text{int}_{xz}^{\text{oom}} \) [37]. We assume a reference frame for which \( u_{xx}, u_{zz}, \) and \( u_{xz}^{\text{oom}} \) are purely real. The factor \( i = \sqrt{-1} \) indicates that the phase of the \( u_{xz} \) component is shifted by \( \pi/2 \), thus resulting in an elliptically polarized strain field in the \( xz \) plane. Figure 2(d) displays the calculated depth profiles of the \( u_{xx}, u_{zz}, \) and \( u_{xz} \) strain components [38] superimposed on the simulated depth distribution of the \( V_{\text{Si}} \) defects [26].

In our case, the spin centers are inserted in an acoustic resonator and, thus, subjected to a combination of two counterpropagating SAWs traveling along \( x \) and \(-x\) with intensities \( I_+ \) and \( I_- \), respectively. We use the parameter \( \eta = (I_+ - I_-)/(I_+ + I_-) \) to distinguish between a standing wave (\( |\eta| = 0 \)), a traveling wave (\( |\eta| = 1 \)), or intermediate cases (0 < |\eta| < 1). The rates \( W_{\pm 1} \) and \( W_{\pm 2} \) of the spin transitions with \( \Delta m_S = \pm 1 \) and \( \Delta m_S = \pm 2 \), respectively, are then given by (see SM [27])

\[ W_{\pm 1} \propto 3 \cos^2 \phi_B (u_{xz}^2 \sin^2 \phi_B + u_{zz}^2) + 4 \eta u_{xz} u_{zz}^\prime \sin \phi_B \]

\[ W_{\pm 2} \propto 3 \left( (u_{xz} \sin^2 \phi_B - u_{zz})^2 + 4 u_{zz}^2 \sin^2 \phi_B \right) + 4 \eta (u_{xz} \sin^2 \phi_B - u_{zz}) u_{zz}^\prime \sin \phi_B. \]  

The transition rates in Eq. (4) were averaged along \( x \) to account for the finite size of the photoluminescence detection spot, which is larger than the SAW wavelength. The angular brackets \( \langle \rangle \) indicate averaging along \( z \) to take into account the depth distribution of the \( V_{\text{Si}} \) centers as well as the strain field, as presented in Fig. 2(d).

Figures 3(a) and 3(b) present the angular dependencies of the \( \Delta m_S = \pm 1 \) and \( \Delta m_S = \pm 2 \) transition intensities, respectively, calculated after Eq. (4) for various \( \eta \). The SARs are always symmetric with respect to the inversion of the \( B_x \) component, since our system has a \((xz)\) mirror plane. For \( \eta = 0 \), the SARs are also symmetric with respect to the inversion of \( B_y \) due to additional presence of the time-reversal symmetry. As \( |\eta| \) increases, the latter symmetry breaks as the strain field of the traveling SAW acquires an elliptical polarization. Particularly, Fig. 3(a) shows that the \( \Delta m_S = \pm 1 \) SAR almost vanishes for \( B_y > 0 \) (0° < \( \phi_B < 180° \)) while it remains strong for \( B_y < 0 \) (180° < \( \phi_B < 360° \)). Such an asymmetric angular dependence is a clear evidence of the broken time-reversal symmetry in the presence of a traveling SAW. Upon inversion of the SAW propagation direction (\( \eta < 0 \), not shown), the angular dependencies of such chiral SAR are flipped with respect to the horizontal axis.

Having developed a microscopic model for the anisotropic SAR, we now apply it to analyze the experimental data given by the circles in Fig. 3(c) and 3(d). The angular dependence of the \( \Delta m_S = \pm 1 \) SAR has a butterfly-like shape with vanishing signal for \( \phi_B = \pm 90° \) and maxima when the magnetic field rotates toward \( \phi_B \approx \pm 45° \) or \( \pm 135° \). In contrast, the angular dependence of the \( \Delta m_S = \pm 2 \) SAR has a cocoon-like shape with maxima for \( \phi_B = \pm 90° \). This SAR does not vanish for any direction of the in-plane magnetic field. The measured angular dependencies are best reproduced by Eq. (4) by assuming \( \eta = 0 \), which yields the solid lines in Fig. 3(c), (d). This result is consistent with the expected standing-wave nature of the acoustic fields within a resonator. We attribute the deviations between experimental data and theoretical predictions to small fluctuations in the position of the laser spot on the SAW path as the sample is rotated during the measurement [27]. We emphasize that our model has no fitting parameters except for the overall intensity to match the readout optical signal. Moreover, the absolute SAR intensities are comparable with those of conventional optically detected magnetic resonance induced by a microwave magnetic field with the amplitude \( B_{rf} \approx 30 \mu T \) [27]. This allows us to give a rough order of magnitude estimate for the spin-strain interaction constant, \( \Xi \sim |\mu_B B_{rf}|/|u_{\alpha\beta}| \sim 10 \mu eV \). Its exact determination requires the measurement of the zero-field splitting as a function of the mechanical stress, which is beyond the scope of this work [39].

In conclusion, we demonstrate here half-integral SAR in SiC at room temperature. Using a SAW resonator patterned on the SiC surface, we are able to address both the \( \Delta m_S = \pm 1 \) and \( \Delta m_S = \pm 2 \) spin transitions of the \( V_{\text{Si}} \) spin-3/2 center with all-optical readout and without requiring extra microwave electromagnetic fields. The SARs reveal a complex dependence on the magnetic field orientation with respect to the SAW propagation direction. Our theoretical model describes these angular dependencies without any fitting parameter, allows us to determine the spin-strain coupling constant, and predicts chiral spin-acoustic interaction for traveling SAWs. Such a room-temperature hybrid spin-mechanical platform can be used to implement quantum sensors [41] with on-chip SAW control instead of microwave electromagnetic fields [2] as
well as to realize acoustically driven topological states [42]. It can also be applied to implement microwave-free spin and optical control of single qubits in SiC [43–45].

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[1] M. J. A. Schuetz, E. M. Kessler, G. Giedke, L. M. K. Vandersypen, M. D. Lukin, and J. I. Cirac, Universal Quantum Transducers Based on Surface Acoustic Waves, Phys. Rev. X 5, 031031 (2015).

[2] A. V. Poshakinskiy and G. V. Astakhov, Optically detected spin-mechanical resonance in silicon carbide membranes, Phys. Rev. B 100, 094104 (2019).

[3] S. Kolkowitz, A. C. B. Jayich, Q. P. Unterheimeier, S. D. Bennett, P. Rabl, J. G. E. Harris, and M. D. Lukin, Coherent sensing of a mechanical resonator with a single-spin qubit, Science 335, 1603 (2012).

[4] S. Maity, L. Shao, S. Bogdanović, S. Meesala, Y.-I. Sohn, N. Sinclair, B. Pingault, M. Chalupnik, C. Chia, L. Zheng, K. Lai, and M. Lončar, Coherent acoustic control of a single silicon vacancy spin in diamond, Nat. Commun. 11, 193 (2020).

[5] B. Machielse, S. Bogdanovic, S. Meesala, S. Gauthier, M. J. Burek, G. Joe, M. Chalupnik, Y. I. Sohn, J. Holzgrafe, R. E. Evans, C. Chia, H. Atikian, M. K. Bhaskar, D. O. Sukachev, L. Shao, S. Maity, M. D. Lukin, and M. Loncar, Quantum Interference of Electromechanically Stabilized Emitters in Nanophotonic Devices, Phys. Rev. X 9, 031022 (2019).

[6] D. Lee, K. W. Lee, J. V. Cady, P. Ovarchaitaypong, and A. C. B. Jayich, Topical review: Spins and mechanics in diamond, J. Opt. B 19, 033001 (2017).

[7] K. J. Satzinger, Y. P. Zhong, H. S. Chang, G. A. Pearis, A. Bienfait, M.-H. Chou, A. Y. Cleveland, C. R. Conner, E. Dumur, J. Grebel, I. Gutierrez, B. H. November, R. G. Povey, S. J. Whiteley, D. D. Awschalom, D. I. Schuster, and A. N. Cleveland, Quantum control of surface acoustic-phonon waves, Nature (London) 563, 661 (2018).

[8] S. Takada, H. Edlbauer, H. V. Lepage, J. Wang, P.-A. Mortemousque, G. Georgiou, C. H. W. Barnes, C. J. B. Ford, M. Yuan, P. V. Santos, X. Waintal, A. Ludwig, A. D. Wieck, M. Urdampilleta, T. Meunier, and C. Bäuerle, Sound-driven single-electron transfer in a circuit of coupled quantum rails, Nat. Commun. 10, 4557 (2019).

[9] H. Zhu, J. Yi, M.-Y. Li, J. Xiao, L. Zhang, C.-W. Yang, R. A. Kaindl, L.-J. Li, Y. Wang, and X. Zhang, Observation of chiral phonons, Science 359, 579 (2018).

[10] E. R. MacQuarrie, T. A. Gosavi, N. R. Jungwirth, S. A. Bhave, and G. D. Fuchs, Mechanical Spin Control of Nitrogen-Vacancy Centers in Diamond, Phys. Rev. Lett. 111, 227602 (2013).

[11] O. Arcizet, V. Jacques, A. Siria, P. Poncharal, P. Vincent, and S. Seidelin, A single nitrogen-vacancy defect coupled to a nanomechanical oscillator, Nat. Phys. 7, 879 (2011).

[12] J. Teissier, A. Barfuss, P. Appel, E. Neu, and P. Maletinsky, Strain Coupling of a Nitrogen-Vacancy Center Spin to a Diamond Mechanical Oscillator, Phys. Rev. Lett. 113, 020503 (2014).

[13] D. A. Golter, T. Oo, M. Amezcue, K. A. Stewart, and H. Wang, Optomechanical Quantum Control of a Nitrogen-Vacancy Center in Diamond, Phys. Rev. Lett. 116, 143602 (2016).

[14] H. Chen, N. F. Oondo, B. Jiang, E. R. MacQuarrie, R. S. Daveau, S. A. Bhave, and G. D. Fuchs, Engineering electron–phonon coupling of quantum defects to a semi-confocal acoustic resonator, Nano Lett. 19, 7021 (2019).

[15] D. Riedel, F. Fuchs, H. Kraus, S. Väth, A. Sperlich, V. Dyakonov, A. A. Soltamova, P. G. Baranov, V. A. Ilyin, and G. V. Astakhov, Resonant Addressing and Manipulation of Silicon Vacancy Qubits in Silicon Carbide, Phys. Rev. Lett. 109, 226402 (2012).

[16] A. L. Falk, B. B. Buckley, G. Calusine, W. F. Koehl, V. V. Dobrovitski, A. Politi, C. A. Zorman, P. X. L. Feng, and D. D. Awschalom, Polytype control of spin qubits in silicon carbide, Nat. Commun. 4, 1819 (2013).

[17] A. Li, H. X. Tang, and M. L. Roukes, Ultra-sensitive NEMS-based cantilevers for sensing, scanned probe and very high-frequency applications, Nat. Nanotechnol. 2, 114 (2007).

[18] A. L. Falk, P. V. Klimov, B. B. Buckley, V. Ivády, I. A. Abríkosov, G. Calusine, W. F. Koehl, A. Gali, and D. D. Awschalom, Electrically and Mechanically Tunable Electron Spins in Silicon Carbide Color Centers, Phys. Rev. Lett. 112, 187601 (2014).

[19] S. J. Whiteley, G. Wolfowicz, C. P. Anderson, A. Bourassa, H. Ma, M. Ye, G. Koolstra, K. J. Satzinger, M. V. Holt, F. J. Heremans, A. N. Cleveland, D. I. Schuster, G. Galli, and D. D. Awschalom, Spin–phonon interactions in silicon carbide addressed by Gaussian acoustics, Nat. Phys. 15, 490 (2019).

[20] 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, Nat. Phys. 10, 157 (2014).

[21] V. A. Soltamov, C. Kasper, A. V. Poshakinsky, 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, Nat. Commun. 10, 1678 (2019).

[22] P. Udvaryi and A. Gali, Ab Initio Spin-Strain Coupling Parameters of Divacancy Qubits in Silicon Carbide, Phys. Rev. Applied 10, 054010 (2018).

[23] V. Ivády, J. Davidsson, N. T. Son, T. Ohshima, I. A. Abríkosov, and A. Gali, Identification of Si-vacancy related parameters of Divacancy Qubits in Silicon Carbide, Phys. Rev. Lett. 113, 227602 (2013).
In large magnetic fields considered here, the spin-acoustic interaction does not couple the $m_s = -3/2$ and $m_s = +3/2$ states. In case of $B \sim D/\mu_B$, any pair within the four spin states can be coupled acoustically.

See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.125.107702 for sample and experimental details, photoluminescence characterization, optically detected magnetic resonance spectrum at zero magnetic field, spatial dependence of the SAR, dependence of the SAR on SAW power, and determination of the matrix elements for the SAW-induced spin transition.

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