

Strained donor-bound excitons in ^{28}Si

David A. Vogl^{1,2,*}, Noah L. Braitsch^{1,2}, Başak Ç. Özcan^{1,2}, Niklas S. Vart^{1,2},
M. L. W. Thewalt³, and Martin S. Brandt^{1,2}

¹Walter Schottky Institute and School of Natural Sciences, *Technical University of Munich*, Am Coulombwall 4, 85748 Garching, Germany

²Munich Center for Quantum Science and Technology, Schellingstraße 4, 80799 Munich, Germany

³Department of Physics, *Simon Fraser University*, Burnaby, British Columbia, Canada V5A 1S6



(Received 10 October 2025; revised 19 November 2025; accepted 9 December 2025; published 17 February 2026)

We present a comprehensive experimental study of the neutral donor to donor-bound exciton transition ($D^0 \rightarrow D^0X$) in isotopically enriched ^{28}Si , focusing on the group V donors P, As, and Sb under finely tuned uniaxial stress along the [100] and [110] crystal axes and magnetic fields from 3.5 mT to 1.7 T. From these measurements, donor-specific deformation potentials are extracted. The uniaxial electron deformation potential Ξ_u is found to be significantly larger than values reported for other states or transitions in silicon and shows clear dependence on the donor species, indicating an increased sensitivity of the D^0X state to strain and central-cell effects. We also observe a magnetic field dependence of the hole shear deformation potential d , suggesting a more complex strain coupling mechanism than captured by standard theory. Diamagnetic shift parameters determined from Zeeman spectra show good agreement with earlier measurements. Our results provide a refined parameter set critical for the design of silicon quantum devices based on D^0X transitions.

DOI: [10.1103/g6yl-q9bl](https://doi.org/10.1103/g6yl-q9bl)

I. INTRODUCTION

Donors in silicon are investigated as a powerful implementation of qubits for quantum computation [1,2]. They pose significant advantages over other leading qubit technologies, like superconducting transmon qubits [3], electrostatically defined quantum dots [4], and ion traps [5]: The donor Coulomb potential offers a natural confinement of the electron, and atomically precise placement [6] in the silicon lattice promises inherent scalability. Owing to the advances in isotopic purification [7], both the electronic and nuclear spins of the donor show exceedingly long coherence times [8–10]. The high nuclear spin of the heavier group V donors has successfully been implemented as a higher-dimensional qudit [11–13], and one- and two-qubit operations on individual donors have been demonstrated repeatedly [14–17]. Fast initialization of the spin state and control of the donor charge state, however, remain challenging.

The optical excitation of neutral donors (D^0) to donor-bound excitons (D^0X) has been demonstrated as a reliable method for both electron and nuclear spin state initializations [18,19] and hybrid optoelectrical readout [20,21] of ensembles of donors. It is based on spin-selective excitation and successive spin-to-charge conversion due to the dominant Auger recombination [22]. Recently, a D^0X readout of as few as 10^4 donors was achieved [23]; however, the application

to individual donors has yet to be demonstrated. One major challenge in scaling down this readout technique to single donors is presented by its sensitivity to strain, leading to a strong spectral shift, broadening, or splitting. Inhomogeneous or shear strain even creates an internal electric field gradient [11], which in extreme cases is expected to reduce the donor-bound exciton lifetime [20,24].

Strain is a fundamental aspect of any nanodevice, as the mismatch in thermal expansion coefficients between different materials inherently introduces strain in the structure at cryogenic temperatures [11,25]. Spin qubits in Si/SiGe heterostructures even rely on the strained environment generated by the lattice mismatch for the confinement of the electronic states [26]. The sensitivity to strain of the $D^0 \rightarrow D^0X$ transition may also be used for *in situ* strain mapping of silicon nanodevices, as recently demonstrated [23].

Hence, precise knowledge of the strain dependence of the D^0X excitation spectrum is desirable. In this context, the impact of strain resulting from implantation damage has been examined in detail [27]. Early investigations explored the effect of strain on the photoluminescence of bound multiexciton complexes in the absence of an external magnetic field [28,29]. More recently, the effects of strain on D^0X transitions in the presence of a magnetic field were studied, where measurements, however, were limited either to a single, fixed strain value [20,30] or to very few data points and small overall stress [23].

This work presents more detailed experimental data for the P, As, and Sb neutral donor to donor-bound exciton transition ($D^0 \rightarrow D^0X$) under [100] and [110] *in situ* variable stress at various magnetic fields. Within each dataset, the established deformation potential theory describes the spectra well, yielding deformation potentials that are mostly consistent with earlier work. However, when comparing across magnetic

*Contact author: david.vogl@wsi.tum.de

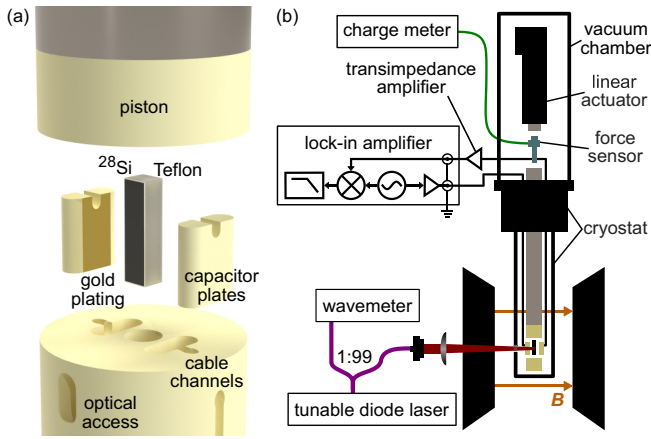


FIG. 1. Schematic of the experimental setup for the detection of Auger electrons generated by the recombination of optically excited D^0X under mechanically applied stress. (a) Exploded view rendering of the sample and its surrounding elements. All components colored in yellow are manufactured from PEEK. (b) Depiction including the laser, magnet, cryostat, lock-in amplifier, and actuator.

fields, we find a clear dependence of the hole shear deformation potential d on field strength, suggesting a previously neglected higher-order coupling between magnetic field, shear strain, and the D^0X hole states. In addition, we obtain a significantly larger electron deformation potential Ξ_u than reported by other methods, which may also be donor dependent.

II. METHODS

A. Electrical detection of D^0X

Following optical excitation of the $D^0 \rightarrow D^0X$ transition, the donor-bound excitons decay predominantly via Auger recombination [22], in which one of the electrons recombines with the hole and transfers its energy to the second electron. This second electron is excited high into the conduction band, leaving behind an ionized donor. Although the excess conduction band electrons rapidly thermalize and are recaptured by the ionized donors, this process still temporarily increases the free charge carrier concentration, allowing for the electrical detection of optically excited donor-bound excitons through impedance measurements.

B. Samples

Our samples are cut from a bulk ^{28}Si crystal isotopically purified to 99.991% as part of the Avogadro project [7]. They have dimensions of $2 \times 2 \times 8 \text{ mm}^3$ and contain about $[^{31}\text{P}] = (1.5 \pm 0.2) \times 10^{14} \text{ cm}^{-3}$, $[^{75}\text{As}] = (3.4 \pm 1.1) \times 10^{14} \text{ cm}^{-3}$, and $[^{121}\text{Sb}] = (1.0 \pm 0.2) \times 10^{14} \text{ cm}^{-3}$. The boron content has not been measured; however, the samples are known to be n -type.

C. Experimental setup

Each sample is loosely placed in the sample holder custom made from polyether ether keton (PEEK) sketched in Fig. 1(a). It allows for optical access and also holds in place

the capacitor plates used for the impedance measurements. In this way we avoid inherent strain due to a tight mount or electrical contacts placed directly on the sample [21]. The sample is further wrapped in thin pieces of Teflon tape to smooth out surface imperfections and thus distribute the applied stress homogeneously over the top and bottom surfaces. The sample is cooled to just above liquid helium temperature in an Oxford Instruments CF935 helium flow cryostat and placed between the pole caps of a Bruker B-E25 electromagnet, as can be seen in the schematic of the experimental setup in Fig. 1(b).

For the excitation of the donor-bound excitons we use a Toptica continuously tunable diode laser with a coarse-tuning range of 1010–1100 nm, a fine-tuning range of 210 pm, and a linewidth specified to be less than 10 kHz. The laser wavelength is stabilized with the help of a High Finesse WS-7 wavemeter, which also allows us to measure the excitation wavelength with high precision.

We probe the impedance of the sample with an ac voltage at a test frequency of $f_{\text{test}} = 903.14 \text{ kHz}$ generated by a Zurich Instruments UHF lock-in amplifier. The ac voltage is applied to one of the capacitor plates, and the electric signal on the other plate is then fed into a Femto DHPA-100 transimpedance amplifier and finally back into the lock-in amplifier for demodulation. In this way, we obtain a measure of the ac conductivity of the test structure containing the sample at the frequency f_{test} .

Compressive stress is applied to the sample from above using an extended piston with a flat surface, driven by a Physics Instruments M-238.5PL high-load dc gear actuator. An integrated noncontact optical linear encoder measures the piston position to a precision of 100 nm. Simultaneously, the force present in the piston is measured with a Kistler 9217A piezoelectric force sensor together with an appropriate Kistler 5015A charge meter. In order to avoid friction introduced by a vacuum feedthrough, the actuator and piston are inside a vacuum chamber directly connected to the cryostat vacuum that is required for the helium.

III. THEORY

The shift of the $D^0 \rightarrow D^0X$ transition energy ΔE under applied stress σ and magnetic field $\mathbf{B}$ can be approximated by the combined changes in energy of the additional electron and hole [20,23,31],

$$\Delta E_{D^0 \rightarrow D^0X}(\epsilon, \mathbf{B}) \approx \Delta E_e(\epsilon, \mathbf{B}) + \Delta E_h(\epsilon, \mathbf{B}), \quad (1)$$

where ϵ denotes the strain associated with σ and changes in the electron-electron and electron-hole interactions are neglected. Following effective mass theory, we describe the weakly bound electron and hole based on the characteristics and symmetry of the conduction band (CB) minimum and valence band (VB) maximum, respectively.

A. Effects of strain on electron and hole states

The CB minimum in silicon is sixfold degenerate. In the presence of the donor potential, however, the translational symmetry of the crystal is broken, and the degeneracy is lifted by the valley-orbit (VO) coupling [32]. In agreement with group theory, the states are then split into a nondegenerate

ground state A_1 and twofold and threefold degenerate excited states E and T_2 , respectively, according to the irreducible representations of the appropriate point group T_d . This VO coupling is commonly parameterized by an overall binding energy in the absence of the VO coupling E_0 and valley couplings Δ_1 and Δ_2 for neighboring and opposing valleys, respectively. Writing the VO coupling in the basis of the six individual CB valleys then yields the valley-orbit Hamiltonian

$$\mathcal{H}_{\text{VO}} = \begin{pmatrix} E_0 & \Delta_1 & \Delta_2 & \Delta_2 & \Delta_2 & \Delta_2 \\ \Delta_1 & E_0 & \Delta_2 & \Delta_2 & \Delta_2 & \Delta_2 \\ \Delta_2 & \Delta_2 & E_0 & \Delta_1 & \Delta_2 & \Delta_2 \\ \Delta_2 & \Delta_2 & \Delta_1 & E_0 & \Delta_2 & \Delta_2 \\ \Delta_2 & \Delta_2 & \Delta_2 & \Delta_2 & E_0 & \Delta_1 \\ \Delta_2 & \Delta_2 & \Delta_2 & \Delta_2 & \Delta_1 & E_0 \end{pmatrix}. \quad (2)$$

In the presence of strain, valley energies are shifted. Due to symmetry, a volume deformation potential Ξ_d and a uniaxial deformation potential Ξ_u are sufficient to describe this shift [29]. The valley-strain interaction may then be solved together with the valley-orbit interaction to describe a repopulation of valleys (VR) due to strain as

$$\mathcal{H}_{\text{VR}} = \mathcal{H}_{\text{VO}} + \Xi_d \sum_i \epsilon_{ii} + \Xi_u \begin{pmatrix} \epsilon_{11} & & & & & 0 \\ & \epsilon_{11} & & & & \\ & & \epsilon_{22} & & & \\ & & & \epsilon_{22} & & \\ & & & & \epsilon_{33} & \\ 0 & & & & & \epsilon_{33} \end{pmatrix}, \quad (3)$$

with ϵ_{ii} the diagonal components of the strain tensor. Strain shifts the energy of all involved states and, depending on the symmetry of the applied stress, may lift the degeneracy of the excited E and T_2 states to varying degrees.

Since the excited states are sufficiently separated in energy from the ground state, the latter is the only state relevant for the transitions measured in our experiment. However, any stress that is not oriented along the [111] crystal direction mixes the E states into the A_1 ground state. Due to this mixing, the ground state solution to the valley repopulation Hamiltonian $\mathcal{H}_{\text{VR}}$ under arbitrary strain yields lengthy analytical solutions. Instead, we present results of the ground state energy only for highly symmetric strain tensors corresponding to stress applied along the [100] and [110] crystal directions, as implemented in the experiment. The strain tensors for stress σ along [100] and [110] are

$$\epsilon^{100} = \begin{pmatrix} s_{11} & 0 & 0 \\ 0 & s_{12} & 0 \\ 0 & 0 & s_{12} \end{pmatrix} \sigma, \quad (4)$$

$$\epsilon^{110} = \begin{pmatrix} (s_{11} + s_{12})/2 & s_{44}/4 & 0 \\ s_{44}/4 & (s_{11} + s_{12})/2 & 0 \\ 0 & 0 & s_{12} \end{pmatrix} \sigma, \quad (5)$$

where $s_{11} = 7.68 \text{ TPa}^{-1}$, $s_{12} = -2.14 \text{ TPa}^{-1}$, and $s_{44} = 12.6 \text{ TPa}^{-1}$ are the stiffness parameters of silicon [33] and $\sigma < 0$ for compressive stress. The solutions for the

shift of the electron energy with strain are then given by

$$\begin{aligned} \Delta E_e(\epsilon^{100}) &= (\Xi_d + \frac{1}{3}\Xi_u)\epsilon_a + 2\Xi_u\epsilon_b - 3\Delta_2 \\ &\quad - 3\sqrt{\Delta_2^2 - 4\Delta_2\Xi_u\epsilon_b/3 + 4\Xi_u^2\epsilon_b^2}, \\ \Delta E_e(\epsilon^{110}) &= (\Xi_d + \frac{1}{3}\Xi_u)\epsilon_a - \Xi_u\epsilon_b - 3\Delta_2 \\ &\quad - 3\sqrt{\Delta_2^2 + 2\Delta_2\Xi_u\epsilon_b/3 + \Xi_u^2\epsilon_b^2}, \end{aligned} \quad (6)$$

where we defined

$$\epsilon_a = (s_{11} + 2s_{12})\sigma, \quad \epsilon_b = \frac{1}{12}(s_{11} - s_{12})\sigma. \quad (7)$$

For small stress such that $\Xi_u\epsilon_b \ll \Delta_2$, to a good approximation, all terms containing ϵ_b cancel, and we are left with a linear energy shift with strain ϵ_a .

The uppermost VBs in silicon consist of twofold degenerate heavy-hole and light-hole bands, characterized by hole magnetic quantum numbers $m_h = \pm 3/2$ and $m_h = \pm 1/2$, respectively, both corresponding to a total angular momentum of $J = 3/2$. At the VB maximum, these two bands are degenerate, but strain lifts this degeneracy and splits the VB maximum states into the heavy-hole and light-hole doublets. An expression for the energy shift as a function of strain may again be found purely by symmetry arguments, yielding the Pikus-Bir Hamiltonian [34]

$$\hat{\mathcal{H}}_{\text{PB}} = a \sum_i \epsilon_{ii} + b \sum_i \left(\hat{J}_i^2 - \frac{5}{4} \right) \epsilon_{ii} + \frac{d}{2\sqrt{3}} \sum_{i \neq j} \hat{J}_i \hat{J}_j \epsilon_{ij}, \quad (8)$$

where a , b , and d are deformation potentials and $\hat{J}_i$ are the angular momentum projection operators. Explicit solutions to this Hamiltonian for [100] and [110] stress are given by

$$\begin{aligned} \Delta E_h(\epsilon^{100}) &= \begin{cases} -a\epsilon_a - 12b\epsilon_b & m_h \pm 3/2, \\ -a\epsilon_a + 12b\epsilon_b & m_h \pm 1/2, \end{cases} \quad (9) \\ \Delta E_h(\epsilon^{110}) &= \begin{cases} -a\epsilon_a - \sqrt{36b^2\epsilon_b^2 + d^2\epsilon_c^2} & m_h \pm 3/2, \\ -a\epsilon_a + \sqrt{36b^2\epsilon_b^2 + d^2\epsilon_c^2} & m_h \pm 1/2, \end{cases} \quad (10) \end{aligned}$$

where we introduced $\epsilon_c = \frac{1}{4}s_{44}\sigma$. The shift and splitting of the D^0 and D^0X states with strain due to the changes in the electron and hole energy are shown in Fig. 2.

B. Effects of magnetic fields on electron and hole states

When an external magnetic field $\mathbf{B}$ is included, the electronic Zeeman interaction has to be considered for both the initial and final states of the $D^0 \rightarrow D^0X$ transition. The neutral donor state D^0 has only one s -like electron with total angular momentum $S = 1/2$. The Zeeman interaction thus splits the ground state into two levels with electron magnetic quantum number $m_e = \pm 1/2$ according to the electron Zeeman Hamiltonian

$$\hat{\mathcal{H}}_{\text{eZ}} = g_e \mu_B \mathbf{B} \cdot \hat{\mathbf{S}}, \quad (11)$$

where g_e is the donor-specific electron g -factor, μ_B is the Bohr magneton, and $\hat{\mathbf{S}}$ is the spin vector operator. Since the VR model does not couple to the spin degree of freedom, the

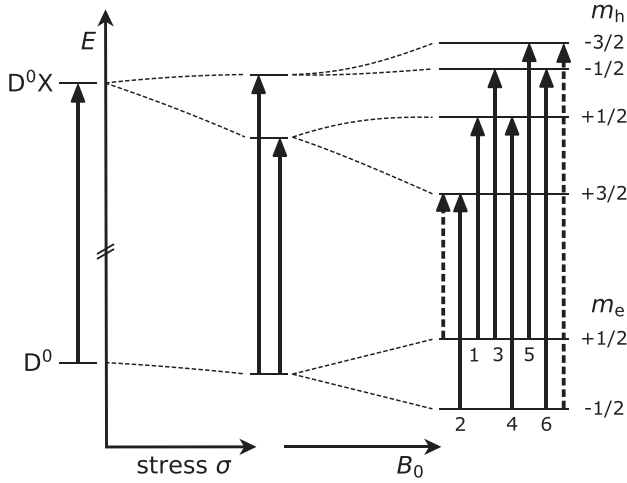


FIG. 2. Schematic of energy levels involved in the $D^0 \rightarrow D^0X$ transition as a function of uniaxial compressive stress σ and magnetic field strength B_0 . Transitions are labeled following the usual convention [9], which reflects their energy ordering in a magnetic field without strain. Applied strain, however, can modify this ordering, as shown. Note that even though m_h is not a good quantum number in the presence of both strain and magnetic field, we still use it as a label for the hole states according to the high-field limit.

electron Zeeman Hamiltonian may be solved independently to yield

$$\Delta E_{eZ}(B_0) = \pm \frac{1}{2} g_e \mu_B B_0, \quad (12)$$

with B_0 the magnitude of the magnetic field $\mathbf{B}$.

In the final D^0X state, the two electrons occupy the same state [35], and thus, their spins cancel, so that the Zeeman interaction is governed by the $J = 3/2$ hole. Due to spin-orbit coupling to the $J = 1/2$ band, the hole Zeeman Hamiltonian takes a nontrivial form [36,37]:

$$\hat{H}_{hZ} = g_1 \mu_B \mathbf{B} \cdot \hat{\mathbf{J}} + g_2 \mu_B \mathbf{B} \cdot \hat{\mathbf{J}}^3, \quad (13)$$

with g -factors g_1 and g_2 and the angular momentum vector operator $\hat{\mathbf{J}}$ for $J = 3/2$. In itself, this spin-orbit coupling yields different g -factors for heavy holes and light holes:

$$\Delta E_{hZ}(B_0) = \begin{cases} \pm \frac{3}{2} g_{hh} \mu_B B_0 & m_h \pm 3/2, \\ \pm \frac{1}{2} g_{lh} \mu_B B_0 & m_h \pm 1/2, \end{cases} \quad (14)$$

where g_{hh} and g_{lh} are functions of g_1 , g_2 , and the direction of the magnetic field relative to the crystal axes.

The Zeeman interaction lifts all remaining degeneracies, resulting in two Zeeman-split neutral donor ground states and four split donor-bound exciton states for a total of eight possible transitions (see Fig. 2). Only six of these transitions are dipole allowed to first order according to the selection rule $\Delta m = 0, \pm 1$. In the presence of both strain and magnetic field, however, the hole angular momentum states are generally mixed [38], and thus, m_h is no longer a good quantum number. In this case, the selection rule may be partially relaxed, depending on the degree of mixing. For the same reason, an exact solution can be found only by solving the strain

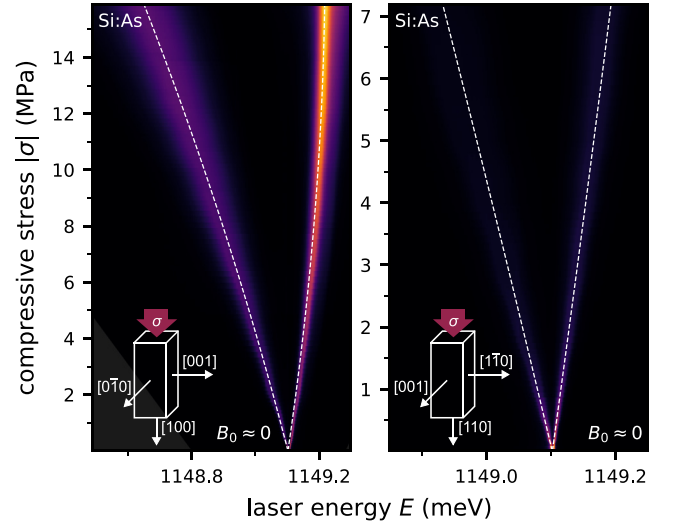


FIG. 3. Arsenic neutral donor to donor-bound exciton transition spectra ($D^0 \rightarrow D^0X$) in isotopically enriched ^{28}Si , observed by measuring the sample ac conductivity under varying uniaxial stress. The two panels correspond to stress applied along the [100] and [110] crystal axes, as labeled. Data are shown as two-dimensional color plots using nearest-neighbor coloring (Voronoi decomposition) without interpolation, and brighter colors indicate a stronger signal intensity. Gray regions indicate areas outside the acquired data range. The white dashed lines represent a global fit of deformation theory to an extended dataset; see text for details.

interaction simultaneously with the hole Zeeman interaction,

$$\hat{H}_{PB}(\epsilon) + \hat{H}_{hZ}(\mathbf{B}) \rightarrow \Delta E_h(\epsilon, \mathbf{B}), \quad (15)$$

where solutions are not necessarily linear in strain or magnetic field.

The external magnetic field also induces a diamagnetic shift of both the neutral donor and donor-bound exciton, which varies quadratically with B_0 [39]. Within the resolution of our measurements, we were not able to resolve any difference in the diamagnetic shift of the hole states, and thus, we model the total diamagnetic shift of the $D^0 \rightarrow D^0X$ transitions as

$$\Delta E_{\text{dia}}(B_0) = \gamma B_0^2, \quad (16)$$

with the diamagnetic shift parameter γ independent of the specific initial or final state involved in the transition [40].

To summarize, our model for the total energy shift of the $D^0 \rightarrow D^0X$ transition constitutes the sum of all contributions as defined in Eqs. (6), (12), (15), and (16):

$$\Delta E_{D^0 \rightarrow D^0X}(\epsilon, \mathbf{B}) = \Delta E_e(\epsilon) - \Delta E_{eZ}(B_0) + \Delta E_h(\epsilon, \mathbf{B}) + \Delta E_{\text{dia}}(B_0), \quad (17)$$

where the electron Zeeman term ΔE_{eZ} enters with a negative sign, as it applies to the initial state of the transition.

IV. EXPERIMENTAL RESULTS

Figure 3 presents color plots of the arsenic $D^0 \rightarrow D^0X$ transition energy $E_{D^0 \rightarrow D^0X}$ measured under variable uniaxial stress σ along the [100] and [110] crystal directions. The

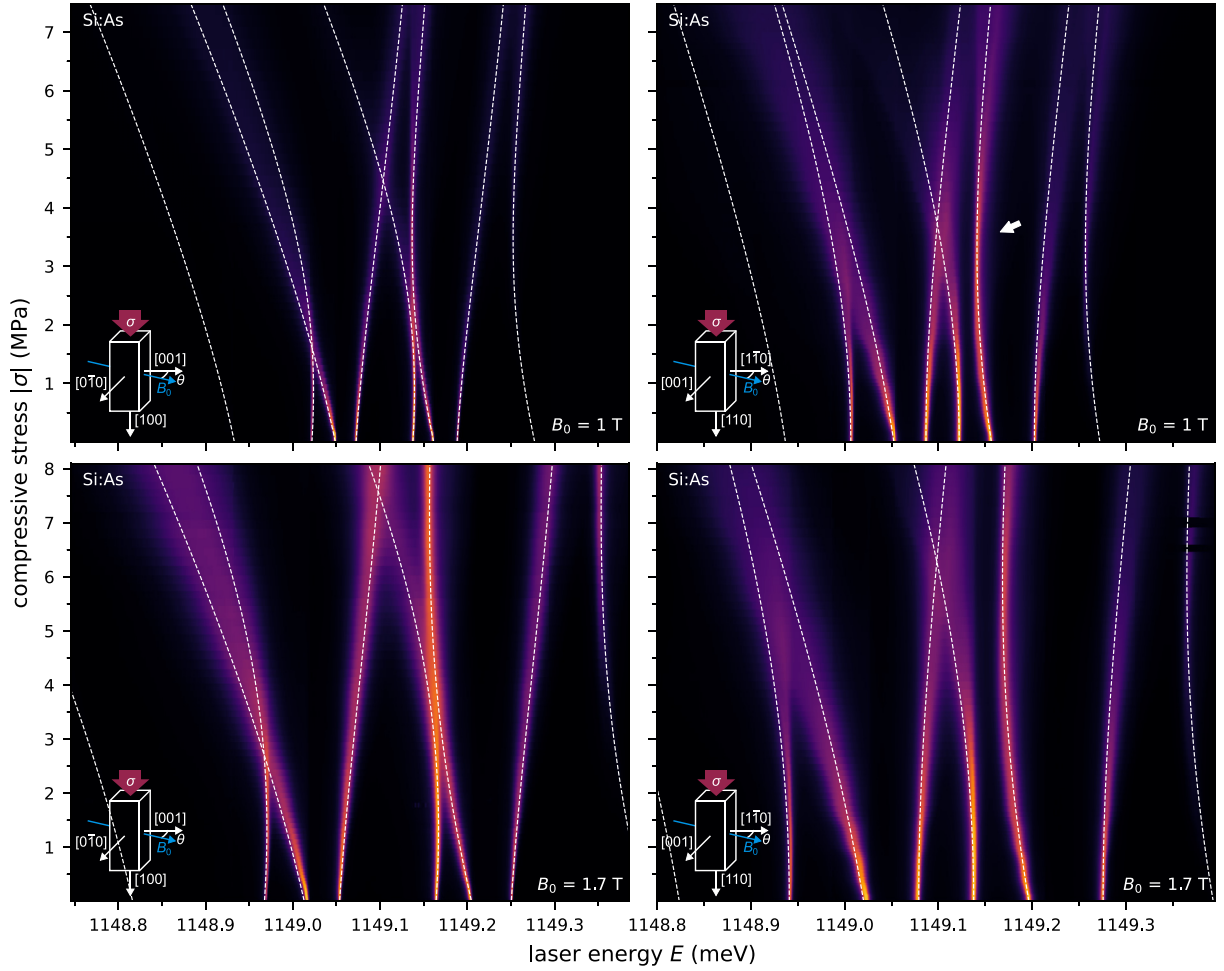


FIG. 4. Arsenic neutral donor to donor-bound exciton transition spectra ($D^0 \rightarrow D^0X$) in isotopically enriched ^{28}Si under varying uniaxial stress and external magnetic fields. Each panel corresponds to a unique combination of stress orientation ([100] or [110]) and magnetic field strength (1.0 or 1.7 T), as labeled. For details regarding the color code and fitted lines, refer to the caption of Fig. 3. The small white arrow highlights one instance where the line narrows as it becomes vertical.

nominal magnetic field B_0 was set as low as possible (limited to 3.5 mT by the remanence of our electromagnet). Insets in the bottom-left corner of each plot illustrate the orientation of applied stress or an external magnetic field relative to the crystal axes. Clear spectral broadening of the arsenic $D^0 \rightarrow D^0X$ transition is evident, which we attribute to inhomogeneous stress across the sample volume. We find that the linewidths approximately scale as $|\sigma \partial E_{D^0 \rightarrow D^0X} / \partial \sigma|$, consistent with the expectation that stress-induced fluctuations produce correlated shifts of the electron and hole energies [41]. Due to this broadening, the signal intensity generally decreases at higher stress. However, this effect is reduced in regions where the transition energy becomes insensitive to stress at first order, as evidenced occasionally in our spectra where a line becomes vertical, an example of which is indicated by the white arrow in Fig. 4.

For both stress orientations we observe a linear increase of the “zero-field” splitting with stress, as the light-hole and heavy-hole states become increasingly separated. The nonlinear regime is reached only for the largest stresses in our measurements. Because Eq. (6) predicts a more pronounced

nonlinear effect for stress along [100], we specifically extended our measurement range to higher stresses for the [100] orientation as shown here. Only for these measurements, we gradually increased the laser power with applied stress to compensate for the signal loss due to broadening. Figure 4 shows similar measurements for both stress orientations, but now with the addition of constant magnetic fields of 1.0 and 1.7 T. The applied field lifts the remaining degeneracies, revealing up to eight distinct transitions. The eight transitions can be grouped within the four-dimensional hole state subspace, which is duplicated and shifted by the Zeeman splitting of the two possible electron spin states $m_e = \pm 1/2$. Thus, for any transition, a corresponding transition can be identified that is shifted only by a constant amount equal to the electron Zeeman splitting. Any crossing or avoided crossing between transitions that belong to different electron spin states m_e is therefore accidental and has no physical significance.

While the two outermost transitions are nominally forbidden to first order, this condition is relaxed by the introduction of strain since the hole eigenstates are no longer pure eigenstates of angular momentum. Indeed, we detect a significantly

TABLE I. Electron and hole g -factors and valley-orbit couplings as used in the global fit of P and As data and the modeling of Sb data.

	g_e^a	$(g_1, g_2)^b$	Δ_2^c (mV)
P	1.99850	(0.82, 0.22)	-2.17
As	1.99837	(0.82, 0.22)	-3.75
Sb	1.99858	(0.82, 0.22)	-2.05

^aReference [42].

^bReferences [20,43,44].

^cReference [45].

enhanced intensity for the higher-energy forbidden line under strain.

A total of 13 datasets for phosphorus and 13 datasets for arsenic were analyzed independently. Each set consists of spectral maps for both stress orientations and magnetic fields of 3.5 mT, 0.35 T, 0.5 T, 1.0 T, and 1.7 T, including repeated measurements for [100] stress at 3.5 mT, where the maximum applied stress was gradually increased. For clarity, the measurements with lower maximum stress are not shown. The arsenic data for 0.35 and 0.5 T, along with all phosphorus data, are presented in the Appendix in Figs. 7 and 8.

The P and As datasets were each fitted with a single global least-squares fit to our model defined in Sec. III. The resulting fits are shown in all spectral maps as white dashed lines. For the fits, the electron and hole g -factors and valley-orbit couplings were assumed to be fixed as in Table I, and the primary free parameters were given by the deformation potentials for the electrons and holes, which were generally shared between all datasets.

The only exception was the hole shear deformation potential d , for which we found it necessary to allow a magnetic field dependence in order to appropriately fit our complete dataset. The remaining free parameters were an independent energy offset E_0 and the angle θ between the magnetic field and the crystal [001] and [110] axes for stress oriented along [100] and [110], respectively. We found that our data and also the Zeeman data presented later are well explained by the hole g -factors taken from the literature for angles $\theta_{100} = (16.2 \pm 0.6)^\circ$ and $\theta_{110} = (5.8 \pm 1.2)^\circ$. These angles are reasonable considering that the samples were aligned only by eye, and small rotations of the sample holder are expected when inserting the holder into the cryostat.

V. DISCUSSION

A. Deformation potentials

We find excellent agreement between our data and model. The best fit results for the deformation potentials are presented in Table II and Fig. 5. Table II also cites a number of previous results for the deformation potentials. It is important to note that while any lattice site point defect in the silicon lattice can be described by equivalent deformation potentials, this does not necessarily mean that they have to be equal. On the contrary, Pikus and Bir showed that deformation potentials depend strongly on the wave function and may vary by several tens of percent [63]. For this reason, the best comparison can be made only with other results for the same $D^0 \rightarrow D^0X$

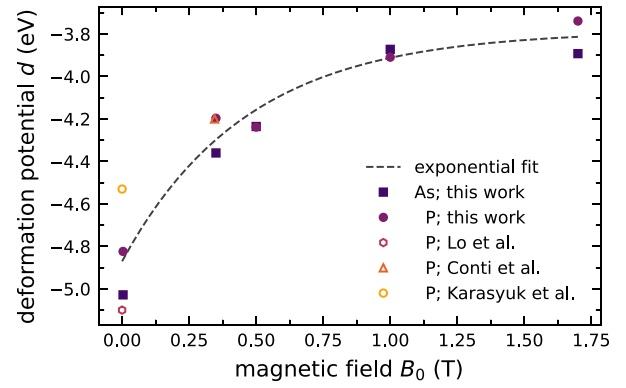


FIG. 5. Variation of the hole deformation potential d with the applied external magnetic field strength B_0 . Our presented deformation potentials are the result of a global fit to a large dataset of the $D^0 \rightarrow D^0X$ transition under various uniaxial stresses and magnetic fields. We also include previous results measured by Lo *et al.* [20], Conti *et al.* [23], and Karasyuk *et al.* [29].

transitions, for which, however, available data are scarce and limited to phosphorus [20,23,29,30]. Results from other methods or transitions may still provide some insight, as for weakly bound states, deformation potentials are expected to be similar. In particular, the deformation potentials for neutral donor states have been established in the literature to be very similar to that of free electrons or excitons, as reported in Table II.

We find that our extracted hole deformation potentials b and d agree very well with previous results for the $D^0 \rightarrow D^0X$ transition and, to a lesser degree, also with those obtained for other states/transitions. Within the experimental uncertainty, we observe no significant variation between the donor species. The hole deformation potential a cannot be determined independently, as it has the same symmetry as certain contributions from the electron deformation potential. Instead, we can collect all hydrostatic terms as $\Xi_d + \Xi_u/3 - a$, which, again, compares reasonably well with the literature.

In contrast, the electron deformation potentials, in particular the uniaxial component Ξ_u , do not agree with literature values. Our measured Ξ_u is significantly larger than reported for other methods but matches the only other result for the $D^0 \rightarrow D^0X$ transition reported for phosphorus by Lo *et al.* [20], who also found a larger Ξ_u . This leads us to believe that the larger Ξ_u is due to the specific nature of the $D^0 \rightarrow D^0X$ transition and not merely a measurement or analysis error. Preliminary density functional theory calculations indicate a stronger localization of the donor-bound exciton state compared to the neutral donor state [64], which may account for the observed increase in Ξ_u . We further find that Ξ_u clearly differs for the two donor species, consistent with an enhanced sensitivity to central-cell effects in a more localized D^0X state, where chemical differences at the donor site become more pronounced.

Our results for a magnetic-field-dependent hole deformation parameter d are summarized in Fig. 5. The deformation potential appears to first decrease strongly with the introduction of an external magnetic field and then saturate at larger fields. Still, d overall reduces to about 3/4 of its original value.

TABLE II. Deformation potentials (in eV) as determined here and published previously.

	Present work ($D^0 \rightarrow D^0X$)		Previous results		
	P	As	$P^0 \rightarrow P^0X$	Other states/transitions	
	Expt.	Expt.	Expt.	Expt.	Theor.
Ξ_u	17.41 ± 0.05	19.05 ± 0.07	15.5^a	8.5 ± 0.2^e 8.6 ± 0.2^g 7.7^h 8.3 ± 0.3^i 11 ± 1^k 8.77 ± 0.07^l 8.6 ± 0.4^m 8.5 ± 0.1^n 11.4 ± 1.1^o 8.6 ± 0.4^p	10.5^q 9.29^r 8.86^s 9.16^t 8.47^v 8.0^w
$\Xi_d + \frac{\Xi_u}{3} - a$	1.39 ± 0.03	1.43 ± 0.04	2.0^a	3.8 ± 0.5^g 1.5 ± 0.3^m	2.5^q 0.29^r -0.77^s 1.72^t 1.79^v 1.2^w
b	-1.7719 ± 0.0019	-1.8179 ± 0.0016	-1.7^a -1.5 ± 0.2^b -7^c -1.72 ± 0.05^d	-1.49 ± 0.05^e -1.35 ± 0.05^f -2.4 ± 0.2^g -1.36 ± 0.13^j -2.10 ± 0.10^m	$-2.33^{q,r}$ -2.21^s -2.35^t -2.58^u -2.27^v -2.18^w
d	$B_0 = 0 : -4.88 \pm 0.19$ $B_0 \rightarrow \infty : -3.78 \pm 0.12$		-5.1^a -4.2 ± 0.3^b -4^c -4.53 ± 0.1^d	-4.08 ± 0.10^e -3.95 ± 0.10^f -5.3 ± 0.4^g -3.1 ± 0.3^j -4.85 ± 0.15^m -5.2 ± 0.3^n	-4.75^q -5.32^t -5.40^u -3.69^v

^aSupplementary information of [20], analyzed data was first presented in [28], measured at $B_0 = 0$; ^bRef. [23], measured at $B_0 = 345$ mT; ^cFit to a single strain value, $B_0 \in [0, 300]$ mT [30]; ^dPhotoluminescence spectra, $B_0 = 0$ [29]; ^ePhotoluminescence spectra, boron-bound exciton, $B_0 = 0$ [29]; ^fPhotoluminescence spectra, neutral boron acceptor, $B_0 = 0$ [29]; ^gIndirect optical absorption edge, $B_0 = 0$ [46]; ^hTemperature-dependent piezoresistance [47]; ⁱTemperature-dependent piezoresistance [48]; ^jCyclotron resonance [49]; ^kGroup V donor hyperfine interaction [50]; ^lDonor piezospectroscopy [51]; ^mIndirect TO phonon-assisted exciton spectra, $B_0 = 0$ [52]; ⁿCyclotron resonance line width [53]; ^oLithium donor hyperfine interaction [54]; ^pEffect of carrier concentration on elastic constants [55]; ^qNonlocal empirical pseudopotential band structure [56]; ^rNonlocal empirical pseudopotential band structure [57]; ^sTight binding band structure [58]; ^tDensity functional band structure [59]; ^u $k \cdot p$ method band structure [60]; ^vLocal empirical pseudopotential band structure [61]; ^wLMTO band structure [62].

A strong argument for magnetic field dependence of d for the $D^0 \rightarrow D^0X$ transition can be found when including previous results [20,23,29]. When we consider the magnetic field at which those results were obtained, they align closely with the overall trend of our data, as is apparent from Fig. 5. A simple exponential fit of our data for both donor species and the three literature values yields deformation potentials of

$$d(B_0 = 0) = (-4.88 \pm 0.19) \text{ eV}$$

$$d(B_0 \rightarrow \infty) = (-3.78 \pm 0.12) \text{ eV},$$

with a characteristic exponent of $\tau = (-2.2 \pm 0.7) 1/T$. We emphasize that d was introduced as a material-specific constant in the Pikus-Bir Hamiltonian [63], which, by definition,

includes only contributions linear in strain and excludes magnetic field components. Consequently, the magnetic field dependence observed here has to be due to some interaction not included in our model. Still, from the fact that the magnetic field dependence of our results as well as those of Lo *et al.* [20], Conti *et al.* [23], and Karasyuk *et al.* [29] may be modeled by a variation of the hole shear deformation potential d , we can conclude that this interaction most likely involves a magnetic-field-dependent coupling of shear strain to the hole state of D^0X . Such strain-magnetic-field interactions are, indeed, not generally forbidden by symmetry [65]. The saturation of the effect at larger magnetic fields may indicate that the interaction involves a mixing of hole states, which could become effectively reduced or decoupled at stronger fields.

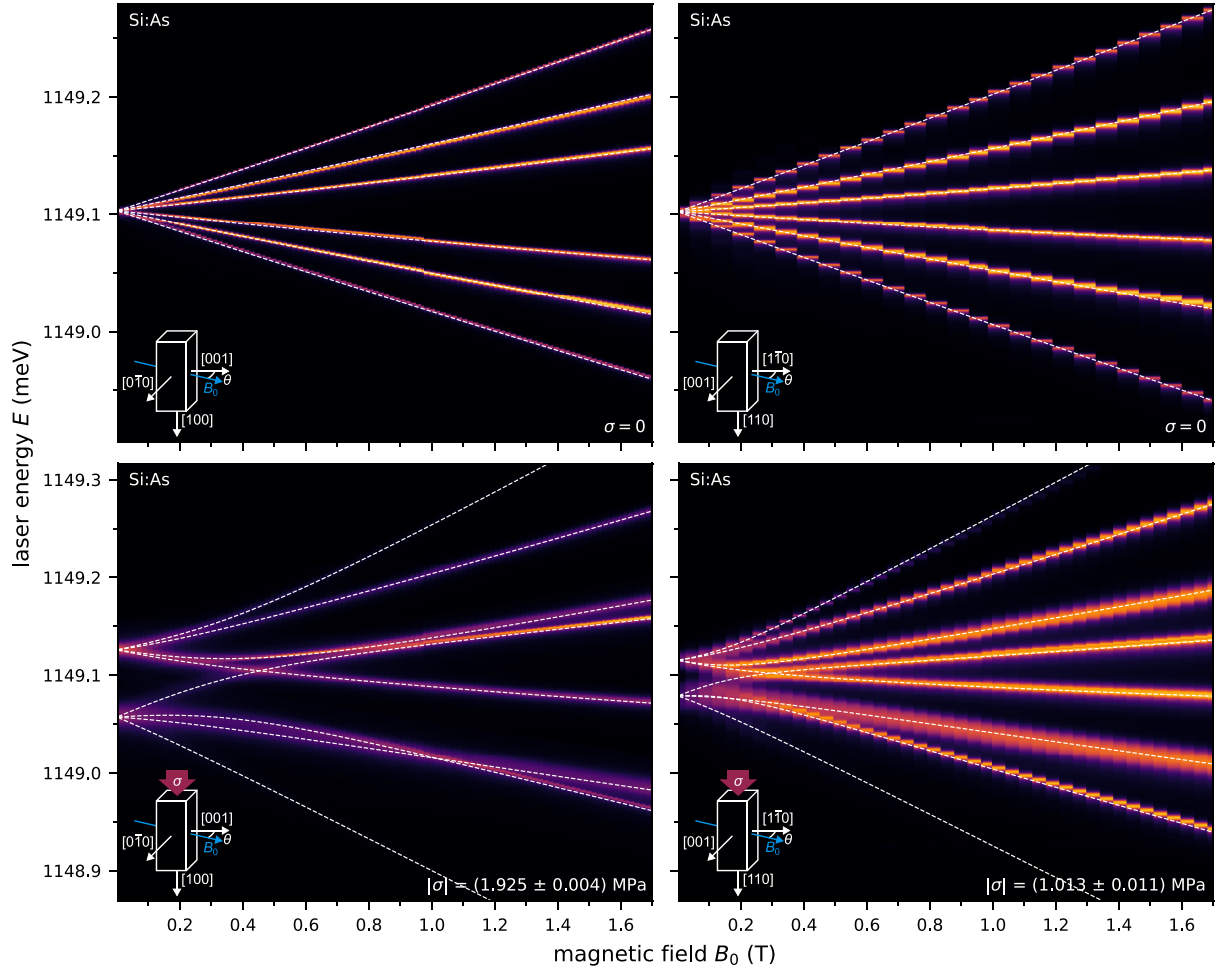


FIG. 6. Zeeman maps of the arsenic neutral donor to donor-bound exciton transition ($D^0 \rightarrow D^0X$) in isotopically enriched ^{28}Si , observed by measuring the sample ac conductivity under varying magnetic fields. The four panels correspond to combinations of nominally zero or a small compressive stress, oriented along either the $[100]$ or $[110]$ crystal axis, as labeled. For details regarding the color code and fitted lines, refer to the caption of Fig. 3.

B. Zeeman spectra

Figure 6 shows Zeeman maps of the As $D^0 \rightarrow D^0X$ transition for the two sample orientations under nominally zero strain and under a small, intentionally introduced strain, as typically encountered for D^0X experiments in slightly strained nanostructures [11,66]. In the presence of this strain, a small zero-field splitting appears, and the transition lines are broadened to various degrees, but individual lines can still be distinguished at relatively low magnetic fields. As previously observed, the higher-energy, nominally forbidden transition exhibits an enhanced intensity in a strained sample. However, this enhancement diminishes at larger magnetic fields, which decouple the angular momentum states and thus restore the selection rules. The signal of the first-order forbidden outer transitions is generally weak and thus difficult to see. They are much more visible in Fig. 11 in the Appendix, where we measure the P and Sb $D^0 \rightarrow D^0X$ transitions at higher laser power.

Again, pairs of lines corresponding to the electron spin projections $m_e = \pm 1/2$ may be identified, all split by the same Zeeman splitting that, however, now increases linearly with the magnetic field strength B_0 and vanishes at zero magnetic

field. The corresponding Zeeman maps for phosphorus are shown in the Appendix in Fig. 9.

We performed a second global fit of our model to all available Zeeman data, treating the diamagnetic shift parameter γ as a shared fit parameter. For the intentionally strained data, the deformation potentials were fixed to our earlier results, which allowed us to accurately determine the applied stress in the Zeeman data while also maintaining excellent agreement between our fit and experimental data. Again, the only additional free parameters were the angle θ , parametrizing a rotation of the sample in the sample holder, and a constant energy offset E_0 . We extracted diamagnetic shifts of $\gamma^{\text{As}} = (1.96 \pm 0.04) \mu\text{eV}/\text{T}^2$ and $\gamma^{\text{P}} = (2.24 \pm 0.04) \mu\text{eV}/\text{T}^2$, in good agreement with literature values [39,40].

C. Simulation of Sb data

Our sample also contains a substantial amount of antimony; however, the Sb $D^0 \rightarrow D^0X$ transition exhibits a much weaker signal in our measurements. This may be due to a much smaller oscillatory strength of the transition [67] or some other effect related to an equilibrium of donor and boron charge states that favors the ionized state of the Sb donor.

For this reason, a notable Sb signal was achieved only for a much larger laser power, where the neighboring P transitions exhibit second-order effects in the electrical detection. These appear as a narrower, inverted line shape superimposed on the primary signal, leading to an apparent splitting, as evident in Figs. 10 and 11 in the Appendix.

The spectral proximity of the Sb transition to the corresponding P transition, a relatively weak signal, and a generally strong broadening made a reliable fit of the Sb data challenging. Instead, we simulate the Sb $D^0 \rightarrow D^0X$ transitions using our model, with the P deformation potentials from Table II, the P diamagnetic shift parameter γ^P determined above, and the material-specific parameters of Sb from Table I. The simulation is shown by white dashed lines in Figs. 10 and 11, tracing the weaker Sb transitions next to the dominant P transitions. We find good agreement between the Sb data and this simulation, whereas simulations based on the As deformation potentials clearly did not reproduce the Sb spectra. We note that this is consistent with the donor binding energy and valley-orbit coupling being very similar for P and Sb but different for As.

VI. SUMMARY AND CONCLUSIONS

We conducted a detailed study of the P, As, and Sb $D^0 \rightarrow D^0X$ transitions in isotopically enriched ^{28}Si under variable uniaxial stresses and external magnetic fields. We performed a global least-squares fit to a large dataset containing multiple magnetic field strengths from 3.5 mT to 1.7 T and stress oriented along the [100] and [110] crystal axes and extracted deformation potentials for the $D^0 \rightarrow D^0X$ transition of P and As with high precision.

Our results show that while the hole deformation potentials are consistent with previous studies, the uniaxial electron deformation potential Ξ_u is donor dependent and significantly larger than values reported for other experimental methods and theory. This suggests an enhanced sensitivity of the D^0X state to strain and central-cell effects, likely arising from increased spatial localization. Additionally, the magnetic field dependence of the hole deformation potential d , consistent with earlier studies on the $D^0 \rightarrow D^0X$ transition when accounting for field strength, suggests a nontrivial coupling of hole states to shear strain that is not explicitly captured in the basic deformation potential theory. Furthermore, the analysis of P and As Zeeman spectra enabled the determination of diamagnetic shift parameters, which were found to agree well with earlier results.

The relatively low intensity of the Sb $D^0 \rightarrow D^0X$ transitions, combined with their proximity to P, made a global fit with multiple parameters challenging. Instead, we simulated the Sb spectra relying on the deformation potentials and diamagnetic shift parameters obtained for P and found good agreement with the experimental Sb data. In contrast, deformation potentials obtained for As did not reproduce the Sb data.

Potential next steps include a more detailed theoretical study with the help of density functional theory or other *ab initio* methods to clarify the origin of the observed differences in deformation potentials, particularly for Ξ_u . Extending the hole Hamiltonian to include higher-order strain terms could help account for magnetic-field-dependent variations in the hole deformation potential d . A more dedicated investigation of samples containing Sb and Bi would allow for an even more complete donor-specific parameter set, supporting both theoretical models and practical applications. Finally, shaping the sample ends in a pyramidal form could further improve the strain homogeneity [29], reducing spectral broadening and allowing for even more precise measurements.

Our results point to a previously neglected strain-magnetic-field interaction that may be relevant not only for donor-bound excitons in silicon but, potentially, for other electronic states or materials as well. The extracted deformation potentials are directly relevant to the development of silicon donor-based quantum devices that rely on the donor-bound exciton transition, like donor-based quantum memories [18,68]. The same transitions could also be used to implement spin-photon interfaces, in analogy to Er^{3+} ions in solid hosts [69]. Such an approach is currently limited by the weak optical cross section of the $D^0 \rightarrow D^0X$ transition, although this challenge may be mitigated via photonic cavity enhancement [70,71]. In any case, the ability to predict and tune $D^0 \rightarrow D^0X$ transition energies under magnetic fields and environmental strain is a critical requirement in these architectures.

ACKNOWLEDGMENTS

The authors thank U. Gerstmann (University of Paderborn) and H. Huebl (Walther-Meißner-Institut) for valuable discussions. We thank N. Abrosimov of the Leibniz-Institut für Kristallzüchtung (IKZ), Berlin, for providing the ^{28}Si samples doped with Sb, P, and As used in this study. This work was funded by the Deutsche Forschungsgemeinschaft (German Research Foundation, DFG) under Germany's Excellence Strategy (EXC-2111, 390814868).

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX: ADDITIONAL DATA

This appendix comprises five figures presenting the remaining $D^0 \rightarrow D^0X$ transition data: Fig. 7 shows As strain maps measured at lower magnetic fields, Figs. 8 and 9 show the P strain and Zeeman maps, respectively, and Figs. 10 and 11 show the Sb strain and Zeeman maps, measured at higher laser power to enhance the Sb signal in the presence of the strong P signal.

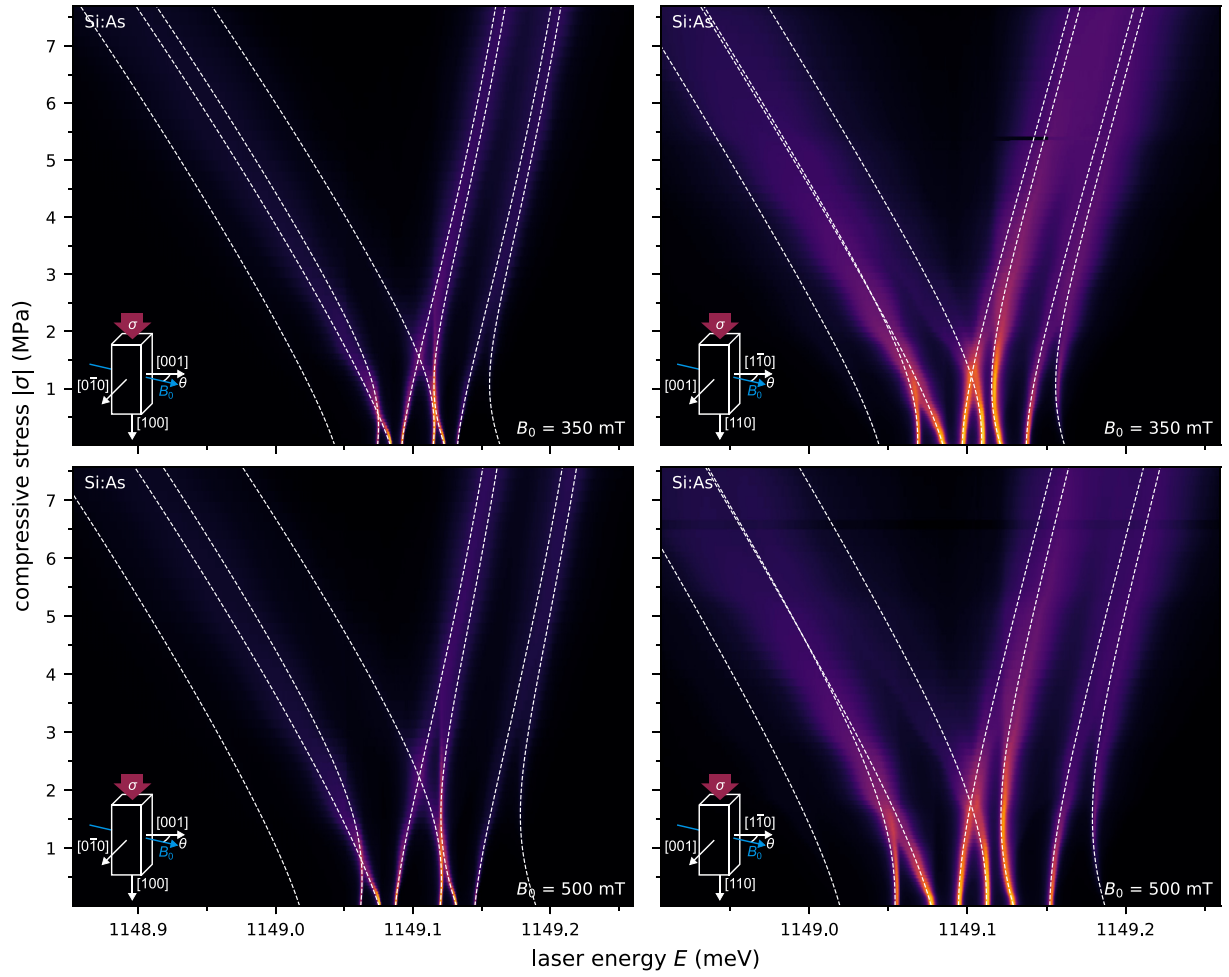


FIG. 7. Arsenic neutral donor to donor-bound exciton transition spectra ($D^0 \rightarrow D^0X$) in isotopically enriched ^{28}Si under varying uniaxial stresses and external magnetic fields. Each panel corresponds to a unique combination of stress orientation ([100] or [110]) and magnetic field strength (350 or 500 mT), as labeled. For details regarding the color code and fitted lines, refer to the caption of Fig. 3.

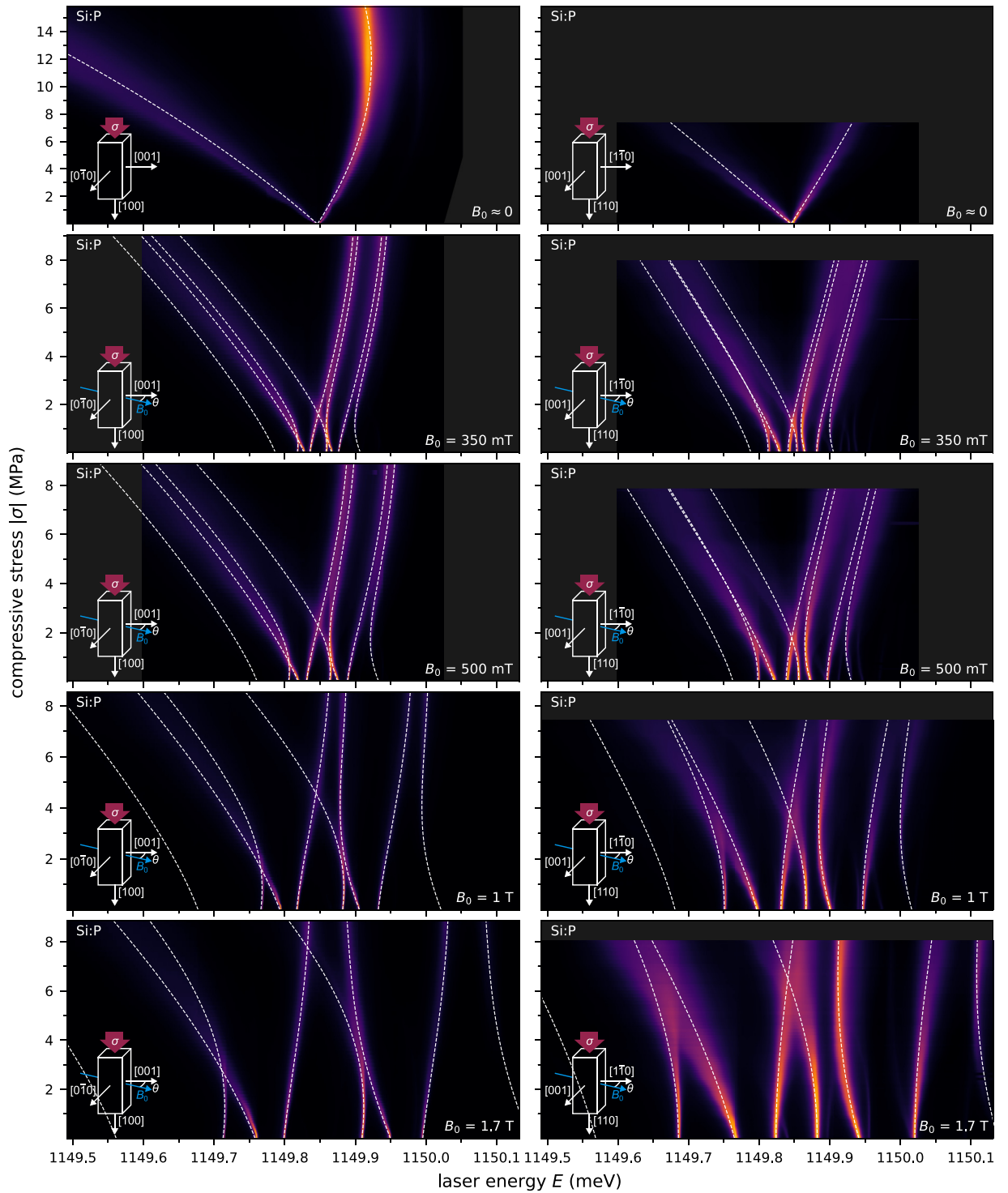


FIG. 8. Phosphorus neutral donor to donor-bound exciton transition spectra ($D^0 \rightarrow D^0X$) in isotopically enriched ^{28}Si under varying uniaxial stresses and external magnetic fields. Each panel corresponds to a unique combination of stress orientation ($[100]$ or $[110]$) and magnetic field strength, as labeled. For details regarding the color code and fitted lines, refer to the caption of Fig. 3.

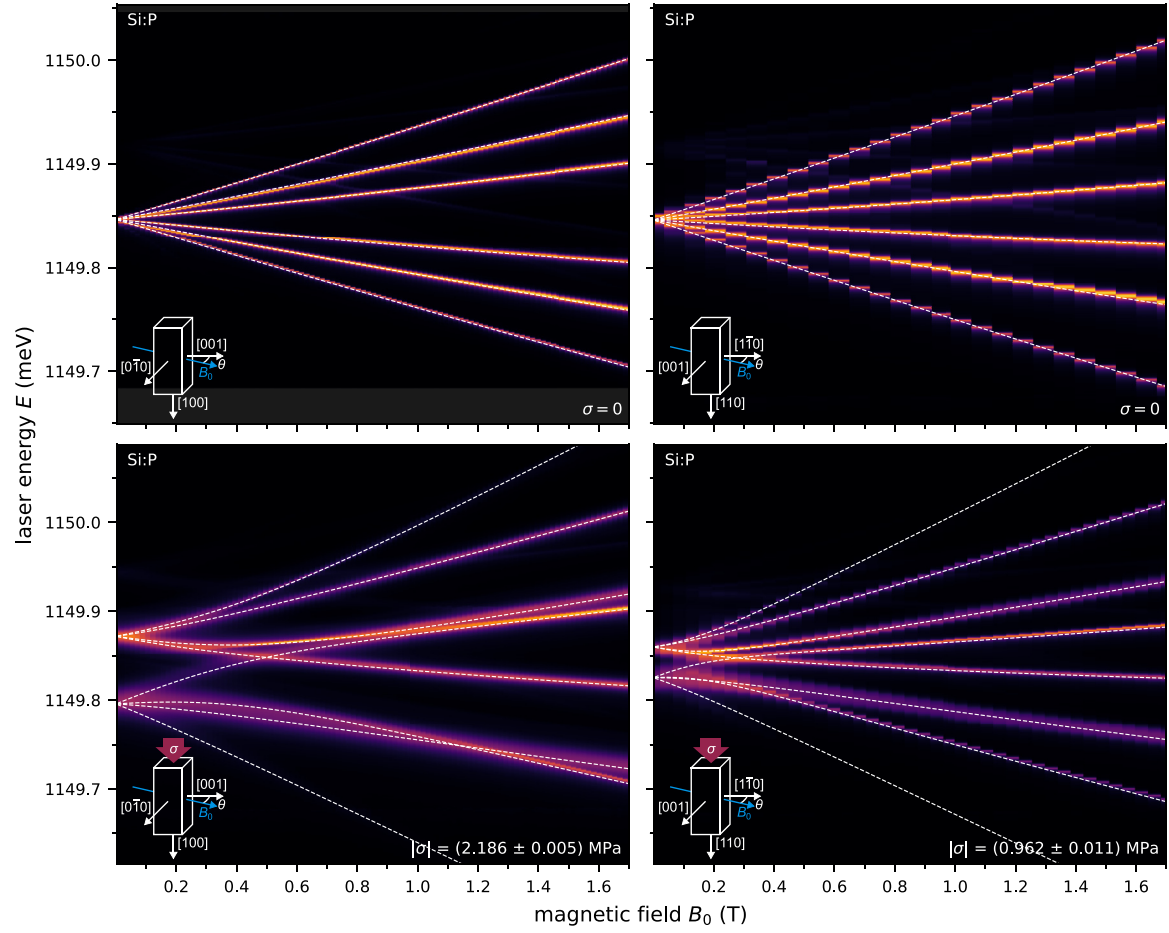


FIG. 9. Zeeman maps of the phosphorus neutral donor to donor-bound exciton transition ($D^0 \rightarrow D^0X$) in isotopically enriched ^{28}Si measured under nominally zero or a small compressive stress, oriented along either the $[100]$ or $[110]$ crystal axis, as labeled. For details regarding the color code and fitted lines, refer to the caption of Fig. 3.

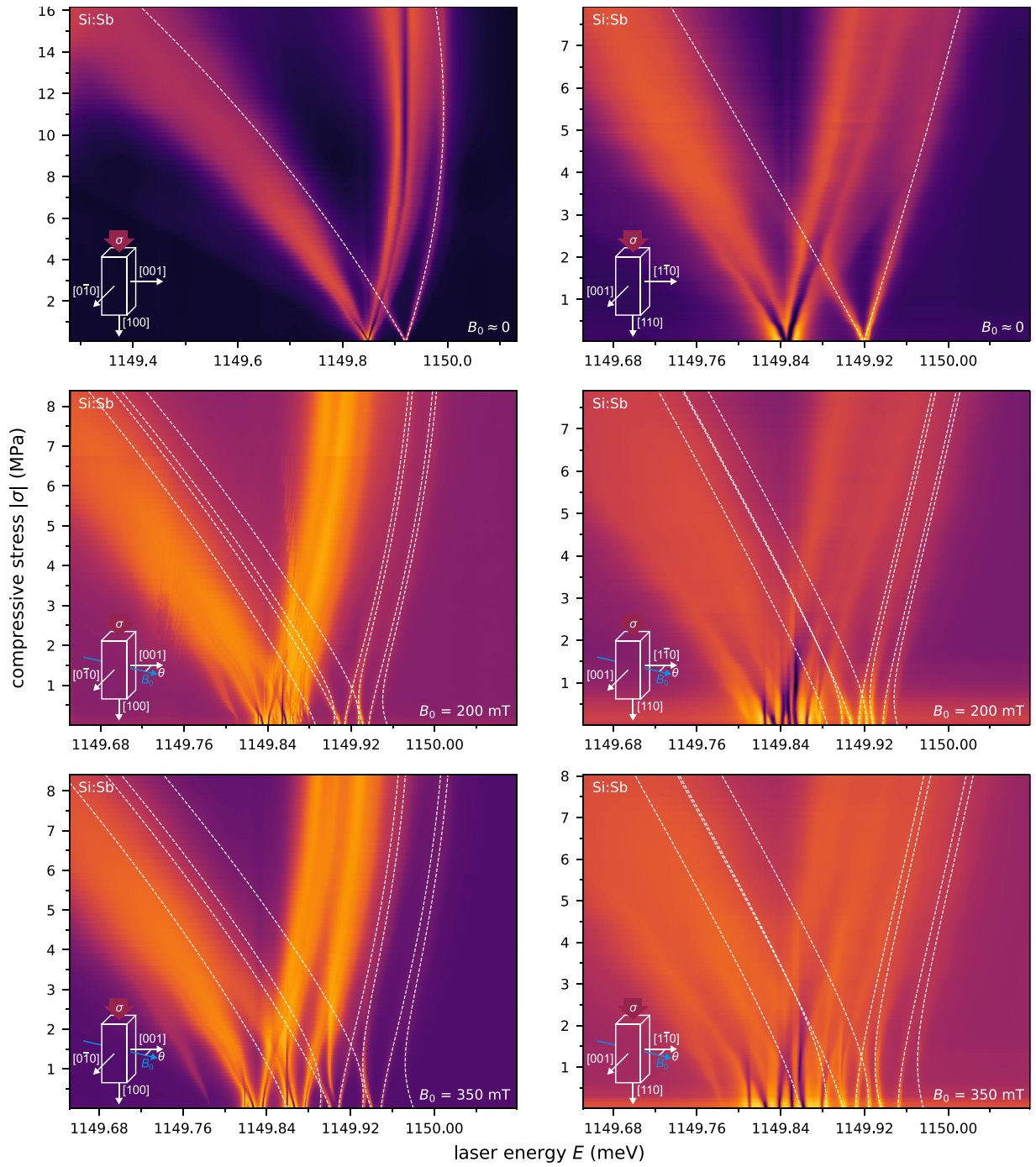


FIG. 10. Antimony and phosphorus neutral donor to donor-bound exciton transition spectra ($D^0 \rightarrow D^0X$) in isotopically enriched ^{28}Si measured with higher laser power under varying uniaxial stresses and external magnetic fields. Each panel corresponds to a unique combination of stress orientation ($[100]$ or $[110]$) and magnetic field strength, as labeled. For details regarding the color code, refer to the caption of Fig. 3. The much weaker antimony transitions are indicated by white dashed lines, showing a simulation of the antimony transitions based on phosphorus deformation potentials. The stronger phosphorus transitions display a higher-order artifact, visible as a narrower, inverted signal. For more details regarding the simulation of the antimony data and the measurement artifact, see Sec. V.

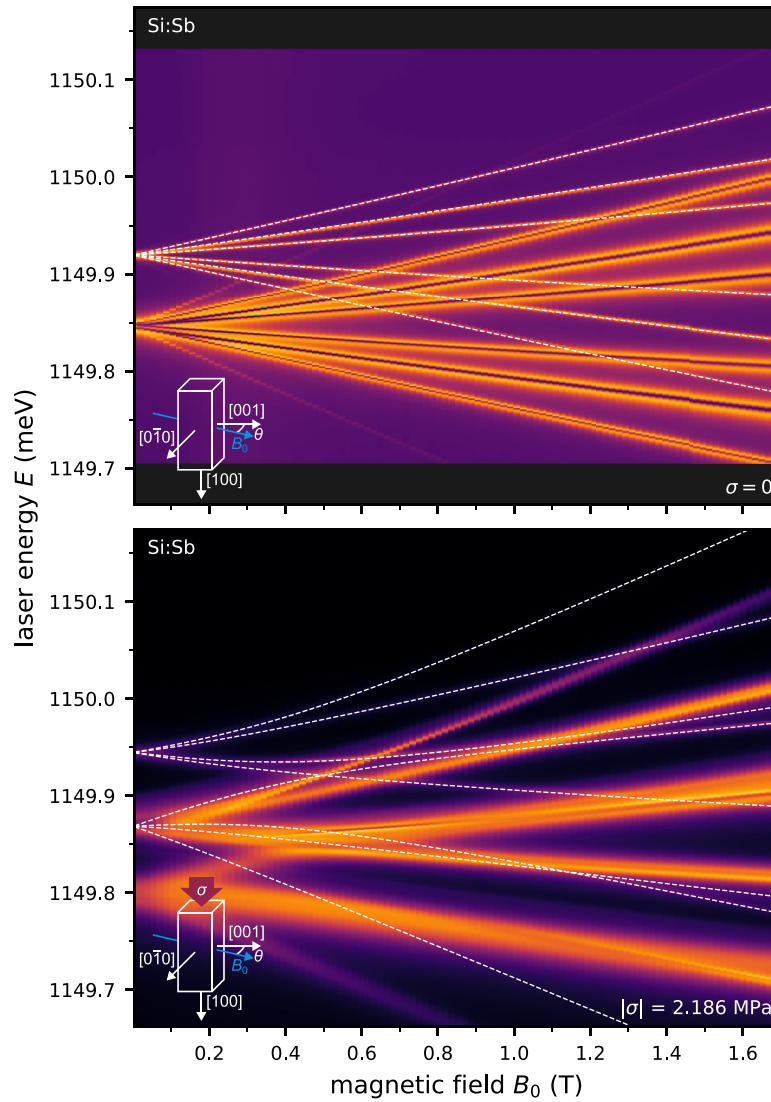


FIG. 11. Zeeman maps of the phosphorus and antimony neutral donor to donor-bound exciton transitions ($D^0 \rightarrow D^0X$) measured with higher laser power under [100] stress and varying magnetic fields. The two panels correspond to nominally zero or a small compressive stress, as labeled. For details regarding the color code and fitted lines, refer to the caption of Fig. 3. The much weaker antimony transitions are indicated by white dashed lines, showing a simulation of the antimony transitions based on phosphorus deformation potentials. The stronger phosphorus transitions display a higher-order artifact, visible as a narrower, inverted signal. For more details regarding the simulation of the antimony data and the measurement artifact, see Sec. V.

-
- [1] B. E. Kane, A silicon-based nuclear spin quantum computer, *Nature (London)* **393**, 133 (1998).
 - [2] A. Morello, J. J. Pla, P. Bertet, and D. N. Jamieson, Donor spins in silicon for quantum technologies, *Adv. Quantum Technol.* **3**, 2000005 (2020).
 - [3] J. Koch, T. M. Yu, J. Gambetta, A. A. Houck, D. I. Schuster, J. Majer, A. Blais, M. H. Devoret, S. M. Girvin, and R. J. Schoelkopf, Charge-insensitive qubit design derived from the Cooper pair box, *Phys. Rev. A* **76**, 042319 (2007).
 - [4] F. A. Zwanenburg, A. S. Dzurak, A. Morello, M. Y. Simmons, Lloyd C. L. Hollenberg, G. Klimeck, S. Rogge, S. N. Coppersmith, and M. A. Eriksson, Silicon quantum electronics, *Rev. Mod. Phys.* **85**, 961 (2013).
 - [5] H. Haffner, C. Roos, and R. Blatt, Quantum computing with trapped ions, *Phys. Rep.* **469**, 155 (2008).
 - [6] S. R. Schofield, N. J. Curson, M. Y. Simmons, F. J. Rueß, T. Hallam, L. Oberbeck, and R. G. Clark, Atomically precise placement of single dopants in Si, *Phys. Rev. Lett.* **91**, 136104 (2003).
 - [7] B. Andreas, Y. Azuma, G. Bartl, P. Becker, H. Bettin, M. Borys, I. Busch, M. Gray, P. Fuchs, K. Fujii, H. Fujimoto, E. Kessler, M. Krumrey, U. Kuetgens, N. Kuramoto, G. Mana, P. Manson,

- E. Massa, S. Mizushima, A. Nicolaus, A. Picard, A. Pramann, O. Rienitz, D. Schiel, S. Valkiers, and A. Waseda, Determination of the Avogadro constant by counting the atoms in a ^{28}Si crystal, *Phys. Rev. Lett.* **106**, 030801 (2011).
- [8] A. M. Tyryshkin, S. Tojo, J. J. L. Morton, H. Riemann, N. V. Abrosimov, P. Becker, H.-J. Pohl, T. Schenkel, M. L. W. Thewalt, K. M. Itoh, and S. A. Lyon, Electron spin coherence exceeding seconds in high-purity silicon, *Nat. Mater.* **11**, 143 (2012).
- [9] M. Steger, K. Saeedi, M. L. W. Thewalt, J. J. L. Morton, H. Riemann, N. V. Abrosimov, P. Becker, and H.-J. Pohl, Quantum information storage for over 180 s using donor spins in a Si-28 “semiconductor vacuum”, *Science* **336**, 1280 (2012).
- [10] K. Saeedi, S. Simmons, J. Z. Salvail, P. Dluhy, H. Riemann, N. V. Abrosimov, P. Becker, H.-J. Pohl, J. J. L. Morton, and M. L. W. Thewalt, Room-temperature quantum bit storage exceeding 39 minutes using ionized donors in silicon-28, *Science* **342**, 830 (2013).
- [11] S. Asaad, V. Mourik, B. Joecker, M. A. I. Johnson, A. D. Baczewski, H. R. Firgau, M. T. Mądzik, V. Schmitt, J. J. Pla, F. E. Hudson, K. M. Itoh, J. C. McCallum, A. S. Dzurak, A. Laucht, and A. Morello, Coherent electrical control of a single high-spin nucleus in silicon, *Nature (London)* **579**, 205 (2020).
- [12] I. Fernández de Fuentes, T. Botzem, M. A. I. Johnson, A. Vaartjes, S. Asaad, V. Mourik, F. E. Hudson, K. M. Itoh, B. C. Johnson, A. M. Jakob, J. C. McCallum, D. N. Jamieson, A. S. Dzurak, and A. Morello, Navigating the 16-dimensional Hilbert space of a high-spin donor qubit with electric and magnetic fields, *Nat. Commun.* **15**, 1380 (2024).
- [13] X. Yu, B. Wilhelm, D. Holmes, A. Vaartjes, D. Schwenbacher, M. Nurizzo, A. Kringhøj, M. R. van Blankenstein, A. M. Jakob, P. Gupta, F. E. Hudson, K. M. Itoh, R. J. Murray, R. Blume-Kohout, T. D. Ladd, N. Anand, A. S. Dzurak, B. C. Sanders, D. N. Jamieson, and A. Morello, Schrödinger cat states of a nuclear spin qubit in silicon, *Nat. Phys.* **21**, 362 (2025).
- [14] A. Morello, J. J. Pla, F. A. Zwanenburg, K. W. Chan, K. Y. Tan, H. Huebl, M. Möttönen, C. D. Nugroho, C. Yang, J. A. van Donkelaar, A. D. C. Alves, D. N. Jamieson, C. C. Escott, L. C. L. Hollenberg, R. G. Clark, and A. S. Dzurak, Single-shot readout of an electron spin in silicon, *Nature (London)* **467**, 687 (2010).
- [15] J. J. Pla, K. Y. Tan, J. P. Dehollain, W. H. Lim, J. J. L. Morton, F. A. Zwanenburg, D. N. Jamieson, A. S. Dzurak, and A. Morello, High-fidelity readout and control of a nuclear spin qubit in silicon, *Nature (London)* **496**, 334 (2013).
- [16] M. T. Mądzik, A. Laucht, F. E. Hudson, A. M. Jakob, B. C. Johnson, D. N. Jamieson, K. M. Itoh, A. S. Dzurak, and A. Morello, Conditional quantum operation of two exchange-coupled single-donor spin qubits in a MOS-compatible silicon device, *Nat. Commun.* **12**, 181 (2021).
- [17] M. T. Mądzik, S. Asaad, A. Youssry, B. Joecker, K. M. Rudinger, E. Nielsen, K. C. Young, T. J. Proctor, A. D. Baczewski, A. Laucht, V. Schmitt, F. E. Hudson, K. M. Itoh, A. M. Jakob, B. C. Johnson, D. N. Jamieson, A. S. Dzurak, C. Ferrie, R. Blume-Kohout, and A. Morello, Precision tomography of a three-qubit donor quantum processor in silicon, *Nature (London)* **601**, 348 (2022).
- [18] A. Yang, M. Steger, D. Karauskaj, M. L. W. Thewalt, M. Cardona, K. M. Itoh, H. Riemann, N. V. Abrosimov, M. F. Churbanov, A. V. Gusev, A. D. Bulanov, A. K. Kaliteevskii, O. N. Godisov, P. Becker, H.-J. Pohl, J. W. Ager, and E. E. Haller, Optical detection and ionization of donors in specific electronic and nuclear spin states, *Phys. Rev. Lett.* **97**, 227401 (2006).
- [19] M. Steger, T. Sekiguchi, A. Yang, K. Saeedi, M. E. Hayden, M. L. W. Thewalt, K. M. Itoh, H. Riemann, N. V. Abrosimov, P. Becker, and H.-J. Pohl, Optically-detected NMR of optically-hyperpolarized ^{31}P neutral donors in ^{28}Si , *J. Appl. Phys.* **109**, 102411 (2011).
- [20] C. C. Lo, M. Urdampilleta, P. Ross, M. F. Gonzalez-Zalba, J. Mansir, S. A. Lyon, M. L. W. Thewalt, and J. J. L. Morton, Hybrid optical-electrical detection of donor electron spins with bound excitons in silicon, *Nat. Mater.* **14**, 490 (2015).
- [21] P. Ross, B. C. Rose, C. C. Lo, Mike L. W. Thewalt, A. M. Tyryshkin, S. A. Lyon, and John J. L. Morton, Electron spin resonance of P donors in isotopically purified Si detected by contactless photoconductivity, *Phys. Rev. Appl.* **11**, 054014 (2019).
- [22] W. Schmid, Auger lifetimes for excitons bound to neutral donors and acceptors in Si, *Phys. Status Solidi B* **84**, 529 (1977).
- [23] P. Conti, S. Dhomkar, P. Ross, J. Mansir, and J. J. L. Morton, Donor-bound-exciton strain microscopy in silicon devices, *arXiv:2408.17382*.
- [24] R. Rahman, J. Verduijn, Y. Wang, C. Yin, G. D. Boo, G. Klimeck, and S. Rogge, Bulk and sub-surface donor bound excitons in silicon under electric fields, *arXiv:1510.00065*.
- [25] J. J. Pla, A. Bienfait, G. Pica, J. Mansir, F. A. Mohiyaddin, Z. Zeng, Y. M. Niquet, A. Morello, T. Schenkel, J. J. L. Morton, and P. Bertet, Strain-induced spin-resonance shifts in silicon devices, *Phys. Rev. Appl.* **9**, 044014 (2018).
- [26] Y. Fang, P. Philippopoulos, D. Culcer, W. A. Coish, and S. Chesi, Recent advances in hole-spin qubits, *Mater. Quantum Technol.* **3**, 012003 (2023).
- [27] T. Peach, K. Homewood, M. Lourenco, M. Hughes, K. Saeedi, N. Stavrias, J. Li, S. Chick, B. Murdin, and S. Clowes, The effect of lattice damage and annealing conditions on the hyperfine structure of ion implanted bismuth donors in silicon, *Adv. Quantum Technol.* **1**, 1800038 (2018).
- [28] M. L. W. Thewalt and J. A. Rostworowski, Effects of uniaxial stress on the luminescence lines due to multiexciton complexes bound to phosphorus in silicon, *Phys. Rev. Lett.* **41**, 808 (1978).
- [29] V. A. Karasyuk, A. G. Steele, A. Mainwood, E. C. Lightowler, G. Davies, D. M. Brake, and M. L. W. Thewalt, Ultrahigh-resolution photoluminescence studies of excitons bound to boron in silicon under uniaxial stress, *Phys. Rev. B* **45**, 11736 (1992).
- [30] T. Loippo, A. Kanninen, and J. T. Muhonen, Strain effects in phosphorus bound exciton transitions in silicon, *Phys. Rev. Mater.* **7**, 016202 (2023).
- [31] M. P. Ross, Bound exciton-assisted spin-to-charge conversion of donors in silicon, Ph.D. thesis, University College London, 2017.
- [32] W. Kohn and J. M. Luttinger, Theory of donor states in silicon, *Phys. Rev.* **98**, 915 (1955).
- [33] W. P. Mason, *Physical Acoustics and the Properties of Solids*, Bell Telephone Laboratories Series (Van Nostrand, Princeton, New Jersey, 1958).
- [34] G. L. Bir, E. I. Butikov, and G. E. Pikus, Spin and combined resonance on acceptor centres in Ge and Si type crystals—I:

- Paramagnetic resonance in strained and unstrained crystals, *J. Phys. Chem. Solids* **24**, 1467 (1963).
- [35] G. Kirczenow, A new model for bound multiexciton complexes, *Solid State Commun.* **21**, 713 (1977).
- [36] J. M. Luttinger, Quantum theory of cyclotron resonance in semiconductors: General theory, *Phys. Rev.* **102**, 1030 (1956).
- [37] A. K. Bhattacharjee and S. Rodriguez, Group-theoretical study of the Zeeman effect of acceptors in silicon and germanium, *Phys. Rev. B* **6**, 3836 (1972).
- [38] Unless both stress and magnetic field are aligned with the same [100] crystal axis, which is not the case in our work.
- [39] K. L. Litvinenko, J. Li, N. Stavrias, A. J. Meaney, P. C. M. Christianen, H. Engelkamp, K. P. Homewood, C. R. Pidgeon, and B. N. Murdin, The quadratic Zeeman effect used for state-radius determination in neutral donors and donor bound excitons in Si:P, *Semicond. Sci. Technol.* **31**, 045007 (2016).
- [40] J. M. Cherlow, R. L. Aggarwal, and B. Lax, Raman scattering and photoluminescence in boron-doped and arsenic-doped silicon, *Phys. Rev. B* **7**, 4547 (1973).
- [41] Uncorrelated electron and hole energy fluctuations could yield substantial inhomogeneous broadening even when $\partial E_{D^0 \rightarrow D^0 X} / \partial \sigma \approx 0$.
- [42] G. Feher, Electron spin resonance experiments on donors in silicon. I. Electronic structure of donors by the electron nuclear double resonance technique, *Phys. Rev.* **114**, 1219 (1959).
- [43] D. P. Franke, Nuclear spins of heavy donors in silicon, Ph.D. thesis, Technische Universität München, 2018.
- [44] A. Kaminskii, V. Karasyuk, and Y. E. Pokrovskii, Luminescence of excitons bound to phosphorus atoms in silicon subjected to a magnetic field, *Zh. Eksp. Teor. Fiz.* **79**, 422 (1980) [*Sov. Phys. JETP* **52**, 211 (1980)].
- [45] C. Jagannath, Z. W. Grabowski, and A. K. Ramdas, Linewidths of the electronic excitation spectra of donors in silicon, *Phys. Rev. B* **23**, 2082 (1981).
- [46] I. Balslev, Influence of uniaxial stress on the indirect absorption edge in silicon and germanium, *Phys. Rev.* **143**, 636 (1966).
- [47] F. J. Morin, T. H. Geballe, and C. Herring, Temperature dependence of the piezoresistance of high-purity silicon and germanium, *Phys. Rev.* **105**, 525 (1957).
- [48] J. E. Aubrey, W. Gubler, T. Henningsen, and S. H. Koenig, Piezoresistance and piezo-Hall-effect in *n*-type silicon, *Phys. Rev.* **130**, 1667 (1963).
- [49] J. C. Hensel and G. Feher, Cyclotron resonance experiments in uniaxially stressed silicon: Valence band inverse mass parameters and deformation potentials, *Phys. Rev.* **129**, 1041 (1963).
- [50] D. K. Wilson and G. Feher, Electron spin resonance experiments on donors in silicon. III. Investigation of excited states by the application of uniaxial stress and their importance in relaxation processes, *Phys. Rev.* **124**, 1068 (1961).
- [51] V. J. Tekippe, H. R. Chandrasekhar, P. Fisher, and A. K. Ramdas, Determination of the deformation-potential constant of the conduction band of silicon from the piezospectroscopy of donors, *Phys. Rev. B* **6**, 2348 (1972).
- [52] L. D. Laude, F. H. Pollak, and M. Cardona, Effects of uniaxial stress on the indirect exciton spectrum of silicon, *Phys. Rev. B* **3**, 2623 (1971).
- [53] R. Ito, H. Kawamura, and M. Fukai, Anisotropic phonon scattering of electrons in germanium and silicon, *Phys. Lett.* **13**, 26 (1964).
- [54] G. D. Watkins and F. S. Ham, Electron paramagnetic resonance studies of a system with orbital degeneracy: The lithium donor in silicon, *Phys. Rev. B* **1**, 4071 (1970).
- [55] J. J. Hall, Electronic effects in the elastic constants of *n*-type silicon, *Phys. Rev.* **161**, 756 (1967).
- [56] M. V. Fischetti and S. E. Laux, Band structure, deformation potentials, and carrier mobility in strained Si, Ge, and SiGe alloys, *J. Appl. Phys.* **80**, 2234 (1996).
- [57] M. M. Rieger and P. Vogl, Electronic-band parameters in strained $\text{Si}_{1-x}\text{Ge}_x$ alloys on $\text{Si}_{1-y}\text{Ge}_y$ substrates, *Phys. Rev. B* **48**, 14276 (1993).
- [58] C. Tserbak, H. M. Polatoglou, and G. Theodorou, Unified approach to the electronic structure of strained Si/Ge superlattices, *Phys. Rev. B* **47**, 7104 (1993).
- [59] C. G. Van de Walle and R. M. Martin, Theoretical calculations of heterojunction discontinuities in the Si/Ge system, *Phys. Rev. B* **34**, 5621 (1986).
- [60] M. Cardona and F. H. Pollak, Energy-band structure of germanium and silicon: The *kp* method, *Phys. Rev.* **142**, 530 (1966).
- [61] P. Friedel, M. S. Hybertsen, and M. Schlüter, Local empirical pseudopotential approach to the optical properties of Si/Ge superlattices, *Phys. Rev. B* **39**, 7974 (1989).
- [62] U. Schmid, N. E. Christensen, and M. Cardona, Calculated deformation potentials in Si, Ge, and GeSi, *Solid State Commun.* **75**, 39 (1990).
- [63] G. L. Bir and G. E. Pikus, *Symmetry and Strain-Induced Effects in Semiconductors* (Wiley, New York, 1974).
- [64] U. Gerstmann (private communication).
- [65] B. Hönerlage and I. Pelant, *Symmetry and Symmetry-Breaking in Semiconductors*, Springer Tracts in Modern Physics Vol. 279 (Springer, Cham, Switzerland, 2018).
- [66] J. Mansir, The effects of strain on donor spin qubits in Silicon, Ph.D. thesis, University College London, 2019.
- [67] P. J. Dean, W. F. Flood, and G. Kaminsky, Absorption due to bound excitons in silicon, *Phys. Rev.* **163**, 721 (1967).
- [68] D. Sleiter, N. Y. Kim, K. Nozawa, T. D. Ladd, M. L. W. Thewalt, and Y. Yamamoto, Quantum Hall charge sensor for single-donor nuclear spin detection in silicon, *New J. Phys.* **12**, 093028 (2010).
- [69] M. T. Uysal, L. Dusanowski, H. Xu, S. P. Horvath, S. Ourari, R. J. Cava, N. P. de Leon, and J. D. Thompson, Spin-photon entanglement of a single Er^{3+} ion in the telecom band, *Phys. Rev. X* **15**, 011071 (2025).
- [70] S. Nur, H.-J. Lim, J. Elzerman, and J. J. L. Morton, Silicon photonic crystal cavities at near band-edge wavelengths, *Appl. Phys. Lett.* **114**, 091101 (2019).
- [71] K.-M. C. Fu, T. D. Ladd, C. Santori, and Y. Yamamoto, Optical detection of the spin state of a single nucleus in silicon, *Phys. Rev. B* **69**, 125306 (2004).