Imaging Spin Flows in Semiconductors Subject to Electric, Magnetic, and Strain Fields

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Using scanning Kerr microscopy, we directly acquire two-dimensional images of spin-polarized electrons flowing laterally in bulk epilayers of n-GaAs. Optical injection provides a local dc source of polarized electrons, whose subsequent drift and/or diffusion is controlled with electric, magnetic, and—in particular—strain fields. Spin precession induced by controlled uniaxial stress along the ⟨110⟩ demonstrates the direct \( k \)-linear spin-orbit coupling of electron spin to the shear (off diagonal) components of the strain tensor, \( \epsilon_{xy} \).

The measured Kerr rotation is a strong function of probe photon energy near the GaAs band edge [inset, Fig. 1(a)]. Here, 30 \( \mu \)m separates the pump and probe spots, so that the signal arises solely from a nonzero spin polarization of the electron Fermi sea. This energy-dependent response provides a relative (and \textit{in situ}) monitor of stress-induced band edge shifts. When imaging, the probe energy is tuned (as shown) below the 1.515 eV GaAs band edge, to minimize perturbation of the Fermi sea.

Figure 1(a) shows a 70 × 140 \( \mu \)m image of the steady-state electron spin polarization in the \( n_e = 10^{16} \text{cm}^3 \) GaAs epilayer due to spin diffusion alone. To emphasize smaller signals, the color scale has been adjusted so that white equals half the peak signal. The spatial extent of the measured spin polarization (~ 60 \( \mu \)m edge to edge) is...
Spin-orbit effects lead to spin splittings of the conduction band along particular crystal momenta \( \mathbf{k} \), and can be characterized by effective magnetic fields. Bulk inversion asymmetry arises from the lack of inversion symmetry in GaAs, leading to a spin splitting for electrons with \( \mathbf{k} \) along the \langle 110 \rangle axes (but no splitting along \langle 111 \rangle or \langle 100 \rangle axes). This ubiquitous coupling, cubic in \( |\mathbf{k}| \), is the origin of the D’yakonov-Perel’ mechanism of electron spin relaxation in bulk GaAs. A second spin-orbit effect arises from structural inversion asymmetry (the “Rashba” term \( |\mathbf{k}| \)), as typically found in 2D heterostructures. Inversion asymmetry of the confining potential along the growth direction \( \hat{z} \) (typically \( |001| \)) can often be characterized by an electric field \( \mathbf{E}_z \), giving a Rashba Hamiltonian \( H_R \propto \sigma \cdot (\mathbf{k} \times \mathbf{E}_z) \).

For typical 2D heterostructures with \( \mathbf{k} \) in the \( x-y \) plane, the effective magnetic field \( \mathbf{k} \times \mathbf{E}_z \) is therefore in plane and orthogonal to \( \mathbf{k} \), with magnitude linear in \( |\mathbf{k}| \). Control of the Rashba spin-orbit term, through a gate-tunable \( \mathbf{E}_z \), is the basis of the original Datta-Das spin transistor \([3]\).

Figure 2 demonstrates an additional spin-orbit effect; namely, the coupling of the electron spin to the strain tensor \( \mathbf{e} \). As described previously \([12–15]\), stress along the \langle 110 \rangle axes of GaAs induces \( \mathbf{k} \)-linear spin splittings in the conduction band through the off-diagonal (shear) elements of \( \mathbf{e} \). The strain Hamiltonian is \( H_S = c_3 \mathbf{\sigma} \cdot \mathbf{e} \), where \( (\varphi_x, \varphi_y, \varphi_z) = (\epsilon_{xx}, \epsilon_{xy}, \epsilon_{xz}, \epsilon_{yy}, \epsilon_{yz}, \epsilon_{zz}) \), \( (x, y, z) \) are the principle \( \langle 100 \rangle \) crystal axes, and the constant \( c_3 \) depends on the interband deformation potentials. Stress applied along the \langle 110 \rangle or \langle 110 \rangle axis of GaAs gives in-plane shear \( \epsilon_{xy} = \epsilon_{yx} \neq 0 \). Thus for electrons moving in

Spin-orbit coupling in GaAs permits coupling to electron spin degrees of freedom through the spatial part of the electron wave function, thus allowing induced precession of electron spins without external magnetic fields \([8–10]\).
the $x$-$y$ plane, $H_S$ has similar symmetry to $H_R$, as it describes an in-plane effective magnetic field, orthogonal to $k$, with magnitude linear in $|k|$. 

Figs. 2(a)–2(c) show $80 \times 80 \, \mu m$ images of steady-state electron spin flow ($k \parallel [110]$) in the presence of increasing [110] uniaxial stress. Spin precession is observed, with increasing spatial frequency, indicating a strain-induced effective magnetic field $B_e \propto \epsilon_{xy}|k|$, oriented along $[\bar{1}1\bar{0}]$. $\epsilon_{xy}$ is inferred from the measured blue-shifts [see Fig. 2(d)] of $\sim 1$ and 2 meV in Figs. 2(b) and 2(c), respectively, indicating strain $|\epsilon_{xy}| \sim 1.5$ and $3.0 \times 10^{-4}$ (and applied stress $\sim 3.6$ and $7.2 \times 10^8$ dyn/cm$^2$) [15]. These strains are small compared to typical $\sim 1\%$ strains due to lattice-mismatched growth; in fact, considerable care was required in sample mounting to avoid spurious and inhomogeneous strains during cooldown. With the cryogenic vise, the stress-induced precession of electron spins is controllable, reversible, and uniform over the sample. Line cuts along [110] [Fig. 2(e)] show many precession cycles ($> 5\pi$ rotation). The inset of Fig. 2(e) confirms that the spatial frequency of the induced precession ($\propto B_e$) scales linearly with the band shift ($\propto \epsilon_{xy}$).

Only shear (off diagonal) strain gives $k$-linear spin-orbit coupling to electron spins. Strain along the (100) axes, either applied or arising from, e.g., lattice-mismatched [001] growth, should not influence electron spins to lowest order. However, shear strain and $k$-linear coupling should exist in lattice-mismatched samples grown along [110] or [111]. One should not regard $B_e$ as arising from electric fields (e.g., stress-induced piezoelectric fields), since such fields are screened in bulk metals.

The line cuts in Fig. 2(e) show that dc spin flows, precessing due to strain, are in phase at large distances from the point of generation. This robust behavior is in marked contrast with the rapid spatial dephasing that occurs when real magnetic fields are used to induce precession in dc spin flows. Figs. 3(a)–3(c) show spin flows with an increasing applied magnetic field ($B_{app} \parallel [110]$), with line cuts in Fig. 3(d). As $B_{app}$ increases, the ensemble spin polarization becomes dephased at distances beyond one precession period, particularly when the precession period falls below the spin diffusion length. This pronounced spatial dephasing is due to the randomizing nature of diffusion. The net spin at a remote location is the combined sum of many random walks. Each path takes a different amount of time, giving a different spin rotation, leading to dephasing. Future devices based on magnetic field manipulation of diffusive spin flow may thus be practically limited to a regime requiring $\pi$ rotation or less. Line cuts through Figs. 2(c) and 3(c) are compared in the inset of Fig. 3(d). Clearly, the spatial coherence of dc spin flows persists over more precession cycles (and greater distance) when the spins are manipulated with strain instead of magnetic field. This is a direct consequence of the $|k|$-linear nature of $B_e$, which correlates precession frequency with electron velocity (and therefore position). Indeed, if electrons moved along only one dimension, the spin flow would not dephase at all (it would still, of course, decohere).

![FIG. 3 (color).](image)

(a)–(c) $80 \times 80 \, \mu m$ images of 2D spin flow ($E = 10 \, V/cm$) at $4 \, K$, with increasing applied magnetic field $B_{app} = 3.5$, 9, and 32 G along [110]. (d) Line cuts through the images. Inset: Line cuts through Figs. 2(c) (black) and 3(c) (red).

![FIG. 4 (color).](image)

$50 \times 50 \, \mu m$ images of 2D spin diffusion ($E = 0$) at $4 \, K$. (a) Stress, $B_{app} = 0$. (b) Stress $= 0$, $B_{app} = 16 \, G$ along [110] as shown. (c) $B_{app} = 16 \, G$, with [110] uniaxial stress. Spins diffusing to the right precess; those diffusing to the left do not. Thus $B_e$ is chiral for radially diffusing spins (see diagram). (d)–(g) Keeping [110] stress, $B_{app}$ is rotated $180^\circ$ in plane. (h) Stress is switched to [110], reversing $B_e$ chirality.
The images in Fig. 4 confirm that $\mathbf{B}_s$ is orthogonal to $\mathbf{k}$, such that $\mathbf{B}_s$ circulates around the point of injection for radially diffusing electrons. Image (a) shows unperturbed spin diffusion (no stress, $\mathbf{B}_{\text{app}} = 0$). In (b), $\mathbf{B}_{\text{app}} = 16 \text{ G}$ along [110] as shown. Spins precess uniformly, regardless of $\mathbf{k}$, giving a faint annulus of oppositely oriented spins (negative signal) around the injection point. In (c), [110] stress is applied and the image becomes asymmetric. Electrons diffusing to the right ($\mathbf{k} \parallel [110]$) undergo precession, while those diffusing to the left ($-\mathbf{k}$) do not. That is, the total field ($\mathbf{B}_t = \mathbf{B}_s + \mathbf{B}_{\text{app}}$) is finite for spins diffusing to the right, but $\mathbf{B}_s$ is effectively zero for spins diffusing to the left. This image is consistent with a uniform $\mathbf{B}_{\text{app}}$ added to a circulating $\mathbf{B}_s$, as shown. Maintaining [110] stress, the image asymmetry rotates and ultimately reverses as $\mathbf{B}_{\text{app}}$ is rotated in the $x$-$y$ plane through 180° (c)–(g). Finally (h), when stress is switched to the [110] axis, the asymmetry again reverses, indicating the opposite chirality of $\mathbf{B}_s$.

For comparison with data, we derive and numerically solve the 2D spin-diffusion equations. For simplicity, the [110] strain axis is taken here to be the $x$ axis, and the electric and magnetic fields are in the $x$-$y$ sample plane. The spin polarization is described by the $(\rho_x, \rho_y, \rho_z)$ components of a $2 \times 2$ density matrix, where $\rho_z$ gives the ensemble spin density. The equations are $O_1 \rho_s = -O_2 \rho_z$, $O_1 \rho_y = -O_3 \rho_z$, and $O_4 \rho_x - O_2 \rho_y - O_3 \rho_z = -G_z$, with operators $O_1 = D \nabla^2 + \mathbf{E} \cdot \nabla - (C_z \varepsilon) D - 1/T_2$, $O_2 = -C_B B_y + C_z \varepsilon(2D \nabla_y + \mu E_y)$, and $O_3 = C_B B_x + C_z \varepsilon(2D \nabla_x + \mu E_x)$, $O_4 = D \nabla^2 + \mathbf{E} \cdot \nabla - (C_z \varepsilon) D - 1/T_1$. $D$ is the spin diffusion constant, $\mu$ is the mobility, $T_2$ and $T_1$ are transverse and longitudinal spin lifetimes, $C_B = \frac{e^2}{m^*}$, the strain coupling constant $C_z$ is given in Ref. [15], $G_z$ is the spin generation, and $\varepsilon$ is the off diagonal strain $\varepsilon_{xy}$.

In contrast with the case of an applied magnetic field, both the model and the data reveal a consequence of $\mathbf{k}$-linear $\mathbf{B}_s$: the spatial period of precession is independent of applied electrical bias. Figure 5 confirms this, showing spin flow along [110]. In the presence of strain [Figs. 5(a)–5(c)], the spatial precession period is independent of bias, whereas for the case of applied magnetic field (d)–(f), the spatial precession period clearly increases with increasing bias. Functional “spin transistor” devices based on rotation of spin from, e.g., source to drain contacts [3–6], may well benefit from the freedom to operate at variable electrical bias. Along with spin manipulation via Rashba coupling (also linear in $\mathbf{k}$), the spin-orbit coupling of spin flows to shear strains of order 0.01%, as detailed in this work, also affords this flexibility.

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FIG. 5 (color). 50 × 80 µm images of 2D spin flow at 4 K with increasing $|\mathbf{k}|$ (current). (a–c) With [110] stress and $\mathbf{B}_{\text{app}} = 0$. Spatial period of precession is fixed. (d)–(f) Stress is 0, $\mathbf{B}_{\text{app}} = 6 \text{ G}$; spatial period varies. Images (c') and (f') are simulations of (c) and (f), using the model described in text.