Current-Induced Polarization and the Spin Hall Effect at Room Temperature

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(Dated: March 23, 2022)

Electrically-induced electron spin polarization is imaged in n-type ZnSe epilayers using Kerr rotation spectroscopy. Despite no evidence for an electrically-induced internal magnetic field, current-induced in-plane spin polarization is observed with characteristic spin lifetimes that decrease with doping density. The spin Hall effect is also observed, indicated by an electrically-induced out-of-plane spin polarization with opposite sign for spins accumulating on opposite edges of the sample. The spin Hall conductivity is estimated as $3 \pm 1.5 \, \Omega^{-1} m^{-1} / [\text{e}]$ at 20 K, which is consistent with the extrinsic mechanism. Both the current-induced spin polarization and the spin Hall effect are observed at temperatures from 10 K to 295 K.

PACS numbers: 75.25.Pn, 75.25.Dc, 85.75.-d, 71.70.Ej, 78.47.+p

The ability to manipulate carrier spins in semiconductors through the spin-orbit (SO) interaction is one of the primary motivations behind the field of spintronics. SO coupling provides a mechanism for the generation and manipulation of spins solely through electric fields, obviating the need for applied magnetic fields. Much of the recent interest in the consequences of SO coupling in semiconductors surrounds the production of a transverse spin current from an electric current, known as the spin Hall effect. Though predicted three decades ago, the first experimental observations of the spin Hall effect have appeared only recently in a variety of materials.

Subsequent work into the spin Hall effect has addressed the importance of extrinsic or intrinsic mechanisms of the spin Hall conductivity, the nature of spin currents, and the potential ability both to produce and to detect spin Hall currents using only electric fields. Previous experiments showing electrical generation of spin polarization in semiconductors through SO coupling have been performed at cryogenic temperatures in GaAs, the archetypical III-V zincblende semiconductor. In contrast, the wide band gap and long spin coherence times of II-VI semiconductors allow many spin-related effects to persist to higher temperatures than typically observed in the GaAs system. Many of the effects of SO coupling on the electrical manipulation of spin polarization have not been studied in detail in these compounds. In ZnSe, the extrinsic SO parameter $\lambda_{\text{ZnSe}} = 1.06 \, \text{eÅ}^2$, as calculated from an extended Kane model, is five times less than that in GaAs, with $\lambda_{\text{GaAs}} = 5.21 \, \text{eÅ}^2$. Despite weaker SO coupling, large extrinsic SO skew-scattering has been observed in the anomalous Hall effect in magnetically doped ZnSe. In this Letter we optically measure electrically-induced spin polarization in ZnSe epilayers that persists to room temperature. We observe in-plane current-induced spin polarization (CISP) in ZnSe with n-doping ranging over two orders of magnitude and out-of-plane electrically-induced spin accumulation at the edges of an etched channel, providing evidence for the extrinsic spin Hall effect. Unlike in previous studies of CISP and the spin Hall effect, both phenomena are measured at 300 K, demonstrating the electrical generation and routing of spins in semiconductors at room temperature.

A series of 1.5 μm thick n-type Cl-doped ZnSe epilayer samples with room temperature carrier concentrations $n = 5 \times 10^{16} \, \text{cm}^{-3}$, $9 \times 10^{17} \, \text{cm}^{-3}$, and $9 \times 10^{18} \, \text{cm}^{-3}$ are grown by molecular beam epitaxy on semi-insulating (001) GaAs substrates. Perpendicular channels of width $w = 100 \, \mu\text{m}$ and length $l = 255 \, \mu\text{m}$ are patterned along [110] and [110] directions of the ZnSe epilayers, allowing an electric field $E$ to be applied along both the crystal axes. A voltage is applied across the device, with the effective $E$ calculated from the measured temperature-dependent resistivity and current to eliminate the effect of contact resistance.

The samples are mounted in the variable temperature insert of a magneto-optical cryostat. Kerr rotation (KR) is measured in the Voigt geometry, with an in-plane applied magnetic field $B$ perpendicular to the laser propagation direction (Fig. 1a). 150-fs pulses from a 76-MHz mode-locked Ti:sapphire laser are frequency-doubled and split into a circularly polarized pump and a linearly polarized probe beam with powers of 1.2 mW and 400 μW, respectively. The Kerr rotation angle $\theta_K$ of the polarization axis of the reflected probe beam measures the projection of electron spin polarization along the propagation direction. Time-resolved KR measurements have found the electron g-factor to be $g = 1.1$ and the spin coherence time to decrease with increasing n-doping, with spin coherence times of 50 ns, 20 ns, and 0.5 ns for the $n = 5 \times 10^{16} \, \text{cm}^{-3}$, $9 \times 10^{17} \, \text{cm}^{-3}$, and $9 \times 10^{18} \, \text{cm}^{-3}$ samples, respectively, at $T = 5 \, \text{K}$ and $B = 0 \, \text{T}$.

In order to characterize the response of electron spins in ZnSe to applied electric fields, we perform spatially...
resolved KR measurements. In this pump-probe technique, the beams are normally incident on the sample and focused to a 15 µm spot (Fig. 1c inset). The relative separation (d) of the pump and probe is varied in the direction of the electric field, and the KR of the probe measures the electron spin polarization injected by the pump along the z-axis. Figure 1b follows the optically injected spin packet as it is dragged along the channel by a DC electric field of 60 mV/µm in the n = 5 × 10^{16} cm^{-3} sample. Extracting the drift velocity from the center of the Gaussian spin packets allows an estimate of the spin mobility of µs = 89 ± 14 cm^{2}/Vs. This is 20 times less than that measured in GaAs [20] and over an order of magnitude smaller than the ZnSe electron mobility µe = 14-40 cm^{2}/Vs at T = 50 K for this sample.

Experiments in GaAs have shown that an internal magnetic field B_{int} acts on electrons accelerated by an electric field, which has been attributed to inversion asymmetry [2] [20] [21] [26]. KR as a function of B with fixed spatial (d = 0) and temporal (13.1 ns) pump-probe separation is shown in Fig. 1c. This signal is periodic in B and symmetric about B = 0, making it a very sensitive probe for detecting B_{int} [3] [20]. The KR signal remains centered at B = 0 as we increase E, showing no evidence of a B_{int} in the n = 5 × 10^{16} cm^{-3} and n = 9 × 10^{17} cm^{-3} samples along either the [110] or [110] channel. The spin coherence time of the n = 9 × 10^{18} cm^{-3} sample is too short to observe KR at 13.1 ns temporal separation, but no evidence of electrically-induced spin precession from a B_{int} is observed using time-resolved KR with B = 0 [2]. These measurements provide an upper bound for the internal magnetic field of 0.1 mT with an E = 91 mV/µm. The lack of any observable B_{int} in ZnSe can be attributed to the weaker spin-orbit coupling in ZnSe and the minimal in the epilayers.

For optical detection of CISP, we block the pump and measure static KR with probe energy tuned near the maximum of the KR signal, typically around 2.8 eV at 50 K. The KR is detected with a lock-in synced to a 2-kHz applied square wave electric field E. Typical magnetic field sweeps of KR at T = 50 K are shown for each sample in Fig. 2 with B || E. The characteristic odd-Lorentzian shape is indicative of spins generated in-plane and perpendicular to B [3]. The data are modeled as spins generated along the y direction, with a background subtracted, and are fit to θ_{el}ω_{L}τ/[(ω_{L}τ)^{2} + 1], where θ_{el} is the KR amplitude and ω_{L} = gµ_{B}B/h is the Larmor precession frequency, µ_{B} is the Bohr magneton, and τ is the spin coherence time [3]. We measure θ_{el} to be independent of the square wave frequency and linear with both E and probe power. The trends in τ between samples match the trend in spin coherence time [19], but the values are not numerically identical. For n = 5 × 10^{16} cm^{-3} and n = 9 × 10^{17} cm^{-3}, τ decreases with increasing E, but the n = 9 × 10^{18} cm^{-3} sample exhibits little change in τ. CISP has also been observed in other samples of lower doping density (n ~ 1 × 10^{16} cm^{-3}), but systematic results are difficult due to large resistivity. Further quantitative optical analysis is performed as in Ref. [3] to estimate the efficiency of the electrical spin generation giving θ_{el} ≈ 12 spins µm^{-3} at 20 K. The sign in the figure corresponds to spins generated along the +y direction when the electric field is in the +x direction.

The microscopic origin of CISP is not well-understood [3] [22]. In-plane spin generation along the Rashba spin-orbit field [1] [22] has been used to explain CISP in two-dimensional electron [24] and hole [25] gases. Following the same formalism, strain-enhanced inversion asymmetry terms in the Hamiltonian manifest as B_{int} and could generate the spin polarization [3] [22]. In general, the internal magnetic field strength shows a close correlation to the amount of strain in GaAs structures [2] [26], but the magnitude of CISP shows little correlation to the strength of B_{int} [3]. In the current experiment in n-ZnSe, the CISP is comparable in magnitude to that in n-GaAs,
The spin Hall effect is probed using a low-temperature scanning Kerr microscope with a spatial resolution of approximately 1 μm. The ZnSe channel is mounted with \( B \perp E \) (\( B \parallel y \)) so in-plane CISP does not precess and is not detected. No differences in spin accumulation between the [110] and [110] channel are observed. Figure 3a shows the geometry for the spin Hall effect measurements, with the laser propagating along \(-z\). The origin is taken to be the center of the channel. Figure 3b shows typical KR data for scans of \( B \) near the edges of the channel at \( y = \pm 48 \) μm on the \( n = 9 \times 10^{18} \) cm\(^{-3}\) sample. The KR curves are analogous to the Hanle effect, in which an out-of-plane spin polarization decreases with \( B \) due to spin precession. These data can be fit to a Lorentzian \( \theta_{el} \), where the profile can be fit by \( \theta_{el} = -n_0 \text{sech} \left( w / 2L_s \right) \sinh \left( y / L_s \right) \), where \( L_s \) is the spin diffusion length (Fig. 3d). These fits give \( L_s = 1.9 \pm 0.2 \) μm at \( T = 20 \) K. Ignoring complications arising from boundary conditions, the spin current density along \( y \) can be written as \( j_y = L_s n_0 / \tau \) and we can calculate the spin Hall conductivity, \( \sigma_{SH} = -j_y / E_x = 3 \pm 1.5 \Omega^{-1} m^{-1} / |e| \) at \( T = 20 \) K. Uncertainties in the overall optical calibration make this only an order-of-magnitude estimate.

The spin Hall conductivity for ZnSe is of comparable magnitude and of the same sign as that predicted by theory for GaAs with a dominant extrinsic spin Hall effect. The extrinsic spin Hall effect has contributions of differing sign from both skew scattering and the side jump mechanism. For the conditions of Ref. skew scattering likely dominates giving \( \sigma_{SH} > 0 \). The dominance of skew scattering should persist in the degenerately n-doped ZnSe studied here since the Fermi energy is well above the conduction band edge. Intrinsic spin Hall conductivity should have the opposite sign \( \sigma_{SH} < 0 \).
and a lower magnitude $\mu_0$ than measured here; hence, the observed spin Hall effect in ZnSe is likely extrinsic.

Measurements of both CISP and the spin Hall effect at higher temperatures show a decrease in the spin coherence time $\tau$ and the peak spin polarization $n_0$, but both phenomena persist up to room temperature (Fig. 4 a,b). Figure 4c shows temperature dependences of the various parameters discussed above. The spin polarization is an order of magnitude weaker at room temperature and $L_s$ decreases from 1.9 $\mu m$ at 20 K to 1.2 $\mu m$ at 295 K. The estimated spin Hall conductivity decreases to $\sigma_{SH} \approx 0.5 \Omega^{-1} m^{-1}/|e|$ at room temperature.

These results demonstrate electrically-induced spin polarization and the extrinsic spin Hall effect at room temperature in a II-VI semiconductor. Despite the absence of a measurable internal field and the weaker spin-orbit coupling in ZnSe compared to GaAs, these phenomena remain measurable. The remarkable ability for all-electrical spin generation at room temperature suggests that spin-based logic is technologically feasible in semiconductor devices.

We thank NSF and ONR for financial support. N.P.S. acknowledges the support of the Fannie and John Hertz Foundation.

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FIG. 4: (a) KR (circles) and fit (line) of CISP at room temperature. Adjacent-point averaging was done to improve signal-to-noise. (b) KR (circles) and fits (lines) of spin Hall polarization at $y = -48 \mu m$ (black) and $y = +48 \mu m$ (blue) for $T = 295$ K. (c) Temperature dependence of density $n_0$, spin diffusion length $L_s$, and spin Hall conductivity $\sigma_{SH}$.

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