Negative differential Rashba effect in two-dimensional hole systems

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We demonstrate experimentally and theoretically that two-dimensional (2D) heavy hole systems in single heterostructures exhibit a decrease in spin-orbit interaction-induced spin splitting with an increase in perpendicular electric field. Using front and back gates, we measure the spin splitting as a function of applied electric field while keeping the density constant. Our results are in contrast to the more familiar case of 2D electrons where spin splitting increases with electric field.

In a solid that lacks inversion symmetry, the spin-orbit interaction leads to a lifting of the spin degeneracy of the energy bands, even in the absence of an applied magnetic field, $B$. In such a solid, the energy bands at finite wave vectors are split into two spin subbands with different energy surfaces, populations, and effective masses. The problem of inversion asymmetry-induced spin splitting in two-dimensional (2D) carrier systems in semiconductor heterojunctions and quantum wells has become of renewed interest recently because of their possible use in realizing spintronic devices such as a spin field-effect transistor, and for studying fundamental phenomena such as the spin Berry phase.

In 2D carrier systems confined to GaAs/AlGaAs heterostructures, the bulk inversion asymmetry (BLA) of the zinc blende structure and the structure inversion asymmetry (SIA) of the confining potential contribute to the $B = 0$ spin splitting. While BLA is fixed, the so-called Rashba spin splitting due to SIA can be tuned by means of external gates that change the perpendicular electric field ($E_\perp$) in the sample. For many years it has been assumed that the Rashba spin splitting in 2D carrier systems is proportional to $E_\perp$ that characterizes the inversion asymmetry of the confining potential. 2D holes contained in a GaAs square quantum well provide an example. In the present work we show both experimentally and theoretically that for heavy holes confined to a triangular well at the GaAs/AlGaAs interface, spin splitting decreases with an increase in $E_\perp$. We demonstrate this negative differential Rashba effect by analyzing the Shubnikov-de Haas oscillations in this system at a constant density. We note that hole systems have recently gained great attention for spintronics applications because ferromagnetic (III,Mn)\textit{V} compounds are intrinsically p type. A detailed understanding of the $B = 0$ spin splitting in hole systems is thus of great importance.

The sample used in our study was grown on a GaAs (001) substrate by molecular beam epitaxy and contains a modulation-doped 2D hole system confined to a GaAs/AlGaAs heterostructure [Fig. 1(a)]. The $\text{Al}_0.3\text{Ga}_{0.7}\text{As}/\text{GaAs}$ interface is separated from a 16 nm thick Be-doped $\text{Al}_0.3\text{Ga}_{0.7}\text{As}$ layer (Be concentration of $3.5 \times 10^{18}$ cm$^{-3}$) by a 25 nm $\text{Al}_0.3\text{Ga}_{0.7}\text{As}$ spacer layer. We fabricated Hall bar samples via lithography and used In/Zn alloyed at 440°C for the ohmic contacts. Metal gates were deposited on the sample’s front and back to control the 2D hole density ($p$) and $E_\perp$. The low temperature mobility for the sample is $7 \times 10^{4}$ cm$^2$/Vs at $p = 2.3 \times 10^{11}$ cm$^{-2}$. We measured the longitudinal ($R_{xx}$) and transverse ($R_{xy}$) magneto-resistances at $T \approx 30$ mK via a standard low frequency lock-in technique.

In single heterostructures, where SIA is the dominant source of spin splitting, the electric field $E_\perp$ experienced by the carriers is determined by the density-dependent self-consistent potential. This potential is determined, in turn, by the sample structure (spacer layer thickness and doping, etc.), and the applied gate biases. In our measurements, we used front and back gate biases to change the potential’s profile and hence $E_\perp$ [Fig. 1(b)], while keeping the density constant. We initially set the front-gate voltage ($V_{FG}$) to 0.55 V and back-gate voltage ($V_{BG}$) to $-100$ V with respect to the 2D hole system, leading to $p = 1.84 \times 10^{11}$ cm$^{-2}$, and measured $R_{xy}$ and $R_{xx}$ as a function of $B$ between $-3$ T to 5 T. Then at $B = 1$ T, we...
increased $V_{BG}$ and noted the change in $R_{xy}$; this change in $R_{xy}$ gives the corresponding change in density ($\Delta p$). $V_{BG}$ was then decreased to recover the original $R_{xy}$ and hence the original $p$. This procedure leads to a change $\Delta E_\perp = e\Delta p/\epsilon$ in $E_\perp$ ($\epsilon$ is the electron charge and $\epsilon$ is the dielectric constant) while keeping the density constant to within 1%. $\Delta E_\perp$ is measured with respect to $E_\perp$ at $V_{BG} = 0.55$ V and $V_{BG} = -100$ V.

Figure 2 shows the low-field Shubnikov-de Haas (SdH) oscillations for two $E_\perp$ differing by 8 kV/cm. The Fourier transform (FT) spectra of these oscillations, shown in Fig. 2 (inset), exhibit four dominant peaks at frequencies $f_-$, $f_{avg}$, $f_+$, and $f_{tot}$, with the relation $f_{tot} = f_+ + f_- = 2f_{avg}$. The $f_{tot}$ frequency, when multiplied by $e/h$, matches well the total 2D hole density deduced from the Hall resistance ($h$ is the Planck’s constant). The two peaks at $f_-$ and $f_+$ correspond to the holes in individual spin subbands although their positions times $e/h$ do not exactly give the spin subband densities [15, 16]. Nevertheless, as discussed below, this discrepancy between $(e/h)f_{avg}$ and the $B = 0$ spin subband densities is minor and $\Delta f = f_+ - f_- = f_{tot} - 2f_-$ provides a good measure of the spin splitting. The vertical lines in the inset of Fig. 2 at the $f_-$ and $f_+$ peaks clearly indicate that $\Delta f$ decreases when $\Delta E_\perp$ is increased from 0 to 8 kV/cm. The vertical line at the $f_{tot}$ peak shows that the total hole density is held constant.

We compare the experimental data with accurate numerical calculations of the magneto-oscillations at $B > 0$. First we perform fully self-consistent calculations of the subband structure at $B = 0$ in order to obtain the Hartree potential $V_H$ as a function of $E_\perp$. We assumed that the concentration of unintentional background impurities in the GaAs space charge layer was $1 \times 10^{14}$ cm$^{-3}$. This assumption is based on our sample parameters; we note, however, that the deduced spin splitting is insensitive to the exact value of the background doping. Using $V_H$ we obtain the Landau fan chart for $B > 0$ from an $8 \times 8 \mathbf{k} \cdot \mathbf{p}$ Hamiltonian that fully takes into account the spin-orbit coupling due to both SIA and BIA. From this fan chart we then determine the magneto-oscillations by evaluating the density of states at the Fermi energy as a function of $B$.

In Fig. 3 the experimental and calculated $\Delta f$ from the corresponding FT spectra are plotted versus $\Delta E_\perp$. It is clear that increasing $E_\perp$ lowers the spin splitting. We also verified that the calculated $B = 0$ spin splitting, defined as the difference between the spin subband densities, shows the same negative differential Rashba effect as $\Delta f$ obtained from the calculated magneto-oscillations. The difference between the $B = 0$ spin splitting times $h/e$ and $\Delta f$ is only $\lesssim 0.14$ T in the range of $E_\perp$ shown in Fig. 3. This confirms that the $B = 0$ spin splitting shows the same negative differential trend.

We can understand these surprising results in the following way. The hole states in the uppermost valence band $\Gamma_8^z$ have the angular momentum $j = 3/2$. In 2D systems, the four hole states split into heavy-hole (HH) states with $z$ component of angular momentum $m = \pm 3/2$ and light-hole (LH) states with $m = \pm 1/2$. Here the quantization axis is perpendicular to the 2D
plane. On the other hand, the Rashba spin-orbit coupling acts like a $k$-dependent effective magnetic field which is oriented in the plane so that it favors to orient the quantization axis of the angular momentum in-plane. However, this is not possible within the subspace of HH states ($m = \pm 3/2$) so that — in contrast to $j = 1/2$ electron systems — the Rashba spin splitting of HH states is a higher-order effect. Neglecting anisotropic corrections, it is characterized by the Hamiltonian \[ H_{\text{SO}}^h = \beta_1^h E_{\perp} i (k_x^1 \sigma_- - k^3 \sigma_+), \] (1) with $\sigma_\pm = 1/2(\sigma_x \pm i \sigma_y)$ and $k_\pm = k_x \pm i k_y$, where $\sigma_x$ and $\sigma_y$ are the Pauli spin matrices in the $x$ and $y$ directions respectively. Using third-order L"{o}wdin perturbation theory \[ \beta_1^h \] we obtain for the Rashba coefficient $\beta_1^h$ of the lowest HH subband $\alpha = 1$
\[ \beta_1^h = a \gamma_2 (\gamma_2 + \gamma_3 e^{2} \sqrt{\left(\frac{1}{\Delta H_{12}^h} - \frac{1}{\Delta H_{11}^h} \right)^{2} + \frac{1}{\Delta H_{12}^l} \Delta H_{12}^l}}, (2) \] where $\gamma_2$ and $\gamma_3$ are the Luttinger parameters \[ \Delta H_{11}^h \] and \[ \Delta H_{12}^h \equiv \Delta H_{12}^l \] for the oth HH and LH subband, respectively. The symbol $a$ denotes a numerical prefactor which depends on the angular momentum perpendicular to the 2D plane. How-
\[ \Delta H_{12}^l \] ever, this is not possible within the subspace of HH states — the Rashba spin splitting of HH states is a hard to define because of uncertainties in the sample pa-
\[ \Delta H_{12}^l \] point on the \[ E_{\perp} \] axis, which would allow a direct com-
\[ \Delta H_{12}^l \]parison of the measured and calculated results, is very hard to define because of uncertainties in the sample pa-
\[ \Delta H_{12}^l \]rameters.

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