Tuning of the spin-orbit interaction in two-dimensional GaAs holes via strain

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We report direct measurements of the spin-orbit interaction-induced spin splitting in a modulation-doped GaAs two-dimensional hole system as a function of anisotropic, in-plane strain. The change in spin-subband densities reveals a remarkably strong dependence of the spin splitting on strain, with up to about 20% enhancement of the splitting upon the application of only about 2×10^{-4} strain. The results are in very good agreement with our numerical calculations of the strain-induced spin splitting.

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Manipulation of the spin-orbit coupling in materials that lack inversion symmetry is considered the basis for novel spintronic devices.[1–3] In two dimensions, these devices utilize the fact that the inversion asymmetry of the confining potential can be tuned with a perpendicular electric field applied via external front- and back-gate biases.[4–9] This structural inversion asymmetry, along with the bulk inversion asymmetry of the zinc-blende structure, leads to a lifting of the spin degeneracy of the energy bands even in the absence of an applied magnetic field. The energy bands at finite wave vectors are split into two spin subbands with different energy surfaces, populations, and effective masses. It is the manipulation of this so-called zero-field spin splitting that forms the underlying principle of many spintronic devices. In addition, the spin-orbit interaction-induced spin splitting is of interest in studying fundamental phenomena such as Berry's phase[10,11] and the spin Hall effect.[12]

There have been recent reports of utilizing strain for tuning the spin-orbit interaction and the resulting spin splitting.[13–16] The studies have focused on magneto-optical (Faraday and/or Kerr rotation) measurements in epitaxially grown but bulk-doped GaAs and InGaAs electron systems. Here, we present strain-induced spin-splitting results for a high-mobility, modulation-doped GaAs *two-dimensional hole* system (2DHS). We utilize a simple but powerful technique to continuously apply quantitatively measurable in-plane strain *in situ*[17] and make magneto-transport measurements which directly probe the densities of the spin subbands. We observe a significant change in spin splitting as a function of strain. The experimental data agree very well with our accurate numerical calculations of the spin splitting, which take the spin-orbit interaction and strain fully into account. We show that the mechanism that gives rise to the strain-induced spin splitting in hole systems is qualitatively different from the mechanism operating in electron systems. Most importantly, the strain enhancement of the spin splitting for the two-dimensional (2D) holes is about 100 times larger than for 2D electrons and, moreover, is essentially independent of the strain direction. Combined, our results establish the extreme sensitivity of the spin-orbit coupling in 2DHSs to strain, and demonstrate the potential use of the 2D holes for spintronic and related applications.

Our sample is grown on a GaAs (311)A substrate by molecular-beam epitaxy and contains a modulation-doped 2DHS confined to a GaAs/AlGaAs heterostructure. The $Al_{0.35}Ga_{0.65}As$/GaAs interface is separated from a 17-nm-thick Si-doped $Al_{0.35}Ga_{0.65}As$ layer (Si concentration of 4×10^{18} cm^{-3}) by a 30 nm $Al_{0.35}Ga_{0.65}As$ spacer layer. We fabricated L-shaped Hall bar samples via photolithography and used In:Zn alloyed at 440 °C for the Ohmic contacts. Metal gates were deposited on the sample's front (10 nm Ti, 30 nm Au) and back (100 nm Ti, 30 nm Au) to control the 2D hole density (p). We measured the longitudinal (R_{xx}) and transverse (R_{xy}) magnetoresistances at T=0.3 K via a standard low-frequency lock-in technique. R_{xx} was measured along the $[01\bar{1}]$ and $[\bar{2}33]$ directions yielding, at $p=2.1\times10^{11}$ cm^{-2}, low-temperature mobilities of 1.7×10^5 and 4.3×10^5 cm^2/V s in the two directions, respectively.

We apply tunable strain to the sample (thinned to ~200 μm) by gluing it on one side of a commercial piezoelectric (piezo) stack actuator with the sample's $[01\bar{1}]$ crystal direction aligned with the poling direction of the piezo [Fig. 1(c)].[17] When bias V_P is applied to the piezostack, it expands (shrinks) along the $[01\bar{1}]$ for $V_P>0$ ($V_P<0$) and shrinks (expands) along the $[\bar{2}33]$ direction. We have confirmed that this deformation is fully transmitted to the sample and, using metal strain gauges glued to the opposite side of the piezo, have measured its magnitude.[17,18] Based on our calibrations of similar piezoactuators, we estimate a strain of 3.8×10^{-7} V^{-1} along the poling direction. In the perpendicular direction, the strain is approximately −0.38 times the strain in the poling direction.[17] In this Brief Report, we specify strain values along the poling direction; we can achieve a strain range of about 2.3×10^{-4} by applying $-300\leqslant V_P\leqslant300$ V to the piezo. Finally, the back gate on the sample is kept at a constant voltage (0 V) throughout the measurements to shield the 2DHS from the electric field of the piezostack.

Figure 1(a) shows the low-field Shubnikov–de Haas (SdH) oscillations, measured in the $[01\bar{1}]$ direction, for seven different values of V_P from −300 to 300 V in steps of 100 V. The Fourier transform spectra of these oscillations, shown in Fig. 1(b), exhibit three dominant peaks at frequencies f_-, f_+, and f_{tot}, with the relation $f_{tot}=f_++f_-$. The f_{tot} frequency,

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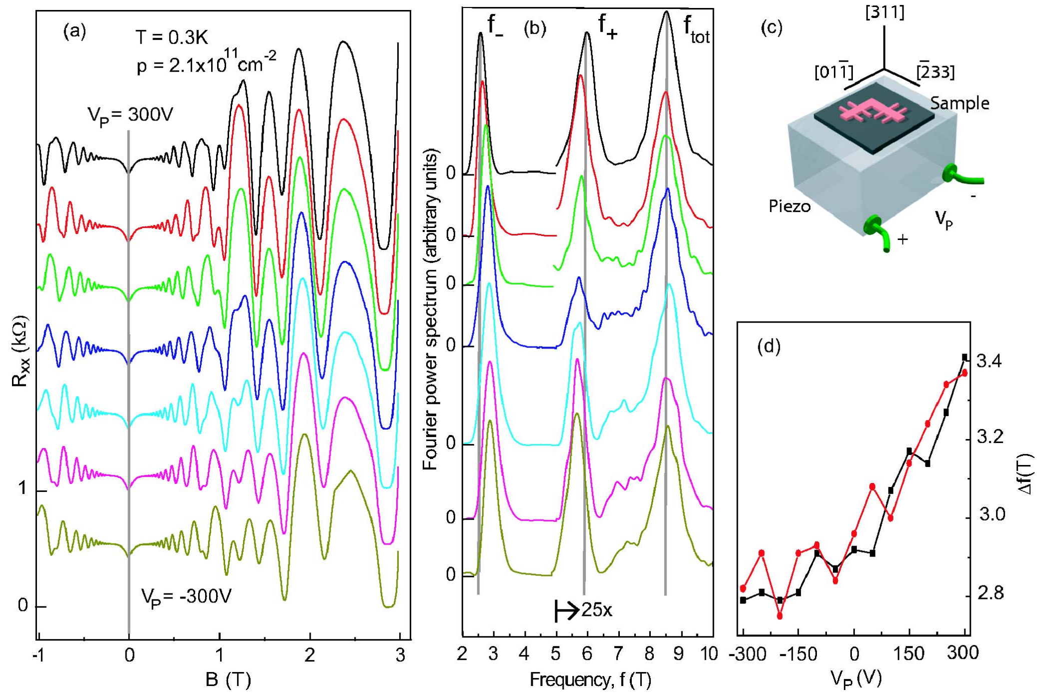

FIG. 1. (Color online) (a) Shubnikov–de Haas oscillations, measured in the $[01\bar{1}]$ direction, for seven different piezo voltages in steps of 100 V. The traces are offset vertically for clarity. (b) Normalized Fourier power spectra of the oscillations in the range $0.2 \leq B \leq 2$ T. The positions of the peaks f_- and f_+ correspond to the densities of the minority- and majority-spin subbands, while the peak labeled f_{tot} gives the total 2D hole density. (c) Experimental setup. The poling direction for the piezo is along $[01\bar{1}]$. (d) Spin splitting versus applied strain. The black squares ($\Delta f = f_+ - f_-$) and the red circles ($\Delta f = f_{tot} - 2f_-$) are from two different methods used to determine the spin splitting.

when multiplied by e/h, matches well the total 2D hole density deduced from the Hall resistance (e is the electron charge and h is the Planck constant). The two peaks at f_- and f_+ correspond to the area enclosed by the Fermi contours of holes in individual spin subbands, although their positions times e/h do not exactly give the spin-subband densities.[9,19,20] As we discuss below, however, this discrepancy between $(e/h)f_\pm$ and the $B=0$ spin-subband densities is minor and $\Delta f = f_+ - f_- = f_{tot} - 2f_-$ indeed provides a very good measure of the spin splitting. The vertical gray lines in Fig. 1(b) clearly indicate that Δf increases when the piezo voltage is dialed up from −300 to 300 V while the total hole density (f_{tot}) remains constant. Figure 1(d) summarizes the change in Δf with strain (in terms of piezo bias) for $p = 2.1 \times 10^{11}$ cm^{-2}; Δf determined from both $(f_+ - f_-)$ and $(f_{tot} - 2f_-)$ are plotted. The results show a significant (about 20%) enhancement of spin splitting with strain. SdH oscillations measured in the $[\bar{2}33]$ direction show the same amount of spin splitting, consistent with the fact that Δf is related to the *areas* of the Fermi contours of the two spin subbands.

In order to understand the data of Fig. 1, we performed self-consistent calculations of the spin splitting as a function of strain, using the 8×8 Kane Hamiltonian augmented by the strain Hamiltonian of Bir and Pikus.[9,21,22] This model takes into account the spin-orbit coupling due to both the structure inversion asymmetry of the GaAs/AlGaAs heterojunction as well as the bulk inversion asymmetry of the underlying zinc-blende structure.[23] Furthermore, it fully incorporates the strain-induced contributions to spin splitting. We adapted this model to the (311) orientation of our sample by a suitable coordinate transformation. To make a direct comparison with the experimental data, we calculated the Landau fan chart for $B > 0$ and determined the magneto-oscillations of the density of states at the Fermi energy.[9,20] We then calculated the Fourier power spectrum of these oscillations and obtained the frequencies f_+ and f_- that correspond to the majority- and minority-spin subbands. The difference between these frequencies Δf can be directly compared to the experimentally determined Δf data of Fig. 1(d).

Figure 2 presents our calculated Δf (solid curves) as a function of strain for three different 2DHS densities. The calculations took the corresponding gate biases for the three different densities into account. It is clear that the calculated Δf exhibits substantial changes with strain. In Fig. 2, we also show the measured Δf values for the same three densities, assuming that $V_P = 0$ corresponds to zero strain. There is an overall very good agreement between the calculated and measured Δf. The agreement is particularly remarkable in view of the fact that the calculations were performed only based on the sample structure and density. In other words, there are no fitting parameters used to match the results of the calculations to the measured values of Δf.

We would like to make the following remarks about the results presented in Fig. 2. First, it is known[19,20] that the frequencies f_+ and f_- are not exactly related to the spin-subband densities at zero magnetic field, p_+ and p_-, via the relation $p_\pm = (e/h)f_\pm$, although this relation approximately holds. For completeness, we also calculated p_+ and p_-. We find that for the data shown in Fig. 2, the calculated Δp is

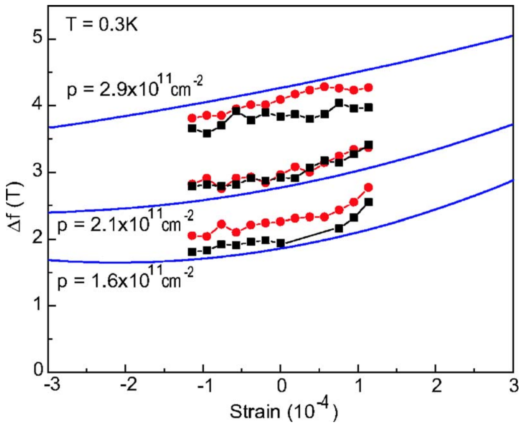

FIG. 2. (Color online) The black squares ($\Delta f = f_+ - f_-$) and the red circles ($\Delta f = f_{tot} - 2f_-$) are the experimentally measured spin splitting. The solid curves are Δf determined from the calculated magneto-oscillations. The three different densities, from lowest to highest, are obtained at front-gate biases of 0.3, 0, and −0.7 V, respectively.

only slightly larger than the calculated $(e/h)\Delta f$ by at most 10%. This means that the results presented in Fig. 2 closely represent the spin splitting at zero magnetic field as well. Second, although there are no fitting parameters in comparing the experimental and calculated Δf, we do have an experimental uncertainty regarding the absolute value of strain. In our experiments, we know the relative changes in values of strain accurately, but we do not know the piezo bias corresponding to zero strain precisely. Thanks to a mismatch between the thermal expansion coefficients of GaAs and the piezostack, at low temperatures, the sample can be under finite strain even at $V_P=0$. This residual strain is cooldown dependent, and unfortunately we do not know its precise value for the data of Fig. 2, which were measured during a single cooldown. Based on our experience with cooldowns of samples glued to similar piezostacks, we expect a residual strain up to about $\pm 1 \times 10^{-4}$. We emphasize that despite this uncertainty, the overall agreement of the experimental and calculated spinsplittings, including its strain dependence, is remarkable. Furthermore, our measurements on a different sample with the piezostack's poling direction aligned to the $[\bar{2}33]$ crystal direction showed similar results and matched well with the corresponding calculations.

Our analysis reveals that the mechanism leading to the strain dependence of spin splitting in 2DHSs is very different from the mechanism responsible for the strain-dependent spin splitting in bulklike electron systems studied previously.[13–16] In the latter case, strain has generally only a weak effect on the energy dispersion, and the spin splitting can be traced back to a small deformation potential often denoted as C_2 that couples electron and hole states in a spin-dependent manner.[22] In 2DHSs, on the other hand, the piezo-induced strain has a twofold effect. First, it changes the heavy-hole-light-hole (HH-LH) energy splitting. Since spin splitting in 2DHSs competes with the HH-LH splitting,[9] this provides a direct way to tune the spin splitting. Second, the strain changes the functional form of the spin splitting of 2DHSs. While in the absence of strain the spin splitting of 2DHSs is cubic in the wave vector k,[9] strain gives rise to a significant spin splitting linear in k. The deformation potentials relevant for these effects [often denoted as D_u and D'_u (Ref. 22)] are much larger than C_2 and therefore lead to a much more pronounced strain-induced spin splitting in hole systems. The effect of the spin-dependent deformation potential C_2 on the spin splitting of hole states is much smaller than the effects discussed here. Finally, in electron systems, the strain dependence is highly anisotropic. No spin splitting occurs for strain along the [100] crystallographic direction.[14,16] The strain-induced spin splitting in 2DHSs, on the other hand, is relatively independent of the direction of the in-plane strain.[22]

For a more quantitative comparison with electron systems, we deduce the spin splitting in a 2D GaAs electron system at a density of 2.1×10^{11} cm^{-2} by using Eq. (6.18) in Ref. 9. The change in spin-subband densities for this system for an applied strain of 1×10^{-4} in the $[01\bar{1}]$ direction is 8.2×10^7 cm^{-2}. From Fig. 2, the corresponding change in spin-subband densities for our sample is 8.4×10^9 cm^{-2}. This is 100 times larger than the 2D electron system value.[24]

Another aspect of the 2DHSs is the tunability of the spin splitting with electric field, which can be manipulated with front- and back-gate biases.[6,7] An important question is whether the strain-induced spin splitting depends on the electric field. Calculations for our heterostructure sample at $p = 2.1 \times 10^{11}$ cm^{-2} show less than 4% difference in strain-induced spin splitting (for $\pm 2 \times 10^{-4}$ strain) when the electric field was changed by ±3 kV/cm. In contrast, our calculations for a 20 nm square well in a GaAs 2DHS with $p = 2 \times 10^{11}$ cm^{-2} indicate that for electric fields of 0 and ±3 kV/cm, the spin splitting decreases with the application of strain ($\pm 2 \times 10^{-4}$, applied in the $[01\bar{1}]$ direction). Furthermore, at 0 kV/cm, applying a positive (tensile) strain of 2×10^{-4} decreases the spin splitting by a larger amount (38%) than applying the same strain in the opposite (compressive) direction (19%). At 3 kV/cm, the situation is reversed and a negative strain (-2×10^{-4}) shows more spin splitting compared to an equivalent positive strain (27% vs 17%). These results are in qualitative agreement with our preliminary data from a 20-nm-wide square quantum well with $p = 2 \times 10^{11}$ cm^{-2} glued to a piezo with the poling direction in the $[01\bar{1}]$ crystal direction.

Next, we discuss the results of a previous study by Kolokolov *et al.*,[25] which we learned of after the completion of our work. In their work, they also use magnetotransport data to study spin splitting as a function of strain in (100) GaAs 2DHS. Although their results are over a larger range of applied strain than our experiments, their data are only in qualitative agreement with their calculations, *even* at zero strain. They attribute the discrepancy between their experimental results and calculations to the segregation of Ga at the AlGaAs/GaAs interface without providing any quantitative analysis of this hypothesis.

We close by highlighting a potential application of our findings. Our results reveal a surprisingly large change in spin splitting in 2D GaAs holes for rather small values of applied strain. This tuning of the spin splitting can be employed to demonstrate various spintronic and/or spin-interference effects in devices, such as Aharonov-Bohm-type ring structures, made in this system. In the spin-interference device proposed in Ref. 2, e.g., the conductance through a ring of radius a is expected to oscillate with a period of $\pi a \Delta k_d$, where Δk_d denotes the change in k_d, defined as the difference of the Fermi wave vectors of the two spin subbands. In our 2DHS sample, at $p=2.1\times10^{11}$ cm^{-2}, the strain-induced change in k_d is $\sim0.9\times10^7$ m^{-1}.[26] Hence, for a ring of radius 220 nm, the ring conductance should go through one period of oscillation. For such measurements, tuning the spin-orbit interaction via strain, rather than perpendicular electric field (gate bias), may prove advantageous: the 2D hole density remains fixed as a function of strain, thus simplifying the experimental measurements and their interpretation. Tuning the spin splitting via gate bias, on the other hand, has the often undesired result of changing the total 2D density and therefore the number of conducting channels in the ring. Furthermore, noise in mesoscopic devices in 2DHSs is very sensitive to gate bias and usually limits the effective range of the gate voltages.[27]

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