Large Rashba Splitting in InAs Quantum Wells due to Electron Wave Function Penetration into the Barrier Layers

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We report on zero-field spin splitting of two-dimensional electron systems. Though absent in the unbiased InAs square asymmetric quantum well (SAQW), the Rashba splitting becomes pronounced by applying a positive *back*-gate voltage. In our SAQW, the Rashba parameter α increases with electron density and is tuned by a factor of about 2 using an additional front gate *without charging* the well. We argue that the band-edge profile provides the important contribution for spin-orbit interaction due to barrier penetration of the envelope wave function. This mechanism can provide the potential for high speed implementation in spintronics.

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Spin splitting of the 2D electron band structure in zero magnetic field has attracted significant interest. This feature has recently been found to be important for fundamental macroscopic phenomena like the unexpected metal-to-insulator transition in 2D [1] or for mesoscopic physics like spin-resolved ballistic 2D magnetotransport [2] or the Berry's phase experiment [3]. The discussion on spin-splitting phenomena in zero magnetic field was pushed forward by Datta and Das in 1990 [4] when tuning the spin state of a field-effect transistor (FET) was proposed as the base for a completely novel type of *spin-polarized* electronic device, so-called *spintronics,* which can be inherently very fast. For this, the Rashba effect, i.e., spin-orbit coupling due to the average electric field in a confining potential is believed to be the most prominent tuning force. For 2D hole systems, spin-orbit interaction due to confinement was earlier proven unambiguously by intersubband spectroscopy, in the absence of any magnetic field [5], and very recently convincingly revisited by magnetotransport studies of the beating pattern in the Shubnikov–de Haas (SdH) oscillations in low magnetic fields [1]. For 2D electron systems, strikingly different strengths for the Rashba effect have been reported [6–11]. Sometimes it was even absent [12], leading to a great amount of ambiguity. Basically, the puzzling question has remained open, why a rather weak electric field E_s applied perpendicular to the 2D hole plane can vary the spin splitting substantially [1]. Though E_s has been of the order of only 10^3 V/cm (a factor of 100 smaller than the strength of typical built-in electric fields due to doping), the subband populations of the two spin states up(+) and down(−)

$$E^{\pm}(k_{\|}) = E_0 + \frac{\hbar^2 k_{\|}^2}{2m^*} \pm \alpha |k_{\|}| \tag{1}$$

were made to differ by up to 20% (starting from 0% if $E_s = 0$) while the hole density was kept constant. In the energy dispersion of Eq. (1), E_0 denotes the edge of the ground subband, $k_{\|}$ is the momentum in the 2D plane, m^* is the effective mass, and α is the parameter for the Rashba spin-orbit splitting which is linear in $k_{\|}$. Fundamental features are therefore still under debate—in theory and experiment.

In this Letter, we report on 2D electron systems (2DES) within an InAs quantum well, a promising material for the realization of the spin FET [4], where we have been able to tune the spin-orbit interaction for a fixed 2DES carrier density. In order to achieve this, we have grown a square asymmetric quantum well (SAQW) by molecular-beam epitaxy (MBE) and have integrated *two* gate electrodes. Very strong variation of the zero-field spin splitting of the 2D subband as a function of the front- *and* back-gate voltage is obtained from the SdH beating patterns. Our investigations prove that the band-edge profile and the effect of electron wave function penetration into the barrier are relevant. Thus, the position of the wave function transverse to the 2D channel can be utilized to control the parameter α efficiently *without charging* the quantum well. This effect will be one of the most important features for future spintronic devices [4] and for implementing their inherent high speed.

Experiments are performed on 2DES in InAs quantum wells taken from different parts of a wafer grown by MBE. A 40-nm $In_{0.75}Al_{0.25}As$ cap layer is grown on top of the quantum well consisting of 13.5-nm $In_{0.75}Ga_{0.25}As$, an inserted 4-nm InAs channel, and a 2.5-nm-thick $In_{0.75}Ga_{0.25}As$ layer. Underneath there is a 5-nm spacer layer of $In_{0.75}Al_{0.25}As$ on top of the Si doped 7-nm-wide $In_{0.75}Al_{0.25}As$. This sequence is grown on a buffering multilayer system accommodating the lattice mismatch to the semi-insulating GaAs substrate [13]. The 2DES is 55 nm below the surface, sufficiently confined to the InAs channel and embedded in the square asymmetric quantum well. The conduction band edge and the carrier distribution along the growth direction, i.e., the square of the envelope wave function, are calculated using a self-consistent Schrödinger-Poisson solver [14] and are depicted in Fig. 1 as an inset. The SAQW is asymmetric in two regards. First, it is grown as a so-called *inverted*

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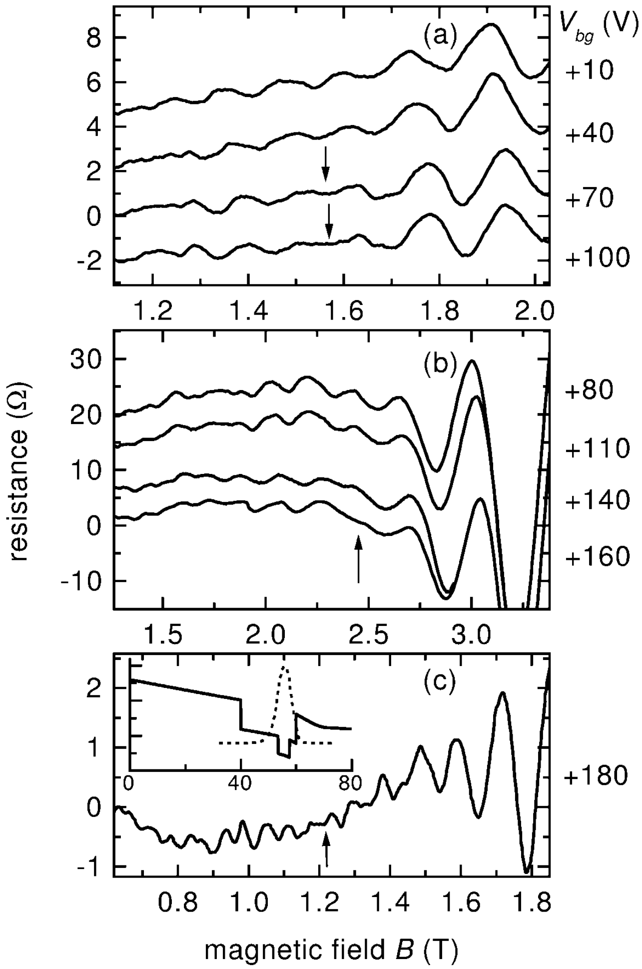

FIG. 1. SdH oscillations measured on different parts of the InAs SAQW wafer for various back-gate voltages V_{bg}, with a second-order polynomial background already subtracted. Arrows indicate node positions. Carrier densities in (a)–(c) are 9.4, 11.1, and 9.65×10^{11} cm^{-2} for the highest V_{bg}. The full line in the inset represents the conduction band edge. Here, the vertical axis expands from -0.3 to 0.65 eV. The horizontal axis is the distance from the surface in nm. The broken line shows ψ^2, i.e., the carrier distribution.

high electron mobility transistor with the modulation doping only underneath the InAs channel. Second, the InAs is embedded asymmetrically in the 16-nm-wide $\mathrm{In}_{0.75}\mathrm{Ga}_{0.25}\mathrm{As}$ quantum well such that the 2DES is close to the modulation-doped, Al-containing interface but remote from the undoped one. This design enables us to explore the role of the band-edge profile on the spin-orbit interaction which is claimed theoretically to provide an important contribution [15,16]. The average built-in electric field $\langle E \rangle$ at the bottom side of the SAQW due to the doping is about 10^5 V/cm.

Resistance measurements were performed in a perpendicular magnetic field using the lock-in technique and an ac current amplitude of less than 1 μA at 39 Hz. An electron mobility $\mu = 160.000$ $\mathrm{cm}^2/\mathrm{Vs}$ was achieved for $N_S = 1.06 \times 10^{12}$ cm^{-2} in the center of a wafer, deduced from $\mu = 1/\rho_{xx} N_S e$ in zero magnetic field with the sheet resistance ρ_{xx}. The effective mass m^* was determined to be $0.036 m_0$ from the temperature dependent SdH amplitudes and is somewhat larger than the InAs conduction band-edge mass of $0.023 m_0$ (m_0 is the free electron mass) [13]. This increase can be attributed mainly to the penetration of the electron wave function into the $\mathrm{In}_{0.75}\mathrm{Ga}_{0.25}\mathrm{As}$ layers. Magnetotransport characterization has been performed down to a temperature as low as 0.28 K, but a beating pattern in the SdH oscillations of the longitudinal resistance R_{xx} was not resolved in samples with only a front gate. Applying a positive front-gate voltage or illuminating by use of a red light-emitting diode (LED) increased N_S and the mobility (up to 215.000 $\mathrm{cm}^2/\mathrm{Vs}$), but without generating a beating pattern due to spin splitting.

Samples with *two* gate electrodes have a 50-nm-thick gold film directly on top of the cap layer as the front gate. Seven voltage probes on the longer edges serve to measure R_{xx} for different parts of a mesa (about 20×60 $\mu\mathrm{m}^2$). The samples exhibit different transport characteristics mostly due to variations of the MBE growth conditions as a function of lateral distance from the center of the wafer. The back-gate electrode is 140 μm underneath the mesa. Tuning a dc voltage source to 200 V would correspond to an applied electric field E_s of about 14×10^3 V/cm assuming a homogeneous sample.

In Figs. 1(a)–1(c) we show the effect of a back-gate voltage V_{bg} on the SdH oscillations for different samples. Though completely absent at *any* negative and moderate positive V_{bg}, a node develops in (a) if $V_{\mathrm{bg}} \geq +70$ V with respect to the 2DES, and in (b) if $V_{\mathrm{bg}} \geq +80$ V [17]. It is worth noting that the nodes appear at a characteristic position for each device and N_S, and get more pronounced if V_{bg} is increased. The nodes are stable and reproduced when we switch the polarity of V_{bg} from positive to negative values and back again. In Fig. 1(c), a beating pattern is shown for another sample when a back-gate voltage of $+180$ V is applied. The different resistance scales in Figs. 1(a)–1(c) reflect the variations in sample quality mentioned above. Finally, we note that a voltage of up to ± 200 V applied between the front and the back gate with a floating 2DES did not result in a beating pattern in the SdH.

The observed SdH beating patterns are interpreted as gate-voltage induced 2D subband splittings due to spin-orbit interaction as described by Eq. (1). In order to extract the Rashba parameter α from the measured traces, we converted the R_{xx} vs B^{-1} data in the low-field regime by Fourier transformation (FT). From double-peak structures in spectra like the ones shown in Fig. 2(a), one can determine the different populations of the spin-split subbands n^+ and n^- according to $n^{\pm} = \nu^{\pm} e/h$. Here, $\nu^{\pm}$ is the FT frequency of the left and right peak, respectively. In our case, only the lowest 2D subband is occupied and α can be calculated from [9]

$$\alpha = \frac{(n^+ - n^-)\hbar^2}{m^*} \sqrt{\pi/[2N_S - 2(n^+ - n^-)]}. \quad (2)$$

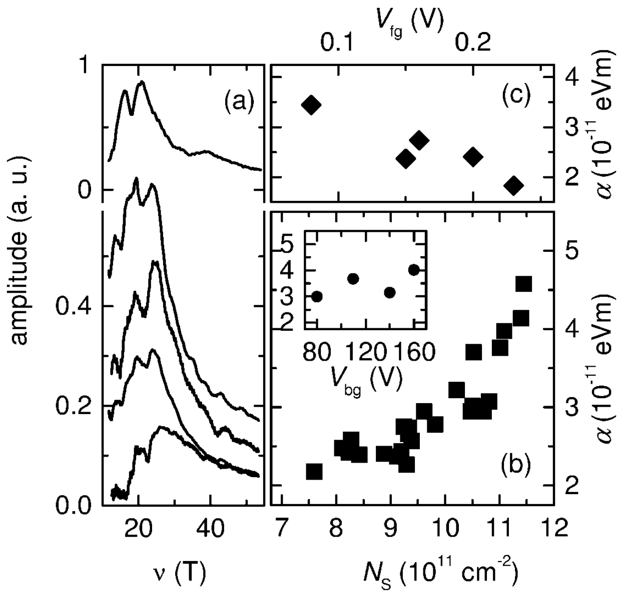

FIG. 2. (a) Fourier transforms of low-field data ($B < 3$ T). The double peak reflects two spin subbands of different density. The uppermost curve is for a sample with $N_S = 8.9 \times 10^{11}$ cm^{-2} at $V_{bg} = +150$ V; the four lower curves are for the data set in Fig. 1(b). Here, V_{bg} increases from top to bottom. FT curves are scaled and shifted along the vertical axis for clarity. (b) The Rashba spin-splitting parameter α calculated from Eq. (2) for three Hall-bar samples ($+80 \leq V_{bg} \leq +200$ V). The inset shows $\alpha(V_{bg})$ extracted from Fig. 1(b). (c) The parameter α as a function of V_{fg} while V_{bg} and N_S were kept constant at $+160$ V and $0.91 \pm 0.02 \times 10^{12}$ cm^{-2}, respectively.

We ignore band nonparabolicity [11] and take the mass $0.036m_0$ for our comparatively small carrier densities $N_S \leq 1.15 \times 10^{12}$ cm^{-2}.

In Fig. 2(b), we have summarized the parameter α as a function of total carrier density N_S obtained on three Hall samples in several cooling sessions. Beating patterns were measured on different mesa regions in the dark, before and after successively increasing the carrier density stepwise by short LED pulses, making advantage of the persistent photoeffect. This tuning of N_S is different from earlier experiments on the Rashba parameter. Though extracted from SdH traces under various conditions [compare Figs. 1(a)–1(c)], the Rashba splitting obeys overall a common behavior; in particular, α increases with increasing carrier density N_S. This unexpected experimental result is observed for a 2DES in a heterostructure for the first time. Via the back-gate voltage, α is controlled within smaller margins. From the SdH data of Fig. 1(b), e.g., we get a variation in α as shown in the inset of Fig. 2(b) which reflects the shift in the FT curves [compare Fig. 2(a)]. The observed maximum values of α are about 4×10^{-11} eV m, almost 3 times larger than in previous studies [8,9,11]. We note that in Fig. 2(b) the spread in the parameter α obtained for the different samples at the same N_S is up to about 20%, which is equal to the typical error if the spin splitting is calculated from a single low-field SdH curve using Eq. (2) [9,11].

In Fig. 2(c), we investigate α as a function of the front-gate voltage V_{fg} for a fixed V_{bg} and a fixed total carrier density $N_S = 0.91 \pm 0.02 \times 10^{12}$ cm^{-2}. This has been ensured by adjusting V_{fg} appropriately after each step of illumination. By this means, we explore the impact of the front-gate voltage on the spin-splitting parameter α. We find that the Rashba splitting *diminishes*, here by almost a factor of 2, if V_{fg} is increased. This observation seems to be similar compared to previous experiments [8,9,11]. However, contrary to those works, we have avoided to vary N_S by V_{fg}. The important result in Fig. 2(c) is that one is able to tune α, i.e., the spin splitting, *without* changing the charge density, the fundamental prerequisite for a true spin FET.

Our experimental data on 2DES in the InAs-based SAQW show that the spin-orbit interaction parameter α increases with N_S and positive V_{bg} but show a negative slope as a function of V_{fg}. In the common picture in which the Rashba effect [Eq. (1)] is driven mainly by the average electric field [6,8,10], we cannot understand why the spin-orbit splitting should crucially depend on the polarity of V_{bg} and why we observe such a large value of α though the applied external electric field E_s increases the built-in electric field $\langle E \rangle$ by only about 10%. Our results differ from the 2D hole system within a symmetric quantum well [1] where the authors were in fact able to induce spin splitting for both gate voltage polarities to approximately the same extent.

In the following, we demonstrate that the characteristic dependencies observed in this work are caused by the band-edge profile. This assumption is based on the idea [15,16] that the discontinuity of the band edges at the SAQW potential barrier is a parameter for spin-orbit interaction as important as a uniform asymmetric electric field. We focus our discussion on these two mechanisms, since it has been pointed out by Lommer *et al.* [18] and proven experimentally by Luo *et al.* for InAs [6], that in a narrow-gap semiconductor the Rashba effect [Eq. (1)] should dominate over a k^3 term which originates from the lack of bulk inversion symmetry. The contribution of the barrier is given as the band offsets weighted by the probability density of the conduction electrons at the interface [15,16], such that in a multiband approach α should scale with $\beta \times (|\psi_b|^2 - |\psi_t|^2)$, where β contains the band structure parameters of the heterostructure and ψ_b and ψ_t are the envelope functions at the bottom and top barriers, respectively [9]. In the case of a symmetric quantum well, where the amplitudes of the envelope function at the quantum well interfaces are the same in a balanced situation, one cannot distinguish between the impact of the barrier and the electric field.

In our SAQW design, however, the probability density is asymmetric with respect to the confining barriers, in particular, the electron wave function is close to the Al-containing spacer layer. Applying a gate voltage on the back with respect to the 2DES, one is able to shift the wave function transverse to the well and thus to change the probability density at the spacer layer. It has been shown early on that, by this means, one is able to vary the magnetotransport characteristics of a 2DES in an AlGaAs/GaAs heterostructure substantially [19]. In that work, the effect of repulsive and attractive scatterers on the mobility at the interface of the heterojunction has been investigated. Sakaki even introduced a new category of FET by proposing the velocity modulation transistor where electrons are swept very fast from a region of high mobility to one of low mobility [20]. In our experiment on an InAs-based heterostructure we observe beating patterns in the SdH traces when the electrons are "pulled" towards the interface underneath the 2DES by a positive V_{bg}. By this means, the electron probability inside the barrier and $(|\psi_b|^2 - |\psi_t|^2)$ are enlarged, resulting in an increased spin-orbit interaction [15,16]. The effect of barrier penetration can also be used to tune α at a constant charge density. In particular, we find that spin-orbit interaction diminishes if V_{fg} is positively biased at fixed N_S [Fig. 2(c)]. This is in agreement with the response when the electrons are attracted towards the front gate, i.e., when the amplitude of the envelope function is reduced at the spacer layer. The gate-controlled position of the wave function can thus be utilized to tune the spin-orbit interaction at a constant N_S. By this means, one can overcome the fundamental transit-time limitation caused by the lateral redistribution of carriers in a conventional 2D FET channel [20] and implement the inherent high speed of spintronics.

In general, the applied field E_s can be ruled out to be responsible for the observed large spin-splitting parameters α, surmounting previous experimental results. In order to quantify the contribution of the barrier in more detail we compare our results to theoretical estimates. In the simplest one-band or Rashba model within the infinite barrier approximation one can calculate the uppermost limit of the field contribution to the Rashba splitting from $\alpha = \alpha_{so} e\langle E\rangle$, where $\alpha_{so} = 110$ Å^2 for bulk InAs [16] and $\langle E\rangle = 10^5$ V cm^{-1} is taken as the average space-charge electric field at the well interface, to a good approximation valid for our smallest carrier density of 0.75×10^{12} cm^{-2}. In this approach, one expects a spin-orbit interaction parameter $\alpha = 1.1 \times 10^{-11}$ eV m. The experimental value of about 2.2×10^{-11} eV m is already larger by a factor of 2. No theoretical estimates for InAs heterostructures are available right now. However, the enhancement seems to be quite reasonable in view of multiband calculations in Ref. [16] for the multilayer system CdTe/InSb. There an enhancement of the same order is predicted if barrier penetration occurs for a Fermi momentum $k_F = 2 \times 10^6$ cm^{-1}, i.e., for our smallest 2D carrier density. For an AlGaAs/GaAs heterojunction, Pfeffer [15] predicted a factor of about 2.4 due to the barrier contribution. The important result of Fig. 2(b) is that the Rashba-splitting parameter α can be even further enhanced. If we increase N_S in the SAQW, both the Fermi energy E_F and the subband energy E_0 [Eq. (1)] are raised, promoting a more effective penetration into the bottom barrier [16]. Finally, we note that in recent experiments on Rashba splitting a 2DES in bulk p-type InAs [21], which resided within a triangular shaped potential with huge confinement, was found to be in agreement with the infinite barrier approximation. Only the average field contributed to the splitting, resulting, as expected from the discussion above, in a smaller α parameter for a given value of $\langle E\rangle$ than in our SAQW.

In conclusion, we have demonstrated that the penetration of the electron wave function into the barrier can provide a powerful tool for controlling the Rashba spin splitting even if the carrier density N_S is kept constant. The barrier contribution to the spin-orbit interaction is found to be larger than the field contribution and depends on the carrier density. Our findings might be utilized advantageously to realize the spin FET [4] without charging the 2D channel.

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