Spin-orbit interaction in a two-dimensional electron gas in a InAs/AlSb quantum well with gate-controlled electron density

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We present experiments on the tuning of the spin-orbit interaction in a two-dimensional electron gas in an asymmetric InAs/AlSb quantum well using a gate. The observed dependence of the spin splitting energy on the electron density can be attributed solely to the change in the Fermi wave vector. The spin-orbit interaction parameter ($\alpha \approx 0.6 \times 10^{-11}$ eV m) as such does not change significantly with electron density.
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Currently there is growing interest in the influence of the spin-orbit interaction on mesoscopic transport phenomena and on the quantum Hall effect.[1–8] The spin-orbit interaction couples the electron spin to the electron motion, which occurs in a two-dimensional electron gas (2DEG) with an asymmetric potential well. Although the interaction has a small magnitude compared to the Fermi energy, it may have major implications on electron transport, as is known from weak-localization phenomena, where the spin-orbit interaction leads to the so-called antilocalization. This process has been used recently by Knap *et al.*[3] in studying the magnetoconductance in $Ga_xIn_{1-x}As$ quantum wells. Polyakov and Raikh discussed the theoretical influence on the integer quantum Hall effect.[4] Furthermore, the spin-orbit interaction plays a crucial role in determining the persistent currents and the Aharonov-Bohm effect in mesoscopic one-dimensional rings, where the spin-orbit interaction induces a Berry phase.[5,6] From a different perspective, Datta and Das[7] suggested an experiment in which electron transport in a 2DEG with spin-polarized injector and collector electrodes is modulated by changing the asymmetry of the 2DEG to control spin-orbit interaction. All these effects, which combine mesoscopic electron transport and spin-orbit interaction, depend on the strength of the spin-orbit interaction, and thus triggered us to address the question whether its strength can be controlled. In this paper we present a study of the spin-orbit interaction in a 2DEG in an AlSb/InAs/AlSb heterostructure with gate-controlled electron density.

The spin orbit interaction in semiconductor heterostructures can be caused by an electric field perpendicular to the 2DEG. In a moving frame of reference, this electric field is ''felt'' by the electron spin as an effective magnetic field lying in the plane of the 2DEG, perpendicular to the wave vector $\vec{k}$ of the electron. The effective Zeeman interaction of the electron spin with the field lifts the spin degeneracy. This is known as the Rashba mechanism.[9] It produces an isotropic spin splitting energy Δ at $B=0$ proportional to k.[10–12] Another way to lift the spin degeneracy is the built-in electric field due to the inversion asymmetry of the host crystal. This is a bulk effect with a component proportional to k^3. This latter component is proportional to $1/d^2$, with d the quantum-well thickness.[13–15] It has been shown by Luo *et al.*, by comparing the spin splitting in quantum wells of 7 and 10 nm, that the Rashba mechanism is dominant for the spin splitting in InAs-based heterostructures at low applied magnetic fields.[12] The heterostructures used have an even thicker quantum well (15 nm), and we thus focus on the Rashba mechanism of spin splitting.

The electric field in an asymmetric 2DEG has a nonzero expectation value because the electric force on the electrons is balanced by a force which arises from the effective-mass discontinuity between the quantum well and the barrier material.[16] The heterostructure has to be asymmetric to have nonzero electric field at the 2DEG. The asymmetry can be present in structurally symmetric heterostructures when the electron donors are located mainly on one side of the quantum-well structure.[17] A way to introduce or modify such an asymmetry is by applying a voltage to a gate on top of the heterostructure, and thus change the electron density and band bending of the heterostructure; for this reason, our samples have a top-gate electrode.

The samples used are taken from a single wafer grown by molecular-beam epitaxy (Fig. 1). A 15-nm InAs layer is grown on top of a ten-period 2.5-nm GaSb/2.5-nm AlSb layer. On the InAs layer 20.5-nm AlSb, 6-nm $Al_xGa_{1-x}Sb$ and 2.5-nm GaSb are grown. The GaSb top layer was added to avoid oxidation of the heterostructure. The InAs/AlSb interfaces were made with InSb-like interfaces to have a high mobility, and low electron density.[18] In the InAs layer a deep well exists that hosts a 2DEG.[19] At zero gate voltage the electron density $n_s = 1.2 \times 10^{16}\ \mathrm{m}^{-2}$ and mobility $\mu = 9.6\ \mathrm{m}^2/\mathrm{V\,s}$ in a single occupied 2D subband are found from the Shubnikov–de Haas (SdH) measurements. Experimental work by Ideshita *et al.*[20] and Furukawa[21] on samples with comparable electron densities has shown that the majority of the carriers are supplied by deep donors in the AlSb, and that surface contributions are small when the thickness

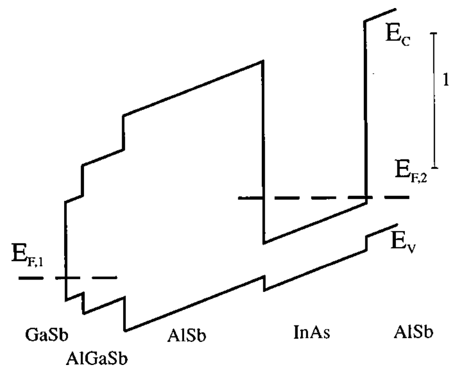

FIG. 1. Schematic AlSb/InAs/AlSb heterostructure band diagram with an applied positive gate voltage, ignoring band bending. $E_{F,1}$ and $E_{F,2}$ are the left and right Fermi energies, respectively. E_c is the conduction band, and E_v the valence band.

of the top layer exceeds 20 nm. In our samples most of the electrons are probably supplied by the AlSb layer, as well as the InAs/AlSb interfaces. Figure 1 shows a schematic band diagram of the heterostructure, with applied positive gate voltage. The AlSb/GaSb interfaces just below the 2DEG do not contribute significantly to the electron density in the InAs quantum well.[22]

When the gate voltage exceeds +1.1 V, signatures of second subband population are found in high-magnetic-field measurements. The electron densities in the second subband are very low. This will not interfere with the phenomena we study at lower magnetic fields, and we will focus our work on one subband only.

The origin of the spin-orbit splitting is the electric field that is present at the 2DEG. The Hamiltonian to describe this was first introduced by Rashba,[9]

$$H_R=\alpha[\vec{\sigma}\times\vec{k}]\cdot\hat{z}, \tag{1}$$

where $\vec{\sigma}$ are the Pauli spin matrices, and $\hat{z}$ is the direction of the electric field in the heterostructure, i.e., the direction of growth if the electric field is due to structural asymmetry which coincides with the direction perpendicular to the plane of the gate. The parameter α is linearly dependent on the expectation value of the electric field at the 2DEG $\langle E_z\rangle$:

$$\alpha=b\langle E_z\rangle \tag{2}$$

In first order, the prefactor b is inversely proportional to the energy gap and the effective mass of the used material, and is treated as a constant. Its value is relatively large for InAs-based heterostructures.[17] The total Hamiltonian is

$$H_{\mathrm{tot}}=H_k+H_R. \tag{3}$$

Here H_k is the kinetic-energy part of the Hamiltonian, $H_k=\hbar^2k^2/2m^\star$ ($m^\star$ is the effective mass) ignoring any nonparabolicity of the energy dispersion relation. The eigenenergies labeled + and − are

$$E^{\pm}(k)=\frac{\hbar^2k^2}{2m^\star}\pm\alpha|k|. \tag{4}$$

Thus the spin splitting energy at zero magnetic field at the Fermi energy is

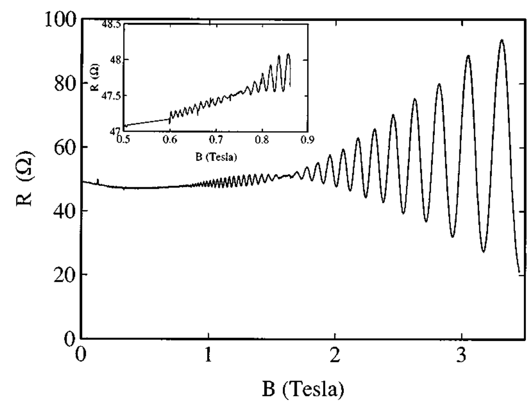

FIG. 2. Longitudinal magnetoresistance ρ_{xx} at $T=1.3$ K and $V_{\mathrm{gate}}=1$ V. The inset shows the left beat at a different scale.

$$\Delta=2\alpha k_F. \tag{5}$$

This spin splitting means that, instead of one degenerate electron gas (if only one subband in the InAs quantum well is populated), there are two electron gases with a slightly different electron density. This can be observed as a beating pattern in the SdH pattern. In the Hamiltonian H_{tot}, we have ignored the Zeeman splitting $g\mu_B\vec{\sigma}\cdot\vec{B}$. Even though g can be large in InAs, the contribution of the Zeeman splitting is much smaller than the energy splitting caused by the Rashba mechanism in the magnetic fields considered. The energy spectrum for the Landau level n is[9]

$$E(n)=\frac{1}{2}\hbar\omega_c, \qquad n=0$$

$$E^{\pm}(n)=\hbar\omega_c\left(n\pm\frac{1}{2}\sqrt{1+n\frac{\Delta^2}{E_F\hbar\omega_c}}\right), \quad n=1,2,\ldots, \tag{6}$$

where the cyclotron frequency $\omega_c=eB/m^\star$ is used, and E_F is the Fermi energy at zero magnetic field. In Eq. (6), the distinct energies labeled + and − are the eigenenergies of the eigenstates of H_{tot} in a magnetic field B.

ρ_{xx} is measured in a regular Hall bar device. This shows a maximum in ρ_{xx} each time a Landau level passes through the Fermi energy of the system, and a minimum when the Fermi energy is situated between two Landau levels. This gives rise to the Shubnikov–de Haas oscillations if the mobility of the 2DEG is high enough. The oscillations in ρ_{xx} are periodic in 1/B with a period $2e/hn_s$.

In Fig. 2, the SdH pattern for $V_{\mathrm{gate}}=1$ V is shown. A beating pattern is observed, showing that indeed two sets of Landau levels are present, each causing SdH oscillations.

At the beat node the oscillation is completely damped so the amplitude of both signals is identical. The inset to Fig. 2 shows ρ_{xx} at low fields and expanded scale. A second beat node can be distinguished. Between the beat nodes there are 25 oscillations, thus the two frequencies differ by only 4%. Apparently the beat pattern is caused by two populations with almost the same electron density.

We exclude that the beating is caused by two regions of different electron density originating from sample inhomogeneity because the beating appears identically in three samples. Also, this beating is not caused by the second sub-

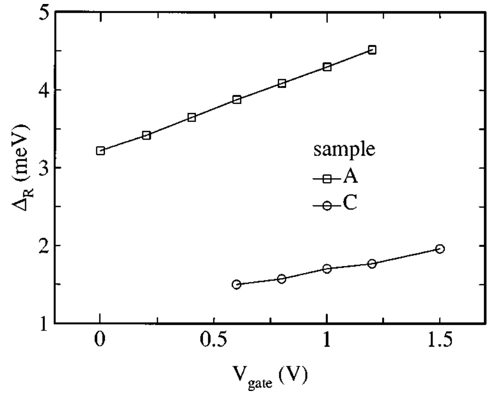

FIG. 3. Spin-splitting energy Δ applied gate voltage. Sample B behaves like sample A.

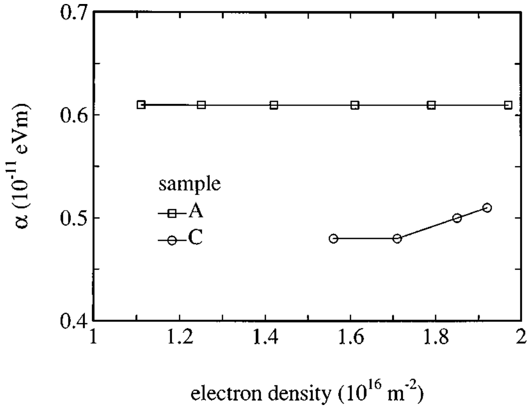

FIG. 4. Parameter α vs electron density.

band population of electrons in the InAs quantum well. These are observed at the same magnetic fields for gate voltages exceeding $V_{\text{gate}}=1.5$ V. Each time the Fermi energy is at the energy of the *plus* Landau level (numbered n), and simultaneously between two spin *minus* Landau levels (numbered m), a beat appears. Thus the beat node condition is[23]

$$E_F = E^+(n),$$
$$E_F = E^-(m) + \frac{1}{2}[E^-(m+1) - E^-(m)]. \tag{7}$$

Equations (6) and (7) are used to determine the spin splitting energy Δ from the magnetic field and the Landau-level numbers where the beat occurs. The Landau-levels can be read from plots of the Landau level index versus inverse magnetic field. The beat observed at the highest magnetic field is the first beat in $1/B$, and thus $m-n=1$, the zeroth being at $1/B \rightarrow 0$. Using Eq. (7) on the first and second nodes yields only a small difference in zero-field energy splitting Δ. This justifies ignoring the Zeeman splitting and using a constant effective mass.

Figure 3 shows the spin-splitting energy vs gate voltage. For the electron densities and InAs quantum well size used, the effective mass is $m^\star = 0.04 m_0$ taken from literature.[24] In the gate-voltage range covered, we find a linear dependence of the spin-splitting energy on the gate voltage. The spin-splitting energies are ≈ 3.5 meV for samples A and B, and ≈ 1.5 meV for sample C. The samples were produced in two nominally identical batches (A and B) and (C). The electron densities differ by only 5%. The observed difference in spin-splitting energy is not understood.

Two mechanisms which change Δ can be distinguished: First, the Fermi wave vector depends on the gate-voltage-dependent electron density n_s through $k_F = \sqrt{2\pi n_s}$, and thus also Δ [Eq. (5)]. Second, the combined effects of the electric field applied by a voltage on the gate, and the presence of mobile carriers determine the shape of the potential well, and thus the expectation value of the electric field at the 2DEG. In principle, the spin-splitting parameter α itself can be changed in this way.

In Fig. 4 the parameter α is plotted versus the electron density obtained from the SdH oscillations using Eq. (5). When the electron density is changed significantly, the spin-splitting parameter α does not change at all or only by less than 10%. Since the electron density itself is linear with gate voltage using a simple capacitor model of the 2DEG with gate, we expect $E \propto n_s/\epsilon$, and thus a linear relationship between α and n_s [Eq. (2)]. Clearly this is not observed.

De Andrada E Silva *et al.*[25] calculated the spin-splitting energy for a comparable heterostructure. In their variational calculations the screening of the electric field is taken into account. They studied electrons densities up to 1×10^{16} m^{-2}, and found that α varies with electron density. Our measurements for higher electron densities show α to be almost constant.

A possible reason for this could be that the interaction parameter α has reached a saturated value. In that case the expectation value of the electric field at the 2DEG cannot be increased by enhancing the asymmetry of the heterostructure. Lommer, Malcher, and Rössler *et al.*[17] emphasized that, as well as layers with different effective mass, the penetration of the electron wave function in the adjacent layers is essential to have a nonzero $\langle E_z \rangle$. With the high electron densities and high electric fields ($\approx 10^7$ V/m) used, the position of the electron wave function in the InAs layer remains the same on increasing the applied gate voltage.[26,27] Thus the penetration of the wave function into the AlSb barrier may hardly change upon applying a gate voltage, and hence the expectation value of the electric field at the 2DEG will not change. We were not able to measure for lower gate voltages, because then the magnetic field at the beat node position shifts to the left of the onset of the Shubnikov–de Haas oscillations. With higher-mobility samples, measurements at lower magnetic fields are possible.[11] It would be interesting to find out whether the spin-orbit interaction parameter does depend on gate voltage in the range of lower electron densities. Recently, we have learned that Engels *et al.*[2] and Nitta *et al.*[1] succeeded in controlling the spin-orbit interaction parameter. Engels *et al.* argued that for positive gate voltage the electric-field profile in the heterostructure is less asymmetric, which leads to a decrease in the spin-orbit interaction strength.

Relating our results to the device proposed by Datta and Das, where the conductance modulation depends on α, and not on the energy splitting Δ between the spin-split subbands, it is questionable whether it can be realized using the heterostructure investigated here. Attempts should be made with heterostructures having a higher mobility. In conclusion, we have demonstrated that the spin-orbit interaction parameter is only weakly dependent on the electron density that was varied between 1.1×10^{16} and 2×10^{16} m^{-2} by using a gate.

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