Weak Localization and Spin Splitting in Inversion Layers on p-type InAs

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We report on the magnetoconductivity of quasi two-dimensional electron systems in inversion layers on p-type InAs single crystals. In low magnetic fields pronounced features of weak localization and antilocalization are observed. They are almost perfectly described by the theory of Iordanskii, Lyanda-Geller and Pikus. This allows us to determine the spin splitting and the Rashba parameter of the ground electric subband as a function of the electron density.

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The multitude of new applications promised by use of the electron’s spin as a degree of freedom in addition to its charge has led to growing interest in the area of spintronics. For semiconductor based spintronics, the required control of the electron spin is expected to be achieved via spin-orbit interaction. In single crystals this interaction originates from two terms: the bulk inversion asymmetry of the crystal lattice and the structure inversion asymmetry. The latter term includes contributions from the electric field and from the boundary conditions and is commonly called Rashba term. For many heterostructures good agreement between calculated Rashba parameters and experimentally deduced values is reached. In the case of two-dimensional electron systems (2DES) in surface inversion layers the spin-orbit interaction and the Rashba parameter are still under debate.

Theoretical considerations have shown that the Rashba term is the main cause of the spin splitting of electric subbands in InAs structures. This is supported by the experiments of Luo et al. on InAs quantum wells. It has been demonstrated for various heterostructures as well as for inversion layers on p-type InAs single crystals that the Rashba term can be influenced by an external gate voltage. This was concluded from beating patterns in Shubnikov-de Haas (SdH) oscillations at various gate voltages. However, contrary to SdH experiments, all proposed spintronic devices operate at zero or low magnetic fields. Calculations by Lommer et al. showed that not only the magnitude but even the sign of the spin splitting can change between low and high magnetic fields for AlGaAs/GaAs heterostructures. For spintronic applications it is thus necessary to determine the spin splitting at near-zero magnetic fields.

Dresselhaus et al. showed that the destruction of weak antilocalization by small magnetic fields can be used to determine the strength of the spin-orbit interaction in GaAs. These authors analyzed their data with the theory of Hikami, Larkin, and Nagaoka. Kawaguchi et al. found that this theory could not correctly reproduce the weak antilocalization observed in inversion layers on p-type InAs. Koga et al. showed that a quantitative description of weak antilocalization in InAlAs/InGaAs/In-

AlAs heterostructures is possible with the model developed by Iordanskii, Lyanda-Geller, and Pikus (ILP). Analyses of weak antilocalization using ILP theory have been performed on AlGaAs/AlInAs quantum wells and AlGaAs/GaAs p-type quantum wells and AlInAs/GaInAs quantum wells. However, this approach so far has not been used to analyze the magnetoconductance of 2DES on bulk narrow-gap semiconductors.

We have performed measurements on Zn doped p-type InAs (100) single crystals with an acceptor concentration of approximately \( N_A = 2 \cdot 10^{17} \text{ cm}^{-3} \). Band bending leads to a 2DES confined in the approximately triangular asymmetric potential well characteristic of a natural surface inversion layer. The narrow band gap of InAs results in strong spin-orbit interaction, with the Rashba term that originates from the asymmetry of the potential well dominating the spin splitting of the electric subbands. Our samples are field-effect transistors in Corbino geometry. The electrodes are defined by optical lithography and deposited by thermal evaporation. They consist of 35 nm thick Aluminium passivated by 10 nm of Gold. The entire structure is covered by a 340 nm thick SiO\(_2\) insulator onto which a gate covering the

FIG. 1: (a) Experimental magnetoconductance for a gate voltage of \( V_g = 15 \text{ V} \) at \( T = 2.65 \text{ K} \) (solid line) as well as a calculated Drude parabola (dashed line). (b) Schematic of the sample geometry. The radius of the inner electrode is 300 \( \mu \text{m} \), the channel length 100 \( \mu \text{m} \), and the radius of the outer electrode 700 \( \mu \text{m} \). (c) Electron mobility versus gate voltage.
considering the structure inversion asymmetry as dominant origin of the zero-field spin splitting in our system and thus neglecting the bulk inversion asymmetry ($\Omega_3 = 0$ in Refs. 17 and 18), only the characteristic magnetic fields of inelastic and of spin-orbit scattering

$$H_\phi = \frac{h}{4De\tau_\phi} \quad \text{and} \quad H_{SO} = \frac{\Delta_0^3\tau_t}{8\hbar D e} = \frac{1}{8\hbar^3 e^2} \cdot \frac{(m^*\Delta_0)^2}{n_s}$$

are relevant in the fitting procedure. In these relations $D$ is the diffusion coefficient, $\tau_\phi$ and $\tau_t$ are the inelastic and transport relaxation times, respectively, and $\Delta_0$ is the spin-splitting energy in zero magnetic field. The characteristic field $H_t$ of transport scattering can be ignored in the fit as it only results in a shift in $\Delta G(B)$.

The diffusion coefficient is given by $D = \frac{n_s v_F^2}{2}$ with the Fermi velocity $v_F = \frac{\hbar k_F}{m^*}$, the Fermi wave vector $k_F$, and the electron effective mass $m^*$.

We calculate the zero-field spin splitting $\Delta_0$ from Eq. (1) and the Rashba parameter from the relation

$$\alpha = \sqrt{\frac{\hbar eH_{SO}}{m^*}}$$

Note that only the absolute value of the Rashba parameter can be determined, not its sign. In case of inversion layers we do not expect a change of sign as their asymmetric surface potentials do not change their overall shape. The analysis is performed for the effective mass $m^*$ of the ground electric subband at the Fermi energy. For high carrier densities $n_s$ this mass is determined from temperature dependent SdH oscillations. At the inversion threshold the band edge mass of the ground subband of $m_0^* = 0.026 \cdot m_e$ is used. Hence, we find

$$m^* = (0.026 + 0.012 \cdot 10^{-12} n_s - 0.001 \cdot 10^{-24} n^2) \cdot m_e,$$

with the electron density $n_s$ in units of cm$^{-2}$.

Figure 3(a) shows the carrier-density dependence of the spin-splitting energy $\Delta_0$. The splitting increases monotonically with the electron density $n_s$ and is in good agreement with band-structure calculations displayed in the same figure. The Rashba spin-orbit parameter $\alpha$ is shown in Figure 3(b). The analysis of weak localization experiments with the ILP theory yields one Rashba parameter for each carrier density. Band-structure calculations yield different Rashba parameters for the two spin subbands because of the slight difference between the Fermi wave vectors for spin-up and spin-down states. However, this difference is small and can be neglected in the comparison with the weak localization data. A decrease of the Rashba parameter with increasing carrier density is observed. Again, the experimental results are in good agreement with the values obtained from the calculations. Figure 3(c) shows the occupations of the spin-split subbands as determined from SdH oscillations. At carrier densities below $2.0 \cdot 10^{12}\ \text{cm}^{-2}$ a good agreement between theory and experiment is observed. The first excited subband is only populated for
carrier densities above about $2.3 \cdot 10^{12} \text{ cm}^{-2}$\textsuperscript{25}. In the theory for a doping concentration of $1.8 \cdot 10^{17} \text{ cm}^{-3}$, population of the first excited subband occurs for carrier densities above $2.0 \cdot 10^{12} \text{ cm}^{-2}$, leading to kinks in the plots. This can be seen most easily in Fig. 3(c) for the spin-up electrons.

Values of the Rashba parameter determined from SdH oscillations in high magnetic field\textsuperscript{7,24} do not agree with the multi-band calculations of Lamari\textsuperscript{6,22} and Winkler\textsuperscript{23} and the results from weak localization reported here. While they are of the same order of magnitude, they increase with increasing carrier density.

Using the effective mass from Eq. 3 and the subband carrier densities of Lamari displayed in Fig. 3(c) the simple relation\textsuperscript{25} $\alpha = \hbar^2 \left( \sqrt{4 \pi n_\uparrow} - \sqrt{4 \pi n_\downarrow} \right) / m^* \alpha$ yields Rashba parameters that agree well with those in Fig. 3(b). Hence the effective mass cannot be responsible for the discrepancy between the results in low and high magnetic fields. We currently do not understand why the splitting of the spin-subband densities from SdH oscillations as well as the increase thereof with growing carrier density are larger than theoretically predicted.

The situation in heterostructures of low carrier density is different, as a good agreement between theory and high-field experiments is found\textsuperscript{12}. This indicates that the simple evaluation of beating patterns in SdH oscillations is not sufficient for the high carrier densities in 2DES inversion layers on p-type InAs crystals. In the carrier-density range well above $10^{12} \text{ cm}^{-2}$ the spin-split energies no longer exhibit linear dispersion. Then band nonparabolicity and higher order terms in the expansion of the Rashba parameter become decisive. Hence it is important to consider the Rashba parameter as a function of both the electric field as well as of the in-plane wave vector\textsuperscript{9,26}. The wave vector dependence exceeds the electric field contribution at high electron densities and leads to a decrease of the Rashba parameter. Obviously, for inversion layers on p-type InAs the evaluation of the weak localization measurements provides more reliable values for the Rashba parameter than that of SdH oscillations.

To conclude, we have studied spin-orbit interaction in the surface inversion layer on p-type InAs single crystals using weak localization at near zero magnetic field. Excellent description of the experimental data could be achieved through the theory of Iordanskii, Lyanda-Geller and Pikus\textsuperscript{17,18}. We find the carrier-density dependence of the spin-splitting energy $\Delta_0$ and the Rashba parameter $\alpha$ of the ground electric subband to be in very good agreement with multi-band calculations, but to differ from previous analyses in which SdH beating patterns were evaluated.

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