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Strong spin–orbit interactions in carbon doped p-type GaAs heterostructures

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Abstract

We have performed magnetoresistance measurements on a two-dimensional hole gas formed 45 nm below the surface of a C-doped GaAs/AlGaAs heterostructure grown in the (1 0 0) direction. Analysis of the beating of Shubnikov–de Haas oscillations and observation of weak anti-localization demonstrate the presence of strong spin–orbit interactions in this system, which is an essential ingredient for realizing spin-based devices. In addition, we measure a phase coherence length for holes of around 4 μm at a temperature of 70 mK, which is promising for studying phase coherent transport in p-type GaAs heterostructures.

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Two-dimensional (2D) systems with strong spin–orbit (SO) interactions are promising for the realization of spintronics devices, due to the fact that in such systems the electron (hole) spin can be affected, not only by magnetic, but also by electric fields. SO interactions are expected to be very strong in p-type GaAs heterostructures, due to the p-like symmetry of the states at the top of the valence band and the high effective mass of the holes. In addition, the p-like symmetry of hole states ensures that they are weakly coupled to nuclear spins, which could provide long spin coherence times.

Carbon doped p-type GaAs/AlGaAs heterostructures grown in the (1 0 0) direction are particularly interesting due to the high mobility and strong SO interactions measured in these systems [1]. We report on magnetoresistance measurements on a two-dimensional hole gas (2DHG) created 45 nm below the surface of a C-doped GaAs/AlGaAs heterostructure. We observe the following three signatures of strong SO interactions: a beating in the Shubnikov–de Haas oscillations, a classical Lorentzian positive magnetoresistance due to the presence of the two spin-split subbands and a weak anti-localization dip in the magnetoresistance.

The Hall-bar is fabricated from a 2DHG located 45 nm below the surface [2]. The Hall-bar is $W = 100\,\mu m$ wide, and the separation between the contacts used for the measurements of the longitudinal resistance is either $L = 500\,\mu m$. The resistivity ρ_{xx} is obtained after scaling the measured resistance by a geometrical factor W/L.

Hall effect measurements performed at 4.2 K give a hole density of $3.8 \times 10^{11}\,cm^{-2}$ and a mobility of $120{,}000\,cm^2/V\,s$. The measurements shown here were performed in a $^3He/^4He$ dilution refrigerator with a base temperature of 70 mK, at which the mobility is $200{,}000\,cm^2/V\,s$.

Fig. 1 shows the longitudinal resistivity ρ_{xx} as a function of the magnetic field. A beating of the oscillations is observed in this curve. Such a beating is characteristic of a two-dimensional system with two subbands participating in transport. In p-doped GaAs heterostructures with a hole density of the order of $10^{11}\,cm^{-2}$, only the heavy hole subband with a projection of the total angular momentum $J_z = \pm\frac{3}{2}$ is populated. Due to the strong spin–orbit

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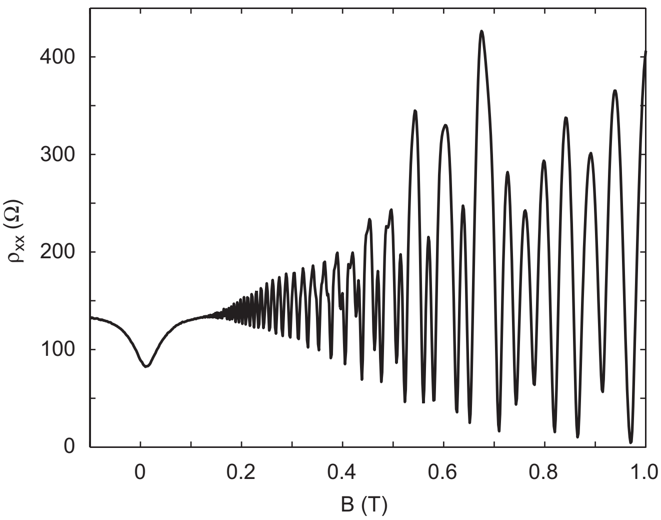

Fig. 1. Longitudinal resistivity ρ_{xx} as a function of the magnetic field B measured at $T = 70\,\mathrm{mK}$.

interactions, this band is split at finite k vector into two spin-split subbands with opposite J_z [3].

In order to determine the respective densities of both subbands, we have performed a Fourier analysis of ρ_{xx} vs. $1/B$ in the magnetic field range from 0.35 to 1 T. In the Fourier transform shown in Fig. 2 we identify three peaks. The two lower peaks at $N_1 = 1.35 \times 10^{11}\,\mathrm{cm}^{-2}$ and $N_2 = 2.45 \times 10^{11}\,\mathrm{cm}^{-2}$ correspond to the densities of the two spin-split subbands, while the peak at $N = 3.8 \times 10^{11}\,\mathrm{cm}^{-2} = N_1 + N_2$ correspond to the total density.

From the densities of the two spin-split subbands determined in Fig. 2, we can deduce the relative charge imbalance $\Delta N/N = 0.29$. In (100) p-type heterostructures, the SO splitting of the heavy hole band is cubic in k vector, $\Delta_{\mathrm{SO}} = \beta k^3$. The SO coupling parameter is estimated to be $\beta = 2 \times 10^{-28}\,\mathrm{eVm}^3$, which gives the SO induced splitting of the heavy hole subband at the Fermi level to be $\Delta_{\mathrm{SO}} \approx 0.85\,\mathrm{meV}$. Due to the large effective mass of the holes the Fermi energy in the system is small, $E_{\mathrm{F}} = 2.5\,\mathrm{meV}$, and therefore the strength of the SO interactions relative to the kinetic energy is large, $\Delta_{\mathrm{SO}}/E_{\mathrm{F}} \approx 33\%$.

A second evidence of spin-split subbands in this system is given by the low field magnetoresistance shown in Fig. 3. The positive, parabolic magnetoresistance is characteristic of the classical Drude magnetoresistance in a system with two subbands of different mobilities [4,1].

In addition to the parabolic classical magnetoresistance, a narrow magnetoresistance dip is observed at zero magnetic field in Fig. 3. This is in contrast to electron systems in GaAs where a peak corresponding to weak localization is observed, due to constructive interference between time-reversed back-scattered paths. The observed magnetoresistance dip is characteristic of weak anti-localization, which arises from destructive interference between time reversed back-scattered paths, when the SO interaction is strong enough to rotate the spin along the trajectories [5].

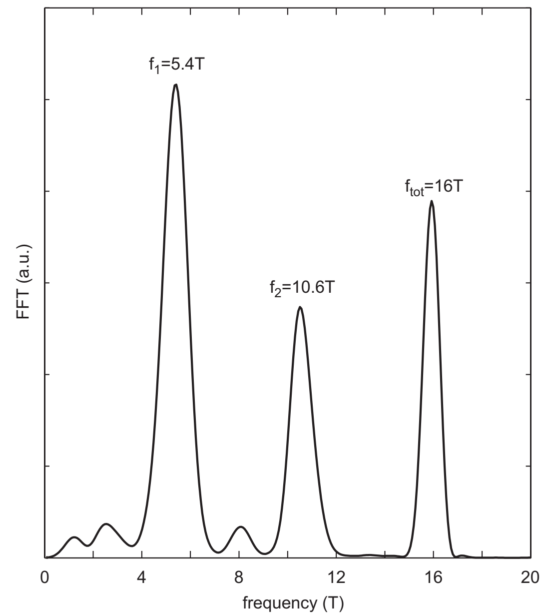

Fig. 2. Fast Fourier transform (FFT) of the magnetoresistance R_{xx} vs. $1/B$ taken in the B-field range from 0.35 to 1 T. The Fourier transforms display three peaks, corresponding to the densities of the two spin-split subbands and the total density.

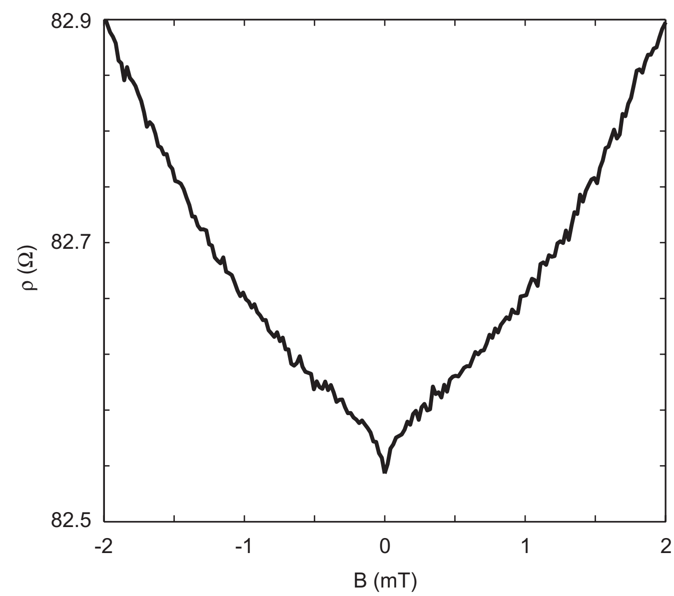

Fig. 3. Blow-up of the magnetic field dependence of the longitudinal resistivity close to $B = 0\,\mathrm{T}$.

In order to evaluate the coherence and SO scattering times in our system, we have compared the experimental results for the weak anti-localization dip with the analytical formula given by the Hikami–Larkin–Nagaoka (HLN) theory [6]. In order to proceed with fitting of the data with HLN theory, we need to calculate the conductivity correction

$$\Delta\sigma(B) = (\sigma(B) - \sigma(0)) - (\sigma_{\mathrm{class}}(B) - \sigma_{\mathrm{class}}(0)), \tag{1}$$

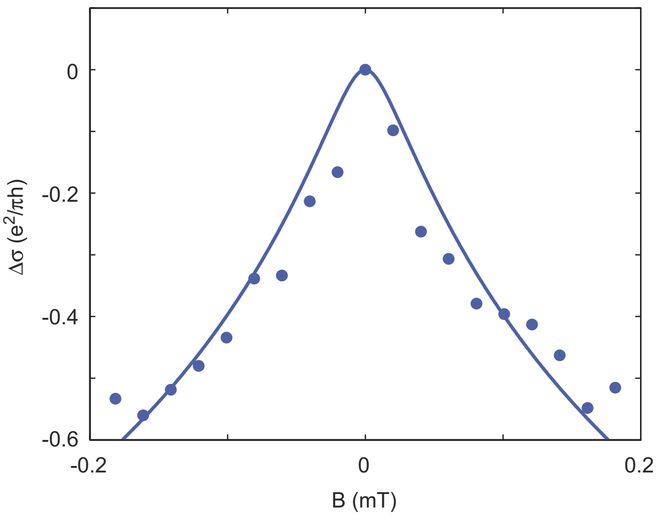

Fig. 4. Fit of the conductivity corrections $\Delta\sigma$ with the HLN theory. The dots are the experimental data, while the solid line is the fit.

where σ is the longitudinal conductivity, obtained from the inversion of the measured resistivity tensor, and σ_{class} is the classical longitudinal conductivity, obtained from the fitted $\rho(B)$ with a parabolic magnetic field dependence. The obtained conductivity correction $\Delta\sigma(B)$ is plotted in Fig. 4, where the dots represent the measured data and the full lines is the fit with the HLN theory. The HLN theory is valid in the diffusive regime, where $B < B_{tr} = \hbar/(2el_{tr}^2)$, where l_{tr} is the elastic mean free path. In our case this condition corresponds to $B_{tr} < 0.1$ mT, due to the high mobility of the 2DHG.

From the fit of the weak-antilocalization dip we have extracted the phase coherence time of holes to be $\tau_\phi = 340$ ps at the base temperature of 70 mK. This corresponds to a phase coherence length of around 4 μm, which is very promising for the fabrication of phase-coherent p-type GaAs nanostructures.

The fact that we observe only a weak anti-localization dip in the magnetoresistance and no weak localization peak clearly indicates that we are in the limit of very strong SO interactions, where the SO scattering time τ_{SO} is very small, $\tau_{SO} < \tau_{tr} < \tau_\phi$ (τ_{tr} and τ_ϕ are the elastic and inelastic scattering times, respectively) [7,8]. From the value of $\Delta_{SO} = 0.85$ meV determined from the beating of Shubnikov–de Haas oscillations, and the elastic scattering time $\tau_{tr} = 41$ ps, we can determine the spin–orbit scattering time $\tau_{SO} = 4\hbar^2/(\Delta_{SO}^2\tau_{tr}) \approx 0.1$ ps [9]. This small value confirms the presence of strong SO interactions.

In conclusion, magnetoresistance measurements on a shallow two-dimensional hole gas created in a C-doped GaAs/AlGaAs heterostructure show that strong spin orbit interaction is present in this system. Therefore this shallow 2DHG offers the possibility to fabricate new types of spin-based quantum devices with the technique of local oxidation using an atomic force microscope [2,10–12].

References

[1] B. Grbić, C. Ellenberger, T. Ihn, K. Ensslin, D. Reuter, A.D. Wieck, Appl. Phys. Lett. 85 (2004) 2277.
[2] B. Grbić, R. Leturcq, K. Ensslin, D. Reuter, A.D. Wieck, Appl. Phys. Lett. 87 (2005) 232108.
[3] R. Winkler, Spin–Orbit Coupling Effects in Two-Dimensional Electron and Hole Systems, in: Springer Tracts in Modern Physics, vol. 191, Springer, Heidelberg, 2003.
[4] H. van Houten, J.G. Williamson, M.E.I. Broekaart, C.T. Foxon, J.J. Harris, Phys. Rev. B 37 (1988) 2756.
[5] G. Bergmann, Solid State Commun. 42 (1982) 815.
[6] S. Hikami, A.I. Larkin, Y. Nagaoka, Prog. Theor. Phys. 63 (1980) 707.
[7] Y. Lyanda-Geller, Phys. Rev. Lett. 80 (1998) 4273.
[8] G. Bergmann, Phys. Rev. Lett. 48 (1982) 1046.
[9] M.I. Dyakonov, V.I. Perel, Sov. Phys. J. Exp. Theoret. Phys. 33 (1971) 1053.
[10] L.P. Rokhinson, V. Larkina, Y.B. Lyanda-Geller, L.N. Pfeiffer, K.W. West, Phys. Rev. Lett. 93 (2004) 146601.
[11] B. Habib, E. Tutuc, M. Shayegan, Appl. Phys. Lett. 90 (2007) 152104.
[12] B. Grbić, R. Leturcq, T. Ihn, K. Ensslin, D. Reuter, A.D. Wieck, Phys. Rev. Lett. 99 (2007) 176803.