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Spin effects in the magnetodrag between double quantum wells

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We report on the selectivity to spin in a drag measurement. This selectivity to spin causes deep minima in the magnetodrag at odd filling factors for matched electron densities at magnetic fields and temperatures at which the bare spin energy is only one tenth of the temperature. For mismatched densities the selectivity causes a $1/B$ periodic oscillation, such that *negative* minima in the drag are observed whenever the majority spins at the Fermi energies of the two-dimensional electron gases are *antiparallel*, and *positive* maxima whenever the majority spins at the Fermi energies are *parallel*.

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The physics of two-dimensional electron gases (2DEG's) has spawned numerous discoveries over the last two decades with the integer and fractional quantum Hall effects being the most prominent examples. More recently, interaction phenomena between closely spaced 2DEG's in quantizing magnetic fields have found strong interest both experimentally[1–3] and theoretically,[4,5] because of the peculiar role the electron spin plays in these systems. Particularly interesting is a measurement of the frictional drag between two 2DEG's, as it probes the density-response functions in the limit of low-frequency and finite wave vector (see Ref. 6, and references therein), a quantity which is not easily accessible otherwise.

Experimental data of drag at zero magnetic field are reasonably well understood. Several puzzling issues however exist for the magnetodrag. First, at matched densities in the 2DEG's, the magnetodrag displays a double peak around the odd filling factor[7,8] when spin splitting is not visible at all in the longitudinal resistances of each individual 2DEG. These double peaks were ascribed to either an enhanced screening when the Fermi energy (E_F) is in the center of a Landau level,[9,7] or to an enhanced spin splitting.[8] Second, at mismatched densities negative magnetodrag has been observed,[10] i.e., an accelleration of the electrons opposite to the direction of the net transferred momentum. This negative drag was speculatively ascribed to a holelike dispersion in the less-than-half-filled Landau levels brought about by disorder.[10]

In this paper we present data taken in a hitherto unexplored temperature-magnetic-field regime which clearly demonstrate the decisive role the electron spin plays in the drag. We find that *both* the above issues have a common origin; they are caused by the fact that the drag is selective to the spin of the electrons, such that electrons with antiparallel spin in each 2DEG have a negative and those with parallel spin have a positive contribution to the drag. At mismatched densities this selectivity causes a novel $1/B$ periodic oscillation in the magnetodrag around zero with frequency $h\Delta n/2e$, with Δn being the density difference between the 2DEG's. Our finding that the drag is selective to the spin of the electrons is surprising since established coupling mechanisms via Coulomb or phonon interactions are *a priori* not sensitive to spin, as spin-orbit interaction is extremely weak for electrons in GaAs.

In a drag experiment a current is driven through one of two electrically isolated layers, the so-called drive layer. Interlayer carrier-carrier scattering through phonons, plasmons or the direct Coulomb interaction transfers part of the momentum of the carriers in the drive layer to those in the drag layer, causing a charge accumulation in the drag layer in the direction of the drift velocity of carriers in the drive layer. The drag (ρ_T) is defined as minus the ratio of the electric field originating from this charge accumulation, to the drive current density. The ρ_T of layers with the same types of carriers is thus expected to be positive, while that of layers with different types of carriers should be negative.

We have studied transport in several double quantum wells fabricated from three wafers that differ in the thickness of their barrier only. The 20 nm wide quantum wells are separated by $Al_{0.3}Ga_{0.7}As$ barriers with widths of 30, 60 or 120 nm. The densities per quantum well are typically $2\times10^{11}\ \mathrm{cm}^{-2}$ and all mobilities exceed $2\times10^{6}\ \mathrm{cm}^2\ \mathrm{V}^{-1}\ \mathrm{s}^{-1}$. The presented results are obtained on 30 nm barrier samples, and qualitatively identical results are obtained on samples fabricated from the other wafers. Measurements were carried out on Hall bars with a width of 80 μm and a length of 880 μm. Separate contacts to each quantum well are achieved through the selective depletion technique[11] using *ex situ* prepared *n* doped buried backgates[12] and metallic front gates. Measurements were performed in a ^{3}He system with the sample mounted at the end of a cold finger. Standard drag tests (changing ground in the drag layer, interchanging drag and drive layer, current linearity, and changing the direction of the applied magnetic field[13]) confirmed that the signal measured is a pure drag signal.

Figure 1 plots ρ_T and ρ_{xx} measured at temperatures of 0.26 and 1.0 K. With increasing magnetic field ρ_{xx} shows the usual Shubnikov–de Haas oscillations which, at 0.26 K, start at a magnetic field of 0.07 T. Spin splitting becomes visible at a magnetic field of 0.51 T, and it is completely developed at 1.2 T. By contrast, at 0.26 K the oscillations in ρ_T show a double peak in magnetic fields as low as 0.11 T (ν=77, see

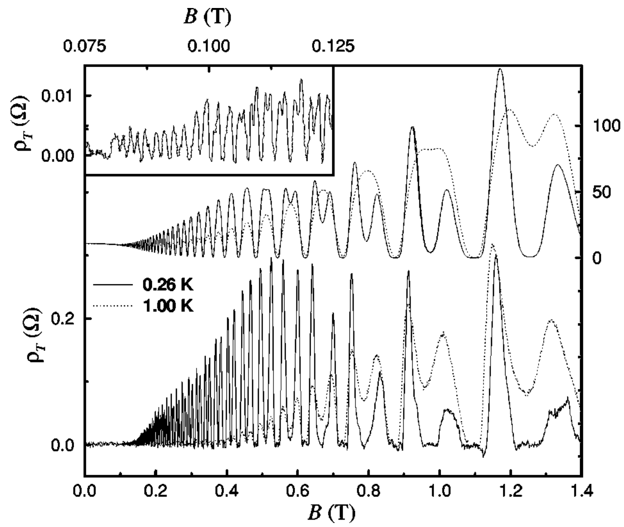

FIG. 1. ρ_T (bottom) and ρ_{xx} (top) at 0.26 and 1.0 K and at matched densities ($n_1=n_2=2.13\times10^{11}$ cm^{-2}), showing the absence of a double peak in ρ_T for completely spin-split peaks in ρ_{xx}. The inset is a blowup of ρ_T at 0.26 K, showing a double peak in fields above 0.11 T.

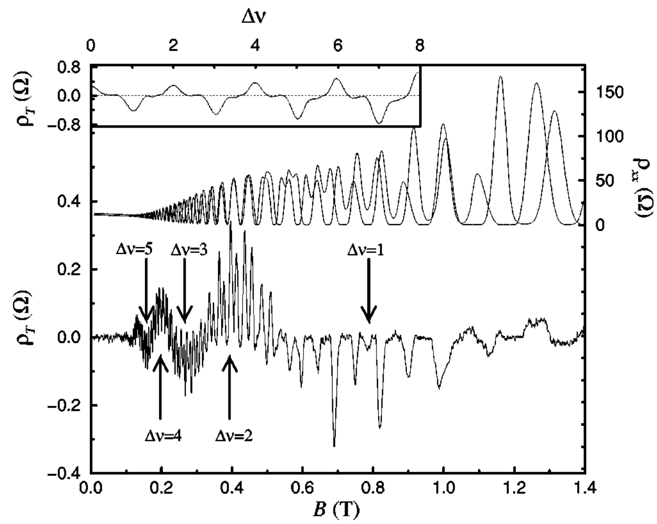

FIG. 2. ρ_T (bottom) and ρ_{xx} (top) for both 2DEG's at mismatched densities ($n_1=2.27$ and $n_2=2.08\times10^{11}$ cm^{-2}) as a function of magnetic field at $T=0.25$ (K). Two sets of oscillations can be distinguished in ρ_T: (i) a quick one resulting from the overlap of the Landau level in the 2DEG's and (ii) a slow one which causes (*positive*) maxima in ρ_T whenever the filling-factor difference between the 2DEG's is *even*, and (*negative*) minima whenever this difference is *odd*. The inset shows ρ_T at fixed magnetic field of 0.641 (T) (maximum in ρ_T in Fig. 1) versus filling-factor difference.

inset). The appearance of a double peak in ρ_T at fields and temperatures where ρ_{xx} shows no spin splitting yet has been predicted theoretically.[9] The theory states that ρ_T consists essentially of the product in the density of states (DOS) at E_F in each layer, multiplied with the strength of the interlayer interaction. This strength supposedly strongly decreases at the center of a Landau level where, due to the large DOS at E_F, screening is very effective. The decrease would then more than compensate for the increase in the product of the DOS of the 2DEG's, thus resulting in a double peak in ρ_T. The theory was consistent with experiments described in a subsequent paper.[7] However, the most critical test for the theory, namely the occurrence of a double peak in ρ_T measured at a fully spin-split Landau level (that does not show fractional features), could not be performed due to the moderate mobility of the sample and the accessible temperature range. Our experiment does allow such a test and Fig. 1 shows that ρ_T does *not* show this predicted double peak for spin-split Landau levels. We further note that at 1 T the longitudinal conductivity in our sample is 50% *higher* than in the experiment[7] and the theory[9] and screening should thus be even more effective in our samples. The theory is thus not applicable to explain our experimental results and one is forced to reconsider the possible role of spin. We note furthermore that at 0.11 T and 0.26 K the bare spin energy ($g\mu_B$B) is only one tenth of the thermal energy so there is a significant thermal excitation between the Landau levels with different spin. This rules out enhanced spin splitting[8,14,15] as the cause for the double peak in ρ_T. In the following we will nonetheless show that it is spin that is causing the double peak, through a mechanism where electrons with parallel spin in each layer have a positive, and those with antiparallel spin have a negative contribution to ρ_T. The minima at a large odd filling factors then occur, because the positive and negative contributions cancel.

In order to prove the above scenario we have measured magnetodrag at mismatched densities. Then successive Landau levels in the 2DEG's pass through their E_F at different magnetic fields. At certain magnetic fields (depending on density and density difference of the 2DEG's) the situation will be such that Landau levels with antiparallel spins will be at E_F in the 2DEG's, while at somewhat different magnetic fields Landau levels with parallel spin will be at E_F. Alternatively we have fixed the magnetic field and used one of the gates in the sample to change the density in one 2DEG, bringing about the same effect. The first measurement is plotted in the lower part of Fig. 2 together with ρ_{xx} of both 2DEG's (top). As is apparent, for mismatched densities ρ_T is no longer always positive. Instead ρ_T consists of the sum of two $1/B$-periodic oscillations: A quick one with the frequency $h(n_1+n_2)/2e$, which results from the overlap of the (in ρ_T for $B>0.17$ T doubly peaked) Landau levels of the 2DEG's, plus a slower one with the frequency $h(n_1-n_2)/2e$, which causes ρ_T to oscillate around zero. The arrows in Fig. 2 indicate the magnetic fields at which the filling-factor difference between the 2DEG's ($\Delta\nu=\nu_1$-ν_2) equals an integer. $\Delta\nu$ is calculated from the densities of the 2DEG's that are obtained from the positions of the minima in the Shubnikov–de Haas oscillations in ρ_{xx}. It is clear that when $\Delta\nu$ is *odd* ρ_T is most *negative*, while when $\Delta\nu$ is *even* ρ_T is most *positive*. The inset of Fig. 2 confirms this even/odd behavior. It plots ρ_T at 0.641 T ($\nu_1=13.5$, maximum ρ_T in Fig. 1) versus $\Delta\nu$ which is changed continuously by decreasing the density of one 2DEG with a gate. In such a measurement the DOS in the other 2DEG is kept constant, thus removing the quick oscillation. However, the periodic slow oscillation with alternating sign still remains and its amplitude increases upon decreasing the density in the second 2DEG.

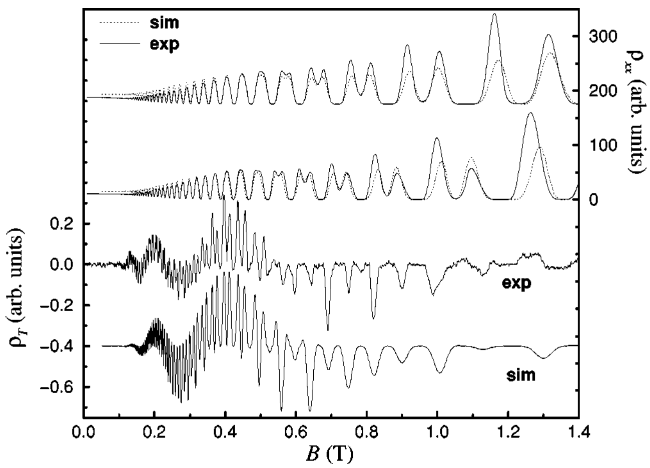

FIG. 3. Comparison of simulation and experiment of ρ_{xx} and ρ_T (details can be found in the text). Top traces show ρ_{xx}, upper curves are offset vertically (solid line is the experiment, dotted line is the simulation). Lower traces show the drag, the simulation is offset vertically.

The observation of *negative* ρ_T at *odd* $\Delta\nu$ and *positive* ρ_T at *even* $\Delta\nu$ hints at the involvement of spin. If spin splitting were fully developed, odd $\Delta\nu$ corresponds to electrons with anti-parallel spin at the E_F's in the 2DEG's. In our experiment, however, negative ρ_T is observed in the regime of incomplete spin splitting. One may then expect a maximum positive ρ_T at $\Delta\nu$=even and a maximum negative ρ_T at $\Delta\nu$ =even$+\Delta\nu_{spin}$, with $\Delta\nu_{spin}$ being the filling-factor difference between spin↑ and spin↓ peaks in ρ_{xx} (which equals 1 only if spin splitting is complete). A simulation of ρ_T (see below), assuming positive coupling between electrons with parallel spins and negative coupling between electrons with antiparallel spins, shows however that ρ_T is most positive for $\Delta\nu$=even and most negative for $\Delta\nu$=odd, irrespective of the magnitude of the spin splitting. This magnitude only influences the amplitude of the oscillations in ρ_T, but does *not* alter its phase or periodicity.

Lacking a theory to compare our results with, we present an empirical model, assuming $\rho_{xx}\propto(\mathrm{DOS}^{\uparrow}+\mathrm{DOS}^{\downarrow})^2$ and $\rho_T\propto \mathrm{B}^{\alpha}(\mathrm{DOS}^{\uparrow}\text{-}\mathrm{DOS}^{\downarrow})_{\mathrm{layer1}}\times(\mathrm{DOS}^{\uparrow}\text{-}\mathrm{DOS}^{\downarrow})_{\mathrm{layer2}}$, with $\mathrm{DOS}^{\uparrow,\downarrow}$ being the density of states at E_F for spin↑ and spin↓, and B is the magnetic field. To account for the unknown change in the coupling between the layers with magnetic field, a factor of B^{α} ($\alpha\approx-3.5$) is used to scale the amplitude of $\rho_T(B)$ to approximately the experimental value. The DOS at E_F is given by the sum of a set of Gaussians with an intrinsic width (due to disorder and temperature) plus a width that increases with $\sqrt{B}$. The intrinsic width (1.5 K) is extracted from the experiment through a Dingle analysis of the oscillatory part of the low field Shubnikov–de Haas oscillations. The coefficient in front of the $\sqrt{B}$ (2.7 K for the lower density 2DEG and 2.3 K for the other) is determined by fitting the simulated ρ_{xx} to the measured one. In the simulation the densities are kept constant (i.e., E_F oscillates) and for the results shown in Fig. 3 we assume an exchange-enhanced spin gap: $\Delta_{\mathrm{spin}}=g\mu_B B+|(n^{\uparrow}-n^{\downarrow})/(n^{\uparrow}+n^{\downarrow})|\times 2E_c$, with E_c being the Coulomb energy $e^2/4\pi\epsilon l_B$, g is the bare g factor in GaAs (-0.44), μ_B is the Bohr magneton, ϵ is the dielectric constant, l_B is the magnetic length, and $n^{\uparrow,\downarrow}$ is the number of particles with spin↑ and spin↓. There is some discussion in the literature whether in low fields the relevant length scale for E_c is l_B or (the much smaller) k_F^{-1} (see Ref. 14 and references therein). In our simulation $0.5l_B$ is appropriate, i.e., the factor of $2E_c$ is used as it reproduces the experimental ρ_{xx} traces. With a fixed enhanced g factor (or even the bare g factor), however, qualitatively similar results for ρ_T are obtained.

Figure 3 shows the results of the simulation. For both ρ_{xx} and ρ_T, the overall agreement between simulation and experiment is satisfactory. For matched densities (not shown) using the same parameters the agreement is equally good. In fields above 0.8 T the asymmetry in the height of the experimental spin-split ρ_{xx} peaks is not reproduced, but this could be due to a different coupling strength of spin↑ and spin↓ edge channels to the bulk,[16] which is not included in the simulation. The asymmetry in the ρ_T peaks at matched densities (Fig. 1, $B>0.65$ T) may have a similar origin. The simulation also fails to reproduce some of the finer details in the amplitude of the quick oscillation in ρ_T, but we find that this amplitude is quite sensitive to overlap between Landau levels in different layers which in turn depends on details in their width and separation.

The two sets of oscillations in ρ_T are observed in all samples from all three wafers at mismatched densities. The slow oscillation can be recognized as such for $T<\sim 1$ K although a few negative spikes remain visible till 1.4–1.9 K (depending on density difference). The inverse period of the slow oscillation is accurately given by $h/2e\times\Delta n$ in the density range studied ($\Delta n\in[0,1.2]\times 10^{11}$ cm^{-2}, $n_1=2.0\times 10^{11}$ cm^{-2}) confirming that the appearance of negative ρ_T for odd $\Delta\nu$ and positive ρ_T for even $\Delta\nu$ is not restricted to one particular density difference.

The appearance of *negative* ρ_T when Landau levels with antiparallel majority spin are at E_F in the 2DEG's is a puzzling result, as it implies that electrons in the drag layer gain momentum in the direction *opposite* to that of the net momentum lost by electrons in the drive layer. In the single-particle picture, this can only occur if the dispersion relation for electrons has a holelike character [i.e., $\partial^2E/\partial k_y^2<0$ (Ref. 10)], but we know of no mechanism through which spins can cause that. The explanation for negative ρ_T must then be sought for beyond the single-particle picture, possibly in terms of spin waves or coupled states between the layers. We note that our empirical formula describing ρ_T consists of the three possible triplet spin wave functions and one could speculate about an interaction between electrons with opposite momentum in the different layers. Considering the observation of the effect in the 120 nm barrier samples, the coupling mechanism is most likely not the direct Coulomb interaction. In any case, our results at least convincingly demonstrate the importance of the electron spin.

Our empirical model seems to accurately describe ρ_T. There is, however, a limitation to its applicability: in fields above 1.2 T the negative ρ_T vanishes in the 30 nm barrier samples. For the density mismatch in Fig. 2 this is easily explained, as in fields above ~1.2 T there is no more chance of finding an overlap between Landau levels with different spin. However, for larger density differences, such that there is the necessary overlap of Landau levels with different spin, we only find positive ρ_T for all temperatures studied (0.25 K$<T<$10 K). We note that at our lowest temperature (0.25 K) the field of 1.2 T corresponds to a complete spin splitting in ρ_{xx}. Samples from the other wafers have similar spin splittings and the negative ρ_T vanishes at comparable fields. It is further worth noting that the upper bound for the magnetic field below which negative ρ_T is observed, does not depend on density or density difference of the 2DEG's (provided an overlap exists between Landau levels with different spin for $B>1.2$ T) and thus not on the filling factor.

Finally, we comment on the interpretation of negative magnetodrag in Ref. 10. Due to the higher lowest temperature (1.15 K), no spin splitting in ρ_{xx} and no slow oscillations in ρ_T were observed. Nevertheless, the remains of half of a slow period which was filled up with the quick oscillation, were visible. It thus seemed that negative ρ_T appeared *only* when in one 2DEG the Landau level at E_F was more than half filled, while in the other the Landau level at E_F was less than half filled. It was argued that disorder induces a holelike dispersion in the less-than-half-filled Landau level, leading to negative ρ_T. Our lower temperatures allow probing the regime where ρ_{xx} shows spin splitting. The less-than-half-filled, more-than-half-filled Landau-level explanation should hold for spin-split Landau levels as well, thus doubling the frequency of the quick oscillation in ρ_T. Our experiment shows no doubling, disproving such a scenario. Moreover, as Fig. 2 shows, negative ρ_T can be observed as well when the (in ρ_{xx} partly or almost completely spin split) Landau levels are both less than half filled (0.62 T, 0.73 T) or both more than half filled (1.0 T). Our data are thus inconsistent with the interpretation given in Ref. 10, while our empirical model does explain the data of Ref. 10.

Summarizing, at matched densities the double peak in the magnetodrag, measured at fields and temperatures where the longitudinal resistance shows no spin splitting at all, is the result of the drag being selective to the spin of the electrons, such that electrons with parallel spin in each layer have a positive contribution to the drag, while those with antiparallel spin have a negative contribution. This selectivity to spin further causes the occurrence of a *negative* drag whenever Landau levels with antiparallel spin are at E_F in the 2DEG's, resulting in a $1/B$-periodic oscillation in the low-field low-temperature drag for mismatched electron densities with the inverse period given by $h\Delta n/2e$. Our empirical model assuming $\rho_T \propto (\mathrm{DOS}^{\uparrow}\text{-}\mathrm{DOS}^{\downarrow})_{layer1} \times (\mathrm{DOS}^{\uparrow}\text{-}\mathrm{DOS}^{\downarrow})_{layer2}$ quite accurately describes the results at matched, as well as mismatched, densities. The origin of the negative coupling between electrons with antiparallel spin, as well as its disappearance when spin splitting in ρ_{xx} is complete, remains to be explained.

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