Spin effects in the magneto-drag 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 magneto-drag at odd fillingfactors 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 novel 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 (2DEGs) are anti-parallel, and positive maxima whenever the majority spins at the Fermi energies are parallel.
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The physics of two-dimensional electron gases (2DEGs) 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 2DEGs 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 2DEGs, as it probes the density-response functions in the limit of low frequency and finite wavevector (see [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 magneto-drag. Firstly, at matched densities in the 2DEGs, the magneto-drag displays a double peak around odd fillingfactor [6] 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 (EF) is in the centre of a Landau level [6,7], or to an enhanced spin-splitting [8]. Secondly, at mismatched densities negative magneto-drag has been observed [1,4], i.e. an accelleration of the electrons opposite to the direction of the net transferred momentum. This negative drag was speculatively ascribed to a hole-like-dispersion in the less-than-half-filled Landau levels brought about by disorder [9].

In this Letter 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 anti-parallel 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 magneto-drag around zero with frequency $h\Delta n/2e$, with $\Delta n$ the density difference between the 2DEGs. 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 $(\rho_T)$ is defined as minus the ratio of the electric field originating from this charge accumulation, to the drive current density. $\rho_T$ 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 $2\cdot10^{11}$ cm$^{-2}$ and all mobilities exceed $2\cdot10^{6}$ cm$^{2}$V$^{-1}$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 $\mu$m and a length of 880 $\mu$m. 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.

Fig. 1 plots $\rho_T$ and $\rho_{xx}$ measured at temperatures of...
0.26 and 1.0 K. With increasing magnetic field $\rho_{xx}$ 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 $\rho_T$ show a double peak in magnetic fields as low as 0.11 T ($\nu=7\pi$, see inset). The appearance of a double peak in $\rho_T$ at fields and temperatures where $\rho_{xx}$ shows no spin-splitting yet has been predicted theoretically\footnote{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 as the cause for the double peak in $\rho_T$. 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 anti-parallel spin have a negative contribution to $\rho_T$. The minima at large odd filling factor then occur, because the positive and negative contributions cancel.}

This strength supposedly strongly decreases at the centre 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 at $E_F$, thus resulting in a double peak in $\rho_T$. The theory was consistent with experiments described in a subsequent paper\footnote{In order to prove the above scenario we have measured magneto-drag at mismatched densities. Then successive Landau levels in the 2DEGs pass through their $E_F$ at different magnetic fields. At certain magnetic fields (depending on density and density difference of the 2DEGs) the situation will be such that Landau levels with anti-parallel spins will be at $E_F$ in the 2DEGs, 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.\ref{fig2} together with $\rho_{xx}$ of both 2DEGs (top). As is apparent, for mismatched densities $\rho_T$ is no longer always positive. Instead $\rho_T$ consists of the sum of two 1/B-periodic oscillations. A quick one with the}. The theory states that $\rho_T$ 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 centre 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 at $E_F$, thus resulting in a double peak in $\rho_T$. The theory was consistent with experiments described in a subsequent paper. However, the most critical test for the theory, namely the occurrence of a double peak in $\rho_T$ measured at a fully spin-split Landau level (that doesn’t 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.\ref{fig1} shows that $\rho_T$ 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\footnote{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 as the cause for the double peak in $\rho_T$. 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 anti-parallel spin have a negative contribution to $\rho_T$. The minima at large odd filling factor then occur, because the positive and negative contributions cancel.} and the theory\footnote{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 as the cause for the double peak in $\rho_T$. 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 anti-parallel spin have a negative contribution to $\rho_T$. The minima at large odd filling factor then occur, because the positive and negative contributions cancel.} 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.

![FIG. 1. $\rho_T$ (bottom) and $\rho_{xx}$ (top) at 0.26 K and 1.0 K and at matched densities ($n_1=n_2=2.13\cdot10^{11}$ cm$^{-2}$), showing the absence of a double peak in $\rho_T$ for completely spin-split peaks in $\rho_{xx}$. Inset is a blow-up of $\rho_T$ at 0.26 K, showing a double peak in fields above 0.11 T.](image1)

![FIG. 2. $\rho_T$ (bottom) and $\rho_{xx}$ (top) for both 2DEGs at mismatched densities ($n_1=2.27$ and $n_2=2.08\cdot10^{11}$ cm$^{-2}$) as a function of magnetic field at $T=0.25$ (K). Two sets of oscillations can be distinguished in $\rho_T$: i) a quick one resulting from the overlap of the Landau level in the 2DEGs and ii) a slow one which causes (positive) maxima in $\rho_T$ whenever the fillingfactor difference between the 2DEGs is even, and (negative) minima whenever this difference is odd. The inset shows $\rho_T$ at fixed magnetic field of 0.641 (T) (maximum in $\rho_T$ in fig.1) versus fillingfactor difference.](image2)
frequency $h(n_1 + n_2)/2e$, that results from the overlap of the (in $p_T$ for $B > 0.17$ T doubly peaked) Landau levels of the 2DEGs plus a slower one with the frequency $h(n_1 - n_2)/2e$, which causes $p_T$ to oscillate around zero. The arrows in fig. 2 indicate the magnetic fields at which the filling factor difference between the 2DEGs ($\Delta \nu = \nu_{\uparrow} - \nu_{\downarrow}$) equals an integer. $\Delta \nu$ is calculated from the densities of the 2DEGs that are obtained from the positions of the minima in the Shubnikov-de Haas oscillations in $\rho_{xx}$. It is clear that when $\Delta \nu$ is odd $p_T$ is most negative, while when $\Delta \nu$ is even $p_T$ is most positive. The inset of fig. 2 confirms this even/odd behavior. It plots $p_T$ at 0.641 T ($\nu_1 = 13.5$, maximum $p_T$ in fig. 3) 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.

The observation of negative $p_T$ at odd $\Delta \nu$ and positive $p_T$ at even $\Delta \nu$ hints 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 2DEGs. In our experiment, however, negative $p_T$ is observed in the regime of incomplete spin-splitting. One may then expect a maximum positive $p_T$ at $\Delta \nu$=even and a maximum negative $p_T$ at $\Delta \nu$=even+$\Delta \nu_{\text{spin}}$, with $\Delta \nu_{\text{spin}}$ the filling factor difference between spin-up and spin-down peaks in $\rho_{xx}$ (which equals 1 only if spin-splitting is complete). A simulation of $p_T$ (see below), assuming positive coupling between electrons with parallel spins and negative coupling between electrons with anti-parallel spins, shows however that $p_T$ 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 $p_T$, but does not alter its phase or periodicity.

In lack of a theory to compare our results with, we present an empirical model, assuming $\rho_{xx} \propto (\text{DOS}^{\uparrow} + \text{DOS}^{\downarrow})^2$ and $\rho_T \propto B^\alpha (\text{DOS}^{\uparrow} - \text{DOS}^{\downarrow}) \text{layer}_1 \times (\text{DOS}^{\uparrow} - \text{DOS}^{\downarrow}) \text{layer}_2$, with DOS$^{\uparrow}\downarrow$ the density of states at $E_F$ for spin-up and spin-down, and $B$ the magnetic field. To account for the unknown change in the coupling between the layers with magnetic field a factor of $B^\alpha (\alpha \approx 3.5)$ is used to scale the amplitude of $p_T(B)$ 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 $\rho_{xx}$ 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: $\Delta_{\text{spin}} = g \mu_B B + (n_1^n - n_1^n)/(n_1^n + n_1^n) \times 2E_c$, with $E_c$ the Coulomb energy $e^2/4\pi\epsilon\ell_B$, $g$ the bare g-factor in GaAs (-0.44), $\mu_B$ the Bohr magneton, $\epsilon$ the dielectric constant, $\ell_B$ the magnetic length and $n_1^n$ the number of particles with spin-up and spin-down. There is some discussion in literature whether in low fields the relevant length scale for $E_c$ is $l_B$ or (the much smaller) $k_F^{-1}$ (see [4] and references therein). In our simulation $0.5l_B$ is appropriate, i.e. the factor of 2$E_c$ is used as it reproduces the experimental $\rho_{xx}$ traces. With a fixed enhanced g-factor (or even the bare g-factor), however, qualitatively similar results for $p_T$ are obtained.

Fig. 3 shows the results of the simulation. For both $\rho_{xx}$ and $p_T$, 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 $\rho_{xx}$-peaks is not reproduced, but this could be due to a different coupling strength of spin-up and spin-down edge channels to the bulk [4], which is not included in the simulation. The asymmetry in the $p_T$-peaks at matched densities (fig. 3, $B > 0.65$ 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 $p_T$, 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 $p_T$ are observed in all samples from all three wafers at mismatched densities. The slow oscillation can be recognised as such for $T < 1$ 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$^{-2}$, $n_1=2.0\times10^{11}$ cm$^{-2}$) confirming that the appearance of negative $\rho_T$ for odd $\Delta \nu$ and positive $\rho_T$ for even $\Delta \nu$ is not restricted to one particular density difference.

The appearance of negative $\rho_T$ when Landau levels with anti-parallel majority-spin are at $E_F$ in the 2DEGs 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 hole-like character (i.e. $\partial^2 E/\partial k_y^2 < 0$), but we know of no mechanism through which spins can cause that. The explanation for negative $\rho_T$ must then be sought for beyond the single particle picture, possibly in terms of spin-waves or couplings states between the layers. We note that our empirical formula describing $\rho_T$ consists of the three possible triplet spin wavefunctions 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 $\rho_T$. There is however a limitation to its applicability: in fields above 1.2 T the negative $\rho_T$ vanishes in the 30 nm barrier samples. For the density mismatch in fig. 2 this is easily explained, as in fields above $\sim$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 $\rho_T$ 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 $\rho_{xx}$. Samples from the other wafers have similar spin-splittings and the negative $\rho_T$ vanishes at comparable fields. It is further worth noting that the upper bound for the magnetic field below which negative $\rho_T$ is observed, does not depend on density or density difference of the 2DEGs (provided an overlap exists between Landau levels with different spin for $B >$1.2 T) and thus not on fillingfactor.

Finally we comment on the interpretation of negative magneto-drag in ref. [10]. Due to the highest lowest temperature (1.15 K), no spin-splitting in $\rho_{xx}$ and no slow oscillations in $\rho_T$ 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 $\rho_T$ 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 hole-like dispersion in the less-than-half-filled Landau level, leading to negative $\rho_T$. Our lower temperatures allow probing the regime where $\rho_{xx}$ 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 $\rho_T$. Our experiment shows no doubling, disproving such a scenario. Moreover, as fig. 2 shows, negative $\rho_T$ can be observed as well when the (in $\rho_{xx}$ 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].

Summarising, at matched densities the double peak in the magneto-drag 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 anti-parallel spin have a negative contribution. This selectivity to spin further causes the occurrence of a negative drag whenever Landau levels with anti-parallel spin are at $E_F$ in the 2DEGs, resulting in a novel 1/B-periodic oscillation in the low field low temperature drag for mismatched electron densities with the inverse period given by $\Delta \rho_n/2e$. Our empirical model assuming $\rho_T \propto (DOS^1 \cdot DOS^3)^{\text{layer}_1 \times (DOS^3 \cdot DOS^1)^{\text{layer}_2}}$ quite accurately describes the results at matched as well as mismatched densities. The origin of the negative coupling between electrons with anti-parallel spin as well as its disappearance when spin splitting in $\rho_{xx}$ is complete remains to be explained.

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