Observation of Screening in the Magneto-Coulomb Drag between Coupled Two-Dimensional Electron Systems

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The coupling between two spatially separated two-dimensional electron gases is studied as a function of magnetic field B. We find oscillations in the transresistivity R_T, which are up to 2 orders of magnitude enhanced compared to the $B = 0$ case. R_T vanishes in the regime of a quantum Hall plateau and shows a twin-peaked structure in the inter-plateau regions. This observation is in good agreement with a recent theory by M. C. Bønsager *et al.* [Phys. Rev. Lett. **77**, 1366 (1996)] who predicted a similar behavior caused by the interplay of screening and Landau quantization. [S0031-9007(97)02546-5]

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A great deal of attention has recently been devoted to double layer systems in which quasi-two-dimensional subsystems of electrons or holes are placed in parallel planes separated by a potential barrier thick enough to prevent particles from tunneling but still allowing for interactions between the particles on both sides. An ideal tool for experimentally probing these interlayer electron-electron interactions has been the so-called "drag" measurement [1–3], where a current is passed through one layer thereby inducing a frictional drag voltage in the other nearby layer. These experiments have stimulated many theoretical investigations (see [4] and references therein for a comprehensive overview), both in explaining the already observed phenomena and also in predicting new phenomena of what might happen in magnetic fields, where to our knowledge no data have been published so far. In this Letter, we now present measurements on the dependence of the frictional drag between two coupled two-dimensional electron gases (2DEGs) as a function of magnetic field. We show that the coupling between the layers is determined not only by the Landau quantization, but also by the screening properties of the coupled electron gases. If, in particular, the Fermi energy of both systems is in the middle of the Landau levels, we observe due to the then enhanced screening a reduction of the interlayer coupling, as recently theoretically predicted [4].

Results are presented from samples which consist of two Si-modulation-doped 20-nm GaAs quantum wells, separated by a 30-nm $Al_{0.33}Ga_{0.67}As$ barrier, the whole structure being grown by molecular-beam epitaxy (MBE) on (100) oriented substrates. The upper 2DEG had an intrinsic carrier density of $n_1 = 3.5 \times 10^{11}$ cm^{-2} and a mobility of $\mu = 2.5 \times 10^5$ cm^2/V s, the respective values for the lower 2DEG were $n_2 = 3.2 \times 10^{11}$ cm^{-2} and $\mu = 2.5 \times 10^5$ cm^2/V s. The wafer also had a buried n^+ GaAs back-gate, which had been patterned *ex situ* by wet etching and after a thorough cleaning procedure reloaded into the MBE chamber, where the remaining structure was grown [5]. This back-gate was separated from the lower 2DEG by a highly insulating low-temperature grown GaAs layer followed by an $Al_{0.33}Ga_{0.67}As$ barrier, the total thickness of the layers being 500 nm. Standard optical lithography was used to pattern single devices into Hall bars, to form AuGeNi Ohmic contacts to the electron gases, and to deposit Ti/Au Schottky front-gates located 80 nm above the upper 2DEG. With front- and back-gates covering the central Hall bar the electron densities in the two layers could be changed independently from each other.

Independent contacts to the layers were achieved using a "selective depletion" scheme [6,7], where negative voltages were applied to appropriate side front- and back-gates crossing the mesa arms. In this independent contact configuration an interlayer bias of 30 mV could be applied with temperature- and B-independent leakage currents <100 pA. This corresponded to a barrier resistance of more than 300 MΩ showing that tunneling between the layers was negligible. Measurements were carried out in a ^{4}He cryostat equipped with a variable temperature insert which made it possible to control the temperature accurately over a wide range. Standard lock-in techniques were used to detect the signals with a constant current I_{drive} of typically 200 nA at a frequency of 1.51 Hz. This low frequency was used to minimize the capacitive coupling between the layers.

While the drive current is passed through one layer, it induces a voltage drop in the other layer when its contacts are not shortened. This drag voltage V_{drag} is caused by momentum transfer from the current driven layer to the closely spaced second layer. For the here investigated system of two coupled electron gases, V_{drag} is expected [4] to have the opposite polarity as the resistive voltage drop in the drive layer and can be related to the transresistance R_T by

$$R_T = (W/L)V_{\mathrm{drag}}/I_{\mathrm{drive}}\,, \tag{1}$$

where (W/L) is the width to length ratio of the sample (this is 1/11 for our Hall bars with a width of 80 μm).

The traces of the transresistance R_T as a function of magnetic field are shown for three different measurement temperatures in Fig. 1, together with the Shubnikov–de Haas (SdH) oscillations of the upper 2DEG, which served here as the drive layer. The electron densities in this

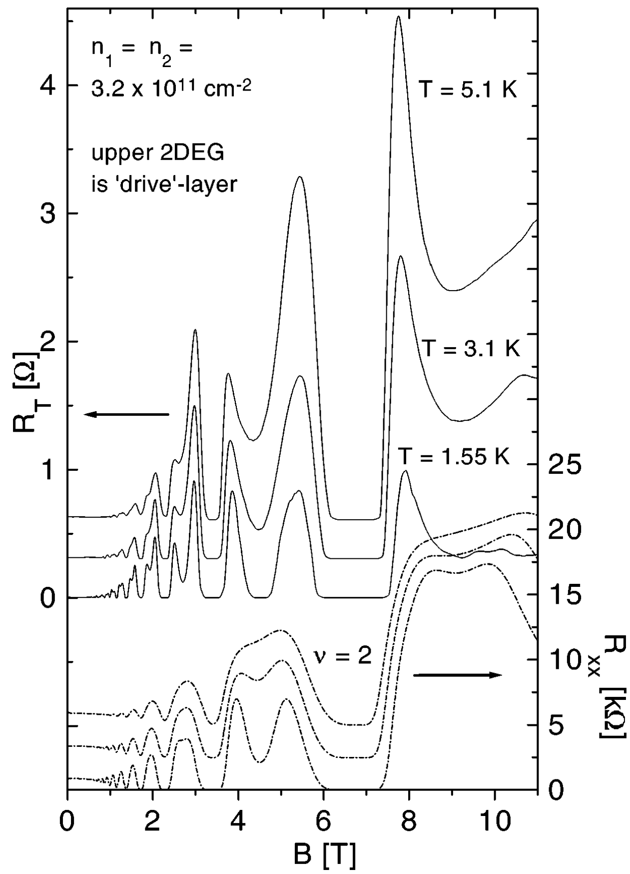

FIG. 1. The transresistance R_T as a function of magnetic field B for a coupled electron gas with a separation barrier of 30 nm, shown for three different temperatures T (plotted with offset for clarity). The electron density of both 2DEGs is $n = 3.2 \times 10^{11}$ cm^{-2}. Also shown for comparison is the longitudinal resistance of the upper 2DEG for the corresponding temperatures (plotted with offset in the same succession). The filling factor $\nu = 2$ is indicated.

measurement were matched by applying appropriate front- and back-gate voltages. To achieve this, the electron density of the lower 2DEG, which was the drag layer, had to be calibrated in a separate measurement before. As the mobilities of the two electron gases are very similar, the SdH traces do not differ very much from each other. That is why we have shown here the exemplary traces of one 2DEG only.

Before we start to discuss the shape of the trace in particular, we want to add some comments why we think that the measured signal is really the transresistance and not any side effect. To check for possible heating effects, we have examined the SdH traces at different temperatures and with different currents. This proved that for our measurement temperatures $T > 1$ K and for the finally used currents of 200 nA the electron temperatures did virtually not change, as also expected from recent experimental and theoretical investigations [8]. The used currents were furthermore low enough that the drag voltage was linear in applied current. Finally, one of the most fundamental checks which must be made to ensure that the measurements have been done correctly, is to verify the reciprocity of the system. This means the results have to be the same on interchanging the driven with the dragged layer as a consequence of Onsager's relation for linear networks. In our measurements we could verify this relation within the experimental uncertainty.

After having ensured that the observed signals have their origin in frictional drag, we want to move on to the discussion of the magnetic field dependence of R_T. As can be extracted from Fig. 1, strong oscillations in the transresistance can be observed. The peak values of the oscillations are for high magnetic fields more than 2 orders of magnitude higher than at $B = 0$. For comparison, at $T = 3.1$ K this zero field value is $R_T = 8$ mΩ. This strong increase with magnetic field is in agreement with the theoretical prediction [4]. We want to point out here that the drag voltage V_{drag}, from which R_T is calculated, has for both $B = 0$ and for nonvanishing B always the same and theoretically expected "correct" sign. Another striking feature is that in the plateau regime of the quantum Hall effect (QHE) the coupling between the layers is so small that within our experimental resolution the transresistance virtually drops to zero. In the inter-plateau regions, we can observe a twin-peaked structure, which is for the lowest measured temperature $T = 1.55$ K visible up to a filling factor $\nu = 15$. For increasing temperature, this twin peak is getting faded, and its first appearance moves to lower filling factors. From a simple comparison with the SdH trace, it is apparent that this double peak cannot simply be related to the spin-splitting. This comparison with the SdH oscillations is based on the assumption that, due to phase space reasons, R_T is mainly proportional to the product of the density of extended states of both 2DEGs. We believe therefore that this double-peak structure has a different origin.

First, one observes a strong dip in R_T at $\nu = 3/2$ at $B \approx 9$ T, where the spin levels are already separated. The dips at the higher filling factors $\nu = 5, 7, 9, \ldots$ can then be seen as the natural expansion to spin-degenerate Landau levels (LLs). The situation around filling factor $\nu = 3$ is more complicated. Simply, one would expect to see also a double-peak structure at $\nu = 5/2$ and $\nu = 7/2$. However, the spin-splitting that we observe here is far from being completely developed. Thus it is at present not clear if it is really justified to speak in this situation already about a complete spin polarization as it is the case for $\nu = 3/2$. From our experimental observations, the following constellation seems furthermore to be necessary for the double-peak structure to occur: As a function of B, both 2DEGs simultaneously undergo a transition from a region of localized states (manifested in clear zeros in the SdH oscillations) to one of extended states in the middle of a LL. This clear transition, however, is for both 2DEGs definitely not given at filling factor $\nu = 3$.

A possible interpretation of our results is represented by a recent theory by Bønsager *et al.* [4] who have investigated the frictional drag in perpendicular magnetic fields for a system consisting of two 2DEGs separated by a barrier of 30 nm, similar to our samples. They have found that the transresistance R_T fulfills roughly the following relation:

$$R_T \propto g_1 g_2 |W_{12}|^2, \tag{2}$$

where g_i is the density of states (DOS) at the Fermi energy (E_F) of the ith electron gas, and W_{12} is the matrix element of the screened interlayer interaction. However, they have not included spin-splitting and the effects of localized states resulting in the QHE. As they point out, localized states do not contribute to transport properties such as R_T. Therefore, the main effect of applying Eq. (2) to our experimental situation should be just to replace g_i by the density of *extended* states (DES) at E_F in the sample, which we name G_i. Having this in mind, it becomes clear that in the regime of the QHE, where the DES drops to zero, the electrons have not sufficient energy to be excited over the QHE gap into extended states, resulting in a negligibly small transresistance, as we have observed it in our experiments.

The most striking features, however, they predict in their theory are the effects of screening. They state that $G(B)$ and the screened interlayer interaction $|W_{12}|^2$ work in opposition; i.e., a large DES weakens the interlayer coupling due to screening. In fact, they present calculations, where in the middle of a filled Landau level (LL) the screening becomes so strong that it more than compensates for the basically quadratic G^2 dependence in Eq. (2). Therefore, the transresistance is suppressed in the middle of a LL, resulting in a twin-peaked structure. It is exactly this effect which might be attributed in our experimental traces to the observed dips in the middle of a LL. This is supported by the fact that our experimental data not only give an overall qualitative agreement with the calculations of Ref. [4], but also a very good quantitative one in the observed signal size.

A further insight in the understanding of our observations might be gained by really calculating the screened interlayer interaction $|W_{12}|^2$ from the measured R_T. Doing this exactly would mean to solve a complicated integral [4]. However, the simple relation of Eq. (2) should at least serve as a good basis for qualitative arguments. In a first step one has to calculate the DES $G(B)$ from the ρ_{xx} trace of SdH oscillations of the 2DEGs. This can to a good approximation be done, using the relation [9]

$$\rho_{xx} \propto G(B)^2 (N + \tfrac{1}{2}), \tag{3}$$

where N is the number of the LL at E_F.

Having calculated the DES for both 2DEGs, one can to a constant factor roughly estimate the screened interlayer interaction $|W_{12}|^2$. In Fig. 2 we present for $T = 1.55$ K such a calculated $|W_{12}|^2$ trace as a function of inverse B, together with the product of the two DES $G_1 G_2$. From this figure it is now obvious that even after the effects of spin-splitting have been eliminated, the estimation of the pure interlayer interaction $|W_{12}|^2$ still shows clearly developed minima in the middle of a LL up to $\nu = 15$. This supports our assumption that this behavior is likely to be caused by the interplay of Landau quantization and enhanced screening.

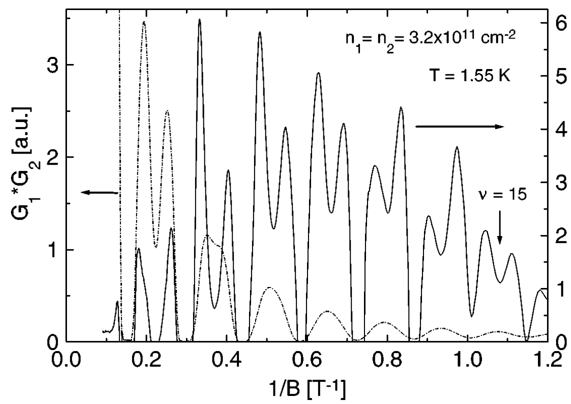

FIG. 2. Calculated interlayer interaction $|W_{12}|^2/T^2$ (full line) for $T = 1.55$ K in arbitrary units as a function of inverse magnetic field (see text for details of the calculation). The calculated product of the DES of the 2DEGs $G_1 G_2$ is also shown for comparison. The dips in $|W_{12}|^2/T^2$ for half-filled LL caused by the enhanced screening are visible up to a filling factor of $\nu = 15$.

This double-peak phenomenon is not only observable for systems that have equal carrier densities, as can be extracted from Fig. 3. Here we have measured R_T for $n_1 = 3.2 \times 10^{11}$ cm^{-2} and $n_2 = 2.0 \times 10^{11}$ cm^{-2} at $T = 3.0$ K. As expected from Eq. (2), the transresistance R_T (solid line) follows mainly the product of the density of extended states of each 2DEG, which is also shown (dotted line). This leads to a vanishing R_T when *only one* of the systems is in the regime of the QHE. However, for

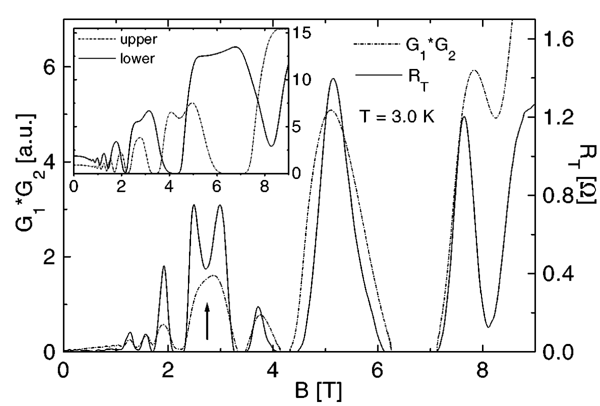

FIG. 3. Transresistance R_T as a function of B for a system with different carrier densities at $T = 3.0$ K, together with the calculated product of the DES of the 2DEGs. The arrow at $B = 2.4$ T indicates the position where the interlayer coupling is suppressed due to enhanced screening. Inset: Longitudinal resistance R_{xx} of the 2DEGs in kΩ, with $n_1 = 3.2 \times 10^{11}$ cm^{-2} and $n_2 = 2.0 \times 10^{11}$ cm^{-2}.

a situation where both 2DEGs undertake (as a function of B) a transition from a region of localized states to one of extended states near the center of a LL band (at $B = 2.8$ T in Fig. 3), this can also lead to a double-peak structure in R_T due to possible screening.

The temperature dependence of the screening minima appearing in the middle of the LLs was also a topic of the theoretical investigations [4], as this enables one to learn something about the kind of screening involved. For simple static screening, R_T is according to theory expected to have an overall T^2 dependence. Therefore, deviations from this screening mechanism can best be observed when R_T is scaled by T^2. In Fig. 4 we have plotted $|W_{12}|^2/T^2$ as a function of T/T_F for three different filling factors [10]. For the lowest filling factor $\nu = 3$, there is a maximum at around $T/T_F \approx 0.03$, which was also predicted by theory. It was argued that this enhancement in $|W_{12}|^2/T^2$ is due to dynamic screening, which is becoming more important with increasing temperature and is also less effective than a static one. For higher filling factors, this maximum is observed to shift to lower T. This is not surprising as for high filling factors correspondingly lower temperatures are required to resolve the Landau quantization. This clear quantization, however, seems to be crucial in order to observe this competition between the increasing DES and the thus enhanced screening.

Though our data agree quite well with many aspects of the cited theory, a final decision if the observed double-peak structure can really be attributed to screening and not to any other phenomena so far not considered that would enhance the resolution of spin-splitting in drag measurements cannot be taken. In any case our experiments have shown that the aspects of spin-splitting cannot be neglected in any way and should thus be part of future theories.

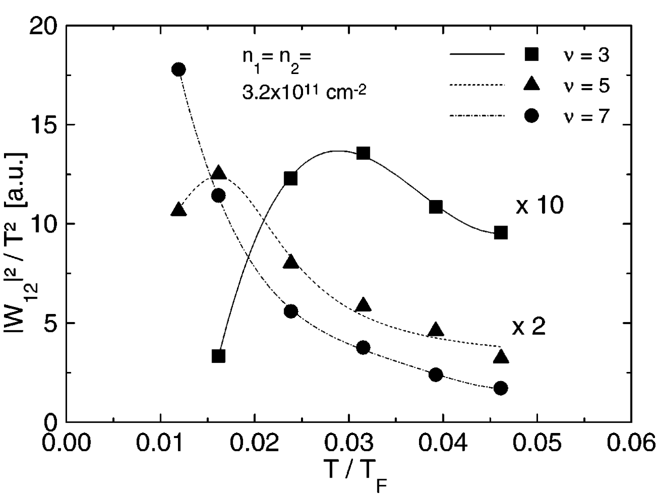

FIG. 4. Temperature dependence of the interlayer coupling with E_F in the middle of the LL bands for a sample with matched carrier densities, the corresponding Fermi temperature T_F being $\approx$130 K. The data for the filling factors $\nu = 3$ and $\nu = 5$ have for reasons of clarity been scaled by factors of 10 and 2, respectively. The interpolation curves through the data points serve only as a guide to the eye.

We want to add at this point that we have also done measurements on samples, where the 2DEGs were separated by an $Al_{0.33}Ga_{0.67}As$ barrier with a width of 60 nm. We have observed there a very similar behavior of the transresistance in magnetic fields with clearly visible screening dips. The main difference was that the overall magnitude of the coupling was by roughly a factor of 3 smaller. We will discuss the details of that dependence on the separation width elsewhere [11].

In conclusion, we have presented measurements of the frictional drag between two coupled 2DEGs as a function of magnetic field. We observe a vanishing coupling when one of the systems is in the regime of the QHE and a dip in the transresistance when the Fermi energy of the two electron gases are both in the extended states in the middle of a Landau level. We have shown that this behavior can be explained by an interplay of Landau quantization on the one hand and the screening properties of the coupled electron gases on the other hand.

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