Frictional drag between parallel two-dimensional electron gases in a perpendicular magnetic field

1996 J. Phys.: Condens. Matter 8 L557

(http://iopscience.iop.org/0953-8984/8/39/001)

J. Phys.: Condens. Matter **8** (1996) L557–L562. Printed in the UK

LETTER TO THE EDITOR

Frictional drag between parallel two-dimensional electron gases in a perpendicular magnetic field

N P R Hill, J T Nicholls, E H Linfield, M Pepper, D A Ritchie, A R Hamilton and G A C Jones

Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, UK

Received 24 July 1996

Abstract. We present measurements in a perpendicular magnetic field of the frictional drag between two closely spaced, but electrically isolated, two-dimensional electron gases. At high temperatures, when the Landau level structure is smeared out, the transresistivity shows a B^2 magnetic field dependence and an approximately linear temperature dependence. As the temperature is lowered below 20 K, the transresistivity shows structure reflecting the formation of Landau levels and, in general, the drag is more sensitive to the spin splitting of the Landau levels than the Shubnikov–de Haas oscillations. When the Fermi energy E_F lies at the centre of a Landau level, the drag can be enhanced by two orders of magnitude over the zero field signal. In contrast, when E_F lies between Landau levels in the quantum Hall regime, the drag signal tends to zero. We have also measured the transverse voltage in the drag layer and find no evidence for a Hall transresistance.

The electron–electron interactions between two closely spaced, but electrically isolated, two-dimensional electron gases (2DEGs) can be directly studied by measuring the drag voltage V_{drag} in one layer when a current I_{drive} is passed though the other. The frictional drag between electron gases was first considered by Pogrebinski [1]; however, due to difficulties in sample fabrication, it was not until 1989 that Solomon *et al* [2] presented drag measurements between a 2DEG and a three-dimensional electron gas. Later, drag measurements were performed [3] between parallel 2DEGs, and between a 2D hole gas and 2DEG [4]. There have been further experimental [5, 6] and theoretical [7, 8, 9, 10, 11, 12] investigations, but to date there have been only theoretical studies [13, 14, 15] in a perpendicular magnetic field B.

The experimental set up for performing drag measurements in a double 2DEG structure is shown schematically in figure 1. The two 2DEGs are electrically isolated from each other and when a current I_{drive} is passed through one layer (with carrier density n_{drive}), electron–electron interactions transfer momentum to the second layer (with carrier density n_{drag}). The voltage V_{drag}, which is measured in an open circuit configuration in the drag layer, is opposite in sign to the resistive voltage drop in the drive layer. By analogy to the resistivity of a single 2D layer, the transresistivity in a double-layer system is defined as

$$\rho_t = \frac{V_{drag}}{I_{drive}}\frac{W}{L} = \frac{m}{n_{drive}e^2\tau_D} \tag{1}$$

where W is the width of the Hall bar and L is the distance between voltage probes in the drag layer.

The drag measurement can be described as an inhomogeneous current-carrying layer that creates a ‘corrugated’ potential which pushes electrons in the neighbouring layer in the

0953-8984/96/390557+06$19.50

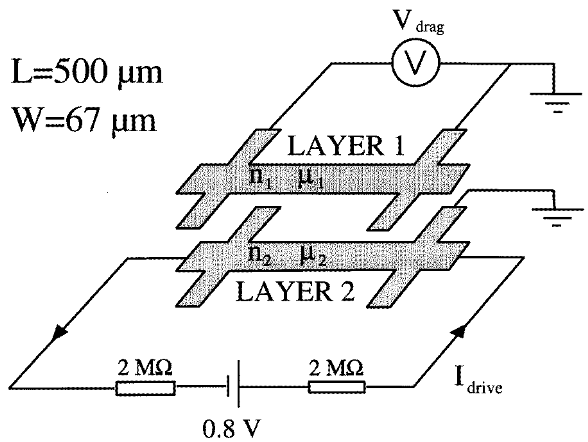

Figure 1. A schematic diagram of the set up for drag measurements in a double-2DEG sample.

direction of current flow. The interlayer scattering rate τ_D^{-1} has been calculated [9] to be

$$\frac{1}{\tau_D} = \frac{\hbar^2}{2\pi^2 n_{drag} m k_B T} \int_0^\infty \mathrm{d}q \int_0^\infty \mathrm{d}\omega \; q^3 \; |V(q,\omega))|^2 \frac{[\mathrm{Im}\,\chi(q,\omega)]^2}{\sinh^2(\hbar\omega/2k_B T)} \qquad (2)$$

where the inhomogeneities in each layer are long-lived density fluctuations, characterized by the polarizability Im $\chi(q,\omega)$, and the interlayer interaction is described by $V(q,\omega)$. At low temperatures and at zero magnetic field Im $\chi \propto \omega$, and for a static screened Coulomb interaction, $V(q,\omega) = e\phi(q)$, equation (2) predicts a $\rho_t \sim T^2$ temperature dependence [7], in agreement with experiment [3]. Further calculations [8], incorporating virtual phonon coupling, can account for the magnitude of the experimental zero-field drag rate. In this letter we present drag measurements in a double-layer system, in the unexplored regime when a magnetic field B is applied perpendicular to the two 2DEGs.

The double-2DEG sample consists of two 200 Å wide modulation-doped GaAs quantum wells separated by a 300 Å $Al_{0.67}Ga_{0.33}As$ barrier. The as-grown carrier densities of the top and bottom 2DEGs are $n_1 = 3.3 \times 10^{11}$ cm^{-2} and $n_2 = 2.3 \times 10^{11}$ cm^{-2}, respectively. The corresponding as-grown low-temperature mobilities are $\mu_1 = 9.0 \times 10^5$ cm^2 V^{-1} s^{-1} and $\mu_2 = 1.3 \times 10^5$ cm^2 V^{-1} s^{-1}. Patterned back-gates were defined in a buried n^+ GaAs layer using *in situ* focused ion-beam lithography [16]. A Hall bar mesa ($W = 67$ μm and $L = 500$ μm), NiCr:Au front gates, and AuGeNi ohmic contacts to the back gates and 2DEGs were fabricated by optical lithography. Independent contacts to the two layers were made using the selective depletion technique [17, 18], and the interlayer resistance was always greater than 1 GΩ. Surface gates and back gates, extending over the active area of the Hall bar, were used to control independently the carrier densities, n_1 and n_2, which were determined by four-terminal Shubnikov–de Haas (SdH) measurements of the individual layers.

Using the dc measurement circuit shown in figure 1, the drag results presented here were obtained with equal carrier densities in the two layers, $n_1 = n_2$. A floating dc current, $I_{drive} = 200$ nA, was passed through the drive layer, with an earth defined by a non-current-carrying ohmic contact. The induced dc drag voltage was measured between two voltage probes in the drag layer, one of which was used to define the earth of that layer. The measured voltage was not affected by the position of the earth in either 2DEG, indicating that interlayer leakage was negligible [2].

Previous drag measurements [3, 4, 5, 6] at zero magnetic field have used ac lock-in techniques; however, when using such techniques in the quantum Hall (QH) regime we encountered problems isolating and reducing an offset voltage. This dc voltage, V_o, which is present even when the drive current is removed, is not specific to double-layer systems, and has been previously measured [19, 20, 21] in single 2DEGs. V_o is generated by rectified low-frequency noise within the sample, and shows [19] quantum oscillations as a function of magnetic field with a periodicity determined by the average carrier density $\langle n \rangle$ of the 2DEG. When a current is passed through the drive layer, I_{drive} gives rise to a resistive voltage drop along the length of the layer which, due to the interlayer capacitance, creates a change in the carrier density of the drag layer of similar profile. Therefore, there is a change in the average carrier density $\langle n_{drag} \rangle$ of the drag layer (as determined from SdH measurements of the drag layer) which is proportional to I_{drive}. The variations in $\langle n_{drag} \rangle$ cause changes in V_o, resulting in an unwanted contribution to the measured drag voltage. By carefully reducing the noise currents, the maximum amplitude of V_o was reduced to 100 nV at 4.2 K. V_{drag} is half the measured change in voltage when $I_{drive} \to -I_{drive}$, and is proportional to the magnitude of I_{drive} and the separation L of the voltage probes. When the drive and drag layers were interchanged, and the direction of the magnetic field was reversed, the transresistivity ρ_t was unchanged, in agreement with the Onsager reciprocity relations. Without optimization, V_o can be as large as 50 μV and gives rise to spurious structure in $\rho_t(B)$. Under such conditions V_{drag} does not obey the Onsager reciprocity relations or scale according to equation (1).

We have also measured the transverse voltage (across the Hall bar) in the drag layer when a current is passed through the drive layer. We find no evidence for a true Hall transresistance; there is, however, a transverse voltage in the drag layer due to a carrier density gradient that is capacitively induced in the drag layer by the Hall voltage in the drive layer. The longitudinal drag voltages measured on either side of the Hall bar in the drag layer correspond to different carrier densities, and the transverse voltage is the difference between these two signals. At high magnetic fields, the transverse voltage measured in the drag layer can be as large as 10% of the longitudinal signal V_{drag}.

Figure 2 shows the transresistivity $\rho_t(B)$ at a matched carrier density of $n_1 = n_2 = 2.3 \times 10^{11}$ cm^{-2} for temperatures in the range $T = 0.9$–29.9 K, together with the SdH oscillations of the upper layer at $T = 1.5$, 4.7, and 32.9 K; the mobility of the top layer is $\mu_1 = 6.2 \times 10^5$ cm^2 V^{-1} s^{-1} at this carrier density. At the highest temperatures, $T \approx 30$ K, the thermal energy $k_B T$ is typically greater than the Landau level (LL) spacing $\hbar\omega_c$, and SdH oscillations are not observed in the magnetoresistance traces of the individual layers. Likewise, figure 2(b) shows that $\rho_t(B)$ exhibits no LL structure and monotonically increases with B. At these high temperatures, the transresistivity at $B = 4$ T is an order of magnitude larger than the zero field signal.

We have been able to fit the high-temperature transresistivity traces to the expression $\rho_t(B) = aB^2$, where the constant of proportionality is approximately linear in temperature $a \approx 0.01$ Ω $\square^{-1}$ K^{-1} T^{-2}. In figure 3 we have plotted $\rho_t(B,T)/T$ versus B^2 for the temperatures $T = 16.2$, 19.0, 25.2, and 29.9 K (successive traces have been vertically offset by 0.05 Ω $\square^{-1}$ K^{-1}). The trace at $T = 29.9$ K tends to a straight line at high field indicating a B^2 dependence. As the temperature is reduced, the LL structure is responsible for deviations away from B^2T behaviour.

At temperatures such that the LL structure is smeared but $k_B T \ll E_F$, it is expected that Im χ and $|e\phi(q)|^2$ are independent of T which, combined with the high temperature expansion $1/\sinh^2(\hbar\omega/2k_B T) \simeq 4k_B^2 T^2/\hbar^2\omega^2 - 1/3$, results in $1/\tau_D \propto T - \text{constant}/T$ [7]. The term linear in T will dominate at high temperatures and may account for the

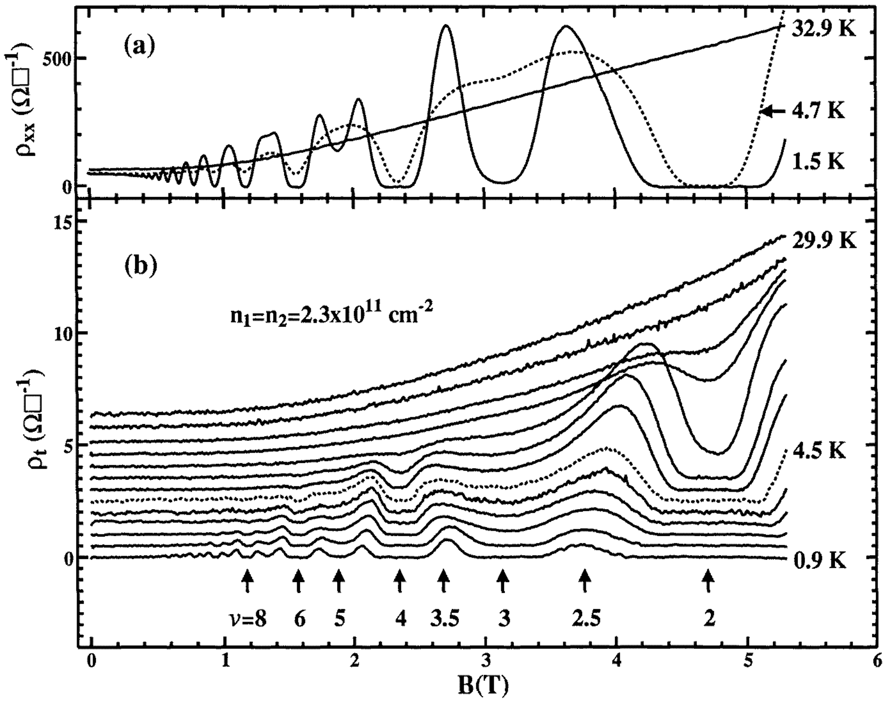

Figure 2. (a) SdH oscillations of the upper 2DEG for $n_1 = 2.3 \times 10^{11}$ cm^{-2} and $T = 1.5$, 4.7, and 32.9 K. (b) Transresistivity sweeps $\rho_t(B)$ at $n_1 = n_2 = 2.3 \times 10^{11}$ cm^{-2} for temperatures $T = 0.9$, 1.5, 2.7, 3.1, 3.7, 4.5, 6.6, 7.9, 11.5, 16.2, 19.0, 25.2, and 29.9 K. Successive traces have been offset by 0.5 $\Omega\ \square^{-1}$, and arrows indicate the filling factors ν. For comparison, the transresistivity at $B = 0$ T is 10 m$\Omega\ \square^{-1}$ at 4.5 K.

observed linear T dependence of $\rho_t(B)$. At zero field, extra coupling mechanisms have been considered which give deviations from a T^2 dependence; for example, the virtual phonon interaction has been shown [8] to weaken the T^2 temperature dependence at high T. Plasmon effects become important at high temperature and a consideration of both coupling mechanisms may be needed to account fully for the observed temperature dependence in a magnetic field.

In the weak-scattering limit, $\omega_c\tau \gg 1$, the polarizability Im $\chi(q, \omega)$ has a peaked structure reflecting the formation of LLs. When integrated over q and ω in equation (2), the function $[\text{Im}\ \chi(q, \omega)]^2$ is enhanced over the smoothly varying one at $B = 0$ T, resulting in an increase of $\rho_t(B)$ over its zero-field value [22]. At present there are no theoretical calculations of $\rho_t(B)$ when $k_BT > \hbar\omega_c$ and $\omega_c\tau \gg 1$ which can account for the B^2 dependence.

For temperatures $T < 19.0$ K, SdH oscillations are observed in both layers and $\rho_t(B)$ also shows structure reflecting the presence of LLs, and when the LL filling factor $\nu = hn/eB$ is close to an integer, there is a minimum in $\rho_t(B)$. As the temperature is reduced further, zeros are observed in the SdH oscillations of each layer and similarly in $\rho_t(B)$. However, a comparison of the low-field $\rho_{xx}(B)$ and $\rho_t(B)$ traces around 4.5 K (both shown with dashed lines) shows that, in general, the transresistivity is less sensitive than the resistivity to the modulation of the density of states at the Fermi level $D(E_F)$ by the

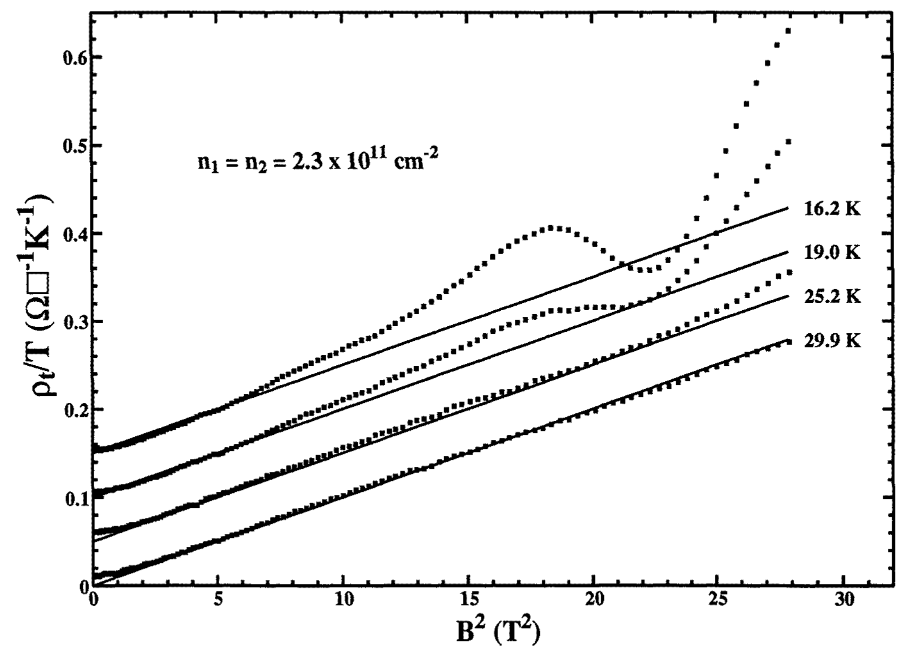

Figure 3. $\rho_t(B, T)/T$ versus B^2 for temperatures $T = 16.2$–29.9 K. The experimental data points together with the solid line $\rho_t(B, T)/T = 0.01\ \Omega\ \square^{-1}\ \mathrm{K}^{-1}\ \mathrm{T}^{-2}\ B^2$ have been vertically offset by $0.05\ \Omega\ \square^{-1}\ \mathrm{K}^{-1}$ for successive temperatures.

formation of LLs. In contrast to the decreased sensitivity to the density of states, $\rho_t(B)$ is more sensitive to the spin splitting of the LLs and shows no structure due to spin degenerate LLs. At $T = 4.5$ K the minimum at $\nu = 3$ in the trace of $\rho_t(B)$ is more pronounced than that in $\rho_{xx}(B)$, and at $\nu = 5$ the transresistivity exhibits clear spin splitting that is absent from the SdH sweep.

The positions of the maxima in $\rho_t(B)$ change as a function of temperature. At low temperatures, $T < 1.5$ K, when a spin-split zero is present in both $\rho_{xx}(B)$ and $\rho_t(B)$, the maxima of both quantities lie at fields corresponding to half-integral filling factors. As the temperature is increased, the spin-split zero becomes activated and the peaks move towards even integer filling factors; this is most clearly demonstrated by the two peaks around $\nu = 3$. The movement of the features in $\rho_t(B)$ is not seen in $\rho_{xx}(B)$ and is not understood at present. The enhancement of $\rho_t(B)$ over its zero-field value increases with decreasing T, and $\rho_t(B = 4\ \mathrm{T})$ at 4.5 K is two orders of magnitude greater than $\rho_t(B = 0)$.

As the temperature is lowered it is expected that $\rho_t(B)$ will show the same structure as the SdH oscillations, reflecting the modulation of $D(E_F)$ by the perpendicular magnetic field. Further, in the QH regime it is expected that the drag voltage should tend to zero. Theoretical predictions have been put forward [13] concerning the temperature dependence when E_F lies at the centre of an LL, predicting a modification of the zero-field T^2 behaviour. These predictions, however, are only valid in the scaling regime, which for GaAs samples occurs [23] at temperatures $T < 200$ mK.

More recently, Bonsager *et al* [14] and Wu *et al* [15] have investigated how a quantizing magnetic field influences the Coulomb contribution to $\rho_t(B)$ through the combined changes in $D(E_F)$ and the screening of the interlayer interaction $V(q,\omega)$. In addition to the usual spin splitting, Bonsager *et al* [14] predict a doubling of the peak structure which we have not observed in our data; the two peaks around the $\nu = 3$ spin-split zero at $T = 0.9$ K show no doublet structure. Both theories predict a reduction of the drag when E_F lies in between LLs and an enhancement over the zero-field value, when E_F lies at the centre of an LL, of approximately one order of magnitude [15] or a factor of 50–100 [14]. Our data show an enhancement of two orders of magnitude, but other mechanisms besides the direct Coulomb interaction are probably important in determining $\rho_t(B)$.

In conclusion, we have presented measurements of the frictional drag in a perpendicular magnetic field, showing that it can be enhanced by two orders of magnitude over the zero-field signal. The drag also shows greater sensitivity to the spin splitting of the LLs than the SdH oscillations. We have measured the transverse voltage in the drag layer and find no evidence for a Hall transresistance. We hope that these results will stimulate further theoretical work in this area.

We wish to thank the Engineering and Physical Sciences Research Council (UK) for supporting this work. JTN acknowledges support from the Isaac Newton Trust, and DAR acknowledges support from the Toshiba Cambridge Research Centre. We would also like to acknowledge the initial work by H Rubel, and thank A-P Jauho and B Y-K Hu for useful communications.

References

[1] Pogrebinski M B 1977 *Sov. Phys. Semicond.* **11** 637
[2] Solomon P M, Price P, Frank D and Tulipe D L 1989 *Phys. Rev. Lett.* **63** 2508
[3] Gramila T J *et al* 1991 *Phys. Rev. Lett.* **66** 1216
[4] Sivan U, Solomon P M and Shtrikman H 1992 *Phys. Rev. Lett.* **68** 2516
[5] Gramila T J *et al* 1993 *Phys. Rev.* B **47** 12957
[6] Rubel H *et al* 1994 *Semicond. Sci. Technol.* **10** 1229
[7] Jauho A P and Smith H 1991 *Phys. Rev.* B **47** 4420
[8] Tso H C, Vasilopoulos P and Peeters F M 1992 *Phys. Rev. Lett.* **68** 2516
[9] Zheng L and MacDonald A H 1993 *Phys. Rev.* B **48** 8203
[10] Flensberg K and Hu B Y-K 1994 *Phys. Rev. Lett.* **73** 3572
[11] Flensberg K, Hu B Y-K, Jauho A-P and Kinaret J M 1995 *Phys. Rev.* B **52** 14761
[12] Swierkowski L, Szymanski J and Gortel Z W 1995 *Phys. Rev. Lett.* **74** 3245
[13] Shimshoni E and Sondhi S L 1994 *Phys. Rev.* B **49** 11484
[14] Bonsager M C, Flensberg K, Hu B Y-K, and Jauho A-P 1996 *Phys. Rev. Lett.* **77** 1366
[15] Wu M W, Cui H L and Horing N J M 1996 *Mod. Phys. Lett.* B **10** 279
[16] Linfield E H, Jones G A C, Ritchie D A and Thompson J H 1993 *Semicond. Sci. Technol.* **9** 415
[17] Eisenstein J P, Pfeiffer L N and West K W 1990 *Appl. Phys. Lett.* **57** 2324
[18] Brown K M *et al* 1994 *J. Vac. Sci. Technol.* B **12** 1293
[19] Fletcher R, Coleridge P T and Feng Y 1995 *Phys. Rev.* B **52** 2823
[20] Kop'ev P S, Nadtochii M Y and Ustinov V M 1989 *Sov. Phys. Semicond.* **23** 1110
[21] Grassie A D C *et al* 1988 *Semicond. Sci. Technol.* **3** 983
[22] Hu B Y-K 1996 Private communication
[23] Wei H P, Lin S Y, Tsui D C and Pruisken A M M 1992 *Phys. Rev.* B **45** 3926