In-Plane Magnetodrag between Dilute Two-Dimensional Systems

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We performed in-plane magnetodrag measurements on dilute double layer two-dimensional hole systems, at in-plane magnetic fields that suppress the apparent metallic behavior, and to fields well above those required to fully spin polarize the system. When compared to the single layer magnetoresistance, the magnetodrag exhibits exactly the same qualitative behavior. In addition, we have found that the enhancement to the drag from the in-plane field exhibits a strong maximum when both layer densities are matched.

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The unexpected observation of a metallic phase and an apparent metal to insulator transition in two-dimensional (2D) systems [1], contradictory to the scaling theory of localization [2], has been the subject of extensive experimental and theoretical work in recent years [3]. Despite this, there remains no conclusive understanding of the origin of the metallic behavior and whether or not the system can be described in a Fermi liquid framework. More recently, the role the electronic spin plays in the metallic phase was considered by applying a magnetic field in the plane of the 2D carriers ($B_{\parallel}$). The application of $B_{\parallel}$, which polarizes the spins of the carriers, has been demonstrated to suppress the metallic behavior [4,5]. To date, there is still no definitive explanation for why the metallic behavior is suppressed when the carrier spins are polarized. Also, the role carrier-carrier interaction plays in the spin polarized regime is unclear. Although some information can be inferred about carrier-carrier interaction from single layer transport measurements in these systems, such as weak-localizationlike corrections [6,7], the near translational invariance of these systems prevents any direct measurement of the carrier-carrier scattering rate. On the other hand, double layer structures provide a system in which carrier-carrier interaction can be studied directly. This arises from the fact that now single layer momentum conservation has been relaxed. Drag measurement [8], performed by driving a current (I_D) through one of the layers and measuring the potential (V_D) which arises in the other layer due to momentum transfer, allows one to measure the interlayer carrier-carrier interactions directly. The drag resistivity (ρ_D), given by V_D/I_D, is directly proportional to the interlayer carrier-carrier scattering rate. In this sense, the drag is a very powerful tool, and it has been used in the past to study a variety of different electronic states [9]. Here, we study the drag as the system is spin polarized to gain insight into the role interactions and spin play in the 2D metallic phase.

In this Letter, we present drag measurements, on dilute double layer hole systems, in an in-plane magnetic field. We accompany these data by the corresponding single layer in-plane magnetoresistance (MR) measurements. We point out that here we have studied the drag in the exact same regime in which numerous single layer in-plane magnetotransport experiments have been performed [3]. The layer densities of our measurements ranged from 3.25 to 0.9×10^{10} cm^{-2}, all of which exhibited metallic behavior at $B = 0$. Our field measurements ranged up to 14 T, well above the fields required to drive the system insulating or to fully spin polarize the carriers. The magnetodrag traces were taken at different temperatures (T) and different matched layer densities (p_m). Our main observation is that the magnetodrag shows exactly the same qualitative behavior as the single layer MR. In addition, quite unexpectedly, we have found that the enhancement to ρ_D from $B_{\parallel}$ is strongly dependent upon the layer densities being matched.

The sample used in this study is a Si δ-doped double GaAs quantum well structure, which was grown by molecular beam epitaxy on a (311)A GaAs substrate. We have used the same sample in our earlier Letter [10] on the drag in this dilute regime at $B = 0$. The sample structure consists of two 150 Å GaAs quantum wells separated by a 150 Å AlAs barrier, corresponding to a center to center layer separation of 300 Å. The average grown densities and low temperature mobilities of each layer are 2.5×10^{10} cm^{-2} and 1.5×10^5 cm^2/V s, respectively. The sample was processed allowing independent contact to each of the two layers, using a selective depletion scheme [11]. In addition, both layer densities are independently tunable using evaporated metallic gates.

The data presented in this Letter were taken in a top loading dilution refrigerator, with a base temperature of 60 mK. The sample was mounted on the end of a tilting probe, with which the sample could be rotated, *in situ*, from 0 to 90° relative to the field. The densities in each layer were determined by independently measuring Shubnikov–de Haas oscillations. We point out that all of the in-plane field measurements presented here were done with the magnetic field aligned perpendicular to the current direction. Drive currents between 50 pA to 2 nA were passed, in the $[\bar{2}33]$ direction, through one of the layers, while the drag signal was measured in the other layer, using standard lock-in techniques at 4 Hz. To ensure that no spurious sources were contributing to our signal, all the standard consistency checks associated with the drag technique were performed [8,10].

We begin our presentation of the data by first looking at the $B_{\|}$ dependence of ρ_D and the single layer resistivity (ρ) at matched layer densities of 2.15×10^{10} cm^{-2}. This is presented in Fig. 1, for $T = 80$, 175, 250, and 400 mK. In the inset in Fig. 1(a), the single layer in-plane MR is presented [12]. Here similar behavior to that reported in previous single layer studies is observed [3,5,7]. At low fields, the MR is well described by a $aB^2 + c$ fit. A crossing point (B_c), indicating a transition from metalliclike ($d\rho/dT > 0$) to insulating behavior ($d\rho/dT < 0$), is observed at a field of $B_c = 3$ T. The characteristic "shoulder" (B^*), indicating the onset of full spin polarization [13], is also seen at $B^* = 5.3$ T. In addition, for fields $B > B^*$, the system exhibits positive MR, consistent with previous reports in GaAs [5,7,14]. In Fig. 1(a), this data is presented, normalized by its zero field value. The corresponding normalized drag data is plotted in Fig. 1(b). Note here the strikingly similar behavior to that seen in the normalized single layer MR in Fig. 1(a). In both cases, the dependence at low fields is well described by a quadratic increase. Also, the drag shows a crossover to a weaker dependence at exactly the same field of 5.3 T, where B^* is observed in the single layer. In addition, the drag increases with field above B^*, just as in the single layer transport. Also, in both cases, the trace becomes much sharper and shows more increase as T is lowered. In the inset in Fig. 1(b), the raw drag data is presented. Note that the only difference observed is the absence of a crossing point in the drag, indicating that here ρ_D exhibits a monotonically increasing T dependence at all fields.

Next we turn our attention to the $B_{\|}$ dependence of ρ_D and ρ at different matched densities at $T = 80$ mK, which is presented in Fig. 2. In the inset in Fig. 2(a), the single layer in-plane MR is plotted for densities of 3.25, 2.15, 1.75, 1.5, and 1.2×10^{10} cm^{-2}. Note here that our data reproduce the same qualitative trends previously

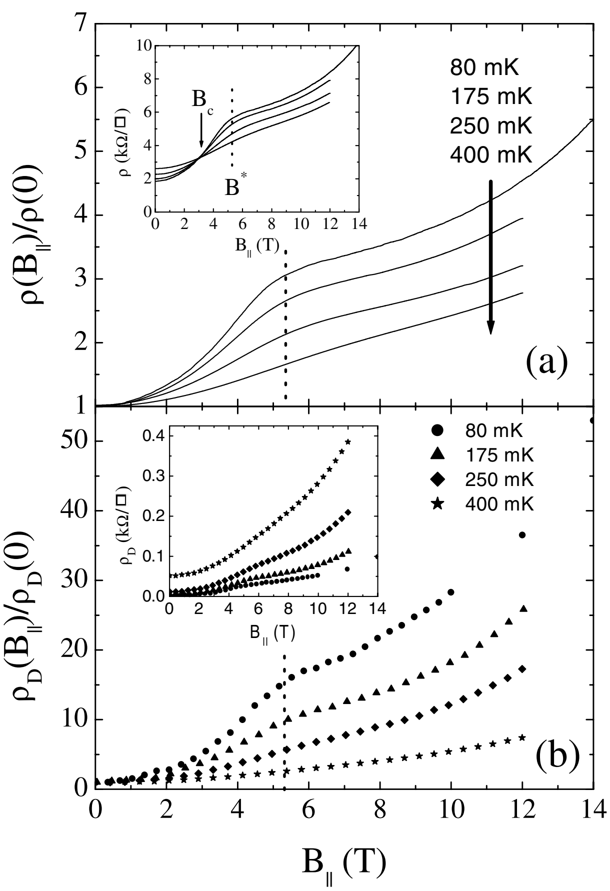

FIG. 1. In-plane magnetotransport data for $p_m = 2.15 \times 10^{10}$ cm^{-2} at $T = 80$, 175, 250, and 400 mK. (a) Inset: ρ vs $B_{\|}$. B_c and B^* are indicated by the arrow and the dashed line, respectively. Main plot: Data from inset normalized by its $B_{\|} = 0$ value. (b) Inset: Corresponding data for ρ_D vs $B_{\|}$. Main plot: Data from inset normalized by its $B_{\|} = 0$ value.

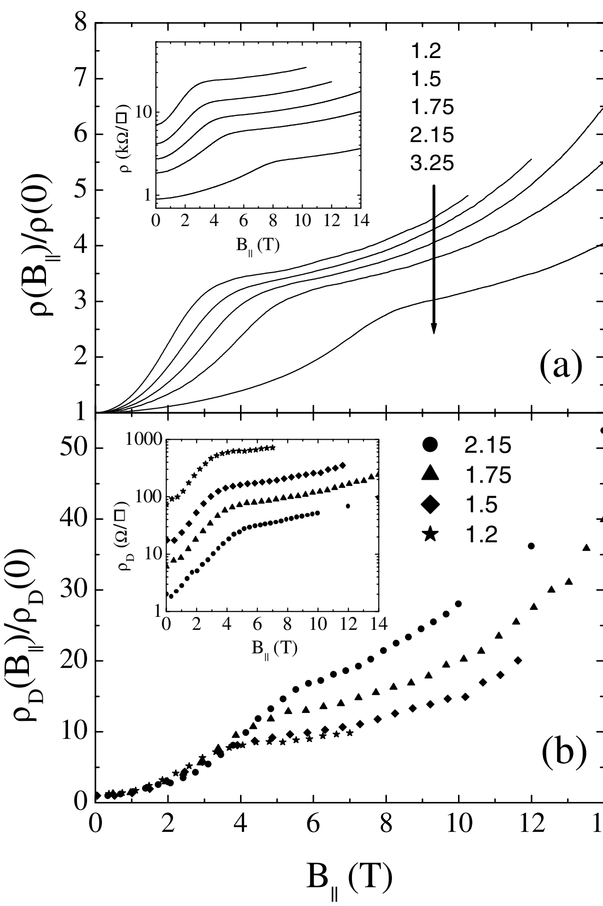

FIG. 2. ρ and ρ_D vs $B_{\|}$ at $T = 80$ mK for different densities. (a) Inset: ρ vs $B_{\|}$ for (from bottom to top) $p = 3.25$, 2.15, 1.75, 1.5, and 1.2×10^{10} cm^{-2}. Main plot: Data from inset normalized by its $B_{\|} = 0$ value. (b) Inset: ρ_D vs $B_{\|}$ for (from bottom to top) $p_m = 2.15$, 1.75, 1.5, and 1.2×10^{10} cm^{-2}. Main plot: Data from inset normalized by its $B_{\|} = 0$ value. Density for each trace is indicated in the legend.

reported, namely, that B^* shifts to lower field as the density is lowered [3–5,7]. Although not shown due to space limitations, if B^* is plotted vs density, a linear dependence with positive intercept, in agreement with previous reports in GaAs [5,7], is obtained. In the inset in Fig. 2(b), we plot the corresponding drag data [15]. Again, we observe qualitatively the same trends observed in the single layer transport; B^*, deduced from the magnetodrag, decreases as p_m is lowered, and if plotted vs p_m a linear fit with positive intercept is obtained. Although the $B_\parallel$ dependence of both ρ and ρ_D exhibit the same qualitative trends, quite interesting differences become evident when they are normalized by their $B_\parallel = 0$ values. This is presented in Figs. 2(a) and 2(b), respectively. The single layer transport data in Fig. 2(a) reveal that as the density is lowered the enhancement to the resistivity increases. This observation is consistent with numerous studies performed in the past [5,7,13]. Note that the normalized drag data, in Fig. 2(b), look quite different from the normalized single layer traces. At low fields, the data seem to collapse, indicating that the enhancement from $B_\parallel$ is independent of matched density. This implies that the matched density dependence of ρ_D (a p_m^{-5} power law was found at low temperatures for $B_\parallel = 0$) is unaffected by a small parallel magnetic field. At higher fields, we find the opposite trend to what we see in the single layer. Here ρ_D shows more enhancement at higher matched density, unlike the single layer resistivity whose enhancement is largest at lower density. In addition, at these higher fields, roughly defined by $B > B^*$, it is clear the dependence of ρ_D on p_m starts to deviate significantly from that found at $B_\parallel = 0$.

Finally, we conclude our study by investigating how ρ_D is affected by mismatching the layer densities in the presence of a parallel magnetic field. In Fig. 3 we plot ρ_D vs the drive layer density (p_{drive}) at $T = 300$ mK, for $B_\parallel = 0$, 2, 3, 5.3, 10, and 14 T. Here the drag layer density (p_{drag}) is fixed at 2.15×10^{10} cm^{-2} and p_{drive} is swept from 3.25 to 0.9×10^{10} cm^{-2}. Note that at zero field we find a strictly monotonic dependence as observed earlier, with no signature at matched density [10]. In general, we have found that at zero field, for $T \lesssim 0.5 T_F$ (T_F is the Fermi temperature), ρ_D follows roughly a $p^{-2.5}$ dependence upon either layer density (p). Note that as $B_\parallel$ is increased, the traces still show monotonic behavior, but the shape of each curve differs more from that at zero field. The trace at $B_\parallel = 14$ T is drastically different from the zero field trace, exhibiting a very sharp increase and then a crossover to a weaker dependence as p_{drive} is lowered through matched density. It is clear from this that the component of the drag arising from $B_\parallel$ has quite a different dependence on density ratio than the zero field component of ρ_D. To examine the component of ρ_D which arises from $B_\parallel$ more carefully, the strong zero field background must be scaled out of the data. This is done in the inset, where the density sweep data at a fixed value of $B_\parallel$ is normalized by the data at zero field. Looking at the figure, it is clear that the enhancement to ρ_D from $B_\parallel$ shows a nonmonotonic behavior upon density ratio, exhibiting a local maximum at essentially matched density. We point out that the same qualitative behavior is also observed at $T = 80$ mK. However, due to small signal measurement limitations, obtaining the data for $p_{\text{drive}} > 2.5 \times 10^{10}$ cm^{-2} at this temperature was not possible. Another interesting feature is that at lower fields, it appears that the peak is slightly to the left of the matched density point and appears to shift towards it as $B_\parallel$ increases. This peak at matched density is quite surprising, in that it implies that the nature of the component of ρ_D arising from $B_\parallel$ is quite different than the zero field component, and we can provide no suitable explanation for it at this point.

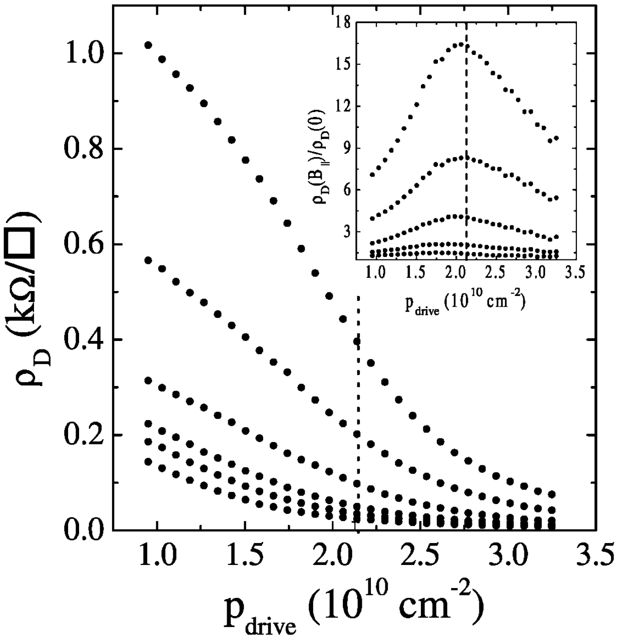

FIG. 3. ρ_D vs p_{drive}, for $p_{\text{drag}} = 2.15 \times 10^{10}$ cm^{-2}, at $T = 300$ mK. The curves are, from top to bottom, for $B_\parallel = 14$, 10, 5.3, 3, 2, and 0 T. Inset: Same data scaled by the dependence at $B_\parallel = 0$. From top to bottom, the curves are for $B_\parallel = 14$, 10, 5.3, 3, and 2 T. In both, matched density is indicated by the dashed line.

The similarity between the $B_\parallel$ dependence of ρ and ρ_D is quite astonishing, due to the fact that the nature of the resistivity and the drag are extremely different. Attempting to explain the origin of the magnetodrag seems a difficult task, primarily since, despite numerous studies accounting for percolation transport [16], screening changes [17], spin-flip scattering [18,19], and orbital effects [20], there exists no definitive explanation as to the origin of the single layer in-plane MR. At this point, some comments on the properties of our magnetodrag data in light of a few of these mechanisms are in order.

We first focus on the change in the screening properties as the system undergoes spin polarization. In single layer systems, the dominant contribution to the resistivity arises from ionized impurity scattering. Therefore, these studies [17] concentrated upon how the static screening of the ionized impurity potential changes as the system is spin polarized. It could be envisioned that similar changes in the screening could increase the strength of the interlayer Coulomb potential. In turn, this could lead to the observed enhancement of the drag with $B_{\|}$. However, in this case we would be concerned with the dynamic screening properties of the 2D system [21], which are quite different from the static properties.

While the similarity of the magnetodrag and the MR offers some clues, any attempts at understanding the origin of the component of ρ_D arising from $B_{\|}$ must focus upon explaining its sensitivity to matched density. Although screening changes could possibly explain the enhancement to ρ_D, it is difficult to see how they could give rise to a drag sensitive to matched density. The peak at matched density shown in the inset in Fig. 3 provides very important information. It tells us that energy and momentum conservation lead to a suppression of the interlayer carrier-carrier scattering process, which gives rise to the magnetodrag, when the layer densities are mismatched. For example, this conservation leads to a peak at matched density in drag processes arising from phonon exchange [22] or $2k_F$ scattering [23]. However, from our zero field density ratio data [10], we feel neither of these gives rise to the magnetodrag. On the other hand, we comment on the possibility of intersubband scattering processes playing an important role in this regime. In these cases, energy and momentum conservation would lead to ρ_D exhibiting sensitivity at matched density.

In single layer MR studies, the effect of finite layer thickness was taken into account by considering the coupling of $B_{\|}$ to the orbital motion of the carriers [20]. In this model, the MR arises from an increase in the scattering rate between subbands produced by the confining potential in the z direction, and the carrier spin does not play any role. This study was successful in providing one possible origin of the high field MR observed in GaAs samples. Generalizing this mechanism to our double layer system, it is possible to envision an intersubband scattering process between carriers in each layer. Here a carrier in each layer would scatter into a different subband produced by its confining potential. Making the assumption that the subband energies do not change with density and gate voltage (which is valid for this sample structure), then energy and momentum conservation would suppress this process for mismatched densities.

Another intersubband scattering mechanism that can be envisioned is a spin-flip scattering process. Recent single layer experiments have provided evidence that magnetic impurity spin-flip scattering could also play an important role in the in-plane magnetotransport [18]. These studies concluded that the application of $B_{\|}$ led to an increase in the spin-flip scattering rate, which in turn suppressed the "metallic" behavior. In the drag it is not quite clear how an interlayer spin-flip scattering process can occur. Whereas a carrier and magnetic impurity can interact through spin exchange, there is no exchange in the interlayer carrier-carrier interaction potential in our double layer system. However, an indirect carrier scattering event via a magnetic impurity can be envisioned, leading to a change in the spin states of the carriers. It is then possible that energy and momentum conservation would require the Fermi wave vectors of each layer to be matched.

In conclusion, we have found that the magnetodrag exhibits exactly the same qualitative behavior as the single layer in-plane MR. In addition, we have found that the magnetodrag is sensitive to the density ratio of the two layers, exhibiting a maximum at matched density.

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