

**Coulomb drag near the metal-insulator transition in two dimensions**R. Pillarisetty,<sup>1</sup> Hwayong Noh,<sup>1,2</sup> E. Tutuc,<sup>1</sup> E. P. De Poortere,<sup>1</sup> K. Lai,<sup>1</sup> D. C. Tsui,<sup>1</sup> and M. Shayegan<sup>1</sup><sup>1</sup>*Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA*<sup>2</sup>*Department of Physics, Sejong University, Seoul 143-747, Korea*

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We studied the drag resistivity between dilute two-dimensional hole systems, near the apparent metal-insulator transition. We find the deviations from the  $T^2$  dependence of the drag to be independent of layer spacing and correlated with the metalliclike behavior in the single-layer resistivity, suggesting they both arise from the same origin. In addition, layer-spacing dependence measurements suggest that while the screening properties of the system remain relatively independent of temperature, they weaken significantly as the carrier density is reduced. Finally, we demonstrate that the drag itself significantly enhances the metallic  $T$  dependence in the single-layer resistivity.

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**I. INTRODUCTION**

Two-dimensional (2D) electron transport in semiconductor heterostructures has provided a rich venue for the study of electron interaction physics, exhibiting such exotic states as the fractional quantum Hall liquid.<sup>1</sup> Here strong interactions, induced by a large perpendicular magnetic field, stabilize this non-Fermi liquid state. Recently, much attention in the field has focused upon dilute 2D systems, which are characterized by large ratios of carrier interaction energy to kinetic energy ( $r_s > 10$ ). These systems exhibit an anomalous metalliclike behavior and an apparent metal-insulator transition,<sup>2</sup> contradictory to the scaling theory of localization.<sup>3</sup> To date, the origin of the metallic behavior is unclear, with several fundamental questions regarding this regime still unanswered. Among the most important of these are the nature of the many-body correlations and screening properties in this dilute limit. To gain insight into both of these issues, we have performed frictional drag measurements.

Drag measurement<sup>4</sup> allows one to directly study carrier-carrier interactions. These experiments are performed, on double layer systems, by driving a current ( $I_D$ ) in one layer, and measuring the potential ( $V_D$ ), which arises in the other layer due to momentum transfer. The drag resistivity ( $\rho_D$ ), given by  $V_D/I_D$ , is directly proportional to the interlayer carrier-carrier scattering rate. Furthermore, the layer spacing ( $d$ ) dependence of the drag provides a powerful probe of both the interlayer correlations and the screening properties, which exist in the system. Any change in either of these properties will manifest itself in the layer spacing dependence of the drag. Recently, the drag was measured between low density hole systems,<sup>5</sup> with  $r_s$  approximately ranging from 10 to 20.<sup>6</sup> In this regime,  $\rho_D$  showed a two to three orders of magnitude enhancement over the theory for weakly interacting systems,<sup>7</sup> and the corresponding low density electron results.<sup>8</sup> In addition, an anomalous temperature ( $T$ ) dependence, which could not be explained in light of previously studied drag processes, was observed, with  $\rho_D$  exhibiting a greater than  $T^2$  dependence at low temperatures. Upon further increase of  $T$ , a crossover to a weaker than  $T^2$

dependence was observed. It was proposed that these deviations arose from many-body correlations in such a strongly interacting regime.<sup>5,9</sup>

In this article, we study the density, temperature, and layer-separation dependence of the drag between strongly interacting 2D hole systems, in the vicinity of the apparent metal-insulator transition. Using these data, we show that the deviations from the  $T^2$  dependence of the drag are not a result of a phonon mediated drag process,<sup>10,11</sup> but rather arise from a novel mechanism related to the large  $r_s$  value of the system. We find these deviations to be independent of layer spacing, implying that they arise from an intralayer correlation effect. Furthermore, we find that the deviations to the  $T^2$  dependence of the drag are correlated with the metalliclike  $T$  dependence in the single-layer resistivity, suggesting that both anomalies have the same origin. Our layer spacing dependence data imply that while the screening properties in this regime remain relatively independent of temperature, they weaken significantly as the carrier density is reduced toward the metal-insulator transition. Finally, we demonstrate that the Coulomb drag effect itself can significantly enhance the metallic  $T$  dependence in the single-layer resistivity.

**II. EXPERIMENTAL DETAILS**

Four different samples were used in this study. Each sample contains a double quantum well structure, consisting of two Si doped  $p$ -type GaAs quantum wells separated by a pure AlAs barrier,<sup>12</sup> which was grown by molecular beam epitaxy on a (311)A GaAs substrate. Sample A, which was used in an earlier study,<sup>5</sup> has an average grown layer density and center to center layer separation of  $2.5 \times 10^{10} \text{ cm}^{-2}$  and 300 Å, respectively. Samples B and C were similar to sample A, with the exception of having different center to center layer separations of 225 and 450 Å, respectively. Sample D was a higher density sample, having an average grown layer density and center to center layer separation of  $7.0 \times 10^{10} \text{ cm}^{-2}$  and 275 Å, respectively. Explicit details of the parameters for each of these four samples are listed in Table I. The samples were processed allowing independent contact

TABLE I. Sample parameters. Mobilities quoted at 300 mK.

Sample	A	B	C	D
Average layer density [ $\times 10^{10} \text{ cm}^{-2}$ ]	2.5	2.5	2.5	7.0
Top layer mobility [ $\times 10^5 \text{ cm}^2/\text{V s}$ ]	1.5	1.9	2.9	5.7
Bottom layer mobility [ $\times 10^5 \text{ cm}^2/\text{V s}$ ]	1.5	1.3	1.7	7.7
Quantum well thickness [ $\text{\AA}$ ]	150	150	150	175
Barrier thickness [ $\text{\AA}$ ]	150	75	300	100
Center to center layer separation [ $\text{\AA}$ ]	300	225	450	275

to each of the two layers, using a selective depletion scheme.<sup>13</sup> In addition, both layer densities are independently tunable using evaporated metallic gates.

The data presented in this paper were obtained using <sup>3</sup>He and dilution refrigerators. The densities in each layer were determined by independently measuring Shubnikov-de Haas oscillations. Drive currents between 50 pA and 10 nA were passed, in the  $[\bar{2}33]$  direction ( $d=300 \text{ \AA}$ ), 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.<sup>4</sup>

### III. RESULTS AND DISCUSSION

We begin our presentation of the data by first looking at the temperature dependence of the drag in the dilute regime at different layer spacings. This is presented in Fig. 1, where we plot  $\rho_D/T^2$  versus  $T$  at matched densities ( $p_m$ ) of  $2.5 \times 10^{10} \text{ cm}^{-2}$ , for  $d=225, 300,$  and  $450 \text{ \AA}$ . For clarity, the data from the  $d=450 \text{ \AA}$  sample have been multiplied by a factor of 6.5. The error bar shown for the  $d=225 \text{ \AA}$  data is due to a small interlayer leakage contribution. Note that both the  $d=225$  and  $450 \text{ \AA}$  samples exhibit the same qualitative

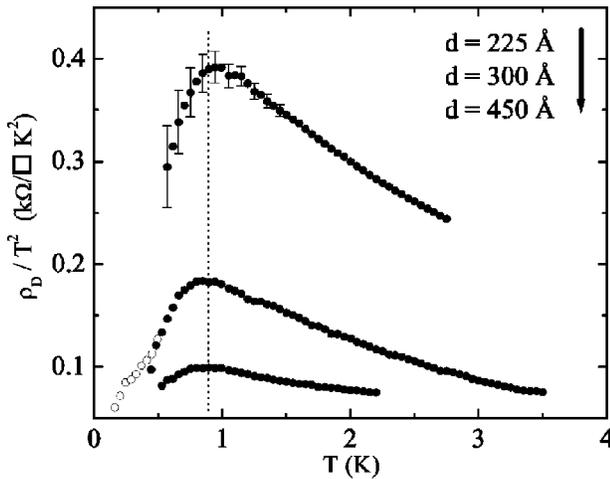


FIG. 1.  $\rho_D/T^2$  vs  $T$  at  $p_m=2.5 \times 10^{10} \text{ cm}^{-2}$ , for different  $d$ . For clarity, data from the  $d=450 \text{ \AA}$  sample has been multiplied by a factor of 6.5. The dashed line marks the peak position. Open circles measured in the dilution refrigerator.

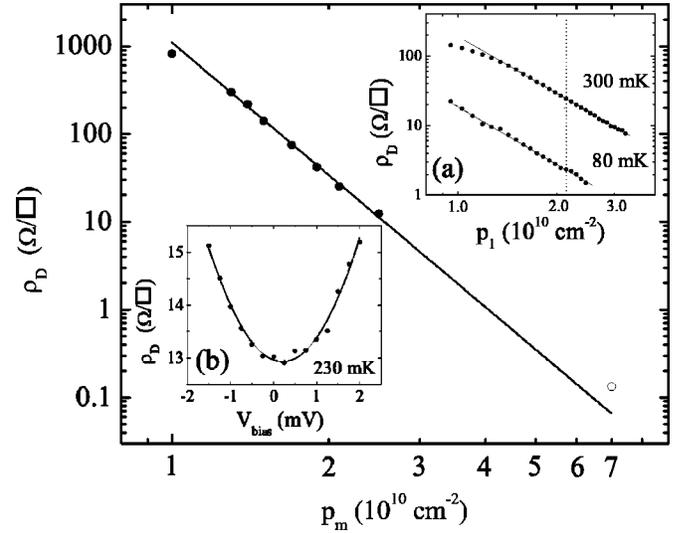


FIG. 2.  $\rho_D$  vs  $p_m$  on log-log scale, at  $T=300 \text{ mK}$ . Data from samples A ( $d=300 \text{ \AA}$ ) and D ( $d=275 \text{ \AA}$ ) are shown by closed and open circles, respectively. The solid line is a fit with slope  $-5$ . Inset (a):  $\rho_D$  vs  $p_1$  on log-log scale, with  $p_2=2.15 \times 10^{10} \text{ cm}^{-2}$ , at  $T=80$  and  $300 \text{ mK}$ . Solid lines are fits with slope close to  $-2.5$ . Dashed line indicates matched density. Inset (b):  $\rho_D$  vs  $V_{bias}$ ,  $p_m=2.1 \times 10^{10} \text{ cm}^{-2}$  and  $T=230 \text{ mK}$ .

behavior, showing a peak in  $\rho_D/T^2$  versus  $T$ , as was reported earlier<sup>5</sup> at  $d=300 \text{ \AA}$ . In addition, the peak position in  $\rho_D/T^2$  versus  $T$ , marked by the dashed line, appears to be independent of layer separation. Although not shown here, we also observed this at lower densities.

Before discussing these data, we would like to show that these deviations from the  $T^2$  dependence are not a result of a phonon mediated drag process.<sup>10,11</sup> It has been well established that a contribution from  $2k_F$  phonon exchange to the drag will produce deviations from the expected  $T^2$  dependence, which are qualitatively similar to those shown in Fig. 1. However, the fractional deviation from  $T^2$  arising from a phonon mediated process should decrease considerably as  $d$  is reduced. This stems from the fact that as  $d$  is reduced, the direct Coulomb component of the drag increases significantly, whereas the phonon mediated component increases with a much weaker  $d$  dependence.<sup>11</sup> The data in Fig. 1 show that the fractional deviation from  $T^2$  is roughly independent of  $d$ . Here, at all three layer spacings,  $\rho_D/T^2$  changes roughly 25% to 30%, from 0.5 to 2.0 K.

Furthermore, to conclusively rule out the phonon mediated process, we present the relative density dependence of the drag at  $d=300 \text{ \AA}$ , in inset (a) of Fig. 2. Here we have measured  $\rho_D$  as a function of one layer density ( $p_1$ ), while keeping the other layer density fixed at  $p_2=2.15 \times 10^{10} \text{ cm}^{-2}$ . It has been demonstrated that the phonon mediated component of the drag is strongly suppressed as the layer densities are mismatched.<sup>10,11</sup> If  $2k_F$  phonon exchange contributes to the drag in our samples, one would expect to see some signature of a local maximum at matched density in these density ratio measurements. However, as shown in the inset, where  $\rho_D$  is plotted on log-log scale against  $p_1$  at both  $T=80$  and  $300 \text{ mK}$ , the drag exhibits no signature of a

local maximum at matched density, and is described by a linear fit with slope close to  $-2.5$ , implying  $\rho_D \propto (p_1 p_2)^{-5/2}$  at low temperatures.<sup>14</sup> The deviation from the fit at low density in the 300 mK trace is a consequence of the density dependent crossover in the  $T$  dependence of  $\rho_D$ .<sup>5</sup>

To provide yet further evidence against the presence of  $2k_f$  phonon exchange in our samples, we have performed density imbalance measurements.<sup>8</sup> These measurements are performed by measuring  $\rho_D$  as a function of interlayer bias ( $V_{bias}$ ). Interlayer bias transfers carriers between the layers, while keeping the total density in both layers fixed. Such a measurement provides a very sensitive probe as to the presence of phonon mediated<sup>10,11</sup> (or direct<sup>8</sup>)  $2k_f$  scattering. A series expansion of the power law  $(p_1 p_2)^{-5/2}$  dependence deduced from our density ratio measurements implies that  $\rho_D$  will exhibit a quadratic increase with interlayer bias. If  $\rho_D$  contains any significant contribution from  $2k_f$  phonon exchange, this will clearly lead to the drag decreasing as a function of  $V_{bias}$ . In inset (b) of Fig. 2, we plot  $\rho_D$  versus  $V_{bias}$  at  $T=230$  mK. Here the layer densities are matched at  $2.1 \times 10^{10} \text{ cm}^{-2}$  at zero bias. It is clear from the figure that  $\rho_D$  exhibits a quadratic increase with  $V_{bias}$ , consistent with our density ratio results. Here  $T/T_F=0.07$ , so thermal broadening of the Fermi surface is negligible. These data conclusively show that  $2k_f$  phonon exchange<sup>10,11</sup> (or direct  $2k_f$  scattering processes<sup>8</sup>) do not yield any significant contribution to the drag at  $d=300$  Å.

In the main plot of Fig. 2, we investigate the matched density dependence of  $\rho_D$ . Here  $\rho_D$  versus  $p_m$  is plotted on log-log scale for densities ranging from  $p_m=1.0$  to  $2.5 \times 10^{10} \text{ cm}^{-2}$ , taken from sample A ( $d=300$  Å), and at  $p_m=7.0 \times 10^{10}$ , taken from sample D ( $d=275$  Å). We find that these data are very well described by a linear fit with slope of  $-5$ , implying that for this density range, corresponding to  $r_s=5.1$  to  $13.5$  (using  $m^*=0.17m_e$ ),  $\rho_D$  follows a  $p_m^{-5}$  dependence at low temperature, consistent with our density ratio results. In the Coulomb drag theory for weakly interacting systems,<sup>7</sup> which is successful in explaining the results of drag experiments performed on high density electron systems<sup>4</sup> with  $r_s \sim 1$ ,  $\rho_D$  is expected to scale as  $p_m^{-3}$ . The stronger density dependence we have observed here is consistent with earlier reports<sup>5</sup> that the drag between low density holes exhibits a significant enhancement over this simple theory, with the discrepancy increasing as the density is reduced. In this context, what is of particular interest is a recent experiment, on low density electron double layer systems with  $d=280$  Å, which studied the drag in a regime of intermediate interaction strength, with  $r_s$  ranging from about 2 to 4.3.<sup>8</sup> This study also found that the drag exhibited a power-law dependence on the matched electron density ( $n$ ), and observed that  $\rho_D \propto n^{-4}$ . This result suggests that there is a crossover in the behavior of the drag from a  $p_m^{-3}$  to a  $p_m^{-5}$  dependence as the  $r_s$  value of the system is increased. This provides yet further evidence that the large enhancement of the drag and the deviations from the  $T^2$  dependence found in the dilute regime arise from correlation effects.

It is important to note that the deviations we have observed could arise from two different types of correlation effects: either interlayer or intralayer correlations. The  $T$  de-

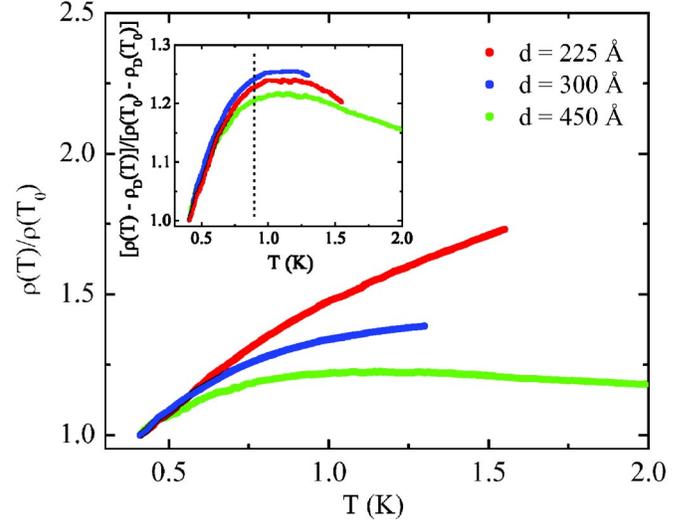


FIG. 3. (Color online)  $\rho(T)/\rho(T_0)$  vs  $T$  at  $p=2.5 \times 10^{10} \text{ cm}^{-2}$  for different  $d$ . Inset:  $[\rho(T) - \rho_D(T)]/[\rho(T_0) - \rho_D(T_0)]$  vs  $T$ . Dashed line marks the peak position in  $\rho_D/T^2$  vs  $T$ .  $T_0=400$  mK.

pendence data for different  $d$  shown in Fig. 1 provides very useful information regarding differentiating between these two effects. If the deviations from the  $T^2$  dependence arise from an interlayer correlation effect, we should expect them to exhibit a significant change as the layer spacing is varied. However, this is not what is observed. Both the fractional deviation from  $T^2$  and the peak position are found to be independent of  $d$ , implying that interlayer correlation effects are not playing a role here, and that the deviations arise from something intrinsic within each of the single layers themselves.

At this point, it is appropriate to compare the deviations from the  $T^2$  dependence of the drag to the metalliclike behavior observed in the individual layers of the samples used in this study. Many believe that this strong metalliclike temperature dependence arises from correlation effects, which exist in such a large  $r_s$  regime. By independently contacting one of the layers in our double-layer system, we can measure the temperature dependence of the single-layer resistivity. However, it is important to realize that the resistivity obtained from such a measurement is significantly enhanced due to the drag effect. Due to its large magnitude, the drag effect will make a significant contribution to the single-layer resistivity. Since the drag has a relatively strong temperature dependence, this will significantly affect the strength of the metallic behavior obtained in a single-layer resistivity measurement. This is demonstrated in Fig. 3, where we have plotted the normalized  $T$  dependence of the single-layer resistivity, at  $p=2.5 \times 10^{10} \text{ cm}^{-2}$ , for different  $d$ . For reference, the single-layer resistivities at  $T=400$  mK are 1.48, 1.83, and 1.85  $k\Omega/\square$  for the  $d=225, 300,$  and  $450$  Å samples, respectively. While all three of the samples here have intrinsically similar properties (resistivity and mobility), it is clear that the metallic behavior becomes much stronger as  $d$  is reduced, as should be expected from the increasing drag contribution. Therefore, it is appropriate to subtract the drag resistivity from the measured single-layer resistivity to obtain

the intrinsic single-layer resistivity—that is the resistivity which would be measured if the layers could be separated infinitely far apart. This is shown in the inset, where we subtract  $\rho_D$  from  $\rho$  and plot the normalized  $T$  dependence of  $\rho - \rho_D$ . Note here that the metallic behavior in all three curves shows roughly the same strength, confirming that the change in the metallic behavior of the single layer resistivity, shown in the main plot, arises from the drag contribution to the resistivity. The most striking feature here is that the temperature at which the metallic behavior is suppressed in  $\rho - \rho_D$  is at roughly the same temperature at which the peak in  $\rho_D/T^2$  versus  $T$  is observed, as shown by the dashed line in the inset. In addition, in these three samples, the metallic temperature dependence produces a roughly 20% to 25% change in  $\rho - \rho_D$ . This is extremely close to the 25% to 30% deviation from  $T^2$ , which  $\rho_D$  exhibits over the same temperature range. These similarities seem to suggest that the deviations from the  $T^2$  dependence of the drag are correlated with the anomalous metallic behavior found in the single layer, and implies that they most likely have the same origin.

The fact that both the single-layer resistivity and the drag exhibit similar anomalies is quite striking, since these are two extremely different transport properties. Although there have been numerous models attempting to explain the origin of the metallic behavior, here we choose to analyze our data in light of one of the most prominent: temperature-dependent screening.<sup>15</sup> In this model, the metallic behavior arises from temperature-dependent changes in the static screening of ionized impurity potentials, which become important at large  $r_s$ . As the temperature is increased from low  $T$ , the screening weakens significantly, leading to the metalliclike increase in the resistivity. It is possible to envision that such a screening change could give rise to the enhancement to the  $T^2$  dependence of  $\rho_D$  found at low  $T$ . However, here we are concerned with the dynamic screening properties of the system as it screens the interlayer Coulomb potential.

If the deviations from the  $T^2$  dependence of the drag arise from a temperature-dependent screening effect then this will surely manifest itself in the layer spacing dependence of the drag. The strength of the  $d$  dependence of  $\rho_D$  is proportional to the screening strength of the interlayer Coulomb potential. If the screening is strong, the interlayer potential will drop rapidly with  $d$  and  $\rho_D$  will show a strong decrease as  $d$  is increased. On the other hand, if screening is weak the interlayer potential will drop off much slower with  $d$ , and  $\rho_D$  will exhibit a much weaker decrease as  $d$  is increased. By investigating the strength of the  $d$  dependence at different temperatures, we can determine whether the dynamic screening properties of the 2D system in this regime exhibit any temperature-dependent behavior. Using data from samples A, B, and C, we have studied  $\rho_D$  as a function of  $d$  at various temperatures, for  $p_m = 2.5, 2.0,$  and  $1.5 \times 10^{10} \text{ cm}^{-2}$ . A typical data set, obtained at  $T = 1.0 \text{ K}$  and plotted on log-log scale, is shown in Fig. 4. As expected, we observe that  $\rho_D$  shows a strong increase with decreasing layer spacing. The solid lines are linear fits of each data set, and their slopes correspond to the exponent,  $\alpha$ , where  $\rho_D \propto d^{-\alpha}$ . Using additional data at different temperatures, which are not shown, we can determine the strength of the  $d$  dependence at each density, for different  $T$ . We present this data in Fig. 5, where we plot  $\alpha$  as

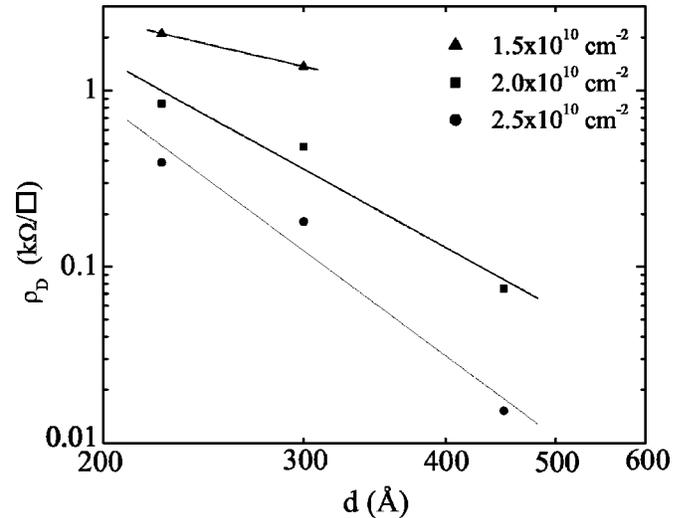


FIG. 4.  $\rho_D$  vs  $d$ , on log-log scale, for  $p_m = 1.5, 2.0,$  and  $2.5 \times 10^{10} \text{ cm}^{-2}$  at  $T = 1.0 \text{ K}$ . Solid lines are the best linear fits of each data set.

a function of temperature for different  $p_m$ . We mention that the  $\alpha$  found for  $p_m = 1.5 \times 10^{10} \text{ cm}^{-2}$  is deduced only using data at  $d = 225$  and  $300 \text{ \AA}$ . Before discussing these data, we would first like to mention that due to the narrow range of data we are not making any quantitative claims on the values of these exponents. On the other hand, a comparison of the relative change of  $\alpha$  with temperature and density is perfectly valid and independent of any of the systematic error in the  $d$  values of our samples. The first point we make is that at all three densities, the exponent shows a weak increase with  $T$ , implying that the dynamic screening properties in this regime are relatively independent of temperature. If anything, the screening strengthens slightly as  $T$  is increased, the opposite of what should be expected from the  $T$ -dependent screening model. Another point which is clear from the data is that the strength of the  $d$  dependence weakens significantly as the carrier density is lowered. This implies that the dynamic screening properties of the 2D system weaken dra-

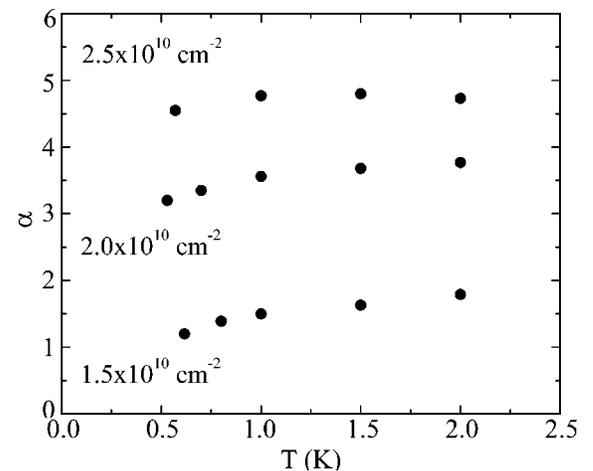


FIG. 5.  $\alpha$  vs  $T$  for  $p_m = 1.5, 2.0,$  and  $2.5 \times 10^{10} \text{ cm}^{-2}$ .  $\alpha$  deduced from fitting  $\rho_D$  vs  $d$  to a  $d^{-\alpha}$  fit.

matically as the carrier density is reduced toward the metal-insulator transition.

Finally, we would like to refer back to the single-layer transport data presented in Fig. 3, which clearly show that in the dilute regime, the drag constitutes a significant fraction of the resistivity. In contrast, at small  $r_s$  (Ref. 4) the drag contribution to the resistivity is roughly 0.1% at these temperatures. This demonstrates that in the dilute regime an electron-electron (e-e) scattering process can yield a substantial  $T$ -dependent correction to the resistivity, and suggests the possibility that the metallic behavior seen in so many dilute 2D systems might arise from an e-e scattering process. For example, a theory on the interaction corrections<sup>16</sup> in this regime has been shown to qualitatively explain the metalliclike temperature dependence measured in experiments.<sup>17</sup> In this theory the disorder breaks the translational invariance of the system, and allows e-e scattering to make a finite contribution to the resistivity. Our data suggest that the magnitude of this interaction correction could possibly constitute a significant fraction of the resistivity. Another possibility is that the electron system forms two channels, with only one carrying the current, which has been suggested by local compressibility measurements.<sup>18</sup> Here interchannel e-e scattering contributes to the resistance of the current carrying channel and

could possibly create the metallic  $T$  dependence. This is analogous to the double-layer system, in which only one layer carries current and the other layer causes dissipation via interlayer e-e scattering.

#### IV. CONCLUSIONS

In conclusion, we have shown the deviations from the  $T^2$  dependence of the drag to be independent of layer spacing and correlated with the metallic  $T$  dependence in the single-layer resistivity, suggesting that both anomalies have the same origin. Our studies of the strength of the layer spacing dependence of  $\rho_D$  imply that the dynamic screening properties in this regime are relatively temperature independent. However, they weaken significantly as the carrier density is reduced. Finally, in this dilute regime, we have demonstrated that the drag effect itself can significantly enhance the metallic behavior in the single-layer resistivity.

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<sup>14</sup>For completeness, we would like to mention that density ratio measurements in the  $d=450$  Å sample exhibit features near matched density, which indicate the presence of a small phonon mediated drag contribution. However, we believe that the deviation from the  $T^2$  dependence in this sample arises from the same mechanism that produces this deviation in the samples with smaller  $d$ . This is since we find that the deviations from the  $T^2$  dependence at  $d=450$  Å are unaffected by significantly mismatching the layer densities, along with the fact that both the fractional deviation to  $T^2$  and the peak position in  $\rho_D/T^2$  vs  $T$  are the same as those found at smaller layer spacing.

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