Anomalous Coulomb Drag in Electron-Hole Bilayers

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We report Coulomb drag measurements on GaAs-AlGaAs electron-hole bilayers. The two layers are separated by a 10 or 25 nm barrier. Below $T \approx 1$ K we find two features that a Fermi-liquid picture cannot explain. First, the drag on the hole layer shows an upturn, which may be followed by a downturn. Second, the effect is either absent or much weaker in the electron layer, even though the measurements are within the linear response regime. Correlated phases have been anticipated in these, but surprisingly, the experimental results appear to contradict Onsager's reciprocity theorem.

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Pairing between quasiparticles constituting a Fermi-liquid system leads to some of the most interesting phenomena in solid-state physics, such as paired atoms in superfluid ^{3}He and Cooper pairs of electrons in superconductors. The presence of electrons and holes in a semiconductor naturally leads to the possibility of binding like that found in a hydrogen atom. The bosonic nature of these excitons follows, because they are paired states of spin-$\frac{1}{2}$ particles. The very short lifetimes (usually nanoseconds) and the charge neutrality of these bound pairs place them outside the realm of transport measurements. Short lifetimes may also inhibit the formation of coherent equilibrium phases like a Bose condensate [1]. Separating the electrons and holes spatially, with a thin barrier, would prevent recombination and lead to increased lifetimes. Exciting predictions have been made on the possibility of novel phases in such electron-hole (*e-h*) bilayers. Early proposals [2] relied on *n*-semiconductor-insulator-*p*-semiconductor structures to achieve this. The rapid improvements in GaAs/AlGaAs heterostructure technology in the 1980s and subsequent development of closely spaced double quantum-well structures in the 1990s led to the first realistic possibilities of making such a system. The Coulomb drag technique, in which a current passed through one layer induces an open-circuit voltage in the other layer, is a direct measure of the interlayer interaction. The effect [3,4], analogous to momentum transfer between layers of a viscous fluid, was first experimentally demonstrated between a pair of two-dimensional electron gases ($2 \times$ 2DEG) [5]. In *e-h* bilayers a divergence of longitudinal Coulomb drag was predicted to occur at the onset of an excitonic condensation [6,7]. An excitonic dipolar superfluid with a phase that couples to the gradient of the vector potential has also been conjectured [8,9]. However, a recent careful calculation [10] of the electron and hole polarizabilities (in an *e-h* bilayer) has emphasized the fact that a finite interlayer scattering rate (i.e., drag) at $T = 0$ is not possible within the Fermi-liquid picture. The $\nu = 1$ bilayer state in $2 \times$ 2DEG and a pair of two-dimensional hole gases ($2 \times$ 2DHG) emulates a true *e-h* bilayer in certain ways [11]. Experiments on these systems showed a remarkable collapse of the Hall voltage and finite drag as $T \rightarrow 0$, suggesting transport by charge neutral entities [12].

The fabrication of closely spaced and independently contacted *e-h* bilayers presents considerable difficulties compared to electron-electron and hole-hole bilayers. These are now well understood [13] and significant improvements have been made [13–16] since the first reported device by Sivan *et al* [17]. Fabrication of *e-h* bilayer devices where the barrier between electron and hole layers is similar to the excitonic Bohr radius of GaAs ($\approx$12 nm) and measurement of Coulomb drag down to millikelvin temperatures are now possible. In this Letter we report Coulomb drag data from four devices (Table I). Generalized structure of these is shown in Fig. 1. The details of the wafer design, growth, band structure and processing techniques have been described earlier [13,16]. We start with an inverted 2DHG with little or no doping, such that it can be backgated after the sample is thinned to about 50 μm. Using the 2DHG as a gate we induce a 2DEG above an AlGaAs barrier. The 2DEG forms only under an interlayer bias, slightly higher than the band gap of GaAs, 1.52 V. The contacts to the 2DEG must not penetrate the barrier, to avoid leakage current between the two gases. This is achieved by using the negative Schottky barrier at an $n+$ InAs/metal interface [13], which requires no annealing. A near-flatband condition must be maintained between the InAs/GaAs and the 2DEG for the mechanism to work. The electron density (n) is fixed by the interlayer bias (V_{eh}) only. The hole density (p) is a function of V_{eh} and the backgate voltage (V_{bg}). By measuring n and p at different V_{eh} but fixed V_{bg}, we can obtain a quantitative measure of the interlayer capacitance and hence the peak-to-peak separation (d) of the wave functions. For the 25 nm barrier, this gives $d \approx 37$ nm and for the 10 nm barrier $d \approx 25$ nm.

Devices A and D, where matched densities were obtained were measured till $\sim$50 mK. The temperature dependence of the Coulomb drag on the hole layer showed an upturn as the temperature was lowered below $T \approx 1$ K,

TABLE I. Summary of the device parameters. Devices A, B, and C have a 25 nm $Al_{0.3}Ga_{0.7}As$ barrier and D has a 10 nm $Al_{0.9}Ga_{0.1}As$ barrier.

Device [wafer ID]	p-doping (cm^{-3})	QW width	Barrier	Matched densities possible
A [A4142]	Undoped	20 nm	25 nm	Yes
B [A4005]	1×10^{17} (carbon)	40 nm	25 nm	No
C [A3524]	2×10^{18} (beryllium)	40 nm	25 nm	No
D [A4268]	5×10^{16} (carbon)	20 nm	10 nm	Yes

followed by a downturn (see Figs. 2 and 3). Devices B and C were measured in the range 6 K–300 mK, and showed an upturn. We emphasize that these features are only seen in devices with very low barrier leakage—typically $I_{\text{leak}} < 50$ pA over a Hall bar 600 μm $\times$ 60 μm in size at an interlayer bias of ~1.6 V. A low temperature upturn in Coulomb drag in similar density and temperature ranges has also recently been reported by Seamons *et al.* [18].

Figure 2 shows the measurement of Coulomb drag using device A in full detail. The drag voltage was measured in two ways, by sending current through the electrons and measuring the open-circuit voltage across the holes ($\rho_{D,h} = V_h/I_e$) or by sending current through the holes and measuring the voltage across the electrons ($\rho_{D,e} = V_e/I_h$). As long as the current is low enough so that the system is in the linear response regime, thermodynamic arguments [19] predict that $\rho_{D,e} = \rho_{D,h}$.

In our data this is well satisfied above $T \sim 1$ K and $\rho_{D,e/h} \propto T^2$ approximately. The origin of this behavior is well known [20]. Below $T \sim 1$ K, as T decreases, $\rho_{D,h}$ starts increasing, passes through a maximum, and decreases in both devices A (Fig. 2) and D (Fig. 3). It does not appear to be going to zero in either case, as $T \to 0$. A finite drag resistivity, at $T = 0$ is not possible within a Fermi-liquid picture. It has only been predicted for a paired electron-hole superfluid [6,7] and an incompressible paired quantum Hall state, with the temperature dependence (near $T = 0$) determined by disorder and not only the available phase space [21]. In this context, it is important to point out that if the scattering rate is calculated using the Born approximation, the square of the interlayer screened

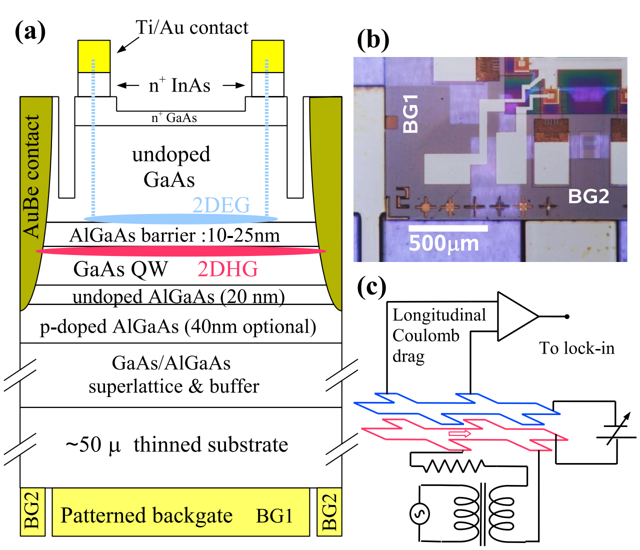

FIG. 1 (color online). (a) Generalized schematic of the devices. The p-doping and hole QW width vary between devices, as given in Table I. (b) Photograph of the sample showing the alignment of the backgates. (c) Schematic of the circuit for Coulomb drag measurements. The backgate and the topgate are omitted for clarity.

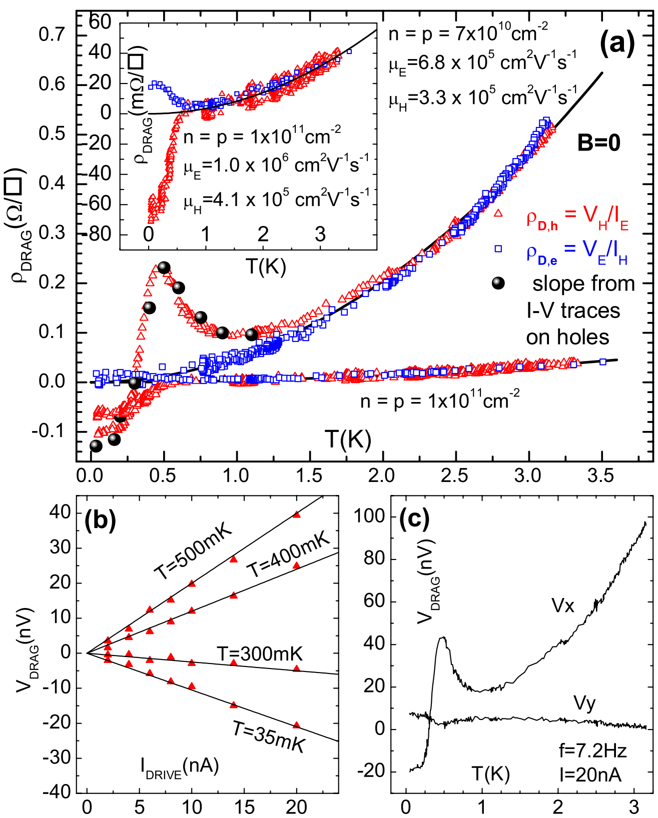

FIG. 2 (color online). (a) Data from device A. The drive current was 20 nA, 7 Hz for all the traces. The solid black lines are best fits to a T^2 behavior. The inset shows an expanded view of the lower trace at $n = p = 1.0 \times 10^{11}$ cm^{-2}. The upturn was no longer observed at this density on the holes, but the downturn can be seen. (b) Raw data showing the linearity of drag voltage with drive current and (c) relatively flat behavior of the out-of-phase component (V_y) as measured by the lock-in, when the in-phase (V_x) component goes through an upturn and sign reversal.

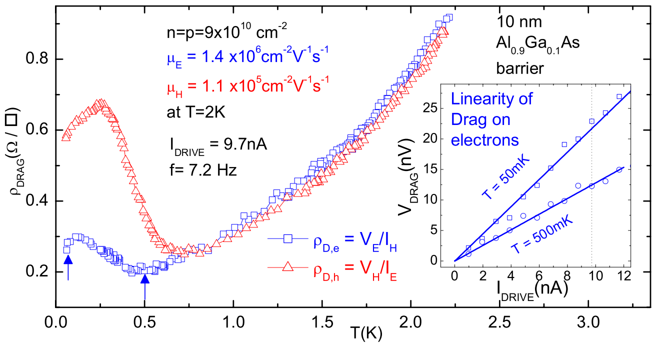

FIG. 3 (color online). Data from device *D*. The upturn and the beginning of the downturn are clearly seen. A much weaker effect is seen for the electrons than the holes. The inset shows that the measurements are clearly within the linear response regime.

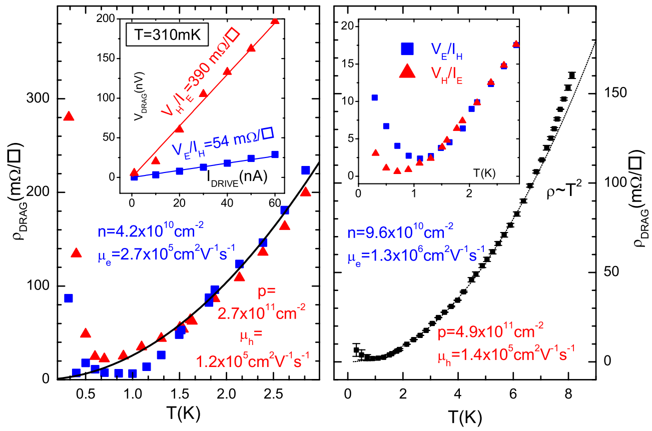

FIG. 4 (color online). (Left) Data from device *B*. The inset shows that the linearity of drag voltage and drive current is not compromised. (Right) Data from device *C*. In the main figure, the error bars represent the difference of the drag voltage measured by interchanging the drag and drive layers. The inset shows the expanded view of the upturn.

Coulomb potential is used and the matrix element will not distinguish an attractive interaction from a repulsive one. Emergence of binding or pairing, that may lead to a qualitative change in the matrix element for the interlayer scattering rate, cannot not be correctly accounted for by simple first order theory of scattering [7]. The initial upturn, that we observe, can be qualitatively explained if a small fraction of the particles enter into a paired state and has been anticipated [6,7]. However, there are two rather surprising aspects of our data, which a simple pair formation hypothesis cannot explain. First, the upturn appears to be followed by a downturn at low densities and low temperatures. Second, the effect is absent or much weaker, when the current is driven through the hole layer. Figures 2(b) and 3 (inset) show that the system continues to be in the linear response regime throughout the temperature range where the upturn (in all the devices), downturn (in devices *A* and *D*) and the sign reversal (in device *A* only) are observed. The effect is free from thermal hysteresis or drifts with time—the data of Fig. 2 represented by the red triangles and blue squares was collected while the temperature was decreasing, the data points represented by large black dots were collected while the device was being warmed up. Data from devices *B* and *C* (measured down to 300 mK) show a similar upturn (see Fig. 4). The effect is very small in device *C*, possibly because of the high hole density. The presence of this upturn over a wide range of densities from matched to strongly unmatched, suggests that equal densities are not a necessary condition to observe this feature. We have verified by shifting the biasing point from one end of the hall bar to another, that leakage errors ($V_{\mathrm{error}} \approx I_{\mathrm{leak}} R_{\mathrm{singlelayer}}$) do not change the measured values of drag significantly. Also devices with high leakage (due to defects in the barrier, gate leakage, etc.) do not show any of these low temperature features. Measurements using currents as low as 1 nA did not reveal any deviation from linear response. Straight line fits to the I_{drive}-V_{drag} data [Figs. 2(b) and 3 (inset) and 4 (left, inset)] show zero offset indicating the absence of rectified noise in the system. If indeed a critical current exists (as may happen for a pinned lattice or a Wigner crystal state) below which the layers behave symmetrically, it appears to be extremely small. Since there is no change of slope in the I_{drive}-V_{drag} traces at low currents, we rule out Joule heating as well. Figure 5 shows the effect of keeping the carrier density of one layer constant, while varying the other for device *D*, which had a 10 nm $Al_{0.9}Ga_{0.1}As$ barrier. The

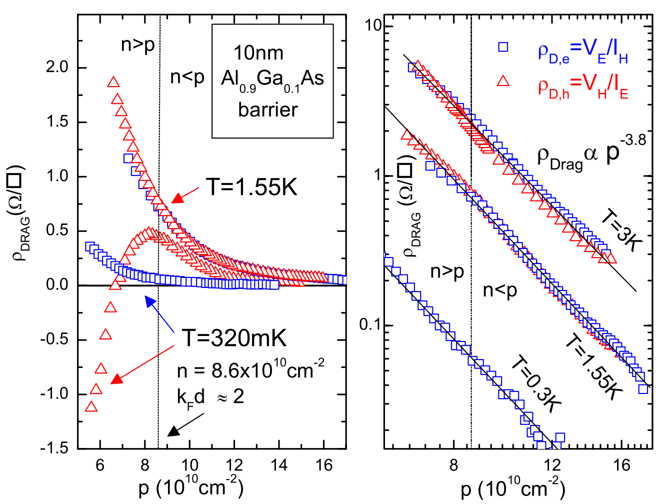

FIG. 5 (color online). Data from device *D*, with a 10 nm $Al_{0.9}Ga_{0.1}As$ barrier. The dotted vertical line in both panels denote the point where $n = p$. At this density, considering an effective peak-to-peak separation of $d = 25$ nm, we get $d/l \approx 2$, with $l = 1/\sqrt{(2\pi n)}$. The red triangles denote drag measured on the holes ($\rho_{D,h}$), the blue squares denote drag measured on electrons ($\rho_{D,e}$). The data at $T = 1.55$ K are repeated on both panels for comparison.

right panel shows that a power law $\rho_{D,e} \propto p^{-3.8}$ holds between 0.3–3 K. The traces taken at $T = 3$ K, 1.5 K show that $\rho_{D,h}$ and $\rho_{D,e}$ agree very well, but not at 0.3 K. Similarly, if the hole density is constant, we get $\rho_{D,h} \propto n^{-0.5}$ (data not shown). If we consider only $\rho_{D,e}$ then even at $T = 0.32$ K, the $n = p$ condition does not appear to be special. On the other hand, as observed in other devices, $\rho_{D,h}$ shows a strong deviation from a simple power law ($\sim T^2$) at $T \sim 1$ K. At matched densities in bilayers, d/l is the same as $k_F d$. It is interesting to ask whether the nature of $\rho_{D,h}$ changes around $n = p$ or when large angle scattering starts dominating (i.e., $k_F d$ is small). However, at this stage we do not have enough data to address this point.

Coulomb drag measurements on 2×2DEGs in a magnetic field have been reported by several authors [22–26]. At large filling factors (i.e., low magnetic fields), it is found that if the deviation from half filling (of the highest Landau level) is opposite in the drive and drag layers, then ρ_D is negative (electron-hole-like) at low temperatures. However, at higher temperatures, when $k_B T$ becomes larger than disorder broadening of the levels, ρ_D turns positive again. The temperature above which negative drag is no longer observed is consistent with experimental values of disorder broadening of the Landau levels in a sample ($\sim$1 K in high mobility samples, estimated from the quantum scattering times, $T \sim \hbar/k_B\tau$). It has also been emphasized that the excitations near the Fermi surface must not have particle-hole symmetry for ρ_D to be nonzero [22,26]. If the Fermi level in any one layer lies exactly at the center of a spin-resolved Landau level, then that level would acquire this symmetry and its contribution to drag would diminish. As the Fermi energy passes through successive levels, a complex sequence of positive, zero, and negative drag can result. The data shown in Fig. 2 has a strong resemblance to that reported in [26] for $\nu = 7.5, 9.5$, etc. This similarity is unexpected at $B = 0$, for the results presented here. Without a mechanism of generating discrete levels (like Landau levels) the concept of disorder broadening cannot be applied. In 2DEGs and 2DHGs, one expects continuous $E(k)$ dispersion. Unless a gap appears, level broadening is not meaningful. One might speculate about the appearance of a gap in a coupled 2DEG-2DHG system due to pairing or localization, but we refrain from doing so at this point.

In conclusion, we have shown that the interlayer scattering rate in closely spaced electron-hole bilayers exhibits novel features over a wide density range, which cannot be explained within the Fermi-liquid picture. While the origin of these is not understood at present, our experimental data is distinctly in the linear response regime and as such the disagreement with the reciprocity theorem [19], may point to a robust aspect of the bilayer ground state.

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