Coulomb Drag in the Exciton Regime in Electron-Hole Bilayers

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(Received 8 August 2008; published 14 January 2009)

Electron-hole bilayers are expected to make a transition from a pair of weakly coupled two-dimensional systems to a strongly coupled exciton system as the barrier between the layers is reduced. Coulomb drag measurements on devices with a 30 nm barrier are consistent with two weakly coupled 2D Fermi systems where the drag decreases with temperature. For a 20 nm barrier, however, we observe an increase in the drag resistance as the temperature is reduced when a current is driven in the electron layer and voltage measured in the hole layer. These results indicate the onset of strong coupling possibly due to exciton formation or phenomena related to exciton condensation.

Two-dimensional (2D) bilayers composed of electrons in one layer and holes in the other are expected to exhibit Bose-Einstein condensation (BEC) of excitons at zero magnetic field [1,2]. Recent progress in several different systems has demonstrated evidence for exciton condensation using both electrical and optical techniques. Quantum Hall bilayer [3] experiments utilize the half-filled Landau level at high magnetic fields to explore BEC in electron-electron [4] and hole-hole [5] bilayers. In optically generated bilayer excitons, evidence for condensation has been building [6,7] and recently BEC has been reported in polariton [8,9] systems. One system where exciton condensation is expected is the electrically generated 2D electron and 2D hole bilayer at zero magnetic field. Here we report evidence for electron-hole pairing in GaAs/AlGaAs based electron-hole bilayers using the Coulomb drag technique. An increase in the drag signal at lower temperature indicates a dramatic increase in coupling between the layers.

Examples of electron-hole bilayers that behave as 2D Fermi systems have been demonstrated for years [10–15], but only recently have bilayers with closely spaced layers that can be measured at the low temperatures needed to enter the exciton regime been fabricated [14,16]. The devices reported here have narrow barriers between the wells, independent electrical contacts to the electrons and holes, and independently tunable density in each layer. Equally important to producing the device is employing a measurement that provides a clear means of identifying non-Fermi liquid behavior. The Coulomb drag measurement [17], where current in one layer induces a voltage in the other, can be quantitatively understood for weakly coupled Fermi liquid bilayers. In this case, the drag resistance develops as a result of interlayer scattering (Coulombic, phonon, etc.) and decreases as the temperature is lowered due to the vanishing phase space for scattering events. At the other extreme, for an exciton condensate it is predicted that the drag resistance will increase dramatically at the critical temperature [18] and

diverge as the temperature is lowered. Even above the critical temperature for BEC, the drag could increase with decreasing temperature due to pairing fluctuations above the critical temperature [19]. This dramatic change of a decreasing drag resistance to an increasing drag resistance is an important theoretical prediction.

The device schematic in Fig. 1(b) shows the concept of the undoped electron-hole bilayer (uEHBL) GaAs heterostructure. A detailed explanation of the device fabrication and operation is given by Seamons *et al.* [14]. The 2D electron gas (2DEG) and the 2D hole gas (2DHG) are induced using gates that create an internal electric field in the heterostructure [20,21]. Carriers are pulled into the top (bottom) 18 nm wide GaAs quantum well by applying a voltage between an overall top (bottom) gate and an n-type (p-type) Ohmic contacts fabricated in a field effect transistor geometry. For the three samples studied here, the double quantum wells are separated by $Ga_{0.1}Al_{0.9}As$ barriers of either 30 nm for sample A (wafer EA1286) or 20 nm for samples B and C (wafer EA1287). This design incorporates both independent contacts and adjustable density of the 2DEG and the 2DHG. To operate the uEHBL a p-type contact of the 2DHG is grounded, while the 2DEG is at a dc interlayer bias $V_{IL} \sim -1.45$ V needed to overcome the band gap of GaAs, thereby allowing simultaneous occupation of both electrons and holes in these closely spaced layers [22]. Both the n-type and p-type contacts are Ohmic. Ideally the gates are completely isolated, but in the actual devices we observe leakage currents both from the gates [20] and between the electron and hole layers. Of the two leakage paths, current flowing between the layers is the most important. For the data reported here, the dc current is less than 1 nA. It is independent of temperature below 3 K, and at the lowest density the leakage currents (both at the gates and between the layers) are the smallest. The main impact of current leakage of the gates is heating at the lowest temperature of a dilution refrigerator, and for the data reported here we used a ^{3}He refrigerator with a base temperature of 0.3 K. Transport is
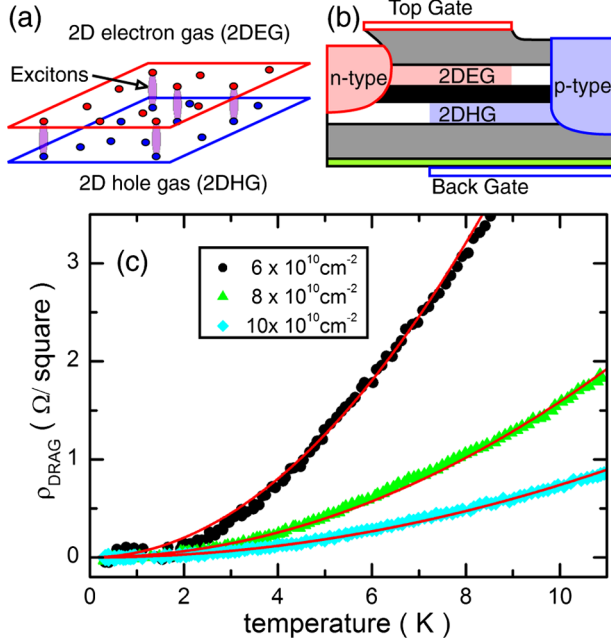
FIG. 1 (color online). (a) Formation of excitons occurs as pairing of electron and hole in opposite layers. (b) Schematic cross section of the uEHBL sample: the layers from the top to bottom are the top gate, $Al_{0.3}Ga_{0.7}As$ 2DEG, $Al_{0.9}Ga_{0.1}As$ barrier (black), 2DHG, $Al_{0.3}Ga_{0.7}As$, SiN insulator, and back gate. (c) Drag resistivity for sample A at matched electron and hole densities of 6×10^{10} cm^{-2} (black, circles), 8×10^{10} cm^{-2} (green, triangles), and 1.0×10^{11} cm^{-2} (cyan, diamonds) is typical for Fermi systems. The red lines are T^2 best fits.

measured using lock-in voltage detection and small ac currents. An isolation transformer combines the ac current through the 2DEG with the required dc voltage V_{IL} of the entire electron layer.

Once the 2DEG and 2DHG are established the density of carriers in each layer is proportional to its respective gate voltage, allowing for independently tunable densities of the 2DEG (n) and the 2DHG (p). The densities were obtained using standard four-terminal longitudinal or Hall resistance at $T = 0.3$ K. At high density, the mobilities exceeded 1×10^6 cm^2/V s and 4×10^5 cm^2/V s for the electrons and holes, respectively. From the density dependence of the mobility, intralayer scattering is dominated by background ionized impurities [14,23].

With $n = p$, Coulomb drag measurements were taken by sending a current through the drive layer while measuring the voltage induced in the drag layer. A semiclassical Boltzmann calculation of the Coulomb drag resistivity (ρ_{DRAG}) for Fermi systems, assuming high density and large layer spacing [17], reduces to $\rho_{drag} = \alpha T^2/(np)^{3/2}d^4$ where $\alpha = \hbar\zeta(3)(4\pi\kappa\varepsilon_0)^2 k_B^2/128\pi e^6$. Here $\hbar$ is Planck's constant, $\zeta(3) \sim 1.202$ is the Riemann zeta function, κ is the dielectric constant of GaAs, ε_0 is the permittivity of free space, k_B is Boltzmann's constant, T is the temperature, and d is the center to center distance between the

GaAs wells in the drive and drag layers. The results for sample A where the electrons and holes are spaced by 48 nm are shown in Fig. 1(c). For the drag measurements reported here, use $I_{DRIVE} = 50$ nA at 3 Hz in the electron layer. As usual for drag measurements, we verified the same drag signal was observed for a range of ac frequencies, varying drive currents in the electron layer, and different Ohmic contact configurations. Because of the large contact and sheet resistance of the hole layer, Joule heating at low temperature prevented interchange of the drag and drive layer at low temperature; for $T > 1$ K, interchange of the drag and drive layers resulted in the same drag resistivity. Using the Shubnikov–de Haas minima in the electron layer, we directly measured the heating caused by driving current in the hole layer.

As expected for Coulomb scattering in Fermi systems, the drag is approximately proportional to T^2 and lower densities result in larger ρ_{DRAG}. The red lines in Fig. 1(c) are T^2 best fits to ρ_{DRAG} over the range from $T = 0.3$ to 10 K. Quantitatively, the prefactor α is a factor of 7 to 10 larger than the approximate expression for drag noted above. Such an enhancement has been observed for hole-hole bilayer [24–26] and electron-hole bilayers [10], and can be understood in part by deviations from the large layer spacing and high density limit where the T^2 approximation is valid. More detailed scattering calculations including realistic modelling of the actual device structure are in good quantitative agreement with the data [23]. The qualitative agreement of the drag resistivity in sample A with the scattering theory for drag indicates widely spaced layers behave as independent Fermi-liquid systems down to a temperature of $T = 0.3$ K.

The most significant result reported here is found when Coulomb drag is measured in devices where the electrons and holes are closer together. In Fig. 2, the drag resistance for all three devices is shown for fixed densities of $n = p = 8 \times 10^{10}$ cm^{-2}. A T^2 best fit line for data taken on sample A is shown with a thick black line. Multiplying the thick line best fit for sample A by $(48 \text{ nm}/38 \text{ nm})^4$ yields the thin black line. The good agreement between the lines in Fig. 2 and the data above 0.5 K indicates the 2D electrons and holes behave as Fermi liquids, but below 0.5 K in sample B and sample C a significant deviation develops. At a critical temperature (T_u) the drag reaches a minimum, and for lower temperatures there is a pronounced *upturn* of the drag where ρ_{DRAG} increases with decreasing temperature. Measuring ρ_{DRAG} over different regions of the Hall bar, or with reversed source and drain contacts for the current, yields the same results shown in Fig. 2. The ρ_{DRAG} at $T = 0.3$ K in sample C was also measured as a function of perpendicular magnetic field, without any dramatic change in the magnitude of the effect. The upturn does not exhibit a maximum value at balanced densities $n = p$ and for unbalanced densities the temperature dependence continues to exhibit an upturn even when the densities differ by up to 30%.
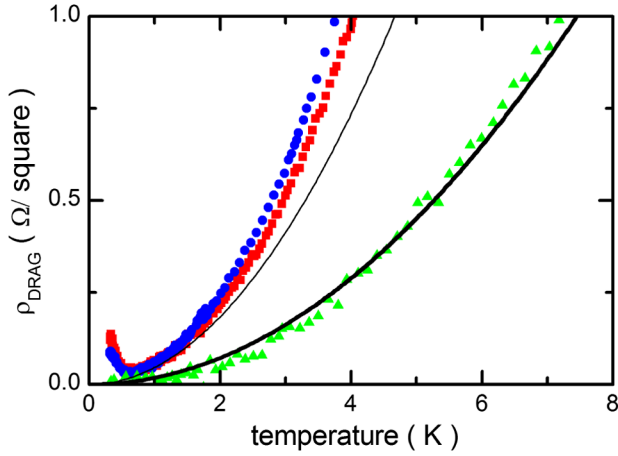
FIG. 2 (color online). ρ_{DRAG} at $n = p = 8 \times 10^{10}$ cm^{-2} for
all three devices [sample A (green triangles), sample B (red
squares), and sample C (blue circles)]. The thick line is a T^2 best
fit for sample A. The thin line is obtained by multiplying the
thick line by the ratio $(d_{30 \; \mathrm{nm\sim barrier}}/d_{20 \; \mathrm{nm\sim barrier}})^4$.

As mentioned earlier, small dc leakage current between
the electron and hole layers are typically present and
independent of temperature below 3 K. For $T > 1$ K,
ρ_{DRAG} is in good agreement with expectations based on
Fermi-liquid theory, and at low temperature the upturn
appears where there is no change in the leakage current.
In addition, the most pronounced upturn in drag is ob-
served for low densities of electrons and holes [Fig. 3(a)],
and this is the same regime where the leakage currents are
smallest. Finally, samples B and C have much different
leakage characteristics, and have nearly the same observed
upturn. For these reasons we believe the increase in drag is
a real effect. Further reduction of the temperature in a
dilution refrigerator (not shown here) resulted in a satura-
tion of the drag resistivity below $T = 0.2$ K. Anomalous
drag with nonmonotonic temperature dependence and lack
of reversibility of the drag and drive layers [27] with some
similar characteristics to the results presented here has
been recently reported in Ref. [16].

In Fig. 3(a), ρ_{DRAG} of sample C is plotted as a function
of temperature for five matched density cases ranging from
6×10^{10} cm^{-2} to 1.0×10^{11} cm^{-2}. The magnitude of
ρ_{DRAG} at a given temperature is strongly dependent on
the density. It is evident in Fig. 3(a) that a minimum in
ρ_{DRAG} at T_u is identifiable for each density case in this
range. While the absolute magnitude of the upturn is
largest for the lowest density signal, there is clearly an
upturn at every density studied even though the overall
drag at high density is reduced. Figure 3(b) shows T_u with
approximate error bars associated for sample B and
sample C as a function of their matched densities. It is
interesting to note that at high density where drag signals
are small, T_u occurs at higher temperature.

The observation of an increasing drag resistance at low
temperature is a clear and qualitative deviation from ex-
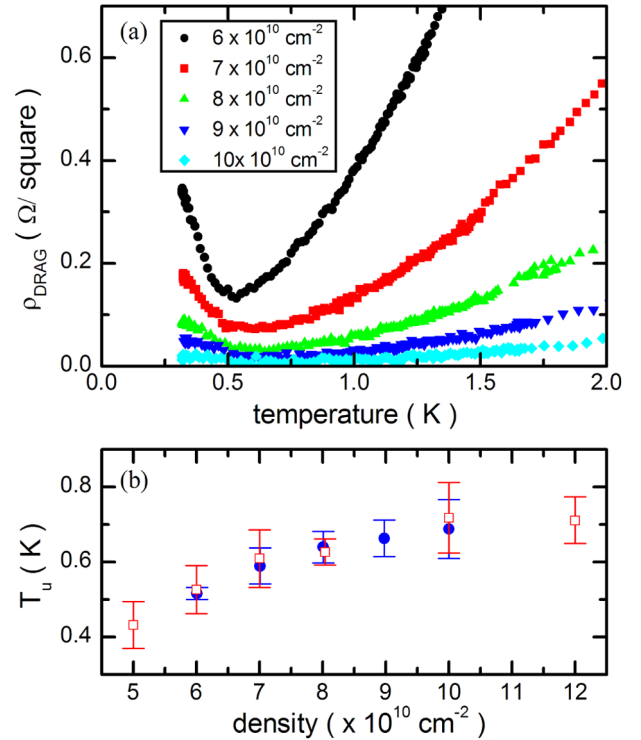pectations based on conventional interlayer scattering the-

FIG. 3 (color online).   (a) ρ_{DRAG} of sample C (20 nm barrier)
as a function of temperature for $n = p = 6 \times 10^{10}$ cm^{-2} (black
circles) to 1.0×10^{11} cm^{-2} (cyan diamonds) in steps of 1×10^{10} cm^{-2}. (b) T_u as a function of $n = p$ for sample B (red open
squares) and sample C (blue circles).

ory for Coulomb drag. Before considering exciton
formation, we first address a number of recent results
that could lead to unusual low temperature drag results.
First, theoretical calculations of Coulomb drag calculating
to the third order for interlayer interactions predict a finite
drag resistance at zero temperature [28]. The predicted
magnitude of the finite drag for parameters appropriate to
the data in Fig. 2 is 10^{-5} $\Omega/\square$ which is far smaller than
0.1 $\Omega/\square$ observed at low temperature. The second possi-
bility is related to fluctuations in the drag resistivity at zero
magnetic field [29] where positive and negative swings on
the order of 10^{-2} $\Omega/\square$ are observed with changes in
density and temperature. In our results with 200 μm
wide Hall bars, the upturn is very repeatable for different
devices and cool downs. We do not observe these meso-
scopic fluctuations of the drag resistivity. The third possi-
bility we consider is an increase in the coupling between
the electron and hole layers as exciton formation occurs.

Exciton formation can affect the drag in a number of
ways. One possibility is that T_u corresponds to the critical
temperature below which an exciton condensate forms.
Vignale and MacDonald [18] predict a discontinuity of
the drag at the critical temperature where excitons form a
condensate and then a subsequent divergence of the drag as
$T \to 0$. In our data, we do not observe a discontinuity, but
rather a more gradual change in the slope. The experimen-
tal system does have disorder, density variations, finite

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currents used in measurements, complicated hole band structure, and many other details that could complicate understanding of any transition to an exciton condensate. Another possibility is that excitons form and condense above the critical temperature for a brief time before rejoining the Fermi sea. This was studied by Hu [19] and is similar to predictions of pairing of composite fermions [30] related to experimental results showing a saturation and increase of the drag at high magnetic field [31]. With a number of approximations, the drag was found to increase as $T^2/\log(T)$ as the temperature approaches the critical temperature from above. Because of the very narrow range of temperature where the drag increases, we were not able to determine an obvious functional form of the data; in fact, we could fit to both a logarithmic increase and an activated increase in drag. Qualitatively, however, the results for pairing fluctuations have similar trends to the measured Coulomb drag. Finally, another possibility that would result in an enhanced drag signal is exciton formation at temperatures too high for condensation to occur. In any of these scenarios, the upturn in drag signals the formation of interlayer electron-hole pairs at zero magnetic field.

In conclusion, temperature dependent Coulomb drag measurements are presented as a function of matched densities for electron-hole bilayers with two different center to center separations. For the larger barrier, the drag resistance can be well described by interlayer Coulomb scattering between fermions. For the narrow barrier device, we observe an increase in the Coulomb drag as the temperature is lowered. The upturn in ρ_{DRAG} was observed in two samples; its presence demonstrates increased coupling between the layers. While it is difficult to demonstrate coherence with a Coulomb drag measurement, the increased coupling suggests pairing of electrons and holes and the formation of excitons in electrically generated electron-hole bilayers.

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