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Density imbalance effect on the Coulomb drag upturn in an undoped electron-hole bilayer

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A low-temperature upturn of the Coulomb drag resistivity measured in an undoped electron-hole bilayer (uEHBL) device, possibly manifesting from exciton formation or condensation, was recently observed. The effects of density imbalance on this upturn are examined. Measurements of drag as a function of temperature in an uEHBL with a 20-nm-wide $Al_{0.90}Ga_{0.10}As$ barrier layer at various density imbalances are presented. The results show drag increasing as the density of either two-dimensional system was reduced, both within and above the upturn temperature regime and with a stronger density dependence than weak-coupling theory predicts. A comparison of the data with numerical calculations of drag in the presence of electron-hole pairing fluctuations, which qualitatively reproduce the drag upturn behavior, is also presented. The calculations predict a peak in drag at matched densities, which is not reflected by the measurements.

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An exciton is a composite boson that forms in bulk semiconductors due to an attractive Coulomb interaction between its fermionic, constituent electron and hole. As such, excitons are expected under certain circumstances to condense at low temperature, where the lowest energy state becomes occupied by a macroscopic number of particles. While the bulk exciton condensate was later determined to be an insulator due to interband transitions which fix the phase of the order parameter,[1] the use of spatially separated electron-hole pairs or "indirect" excitons was predicted to mitigate this issue sufficient for a phase transition to occur.[2,3]

Indirect excitons may be generated optically[4] or via field effect[5,6] in double quantum wells. The distinct advantages of field-effect devices, such as the uEHBL used in this study, are that the densities in each well can be adjusted and then maintained at constant values using gate voltages and the layers have separate electrical contacts to each. Together these allow for the interlayer Coulomb interaction between the electrons and holes to be probed directly using Coulomb drag measurements. Conceived of by Progrebinsky[7] and Price[8] and first demonstrated between two-dimensional electron gases (2DEGs) by Gramila *et al.*,[9] in the Coulomb drag technique a current is driven in one layer of a bilayer device causing a longitudinal voltage to arise in the adjacent layer via interlayer scattering. The measured quantity is the drag resistivity $\rho_D = V_{\mathrm{drag}}/I_{\mathrm{drive}}(L/W)$, where I_{drive} is the current in the drive layer, V_{drag} is the induced voltage in the drag layer, and L/W is the number of squares. In the "weakly coupled" limit, low temperature T and large interlayer separation d, the ρ_D is expected to have a T^2 dependence, due to phase space restrictions on the scattering set by the thermal broadening, and thereby decrease to zero as $T \to 0$.[9,10] Deviation of ρ_D from this behavior, possibly due to enhanced interlayer coupling, would thus suggest a departure from Fermi-liquid physics.

Seizing upon this possibility, Vignale and MacDonald[11] predicted that ρ_D in an electron-hole bilayer system with a superfluid condensate would jump discontinuously at the condensation temperature T_C and diverge as $T \to 0$. In their theory, the current was partitioned into a superfluid portion carried by the condensate and a normal portion carried by the quasiparticles. Further theoretical work by Joglekar *et al.*,[12] which treated the system as a dipolar condensate, confirmed the expected divergence in ρ_D as a consequence of the reduction in the quasiparticle density and the consequently larger electric field required to drive the normal component of the current. Hu[13] also predicted an enhancement of ρ_D above T_C due to electron-hole pairing fluctuations. This mechanism, which is analogous to short-lived Cooper pairs in superconductors, is discussed further below. Thus, any evidence of electron-hole pairing in a bilayer device is expected to manifest in ρ_D measurements as a function of T.

Condensate formation in bilayers was also predicted to manifest as a supercurrent;[2] however, new theory predicts additional restrictions on the experimental setup for observing this supercurrent.[14] For any pairing to occur, however, a requirement for devices with $d \le n^{-1/2}$, where $n^{-1/2}$ is the typical interparticle distance of the two-dimensional system (2DS) with density n, is expected.[15] Practically speaking, such devices are difficult to fabricate and this, in turn, has made finding an electron-hole condensate in a bilayer an elusive goal.

The first measurements of ρ_D in an electron-hole bilayer were accomplished almost two decades ago by Sivan *et al.*[16] and exhibited behavior characteristic of weakly coupled 2DSs dominated by Coulomb scattering. Recently, however, electron-hole bilayer devices with thinner barrier layers (≤ 20 nm) and lower densities ($< 10^{11}$ cm^{-2}) were produced[17–20] and deviations from the weak-coupling T^2 drag behavior began emerging. Early indications came from Seamons,[17] where a distinct upturn of ρ_D measured in the hole layer was found at $T \sim 0.5$ K in two 20 nm barrier width samples. No upturn in ρ_D measured in the electron layer was found, however, possibly because of self-heating from driving current through the highly resistive two-dimensional hole gas (2DHG). Self-heating also precluded measuring ρ_D of the electron layer in this work.

Similar results were concurrently found by the Cambridge group,[18,19] who also highlighted how the difference in ρ_D from interchanging the drag and drive layers directly contradicts the Onsager reciprocity theorem. It was subsequently shown that the ρ_D upturn was followed by a downturn and

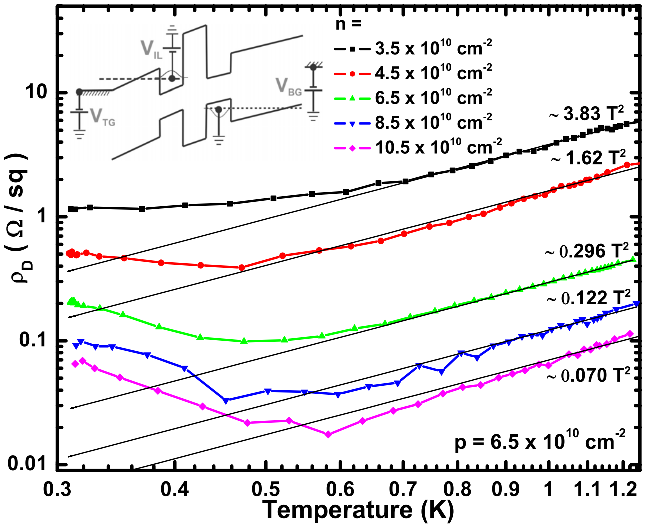

FIG. 1. (Color online) Upturn in ρ_D measured as function of T for n ranging from 3.5 to 10.5×10^{10} cm^{-2} at $p = 6.5 \times 10^{10}$ cm^{-2}. Thin black lines are T^2 best fits. Inset shows a schematic of the band structure during operation.

saturation at a small negative value.[19] Finally, a direct relationship between T_U, the temperature at which the minimum in ρ_D occurs, and matched electron and hole densities $n = p$ was revealed.[17,20] While the details of the ρ_D upturn phenomena remain speculative, exciton formation or condensation is often conjectured to be its source. Beginning to examine this conjecture using the simple means of density imbalance is the primary goal of this Rapid Communication.

Here the effects of density imbalance on the low temperature upturn of ρ_D in an uEHBL are reported. The ρ_D was measured as a function of T for various unmatched densities $n \neq p$ in both 2DSs of the uEHBL. The data showed that ρ_D increased as the density of either 2DS was reduced, with a stronger density dependence than weak-coupling theory predicts. Numerical calculations of electron-hole pairing fluctuation theory were also done for similar density imbalances.[13] While the calculations qualitatively reproduced the upturn observed in the measurements, they also predicted a peak in ρ_D centered at $n = p$, which was not observed.

The details of fabricating and operating uEHBLs were previously discussed.[5,20,21] Based on these results, Hwang and Das Sarma[22] determined the 2DS's mobility in uEHBLs was background charged impurity scattering limited and the enhancement of ρ_D well above T_C was due to exchange effects. A schematic depicting the band structure of an uEHBL during operation, including the top-gate voltage V_{TG}, interlayer voltage V_{IL}, and back-gate voltage V_{BG}, is shown in the inset of Fig. 1. The n and p are predominantly determined by $|V_{\mathrm{TG}} - V_{\mathrm{IL}}|$ and V_{BG}, respectively. The sample (EA1287 6.3) used in this study had a 20 nm wide $\mathrm{Al}_{0.90}\mathrm{Ga}_{0.10}\mathrm{As}$ barrier separating 18 nm GaAs quantum wells. The n and p were measured simultaneously at $T = 0.3$ K prior to each ρ_D temperature sweep using low-field Hall measurements by a standard ac lock-in technique with 10 nA drive currents in each 2DS. The ρ_D measurements were also performed with a standard ac lock-in technique using a 50 nA drive current in the 2DEG at 3.5 Hz. Since the 2DEG is held at $V_{\mathrm{IL}} = -1.465$ V, the current is coupled in via an isolation transformer.

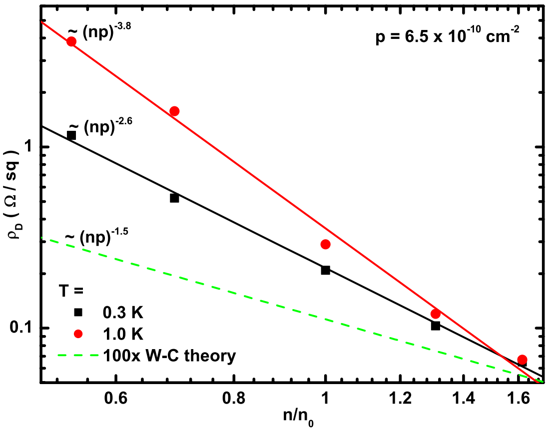

FIG. 2. (Color online) ρ_D as a function of (n/n_0), where $n_0 = p = 6.5 \times 10^{10}$ cm^{-2} at $T = 0.3$ and 1.0 K. The dotted line is 100× weak-coupling analytic theory at $T = 0.3$ K.

Following a similar discussion given in Ref. 20 for both $n = p$ and $n \neq p$ the same drag signal was verified for a range of ac frequencies, drive currents, and ohmic contact configurations. The drag signal also showed no correlations with any changes of the sheet resistances. An interlayer leakage current of ~1 nA or less was measured in this uEHBL. It was independent of temperature within the upturn regime and above it, up to 3 K, where the drag was in good agreement with Fermi-liquid theory. At $n = p$ this leakage was smallest at the lowest densities, where the upturn was most pronounced, and similar behavior was observed at $n \neq p$. The agreement between the drag at high temperature and Fermi-liquid theory combined with additional observations that the upturn in drag is not correlated with the leakage behavior indicates that the upturn is a reliable measurement.

Measurements of the upturn in ρ_D at $p = 6.5 \times 10^{10}$ cm^{-2} for various drive layer densities n are given in Fig. 1. The black lines are best fits $A \cdot T^2$, where A is the single fitting constant and T^2 is the characteristic temperature dependence that results from phase-space requirements in weak-coupling Fermi-liquid theory.[10] Similar results were found for ρ_D measurements at $n = 8.5 \times 10^{10}$ cm^{-2} for various drag layer densities p. Summarizing the behavior, the fit lines provide a clear indication that for $T > T_U$ the ρ_D followed the expected T^2 dependence for Coulomb scattering of a weakly coupled 2DEG and 2DHG. The data also adhered to the following weak-coupling predictions: (1) at $p = n$, the ρ_D increased as matched density was reduced; and, (2) for $p \neq n$, the ρ_D increased if either density was reduced.

In the upturn regime, $T \leq T_U$, the following behaviors are visible: (1) at $p = n$, the T_U increased as total density $n + p$ was increased, similar to what was previously reported;[20] and, (2) for $p \neq n$, the T_U also increased as either p or n was increased. Figure 1 also indicates the upturn is most strongly dependent on T at $n = 10.5 \times 10^{10}$ cm^{-2} and becomes comparatively weaker as n decreases, eventually showing a saturation behavior at $n = 3.5 \times 10^{10}$ cm^{-2}.

In Fig. 2, the same ρ_D data from Fig. 1 at $T = 0.3$ and 1.0 K are plotted as a function of (n/n_0), where $n_0 = p = 6.5$

$\times 10^{10}$ cm^{-2}. The dotted line in Fig. 2 is calculated using the analytic expression for ρ_D, which applies in the limit of large layer spacing d and for low T, given by $\rho_D = \alpha T^2/(np)^{3/2} d^4$, where $\alpha = \hbar \xi(3)(4\pi\kappa\varepsilon_0 k_B)^2/128\pi e^6$.[10] Here $\hbar$ is Planck's constant, $\xi(3) \sim 1.202$ is the Riemann zeta function, κ is the dielectric constant of GaAs, ε_0 is permittivity of free space, and k_B is Boltzmann's constant. The weak-coupling theory is known to dramatically underestimate the measurements[5] and, to aid in the comparison, the dotted line is 100× the theoretical results at $T=0.3$ K.

Summarizing, the main result from Fig. 2 is the monotonic decrease in the measured ρ_D as np was increased, both above and within the upturn regime. This decrease in ρ_D was consistent through the $n=p$ case and for both varying n and p measurements (latter is not shown). As discussed further below, this monotonic decrease with np does not follow the predicted behavior for ρ_D in the upturn regime, where a peak at $n=p$ was predicted.[13]

Additionally, the log-log plot in Fig. 2 also allows for a direct comparison of the $\rho_D(np)$ dependence in each regime. Weak-coupling theory predicts $(np)^{-3/2}$, as shown above. The measurements, however, roughly follow $(np)^{-2.9}$ and $(np)^{-3.7}$ at $T=0.3$ and 1.0 K, respectively. These exponents are both larger than ~ 1.8, which was predicted[23] for this uEHBL based on the theory in Ref. 22. Larger exponents were also previously observed in both 2DHG-2DHG and 2DEG-2DEG drag.[24,25]

To begin examining the experimental results above, a comparison to numerical calculations of Hu's drag equation is made in the following.[13] The reason most often quoted for the upturn in ρ_D is electrons and holes entering a paired state,[17,19,20] as anticipated by Vignale *et al.*,[11] Hu,[13] and Balatsky *et al.*[15] The drag equation devised by Hu, however, offers the simplest means to begin appraising the density imbalance effect on the drag upturn observed in the experimental data. Hu's pairing fluctuation analysis indicates ρ_D will be significantly enhanced above the mean-field transition temperature T_C, similar to the effect of ephemeral Cooper pairs on the conductivity above T_C in superconductors. The calculation neglects to account for impurity potentials and band-structure effects. It uses a simple local interlayer interaction $V(q) = V_0$, which, unlike the more realistic Coulomb interaction,[10,26] fails to cut off the large momentum transfer contributions and thereby significantly overestimates the drag. Despite this well-understood shortcoming, the pairing fluctuation analysis provides the only qualitative comparison for the upturn in ρ_D with the density imbalance data.

An example of a ρ_D calculation is shown in Fig. 3, alongside measured results at $p=n=6.5\times 10^{10}$ cm^{-2} from Fig. 1. For this curve $T_C=0.36$ K was chosen by hand so that T_U of the calculated curve would best match the $n=p$ data. The measured data and the calculated curve show qualitatively similar *nonmonotonic* dependencies on temperature; both traces show ρ_D decreasing with T and then abruptly upturning at T_U. However, the calculated curve predicts a drag magnitude 3 orders larger than the measured data. It also has different temperature dependencies than the data for both $T \le T_U$ and $T > T_U$. In the former, the measured data are finite, while the calculations follow a $T^2 \ln[1/\ln(T/T_C)]$ dependence, which diverges. For $T > T_U$, the calculations follow $T^2/\ln(T/T_C)$ dependence, which differs from the T^2 dependence of the data, indicated by the thin black line in Fig. 3.

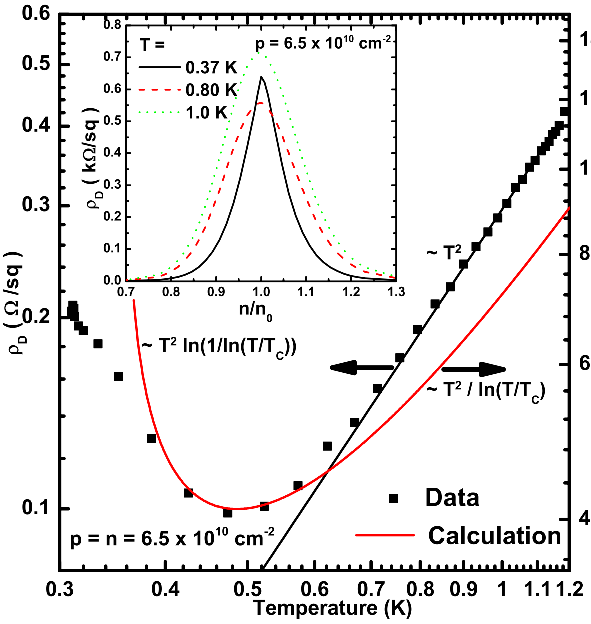

FIG. 3. (Color online) Results of pairing-fluctuation calculations of ρ_D as a function of T plotted alongside measured data for $p=n=6.5\times 10^{10}$ cm^{-2}. The solid black line is a T^2 fit to the measured data. Inset: calculations of ρ_D plotted as a function of (n/n_0) at $T=0.37$, 0.80, and 1.0 K where $n_0=p=6.5\times 10^{10}$ cm^{-2} and n was varied from 4.5 to 9.0×10^{10} cm^{-2}.

The T_C for the calculated ρ_D curves at $n \ne p$ were determined according to the following procedure. For $n < p$ the $T_C = 0.36(n/p)$ K. For curves at $p < n$ the $T_C=0.36$ K was used. This procedure assumes the density of excitons n_{ex} is some fraction of the lesser of n and p and that the transition temperature is proportional to the density, in accordance with the discussion in Ref. 27.

Calculated results at $T=0.37$, 0.8, and 1.0 K are plotted in the inset of Fig. 3 as a function of (n/n_0), where $n_0=p=6.5\times 10^{10}$ cm^{-2} and p was held constant while n was varied from 4.5 to 9.0×10^{10} cm^{-2}. These results predict ρ_D is sharply peaked at $n=p$ for temperatures within and above the upturn regime ($T > 0.5$ K), in stark contrast to the measured results in Fig. 2, where ρ_D increased monotonically with decreasing density.

Thus, while it appears from Fig. 3 that measured data have qualitatively similar nonmonotonic temperature dependence to predictions based on pairing fluctuations, the results in Fig. 2 and the inset of Fig. 3 indicate a sharp difference in their dependence on density imbalance. On the surface, this suggests the ρ_D upturn phenomena observed in the measured results are not a manifestation of electron-hole pairing fluctuations above T_C.

In conclusion, the effects of density imbalance on the low-temperature upturn in ρ_D of an uEHBL were investigated using Coulomb drag measurements. Reducing either 2DS density was found to increase ρ_D for $T \le T_U$ and $T > T_U$. In each regime ρ_D also had stronger np dependence than what was predicted by weak-coupling theory. While calculations of ρ_D in the presence of electron-hole pairing fluctuations were qualitatively able to reproduce the measured upturn behavior, they predicted a peak in ρ_D at $n=p$ that was absent from the measured data.

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