Evidence for virtual-phonon exchange in semiconductor heterostructures

T. J. Gramila* and J. P. Eisenstein
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

A. H. MacDonald
Department of Physics, Indiana University, Bloomington, Indiana 47405

L. N. Pfeiffer and K. W. West
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
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Measurements of frictional drag between adjacent electron gases in double quantum wells provide strong evidence for phonon-mediated electron-electron interactions. These interactions, which dominate the contribution from simple Coulomb scattering at layer spacings larger than a few hundred Å, are between 20 and 100 times stronger than expected for sequential emission and absorption of real phonons. The observed range of the interactions, substantially smaller than the acoustic phonon mean free path, points to an electron scattering mechanism involving virtual-phonon exchange.

Electron-electron (e-e) interactions can fundamentally influence the nature of degenerate electron gases. While direct measurement of e-e scattering rates is usually difficult, various transport techniques have been applied to the study of these interactions. These include determinations of electron dephasing times τ_ϕ, in the diffusive regime[1] through the effects of weak localization, and recently, in the ballistic regime[2] through interference effects on μm length scales. In alkali and noble metals, e-e scattering rates have been estimated by comparing thermal and electrical conductivities.[3] A more direct approach has been the measurement of frictional drag between isolated electron systems.[4,5] The contribution of e-e interactions to the scattering rates determined via these techniques has generally been attributed to Coulomb processes. Phonon-mediated e-e interactions, however, are also potentially important.

In their pioneering work, Hubner and Shockley[6] explored a regime in which phonons do provide a coupling mechanism for electrons. This coupling, between electrons in doped semiconductor layers separated by a thick insulating region, ~ 100 μm, was manifested by the development of a voltage in one layer while current was driven through the adjacent layer. Real phonons were found to be responsible for the interlayer interaction. In this paper, we use a similar technique to explore e-e interactions at much shorter distances, but still in a regime where phonons dominate the interactions. In our experiments, frictional drag between two parallel two-dimensional electron gases (2DEG's) is measured. We find that simple Coulomb scattering, which was important in our earlier study,[5] is dominated by a second, longer range, mechanism if the layer spacings exceeds a few hundred angstroms. The temperature, density, and layer spacing dependence of this second process strongly suggest a phonon-mediated e-e interaction. Unlike the experiment of Hubner and Schockley, however, the magnitude of the coupling cannot be accounted for by real phonon exchange. Furthermore, the observed range of this phonon-mediated interaction, while long compared to that of the Coulomb interaction, is much shorter than the phonon mean free path. These observations provide experimental evidence for an unusual electron scattering mechanism involving the exchange of virtual phonons between the two 2DEG's.

The present frictional drag technique consists of measuring the voltage V_D, induced in one 2DEG when a current I is driven through a second, parallel 2DEG. Since the layers are electrically isolated and tunneling is negligible, V_D is due entirely to interlayer e-e interactions and the ratio V_D/I directly determines the interlayer momentum relaxation rate, τ_D^{-1}. Details of the measurement procedure have been given elsewhere.[5] A similar technique has been used to study interactions between a 2D and a 3D electron system,[4] and recently, between a 2DEG and a 2D hole gas.[7] In our earlier study[5] of drag between two 2DEG's, τ_D^{-1} exhibited a nearly quadratic temperature dependence in a sample with *closely spaced* layers. Calculations based on interlayer Coulomb scattering were found in good agreement with the magnitude of the scattering rate, although observed deviations from a simple T^2 temperature dependence were not accounted for. The variation observed in τ_D^{-1} for a small increase in layer spacing further supported the importance of interlayer Coulomb interactions. For even larger layer spacings, however, the observed scattering rates[8] cannot be accounted for by Coulomb interactions. In this paper, we explore the interactions in this large spacing regime, and examine the nature of the unexpectedly strong long-range e-e coupling. First, we present the experimental evidence for a phonon-mediated e-e interaction. We then argue, based on the magnitude of the observed scattering rates and the behavior at very large layer spacing, that real-phonon exchange cannot account for this long-range interaction, and instead, that a virtual-phonon exchange process is the coupling mechanism.

The samples used in this work are modulation-doped $GaAs/Al_{0.3}Ga_{0.7}As$ double quantum wells grown by molecular-beam epitaxy. Two nearly identical 2DEG's, each with an electron density N near 1.5×10^{11} cm^{-2} and mobility exceeding 2×10^6 cm^2/V s, occupy two 200-Å-wide GaAs quantum wells separated by an undoped $Al_{0.3}Ga_{0.7}As$ barrier. Four samples, A, B, C, and D, with barrier thicknesses of 500, 225, 175, and 5000 Å, respectively, are discussed. They are otherwise structurally identical.

Figure 1 shows the measured interlayer drag scattering rate, τ_D^{-1}, divided by T^2, versus temperature T for sample A. With its 500-Å barrier, the contribution of Coulomb scattering to τ_D^{-1} should be negligible for this sample. The dashed line in the figure represents a realistic estimate of the interlayer Coulomb scattering rate ($\tau_D^{-1} \sim T^2$). The estimate is based on calculations[5] consistent, as discussed above, with the magnitude and spacing dependence seen in our earlier measurements of τ_D^{-1} in thinner barrier samples. Obviously, a different mechanism dominates the interlayer interactions in this sample.

The long-range nature of the scattering mechanism for sample A can be seen by comparing τ_D^{-1}/T^2 with the deviations from simple Coulomb behavior observed[5] for the more closely spaced layers in samples B and C. Apart from a difference in the magnitude of Coulomb scattering, τ_D^{-1}/T^2 for the three samples is nearly identical. This is illustrated in the inset in Fig. 1. The difference in Coulomb scattering ($\tau_D^{-1} \propto T^2$) between the samples has been removed by simply subtracting the constant values 0.41 and 1.08×10^6/s K^2 from the measured τ_D^{-1}/T^2 for samples B and C, respectively. The existence of a second scattering process with a weak layer spacing dependence is clear from the striking similarity of the three data sets. This weak spacing dependence suggests a phonon-mediated interaction, since low-temperature acoustic phonon mean free paths in these samples are orders of magnitude larger than these layer spacings. Furthermore, the temperature dependence displayed in Fig. 1, while obviously inconsistent with the constant τ_D^{-1}/T^2 expected for Coulomb scattering, strongly implies a phonon-mediated interaction. The observed τ_D^{-1} is remarkably similar to the well-known acoustic-phonon-limited mobility scattering rate, τ_{ph}^{-1}, for 2D electrons in GaAs. At high temperatures τ_{ph}^{-1} is linear in T, but crosses over[9] to T^5 or T^7 in the low-temperature Bloch-Grüniesen regime, where thermal phonon wave vectors are less than $2k_F$. For the electron density of these samples the crossover occurs at a few degrees Kelvin. Thus, τ_{ph}^{-1}/T^2 exhibits a temperature dependence broadly similar to the observed τ_D^{-1}/T^2.

Further insight into the nature of the scattering mechanism is provided by measurements as a function of electron density. Applying a bias voltage to an overall Schottky top-side gate alters the density, N_V, of the upper voltage probe 2DEG while the density, N_I, of the current carrying lower 2DEG's remains nearly fixed. Shubnikov–de Haas measurements on the individual layers calibrate the effect of this gate bias. Figure 2 shows τ_D^{-1}/T^2 vs N_V for sample B at three representative temperatures, offset for visibility. The most important feature of these measurements is the peak in τ_D^{-1}/T^2 vs N_V in the 2.3-K data. The peak occurs when the densities in the two layers are matched. This criterion was tested by applying a small additional bias *between* the two 2DEG's, which moves charge from one 2DEG to the other, much like a simple capacitor. The inset in Fig. 2 shows the peak position is shifted by interlayer bias and tracks the new matched densities, marked by arrows.

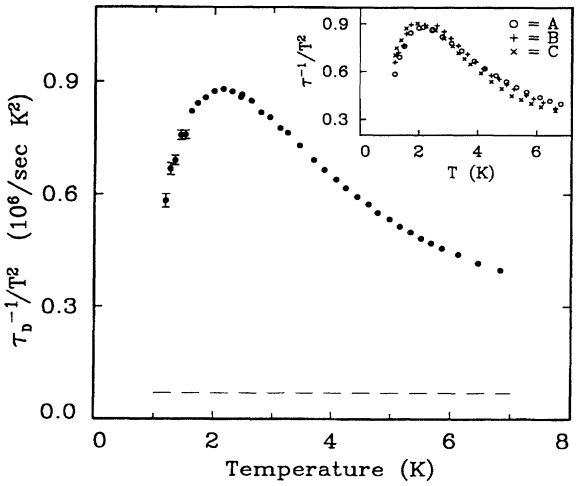

FIG. 1. Temperature dependence of frictional drag scattering rate divided by T^2 for sample A (500-Å barrier). The dashed line shows estimated Coulomb contribution. Inset: τ_D^{-1}/T^2 for three barrier thickness (500, 225, and 175 Å) samples with differences in Coulomb scattering subtracted, illustrating the long-range nature of the coupling mechanism dominant in sample A.

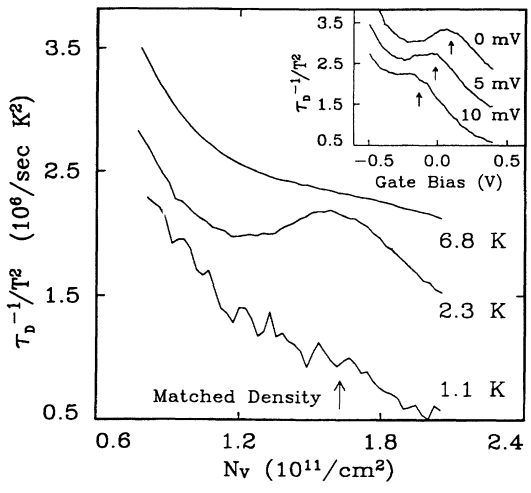

FIG. 2. Dependence of frictional drag in sample B on electron density, N_V, of voltage probe 2DEG at three temperatures, offset for clarity. The arrow indicates where the two layer densities are equal. Inset: drag at 2.3 K with interlayer bias voltages (0, 5, and 10 mV) applied, offset, and plotted vs top gate voltage, which varies N_V. Arrows denote the three gate voltages corresponding to matched densities.

The temperature dependence observed for this peak at matched densities (Fig. 2) indicates its origin is the long-range scattering mechanism discussed earlier, and not Coulomb scattering. At 2.3 K, where τ_D^{-1}/T^2 for the long-range process (Fig. 1, measured at nearly matched densities) is nearly maximum, the peak in the density dependence is large. At both 6.2 and 1.12 K, where τ_D^{-1}/T^2 for the long-range process is small, the peak is unobservable in the density sweeps. This correspondence is confirmed in density sweeps at intermediate temperatures, not shown in the figure.

The presence of this peak is an important key for identifying the nature of the long-range scattering mechanism. In fact, absorption and emission of acoustic phonons by a single 2DEG at these temperatures is dominated[10] by transitions with in-plane wave vectors near $2k_F$, because of the large phase space available for backscattering of electrons in two dimensions. Matching $2k_F$ for both electron systems, then, enhances phonon-mediated interlayer e-e interactions. By contrast, we have shown[5] that at this layer spacing, momentum transfer via interlayer Coulomb interactions is dominated by small angle scattering, $\theta \leq 15°$. It will exhibit no peak at matched densities; instead, it increases smoothly[5,11] with decreasing N_V. This contribution to τ_D^{-1}/T^2 is evident in Fig. 2 in the sloping background at 2.3 K, and is dominant in the 6.2- and 1.12-K data sets. The peak in the density dependence of τ_D^{-1}, indicating a $2k_F$ scattering process, is therefore significant additional evidence for phonon-mediated e-e interactions.

Thus, the temperature, spacing, and density dependence of the interlayer scattering rates all separately point to a phonon-mediated interaction. Together they provide strong evidence for a phonon coupling mechanism. The magnitude of τ_D^{-1}, however, is puzzling when compared to the interaction of phonons with a single current carrying electron layer. This interaction, characterized by $\tau_{\rm ph}^{-1}$, has been assessed through measurements of the temperature-dependent electronic mobility. Relating $\tau_{\rm ph}^{-1}$ to a phonon heat flux and then to a voltage, through published values of the lattice heat capacity[12] and thermopower,[13] results in a $\tau_D^{-1} \sim 10^5$ times too small at 7 K. Such a simple estimate, however, significantly underestimates the real-phonon exchange contribution to τ_D^{-1}. We have made a more accurate estimate by calculating the nonequilibrium phonon distribution produced by the current flow in the first layer, and then allowing these phonons to interact with the second 2DEG. This calculation is similar to previous approaches[14] for calculating $\tau_{\rm ph}^{-1}$, and includes deformation potential (13.5 eV) and piezoelectric electron-phonon couplings as well as screening effects. A benchmark of the accuracy of this numerical calculation is the value it gives for $\tau_{\rm ph}^{-1}$; the result is within 10% of that which we measure at 7 K. Values of τ_D^{-1} calculated with this model, while exhibiting a roughly correct temperature dependence, are still between 20 and 100 times smaller than those observed. This is illustrated in Fig. 3, where τ_D^{-1}/T^2 for sample C (solid circles), is compared to the calculation. The calculated rates, multiplied by 27, are plotted as a dashed line. Although this disagreement in magnitude is large,

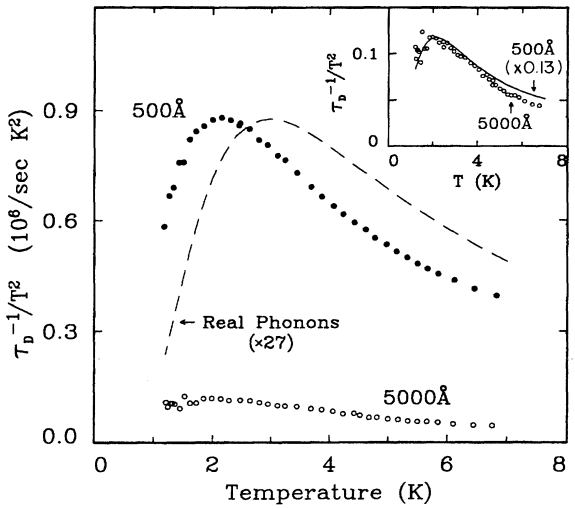

FIG. 3. Temperature dependence of real-phonon exchange calculation (expanded 27×) compared to measured drag for sample A (500-Å barrier). Measurements of sample D (5000-Å barrier) display a substantially reduced scattering rate. Inset: Expanded view of drag in sample D shows the temperature dependence of sample A is retained.

the qualitative agreement in the shape of the two curves is striking. The overall temperature dependence of the calculated rates derives from the availability of thermally excited phonons with wave vectors $2k_F$. As discussed above for the phonon limited mobility, the resultant crossover from a linear to a stronger dependence in T is characteristic of the interaction of a 2DEG with phonons. The observation that real-phonon exchange, apart from a shift in the peak of τ_D^{-1}/T^2, reproduces the measured temperature dependence further implicates phonons as the coupling mechanism.

The small scattering rate calculated for real-phonon exchange, however, discounts the identification of this simple interaction as the interlayer coupling mechanism. Virtual-phonon exchange has also been proposed as a phonon coupling mechanism.[8] Recent calculations[15,16] for this mechanism result in a magnitude of τ_D^{-1}/T^2 more consistent with our measurements, while retaining the characteristic temperature dependence described above. The strength of a virtual-phonon interaction results in part from the different dimensionality of the electron and phonon systems. Because the electron system is 2D, only the in-plane component of the 3D phonon wave vector is constrained by momentum conservation. The relaxation of energy conservation afforded virtual phonons, therefore, provides considerably enhanced access to phonon phase space: For a given electronic transition, the allowed intermediate phonon states are a line in phonon phase space having a fixed in-plane, but arbitrary out-of-plane, wave vectors. By contrast, just two points represent the allowed states for energy-conserving real phonons.

The difference between the results of calculations for virtual-phonon coupling[15,16] and the present real-phonon calculation, however, lies almost exclusively in the magnitudes of the scattering rates. To clearly identify the nature of the phonon interaction, further distinction is

necessary. Discriminating between the two mechanisms on the basis of temperature dependence is difficult, as the dependences are so similar. There exists, however, a fundamental difference in behavior for the two processes at very large layer spacings. A real-phonon exchange interaction will be independent of the spacing between the electron layers d until d becomes comparable to the phonon mean free path. Virtual-phonon exchange, on the other hand, can be more strongly spacing dependent because it involves phonons that do not conserve energy. Clearly, the further apart the layers, the longer these phonons must travel to produce interlayer coupling. As this distance increases, the range of phonon energies which can contribute to the virtual process must narrow, and the interaction will get weaker. The observation of a substantial reduction in the magnitude of τ_D^{-1} for d well less than the phonon mean free path would therefore directly support a virtual-phonon process.

To test for such an effect, we have measured the drag in a sample with a 5000 Å barrier (sample D). Thermal conductivity measurements in similar samples[17] determine a phonon mean free path orders of magnitude larger than this (~mm), so τ_D^{-1} would match that of sample C for a real-phonon exchange process. Measurements for sample D, plotted in Fig. 3 as open circles, reveal τ_D^{-1}/T^2 is nearly 8× smaller than for the 500-Å barrier sample. The observed temperature dependence, however, remains virtually identical, as shown in the inset where τ_D^{-1}/T^2 for sample D are plotted with an expanded vertical scale. Included for comparison are the rates for sample C divided by 7.5 (solid line). This comparison provides a clear indication that the interlayer scattering mechanism is rooted in the same physical process in both samples. The substantial change in the magnitude of the τ_D^{-1}, then, is evidence strongly supportive of a coupling mechanism involving virtual-phonon exchange.

Our measurements further indicate that the length scale appropriate to the interaction, while quite large compared to the Coulomb interaction, is smaller than 5000 Å. If we assume an exponential dependence, the characteristic length is ~ 2500 Å. While these measurements provide a reasonable indication of the extent of the interaction, a full understanding of the layer spacing dependence for this virtual-phonon exchange interaction will require further theoretical work, as well as additional measurements at intermediate layer spacings. The spacing dependence we observe, however, provides experimental evidence supporting virtual-phonon exchange independent of the details of any particular calculation.

In conclusion, we have presented measurements of frictional drag between parallel 2DEG which reveal a long-range e-e interaction whose temperature, layer spacing, and density dependence are consistent with a phonon-mediated coupling. Scattering rates calculated for real-phonon exchange are substantially smaller than those observed, and range of the phonon-mediated interaction is much shorter than the acoustic phonon mean free path. These observations support an electron scattering mechanism involving virtual-phonon exchange.

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*Present address: Department of Physics, Pennsylvania State University, University Park, PA 16802.

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