Mutual Friction between Parallel Two-Dimensional Electron Systems

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Frictional drag between isolated two-dimensional electron gases separated by a thin barrier has been observed at low temperatures in GaAs/AlGaAs double-quantum-well structures. Separate electrical connection to the two electron systems allows the injection of current into one and the detection of a small drag voltage across the other. The drag voltage is a direct measure of the interwell momentum relaxation rate. Measurements of this rate are in qualitative agreement with calculations of an interwell Coulomb scattering model.

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Semiconductor-based two-dimensional electron gases (2DEGs) are increasingly being used as a starting point for constructing quasi-three-dimensional electron systems with controllable physical properties. A common generalization is the stacking of two or more 2DEGs in multiple-quantum-well structures with varying amounts of Coulomb and tunnel coupling between the layers. For the simplest such structure, the double quantum well (DQW), recent experiments[1] have suggested that interwell Coulomb effects can dramatically alter the single-electron energy levels in samples with thin tunnelable barriers. Even in DQW's with negligible tunneling, Coulomb effects are anticipated[2] to produce new correlated many-electron states that exhibit the fractional quantum Hall effect. Central to all these problems is the nature of the interwell electron-electron scattering. We expect such processes will play an essential role in determining the transport and optical properties of DQW systems. In the work reported here, interlayer interactions in a DQW are directly detected via the frictional drag of one 2DEG upon the other.

Coulomb drag between barrier-separated 2D electron gases was first theoretically discussed by Pogrebinskii[3] and later by Price.[4] In a recent experiment, Solomon *et al.*[5] have observed a drag effect between a three-dimensional system and a 2DEG. Although Coulomb scattering was suggested as the underlying mechanism, a subtle thermal effect occurring near the source and drain contacts was invoked[6] to explain the sign of the data at low temperatures. The results presented here, in contrast, represent the first observation of a drag effect between two purely 2D systems. The sign of the effect is consistent with interwell momentum relaxation. While some discrepancies remain, the magnitude and temperature dependence of the observed drag voltage, as well as its dependence on the thickness of the separating barrier, are in good accord with calculations of the Coulomb scattering rate.

The samples used in this investigation are modulation-doped GaAs/AlGaAs DQW structures grown by molecular-beam epitaxy. Two GaAs layers, each 200 Å thick, are embedded in the alloy $Al_{0.3}Ga_{0.7}As$. The undoped separating barrier layers are 175 and 225 Å thick for the two samples grown. Si delta-doping layers are placed 700 Å above and 900 Å below the quantum wells. These dopants create nearly equivalent[7] 2DEGs in the lowest electric subband in each well. In both samples each 2DEG has a density and a sheet mobility[7] near 1.5×10^{11} cm^{-2} and 3.5×10^{6} cm^2/V s. This density results in a Fermi temperature T_F of roughly 60 K. Standard photolithographic techniques are used to pattern a mesa on the sample front surface. Resembling a Hall-bar geometry, the active region of this mesa is a 20×220-μm bar to which five broad arms are attached. Standard In diffusion contacts are placed at the ends of each arm, about 1.5 mm from the central bar. The geometry of the central mesa region is depicted in Fig. 1(a).

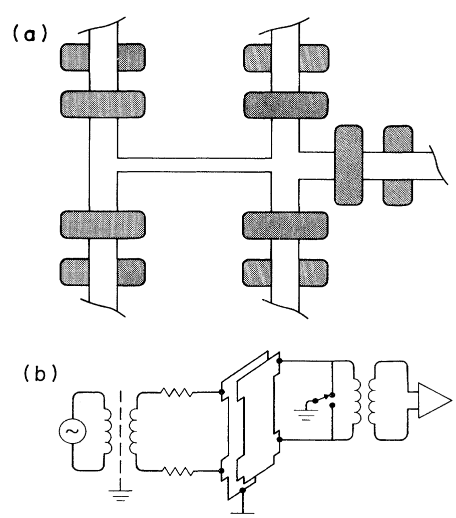

FIG. 1. (a) Sample geometry, including the mesa and the front and back gates in grey. The central bar is 20 μm wide. Each mesa arm is terminated with an indium diffusion contact roughly 1.5 mm from this central region. (b) Schematic of the measurement configuration.

Essential to this experiment is the ability[8] to create separate Ohmic contact to the individual 2DEGs in the DQW. The In contacts at the arm ends connect to both of the 2D systems at once. Each can, however, separately contact either 2D gas in the central bar. This is accomplished by selectively depleting one or the other 2D gas in a narrow region of the arm leading to the central bar. Evaporated Al Schottky gates straddle each arm, one on the front and the other on the back of the sample [cf. Fig. 1(a)]. To achieve reasonable lateral definition of the back-gate depletion fields, the entire sample is thinned to about 50 μm. Applying an appropriate negative voltage to one of these gates will deplete the closest 2DEG without substantially altering the other. In this way, each arm provides contact to one or the other 2DEG in the central bar.

The measurement configuration is shown schematically in Fig. 1(b). A constant current (typically 200 nA) at 25 Hz is imposed on the 2DEG in one of the wells (the drive well), and the drift of those electrons creates a frictional drag on the electrons in the adjacent quantum well. This drag is balanced by the development of a voltage in the second well (the output), which we measure with a high-impedance detection circuit. Because this signal is due to the interactions of electrons physically separated by the AlGaAs barrier, the induced voltage is small, of order nanovolts. It was necessary, therefore, to identify and eliminate any spurious voltages present in the output circuit. The common-mode voltage in the drive circuit, for example, capacitively couples to the output. This voltage was reduced to a negligible level by using an electrostatically shielded input transformer and grounding the drive well through the fifth mesa contact.

A potentially serious source of voltage in the output circuit is the finite leakage resistance between the wells. Typical measured values of the roughly temperature-independent leakage resistance are 2 MΩ or greater, compared to a sheet resistance of order 10 $\Omega/\square$. The effects of this leakage can be isolated by transformer coupling the output circuit and switching ground between the inputs to the transformer. Since the drag voltage is a true differential signal it is unaffected by the switching, but any leakage signal will change sign. The magnitude of the leakage-induced voltage thus measured was small for the 225-Å barrier sample, a few percent or less of the drag voltage. For the 175-Å barrier sample the leakage became significant only below 2 K, reaching as much as 25% of the drag voltage at low temperatures. Application of a small dc bias between the two wells, typically 3 mV, increased the leakage resistance by more than an order of magnitude. This may be due to a shutdown of resonant tunneling between the quantum wells. The change in the 2D densities due to this bias was only a few percent. This application of bias reduced the leakage-induced output voltage to the level seen with the unbiased 225-Å barrier sample.

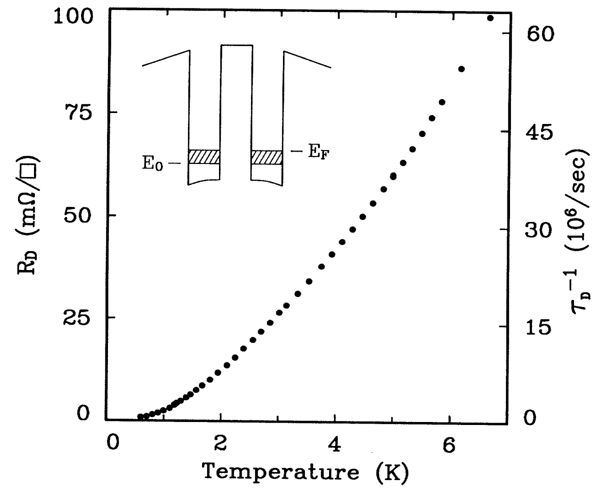

FIG. 2. Temperature dependence of observed frictional drag between two 2D electron systems separated by 175-Å barrier. Data are plotted as an equivalent resistance and a momentum-transfer rate. Inset: An idealized conduction-band diagram for a DQW structure indicating the ground subband energy E_0 and the Fermi energy E_F.

The measured drag signal for the 175-Å barrier sample is shown in Fig. 2 as an equivalent resistance R_D (drag voltage/drive current) versus temperature, scaled by the aspect ratio of the central bar of the mesa. The errors due to both noise and leakage are less than the size of the symbols. The signal is identical, within experimental uncertainty, when the roles of the drive and output quantum wells are exchanged, and after thermally cycling the sample. The measurements reported here were made with currents low enough that the drag voltage was linear in the applied current. The temperature equivalent of the current-induced drift velocity v_d, defined by $k_B T_d = v_d p_F$, with p_F the Fermi momentum, is only 30 mK for the highest currents used. This compares to measurement temperatures ≥ 1 K; smaller currents were used at lower temperatures. To check for possible electron heating, we examined the amplitude of the Shubnikov–de Haas oscillations for various drive currents. The temperature dependence of these oscillations allows a calibration of the electron temperature versus applied current. In all cases, the final drive current used produced less than a 2% change in the electron temperature.

It is important to note that the sign of the observed drag voltage is the *opposite* of the resistive voltage drop in the drive well. This is expected for a momentum-transfer process between the electrons in the two wells, since the voltage is due to the buildup of the charges swept along in the direction of the drift velocity in the drive well. We can characterize this momentum-transfer process by means of a scattering time τ_D, by analogy with standard Drude transport. The rate at which momentum is transferred from the drive well can be written simply as $m^* v_d/\tau_D$, where v_d is the drift velocity of the electrons in the drive well. Because no current is allowed to flow in the output well, this "force" is precisely opposed by the electric field resulting from charge buildup. The relationship of the drag voltage V_D to the drive current I is simply

$$V_D/I = -(L/W)m^*/Ne^2\tau_D\,, \qquad (1)$$

where N is the electron density in the drive well, and L and W are the length and width of the region in which the drag occurs. Our measurements, then, determine the scattering rate τ_D^{-1}. This is shown on the right vertical axis of Fig. 2. We note that the interwell scattering rate is only 1% of the mobility scattering rate at the highest temperatures studied.

For the case of direct electron-electron scattering between the two quantum wells, one expects that the scattering rate at low temperatures will be proportional to T^2, simply from the thermal broadening of the Fermi function for each electronic system. As Fig. 2 reveals, this is qualitatively the case. Identification of the mechanism producing the scattering requires quantitative theoretical estimates for an assumed model. For a barrier thickness of order 200 Å, which is comparable to the average interelectron distance in each 2DEG, an obvious candidate is simple Coulomb scattering.

The drag voltage due to Coulomb scattering may be evaluated using Boltzmann transport theory. Neglecting the finite width of the 2D layers we find that for $T \ll T_F/2k_F d$ and $q_{\mathrm{TF}} d \gg 1$, the momentum-transfer rate may be expressed as

$$\tau_D^{-1} = \frac{\pi\zeta(3)(k_B T)^2}{32\hbar E_F (q_{\mathrm{TF}} d)^2 (k_F d)^2}\,, \qquad (2)$$

where q_{TF} is the single-layer Thomas-Fermi screening wave vector, E_F is the Fermi energy, d is the layer separation, and k_F is the Fermi wave vector. The d^{-4} dependence of τ_D^{-1} is characteristic of Coulomb scattering between parallel 2DEG's. It results, in part, from the e^{-qd} factor in the Fourier-transformed interlayer Coulomb interaction. This factor suppresses scattering events with $q > d^{-1}$. In addition, the contribution to the momentum relaxation at small wave vectors is proportional to the square of the screened interlayer interaction weighted by $1-\cos\theta \sim q^2$ and by a factor $1/\sin\theta \sim q^{-1}$, where θ is the scattering angle between initial and final single-particle states near the Fermi level. The latter factor reflects the scattering-angle dependence of the available volume of phase space within $k_B T$ of the Fermi energy. Its divergence as θ approaches 0 or π is responsible for the anomalous $T^2 \ln T$ quasiparticle damping[9] in single-layer 2D systems. Novel features of the screening in double-layer systems also play an important role in determining the d dependence of τ_D^{-1}. In the random-phase approximation the double-layer screening wave vector[10] $q_{\mathrm{sc}} = 2q_{\mathrm{TF}}(1+q_{\mathrm{TF}} d)$. For large separation q_{sc} is dominated by the term proportional to d, which may be understood as resulting from the contribution to the screening potential from a capacitive voltage which is present when the local charge densities in the two layers differ. In our samples $q_{\mathrm{sc}} \sim 10 q_{\mathrm{TF}}$ so the enhanced screening reduces τ_D^{-1} by roughly 2 orders of magnitudes.

The observed drag voltage in the 175-Å barrier sample corresponds via Eq. (2) to a layer separation of ~ 240 Å, in rough agreement with the known sample geometry. Detailed numerical evaluation[10] of τ_D^{-1} accounting realistically for finite well widths and including vertex corrections to the RPA interlayer scattering amplitude[11] results in a value for a drag resistance that is within 50% of our measurements, strongly supporting the identification of Coulomb interactions as the drag mechanism. Examination of the detailed temperature dependence of the measured drag resistance, however, indicates that it is not in complete agreement with the simple Coulomb drag model. Figure 3 shows τ_D^{-1}/T^2 for both the 175- and 225-Å barrier samples. There are significant deviations from a T^2 behavior at both low and high temperatures. The high-temperature behavior may reflect the breakdown of the assumption $T \ll T_F/2k_F d$. In fact, if the conditions $T_F/2k_F d \ll T \ll T_F$ can be realized, phase-space limitations associated with the predominance of small-angle scattering can actually[12] lead to $\tau_D^{-1} \propto T$. This would show a falloff when plotted as in Fig. 3. For our samples, $T_F/2k_F d \sim 8$ K, suggesting this effect may not dominate the observed falloff, which commences around 2K. Of potentially greater concern is the dropoff at low temperatures; this finds no explanation in the Coulomb drag model.

Momentum transfer by phonons can also be en-

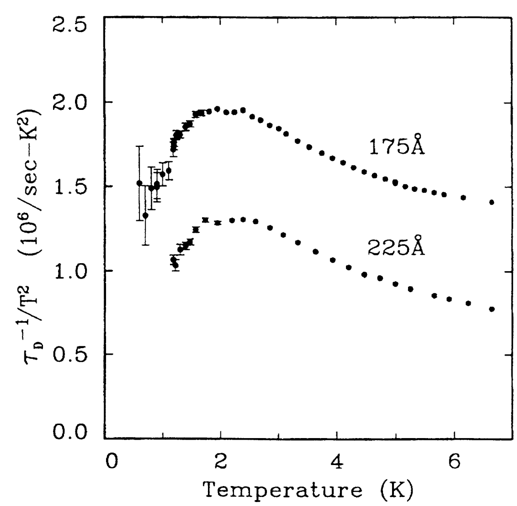

FIG. 3. Temperature dependence of the interwell momentum-transfer rate divided by T^2 for both the 175- and 225-Å barrier samples.

visioned. For example, the momentum released into the phonon bath by the current-carrying 2DEG is determined by the phonon-limited mobility μ_{ph}. Some fraction of this excess phonon momentum can be absorbed by the remote 2DEG. Since μ_{ph}^{-1} crosses over from a linear temperature dependence at high temperatures to a much higher power (T^5 or T^7) in the Bloch-Grüneisen regime around a few K, the resulting drag would likely exhibit a temperature dependence similar to the data in Fig. 3. From calculations[13] of μ_{ph} appropriate to our sample, we find that the fraction of the excess phonon momentum generated that must be absorbed by the remote 2DEG to account for the magnitude of the observed drag varies from (1–2)% at high temperatures to nearly 50% near 0.5 K. This seems unlikely since the probability for thermal-phonon absorption by the 2DEG in similar GaAs structures has been estimated to be in the 10^{-4} range.[14] Geometric considerations suggest little possibility for enhancement of this through multiple passes.

To further explore the mechanism of interwell momentum transfer, we compare the results obtained with the 175- and 225-Å barrier samples. As the quantum wells are 200 Å wide, the increase of 50 Å in the barrier thickness changes the well center-to-center distance by only 12%. Aside from the thicker barrier, this sample was grown to identical specifications as the 175-Å barrier sample. The resulting 2DEG densities and mobilities differed from the earlier sample by only a few percent. The drag data for the 225-Å barrier sample are shown as the lower trace in Fig. 3, plotted again as τ_D^{-1}/T^2. The deviations from a strict quadratic dependence on temperature are strikingly similar to that observed for the 175-Å barrier sample, confirming the presence of a common mechanism. The overall magnitude is roughly 65% of that for the thinner barrier sample. This large reduction is not consistent with the phonon mechanism outlined above, since low-temperature phonon mean free paths in GaAs heterostructures are known[14] to be in the mm range. In contrast, Coulomb drag depends strongly on the spacing between the 2D layers, scaling as d^{-4} within the limits appropriate to Eq. (2). Using the center-to-center distances for our samples, Eq. (2) predicts a 60% ratio of the drag voltages. Detailed calculation appropriate to our samples reduces this ratio to ~50%, still in good agreement with our observations.

The observed mutual friction exhibits a sign, magnitude, temperature, and barrier-thickness dependence which are all in reasonable agreement with a simple Coulomb drag mechanism. However, deviations from the expected T^2 temperature dependence, especially at low temperatures, suggest that other effects may be playing a role in the interwell momentum relaxation. In addition to the real-phonon-exchange process discussed above, virtual-phonon processes may alter the Coulomb interaction. Finite-size effects could also be significant. For example, the electron mean free path deduced from the sample mobility is comparable to the width of the region in which the drag is measured. Future experiments are planned which should illuminate these issues.

In conclusion, a mutual friction between two closely spaced two-dimensional electron gases has been observed. The magnitude of the drag voltage induced in one 2DEG by a current in the other is a direct measure of the momentum relaxation rate between them. Typically 1000 times less than the mobility relaxation rate, this process is in qualitative agreement with a simple Coulomb scattering model.

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