

Many-body correlations probed by plasmon-enhanced drag measurements in double-quantum-well structures

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Electron drag measurements of electron-electron scattering rates performed close to the Fermi temperature are reported. While evidence of an enhancement due to plasmons, as was recently predicted [K. Flensberg and B. Y.-K. Hu, *Phys. Rev. Lett.* **73**, 3572 (1994)], is found, important differences with the random-phase approximation based calculations are observed. Although static correlation effects likely account for part of this difference, it is argued that correlation-induced multiparticle excitations must be included to account for the magnitude of the rates and observed density dependences. [S0163-1829(98)00440-8]

The plasmons of two-dimensional electron gas (2DEG) systems provide a valuable platform for the study of electronic many-body correlation effects. Fundamental elements of 2DEG plasmons, however, have been studied¹⁻³ without resorting to these higher-order effects. Of particular interest to our work is the system consisting of two 2DEG's. In addition to the conventional (optic) mode, with a plasmon energy whose leading dependence¹ on wavevector q is $q^{1/2}$, such a system supports a second plasmon mode² the dispersion relation of which is linear in q at small q . Recently, theoretical work⁴⁻⁶ has moved beyond the random-phase approximation (RPA) to consider the role of many-body correlation effects. While the role of these correlations are generally believed to lower the plasmon frequencies and provide additional damping in the limit of low densities, a recent calculation⁵ has found that their effects can be important even at relatively high densities. As both intralayer and interlayer correlations are possible in the double-layer system, both layer spacing and electron density dependencies are critical to the study of plasmon effects.

The traditional experimental probe of 2DEG plasmons has been Raman scattering.⁷ Such studies have, for example, confirmed the existence of the acoustic mode in super lattice structures. The electron densities used in optical studies to date, however, have been high enough that correlation effects were not evident. In this paper, we discuss results of a complementary experimental approach to the study of 2DEG plasmon modes: electron drag measurements. The motivation for these studies results from recent theoretical predictions of Flensberg and Hu⁸ that plasmons are observable in such measurements, and preliminary measurements of Eisenstein.⁹ We find convincing evidence for the role of plasmons in this transport style experiment. This evidence, the overall temperature dependence of the measurements as well as the general density dependence, confirm recent measurements observing the enhancement of electron drag by plasmons.¹⁰ The new results presented here, however, result from an exploration of a range of densities below that of both the earlier optical measurements and recent drag measurements, as well as the first studies of the layer spacing depen-

dence of plasmon enhanced drag. We find that for remotely spaced layers a disagreement in magnitude with theoretical predictions exists, and that there is a greater width in the peak that develops in the density dependence. We also find that the dependence on the relative electron densities for low overall densities yields a behavior inconsistent with fundamental aspects of RPA-based theoretical predictions; that the maximum enhancement does not occur at matched densities. These results are evidence for an additional plasmon damping mechanism, and we argue that dynamic correlations play an important role in the plasmon enhancement of drag.

In electron drag measurements,¹¹⁻¹³ electron-electron ($e-e$) scattering rates are probed through the momentum transferred, via $e-e$ scattering, from one current carrying electron system to a second nearby system. It has been shown^{11,12} that the ratio of the voltage induced in one 2DEG to the current in the other, electrically isolated, 2DEG directly determines the interlayer $e-e$ momentum transfer rate τ_D^{-1} . This determination of the "drag" scattering rate is a consequence of the balance that is established between the force of the electric field that develops in the drag layer and the effective force of interlayer $e-e$ scattering.

A crucial question for this work is how plasmons can play a substantial role in what is essentially a dc transport measurement, as both plasmon modes lie above^{2,3} the single-particle excitation spectrum. It was recently predicted,⁸ however, that plasmons will have a dramatic effect on drag. The key element of the calculations is that coupling of currents to plasmon modes is made possible by high temperature (T) modifications of the single-particle excitation spectrum when T is of order the Fermi temperature T_F . Earlier high-temperature approaches¹⁴ neglected these effects and predicted no plasmon-related enhancement. Because plasmon excitations substantially alter the 2DEG screening response, drag scattering rates, which result from screened interlayer interactions, will be substantially affected. According to the RPA-based calculations,⁸ the interlayer $e-e$ scattering is increased by plasmons for $T > 0.2T_F$, with the increase peaked at $T \sim 0.5T_F$. The *increase* results from the real part of the

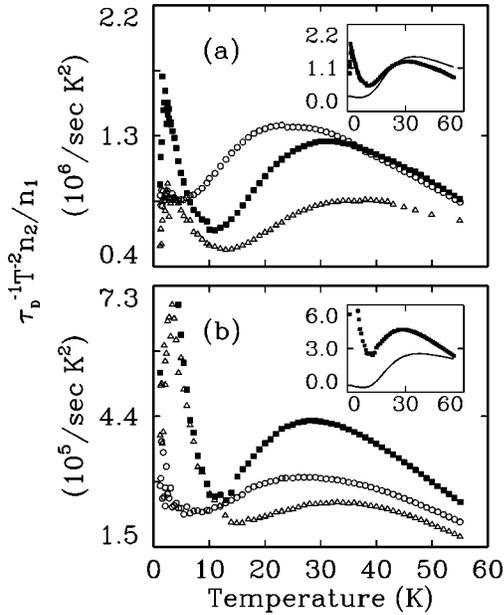


FIG. 1. Scaled drag rate $\tau_D^{-1}T^{-2}n_2/n_1$ as a function of temperature for (a) 225-Å-barrier sample and (b) 500-Å-barrier sample. Solid squares are for $n_2/n_1=1$, circles for $n_2/n_1=0.5$, and triangles for $n_2/n_1=1.3$. Inset: Theoretical curve based on RPA (solid line) and the experimental data (solid square) for matched density.

effective dielectric constant going to zero at a plasmon resonance, so screening is *reduced*. Reduction of the effect at higher T is attributed to Landau damping of the plasmons.

The samples used in these measurements are modulation-doped GaAs/Al_{0.3}Ga_{0.7}As double quantum well structures grown by molecular-beam epitaxy. Two samples were used, both with 200-Å-wide wells, but one with a 225-Å barrier between the wells, and the other 500 Å. Electron densities for both samples were $1.55 \times 10^{11} \text{ cm}^{-2}$, yielding $T_F \sim 65 \text{ K}$, with mobilities of all layers exceeding $2 \times 10^6 \text{ cm}^2/\text{V s}$. By applying voltage to an overall top gate or bias between the layers, the electron densities of the individual layers could be adjusted, as calibrated by Shubnikov–de Haas measurements. We denote the electron density of the drag/drive layer as n_2/n_1 .

Figure 1 shows the measured temperature dependence of τ_D^{-1} scaled by T^2 and the density ratio n_2/n_1 , for both layer spacings at various density ratios. The drag rates show two distinct maxima, at low and high temperatures. The peaks below 10 K result from a virtual phonon exchange process,¹³ this work focuses on the high-temperature behavior. For matched densities ($n_2/n_1=1$), both samples show an increase in the scaled drag rate $\tau_D^{-1}T^{-2}n_2/n_1$ near 15 K, a maximum near 30 K, and a subsequent decrease with increasing temperature. This temperature dependence is expected⁸ for plasmon enhancement of drag, as discussed earlier. We have also measured the temperature dependences for mismatched densities (Fig. 1), and find a shift in the maximum of $\tau_D^{-1}T^{-2}n_2/n_1$ as the drag layer density, n_2 , is changed. For $n_2/n_1=0.5$, the peak moves to 25 K or less in both samples, and for $n_2/n_1=1.3$ it moves to $\sim 35 \text{ K}$. The direction and rough magnitude of this shift is consistent with the RPA plasmon calculations, providing additional

evidence for a plasmon-based drag enhancement.

It is important to note, however, the discrepancies between our measurements and the published calculations. Inset in Fig. 1 is a comparison of the measured $\tau_D^{-1}T^{-2}n_2/n_1$ at matched density with the calculations⁸ of Flensberg and Hu. Theoretical rates appropriate to our sample geometries were derived from T dependences for identical 200-Å-wide quantum wells with densities $n=1.5 \times 10^{11} \text{ cm}^{-2}$, with layer separations 800 and 400 Å. A small correction factor, taken from a plot of numerical results of the explicit spacing dependence at 40 K, was then applied to match to our well center to center spacings of 700 and 425 Å, respectively. For the 225-Å barrier sample the measured rates peak at a temperature below that predicted by theory, with reasonable agreement in magnitude. For the 500-Å barrier sample, however, the measured magnitude lies above that calculated. The calculations are reasonably accurate in determining the zero-temperature limit of Coulomb scattering as determined¹³ in these samples (better established, perhaps, for the 225-Å sample); a critical point if magnitude comparisons are to be made. The data for the 500 Å barrier sample show similar behavior to that seen in earlier measurements.¹⁰

An additional discrepancy with calculations exists in the behavior of $\tau_D^{-1}T^{-2}n_2/n_1$ as the densities are mismatched. The 500-Å-barrier sample data indicate a maximum near matched density, in agreement with the general behavior predicted by theory for both spacings. For the sample with more closely spaced layers, however, we find that $\tau_D^{-1}T^{-2}n_2/n_1$ is greatest when $n_2=0.5n_1$.

Two sources for these discrepancies must be considered. The first is a shift in the plasmon spectrum induced by correlation effects. One might assume that at the densities of our samples ($r_s \sim 1.4$), such effects would be small. Investigations⁵ of static many-body correlations in a double-layer system, however, show that for 250-Å layer spacings, by $r_s \geq 5$ the acoustic plasmon is so suppressed that it enters the single-particle continuum and is destroyed. While correlation-induced changes in the plasmon spectrum for our samples will be much smaller, they are clearly possible. Static correlation effects are found to *suppress*⁵ the energies of the plasmon modes, so the plasmon enhancement should occur at a lower temperature, providing better agreement with the observed peak positions in the temperature dependence of $\tau_D^{-1}T^{-2}n_2/n_1$ for both samples. Small shifts, however, would tend to *increase* the coupling to the single-particle spectrum, resulting in a *larger* drag enhancement. Such behavior is found when RPA calculations are modified¹⁰ with the Hubbard approximation, which includes intralayer exchange interactions. The calculations show a shift toward lower peak temperatures and an increased magnitude, providing better agreement with the measurements of Ref. 10. A net increase in magnitude of the enhancement, however, is inconsistent with our results for the 225-Å-barrier sample, where the calculated RPA rates already match the observed magnitude. We would anticipate that eventual suppression of $\tau_D^{-1}T^{-2}n_2/n_1$ resulting in little net change in magnitude could also occur, but only for relatively large changes in the plasmon mode energies, yielding a substantial alteration of the temperature dependences including the peak position, which is not observed in our measurements.

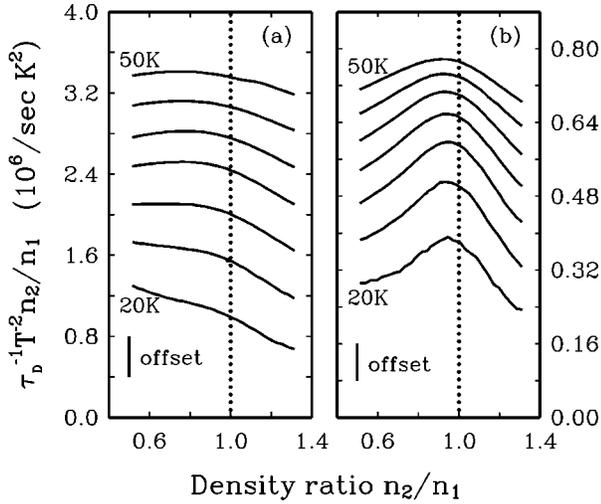


FIG. 2. Dependence of the scaled drag rates on the density ratio n_2/n_1 (drag/drive density), for (a) 225-Å-barrier sample and (b) 500-Å-barrier sample. Each curve represents the result for every 5 K from 20 to 50 K and is offset for clarity by the amount shown. A dotted line indicates matched density.

The second possible source for the discrepancies lies in plasmon dissipation channels only present due to correlation effects. It is well known that a conventional RPA approach to plasmons results in fully undamped modes, precisely because the plasmons lie above the single particle spectrum. Realistic estimates of the plasmon widths, therefore, must include coupling to multiparticle excitations, intrinsically a correlation effect. The existence of a multiparticle damping channel could substantially reduce the degree of drag enhancement provided by plasmons, potentially offsetting increases due to static correlation effects. Such damping has been calculated⁶ for plasmons of a single 2DEG in the density range of this work, but to our knowledge no such calculations exist for double-layer systems. Finite-temperature effects, furthermore, would also be expected to play a role in the temperature range of the current measurements.

To further explore these questions, we have measured the detailed dependence of $\tau_D^{-1} T^{-2} n_2/n_1$ on the relative densities of the two electron layers at various temperatures. This measurement probes the plasmon enhancement while both the plasmons and the single-particle excitations of one layer are changed. For the data in Fig. 2, only the drag layer density n_2 is varied, while n_1 is fixed at $1.55 \times 10^{11} \text{ cm}^{-2}$. This is, perhaps, a more sensitive probe of the plasmon enhancement, depending critically⁸ on the balance between exciting the plasmons and damping them through the single-particle excitations. The response is expected to be sharply peaked at matched densities. For the 500-Å barrier sample, the scaled drag shows a clear peak near matched density, which broadens noticeably as T increases. The width of this peak, however, is much greater than predicted by theory (not shown) at all measured temperatures. For the 225-Å-barrier sample, the broadening is so large that no clear peak is discernible in the data.

The difference between our measurements and the RPA-based calculations is significant for both samples. The scale for these differences is set by the observation that the width for the 500-Å-barrier sample at 30 K is very close to that

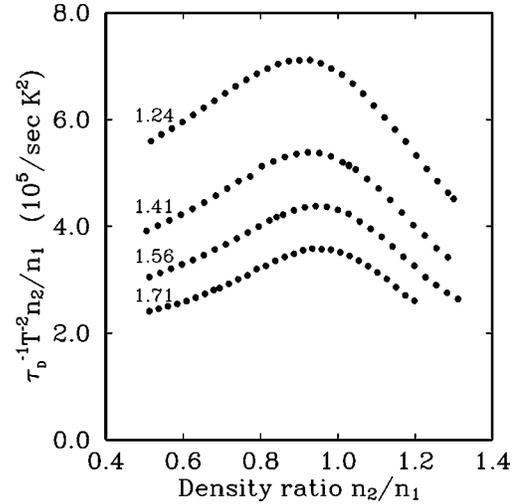


FIG. 3. Dependence of the scaled drag rates in 500-Å-barrier sample on the density ratio n_2/n_1 for four different matched densities at 30 K. Numbers beside each curve represent the matched densities in 10^{11} cm^{-2} .

predicted for a 200-Å-barrier sample. Although some suppression of the mode should occur due to static correlation effects, this suppression would, once again, result in an increase in the drag enhancement. As any substantial enhancement is inconsistent with our measurements, we consider it unlikely that correlation-induced shifts in the plasmon spectrum are the sole reason for the broad widths we observe. Indeed, the recent Hubbard approximation based calculations show no considerable increase in the width of the density dependence. Instead, damping of the plasmons via correlation induced multiparticle excitations must again be considered. If the plasmon modes are broadened by multiparticle excitations, then the density dependence would be broadened, as there would be a distribution, beyond thermal effects, of energy spacings between the plasmons and the single-particle spectrum. It is our contention that correlation-induced multiparticle damping plays a significant role in plasmon-enhanced drag.

Important evidence for this contention comes from the density dependence of $\tau_D^{-1} T^{-2} n_2/n_1$, measured for various densities in the drive layer at 30 K. As seen in Fig. 3, there is a gradual increase in the width of the peak with decreasing density. Most important in these data, however, is the position of the peak. Our measurements show that the maximum in $\tau_D^{-1} T^{-2} n_2/n_1$ occurs at mismatched densities, and that the lower the n_1 , the further the peak is found from matched densities. Numerical fits to the data confirm that the deviations are not artifacts of a sloping background. For the published calculations, where the only plasmon damping is coupling to single-particle excitations, the peak $\tau_D^{-1} T^{-2} n_2/n_1$ must occur⁸ at matched densities. Essential to this result is the fact that the drag scattering rate depends on the product of the response of both layers, combined with a symmetry resulting from the fact that the source of the drag enhancement, coupling between the single-particle excitations and plasmons, is also the damping mechanism.

The theoretical argument resulting in a peak at matched density fails, however, if an additional damping mechanism is present. As our samples have 20 times higher mobility

than a sample of Ref. 10, it is unlikely that disorder scattering¹⁵ provides the additional damping. Instead, multiparticle excitations, which are known to be important in the plasmon damping in single-layer systems⁶ could provide the additional damping. Correlation effects, furthermore, are widely recognized to become greater at lower electron densities. The observed increase in the deviation of the peak from matched density as n_1 is lowered appears, therefore, to be consistent with a multiparticle excitation damping mechanism. Although the overall effect of plasmon-enhanced drag is related to single-particle excitations of plasmon modes, the observation of a peak in $\tau_D^{-1} T^{-2} n_2/n_1$ at mismatched densities reveals an additional damping channel. This is a strong indication that correlation effects, including the role of multiparticle excitations in plasmon damping, must be included to explain our measurements.

In summary, we have observed an enhancement by plasmons of the interlayer $e-e$ scattering rates probed by electron drag measurements. While our results agree, in general, with RPA-based calculations, we find differences in the detailed

temperature dependences and in the density dependences. These differences clearly confirm the need to include correlation effects in calculations of plasmon-enhanced drag. While changes in the plasmon dispersion curve due to static correlation effects may account for part of the difference in temperature dependence, we expect such corrections to cause greater discrepancies in the magnitude of the scattering rates. We have proposed that dynamic correlation effects must also be included to explain our observations. These multiparticle excitations would provide additional damping of the plasmons, which would be consistent with the magnitude of the scattering rates, the large width of the peak in the rates as a function of density, and the observation that the maximum in the scaled drag rates does not occur at matched densities. A full examination of such effects awaits further detailed theoretical investigation.

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