Phonon mediated drag in double layer two dimensional electron systems

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Experiments studying phonon mediated drag in the double layer two dimensional electron gas system are reported. Detailed measurements of the dependence of drag on temperature, layer spacing, density ratio, and matched density are discussed. Comparisons are made to theoretical results [M. C. Bønsager et al., Phys. Rev. B 57, 7085 (1998)] which propose the existence of a new coupled electron-phonon collective mode. The layer spacing and density dependence at matched densities for samples with layer spacings below 2600 Å do not support the existence of this mode, showing behavior expected for independent electron and phonon systems. The magnitude of the drag, however, suggests the alternate limit; one in which electrons and phonons are strongly coupled. The results for still larger layer spacing show significant discrepancies with the behavior expected for either limit.

I. INTRODUCTION

Electron-phonon interactions directly affect numerous physical properties in solids. It is generally the case, however, that electrons and phonons are considered independently, with each system a weak perturbation on the other. This distinction is usually clear in consideration of collective modes of the electron system. Plasma oscillations, in particular, have been studied extensively by considering only the effects of Coulomb interactions between electrons. Of particular interests to this work is the limit in which the assumption of independent electron and phonon systems is not valid. If the interactions between electrons and phonons are strong enough, phonon mediated electron-electron (e-e) scattering could support a new collective mode.

A recent theoretical calculation proposed this type of electron-phonon collective mode in a double layer two-dimensional electron gas (2DEG) system, where both Coulomb and phonon mediated interactions are important. It was shown that a mode similar to plasmons emerges when the excitation energy $\omega$ approaches $s q$, where $s$ is the sound velocity and $q$ is the wavevector. The work predicted that this mode could be detected in measurements of phonon-mediated e-e scattering between two 2DEG layers. This coupled mode was argued to dominate and enhance such scattering when the phonon mean free path, $l_{ph}$, is larger than a critical value, $l_c$. The unexpectedly large magnitude observed in experiment provides clear motivation for investigating its existence, which would indicate a breakdown of the assumption of independent systems. When $l_{ph} < l_c$, this new mode was predicted to be negligible in the scattering process, and electrons and phonons could instead be treated independently. It was also established that the layer spacing and density dependences would show different behavior in the regimes of strongly coupled or independent electron-phonon systems. For small $l_{ph}$, i.e. the independent system regime, the scattering decreases logarithmically with increasing layer spacing, $d$, until $d \sim l_{ph}/2k_F L$, beyond which it decreases exponentially ($k_F$ and $L$ are the Fermi wavevector and the width of the quantum well respectively). In the coupled mode regime, i.e. large $l_{ph}$, the scattering also varies logarithmically with $d$ but exhibits a local maximum at $d \sim \sqrt{l_{ph}/k_F}$, beyond which it also rapidly declines.

The dependence on the density ratio of the two layers is expected to show almost identical behavior in either regime, characterized by a peak at matched density. It was argued that distinct behaviors were present in the dependence on total density with the individual densities matched. For temperatures, $T$, between 2 K and 4 K, the scattering is predicted to increase with density in the coupled mode regime, while it remains nearly constant or decreases in the short mean free path regime. In both regimes, the scattering decreases with density at 1 K. The matched density dependence provides the central experimental test for the existence of the coupled collective mode.

In this paper, we report measurements of phonon-mediated drag examining the dependence on temperature, layer spacing, relative density, and matched densities. In addition to testing for the existence of the proposed coupled mode, these measurements explore the general properties of phonon drag in detail. New measurements on remotely spaced layers clearly confirm the fundamental elements of the phonon scattering process which is the basis for phonon drag, including the dominance of $2k_F$ scattering. These new measurements include density dependence measurements which are the first performed in samples in which all Coulomb scattering is absent. Additional measurements probe specific aspects of phonon drag, focusing on elements related to the existence of a coupled electron-phonon mode. The
layer spacing dependence confirm the logarithmic behavior predicted theoretically for closely spaced layers. The value of \( l_{ph} \) determined by fitting to the theoretical layer spacing dependence is found to be small and within the independent system regime. The dependence on total matched density for a sample in this regime closely mimics theoretical predictions for \( l_{ph} \ll \ell_c \), providing additional evidence for independent systems. Contradictory evidence is provided by the magnitude of the drag signal, which is substantially larger than predicted for small \( l_{ph} \), and by the value determined for \( l_{ph} \) from the density dependence, which is much smaller than that found in thermal conductivity measurements on other samples. These apparent contradictions raise questions regarding phonon drag which have not been addressed in theoretical studies to date. Measurements of phonon drag in samples with the largest layer spacing, 5200 \( \text{Å} \), raise additional questions regarding the underlying mechanism of phonon drag. The overall magnitude of the measured signal, in agreement with earlier measurements, lies well below the logarithmic dependence which applies for smaller layer spacings. Measurements of the dependence on matched densities at various temperatures, performed to test whether the deviation may be related to the independent or strongly coupled regime, provides no clear guidance, as the dependence observed is inconsistent with the predictions for either regime.

In the following section, the background of phonon drag and experimental details are presented. General properties of phonon-mediated drag are explored through measurements discussed in the following section. The subsequent section directly examines the possible existence of the coupled electron-phonon mode by measurements of the layer spacing dependence and the dependence on total density, and through comparison of these measurements with existing theoretical calculations. Finally, we present the results for a very remotely spaced layer sample and discuss several features which cannot be explained by current theory.

II. PHONON DRAG: BACKGROUND AND TECHNIQUE

Interactions between electrons are known to have dramatic effects on the properties of 2DEG systems. While direct measurement of these interactions is generally difficult, it was proposed by Pogrebinskii and later by Price that the e-e interactions might be measurable in a double layer, independent, 2D electron system due to the presence of interactions between layers. Such measurements, termed electron drag, have been achieved in the double layer 2DEG system, as well as in a 2D/3D electron system and the electron-hole double layer system.

In electron drag, a current, \( I \), is driven through one of two closely spaced but electrically isolated 2DEG layers. Scattering between electrons in opposing layers results in a transfer of momentum from the current carrying layer to the other, effectively dragging the electrons in the second layer. If current is not permitted to flow from the second layer, charge accumulates at one end resulting in a voltage, \( V_D \). The voltage increases until the force of the electric field due to charge accumulation balances the effective drag force resulting from interlayer interactions. Measurements of the drag resistivity, \( \rho_D \), the ratio of the induced voltage to the drive current per square, has been shown to be directly related to an interlayer electron-electron scattering rate, \( \tau^{-1} \), through a simple Drude style relation: \( \rho_D = m^*/ne^2\tau_D \), where \( m^* \) is the effective mass and \( n \) is the electron density. This technique thus provides quantitative evaluation of e-e scattering.

Prior studies have established two distinct contributions to the interlayer e-e interactions: direct Coulomb scattering, and phonon exchange scattering. For very closely spaced layers, the Coulomb contribution dominates, resulting in \( \rho_D \) that varies as \( T^2 \) at low temperatures. This contribution to interlayer scattering has a strong layer spacing dependence, \( d^{-4} \). This results from a cutoff in the maximum scattering wavevector at the inverse of the layer spacing and modifications to screening efficiency as the layer spacing is changed. The strong layer spacing dependence permits phonon scattering to dominate \( \rho_D \) for remotely spaced layers. However, the contribution of phonon scattering is still evident even for closely spaced layers through a peak near 2 K when \( \rho_D \) is scaled by \( T^2 \), emphasizing deviations from the quadratic dependence of Coulomb scattering.

While previous studies clearly established the existence of a phonon mediated e-e scattering process and the important role of 2KE scattering, questions regarding details of the underlying mechanism, especially in regard to the magnitude of \( \rho_D \), are still not conclusively understood. Gramila et al. showed that real phonon exchange, while generating approximately the right temperature dependence, could not explain the magnitude of \( \rho_D \), and proposed a virtual phonon exchange. Tso et al. included virtual phonon exchange in a calculation of \( \rho_D \) and obtained reasonable agreement in both magnitude and temperature dependence, but questions have been raised about the electron-phonon coupling used in their work. Zhang et al. used a first-principles approach but found a phonon mediated drag which has the same layer spacing dependence as the Coulomb interaction, inconsistent with prior experimental results. Virtual phonons have also been considered by Badalyan et al. The existence of the coupled electron-phonon collective mode was proposed by Bonsager et al. as a possible basis for the strong scattering if the phonon mean free path is large. The aim of this work is to firmly establish the essential physical elements of phonon drag and to test for the existence of the coupled electron-phonon collective mode.

The samples used in the study are GaAs/Al_{0.3}Ga_{0.7}As double quantum well structures grown by Molecular Beam Epitaxy. Two 2DEG layers formed in 200 \( \text{Å} \) wide...
quantum wells are separated by a potential barrier. Samples with barrier thicknesses of 225, 500, 2400, and 5000 Å were used, corresponding to well center-to-center spacings, d, of 425, 700, 2600, and 5200 Å, respectively. The density of each 2DEG layer as grown is approximately $1.5 \times 10^{11}$ cm$^{-2}$ with mobilities $\sim 2 \times 10^6$ cm$^2$/Vs. An active region, in which interactions are probed, was defined through standard photolithographic techniques in a mesa approximately 440 µm long and 40 µm wide. Electrical connection was provided through Au/Ge/Ni ohmic contacts. The ability to separately contact the individual 2DEG’s was provided through a gating technique which uses both front and backside aluminum Schottky gates. The use of an interlayer bias and application of a voltage to an overall top gate allowed the density of the layers to be altered, as calibrated by Shubnikov-de Haas measurements. In the drag measurement itself, low-frequency, low-excitation currents of $\sim 100$ nA were used, with the nV or smaller drag signals detected using established drag techniques.

III. GENERAL PROPERTIES OF PHONON DRAG

This section presents new measurements of the temperature and density dependences of phonon drag in a sample with $d = 2600$ Å. General features of the phonon scattering process are discussed. These include a temperature dependence which is characteristic of an electron-phonon scattering processes and the dominant role of $2k_F$ scattering.

A. Temperature dependence

Measured drag resistivity, $\rho_D$, scaled by $T^2$ as a function of temperature for the 2600 Å spacing sample is shown in Fig. 1. For this layer spacing, the strong $d$ dependence of the Coulomb interaction makes its contribution to $\rho_D$ completely negligible. The magnitude of Coulomb scattering can be estimated based on its $d^{-4}$ spacing dependence and its magnitude as determined in other samples. The estimate for the Coulomb component of $\rho_D/T^2$ ($\sim 0.5$ $\mu\Omega/\Box$K$^2$) is three orders of magnitude less than the phonon contribution. The most striking feature in these data is a clear transition which occurs near 2 K from a strong temperature dependence at lower temperatures to a dependence weaker than quadratic at higher temperatures. The general character of the transition is identical to that observed in other samples, for both closely spaced layers where Coulomb scattering is present and for a sample even more remotely spaced. This transition is a general feature of 2DEG phonon scattering and was first observed in the Bloch-Grüneisen transition of acoustic-phonon-limited mobility in 2DEG’s.

![FIG. 1. Drag resistivity divided by $T^2$ versus temperature for $d = 2600$ Å. The densities of both layers are matched at $1.53 \times 10^{11}$ cm$^{-2}$. Coulomb scattering is completely negligible in this data. A transition from a strong to a weak temperature dependence occurs in $\rho_D/T^2$ near 2 K. The behavior reflects the important role of $2k_F$ scattering, which is characteristic of electron-phonon scattering.](image)

There are two essential elements which contribute to this change in temperature dependence. The first is a sharp cutoff for the wavevectors of phonons which can be scattered by the electron system. At low temperatures, only phonons with wavevector $q < 2k_F$ can be thermally excited. All such phonons can participate in the scattering process. As the temperature increases, progressively larger wavevector phonon states become occupied. The increase in wavevector provides both a larger momentum transfer and access to more of the electron phase space, leading to a strong temperature dependence for phonon scattering. This increase continues until phonons with $q \sim 2k_F$ become thermally excited. Low energy excitations of the electron system are absent for changes in $q > 2k_F$, so phonons with these $q$’s cannot scatter and conserve both energy and momentum. The transition to a weaker temperature dependence resulting from this cutoff will scale with the size of the Fermi surface.

A second element which contributes to the behavior is the enhanced phase space available for large angle scattering in the electron system, which diverges at zero temperature for a scattering wavevector equal to $2k_F$. The divergence allows $2k_F$ phonons to dominate scattering, even at temperatures below the energy of such phonons. The important role of $2k_F$ scattering is illustrated in Fig. 1. It shows the relative net momentum $P_Q$ transferred to the phonon system per unit time calculated for a single current carrying electron layer as a function of wavevector parallel to the 2DEG, $Q$. The
calculation is directly related to earlier approaches for calculating phonon scattering. At 7 K, the momentum transfer rate is dominated by phonons in the vicinity of \( Q = 2k_F \) for both deformation potential and piezoelectric coupling. As the temperature is reduced to \( \sim 3 \) K, this peak sharpens, with \( \sim 2k_F \) scattering continuing to dominate the momentum transfer process. Even at 1.02 K, a fraction of the energy of a 2\( k_F \) phonon, 2\( k_F \) phonons continue to represent a significant portion of the total momentum, although low \( Q \) phonons also become important.

This predominance of 2\( k_F \) scattering is critical for determining the temperature which characterizes the change in temperature dependence. If there were simply a cutoff at 2\( k_F \), the transition would be expected to occur when the characteristic phonon wavevector equals 2\( k_F \); at a temperature of \( T_c = 2k_F \hbar s/k_B \), where \( s \) is the sound velocity. By using the longitudinal acoustic-phonon velocity for \( s \), the transition temperature \( T_c \sim 7.8 \) K is obtained; the transverse sound velocity yields \( T_c \sim 4.6 \) K. However, the strong contribution of 2\( k_F \) scattering still dominates well below this temperature. This dominance permits the scattering rate to be determined primarily by the thermal occupancy of 2\( k_F \) phonons, even at temperatures well below the expected transition. Indeed, the characteristic shape for the drag momentum transfer of 2\( k_F \) phonons continues to represent a significant portion of the total momentum, although low \( Q \) phonons also become important.

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Evidence for the dominance of 2\( k_F \) phonons in the drag process is available in the dependence of \( \rho_D \) on density. The dependence of \( \rho_D \) on the relative densities of the two layers is shown in Fig. 3. In this measurement, the density of one layer is fixed while the density of the other is changed using an overall top gate. Measurements at different temperatures for the 2600 Å spacing sample are shown. The key aspect of this measurement is a clear maximum in the drag resistivity when the densities of both layers are matched. At matched densities, each electron system has an identical Fermi surface size so the dominant emission of 2\( k_F \) phonons in one layer matches those phonons most likely to be absorbed by the other. When the densities of two layers are mismatched, 2\( k_F \) phonons of the higher density layer have \( q \)'s too large to permit absorption in the other layer. The substantial reduction in phonon exchange at \( q \)'s other than 2\( k_F \) cause a significant reduction in \( \rho_D \) as compared to matched densities. While the peak at matched density has been observed earlier in a \( d = 425 \) Å sample at 2.3 K and in

**FIG. 2.** Calculations of the net momentum transfer rate from a single-layer electron system to phonons for both deformation potential (DP) and piezo-electric (PE) coupling at various temperatures as a function of \( Q/k_F \). Rates are plotted relative to the DP coupling results at 7.0 K. The cutoff in phonon scattering at 2\( k_F \) is evident with a strong contribution from 2\( k_F \) scattering for all temperatures.

**FIG. 3.** Measured drag resistivity versus layer density ratio for \( d = 2600 \) Å at four different temperatures. The top layer density, \( n_{\text{top}} \), is varied while the bottom layer density \( n_{\text{bot}} \) is fixed at \( 1.53 \times 10^{11} \) cm\(^{-2}\). The peak at matched densities confirm the importance of 2\( k_F \) scattering, which persists even to the lowest temperatures. Coulomb scattering is entirely negligible in this sample.

Fig. 2 can be reasonably well represented by simply the thermal occupancy of the 2\( k_F \) phonons. At the lowest temperatures, where the contribution of 2\( k_F \) phonons is lost, a characteristic strong power law dependence is recovered.
IV. COUPLED ELECTRON-PHONON MODE

In this section, measurements of layer spacing and matched density dependence are presented and compared to theoretical predictions. Fits to the phonon mean free path determined by this comparison, detailed density dependence measurements, and the overall magnitude of $\rho_D$ are considered as tests of the existence of a coupled electron phonon collective mode.

A. Layer spacing dependence

It has been experimentally established that phonon drag has a weak layer spacing dependence. A specific form of the dependence has not been studied in detail, however, until the recent calculation by Bønsager et al.\textsuperscript{[4]} Their work predicts that in the limit of small phonon mean free path, drag varies as $\ln(d_a/d)$ until $d$ reaches $d_a$, which equals $l_{ph}/2k_FL$. For $d > d_a$, $\rho_D$ decreases more abruptly as $(d_a/d)\exp(-d/d_a)$. In the coupled mode regime, which requires large phonon mean free paths, drag was also expected to decrease logarithmically as long as $d$ is less than $d_B = (1 + q_{TF}/2k_F)/16k_FC_{DP}$, where $q_{TF}$ is the Thomas-Fermi wavevector and $C_{DP}$ is the dimensionless deformation potential coupling constant as defined in eq. (30) of their paper. For the parameters typical of our samples, $d_B$ is approximately 5000 Å. For $d$ greater than $d_B$, it was found that $\rho_D$ has a local maximum at $d \sim \sqrt{l_{ph}/k_F}$, beyond which the electron-phonon coupled mode, which involves both electron layers, begins to separate into two independent modes, substantially reducing interlayer drag.

Measurements of the layer spacing dependence of $\rho_D$ provides a test of both this general theoretical approach, as a logarithmic spacing dependences should be observed, and as an indication of the existence of the electron-phonon collective mode. Measurements of $\rho_D$ for five different values of $d$ are shown in Fig. 4. Data for one layer spacing, $d = 375$ Å, is reproduced from the work of Ref. 2; current measurements for $d = 425, 700, 5200$ Å generally confirm prior experimental results. The 2600 Å spacing has not been previously measured. The data is plotted as $\rho_D/T^2$, where Coulomb contributions can be represented by a horizontal line. Visual inspection shows that the phonon contribution to $\rho_D$, which can be estimated by the deviation from a quadratic temperature dependence, shows little variation for layer spacing 700 Å or less, but reduces significantly for larger layer spacings. This variation can be quantified after subtraction of the Coulomb contribution of $\rho_D$. This contribution for $d = 700$ Å is that determined in Ref. 3 and 4; a $d^{-4}$ spacing dependence was used to infer the value for smaller layer spacings. No subtraction is necessary for $d = 2600$ Å and 5200 Å. The resultant phonon scattering for the $d = 700$ Å sample was used to fit the Coulomb adjusted data sets; a single multiplicative constant was applied to a $d = 500$ Å sample at 4.2 K, the behavior for both of those measurements included a significant contribution of Coulomb scattering. The data presented here can be directly compared to calculations of phonon drag without the significant added uncertainty arising from a subtraction of Coulomb scattering. The elimination of Coulomb scattering also permits the observation of a peak in the Fermi surface. Since the size of $2k_F$ is well below a nanovolt. This observation of a maximum in $\rho_D$ at matched density for this low temperature clearly supports the dominant role of $2k_F$ scattering, even for a temperature below the peak in $\rho_D/T^2$ of Fig. 1, and well below the temperature corresponding to the energy of a $2k_F$ phonon.

Further evidence for phonon scattering across the Fermi surface can be obtained from the temperature dependence measured for various matched layer densities. Measurements of $\rho_D/T^2$ are shown in Fig. 4 for three different densities with $n$ changing by a factor of 2. This measurement directly tests the assumption that the observed transition temperature is determined by the size of the Fermi surface. Since the size of $2k_F$ scales as $\sqrt{n}$, decreasing the density should move this transition to lower temperatures. Both the observed direction and magnitude of this change are in agreement with a dominance of phonon drag by $2k_F$ phonon exchange.
obtain a best fit to the other layer spacings. Nearly identical results for the 375 Å and 425 Å spacing samples are obtained if their Coulomb contribution is permitted to be a free fitting parameter. The overall relative magnitude of phonon drag determined through this fitting is shown in Fig. 5. A logarithmic layer spacing dependence is evident for the data with \( d \leq 2600 \) Å. This behavior does not extend to the 5200 Å spacing sample, the behavior of which will be postponed for a later section; we focus here on the smaller layer spacings.

The logarithmic dependence seen in Fig. 5 can be used to determine a value for the phonon mean free path, assuming that the drag corresponds to the independent system regime where \( \rho_D \propto \ln(d_a/d) \). The corresponding spacing dependence is shown in the figure as a dashed line. The value determined for the phonon mean free path from this fit is 15 µm. This value is substantially less than the critical value which determines the onset of the dominance of the coupled mode regime; that value was shown to be \( \sim 200 \) µm for the parameters of our sample. This small value for \( l_{ph} \) appears to indicate that the coupled electron-phonon collective mode is absent.

A difficulty with the value obtained for \( l_{ph} \) is that it differs considerably from the phonon mean free path determined through thermal conductivity measurements on similar samples. Measurements by Eisenstein et al. found \( l_{ph} \) to be nearly two orders of magnitude larger. It is possible that this difference can be accounted for by the fact that the phonons which scatter from the 2DEG are predominantly \( 2k_F \) phonons. Interactions with the electron system could result in a \( l_{ph} \) for \( 2k_F \) phonons substantially shorter than for phonons with other wavevectors. The removal of \( 2k_F \) phonons from a thermal conductivity measurement could have a small effect, as a broad range of phonon wavevectors contribute as determined by the Bose distribution. The scale of the difference in \( l_{ph} \) weakens the use of its value as determined in Fig. 5 as a sole indicator for the absence of an electron-phonon collective mode.

**B. Matched density dependence**

An important additional test for the existence of the electron-phonon collective mode is the dependence on total matched density at various temperatures. This dependence has been calculated to show distinctly different behavior in the two regimes of \( l_{ph} \). At 1 K in both regimes, \( \rho_D \) should decrease monotonically as the density increases. At higher temperatures, a peak in the density dependence emerges for \( l_{ph} < l_c \), i.e. for the case where no electron-phonon collective mode contributes to drag. The emergence of this peak at 2 to 4 K is accompanied by a change in the background density dependence. The decrease with increasing density seen at 1 K is smaller at 2 K. For 3 K and 4 K, there is only a small overall
change with density in the magnitude of $\rho_D$. This behavior contrasts with that expected for $l_{ph} > l_c$, where the coupled electron-phonon collective mode dominates. In this regime, $\rho_D$'s behavior changes from a decrease with increasing density at 1 K to a substantial increase with density for higher temperatures. By 4 K the dependence is nearly proportional to density. These general differences in behavior, which are related to differences in screening and the role of the coupled electron-phonon collective mode, should be readily discernible in experiments.

Measurements of the density dependence of $\rho_D/T^2$ for the 2600 Å spacing sample are shown in Fig. 7. The general dependence seen at 1.2, 2.0, 3.0 and 4.0 K is strikingly similar to that predicted in the calculation of Ref. 1 for the small $l_{ph}$ regime. For each temperature measured, both the overall dependence on density and the emergence of the peak at high temperatures is in good agreement with predictions based on weak coupling and display clear differences from expectations for the strong coupling regime. These measurements clearly support the assertion that phonon drag in this sample corresponds to the short phonon mean free path regime, that is, the regime for which the coupled electron-phonon collective mode is absent.

A key element which distinguishes these measurements is the confidence that Coulomb scattering can be neglected. Earlier measurements which confirmed the existence of a peak in the relative density dependence at various matched densities, as had been seen in Ref. 4, also explored the dependence of $\rho_D$ at 4.2 K on total matched density. Those measurements, however, explore a density regime generally above the theoretical investigations of Ref. 1, and required a subtraction of Coulomb scattering. The relatively small increase of $\rho_D$ observed ($\sim 25\%$) for densities between 2 and $3.8 \times 10^{11}$ cm$^{-2}$ appear inconsistent with extrapolation of the current 4 K measurements; but this small increase assumes subtraction of a Coulomb contribution with a density dependence that has not been established in experiment. The measurements presented here can be compared to theory without the additional uncertainty introduced by such subtraction.

C. Magnitude of the drag

Although both the layer spacing and the matched density dependence show results clearly consistent with the short mean free path regime, there remains a contradiction as regards the magnitude of $\rho_D$. The measured magnitude is inconsistent with calculations assuming a small phonon mean free path, and is in much better agreement with the assumption of a large $l_{ph}$. It could be argued that the magnitude of $\rho_D$ alone could be considered evidence for the existence of a coupled electron-phonon collective mode. It is this mode which provides the increase in $\rho_D$ in Ref. 1 beyond that expected for ordinary phonon exchange, which has been shown to be too small to account for the strength of the phonon based interactions. This argument cannot be considered conclusive, however, as there is considerable uncertainty in the overall magnitude calculated for $\rho_D$. This uncertainty arises from the use of the random-phase approximation (RPA) for screening. It is possible that the use of a more complete description of screening would generate a substantially larger magnitude for $\rho_D$ where $l_{ph} < l_c$, which must increase by an order of magnitude to match the observed $\rho_D$. The contradiction between evidence for a short phonon mean free path, as seen in the layer spacing and density dependences, and that for a long phonon mean free path, as seen in the magnitude of $\rho_D$, remains. The question of the existence of the coupled electron-phonon collective mode has thus not been conclusively addressed.

V. REMOTELY SPACED LAYER SAMPLE

The discussion above is restricted to those samples for which a logarithmic spacing dependence is observed. Measurements made on a sample with $d = 5200$ Å has a magnitude for $\rho_D$ which lies well below that expected from the logarithmic dependence, consistent with prior measurements. A deviation from a logarithmic dependence is expected in the short $l_{ph}$ regime for layer spacings larger than $d_a$ where $\rho_D$ decreases exponentially
with \( d \). Use of the value of \( l_{ph} \) derived from the spacing dependence measurements yields a value for \( d_a \) of 3.8 \( \mu \)m. Significant deviations from a logarithmic dependence should not occur in the small \( l_{ph} \) limit until the spacing is an order of magnitude larger than 5200 Å.

The unexpected reduction in \( \rho_D \) requires consideration of alternate origins. A possible explanation is that drag occurs in the large \( l_{ph} \) collective mode limit despite the evidence for a small \( l_{ph} \) regime. In this regime, a change in characteristic behavior occurs at a length scale much smaller than for the small \( l_{ph} \) regime. This characteristic layer spacing in our samples corresponds to a length of approximately 5000 Å. If the large \( l_{ph} \) limit applies, a substantial deviation below the observed logarithmic dependence for \( d = 5200 \) Å could then be consistent with expectations for an electron-phonon collective mode.

The absence of a clear indication of which regime is appropriate provides motivation for re-examining the dependence on matched densities for the 5200 Å sample. Such a measurement is extremely difficult, requiring accurate detection of signals as small as 250 pV. The central difficulty in measuring such small signals lies in ensuring that potential spurious signals are absent; this was verified here to a level of 30 pV. An additional complication for the measurement is that large layer spacings require a substantial interlayer bias to be applied, limiting the range of densities measured to between 1.1 and 1.7 \( \times 10^{11} \) cm\(^{-2} \) per layer.

The results of these measurements are shown in Fig. 8. A reduction in \( \rho_D \) with increasing density at 1.2 K is consistent with the behavior of the 2600 Å spacing sample. For higher temperatures, however, there are distinct differences from the earlier measurements. A clear reduction in magnitude with increasing density is observed for all measured temperatures. There is no sign of a peak in the density dependence, as was clearly evident for the 2600 Å spacing sample. These data are inconsistent with both the small \( l_{ph} \) limit, which well describes the density dependence for the 2600 Å spacing sample, and with the large \( l_{ph} \) limit. In either case a peak in the density dependence can be discerned, but no peak is apparent in the 5200 Å spacing measurements. In both cases, the theoretical dependence at high temperatures makes a clear departure from the decreasing dependence typical at \( \sim 1 \) K: to a weak density dependence for small \( l_{ph} \) and to a strongly increasing density dependence for large \( l_{ph} \). The 5200 Å spacing sample, by contrast, retains a decreasing density dependence as the temperature is increased, clearly contradicting either theoretical prediction.

The unusual behavior seen for this sample is not reflected in measurements exploring more fundamental elements of the electron-phonon scattering process, such as the presence of a cutoff at \( 2k_F \). This can be seen in the data of Fig. 9, which shows the temperature dependence of \( \rho_D/T^2 \) for two densities. The data show the change in \( T \) dependence characteristic of this cutoff, and a shift in the transition temperature corresponding to the change in the size of the Fermi surface. Quantitative information about this transition temperature is somewhat uncertain,
as it was not possible to verify the lack of spurious signals to a level below 30 pV. Adding a small offset to the measured signal can change the apparent peak position. The general confirmation of the properties related to the $2k_F$ wavevector cutoff in the 5200 Å spacing sample makes its magnitude and its dependence on matched densities more puzzling. The only free parameter in the theoretical calculations is $l_{ph}$, which determines whether the electron and phonon systems are weakly or strongly coupled. We would expect this parameter not to vary between samples, as they are all essentially identical apart from the size of the barrier. Yet the 5200 Å spacing sample is clearly distinct in behavior from the more closely spaced layer samples, and from theoretical predictions for either $l_{ph}$ regime. The measurements for this sample strongly suggest that understanding of interlayer phonon mediated electron-electron scattering is not yet complete.

VI. CONCLUSIONS

Extensive measurements of phonon mediated electron-electron scattering have been performed using electron drag on double layer 2DEG samples. Measurements for a sample in which Coulomb scattering is absent explored fundamental elements of this scattering process. These include the presence of a cutoff for scattering of phonons having wavevectors greater than twice the Fermi wavevector of the electron system and the dominance of $2k_F$ scattering even at relatively low temperatures. These properties of phonon drag, which are directly related to elements of electron-phonon scattering in single layers, have been verified in temperature and density dependence measurements.

Additional measurements explore the existence of a coupled electron-phonon collective mode, as has been recently proposed for 2DEG systems. Contradictory evidence concerning the existence of this mode has been observed. Both the dependence of the scattering on layer spacing below 3000 Å and its dependence on matched layer densities at various temperatures show behavior consistent with the absence of this mode. The overall magnitude of the scattering, however, suggests the presence of the collective mode. The phonon mean free path, as determined by fits to the spacing dependence assuming the absence of the mode, also differs by orders of magnitude with previous measurements of this length via thermal conductivity. Phonon drag measurements for a sample with a 5200 Å layer spacing raise further questions about details of the scattering process. Although the fundamental elements of scattering related to the size of the Fermi surface are confirmed in this sample, its scattering strength is well below the logarithmic spacing dependence found for more closely spaced layers. The sample further shows a decrease in scattering strength as the density of both layers is increased, a behavior generally inconsistent with theoretical predictions assuming either the absence or presence of the collective mode.

In general, while basic properties of phonon drag are well established, these measurements show that a full understanding of the process, especially with respect to the magnitude of the scattering and the presence of a coupled electron-phonon collective mode, requires further investigations.

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