Coupled Electron-Hole Transport: Beyond the Mean Field Approximation

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We demonstrate that Coulomb drag between spatially separated quasi-two-dimensional electron and hole gases is strongly enhanced by Coulombic correlations. The correlations modify the carrier concentration dependence and the temperature dependence of transresistance and remove the persistent order of magnitude disagreement between the experimental data and the theories based on the mean field (random phase) approximation. Disorder scattering is shown to influence the results, particularly strongly at low concentrations.

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A great deal of attention has been recently devoted to double layer systems in which two quasi-two-dimensional subsystems (electron or hole gases) are placed in parallel planes separated by a potential barrier thick enough to prevent particles from tunneling across it but allowing for the interactions between the particles on both its sides. In such systems many body correlations due to Coulomb interactions are a crucial ingredient of the detailed description of their behavior. For example, it was suggested that in electron-hole double layer systems carriers of opposite charge occupying adjacent layers attract each other and may form excitons which condense into a superfluid phase [1]. Also, a rich phase diagram due to Coulombic correlations is anticipated [2] in a double layer system, including Wigner crystal and charge density wave phases. In the presence of perpendicular high magnetic field the Coulombic correlations are essential in theoretical models explaining observed phenomena like the appearance of a new incompressible ground state which exhibits the fractional quantum Hall effect [3] or magnetic field driven destruction of quantum Hall effect states [4]. In contrast to the situation encountered in high magnetic fields, the experimental detection of effects of Coulombic correlations has proven to be difficult in their absence. Recently, however, attempts to describe transport properties of electron-hole double layer systems [5] using mean field theories [random phase approximation (RPA)], which ignore short range correlations, consistently underestimate the interlayer Coulomb drag by an order of magnitude.

Transport measurement techniques used in experiments of Ref. [5] are designed to probe the mutual friction between two gases due to the interlayer momentum exchange in the electron-hole scattering processes. The system consists of two intrinsic thick GaAs layers deposited on opposite sides of about 200 Å thick AlGaAs barrier, which are filled with carriers of opposite sign by applying an appropriate electric bias [5]. An electric current is allowed to flow in the drag layer which, due to the across-the-barrier momentum transfer, drags the carriers in the other layer. If, however, the current in the second layer is not allowed to flow, the carriers in this layer are swept to one end until the induced electric field balances exactly the drag force. The quantity measured is transresistance R_T defined as the ratio of the potential difference in the second layer to the current in the drag layer. Earlier, similar measurements have been performed in electron-electron double layer systems [6].

Experimentally [5], the transresistance R_T decreases with the increase of the electron concentration more rapidly than it does with the increase of the concentration of holes. Also, R_T is proportional to the temperature at high electron concentrations but then becomes almost T independent when either concentration is lowered by an order of magnitude. Existing theoretical models are incapable of accounting for these observations, particularly at lower concentrations: Application of the RPA theory predicts the transresistance values between a factor of 5 to 1 order of magnitude too small [5]. The generalized RPA approach of Ref. [7] modifies the RPA results in the desirable direction reducing the discrepancy at the highest carrier concentrations. At low carrier concentrations, however, the generalized RPA predicts very strong temperature dependent R_T in conflict with the almost temperature independent experimental one and, at the lowest temperatures, it predicts its value still nearly an order of magnitude too low.

We will argue in this Letter that the experimentally observed transresistance for the electron-hole double layer system can be explained by direct Coulomb scattering between carriers, provided short range correlations present in the system are correctly accounted for. The interaction between the carriers in different layers is attractive, and together with the repulsive interactions within each layer they produce a larger probability of finding electron and hole close together. In extreme cases of very low carrier concentrations and small interlayer distances this correlation effect may lead to the formation of excitons and to their subsequent condensation [1]. In the less extreme experimental situation of Ref. [5], when the distance between the layers is larger than the effective

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Bohr radius, the excitonic formation is unlikely. The correlations, however, are still strong enough to enhance the effective electron-hole interaction and to boost the interlayer drag force.

In previous approaches to the calculation of transresistance (with the exception of Ref. [7]) the carrier-carrier interactions were taken into account in the mean field approximation [5,8,9] (and references therein) in which effects of interactions are replaced by the average field due to all other particles. However, it is well known that for low densities and short distances the presence of the exchange correlation hole diminishes the electron-electron [10,11] interaction and enhances the interaction between electrons and holes [11–13]. In the local field approach this effect is approximated by replacing the bare Coulomb interactions with effective potentials which take the correlations into account. In this spirit, the expression for the transresistance derived in Ref. [9] can be written as

$$R_T = \frac{-\beta \hbar^2}{4\pi^2 e_1 e_2 n_1 n_2} \int_0^\infty dq\, q^3 \int_0^\infty d\omega \left| \frac{V_{\rm eff}^{12}(q)}{\varepsilon(q,\omega)} \right|^2 \frac{\operatorname{Im}\chi_s^1(q,\omega) \operatorname{Im}\chi_s^2(q,\omega)}{\cosh(\beta\hbar\omega) - 1}, \tag{1}$$

where $\beta = 1/k_B T$ and subscripts or superscripts $\alpha = 1, 2$ refer to two layers of the system and $e_\alpha = +e$ for the hole-filled layer and $-e$ for the electron-filled one. $\chi_s^\alpha(q,\omega)$ is the response function of the noninteracting two-dimensional gas in a layer α. The dielectric function for the two-component system [11]

$$\varepsilon(q,\omega) = [1 + V_{\rm eff}^{11}(q)\chi_s^1(q,\omega)][1 + V_{\rm eff}^{22}(q)\chi_s^2(q,\omega)] - [V_{\rm eff}^{12}(q)]^2 \chi_s^1(q,\omega)\chi_s^2(q,\omega) \tag{2}$$

screens in Eq. (1) the effective interlayer Coulomb interaction $V_{\rm eff}^{12}(q)$. Simplified derivation [5] of transresistance, without correlation effects, using Fermi's "golden rule" to calculate the rate of interlayer momentum and energy transfer, provides a straightforward physical interpretation of Eq. (1). Because of the interlayer interaction, the carriers in the first layer lose, as described by $\operatorname{Im}\chi_s^1(q,\omega)$, momentum $\hbar q$, and energy $\hbar\omega$, which are then gained by the carriers in the second layer [cf. $\operatorname{Im}\chi_s^2(q,\omega)$]. We note that Eqs. (1) can also be derived from the general theory of the linear response for the two-component system [14].

We calculate $V_{\rm eff}^{\alpha\alpha'}$ using the local field approach of Singwi, Tosi, Land, and Sjölander (STLS) [15] which accounts for the short range correlations in a nonperturbative way. The method was generalized to the two-component plasmas [16], and we use its version designed for the two layer systems [11–13,17] in which the effective interaction potentials are written in the following form:

$$V_{\rm eff}^{\alpha\alpha'}(q) = \left(\frac{2\pi e_\alpha e_{\alpha'}}{\varepsilon_0 q} e^{-qd(1-\delta_{\alpha\alpha'})} \right) F^{\alpha\alpha'}(q)[1 - G^{\alpha\alpha'}(q)]. \tag{3}$$

The first factor in the parentheses accounts for the bare Coulomb interaction between carriers within the same ($\alpha = \alpha'$) and in different ($\alpha \neq \alpha'$) layers, separated by the barrier of width d. $F^{\alpha\alpha'}(q)$ are form factors due to the finite thickness of the layers [7]. The static local field corrections $1 - G^{\alpha\alpha'}(q)$ account for short range correlations. ε_0 is the background static dielectric constant of the host material. Full derivation of Eq. (3) for the spatially separated electron-electron and electron-hole systems are given in Refs. [11] and [13].

Physical interpretation of Eq. (3) is as follows. The calculated STLS local field $G^{\alpha\alpha'}(q)$ for $\alpha = \alpha'$ vanishes at $q = 0$ and tends to 1 for q larger than twice the Fermi momentum leading to a reduction of the carrier-carrier interactions for larger momentum transfers. In the real space, they account for the depletion of the probability of finding an electron (or a hole) around a particular charge carrier because they tend to avoid each other [10]. For $\alpha \neq \alpha'$, the role of the interlayer correlations is different in the electron hole than it is in the electron-electron double layer systems. In the former case [13], $1 - G^{\alpha\alpha'}(q) > 1$, i.e., the interlayer correlations enhance the strength of the effective interlayer interaction between an electron and a hole. This reflects the fact that in the real space the probability of finding a hole in one layer lying directly opposite an electron in the other one is enhanced due to the attractive Coulomb interactions [12,13]. For the electron-electron double layer system the effect of the interlayer Coulombic correlations is opposite: it reduces the strength of the interlayer effective interactions [11].

The replacement of the bare Coulomb potential with the effective potential strongly modifies dynamic screening [Eq. (2)] and thus the collective excitation spectrum of the double layer system [17]. Two collective excitation plasmon modes are present: the acoustic one with linear dispersion in the long wavelength limit in which both subsystems oscillate in phase, and the optical one with the square root dispersion law in which they oscillate out of phase [18]. Since at finite temperatures the momentum and energy transfers corresponding to the plasmon poles, in particular the acoustic ones which are easier to excite thermally, significantly contribute to the transresistance, results obtained from Eq. (1) can be very sensitive to the form of the interaction potential.

We account for disorder scattering by introducing single-particle memory functions $\gamma_\alpha(q,\omega)$ for carriers in each layer [10]. They modify the (Lindhard) response functions of the noninteracting two-dimensional gases $\chi_0^\alpha(q,\omega)$ yielding the susceptibilities in the presence of disorder:

$$\chi_s^\alpha(q,\omega) = \frac{\chi_0^\alpha(q,\omega + i\gamma_\alpha)}{1 - [i\gamma_\alpha/(\omega + i\gamma_\alpha)][1 - \chi_0^\alpha(q,\omega + i\gamma_\alpha)/\chi_0^\alpha(q)]}. \tag{4}$$

In Eq. (4), the memory functions $\gamma_\alpha(q,\omega)$ are replaced with the inverse of the relaxation times, $\gamma_\alpha = \tau_\alpha^{-1}$, related to the measured mobilities in each layer by the usual Drude expression. In such case, Eq. (4) agrees with Mermin's expression [19] for the response function. It has a standard diffusive form in the long wavelength–low frequency hydrodynamic limit.

In Fig. 1 we present theoretically predicted electron [panel (a)] and hole [panel (b)] concentration dependence of the transresistance for the electron-hole double layer system experimentally investigated by Sivan, Solomon, and Shtrikman [5]. Three solid lines represent the predicted transresistance with intralayer and interlayer correlations and with disorder scattering included. The latter is accounted for by mobilities in each well taken from the experimental data provided in Ref. [5]. We note good to excellent agreement between the results of the complete theory (solid lines) and the experimental data (symbols) over the entire range of concentrations which is impossible to achieve in the RPA approximation (dashes). The difference between the results of the present theory and those in the RPA approximation emphasize the importance of the Coulombic correlations in this system.

Role of correlations.—The correlations within each layer tend to reduce the intralayer effective potentials $V_{\rm eff}^{\alpha\alpha}$, reducing screening [cf. Eq. (2)] and consequently enhancing the transresistance in the electron-electron and electron-hole [7] double layer systems alike. The interlayer correlations influence the transresistance in a more direct way. In the electron-hole system the correlations tend to increase the probability of finding a hole close to an electron enhancing the across-the-barrier momentum transfer leading to an additional increase of the transresistance. In the electron-electron systems they obviously tend to diminish the transresistance. The relative importance of the interlayer correlations with respect to the intralayer ones increases with the reduction of the potential barrier width and with the reduction of carrier concentrations.

Temperature dependence.—At temperatures much lower than the Fermi temperature in either layer only low lying excitations of both subsystems contribute to the energy-momentum transfer processes between the layers. It then immediately follows that $R_T \propto T^2$ [6]. For high temperatures the entire excitation spectrum of the double layer system with momenta lower than $\hbar/d$ [limited by the interlayer interaction, Eq. (3)] contributes to the drag force so R_T nearly saturates as a function of T. In between these two extremes a smooth transition from T^2 to nearly T-independent transresistance occurs at temperatures which are lower the lower Fermi temperatures (i.e., carrier concentrations) are. The temperatures between 10 and 40 K, at which the experiments are performed, fall below the saturation region for the highest concentrations used but enter this region as the concentrations are lowered. This saturation of the temperature dependence of the transresistance for lower carrier concentrations is evident in both the experimental and the theoretical results in Fig. 1. We show in Fig. 2 the predicted temperature dependence of R_T for somewhat broader temperature intervals than in Ref. [5]. The saturation is evident for lower electron concentration [panel (a)] for temperatures higher than Fermi temperatures of both types of carriers. For higher electron concentrations [panel (b)] the saturation is not yet achieved because the electron gas Fermi temperature is very high. In the RPA approximation the saturation does not occur within the experimental temperature range even for the lowest concentrations used because RPA overestimates, due to lack of correlations, the energy of the collective excitations [17].

Role of disorder.—Disorder scattering brings about the diffusive character of the motion of carriers increasing the effective interaction time between them over that for purely ballistic motion. Consequently, the frictional drag between the layers increases [9]. The dotted line in Fig. 1 represents, for the lowest temperature considered, the calculated transresistance with all correlations included but with disorder scattering neglected. As expected, the scattering increases R_T by a factor of about 2 for the lowest

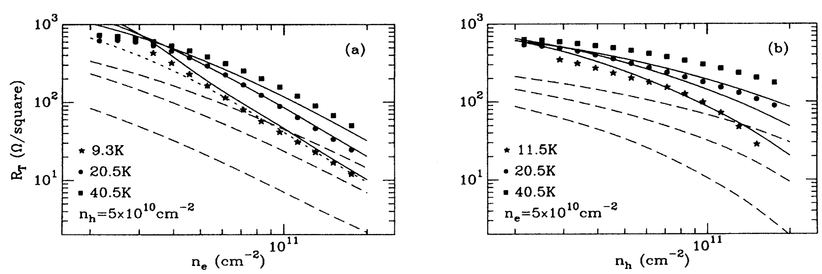

FIG. 1. R_T per square vs electron (a) and hole (b) concentrations with correlations and with disorder scattering (solid lines), in the RPA without disorder (dashes) for three temperatures of the experiment (solid symbols) [5], and with correlations but without disorder for $T = 9.3$ K [dots in (a)]. Barrier thickness: 200 Å; quantum well widths: 100 Å each; $\varepsilon_0 = 12.5$; effective masses: 0.45 (hole), 0.067 (electron).

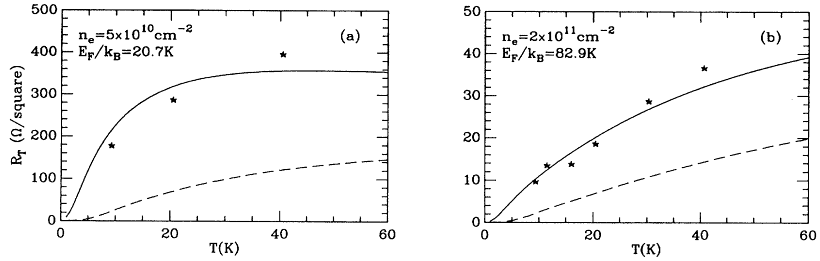

FIG. 2. R_T per square vs T with correlations and with disorder scattering (solid lines), and in RPA without disorder (dashes). Solid symbols—experiment [5]. Parameters as in Fig. 1.

electron concentrations. For higher temperatures the effect of the disorder scattering is still evident although it is somewhat smaller.

In summary, we have obtained the excellent agreement between the experimental transresistance data [5] and theory which includes the STLS-like local field corrections. At low carrier densities the effect of correlations is to increase the transresistance by up to an order of magnitude. Correlations tend to suppress the strength of collective excitations leading to weaker temperature dependence at low concentrations. We note that, while the effects of correlations in the 2D electron systems in high magnetic fields are well established, this is the first time when the essential role of the Coulombic correlations was demonstrated for the double layer system without the external magnetic field.

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