Dynamical correlations in Coulomb drag effect

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Abstract

Motivated by recent Coulomb drag experiments in pairs of low-density two-dimensional (2D) electron gases, we investigate the influence of correlation effects on the interlayer drag rate as a function of temperature. We use the self-consistent field method to calculate the intra and interlayer local-field factors $G_{ij}(q, T)$ which embody the short-range correlation effects. We calculate the transresistivity using the screened effective interlayer interactions that result from incorporating these local-field factors within various approximation schemes. Our results suggest that dynamic (frequency dependent) correlations play an important role in enhancing the Coulomb drag rate.
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There has been extensive theoretical and experimental activity on the frictional drag in coupled quantum-well systems in recent years [1]. The drag effect originates [2,3] from the interlayer Coulomb interactions between two spatially separated electron systems. When a current I is allowed to pass in only one of the layers, the charge carriers in the second layer are dragged due to the momentum transfer process. Here the distance between the layers is large enough so that tunneling effects are not significant. A drag voltage V_D is measured under the condition that no current flows in this second layer. Thus, the transresistivity $\rho_D = (w/l)V_D/I$ (where w/l is a geometrical factor) probes the Coulomb interaction effects in double-layer electron systems in a transport experiment. The drag effect is being studied experimentally in a variety of setups in which the charge carriers electrons, holes, or one of each [2–4]. The theoretical efforts have concentrated on calculating the momentum transfer rate due to different mechanisms within many-body theory [1,5,6].

We consider two parallel quantum wells separated by a distance d. The bare Coulomb interaction between the electrons is given by $V_{ij}(q) = (2\pi e^2/\varepsilon_0)e^{-qd(1-\delta_{ij})}F_{ij}(q)$, in which

i and j label the layers, and ε_0 is the background dielectric constant. The intra and interlayer Coulomb interactions are modified by $F_{ij}(q)$ describing the finite extent of the quantum wells in the direction perpendicular to the layers [2]. The 2D electron density n is related to the Fermi wave vector by $n = k_F^2/2\pi$. We use the dimensionless electron gas parameter $r_s = \sqrt{2}/(k_F a_B^*)$, in which $a_B^* = \varepsilon_0/(e^2 m^*)$ is the effective Bohr radius in the semiconducting layer with electron effective mass m^*.

The transresistivity measured in a Coulomb drag experiment for double-layer systems has been derived through a variety of theoretical approaches [1,5]. For simplicity and without loss of generality, we consider equal electron densities in both layers. In a microscopic approach, the drag resistivity is given by

$$\rho_D = \frac{1}{8\pi^2 e^2 n^2 T} \int_0^\infty dq\, q^3$$
$$\times \int_0^\infty d\omega \left| \frac{W_{12}(q,\omega)\, \text{Im}\, \chi_0(q,\omega)}{\sinh(\omega/2T)} \right|^2, \quad (1)$$

where we have assumed $\hbar$ and $k_B = 1$. Here, $\chi_0(q,\omega)$ is the 2D dynamic susceptibility, describing the density-density response function of a single layer electron system. $W_{12}(q,\omega)$ is the dynamically screened interlayer effective interaction. We compare various approximations for

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$W_{12}(q, \omega)$ in the following. First, the random-phase approximation (RPA) uses $W_{12}(q, \omega) = V_{12}(q)/\varepsilon(q, \omega)$ where $\varepsilon(q, \omega) = [1 - V_{11}(q)\chi_0(q, \omega)]^2 - [V_{12}(q)\chi_0(q, \omega)]^2$ is the screening function for the coupled quantum-well system, which uses the bare intra and interlayer electron–electron interactions (ignoring the correlation effects). The RPA simply considers the interaction of a test charge and it is strictly valid at high densities, i.e. $r_s \ll 1$. When the electron densities in the layers are reduced correlation effects are thought to become important and one needs to go beyond the RPA description.

One popular way of accounting for the exchange-correlation effects has been the self-consistent field method of Singwi et al. [7], also known as the STLS method. In the STLS scheme the bare Coulomb interactions are modified by the local-field factors, viz. $V_{ij}^{\text{eff}}(q) = V_{ij}(q)[1 - G_{ij}(q)]$. Also the screening function $\varepsilon(q, \omega)$ is amended to include $G_{ij}(q)$. We shall call this approximation STLS-I which has been extensively used in the drag calculations. We also consider a different approach by writing down the response function of the double-layer system as $\chi^{-1} = \chi_0^{-1} - V^{\text{eff}}$, where all the quantities are 2×2 matrices. On the other hand, the screened interaction will be defined in terms of the irreducible response function given as

$$\chi_{\text{irred}}^{-1} = \chi^{-1} + V, \tag{2}$$

where V is the bare Coulomb interaction matrix. Finally, the screened interaction to be used in the drag calculations takes the form

$$W = (1 - V\chi_{\text{irred}})^{-1} V = (V^{-1} - \chi_{\text{irred}})^{-1}. \tag{3}$$

Combining the above relations we obtain

$$W^{-1} = V^{-1} - (\chi_0^{-1} + U)^{-1}, \tag{4}$$

in which the screened interaction is expressed on terms of the bare Coulomb interactions, free response functions, and the local-field factors, since $U_{ij} = V_{ij}G_{ij}$. The above expression reduces to the RPA as expected when $U = 0$. A variant of this method of calculating the effective interactions was introduced by Zheng and MacDonald [5]. Noticing that this approach yields different results than the previous STLS approximation, we call it STLS-II.

Fig. 1 compares various approximations with the experimental data of Hill et al. [2]. We find that the STLS-I scheme provides a reasonable agreement. At large
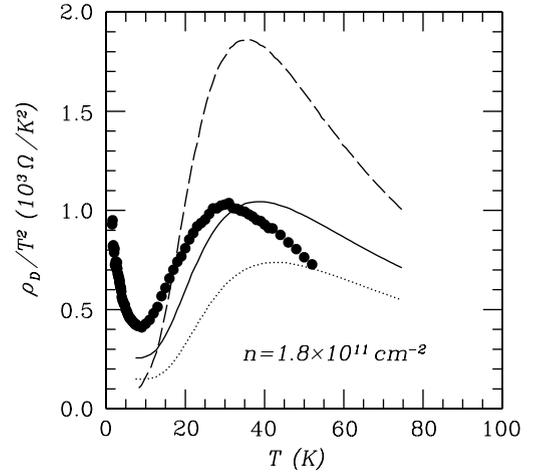

Fig. 1. The scaled transresistivity ρ_D/T^2 data of Hill et al. [2] as a function of T, compared to RPA (dotted), STLS-I (solid) and STLS-II (dashed) schemes.

temperatures ($T \sim E_F$) plasmon modes in coupled quantum wells enhance the observed drag resistivity. The RPA and STLS-II schemes under and over estimate, respectively, the effects of plasmons. STLS-I and STLS-II calculations show the significance of correlation effects in high temperature drag measurements. Results of Fig. 1 also indicate the importance of the choice of the interlayer interaction $W_{12}(q, \omega)$. Further work using the frequency dependent local-field factors may result in better agreement between experiment and theory.

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