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Exchange and correlation effect on spin Coulomb drag in a quasi-two-dimensional electron system

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Abstract

We investigate the effect of many-body electronic correlations on spin Coulomb drag (SCD) beyond the random phase approximation (RPA). We make use of the fully spin-resolved static and dynamical many-body local field factors of the two-dimensional electron gas (2DEG) to improve the calculations of the particle-hole and plasmon-mediated contributions to the SCD. Also, we incorporate in our calculations the transverse thickness of the quantum well in which the 2DEG resides. In contrast to the conventional charge Coulomb drag, in the SCD the effect of layer thickness is significant even at relatively high temperature and densities. The final outcome of our study is that the enhancement of the spin drag caused by many-body local field effects largely compensates the reduction of the effect coming from the finite well thickness, restoring good agreement with the experimental observations by C.P. Weber et al., Nature 437 (2005) 1330.

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1. Introduction

As shown recently [1], the Coulomb interaction results in a spin Coulomb drag (SCD) effect within a single two-dimensional electron gas (2DEG) in close analogy to the familiar charge Coulomb drag in bi-layers. Because friction between the two spin components leads to a decay of the spin current even in the absence of impurities, the SCD has recently become a subject of intensive investigations [2]. In contrast to the two-terminal resistance of a 2DEG, the spin transresistivity is controlled by inter-spin Coulomb interaction and provides an effective tool to probe the many-body electronic correlations. Until now, however, all calculations of the spin transresistivity have treated the electron–electron interaction within the framework of random phase approximation (RPA) [1,3,4].

In this paper we calculate the SCD taking into account electronic correlations beyond RPA. Following Ref. [5], we make use of the fully spin-resolved static many-body local field factors of the 2DEG (obtained from diffusion Monte Carlo simulations) to improve the calculation of the particle–hole contribution to the SCD, and of dynamical local field factors to improve the calculation of the plasmon-mediated contribution. Also, we incorporate in our calculations the transverse thickness of the quantum well in which the 2DEG resides. In contrast to the conventional charge Coulomb drag where the inter-layer spacing causes an exponential suppression of large angle scattering events, the main contribution to the SCD comes from events with a momentum transfer of the order of the Fermi momentum. Hence, the form factor that takes into account the thickness of the 2DEG differs essentially from unity, and the effect of layer thickness is significant even at relatively high temperature and densities.

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We obtain that the joint effect of the dynamic and static many-body exchange and correlation (xc) enhances moderately the spin drag in comparison with the RPA-based calculations thereby largely compensating the reduction effect, coming from the effect of finite well width. Thus, the resulting spin drag rate remains in good agreement with the experimental findings of Ref. [2].

2. Theoretical concept

We calculate the temperature, T, dependence of the spin drag resistivity from the following formula

$$\rho_{\uparrow\downarrow}(T) = \frac{\hbar^2}{2e^2 n_\uparrow n_\downarrow TA} \sum_{\vec{q}} q^2 \int_0^\infty \frac{d\omega}{2\pi} |W_{\uparrow\downarrow}(q,\omega)|^2 \times \frac{\mathrm{Im}\Pi^0_\uparrow(q,\omega)\mathrm{Im}\Pi^0_\downarrow(q,\omega)}{\sinh^2(\hbar\omega/2T)}, \tag{1}$$

where A is the normalization area, $W_{\uparrow\downarrow}(q,\omega)$ the dynamically screened effective interaction between electrons with spins $\sigma = \uparrow$ and $\sigma = \downarrow$, $\Pi^0_\sigma(q,\omega)$ is the finite temperature non-interacting polarization function, n_σ the electron density.

The effective electron–electron interaction, taking into account the local field factors, is given by the Vignale–Singwi formula [6]

$$W_{\uparrow\downarrow}(q,\omega) = \frac{V_{\uparrow\downarrow}(q,\omega)}{\varepsilon(q,\omega)} + v(q)G_{\uparrow\downarrow}(q,\omega)F(qd), \tag{2}$$

where the unscreened effective interactions are given by

$$V_{\sigma\sigma'}(q,\omega) = v(q)(1 - G_{\sigma\sigma'}(q,\omega))F(qd) \tag{3}$$

and the spin resolved local field factors $G_{\sigma\sigma'}$ decrease the bare Coulomb interaction $v(q) = 2\pi e^2/\kappa_0 q$ by a factor of $1 - G_{\sigma\sigma'}(q,\omega)$.

In Eq. (2) $\varepsilon(q,\omega)$ is an effective dielectric function, which can be represented in the following manner

$$\varepsilon(q,\omega) = (1 + V_+(q,\omega)\Pi^0(q,\omega))(1 + V_-(q,\omega)\Pi^0(q,\omega)), \tag{4}$$

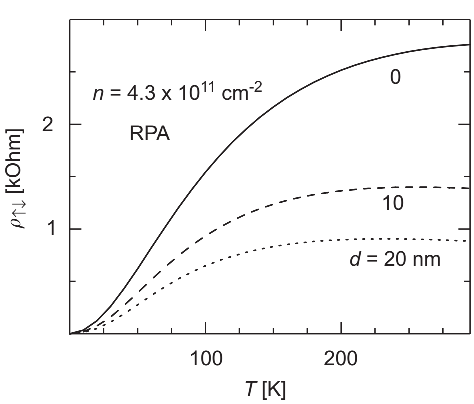

Fig. 1. Spin drag resistivity as a function of temperature, calculated within RPA. The solid, dashed, and dotted curves correspond, respectively, to the spin drag resistivity for the quantum well width $d = 0$, 10, and 20 nm.

where

$$V_\pm(q,\omega) \equiv \frac{V_{\uparrow\uparrow}(q,\omega) \pm V_{\uparrow\downarrow}(q,\omega)}{2}. \tag{5}$$

Introducing the corresponding notation for the local field factors, $G_\pm \equiv (G_{\uparrow\uparrow} \pm G_{\uparrow\downarrow})/2$, we can write

$$V_+(q,\omega) = v(q)(1 - G_+(q,\omega))F(qd),$$
$$V_-(q,\omega) = -v(q)G_-(q,\omega)F(qd). \tag{6}$$

where G_+ and G_- are known as the "charge-channel" and the "spin-channel" local field factors, respectively.

The form factor $F(qd)$ accounts for the electron density profile in a quantum well. We assume that the electrons are confined in a square quantum well of thickness d in the

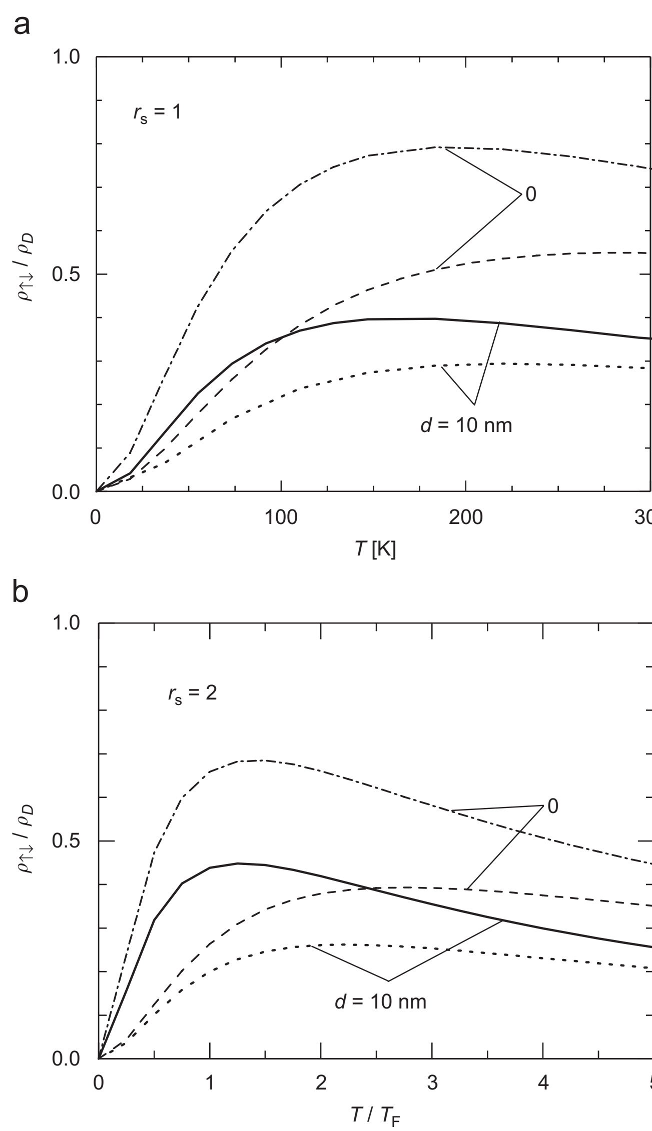

Fig. 2. The scaled spin drag resistivity as a function of temperature for (a) $r_s = 1$ and (b) $r_s = 2$. The solid and dash–dotted curves are calculated, respectively, for a 2DEG of the width $d = 0$ and 10 nm beyond the RPA. The dashed and dotted curves correspond to the spin transresistivity, calculated within the RPA, respectively, for a 2DEG of the width $d = 0$ and 10 nm. The ordinary charge Drude resistivity, ρ_D, is calculated for the mobility $\mu = 300\,\mathrm{V\,cm^{-1}\,s^{-1}}$.

transverse z-direction and infinite depth, and that scattering processes take place only within the lowest subband. The density profile in such a well is given by $\rho(z) = (2/d)\sin(\pi z/d)^2$, from which we obtain the form factor

$$F(\eta) = \frac{8\pi^2 + 3\eta^2}{\eta(4\pi^2 + \eta^2)} - \frac{32\pi^4(1 - e^{-\eta})}{\eta^2(4\pi^2 + \eta^2)^2}. \tag{7}$$

It is easy to see that $F(qd) = 1 - (1/3 - 5/4\pi^2)qd$ for $qd \to 0$ and $F(qd) \to 3/(4\pi^2 qd)$ for $qd \to \infty$. Taking $d = 12$ nm and $q \approx k_F$ we have also $qd \approx 2$ so $|F(qd)|^2 \approx 0.5$ for $n = 4.3 \times 10^{11}\,\mathrm{cm}^{-2}$.

3. Results

In Fig. 1 we plot the spin transresistivity in RPA for $d = 0$, 10, and 20 nm. The solid curve represents the result of the RPA calculation for an ideal 2DEG of zero width [1]. This was found to be in good agreement with experimental data in Ref. [2]. As seen from Fig. 1 an increase in the width of the quantum well is accompanied by a strong reduction of the spin drag. The physical reason for this effect is that the SCD is dominated by large angle scattering events $qd > 1$ where the form factor $F(qd)$ is smaller than unity.

In our actual calculations beyond RPA, we include both the static and dynamic local field factors, to take into account the interaction effects, mediated, respectively, by electron–hole pairs and by plasmons. In Figs. 2a and b we show the combined effect of finite layer width and local field factors beyond RPA. More precisely, we compare the spin transresistivity, calculated for $r_s = 1$ and $r_s = 2$ within the present scheme with the corresponding RPA results for $d = 0$. It is seen that even at such small values of r_s, the local field factors significantly enhance the SCD, largely compensating the reduction due to the finite width of the well.

Thus, we conclude that the combined effect of the finite layer thickness and local field corrections restores a good agreement between theory and experiment. We verify this conclusion for the experimental situation of Ref. [2]. We make use of the formula

$$D_s/D_c = (\Pi_0/\Pi_s)(\rho/(\rho + \rho_{\uparrow\downarrow})), \tag{8}$$

to convert the experimentally determined values of the spin diffusion constant, D_s, [2], into the corresponding values for $\rho_{\uparrow\downarrow}$. In doing this, we also take into account the many-body enhancement of the spin susceptibility, $\Pi_s/\Pi_0 > 1$, which in Ref. [2] was roughly approximated as $\Pi_s/\Pi_0 = 1$. With all this taken into account we find that our calculation agrees rather well with the experimental data of Ref. [2]. Ignoring either the local field factors or the finite width of the quantum well would spoil this nice agreement.

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