Coulomb Drag Study of Non-Homogeneous Dielectric Medium: Hole-Hole Static Interactions in 2D-GaAs DQW

Sharad Kumar Upadhyaya* and L.K. Saini

Department of Physics, Sardar Vallabhbhai National Institute of Technology, Surat, (395007), Gujarat, India
asharadupadhyay1992@gmail.com, bdrlalitsaini75@gmail.com

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Abstract. The induced (drag) resistivity ($\rho_D$) is calculated numerically in low temperature, large interlayer separation and weak interactive regime for 2D hole-hole (h-h) static interactions using the RPA method, with the geometry of non-homogeneous dielectric medium. Exchange-correlations (XC) and mutual interaction effects are considered in low/high density regime for analysing the drag resistivity. It is found that the drag resistivity is found enhanced on using the XC effects and increases on increasing the effective mass. In Fermi-Liquid regime, drag resistivity is directly proportional to $r^2/n^3$ at low temperature. Temperature (T), density (n), interlayer separation (d) and dielectric constant ($\epsilon_2$) dependency of drag resistivity is measured and compared to 2D e-e and e-h coupled-layer systems with and without the effect of non-homogeneous dielectric medium.

Introduction

Coulomb drag (CD) is a transport phenomenon that occurs in coupled layer structure, when a current is allow to flow by an active layer and a drag/induced voltage is detected in passive layer, without the tunnelling effect [1–13]. An insulated wall seperates both the layers electrically. Drag resistivity ($\rho_D$) is a general phenomena of momentum and energy transfer rate by the interaction of electron-electron (e-e), electron-hole (e-h), hole-hole (h-h), pasmons and phonons etc. With the Fermi-liquid state, the phase space give the dependency of drag resistivity, as $\rho_D \propto T^2/n^3$ at low temperature regime.

Consequently, coulomb drag effect was devoted to the numerically and quantitatively results, for measuring the strength of the screening due to induced field [14,15], electron-electron bilayer system of 2D-3D [7,16], two dimensional (2D) electron-electron (e-e) [16–20]. A vast range of curiosity have emerged for studying transport based properties. Mutual coulomb scattering can theoretically be realised cause of the exchange of momentum ($\hbar q$) and energy ($\hbar \omega$) between the coupled layers system. Following the ground breaking experimental work in the AlGaAs/GaAs double quantum wells (DQW) [17,20]. Drag effect became an important part for measuring the many body properties. It had been used to analyze the properties of electrons, holes, phonons, plasmons. Interactions in low density regime [21,22], excitons impact of e-h double layers systems [23–25].

Theoretically, a vast and explored field of CD phenomena which suggested several extensions and generalizations in the field of non-homogeneous dielectric medium. The theory of CD effect has extended to multi-layer between two 2D electron and/or hole system, which is an fascinating electronic system of 2D-GaAs DQW [2,3,6,8,11–13,26–30]. For the simplest such structure, CD in bilayer systems is a very interesting phenomenon. We consider two 2D-GaAs distanced by a insulated wall of $Al_2O_3$, with the case of a large interlayer separation limit ($k_FD \gg 1$), where d is
a distance of the wall and $k_F$ is the Fermi wave vector of 2D-sheets. It is a general and well known results for $\rho_D$, which present the dependency to temperature and interlayer separation, as $T^2 d^{-4}$ in low temperature, large separation and weak interaction limit.

**Theoretical Formalism**

With considering a double layer systems of 2D-GaAs, which contain holes in both the layers. The numerical results of drag resistivity is measured by using the solution of RPA method in weak interaction ($r_s \sim 1$), at low temperature ($T_F \gg T$), and large interlayer distance limit ($k_F d \gg 1$). The interlayer screening ($U_{12}(q)$) caused of hole-hole (h-h) static interaction is considered in this manuscript. In low concentration regime ($r_s \gg 1$), the RPA method don’t able to hold consistency cause of exchange correlations (XC) effects are not considered. The total screening between the electron and/or hole extracted enhanced results because of XC effects. The LFC introduced by the HA and STLS approximation, which consider the XC effect into account.

A general expression of drag resistivity \[2,3,6,8,11–13,26–30\] may be present as,

$$\rho_D = -\frac{\hbar^2}{8\pi^2 e^2 n_1 n_2 k_B T} \int_0^{q_*} dq \, q^3 |U_{12}(q)|^2 \int_0^\infty d\omega \frac{|\Im \chi_1(q,\omega)||\Im \chi_2(q,\omega)|}{\sinh^2 \left( \frac{\hbar \omega}{2k_B T} \right)}$$ \hspace{1cm} (1)

To evaluate the drag resistivity, nonlinear susceptibility function (NLSF) and effective interlayer interaction are main function. This gives the dependency of temperature T, density n, interlayer distance d, etc….

**Nonlinear Susceptibility Function (NLSF)**

The non-interacting NLSF $[\chi(q, \omega)]$ in weakly interactive and low frequency regime (Ballistic regime) ($\omega \tau \gg 1$ or $k_F \ell \gg 1$), as seen in Eq. (2), which extracted temperature dependency of $\rho_D$ in Fermi-liquid regime. Analytically, it is entirely determined by the denominator $\sinh^2 \left( \frac{\hbar \omega}{2k_B T} \right)$ in Eq. (1), which restricts the integral with respect to frequency, $\hbar \omega < 2k_B T$. The non-interacting NLSF $\chi_{1(2)}(q, \omega)$ \[1,3,8,11,12,31\] which is presented by the equation as,

$$\chi(q, \omega) = -\int \frac{d\xi}{4\pi^2} \frac{(f^0(\xi_1) - f^0(\xi_1 + \hbar \omega))}{\xi_1 - \xi_1' + \hbar \omega - i\delta}$$ \hspace{1cm} (2a)

$$3\chi(q, \omega) = -\int \frac{d\xi}{4\pi^2} (f^0(\xi_1) - f^0(\xi_1 + \hbar \omega)) \delta(\xi_1 + \xi_1' - \hbar \omega)$$ \hspace{1cm} (2b)

**Interlayer Interaction $[U_{12}(q)]$**

To evaluating the screening effects of holes in the double layer systems, a typical toolbox of Dyson equation is taken into consideration within the random phase approximation (RPA) method \[2,3,6,8,11–13,26–30\]. This finally presents the standard equation of interlayer interaction as,

$$U_{12}(q) = \frac{U_{12}(q)}{\epsilon(q)}$$ \hspace{1cm} (3a)

$$\epsilon(q) = (1 + U_{11}(q)\{1 - G_{11}(q))\chi_1(q))(1 + U_{22}(q)\{1 - G_{22}(q)}\chi_2(q) - (q))^2\chi_1(q)\chi_2(q)$$ \hspace{1cm} (3b)

The screening effects is measured by the Eq. (3a) for interactive weak field cause of stationary point charge source is present at active layer and drag the carriers in other layer. Where $\epsilon(q)$ is the dielectric function. $U_{12}^0(q)$ and $U_{11}^0(q)$ are known as bare intra and interlayer potential, respectively and local form factor (LFF) $F_{ij}(qd)$ are key equations. To evaluating the form factor $F_{ij}(qd)$,
electrostatic problem needs to solve by using the solution of Poisson equation, by assuming the different-different screening of substrate layer, insulated layer, and top layer (such as, air) [3,8,11–13,32]. The form factors for non finite width [3,8,11–13,32],

$$F_{11}(d) = \frac{\epsilon_2 \exp(qd)[\epsilon_2 \cosh(qd)+\epsilon_1 \sinh(qd)]}{[(\epsilon_1+\epsilon_2)(\epsilon_3+\epsilon_2) \exp(2qd)-(\epsilon_1-\epsilon_2)(\epsilon_3-\epsilon_2)]}$$  \hspace{1cm} (4a)  

$$F_{12}(d) = \frac{\epsilon_2 \exp(qd)}{[(\epsilon_1+\epsilon_2)(\epsilon_3+\epsilon_2) \exp(2qd)-(\epsilon_1-\epsilon_2)(\epsilon_3-\epsilon_2)]}$$  \hspace{1cm} (4b)  

Where $F_{22}(d)\text{ may be obtained by replacing } \epsilon_1 \leftrightarrow \epsilon_3 \text{ in Eq. (4a).}$

The method of RPA with including the XC effects is a implications of measuring the required results. The LFC of using the HA and STLS approximation are commonly used approximations for considering the XC effects. $\rho_D$ is enhanced on using the LFC, as seen in Eq. (3). The LFC is evaluated by the solution of the static structure factor $S(q)$ by using the fluctuation dissipation theorem [3–5,13,33,34].

\[ G(q) = -\frac{1}{n} \int_0^\infty \frac{dk}{(2\pi)^2} \frac{q\cdot k\cdot U^0(k)}{\frac{q^2}{U^0(q)}} S(|k - q| - \delta) \]  \hspace{1cm} (5)  

**Result and Discussion**

In this section, we have discussed about the structure and results of $\rho_D$ in screened double layer systems od 2D-GaAs at low temperature and Boltzmann regime. Present approach for the solution of $\rho_D$ expression, which is a solution of the Boltzmann kinetic equation (BTE). The system is taken under the low temperature limit $T \ll T_F$, the large interlayer distance $k_F d \gg 1$ [2,3,6,8,11–13,26–30]. With the weak interactions limit and low frequency regime, $\rho_D$ behaves as $T^2 \epsilon_2^2 n^3 d^4$ in the limit of $T \ll T_F$, as shown in Fig. (1a, 1b). This is the same variables dependency found for the drag resistivity [2,3,6,8,11–13,26–30].

![Figure 1](image_url)  

*Figure 1: The plots show the behavior of the absolute value of $\rho_D$ with respect to temperature ($T$) and concentration ($n$), as shown in Fig. (1a, 1b), respectively. Where the dielectric constant of the barrier is $Al_2O_3$ ($\epsilon_2 = 9$) and inter-layer distance is $d = 30 \text{ nm.}$*
The measured data of $\rho_D$ for h-h interactions is compared by measured results of e-e and e-h interactions [1,13]. $\rho_D$ is found 14.47, 16.18 m$\Omega$ for e-e and e-h interactions [11,13] for the parameters such as, the carrier concentration $n \sim 3 - 20 \times 10^{10} \text{ cm}^{-2}$, temperature is $t = 0.5 \text{ K}$, the interlayer separation is $d = 30 \text{ nm}$, the dielectric constant of the barrier is $\epsilon_2 = 9$, interlayer distance $d = 30 \text{ nm}$, effective mass of hole is $0.45 m_e$. For these parameter, h-h interactions found enhanced results compare to e-e and e-h interactions, as seen in Fig. (1a, 1b) for the RPA method with and without including the LFC effects.

Articles on $\rho_D$ in coupled-layer structure measured enhanced results of stationary and weak screening with including the LFC, as seen in Fig. (1a, 1b). It is found consistently better results for h-h interactions than RPA method, because of LFC based on HA and STLS approximation. The RPA model does not account for XC impacts, which are taken into account by LFC. The expressions of LFC impact the effect of interlayer interaction effective and cause of this, $\rho_D$ is found enhanced [3,11–13]. This is because the coupling between the charge carriers has increased as a result of the increase in coupling, as seen in Fig. (1a, 1b).

**Conclusion**

In this section, its aim is to demonstrate the improvement of $\rho_D$ as a result of h-h screening, as well as the impact of LFC, compare to e-e and e-h screening of weakly coupling condition. $\rho_D$ is measured for density $r_s = 1.154-2.979$, at low temperature and large interlayer distance in a double layer structure, separated by a thick wall. The measured results of $\rho_D$ are consistently better compare to the system of a simple double layer systems.

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