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Double-resonant structure in the high-frequency transresistance of coupled electron-hole systems

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Abstract. The linear dc and high-frequency transresistivity of coupled electron-hole systems are investigated using the Lei-Ting balance equations approach extended to include many-body corrections. A possible indirect method of experimentally measuring the dynamical transresistivity in the high frequency (terahertz) regime is designed basing on the detailed analysis on the relationship between the directly measurable resistivities in the electron- and hole-layer and the dynamical transresistance. The theoretically predicted dc transresistance is in good agreement with the experimental data for the given electron-hole system experimentally investigated. The calculated dynamical transresistance exhibits pronounced double-resonant structure, which can be attributed to the cooperation and competition between the two plasmon modes. It is pointed out that the behavior of the frequency-dependent transresistance is temperature-sensitive and the dynamical transport properties are essentially influenced by the short range correlations.

PACS. 72.30.+q High-frequency effects; plasma effects – 73.50.Mx High-frequency effects; plasma effects

1 Introduction

Recently, there has been considerable interest in the Coulomb drag between spatially separated electron-electron and electron-hole systems, which was experimentally observed by Gramila [1] and Sivan [2]. In these two-layer charged systems, there are two branches to its longitudinal collective excitation spectrum [3]. It is natural that these collective excitation modes will significantly influence Coulomb drag, because these are precisely the excitations that mediate the momentum and energy transfer between the two layers. Flensberg and Hu [4] have theoretically investigated the role of the two plasmon modes in the inter-layer momentum transfer due to Coulomb interaction between two parallel quasi-two-dimensional electron gases. Their theoretical calculations demonstrated that the plasmon modes can substantially enhance, even by an order of magnitude, the Coulomb drag rate for the experimentally measured systems with equal Fermi velocities and its contributions result in the deviations from the famous T^2 behavior. Subsequently, they argued that the optimum situation for plasmon enhancement occurs when two layers have the same Fermi velocities $v_{F,1} = v_{F,2}$ and the transport measurement of Coulomb drag rate provides a sensitive probe for the double-layer coupled plasmon modes. On the contrary, if $v_{F,1} \gg v_{F,2}$, the phase velocity of the plasmons is much higher than $v_{F,2}$, making it difficult for the scattering of particles in layer 2 to be enhanced by the plasmons. This is just the case that appeared in the coupled electron-hole systems studied by Sivan *et al.* [2]. Due to the large mismatch between the effective masses of electrons and holes, in order to satisfy the optimum condition of plasmon enhancement the concentration of holes must be about 45 higher than that of electrons. This restriction is so severe that the effect of the plasmon enhancement is very weak in the Sivan *et al.* systems [4]. On the other hand, many-body corrections due to the effects of exchange and correlation play a significant role in describing the coupled electron-hole transport, which can largely enhance the Coulomb drag rate and remove the obvious disagreement between the experimental data and the theories under RPA [5]. Moreover, the correlations will also affect the plasmon modes, and then modify the carrier concentration and the temperature dependence of transresistance in an elaborate way [6].

In the present paper, we propose calculations to markedly exhibit the two plasmon modes in the electron-hole systems. Plasmon can manifest itself saliently in resonant behavior of the linear high-frequency conductivity in semiconductor and this interesting phenomenon has been already explored intensely for a long time [7–10]. The most obvious way collective excitations contribute to the dynamical conductivity's resonant feature is through the inclusion of screening, the zeros of the dielectric function.

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In contrast to the single layer systems, the dielectric function of the coupled two-layer systems has more complicated properties and contains richer information. Therefore, it is believed that the plasmon modes have a more profound effect on the high-frequency transfer transport properties in the double-layer systems.

So far, most theories have concentrated on dc transresistance [4–6,11]. Only Zhang and Takahashi [12] calculated the frequency dependence of conductivity in the zero-temperature limit for two electron layers, taking into account both the direct electron-electron interaction and the phonon-mediated electron-electron interaction. A few years ago, the balance-equations approach for several types of carriers systems [13] was applied to the coupled electron-hole transfer transport [14]. Such an approach has previously been used to investigate the steady-state nonlinear dc and linear high frequency transport properties of type-II superlattices [10], and a two-component plasma consisting of minority electrons and majority-holes in a single GaAs–AlGaAs quantum well [15]. Here we extend this method to include the many-body corrections within the local-field corrections developed by Singwi *et al.* (STLS) [16] and analyze the linear high-frequency behavior of transresistance in coupled electron-hole systems. We find a novel double-resonant structure in the dynamical transresistance, which can be attributed to the cooperation and competition between the two plasmon modes.

2 Balance-equations for double-well systems

In the present study we consider a double well structure, with electrons in one well and holes in the other. The two quantum wells have the common width w and the center-to-center distance between the two wells is d. Carriers in each well are free in the x-y direction and confined in the z direction. In the calculation, we assume that (i) the potential barrier separating the two wells is sufficiently high that tunneling can be neglected and carriers confined to just one well, and (ii) the width of the well is narrow and the carrier area density is not too high so that only the lowest subband is occupied. The wavefunction of the carrier in the jth well can be written as

$$\psi_{j\mathbf{k}}(\mathbf{r},z)=e^{i\mathbf{k}\cdot\mathbf{r}}\zeta_j(z),\qquad (j=1,2),\tag{1}$$

with energy $\varepsilon_{j\mathbf{k}}=k^2/2m_j$, where m_j is the effective mass of carrier in the jth well and $\mathbf{r}\equiv(x,y)$ and $\mathbf{k}\equiv(k_x,k_y)$ are two-dimensional vectors in coordinate and momentum spaces, respectively. $\zeta_j(z)$ is the envelope wave function in the jth well. Each well is a carrier-phonon-impurity system and the electron-well is coupled with the hole-well due to the Coulomb interactions between electrons and holes. The bare intra-layer and inter-layer Coulomb interactions take the form

$$V_{jj'}(q)=(-1)^{|j-j'|}\frac{2\pi e^2}{\kappa q}H_{jj'}(q),$$
$$H_{jj'}(q)=\int dz\int dz' e^{-q|z-z'|}|\zeta_j(z)|^2|\zeta_{j'}(z')|^2,\tag{2}$$

where κ is the dielectric constant of the material.

Consider a small amplitude high-frequency signal electric field of frequency ω,

$$E(t)=E_{1m}\cos(\omega t)=E_{1m}\mathrm{Re}(e^{-i\omega t}),$$

applied to the driving layer (layer 1), the electron-well here, along the x direction. After transient process, not only will the center of mass of the electrons execute simple harmonic vibration in the applied field direction at the given frequency ω [10], but the holes in the dragged layer (layer 2) can also be driven at the same frequency due to the Coulomb interactions between the two wells. Hence, an ac electric field with an amplitude E_{2m} and an oscillatory current will be induced in the hole-well having the same frequency as the driving electric field. In this paper, we focus our attention on the linear high-frequency conduction. Then the electrons and holes are all at a common temperature, *i.e.*, the lattice temperature T, as in the linear dc case. According to the Lei-Ting balance equations for several types of carriers, the linearized equations of motion for the centers of mass of the electrons and holes yield [10]

$$\begin{aligned}-\omega N_e m_e v_{1m}=&-N_e eE_{1m}+(v_{1m}/\omega)\,F^{(1)}(\omega)\\&+(1/\omega)\,(v_{1m}-v_{2m})\,F_{12}(\omega),\end{aligned}\tag{3}$$

and

$$\begin{aligned}-\omega N_h m_h v_{2m}=&N_h eE_{2m}+(v_{2m}/\omega)\,F^{(2)}(\omega)\\&+(1/\omega)\,(v_{2m}-v_{1m})\,F_{12}(\omega),\end{aligned}\tag{4}$$

where N_e (m_e) and N_h (m_h) are the electron and hole area densities (effective masses), respectively. v_{jm} is the amplitude of the drift velocity for electrons ($j=1$) and holes ($j=2$). The resistive forces $F^{(j)}(\omega)$, due to impurity and phonon scatterings within the jth well, are given to the lowest order by ($j=1,2$) [10]

$$\begin{aligned}F^{(j)}(\omega)=&\sum_{\mathbf{q}}\frac{q_x^2}{q^2}|U_{jj}(q)|^2\left[\hat{\Pi}^{(j)}(\mathbf{q},0)-\hat{\Pi}^{(j)}(\mathbf{q},\omega)\right]\\&+\sum_{\mathbf{Q}\lambda}q_x^2|M_{jj}(\mathbf{Q},\lambda)|^2\left[\Lambda^{(j)}(\mathbf{Q},\lambda,0)-\Lambda^{(j)}(\mathbf{Q},\lambda,\omega)\right],\end{aligned}\tag{5}$$

where

$$\begin{aligned}\Lambda^{(j)}(\mathbf{Q},\lambda,\omega)=&\\&\hat{\Pi}^{(j)}(\mathbf{q},\omega-\Omega_{Q\lambda})\left[n\left(\frac{\Omega_{Q\lambda}}{T}\right)-n\left(\frac{\Omega_{Q\lambda}-\omega}{T}\right)\right]\\&+\hat{\Pi}^{(j)}(\mathbf{q},\omega+\Omega_{Q\lambda})\left[n\left(\frac{\Omega_{Q\lambda}}{T}\right)-n\left(\frac{\Omega_{Q\lambda}+\omega}{T}\right)\right].\end{aligned}\tag{6}$$

$U_{jj}(q)$ and $M_{jj}(\mathbf{Q},\lambda)$ are the coupling matrix elements of carrier-impurity and carrier-phonon interactions within the jth quantum well, which are given in reference [17].

The function $F_{12}(\omega)$ due to electron-hole interaction is given by

$$F_{12}(\omega) = -\sum_{\mathbf{q}} |V'_{12}(q)|^2 q_x^2 \left[\Gamma(\mathbf{q},0) - \Gamma(\mathbf{q},\omega)\right], \quad (7)$$

in which

$$\Gamma(\mathbf{q},\omega) = \int_{-\infty}^{\infty} \frac{d\omega'}{\pi} n\left(\frac{\omega'}{T}\right) \Big[\Pi_2^{(1)}(\mathbf{q},\omega)\Pi^{(2)}(-\mathbf{q},\omega-\omega') - \Pi^{(1)}(\mathbf{q},\omega+\omega')\Pi_2^{(2)}(-\mathbf{q},-\omega')\Big], \quad (8)$$

with the imaginary part

$$\Gamma_2(\mathbf{q},\omega) = \int_{-\infty}^{\infty} \frac{d\omega'}{\pi} \left[n\left(\frac{\omega'}{T}\right) - n\left(\frac{\omega'-\omega}{T}\right)\right] \times \Pi_2^{(1)}(\mathbf{q},\omega')\Pi_2^{(2)}(-\mathbf{q},\omega-\omega'). \quad (9)$$

According to STLS [5,16], the effects of exchange and correlation can be taken into account by simply replacing the bare Coulomb interactions with the effective potentials modified by the local field factors

$$V'_{jj'}(q) = V_{jj'}(q)\left[1 - G_{jj'}(q)\right]. \quad (10)$$

Therefore, in order to revolve the influence of short range correlations on transport, we should do this substitution in the Lei-Ting balance equations. Recently, we proposed an analytical expression and develop a sum-rule version within the self-consistent approach of STLS for the inter-layer local field corrections in the weakly coupled two-layer systems [18]. Employing this analytical form of local field factor, we can greatly simplify the calculations. Of course, by assuming $G_{jj'}(q) = 0$ in these equations, the short range correlations can be excluded and the RPA results are recovered. Furthermore, in all the above equations, $\Pi^{(j)}(\mathbf{q},\omega)$ are the density-density correlation functions of electrons ($j = 1$) or holes ($j = 2$) alone, which, within the STLS approach, are given by

$$\Pi^{(j)}(\mathbf{q},\omega) = \frac{\Pi_0^{(j)}(\mathbf{q},\omega)}{1 - V'_{jj}(q)\Pi_0^{(j)}(\mathbf{q},\omega)}, \quad (11)$$

where $\Pi_0^{(j)}(\mathbf{q},\omega)$ is the density-density correlation function in absence of the inter-particle Coulomb interaction

$$\Pi_0^{(j)} = 2\sum_{\mathbf{k}} \frac{f\left((\varepsilon_{j\mathbf{k}+\mathbf{q}} - \mu_j)/T\right) - f\left((\varepsilon_{j\mathbf{k}} - \mu_j)/T\right)}{\omega + \varepsilon_{j\mathbf{k}+\mathbf{q}} - \varepsilon_{j\mathbf{k}} + i\delta}. \quad (12)$$

$f(x) = [\exp(x) + 1]^{-1}$ is the Fermi-Dirac function, and the chemical potential μ_j is determined through the relation

$$N_j = 2\sum_{\mathbf{k}} f\left((\varepsilon_{j\mathbf{k}} - \mu_j)/T\right). \quad (13)$$

3 High-frequency transresistivity

At present, most experiments [1,2,6] focused on the configuration, in which only one of the quantum wells (layer 1 here) is subject to an electric field, and no net current is allowed to flow in the dragged layer (layer 2 here) but a voltage arises due to charge accumulation which balances the drag-induced carrier drift. This is because of the fact that under such conditions, measurement of the voltage is directly proportional to the inter-layer drag rate, thus provides a convenient, direct and sensitive probe of the important inter-layer Coulomb interactions. Therefore, we devote ourselves to theoretical investigation of the linear high-frequency behavior for the Coulomb drag in the case of so-called “open circuit” in the dragged layer. Owing to $v_{2m} = 0$, it is easily seen from equation (4) that

$$E_{2m} = \frac{1}{N_h e\omega} v_{1m} F_{12}(\omega). \quad (14)$$

On the other hand, the current density carried by the electrons in the driving layer is $J_{1m} = -iN_e e v_{1m}$. The linear high-frequency complex transresistivity can be defined as $\rho_T(\omega) \equiv E_{2m}/J_{1m}$. Substituting equation (14) into the definition, one can obtain

$$\rho_T(\omega) = i\frac{1}{N_e N_h e^2}\frac{F_{12}(\omega)}{\omega}, \quad (15)$$

with the real part $R_T(\omega)$ given by

$$R_T(\omega) = -\frac{1}{N_e N_h e^2 \omega}\sum_{\mathbf{q}} \left|V'_{12}(q)\right|^2 q_x^2 \times \int_{-\infty}^{\infty} \frac{d\omega'}{\pi}\left[n\left(\frac{\omega'}{T}\right) - n\left(\frac{\omega'-\omega}{T}\right)\right] \times \Pi_2^{(1)}(\mathbf{q},\omega')\Pi_2^{(2)}(-\mathbf{q},\omega-\omega'), \quad (16)$$

which illustrates the inter-layer momentum relaxation in the case of linear high-frequency transport. It is noted that in the zero-frequency limit equation (16) reduces to the linear expression for the dc transresistivity [4,5,10, 11]:

$$R_T(0) = -\frac{1}{N_e N_h e^2}\mathrm{Im}\left.\frac{\partial F_{12}(\omega)}{\partial \omega}\right|_{\omega=0} = \frac{1}{N_e N_h e^2 T}\sum_{\mathbf{q}} q^2 \left|V'_{12}(q)\right|^2 \times \int_0^{\infty}\frac{d\omega'}{\pi}\left[e^{\frac{\omega'}{2T}} n\left(\frac{\omega'}{T}\right)\right]^2 \hat{\Pi}_2^{(1)}(\mathbf{q},\omega')\hat{\Pi}_2^{(2)}(\mathbf{q},\omega'). \quad (17)$$

4 A possible experimental method to measure the high-frequency transresistivity

In above paper the definition of the dynamical transresistivity is given and the theoretical expression equation (16) is derived for the coupled electron-hole systems by means of Lei-Ting balance equations approach for several types of carriers. Through equation (16), we can theoretically investigate dynamical transfer transport properties of the coupled electron-hole systems, especially the effect of plasmons on the dynamical transresistance. In general, the resonant effect of plasmon becomes pronounced in the dynamical transport in two-dimensional systems when the frequency of the external ac electric field is of the order of the Fermi energy [9], *i.e.* typically in the terahertz (THz) regime for the carrier densities $10^{10} \sim 10^{11}$ cm^{-2} in the modulation-doped quantum wells. At such high external driven frequency the direct measurement of the dynamical transresistance in the coupled electron-hole systems according to the definition is difficulty due to experimental inaccessibility of the THz longitudinal electric fields. However, the information of the dynamical transresistance can be indirectly extracted from those measurable quantities in the THz regime. A possible method is suggested as follows.

In the coupled electron-hole systems, the normally incident THz radiation (which is perpendicular to the layer plane of the two-dimensional quantum wells) provides a high frequency oscillating electric field along the layer plane in both electron- and hole-layer, because the center-to-center spacing d is far less than the wavelength of the THz electromagnatic wave. Therefore, the resistivity $\rho_1^{(e)}$ of electrons can be directly measured when the hole-layer keeps open configuration. On the other hand, if current allows to flow not only in the electron-layer but also in the hole-layer, we can also individually detect the resistivity $\rho_2^{(e)}$ of electrons in the electron-layer. It is obvious that the two quantities are different due to different effects of the additive second layer (the hole-layer here) on the electron-layer in the two different configurations and both of them contain the information of the dynamical transresistance of this coupled electron-hole system. In the first configuration, the resistivity $\rho_1^{(e)}$ can be easily obtained from equation (3)

$$\rho_1^{(e)} = \frac{E_{1m}}{iN_e e v_{1m}} = \rho_e + \rho_T, \tag{18}$$

where $\rho_e = \left(-im_e/N_e e^2\right)\left[\omega + F_1(\omega)/N_e m_e \omega\right]$ is the dynamical resistivity of the individual electron-layer. In the second configuration, no induced electric field arises in the two layers because currents are allowed to flow in both of the two layers. Therefore the linearized balance equations of motions for the centers of mass of holes can be written as

$$\begin{aligned} -\omega N_h m_h v_{2m} = {} & N_h e E_{1m} + \left(v_{2m}/\omega\right) F^{(2)}(\omega) \\ & + (1/\omega)\left(v_{2m} - v_{1m}\right) F_{12}(\omega). \end{aligned} \tag{19}$$

With the help of equations (3, 19) v_{1m} can be easily solved as

$$v_{1m} = \frac{N_e\left(\frac{F_2}{\omega}+\frac{F_{12}}{\omega}+\omega N_h m_h\right)-\frac{F_{12}}{\omega}N_h}{\left(\frac{F_1}{\omega}+\frac{F_{12}}{\omega}+\omega N_e m_e\right)\left(\frac{F_2}{\omega}+\frac{F_{12}}{\omega}+\omega N_h m_h\right)-\left(\frac{F_{12}}{\omega}\right)^2} eE_{1m}. \tag{20}$$

Then we can write the experimentally measurable quantity $\rho_2^{(e)} = E_{1m}/iN_e e v_{1m}$ as

$$\rho_2^{(e)} = \left[\rho_e + \rho_T\left(\frac{N_e\rho_e}{N_h\rho_h}+1\right)\right]\frac{1}{1+\frac{N_e-N_h}{N_h}\frac{\rho_T}{\rho_h}}, \tag{21}$$

in which $\rho_h = \left(-im_h/N_h e^2\right)\left[\omega + F_2(\omega)/N_h m_h \omega\right]$ represents the dynamical resistivity of the individual hole-layer. Especially when the carrier concentrations in the two layers are equal, $\rho_2^{(e)}$ can be simplified as

$$\rho_2^{(e)} = \rho_e + \rho_T\left(\frac{\rho_e}{\rho_h}+1\right). \tag{22}$$

Similarly, the two directly measurable resistivities $\rho_1^{(h)}$ and $\rho_2^{(h)}$ in the hole-layer corresponding to the two cases in which the electron-layer keeps "opened" and "closed", respectively, can be derived as

$$\rho_1^{(h)} = \frac{E_{1m}}{iN_h e v_{2m}} = \rho_h + \rho_T, \tag{23}$$

and

$$\rho_2^{(h)} = \rho_h + \rho_T\left(\frac{\rho_h}{\rho_e}+1\right). \tag{24}$$

From the four relations equations (18–24), we can easily extract the dynamical transresistance of the coupled electron-hole systems from the four experimentally detectable quantities

$$\rho_T = \sqrt{\left(\rho_2^{(e)}-\rho_1^{(e)}\right)\left(\rho_2^{(h)}-\rho_1^{(h)}\right)}, \tag{25}$$

in the case of $N_e = N_h$.

5 Double-resonant structure in the dynamical transresistance

Basing on equations (16, 17) we can numerically calculate the linear dc and high-frequency transresistances for the coupled electron-hole systems. In the following calculations, we take the double AlGaAs–GaAs quantum-well structure with $w = 10$ nm, $d = 30$ nm, and the same carrier concentrations in the two layers $N_e = N_h = 0.5 \times 10^{11}$ cm^{-2} as an example. The material parameters are typical values of GaAs: $m_e = 0.067m_0$ (m_0 is

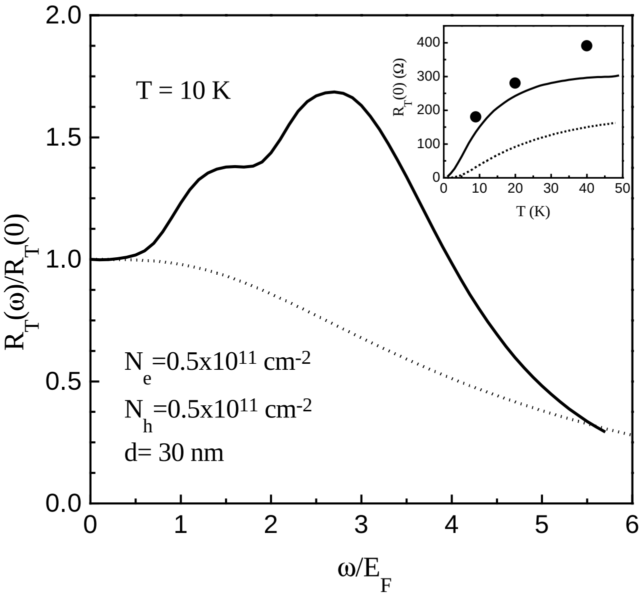

Fig. 1. The calculated normalized real part of the complex transresistance $R_T(\omega)/R_T(0)$ are shown as a function of the driving frequency ω/E_F for the coupled electron-hole layers with well width $w = 0.1$ nm, layer spacing $d = 30$ nm and the equal carrier concentrations of 0.5×10^{11} cm^{-2} in the two layers at the temperature of 10 K. These parameters correspond to the experiment of Sivan *et al.* [2]. The discrete points are $R_T(\omega)/R_T(0)$ evaluated by neglecting the plasmon contribution. E_F is the Fermi energy of the electron layer at the absolute zero temperature. Inset: the temperature dependence of the linear dc transresistance by using equation (17) with (solid line) and without (dashed line) considering the short range correlations are plotted for the same system. The solid dotes represent the experimental data measured by Sivan *et al.*

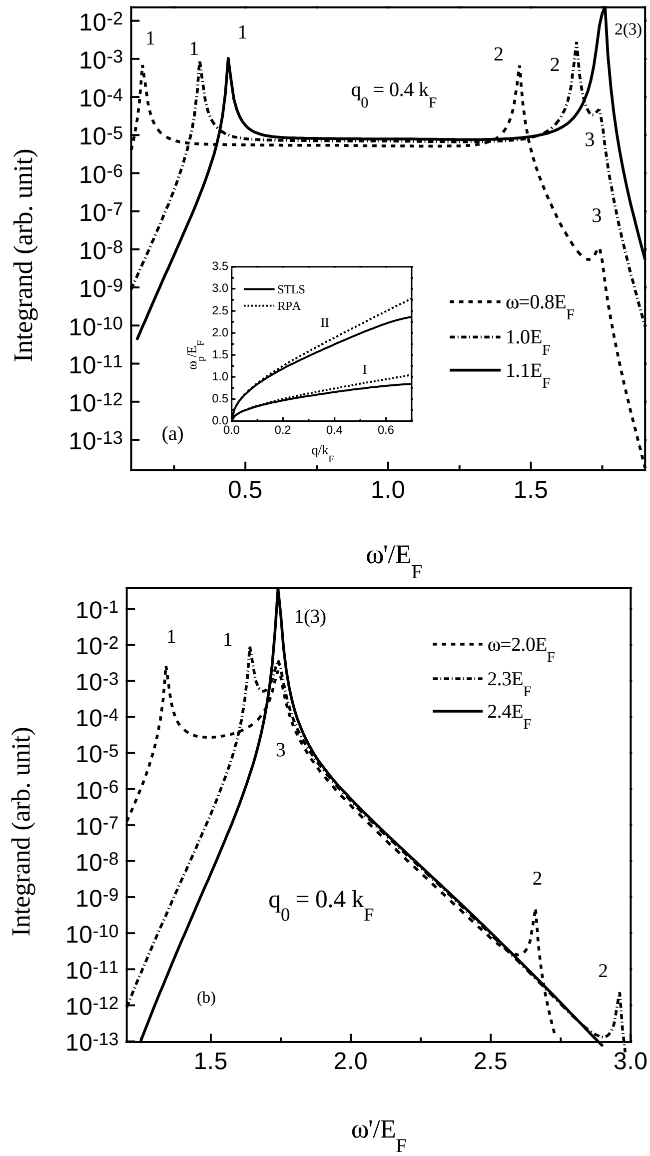

Fig. 2. Integrand of equation (16) as a function of energy transfer ω'/E_F at the fixed $q_0 = 0.4k_F$ (k_F is the Fermi wavevector of the electron layer at zero temperature) and several driving frequencies ω for the same system as Figure 1. (a) $\omega/E_F = 0.8$ (dashed line), 1.0 (dotted-dashed line) and 1.1 (solid line). (b) $\omega/E_F = 2.0$ (dashed line), 2.3 (dotted-dashed line) and 2.4 (solid line). In the inset of (a), the dispersion relations of the two plasmon modes I and II are depicted by solid curves (STLS results) and dashed curves (RPA), respectively. In (a) and (b), the peaks labeled as 1 and 2 are attributed to the contributions of the plasmon I, while the 3 peak corresponds to that of the plasmon II.

the free-electron mass), $m_h = 0.4m_0$, and the static dielectric constant $\kappa = 12.9$. This system is experimentally measured by Sivan and the solid dots in the inset of Figure 1 represent the experimental data [2]. The theoretically computed temperature-dependent linear dc transresistances with including (STLS) and excluding (RPA) the short range corrections are also plotted in the inset by the solid line and the dashed line, respectively. It is obvious that the short range corrections play a substantial role in the Coulomb drag and its contributions make the fit to the experimental data significantly improve [5].

In Figure 1 we plot the calculated normalized real part of the high-frequency transresistance $R_T(\omega)/R_T(0)$ as a function of normalized frequency ω/E_F (E_F is the Fermi energy of the electron-layer at zero temperature) at the lattice temperature of 10 K. For comparison we also show the results obtained by neglecting the plasma pole contributions as discrete points. From the figure, we can easily see that the enhancement in $R_T(\omega)/R_T(0)$ due to the collective modes is very pronounced, resulting in the exciting feature in the frequency-dependent transresistance: a strong plasma resonance. The enhancement exists in a very broad frequency range, nearly from $0.5E_F$ to $5.5E_F$ and the strongest contribution can raise the dynamical transresistance by about a hundred percentage. This similar feature of the linear dynamical resistivity has long been recognized in the single quantum-well [8] and the type-II superlattice systems [9,10]. Of course, the distinctive plasmon dispersion curves $\omega_p(q)$ in different systems show distinguishable discrepancies in the delicate frequency

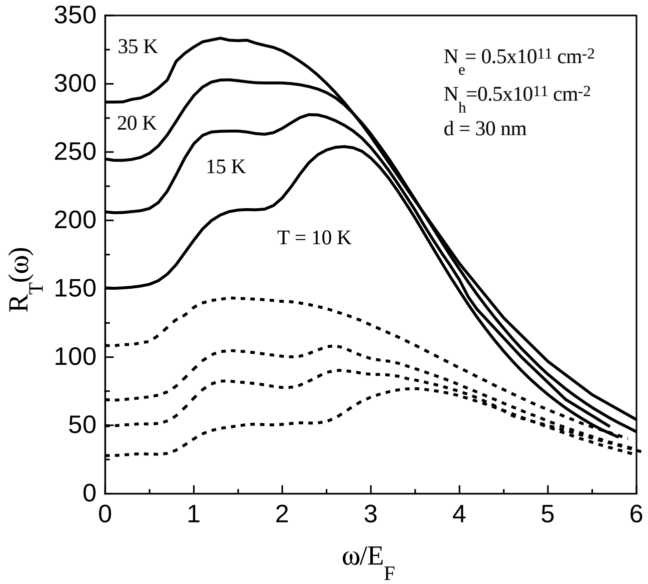

Fig. 3. The calculated frequency dependence of the real part of the complex transresistance $R_T(\omega)$ at temperatures $T = 10$, 15, 20, and 35 K for the same system. Solid lines – theory with correlations (STLS here); dashed lines – RPA results.

behavior of dynamical transport. As illustrated in the inset of Figure 2a, the special plasmon dispersion curves of the electron-hole systems concerned in the present paper, which consist of two branches, one in lower energy (branch I) $\omega_p^{(I)}(q)$ and another in higher energy (branch II) $\omega_p^{(II)}(q)$, provide two accessible channels to contribute to dynamical transport. Because of the different energy spectrums in the two plasma modes, the weight and the frequency threshold of enhancement in one channel are different from those in other one, indicating a possible sophisticate structure in the frequency-dependent transresistance. The theoretical investigation here, as displayed in Figure 1, shows a very striking feature, double-resonant peaks, in the frequency behavior of transresistance for the given electron-hole system at the temperature of 10 K, which is appreciably different from the previous findings [7–10,12]. In the following, we give a detailed explanation of how the particular two plasma modes result in this double-resonant phenomenon.

The argument that there are different weight and the frequency threshold of enhancement in these two channels is graphically depicted in Figures 2a and 2b, which show the integrand of equation (16) as a function of ω' for fixed $q_0 = 0.4k_F$ (k_F is the Fermi wavevector of electron-layer at the absolute zero temperature) and several frequencies ω of the external driving ac electric field. The relatively flat parts of these curves are the single-particle contribution to the dynamical transresistence, while the three peaks are the plasmon contributions. In the inset of Figure 2a, the plasma modes I and II are also shown for this given system at the finite temperature $T = 10$ K. At $q_0 = 0.4k_F$, the energies of modes I and II are about $0.6E_F$ and $1.7E_F$, respectively. Therefore, it is clear that the two peaks labeled as 1 and 2 are attributed to the lower plasmon I, while the peak 3 results from the upper plasmon II. Since the plasmon I is lower in energy than the plasmon II and hence is easier to excite. In consequence of this fact, as expressed by the dashed line in Figure 2a, the plasmon I predominates in the enhancement effects for the case of the lower driving frequency $\omega = 0.5E_F$. With increasing of the driving frequency, the plasmon II starts to give a perceptible contribution to the integrand. Up to about $\omega = 1.1E_F$, at which the equality $\omega_p^{(I)}(q_0) + \omega = \omega_p^{(II)}(q_0)$ is satisfied, the peak 3 happens to meet with the peak 2 and the two plasma modes are in perfect harmony. The value of the plasmon peak at this point (solid line in Fig. 2a) is raised even by a order of magnitude in contrast to the cases of other driving frequencies. As results, the frequency-dependent real part of the transresistance $R_T(\omega)/R_T(0)$ reaches a maximum at $\omega = 1.2E_F$ or so. When the peak 3 is more closer to the peak 1 at higher driving frequencies, a upturn of $R_T(\omega)/R_T(0)$ appears again due to the more stronger contributions of the plasma modes as diagramed in Figure 2b. In addition, similar to the situation in Figure 2a, there exists a new merging of the peaks 1 and 3 at the particular driving frequency which satisfies $\omega - \omega_p^{(I)}(q_0) = \omega_p^{(II)}(q_0)$. It is out of question that the second maximum in $R_T(\omega)/R_T(0)$ at $\omega = 2.4E_F$ is attributed to the strongest enhancement effects. Note that at further large driving frequencies, the plasmon enhancement become trivial and negligible and hence a fast falloff of $R_T(\omega)/R_T(0)$ with ω is found.

6 Temperature dependence

We now briefly discuss the dependence of dynamical transresistance on the temperature and the role of the short range correlations. As the temperature is raised, the enhanced Landau damping erodes the oscillator strength of the two plasmon modes, increasingly blurring the distinction between the two resonant peaks in $R_T(\omega)$. Figure 3 explicitly shows the dimming of the double-resonant structure at the temperature $T = 15$ and 20 K for the same system above-mentioned. Not only that, the positions of the predicted maxima move to lower driving frequencies due to the strengthened influence of Landau damping [4,6]. At the further higher temperature $T = 35$ K the double-resonant structure degenerates into the conventional single resonant shape. For the sake of comparison, we also plot the corresponding results within RPA by dashed curves in Figure 3. The nearly a fact of two to five disagreement between the STLS and RPA theories emphasizes again the importance of the Coulomb correlations in the systems. On the other hand, the short range correlations also suppress the energies of the plasmon modes (the inset of Fig. 1), *i.e.*, raise the Landau damping effects [6]. So the plasmon enhancement and the two maxima in $R_T(\omega)$ should occur at the lower driving frequencies for the fixed temperature.

7 Conclusions

In summary, we have performed theoretical studies on the transfer transport for the Sivan's electron-hole system by means of Lei-Ting balance equations approach for several types of carriers. In order to measure the dynamical transresistance in the high frequency (THz) regime, we have carefully analyzed the relationship between those four directly mearsurable quantities $\rho_i^{(e,h)}$ $(i = 1, 2)$ and the dynamical transresistance ρ_T basing on the balance equations approach and designed an experimental scheme to indirectly extract the information of the high-frequency transresistance. Taking into account the short range correlations, the theoretical results satisfy very well with the experimental data for the linear dc transresistance. Moreover, frequency-dependent dynamical transresistance displays an unusual and temperature-susceptible double-resonant structure in the plasmon-dominated regime for the investigated system, and we have substantiated that this structure results from the cooperation and competition between the two plasmon modes. The important influence of the short range correlations on the dynamical transresistance has also been surveyed. Therefore, we can conclude that the measurement of dynamical transport provides a reliable probe for the two plasmon modes and many-body correlations in electron-hole systems.

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References

1. T.J. Gramila, J.P. Eisenstein, A.H. MacDonald, L.N. Pfeiffer, K.W. West, Phys. Rev. Lett. **66**, 1216 (1991); Surf. Sci. **263**, 446 (1992); Phys. Rev. B **47**, 12957 (1993).
2. U. Sivan, P.M. Solomon, H. Shtrikman, Phys. Rev. Lett. **68**, 1196 (1992).
3. Y. Takada, J. Phys. Soc. Jpn **43**, 1627 (1977); S. Das Sarma, A. Madhukar, Phys. Rev. B **23**, 805 (1981).
4. K. Flensberg, Y.-K. Ben Hu, Phys. Rev. Lett. **73**, 3572 (1994); Phys. Rev. B **52**, 14796 (1995).
5. L. Świerkowski, J. Szymański, Z.W. Gortel, Phys. Rev. Lett. **74**, 3245 (1995); Phys. Rev. B **55**, 2280 (1997).
6. N.P.R. Hill, J.T. Nicholls, E.H. Linfield, M. Pepper, D.A. Ritchie, G.A.C. Jones, B. Yu-Kuang Hu, K. Flensberg, Phys. Rev. Lett. **78**, 2204 (1997).
7. T. Ando, A.B. Fowler, F. Stern, Rev. Mod. Phys. **54**, 437 (1982).
8. X.L. Lei, J.Q. Zhang, J. Phys. C **19**, L73 (1986); J.E. Hasbun, J. Appl. Phys. **75**, 270 (1994).
9. X.L. Lei, N.J.M. Horing, J.Q. Zhang, Phys. Rev. B **33**, 2912 (1986); Phys. Rev. B **35**, 2834 (1987).
10. X.L. Lei, H.L. Cui, N.J.M. Horing, Phys. Rev. B **38**, 8230 (1988).
11. L. Zheng, A.H. MacDonald, Phys. Rev. B **49**, 5522 (1994); K. Flensberg, B. Yu-Kuang Hu, A.-P. Jauho, J.M. Kinaret, Phys. Rev. B **52**, 14761 (1995).
12. C. Zhang, Y. Takahashi, J. Phys.-Cond. **5**, 5009 (1993).
13. X.L. Lei, D.Y. Xing, M. Liu, C.S. Ting, J.L. Birman, Phys. Rev. B **36**, 9134 (1987).
14. H.L. Cui, X.L. Lei, N.J.M. Horing, Superlatt. Microstruct. **13**, 221 (1993).
15. H.L. Cui, X.L. Lei, N.J.M. Horing, Phys. Rev. B **37**, 8223 (1988).
16. K.S. Singwi, M.P. Tosi, R.H. Land, A. Sjölander, Phys. Rev. **176**, 589 (1968).
17. X.L. Lei, Joseph, L. Birman, C.S. Ting, J. Appl. Phys. **58**, 2270 (1985).
18. B. Dong, X.L. Lei, J. Phys.-Cond. **10**, 7535 (1998).