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Geometry effects on quasi-particle inelastic scattering rate in a coupled-quantum-layers system at finite temperature: A theoretical study

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ABSTRACT

Geometry effects on intra-layer inelastic scattering rate of interacting electrons in a coupled-quantum-wells structure, at finite temperature, is theoretically investigated. The random phase approximation is employed to calculate the dynamically screened electron–electron interactions at different temperatures, electron energies and densities. This study is limited to the electrons which are close to the Fermi level so that only quasi-particles contribute to the scattering rate. It is shown that while scattering rate increases slightly with increasing well separation, this effect weakens quickly and broadening tends to a certain limit which is the electron broadening in a single quantum layer. Moreover, the thickness effect in a coupled-quantum-wells structure shows a strong decreasing trend with increasing well width. While the electrons in the same layer make a substantial contribution to screening and as a result to inelastic scattering rate, the electrons in the adjacent layer play an important role, as well.

1. Introduction

The coupled-quantum-wells structure, consisting of two parallel semiconductor quantum layers which are coupled through Coulomb interaction, is an interesting member of the nanostructures family. Its special properties have been, both theoretically and experimentally, investigated for more than two decades [1–9]. Still, people look for novel features in double quantum wells (DQW) for further applications [10–15].

In a DQW, electronic many-body effects including electron–electron intra- and inter-layer interactions, play a significant role in the physical properties of the system. The quasi-particle inelastic scattering rate (the quasi-particle broadening) gives information about how fast electrons get scattered, or equivalently how long quasi-particles stay in the system before annihilation, due to Coulomb electron–electron interaction. The quasi-particle lifetime (inverse of inelastic scattering rate) which determines relaxation time for interacting electrons, is an important quantity to study transport and tunneling properties of the system [16–17].

Inelastic scattering rate of quasiparticles in a single quantum layer at zero and finite temperatures, has been studied, in detail [17–25]. Zheng and Das Sarma [18] showed that the so-called GW method for calculating electron self-energy is able to address the lifetime measurements by Murphy et al. [17]. At the same time, Jungwirth and MacDonald came up with similar calculations which were able to address the experimental results, very well [19]. Sharma and Ashraf considered the electron–electron scattering in the presence of a random disorder potential in a two-dimensional degenerate electron gas (2DEG) system, computationally, and showed that quasi-particle Fermi liquid theory can be applied to such a system [22]. Using the same theoretical method *i.e.* the random phase approximation (RPA), Vazifehshenas and Salavati-fard have investigated quantum size effect on inelastic scattering rate in a single quantum layer, at finite temperature [23]. The calculations showed that the infinitely deep quantum well, as a simple model for 2DEG, is able to reproduce the results of bulk system [26] at large thickness limit [23]. Moreover, by employing the STLS and the temperature-dependent Hubbard approximations, they have studied the local field corrections on the electron–electron scattering lifetime in a 2DEG system, at finite temperature [24,25].

Zheng and Das Sarma calculated inelastic scattering rate in a DQW at zero temperature [27]. They studied contributions from quasi-particle, acoustic and optical plasmon excitations to calculate the total scattering rate. In another theoretical work, Reizer and Wilkins tried to address experimental measurements of inelastic scattering rate in a DQW at finite temperate [17] by using the golden-rule method and including the nongolden-rule

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contribution of the same order in the interaction [28]. While their theoretical work was not in a good agreement with the experiment, it still provided a useful insight about the problem. Finally, Jungwirth and MacDonald presented calculations for the dc tunneling conductance between coupled two-dimensional clean electron gases at finite temperature and found an excellent agreement with the experiment [19]. Vortex corrections to RPA were considered in this work, as well. It is worth pointing out that the lifetime measurements by Murphy et al. were based on tunneling experiment in a DQW structure [17].

In the work presented here, by employing the RPA for dynamical dielectric function of the interacting system, we study geometry effects on inelastic scattering rate due to quasiparticles in a DQW system, at finite temperature.

The rest of the paper is structured as follows: in the next section, theoretical formalism for calculating inelastic scattering rate is presented and the model we use for a DQW is described. Numerical results are given and discussed in Section 3 which is divided into two subsections: the well separation effects and the thickness effects. Finally, the highlights of this work are summarized in the last section.

2. Theoretical formalism

We consider an n-doped GaAs-based DQW structure and calculate geometry effects on the intra-layer inelastic scattering rate due to quasi-particles by making use of the GW method, at finite temperature. We assume that electrons are limited to the first sub-band in either layer and scattering does not change their sub-band index. Moreover, since we are interested in pure electronic effects, this study is limited to the low temperature and fast electron regime, so that we could disregard phonons and impurities, respectively [18].

In the original GW method, the electron self-energy, Σ, can be calculated using the dressed Green function, G, and the screened interaction, W [29]. As an approximation to this method, the non-interacting Green function, G^0, is replaced for the dressed Green function in the GW expression for Σ. This approximation has been extensively used to calculate the electron self-energy in many-body problems.

In the Matsubra formalism the electron self-energy within the GW approximation at finite temperature can be calculated as [29]:

$$\Sigma_{ii}(\mathbf{k}, \omega_n) = -\frac{1}{\beta\nu}\sum_{\mathbf{q}}\sum_{\nu_n} W_{ii}(\mathbf{q}, \nu_n) G_{ii}^0(\mathbf{k}+\mathbf{q}, \omega_n+\nu_n) \tag{1}$$

where $\beta^{-1} = k_B T$, ν is the volume of electron gas and i is the layer index. Also, $\omega_n = (2n+1)\pi/\beta\hbar$, $\nu_n = (2n\pi)/\beta\hbar$ and n is an integer number. The non-interacting Green function is defined as $G^0(\mathbf{k}, \omega_n) = 1/[i\omega_n - \hbar^{-1}(E_{\mathbf{k}} - \mu)]$ with $E_{\mathbf{k}} = \hbar^2 k^2/2m^*$ and $\mu/E_F = T/T_F \ln(e^{T_F/T} - 1)$ being the dimensionless chemical potential. Furthermore, m^* represents the conduction band electron effective mass, E_F and T_F are Fermi energy and temperature, and W_{ii} is the dynamically screened intra-layer electron–electron interaction which is given, at finite temperature, as [30]:

$$W_{ii}(q, \omega, T) = \frac{\left(1 - v_{jj}(q)\chi_{jj}^0(q, \omega, T)\right)v_{jj}(q) + v_{ji}^2(q)\chi_{ii}^0(q, \omega, T)}{\det[\varepsilon(q, \omega, T)]} \tag{2}$$

where the determinant of dynamical dielectric matrix within the RPA is calculated as the following:

$$\det[\varepsilon(q, \omega, T)] = \left[\left(1 - v_{jj}(q)\chi_{jj}^0(q, \omega, T)\right)\left(1 - v_{ii}(q)\chi_{ii}^0(q, \omega, T)\right)\right] - v_{ji}(q)v_{ij}(q)\chi_{ii}^0(q, \omega, T)\chi_{jj}^0(q, \omega, T) \tag{3}$$

It is worth mentioning that the RPA, which considers the long-range Coulomb interactions and ignores the short-range exchange-correlation effects, is exact in the high electron density limit. For systems with low electron density in which the short-range interactions are important, it is necessary to include local field corrections to the RPA to have a reliable dielectric function [29].

It is common to use the dimensionless density parameter, r_s, for the electron density. This quantity is defined as the average distance between non-interacting electrons in the system. For a 2DEG, the dimensionless density parameter is calculated as $r_s = 1/(a_B^*\sqrt{\pi n})$ in which n is the electron density and a_B^* is the effective Bohr radius. It is quite reasonable to include local field corrections to the RPA for $r_s > 1$.

In Eq. (3), χ^0 is the density–density response function in the non-interacting electron system for which the analytical expressions, at finite temperature, are given elsewhere [31]. Also, $v_{ii} = v_{jj}$ ($v_{ij} = v_{ji}$) is the unscreened electron–electron intra-layer (inter-layer) potential. The Coulomb interaction matrix elements could be found from the following equation:

$$V_{ij}(q) = \frac{2\pi e^2}{q\kappa} F_{ij}(q)\exp\left(-qd\left(1 - \delta_{ij}\right)\right) \tag{4}$$

where κ is the dielectric constant of the host semiconductor, d is the center-to-center well separation in DQW and F_{ij} is a form factor matrix element which includes information about the geometry of the system. The form factor matrix elements are, in general, defined as:

$$F_{ij}(q) = \iint dz dz' |\Psi_i(z)|^2 \left|\Psi_j(z')\right|^2 \exp\left[-q\left(z - z'\right)\right] \tag{5}$$

with Ψ_i being the envelope function of ith quantum layer.

We model a DQW structure as two parallel infinitely deep square quantum wells with thickness L which are separated from each other by spacing d. For such a system, the envelope functions are known and the intra- and inter-layer form factors (diagonal and off-diagonal elements of the form factor matrix) could be analytically derived as [23,31]:

$$F_{ii}(qL) = \frac{3(qL) + 8\pi^2/(qL)}{(qL)^2 + 4\pi^2} - \frac{32\pi^4[1 - exp(-qL)]}{(qL)^2(q^2L^2 + 4\pi^2)^2} \tag{6}$$

$$F_{ij}(qL) = \frac{64\pi^4 \sinh^2(qL/2)}{(qL)^2\left(q^2L^2 + 4\pi^2\right)^2}\exp(-qd) \tag{7}$$

One is able to calculate the intra-layer inelastic scattering rate for electrons with momentum k and unscreened energy ξ_k, which is measured with respect to the Fermi level of ith layer ($\xi_k = k^2/2m^* - E_F$), as the following ($\hbar = 1$) [18]:

$$\Gamma_{ii}(\mathbf{k}, \xi_k, T) = \tau_{ii}^{-1}(\mathbf{k}, \xi_k, T) = -2\mathrm{Im}\Sigma_{ii}(\mathbf{k}, \xi_k, T) \tag{8}$$

with

$$\mathrm{Im}\Sigma_{ii}(\mathbf{k}, \xi_k, T) = \frac{1}{\nu}\sum_{\mathbf{q}} \mathrm{Im}\left(W_{ii}(q, \xi_{\mathbf{q}+\mathbf{k}} - \xi_k, T)\right) \times \left(f_B(\xi_{\mathbf{k}+\mathbf{q}} - \xi_k, T) + f_F(\xi_{\mathbf{k}+\mathbf{q}}, T)\right) \tag{9}$$

where f_B and f_F are the Bose–Einstein and the Fermi–Dirac distribution functions, respectively.

3. Results and discussions

It is well known that in an interacting electron system, quasiparticles, acoustic and optical plasmons contribute to inelastic