Physica B 462 (2015) 112–116

Contents lists available at ScienceDirect

Physica B

journal homepage: www.elsevier.com/locate/physb

Geometrical asymmetry effects on energy and momentum transfer rates in a double-quantum-well structure: Linear regime

T. Vazifehshenas [a], T. Salavati-fard [b,*]

[a] Department of Physics, Shahid Beheshti University, G. C., Evin, 1983969411, Tehran, Iran
[b] Department of Physics and Astronomy, University of Delaware, Newark, DE 19716 USA

ARTICLE INFO

Article history:
Received 3 October 2014
Received in revised form
16 December 2014
Accepted 22 January 2015
Available online 22 January 2015

Keywords:
Energy transfer rate
Coulomb drag
Coupled quantum wells
Asymmetric geometry
Hubbard local field correction.

ABSTRACT

We investigate theoretically the effect of spatial asymmetry on energy and momentum transfer rates in a double-quantum-well system using balance equation approach. Our study is limited to the linear regime where the applied electric field is sufficiently weak. We calculate the screened potential by using the random phase approximation and the Hubbard approximation for the cases of high and low electron densities, respectively. Our numerical results predict that the spatial asymmetry affects, considerably, both the energy transfer and drag rates as a result of changes in plasmon modes. Also, we find that the spatial asymmetry effect disappears at lower temperatures by inclusion of the short-range interaction.

1. Introduction

It has been more than two decades that nanostructures play a significant and promising role in the realm of science and technology. Double-quantum-well (DQW) structure which is one the most interesting members of semiconductor nanostructures family, has being broadly studied during past years [1–17]. This structure consists of two coupled parallel quantum layers which are separated from each other by several nanometers. In this coupled system, the inter-layer interaction creates several outstanding many-body effects such as momentum transfer or Coulomb drag and also energy transfer between adjacent layers. In coupled quantum systems, under certain circumstances, when an external electric field is being applied to one of them, surprisingly, a voltage difference can be measured in the other system due to momentum transfer phenomenon. There are many papers describing various aspects of momentum transfer using experimental and theoretical techniques [4–13]. It is quite interesting that different electronic temperatures in two layers yields to the electronic energy transfer effect between electrons in different layers, interacting with each other through Coulomb potential, located in close vicinity and without any possibilities for inter-layer tunneling. This is a hot electron transport effect and can be happened in linear and non-linear regimes, corresponding to the absence and presence of an applied electric field, respectively. Solomon et al. [4,14] observed both momentum and energy transfer between two closely spaced two-dimensional electron gas layers and also between coupled two- and three-dimensional electron gas systems via Coulomb mutual scattering at different temperature regimes. They found that momentum and energy transfer effects compete. To the best of our knowledge, there is no experimental work reporting measurements of the energy transfer rate for a DQW structure at different temperatures. Nevertheless, this many-body effect is still interesting from the theoretical point of view. Utilizing the energy-balance approach, the behavior of the energy transfer rate in double quantum systems such as DQW, double-quantum-wire and double-layer graphene has been investigated in a few papers [15–21].

In spite of the fact that the symmetric DQW structure has been vastly studied, surprisingly, there are limited studies on the many-body properties of spatially asymmetric DQW structure [22–24] and therefore it is still exciting to investigate these many-particle nanoscale effects in an asymmetric geometry. The importance of studying the geometrical asymmetric structures originates from the fact that most real systems are not completely symmetric. Also, being slightly asymmetric rather than perfectly symmetric could be considered as an additional flexibility for engineering the system. As a result, considering spatial asymmetry into theoretical calculations might lead to an insight about the real and more interesting systems.

* Corresponding author. Fax: +1 302 8311637.
E-mail address: taha@udel.edu (T. Salavati-fard).

http://dx.doi.org/10.1016/j.physb.2015.01.024
0921-4526/

Motivated by the above mentioned ideas, in the research presented here we study the Coulomb drag and energy transfer rate in a geometrically asymmetric DQW structure and compare our numerical results with calculations for the symmetric system [13,20]. The goal is to conduct systematically theoretical study in the effect of geometrical asymmetry on the energy and momentum transfer rates. Here, the study of energy and momentum transfer rates is limited to linear regime with sufficiently weak external electric field and includes contributions of both plasmon and quasi-particle excitations through dynamic screening approximations for the dielectric matrix of the system. Also to show the significant contribution of plasmon excitations, we calculate energy transfer rate within static screening approximation, as well. Furthermore, we calculate the energy and momentum transfer rates beyond the RPA by including both the zero- and finite-temperature Hubbard local field correction factors, which take into account the effect of short-range exchange interactions in the screened potential.

The rest of the article is organized as following. In the next section, we describe the model and theoretical formalism of energy transfer rate and Coulomb drag for an asymmetric DQW system. Also, we explain briefly the zero- and finite-temperature Hubbard local field corrections for a two-dimensional system which is known to be necessary at low electron densities. The Section 3 is dedicated to provide numerical calculations for both asymmetric and symmetric systems at two different electron densities. Discussions are also included in Section 3. Finally in Section 4, the conclusion of our work is provided.

2. Theoretical formalism

The system we study can be modeled as two parallel n-type doped GaAs-based infinite square quantum wells of widths L_1 and L_2which are separated by a distance $d$along the z-axis. The two layers have the sheet electron densities n_1 and n_2 and the electron temperatures T_1 and T_2. We consider the case that only the lowest subband in each quantum well is occupied and assume two layers are placed close together to ensure an effective inter-layer interaction but far enough to prevent the electron tunneling between them. As mentioned earlier, the inter-layer Coulomb interaction in a DQW structure is responsible for the energy and momentum transfer phenomena. Considering the screening effect, the dynamic effective inter-layer interaction,$W_{12}(\mathbf{q}, \omega)$, is defined as:

$$W_{12}(\mathbf{q}, \omega) = \frac{V_{12}(q)}{\det[\varepsilon(\mathbf{q}, \omega)]} \tag{1}$$

where $\mathbf{q}$ is a two-dimensional wave vector in the plane of quantum well,$V_{12}(q)$ is the unscreened inter-layer (off-diagonal) element of the Coulomb interaction matrix and $\varepsilon(\mathbf{q}, \omega)$ is the dielectric matrix of the system. There are different many-body approximations for calculating the dielectric function of an interacting system. In the limit of high electron density, the random phase approximation (RPA) is an appropriate approach to consider the long-range correlation characteristic of an electron gas system. In a double layer system, the determinant of the RPA dielectric matrix is given by [2]:

$$\det[\varepsilon(\mathbf{q}, \omega, T_1, T_2)] = \big(1 - V_{11}(q)\chi_1(\mathbf{q}, \omega, T_1)\big)\big(1 - V_{22}(q)\chi_2(\mathbf{q}, \omega, T_2)\big) - V_{12}(q)\chi_1(\mathbf{q}, \omega, T_1)V_{21}(q)\chi_2(\mathbf{q}, \omega, T_2) \tag{2}$$

Here$\chi(\mathbf{q}, \omega, T)$ is the finite-temperature dynamic two-dimensional Lindhard polarization function and the explicit forms of its real and imaginary parts can be found in literature [2]. The above matrix elements of the unscreened electron–electron interaction,$V_{ij}(q)$, are of the form:

$$V_{ij}(q) = \frac{2\pi e^2}{\kappa q} F_{ij}(\mathrm{q}) \tag{3}$$

where $i, j = 1, 2$are the layer indices, κ is the dielectric constant of the host semiconductor and $F_{ij}(q)$represents the elements of form factor matrix which basically depend on the geometrical parameters of the system and defined as [2]:

$$F_{ij}(q) = \iint dz dz' \left|\zeta_i(z)\right|^2 \left|\zeta_j(z')\right|^2 \exp[-q(z - z')] \tag{4}$$

In above equation $\zeta_i(z)$ is the envelope wave function of lowest subband in the ith layer. The analytic expressions for form factor functions have been derived only for a few spatially symmetric systems; for example, in a system of two infinite square wells of equal width, L, the diagonal and off-diagonal elements of the form factor matrix are obtained as [25]:

$$F_{ii}(x) = \frac{3x + 8\pi^2/x}{x^2 + 4\pi^2} - \frac{32\pi^4[1 - exp(-x)]}{x^2(x^2 + 4\pi^2)^2} \tag{5}$$

$$F_{ij}(x) = \frac{64\pi^4 \sinh^2(x/2)}{x^2(x^2 + 4\pi^2)^2} \exp(-qd) \tag{6}$$

where $x = qL$. In the presence of spatial asymmetry i.e. the case we are interested in, the inter-layer form factor is obtained numerically from Eq. (4).

In this work, we are focusing on the effect of spatial asymmetry on the rates of energy and momentum transfer in a DQW system. These two important transport processes are strongly dependent on the inter-layer screened Coulomb interactions. Using the balance equation transport theory [26], the expressions for the energy transfer rate (power transfer) and the momentum transfer rate (Coulomb drag) can be derived in terms of the electron drift velocity and electron temperature. In our coupled double layer system, we assume an electric current is driven through one of the layers ($v_{d1} \neq 0$) while no current flows in the other ($v_{d2} = 0$) but an induced electric field is formed in second layer ($E_2 \neq 0$). When the drive bias voltage is low enough to be within the linear regime, it is reasonable to take $v_{d1} \to 0$ at the end of calculations. From the balance equation transport theory [19,27], the rate of energy transfer is given by ($\hbar = 1$):

$$P_{12}(v_{d1} - v_{d2}) = -\sum_{\mathbf{q}} \int_{-\infty}^{+\infty} \frac{\omega d\omega}{\pi} \left|W_{12}(\mathbf{q}, \omega)\right|^2 \times \left[n_B\left(\frac{\omega}{K_B T_1}\right) - n_B\left(\frac{\omega - \omega_{12}}{K_B T_2}\right)\right] \mathrm{Im}\chi_1(\mathbf{q}, \omega, T_1)\mathrm{Im}\chi_2(-\mathbf{q}, \omega_{12} - \omega, T_2) \tag{7}$$

and also the rate of momentum transfer is obtained as

$$f_{12}(v_{d1} - v_{d2}) = -\sum_{\mathbf{q}} \int_{-\infty}^{+\infty} \frac{q_x d\omega}{\pi} \left|W_{12}(\mathbf{q}, \omega)\right|^2 \times \left[n_B\left(\frac{\omega}{K_B T_1}\right) - n_B\left(\frac{\omega - \omega_{12}}{K_B T_2}\right)\right] \mathrm{Im}\chi_1(\mathbf{q}, \omega, T_1)\mathrm{Im}\chi_2(-\mathbf{q}, \omega_{12} - \omega, T_2) \tag{8}$$

Here $n_B(x) = 1/(\exp(x) - 1)$ is the Bose–Einstein distribution function and $\omega_{12} = q_x(v_{d1} - v_{d2})$. In the linear regime (weak electric field regime), the drag rate, $\tau_D^{-1} = -f_{12}(v_{d1})/(m_1 n_2 v_{d1})$, can be expressed by the following simple form [2]:

$$\tau_D^{-1} = \frac{1}{8\pi^2 m_1 n_2 K_B T} \int_0^\infty q^3 dq \int_0^\infty d\omega \frac{\left|W_{12}(\mathbf{q}, \omega)\right|^2}{\sinh^2(\omega/2K_B T)} \times \mathrm{Im}\chi_1(\mathbf{q}, \omega, T)\mathrm{Im}\chi_2(\mathbf{q}, \omega, T) \tag{9}$$

In the above equation, it is assumed that $T_1 = T_2 = T$.

It is well known that the exchange and correlation interactions are non-negligible at low electron density systems and therefore the RPA calculations ignoring short-range interactions is not reliable anymore. In this case, we can improve the RPA dielectric matrix by