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Thickness and local field effects on energy transfer rate in coupled quantum wells system: Linear regime

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ABSTRACT

We investigate theoretically the dependence of energy transfer rate in Double-Quantum-Well system on the well thickness by using the balance equation formalism. Also, by including the local field correction in our calculations through the zero- and finite-temperature Hubbard approximations, we study the effect of the short-range interactions on the energy transfer phenomenon. Calculations consider both the static and dynamic screening approximations. Our numerical results predict that the energy transfer rate increases considerably by increasing the layers' thicknesses and by taking into account the short-range interactions, as well.

1. Introduction

Double-Quantum-Well (DQW) structure, in which two parallel quantum layers separated by a few nanometers and coupled through the Coulomb interaction has been extensively studied theoretically and experimentally in past years. Due to its special physical properties and applications, this structure is still interesting for research. In this coupled system, the interlayer interaction plays an important role and is responsible for some interesting phenomena such as momentum transfer or Coulomb drag and energy transfer between spatially separated layers without exchanging any carrier. The Coulomb drag in a double-quantum-layer system in which a current driven through one layer induces a voltage difference in the other layer, provides a unique approach to investigate the electron–electron interaction directly in a low-dimensional many-body system from a transport measurement [1–3]. The various aspects of this effect have been studied in detail, in several experimental and theoretical works [4–13]. By allowing different electronic temperatures in two adjacent layers, the energy of electrons in one layer can be transferred to the electrons in another one, located in close proximity but with no interlayer tunneling. This hot electron transport process can occur with or without an externally applied electric field [4–14] called non-linear and linear regimes, respectively. Based on the energy-balance formalism, the rates of energy transfer in double quantum systems have been investigated in few papers and their dependence on the temperature, electron density and separation between structures have been reported [15–19]. Specially, Tanatar considered coupled quantum wires [18] and wells [19] system due to Coulomb interaction theoretically and calculated the effects of the static and dynamic screenings within the random phase approximation (RPA) on the energy transfer rate in both linear and non-linear regimes. In high electron density systems, the RPA which accounts for the long range screening has worked very well. Nevertheless, in the limit of low density, it is necessary to improve the RPA by including the effects of short-range interactions through the local field correction. The so-called Hubbard approximation which takes exchange effects into account is a first improvement upon the RPA.

In the work presented here, we first investigate theoretically the layer thickness effect on the energy transfer rate for a DQW system by using the balance equation approach at linear regime and employing the temperature dependent RPA dielectric function for screened interaction. We also calculate the energy transfer rate beyond the RPA by including both the zero- and finite-temperature Hubbard local field correction factors in the screened potential. This study includes both static and dynamic screening effects.

The article is organized as follows. In Section 2 we describe the model and summarize theory of energy transfer rate for a DQW system. We also present the screened interlayer potential formalism within the RPA and Hubbard approaches for coupled quantum layers. Section 3 is dedicated to numerical results and discussion. Finally, in Section 4 the conclusion of our work is given.

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2. Theory

We consider a system of two parallel identical rectangular quantum wells of width L which are spatially separated from each other in the z direction by a center to center spacing d. We study the case of n-doped GaAs-based quantum layers and neglect the holes contribution. In each layer the sheet electron density is related to the Fermi wave vector, k_F, as $n=k_F^2/2\pi$ and to the Fermi temperature, T_F, by $n=m^*T_F/\pi$ where m^* is the electron conduction band effective mass. It is convenient to introduce the dimensionless density parameter, r_s, the ratio of average distance between electrons in a non-interacting electron gas to the effective Bohr radius $a_B^*=(m^*e^2/\varepsilon_s)^{-1}$ (where ε_s is the background dielectric constant) which is obtained for a two-dimensional system as $r_s=1/(a_B^*\sqrt{\pi n})$. We are interested in investigating the transport properties of our coupled system in steady state. The balance equation approach to linear and non-linear hot electron transport theory formulated by Lei and Ting [20] is a powerful tool in describing the response of the semiconductor nanostructures to the externally applied fields in terms of the electron drift velocity and temperature. In our coupled 2DEG system, we assume that one of the layers (layer 1) with electron temperature T_1 is subjected to an electric field, E, which causes the electrons within this layer to move with a drift velocity $v_{d1}=\mu E$ (μ is the electron mobility). The other layer (layer 2) is supposed to be in an open circuit condition, i.e. $v_{d2}=0$ and has an electron temperature T_2. There are two different energy transfer regimes called linear and non-linear according to the weak and strong electric field, respectively. In the linear regime where the applied electric field is sufficiently weak, the temperature difference between the electrons in two adjacent quantum wells is responsible for the energy transfer phenomenon, so one can consider $v_{d1}\to 0$ at the end of calculations. For non-linear case, the electrons in layer 1 are subject to stronger electric field and v_{d1} cannot be neglected.

From the energy balance equation, the energy transfer rate between two layers due to interlayer Coulomb coupling is given by [21]

$$P_{12}(v_{1d}-v_{2d})=-\sum_{\mathbf{q}}\int_{-\infty}^{+\infty}\frac{\omega d\omega}{\pi}\left|W_{12}(\mathbf{q},\omega)\right|^2\left[n_B\left(\frac{\omega}{T_1}\right)-n_B\left(\frac{\omega-\omega_{12}}{T_2}\right)\right]\mathrm{Im}\chi_1(\mathbf{q},\omega,T_1)\mathrm{Im}\chi_2(-\mathbf{q},\omega_{12}-\omega,T_2) \tag{1}$$

In the above equation $\mathbf{q}$ is a two-dimensional wave vector in the quantum well plane, $\omega_{12}=q_z(v_{1d}-v_{2d})$, $W_{12}(\mathbf{q},\omega)=V_{12}(\mathbf{q})/\det[\varepsilon(\mathbf{q},\omega)]$ is the dynamically screened interlayer potential, $\chi(\mathbf{q},\omega,T)$ is the temperature dependent 2D non-interacting susceptibility [2] and $n_B(x)=1/(\exp(x)-1)$ is the Bose–Einstein distribution function. Here, $V_{12}(\mathbf{q})$ and $\varepsilon(\mathbf{q},\omega)$ are the bare interlayer Coulomb potential and dynamic two-component dielectric matrix. In general, the exact $\varepsilon(\mathbf{q},\omega)$ is a very complicated quantity so cannot be calculated analytically and needs to be approximated. The most common approximation to calculate the dielectric function of a many-body system is RPA which considers only the long-range interactions and neglects the short-range effects. It is well-known that in high electron density systems, the RPA is an effective and reliable approximation for $\varepsilon(\mathbf{q},\omega)$. On the contrary, for low electron density systems, the short-range interactions play more significant role and the RPA results are not accurate any more. The determinant of dynamical dielectric matrix for a double system within the RPA is given by

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

In the above expression the intra-layer ($i=j$) and interlayer ($i\neq j$) bare Coulomb potential matrix elements obtained from

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

Here i, $j=1$, 2 and $F_{ij}(q)$ is the form factor of quantum well which contains all the information about the geometry of system. This function is defined by the following equation [2]:

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

where $\Psi_i(z)$ is the envelope function of ith quantum well. For a system of two infinitely deep rectangular quantum wells with equal well width L and the center to center spacing d, the intra- and interlayer form factors are calculated analytically [2–22]

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

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

where $x=qL$.

As mentioned earlier, the short-range exchange and correlation interactions become more important at low electron density systems. In this case we should go beyond the RPA by introducing the local field correction factor into the dielectric function of system. The Hubbard local field correction, $G_H(q)$, which is an exchange correction to the RPA [23] has been analytically calculated for a two-dimensional electron gas system by Jonson [24]

$$G_H(q)=\frac{1}{2}\frac{q}{\sqrt{q^2+k_F{}^2}} \tag{7}$$

Hwang and Das Sarma introduced the temperature dependent Hubbard local field correction by substituting thermal Fermi wave vector $k_F(T)=\sqrt{2m^*\mu(T)}$ for k_F where $\mu(T)$ is the chemical potential [25]:

$$G_H(q,T)=\frac{1}{2}\frac{q}{\sqrt{q^2+2m^*\mu(T)}} \tag{8}$$

This idea has been used in a few previous works [26–28]. To include the local field correction into the $\det[\varepsilon(\mathbf{q},\omega,T_1,T_2)]$, we replace the intra-layer potential V_{ii} by $V_{ii}(1-G_H(q))$ and neglect the short-range effects on the interlayer interactions.

3. Numerical results and discussion

We consider a DQW structure containing two parallel identical n-type doped GaAs-based quantum layers that are coupled due to the screened Coulomb interaction. The quantum wells are assumed to be infinity deep so electron tunneling between layers is impossible. We calculate the energy transfer rate between two layers in linear regime by employing both the static and dynamic screening functions and using the parameters of Ref. [19]. Here, we study theoretically the dependence of energy transfer rate on the layer thickness. Moreover, by using the zero and finite temperature Hubbard local field corrections, we investigate the short-range effects on the energy transfer rate. We restrict our study to the case $r_s=2$ and interlayer separation $d=50$ nm. Also, according to the Ref. [19] the electron temperature of layer 1 is kept constant at $T_1=T_F$ in all calculations.

The energy transfer rate as functions of dimensionless electron temperature of layer 2 for three different layer thicknesses is depicted in Fig. 1. Here, the dielectric matrix is calculated within the static RPA. As it is shown, the energy transfer rate increases by increasing layer thickness. This behavior can be explained by the