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Energy-transfer rate in Coulomb coupled quantum wires

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We study the energy transfer rate for electrons in two parallel quantum wires due to interwire Coulomb interactions. The energy transfer rate between the wires (similar to the Coulomb drag effect in which momentum transfer rate is measured) is calculated as a function of temperature for several wire separation distances. We employ the full wave vector and frequency dependent random-phase approximation at finite temperature to describe the effective interwire Coulomb interaction. We find that the energy transfer rate at intermediate temperatures (i.e., $T\sim 0.3E_F$) is dominated by the collective modes (plasmons) of the system. Nonlinear effects on the energy transfer rate is also explored. © *1997 American Institute of Physics.* [S0021-8979(97)05109-8]

I. INTRODUCTION

The momentum and energy transfer between spatially separated electron gases is known to influence the transport properties of individual systems because of the Coulomb coupling.[1] In particular, the Coulomb drag effect, where a current in one layer drives a current in the other one due to the momentum loss caused by interlayer electron-electron interactions, has been observed in various experiments.[2] There has been a growing theoretical activity in the past few years touching upon various aspects of the drag phenomenon.[3–7] The Coulomb drag effect (momentum transfer rate) for cylindrical quantum wire structures are recently considered by Qin[8] and Tanatar.[9]

In this article we study the energy transfer rate between two parallel cylindrical wires under experimental conditions similar to the drag effect. The importance of the energy transfer rate between two Coulomb coupled quantum wells were pointed out by Price.[1,10] The model of a double-quantum-wire structure we use in this calculation was envisaged by Gold[11] in the context of charge-density-wave instability. Semiconductor based quasi-one-dimensional (Q1D) electron systems, relying on carrier confinement in transverse directions, is a subject of continuing interest. The primary motivation for studying these low-dimensional systems comes from their technological potential such as high-speed electronic devices and quantum-wire lasers. Other than the practical implications, electrons in Q1D structures offer an interesting many-body system for condensed-matter theories.

We calculate the temperature dependence of the energy transfer rate between two parallel quantum wires. It is assumed that the quantum wires may be separately contacted and kept at two different carrier temperatures, as in the case of quantum-well structures.[2,3] Our calculation is mainly based on the random-phase approximation (RPA) which strictly speaking applies only for high density systems. We first demonstrate the contribution of plasmon modes to the energy transfer rate for $T\geqslant 0.3E_F$. Next we investigate the influence of local-field corrections which describe the exchange and correlation effects neglected by the RPA. We find that for realistic systems at the experimentally attainable densities with the present technology such corrections can be quite significant. We also explore the dependence of energy transfer rate between the quantum wires on the externally applied electric field, the so-called nonlinear regime.

II. MODEL AND THEORY

We consider two identical cylindrical wires with radius R and infinite potential barriers. The double-quantum wire structure is characterized by the distance d between the axes of the cylindrical wires.[11] Assuming that the quantum wires do not penetrate each other and there is no tunneling between them, we require $d>2R$. The linear electron density N in each wire is related to the Fermi wave vector by $N=2k_F/\pi$. We also define the dimensionless electron gas parameter $r_s=\pi/(4k_Fa_B^*)$, in which $a_B^*=\epsilon_0/(e^2m^*)$ is the effective Bohr radius in the semiconducting wire with background dielectric constant ϵ_0 and electron effective mass m^*. The explicit forms of intra- and interwire Coulomb interactions in the double-wire system have been given elsewhere.[11] We assume that only the lowest subband in each wire is occupied. This will hold as long as the difference between the second and first subbands, Δ_{21} remains much larger than T (we take the Boltzmann constant $k_B=1$). A simple calculation shows that $\Delta_{21}\approx 10(4/\pi)^2r_s^2/(R/a_B^*)^2E_F$, which means that the one-subband approximation will be valid for $R\simeq 2a_B^*$ and $r_s\geqslant 1$. In a GaAs quantum wire, for which $\epsilon_0=13$ and $m^*=0.067m_e$, the effective Bohr radius $a_B^*\approx 100$ Å. Generalization of our formalism to the multi-subband case should be straightforward.

The energy transfer rate from one quantum wire to the other (to lowest order in the interwire interaction) is given by[12]

$$P_{12}(v_1-v_2)=-\sum_q\int_{-\infty}^{\infty}\frac{d\omega}{\pi}|W_{12}(q,\omega)|^2\times\left[n\left(\frac{\omega}{T_1}\right)-n\left(\frac{(\omega-\omega_{12})}{T_2}\right)\right]\times\omega\ \mathrm{Im}\ \chi_1(q,\omega)\ \mathrm{Im}\ \chi_2(-q,\omega_{12}-\omega). \quad (1)$$

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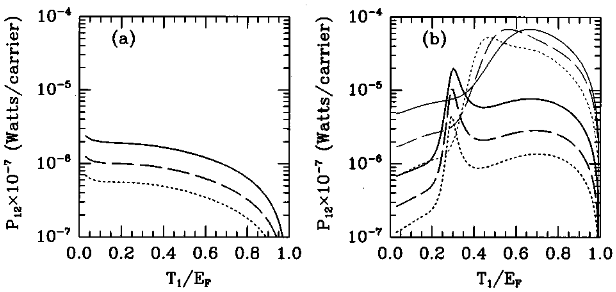

FIG. 1. (a) The energy transfer rate in the static screening approximation as a function of temperature for interwire separations $d=5a_B^*$ (solid), $6a_B^*$ (dashed), and $7a_B^*$ (dotted). (b) The same as in (a) in the dynamic screening approximation. The thin curves are calculated with the local-field corrections.

In the above expression, $\omega_{12}=q(v_1-v_2)$ where v_1 and v_2 are electron drift velocities, $W_{12}(q,\omega)=V_{12}(q)/\varepsilon(q,\omega)$ is the dynamically screened interwire potential, Im $\chi(q,\omega)$ is the imaginary part of the temperature dependent 1D susceptibility[13] and $n(\omega)$ is the Bose distribution function. The screening function $\varepsilon(q,\omega)$ for two identical wires is expressed as

$$\varepsilon(q,\omega)=[1-V_{11}\chi_1][1-V_{11}\chi_2]-V_{12}^2\chi_1\chi_2\,. \tag{2}$$

The above expression for the energy transfer rate is derived within the balance equation approach to nonlinear electrical transport in low dimensional semiconductors[12] and is believed to describe the relevant experimental situation quite accurately. We emphasize that the full wave vector, frequency and temperature dependence of the dynamical susceptibilities as well as the screening function $\varepsilon(q,\omega)$ should be used to capture the plasmon contribution in the drag phenomenon. In the case of Coulomb drag experiments, one of the quantum wires (say wire 1) is subject to an electric field, and in the other one no current is allowed to flow (i.e., $v_2=0$). Linear and nonlinear regimes are distinguished by further setting $v_1=0$.

III. RESULTS AND DISCUSSION

We evaluate the energy transfer rate P_{12} in the linear regime for a GaAs system, in several approximations. First, we assume that the interwire potential is statically screened, $W_{12}(q)=V_{12}(q)/\varepsilon(q,0)$. Figure 1(a) shows the temperature dependence of the energy transfer rate for parallel quantum-wires each with radius $R=2a_B^*$ and $r_s=2$. The temperature of the second wire is kept at $T_2=E_F$. Curves from top to bottom are for center-to-center distances $d=5a_B^*$, $6a_B^*$, and $7a_B^*$, respectively (thick lines). We observe that the energy transfer rate decreases monotonically as T_1 increases (and vanishes when $T_1=T_2$) for all separations. For $T_1>T_2$, the energy transfer rate changes sign.

We next include the full frequency dependence of the effective potential $W_{12}(q,\omega)$ at finite temperature. In Fig. 1(b), we show the calculated energy transfer rate as a function of T_1 for wire separations $d=5a_B^*$, $6a_B^*$, and $7a_B^*$ (thick lines, top to bottom, respectively). We notice that the inclusion of dynamical screening effects yields qualitatively and quantitatively different results for the energy transfer rate. A peak at low temperatures ($T_1\sim0.3E_E$) in P_{12} appears which is roughly independent of the wire separation distance. Similar results were found for the drag rate in the double-quantum-well systems, and the high-temperature enhancement was attributed to the contribution of plasmons.[6] In double-quantum-wire systems plasmons also contribute efficiently to the drag rate.[10] The static screening approximation, on the other hand, misses this contribution completely.

It is believed that the RPA becomes less reliable for electron densities such that $r_s>1$ (low density) and even so for low-dimensional systems. For instance, for double-layer electron-hole systems it was found necessary to go beyond the RPA to obtain reasonable agreement with the observed momentum transfer rates.[7] We incorporate the correlation effects in an approximate way using the static local-field corrections $G_{ij}(q)$. They modify the bare Coulomb interaction with the replacement[14] $V_{ij}(q)\to V_{ij}(q)[1-G_{ij}(q)]$. As a result the low temperature peak due to plasmons in the energy transfer rate is enhanced and moves to higher temperatures, as may be seen in Fig. 1(b) (thin lines).

The collective excitation modes of the coupled quantum-wire system is obtained from the solution of $\varepsilon[q,\omega_{\rm pl}(q)]=0$. The fluctuations in the charge density lead to in- and out-of-phase oscillations of the charges and are also known as the optical and acoustic plasma modes, respectively. The long-wavelength limit of the plasmon dispersions (in the RPA) in units of E_F are given by[11,15]

$$\omega_{\rm pl}^{\rm op,ac}=\frac{16}{\pi}r_s^{1/2}\frac{q}{k_F}\begin{cases}\ln(4/q^2Rd)-2\gamma+73/120\\ \ln(d/R)+73/120\end{cases}, \tag{3}$$

where $\gamma=0.577\ldots$ is the Euler constant. At finite temperatures $(T\neq0)$ we find the plasmon modes by solving $\mathrm{Re}[\varepsilon(q,\omega_{\rm pl}(q))]=0$, when the damping is small. There are mainly two effects of the local-field corrections on the plasmon dispersion curves. First the plasmon modes are softened and second the two modes merge together at a lower wave vector in the presence of $G_{ij}(q)$. Temperature effects on the other hand increase the plasmon dispersion. Both these effects yield the calculated P_{12} as shown in Fig. 1(b).

Having shown the effects of plasmons on the energy transfer rate for a coupled quantum wire system, we now turn our attention to the nonlinear regime. We use Eq. (1) with drift velocity v_1 to simulate the effect of applied electric field in the first wire, and set $v_2=0$ in the second wire as in the drag effect measurements. The density response function for the drive wire is now calculated at shifted frequencies, i.e., $\chi(q,\omega-qv_1)$. The energy transfer rate P_{12} in this nonlinear situation is displayed in Fig. 2 for $R=2a_B^*$ wires at $d=5a_B^*$. We observe that as v_1 increases (larger electric fields) P_{12} increases in magnitude. In the nonlinear regime, energy transfer is possible even when the temperatures of quantum wires are the same. Nonlinear effects on the momentum transfer rate in quantum wires were studied by Hu and Flensberg.[16] Our results indicating the importance of plasmon mediated drag and energy transfer rate are in agreement.

Experiments[2] measuring the Coulomb drag rate on two-dimensional (2D) systems so far were carried out at low temperatures $(T\ll E_F)$. Flensberg and Hu[6] suggested pos-

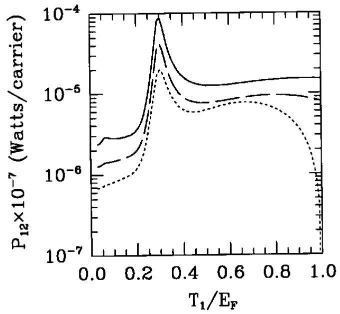

FIG. 2. The energy transfer rate in the dynamically screened RPA as a a function of temperature in the nonlinear regime. Solid, dashed, and dotted lines are for $v_1 k_F/E_F = 2$, 1, and 0, respectively, in a $R = 2a_B^*$ and $d = 5a_B^*$ double-wire system.

sible plasmon enhancement in the temperature region $T \sim E_F$. Similar effects in double quantum-wire systems were also considered.[9] The present day technology of quantum-wire manufacturing is rapidly developing.[17] Experiments to test some of our predictions would be most interesting. Electron temperature transfer by Coulomb scattering has been observed in coupled heterostructures.[18] The energy transfer rate of electrons can also be measured by hot-electron photoluminescence (HEPL) type of experiments.[19] In these measurements the effective electron temperature is determined by a line-shape analysis. In practice, a multiwire array would enhance the observed photoluminescence intensity. Effects discussed here should also occur in electron-hole double quantum wire systems. The role of intrawire interactions on the energy transfer rate is also included in our work, since the full wave vector and frequency dependence of the screening function $\varepsilon(q,\omega)$ is employed. More realistic calculations should take into account the temperature dependence of the intra- and interwire local-field corrections $G_{ij}(q)$. Our calculated P_{12} is of the same order of magnitude with the energy relaxation rates via LO-phonons in quantum wires.[20] We have not included the energy-transfer rate due to LO-phonons in our calculations to identify the interwire Coulomb coupling mechanism. Treating the two effects on an equal footing would be more relevant for comparison with future experiments.

In summary, we have considered the Coulomb drag effect between two parallel cylindrical quantum wires. The temperature dependence of the energy transfer rate from one wire to another is significantly enhanced when a dynamically screened effective interwire interaction is used. This enhancement is due to the optical and acoustic plasmons in the double-quantum-wire system. The local-field effects describing correlations beyond the simple RPA seem also to be very important for low densities altering the energy transfer rate considerably.

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