Pergamon

Solid State Communications, Vol. 99, No. 1, pp. 1–5, 1996

0038-1098/96 $12.00 + .00

PII S0038-1098(96)00268-2

COULOMB DRAG EFFECT IN PARALLEL CYLINDRICAL QUANTUM WIRES

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(*Received* 16 *February* 1996; *accepted* 25 *April* 1996 *by R.T. Phillips*)

We study the Coulomb drag rate for electrons in two parallel quantum wires. The double-quantum wire structure is modeled for a GaAs material with cylindrical wires having infinite potential barriers. The momentum transfer rate between the wires (Coulomb drag effect) is calculated as a function of temperature for several wire separation distances. We employ the full wave vector and frequency dependent random-phase approximation (RPA) at finite temperature to describe the effective interwire Coulomb interaction. We find that the drag rate at high temperatures (i.e., $T \geq E_F/2$) is dominated by the collective modes (plasmons) of the system similar to the case in double-well structures. Including the local-field effects in an approximate way we estimate the importance of intrawire correlations to be significant. Copyright ©1996 Published by Elsevier Science Ltd

1. 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 wealth of theoretical activity in the past few years touching upon various aspects of the drag phenomenon [3–7]. More theoretical approaches based on the Boltzmann transport equation and diagrammatic linear response formalism started to appear recently [8]. The Coulomb drag effect for cylindrical quantum wire structures are recently considered by Qin [9] where two concentric cylindrical wires with variable radii provided 2D-2D and 2D-1D nature of the momentum transfer mechanism.

In this paper we study the Coulomb drag effect between two parallel cylindrical wires. Such a double-quantum-wire structure was envisaged by Gold [10] in the context of charge-density-wave instability. Quasi-one-dimensional (Q1D) electron systems as they occur in semiconducting structures, based on carrier confinement in transverse directions, is a subject of continuing interest. The chief 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. The Q1D electrons are embedded in a uniform positive background to maintain charge neutrality. We treat the electron system as a Fermi liquid, i.e., with a well defined Fermi surface at zero temperature and interaction via Coulomb potential, which seems to be supported by the experimental observations [11, 12] of collective excitations in GaAs quantum wires. It is believed that even though the Q1D electrons are not strictly Fermi liquids, the finite temperature and disorder effects restore such a picture [13].

In this work, we calculate the temperature dependence of the drag rate between two parallel quantum wires. 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 drag rate for $T \geq 0.5\,E_F$. 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 very important.

The rest of this paper is organized as follows. In Sec. II we outline the model of a double-quantum-wire structure and the Coulomb drag effect. Our results for the drag rate as a function of temperature are provided in Sec. III. We conclude with a brief summary.

2. MODEL AND THEORY

We consider two identical cylindrical wires with radius R and infinite potential barriers [14]. The double-quantum wire structure is characterized by the distance d between the axes of the cylindrical wires [10]. 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 $r_s = \pi/(4k_F a_B^*)$, in which $a_B^* = \epsilon_0/(e^2 m^*)$ is the effective Bohr radius in the semiconducting wire with background dielectric constant ϵ_0 and electron effective mass m^*. The intra and interwire Coulomb interactions in the double-wire system are given by [10, 14]

$$V_{11}(q) = \frac{e^2}{2\epsilon_0}\frac{144}{(qR)^2} \times \left[\frac{1}{10} - \frac{2}{3(qR)^2} + \frac{32}{3(qR)^4} - 64\frac{I_3(qR)K_3(qR)}{(qR)^4}\right] \quad (1)$$

$$V_{12}(q) = \frac{e^2}{2\epsilon_0}(96)^2\left[\frac{I_3(qR)}{(qR)^3}\right]^2 K_0(qd), \quad (2)$$

respectively, where $I_n(x)$ and $K_n(x)$ are the modified Bessel functions.

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 Boltzmann constant $k_B = 1$). A simple calculation shows that $\Delta_{21} \approx 10\,(4/\pi)^2 r_s^2/(R/a_B^*)^2 E_F$, which means that the one-subband approximation will be valid for $R \simeq 2a_B^*$ and $r_s \geq 1$. In a GaAs quantum wire, for which $\epsilon_0 = 13$ and $m^* = 0.067\,m_e$, the effective Bohr radius $a_B^* \approx 100\,\text{Å}$.

The Coulomb drag rate τ_D^{-1} between the electrons in two identical parallel quantum wires (to lowest order in the interwire interaction) is given by [2, 4, 6, 7]

$$\tau_D^{-1} = \frac{1}{4\pi m^* N T}\int_{-\infty}^{\infty} dq\, q^2 \times \int_0^{\infty} d\omega \left|\frac{W_{12}(q,\omega)\,\mathrm{Im}\chi(q,\omega)}{\sinh(\omega/2T)}\right|^2, \quad (3)$$

(we take $\hbar$ and k_B equal to unity). It measures the rate of momentum transferred from one wire to the other. In the above expression, $W_{12}(q,\omega) = V_{12}(q)/\varepsilon(q,\omega)$ is the dynamically screened intrawire potential, and $\mathrm{Im}\chi(q,\omega)$ is the imaginary part of the temperature dependent 1D susceptibility [15]. The screening function $\varepsilon(q,\omega)$ for two identical wires is expressed as

$$\varepsilon(q,\omega) = [1 - V_{11}(q)\chi(q,\omega)]^2 - [V_{12}(q)\chi(q,\omega)]^2. \quad (4)$$

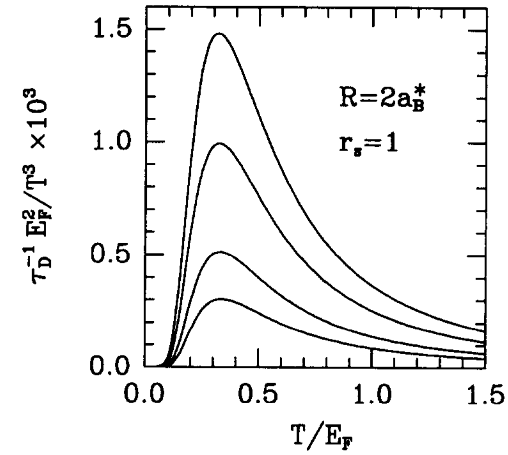

Fig. 1. The drag rate in the static screening approximation as a function of temperature for interwire separations $d = 4.5\,a_B^*$, $5\,a_B^*$, $6\,a_B^*$, and $7\,a_B^*$ (from top to bottom, respectively).

The above expression for the drag rate is derived either using the Boltzmann equation or the diagrammatic perturbation theory [4, 8] and is believed to describe the relevant experimental situation quite accurately. It was emphasized that the full temperature dependence of the dynamical susceptibility should be used to capture the plasmon contribution at high temperatures. Furthermore, the validity of the above drag rate expression is based [6] on the fact that the intrawire scattering time $\tau(k)$ due to impurities is more or less independent of k. Since the actual screened electron-impurity interaction in quantum wires is short-ranged due to screening by the conduction electrons, a self-consistent Born approximation calculation yields k-independent self-energies for finite temperature [16].

3. RESULTS AND DISCUSSION

We evaluate the drag rate τ_B^{-1} 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 shows the temperature dependence of the drag rate scaled by T^3 for parallel quantum-wires each with radius $R = 2\,a_B^*$ and $r_s = 1$. Curves from top to bottom are for center-to-center distances $d = 4.5\,a_B^*$, $5\,a_B^*$, $6\,a_B^*$, and $7\,a_B^*$, respectively. We observe that the scaled drag rate peaks around $T \sim 0.2 - 0.3\,E_F$ for all separations. Our statically screened results show qualitative similarity to the drag rates obtained by Qin [9] for two concentric cylindrical wires.

We next include the full frequency dependence of the effective potential $W_{12}(q,\omega)$ at finite temperature. In Fig. 2, we show the calculated drag rate as a function

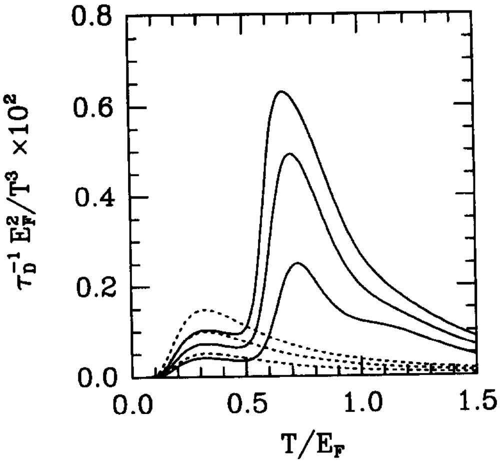

Fig. 2. The drag rate in the dynamically screened RPA as a a function of temperature. Solid lines from top to bottom indicate $d = 4.5a_B^*$, $5a_B^*$, and $6a_B^{last}$, respectively. Dotted lines show the corresponding static screening results.

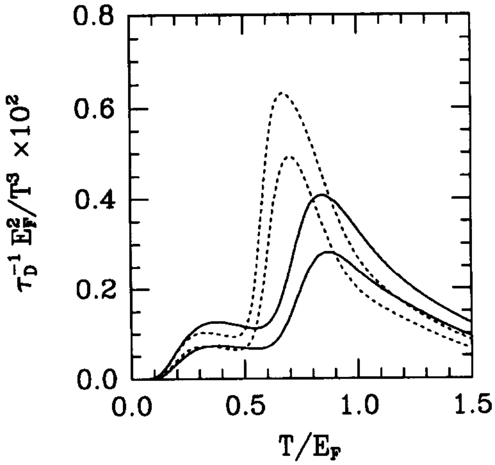

Fig. 3. The drag rate with (solid lines) and without (dotted lines) the local-field correction $G(q)$. The upper and lower curves are for $d = 5a_B^*$ and $6a_B^*$, respectively.

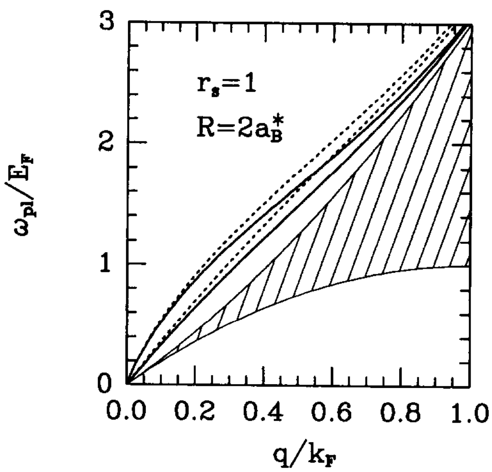

Fig. 4. The plasmon dispersion curves in a double-quantum-wire system. The dotted and solid lines indicate the RPA and Hubbard approximation, respectively. The hatched region is the particle-hole continuum.

of T for wire separations $d = 4.5a_B^*$, $5a_B^*$, and $6a_B^*$ (solid lines, top to bottom, respectively). We notice that the inclusion of dynamical screening effects yields qualitatively and quantitatively different results for the drag rate. Results for statically screened interactions are also depicted by dotted curves for comparison. The peak at low temperatures in the scaled drag rate are now suppressed whereas a second peak appears at high temperatures. 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 as observed in Fig. 2. 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. In fact, for double-layer electron-hole systems it was found necessary to go beyond the RPA to obtain reasonable agreement with the observed drag rates [7]. Here we incorporate the correlation effects in an approximate way using local-field corrections. A simplified attempt to go beyond the RPA is provided by the Hubbard approximation in which the Pauli hole around electrons is taken into account. Neglecting the interwire correlations but including the intrawire exchange effects (i.e., Hubbard approximation) we take [10, 14]

$$G_{ij}(q) = \frac{1}{2}\frac{V_{ij}(\sqrt{q^2 + k_F^2})}{V_{ij}(q)}\delta_{ij}, \qquad (5)$$

so that the bare Coulomb interactions are replaced by $V_{ij}(q) \rightarrow V_{ij}(q)[1 - G_{ij}(q)]$ in the screening function $\varepsilon(q, \omega)$. The interwire local-field correction should decrease with increasing separation d, thus our simple approximation is justified. Even the above approximate approach gives noticeably different results than the RPA. In Fig. 3, we show the drag rate with (solid lines) and without (dotted lines, RPA) the local-field corrections. The lower temperature peaks are enhanced to their value in the static screening approximation. The plasmon enhancement is still sizable but somewhat reduced. This follows from the fact that local-field effects in general lower the plasmon dispersions.

The collective excitation modes of the coupled quantum-wire system is obtained from the solution of $\varepsilon(q, \omega_{\rm pl}(q)) = 0$. At $T = 0$, one obtains [10, 17]

$$\omega_{\rm pl}^2(q) = \frac{\omega_+^2 e^{A_\pm(q)} - \omega_-^2}{e^{A_\pm(q)} - 1}, \tag{6}$$

where $\omega_\pm = |q^2/2m^* \pm qk_F/m^*|$, and $A_\pm(q) = (\pi q/m^*)/[V_{11} \pm V_{12}]$. The $\pm$ signs refer 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) are given by [10, 17]

$$\omega_{\rm pl}(q)/E_F = \frac{16}{\pi} r_s^{1/2} \frac{q}{k_F} \times \begin{cases} \ln(4/q^2Rd) - 2\gamma + 73/120 & \text{(optical)}, \\ \ln(d/R) + 73/120 & \text{(acoustic)}, \end{cases} \tag{7}$$

where $\gamma = 0.577\ldots$ is the Euler constant. At finite temperatures ($T \neq 0$) we find the plasmon modes by solving $\mathrm{Re}[\varepsilon(q, \omega_{\rm pl}(q))] = 0$, when the damping is small. We show in Fig. 4 the optical (upper curves) and acoustic (lower curves) plasmon dispersions in a double-wire system with (solid lines) and without (dotted lines) the local-field corrections at $T = 0$. Also shown by the shaded region is the particle-hole continuum for Q1D single-particle excitations. There are mainly two effects of the local-field corrections on the plasmon dispersion curves. Firstly the plasmon modes are softened and secondly the two modes merge together at a lower wave vector in the presence of $G(q)$. Both these effects suppress the plasmon contribution to the drag rate and we obtain in Fig. 3 the reduced magnitudes in the plasmon dominated region.

Experiments [2] to date on 2D systems were carried out at low temperatures ($T << E_F$). Flensberg and Hu [6] suggested possible plasmon enhancement in the temperature region $T \sim E_F$. We find that similar behavior should also be observed in double-quantum-wire structures. The present technology of quantum-wire manufacturing is rapidly developing. We note that a parallel double-wire structure is easier to build and work with than concentric wires. Experiments to test some of our predictions would be most interesting. The role of intrawire interactions on the drag rate is largely neglected in the previous work. Our calculations indicate that they may be important in changing the drag rate significantly in quantum-wire structures. More realistic calculations should take into account the improved local-field corrections [18] both for the intra and interwire interactions, perhaps also including the temperature dependence of $G_{ij}(q)$.

In an interesting paper, Gold [10] has shown that there exists a critical distance d_c (for a given wire radius R and electron density parameter r_s) below which a double-quantum wire structure would be unstable due to charge-density waves. Hence in a Coulomb drag experiment the separation distance between the wires should be such that one is away from this point of instability. For the parameters we use in this calculation the system remains in the stable Fermi liquid regime.

In summary, we have considered the Coulomb drag effect between two parallel cylindrical quantum-wires. The temperature dependence of the drag rate 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 to be very important for low densities altering the drag considerably.

Acknowledgements—This work is partially supported by the Scientific and Technical Research Council of Turkey (TUBITAK) under Grant No. TBAG-AY/77. We thank Dr. B. Y.-K. Hu for a very helpful communication and C. R. Bennett and Prof. C. M. Sotomayor-Torres for useful discussions.

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