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LETTER TO THE EDITOR

Dynamical screening effects in a coupled quasi-one-dimensional electron–phonon system

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Abstract. A fully dynamical and finite-temperature study of the electron momentum relaxation rate and mean free path in a coupled system of electrons and bulk LO phonons in a quantum wire structure is presented. Electron–electron and electron–phonon interactions are treated on an equal footing within the leading-order perturbation theory and random-phase approximation. It is demonstrated that coupled-mode effects drastically change the transport properties of the system at low temperatures. In particular, the 'plasmon-like' and 'LO-phonon-like' excitations yield comparable rates which, as a consequence of the singular nature of the 1D density of states, can be large at the threshold. This is in contrast to room temperature results where only the LO-phonon mode contributes significantly to the rate.

Recent technological advances have led to the realization of electron systems confined essentially in quasi-one-dimensional (Q1D) structures (quantum wires). These systems, by virtue of their reduced phase space may, in principle, exhibit high carrier mobility [1] which has important implications for high-speed devices. The momentum relaxation rate (MRR), Γ_k, for an electron with axial wave vector k, is an important quantity in transport calculations and determines the electron mean free path, l_k ($=v_k/\Gamma_k$, with v_k the electron velocity). In this letter, the consequences of dynamic screening for the electron–phonon interaction are considered and, in particular, the influence of coupled modes and finite temperature on the MRR are studied.

Several formulations [2] of the hot-electron scattering problem with differing predictions [3] exist in the literature. We assume a test electron to be injected into the conduction band without modifying the properties of the coupled electron–hole system. We take the viewpoint of Das Sarma and collaborators [2] in using the standard electron scattering theory [4] and treating the system as being not completely isolated (i.e., the system is in quasi-equilibrium and it is assumed to be coupled to an external heat bath allowing phonons to decay with some phenomenological parameter).

Screening effects on the electron–phonon interaction in doped bulk semiconductors were treated by several researchers both theoretically [5, 6, 7] and experimentally [8, 9]. In the analogous quasi-two-dimensional (Q2D) systems theoretical work [10] on doped quantum wells predicts the importance of coupled-mode effects as, of course, they are in the bulk. Experimental support for the importance of carrier–plasmon interactions for energy relaxation in Q2D systems is given by Straw *et al* [11] There is, however, an important difference between bulk and Q2D structures which was pointed out by Lei (see [10]). In doped bulk semiconductors it is often the case that the plasmon energy is greater than that of the optical phonons. In this regime, the dynamic dielectric function can be approximated by its static value [5]. In Q2D, the plasmon dispersion starts from zero; thus the plasmon energy is in general less than that of the optical phonon. The frequency dependence of the dielectric function cannot *a priori* be neglected. Similar arguments hold for Q1D semiconductor systems. Our aim is to assess the relative importance of electron–electron and electron–phonon interactions for different temperature regimes in Q1D systems. Comparison with previous significant theoretical work will also be made.

The system considered here is a circular GaAs quantum wire of radius R and of effectively infinite length L. The carriers are assumed to occupy only the lowest subband (extreme quantum limit) and hence the wire radius is set at 50 Å, and the linear carrier concentration at $n = 10^6\ \mathrm{cm}^{-1}$ in the numerical calculations. The choice of circular cross-section is one of mathematical convenience since it yields analytical results for the relevant matrix elements [12]. The effect of different wire cross-sections on the intrasubband plasmon energy is only marginal [13]. The material parameters for GaAs are tabulated [14] and are not quoted here for brevity. We assume that the Q1D electrons interact with bulk LO-phonon modes, not taking the confinement effects on phonons into account. This is justified by the recent thorough work of Rucker *et al* [15] where a comparison is made between an *ab initio* microscopic calculation and the bulk phonon approximation.

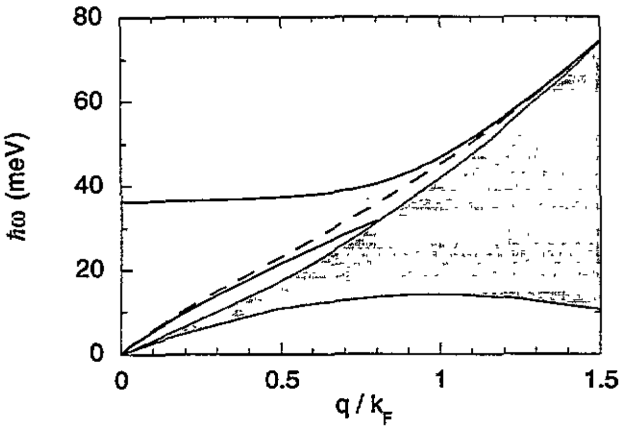

Figure 1. The undamped coupled intrasubband collective excitations of the quantum wire (solid curves) as a function of axial wave vector q in units of the Fermi wave vector k_F. The dashed curve corresponds to the uncoupled intrasubband plasmon and the shaded region corresponds to the single-particle continuum.

The total dielectric function for the coupled electron–phonon systems at temperature T, within the random-phase approximation, is given by [4]

$$\varepsilon(q,\omega;T) = 1 + \frac{\omega_{\mathrm{LO}}^2 - \omega_{\mathrm{TO}}^2}{\omega_{\mathrm{TO}}^2 - \omega^2} - V_q^{\infty}\chi_0(q,\omega;T) \tag{1}$$

where $V_q^{\infty} = V_q/\varepsilon_{\infty}$ is the bare Coulomb interaction scaled by the high-frequency dielectric constant, and $\chi_0(q,\omega;T)$ is the temperature-dependent Lindhard function for a Q1D system [16] in the extreme quantum limit. The Coulomb interaction has a simple analytical form given by Gold and Ghazali [12], $V_q = (e^2/2\pi\varepsilon_0 L)F(q)$, where

$$F(q) = \frac{36}{(qR)^2}\left[\frac{1}{10} - \frac{2}{3(qR)^2} + \frac{32}{3(qR)^4} - \frac{64}{(qR)^4} I_3(qR)K_3(qR)\right] \tag{2}$$

and $I_3(x)$ and $K_3(x)$ are modified Bessel functions. The undamped coupled modes of the system at $T = 0$ are obtained from $\mathrm{Re}[\varepsilon(q,\omega;T)] = 0$, and these are illustrated in figure 1 together with the uncoupled intrasubband plasmon for comparison. We note that the uncoupled plasmon is free of Landau damping at zero temperature. The dispersion of coupled modes with several subbands for quantum wire systems at $T = 0$ was studied by Wendler and co-workers [17].

We calculate the MRR within the Born approximation using [16]

$$\Gamma_k(T) = \frac{L}{\pi}\int_{-\infty}^{\infty}(q/k)V_q^{\infty}\,\mathrm{Im}\left[\varepsilon^{-1}(q,\omega_{kq};T)\right]N_B(\omega_{kq})\left[1 - f_0(E_{k+q})\right]\mathrm{d}q \tag{3}$$

where $E_k = k^2/2m^*$, $\omega_{kq} = E_{k+q} - E_k$, and N_B and f_0 are Bose and Fermi distribution functions, respectively. The above expression may be derived rigorously from a many-body formalism which assumes that the Coulomb and LO-phonon interaction lines are screened by the electron gas [16, 4]. We note that it differs from the Fermi Golden Rule expression.

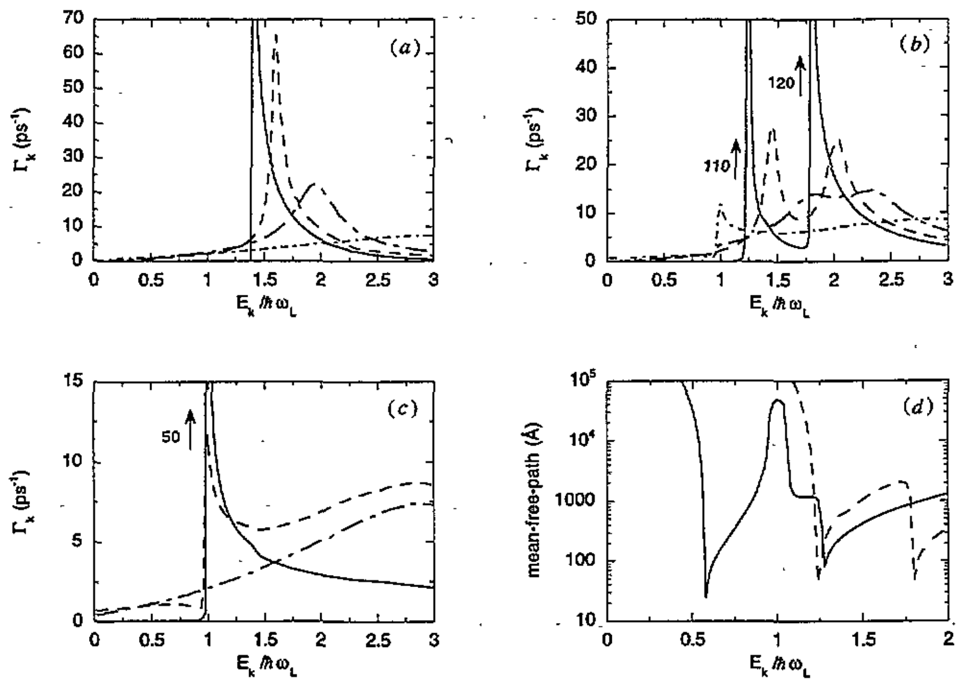

Figure 2. (a) The MRR via the uncoupled intrasubband plasmon as a function of E_k for $T = 0$ (solid), $T = 50$ K (dashed), $T = 100$ K (long-dashed chain) and $T = 300$ K (short-dashed chain). (b) The MRR via the coupled modes as a function of E_k for the same values of T as in (a). (c) The MRR at $T = 300$ K calculated via the many-body formulation for coupled modes (dashed), for the uncoupled plasmon (chain) and via Fermi's Golden Rule for uncoupled bare LO phonons (solid). In (b) and (c) the arrows indicate the maximum value of the MRR where it is off the scale. (d) The mean free path, l_k, as a function of E_k for $n = 5 \times 10^5$ cm^{-1} (solid) and $n = 10^6$ cm^{-1} (dashed).

Figure 2(a) illustrates Γ_k for the case of uncoupled plasmons, and it is seen that the numerical results and temperature dependence are close to those reported by Hu and Das Sarma [16]. At threshold the $T = 0$ MRR is infinite since there is no damping. The value at which this threshold occurs is determined from the kinematics of the problem and evidently depends on the linear carrier concentration n. Spurious finite-temperature single-particle interactions which yield infinite contributions to the scattering rate (equation (3)) without the factor q/k are suppressed when the MRR is calculated since the q/k-term in the integrand gives these a small weight. This fact is intimately related to a well-known property of a Q1D electron gas in the extreme quantum limit; namely, that two-body interactions can only lead to an exchange of particles which for electrons is physically irrelevant, and the many-body state is not therefore changed. This is not built into the Born approximation which treats the injected electron as distinguishable. A more detailed discussion of this aspect of the problem is given by Hu and Das Sarma [16], although these authors ignore coupled-mode effects and assume only plasmon excitations. This, as will shortly be demonstrated, is an oversimplification in 1D.

Figure 2(b) shows the behaviour of the MRR in the coupled-mode system. At $T = 0$, there are two well defined thresholds both yielding a large MRR. The lower-energy threshold is due to the 'plasmon-like' excitation, whereas the other is due to the 'LO-phonon-like' mode, which does not occur at $E_k = \omega_{\mathrm{LO}}$ but at a slightly higher energy due to the coupling. Figure 2(b) emphasizes again the conclusions first presented by Hu and Das Sarma [16] that the carrier–'plasmon' interaction is important in determining the mean free path of injected carriers at low temperatures. Further, these results demonstrate for the first time that in Q1D systems in the extreme quantum limit and at low temperatures plasmons and LO-phonon modes yield a comparable MRR. For the carrier concentration and wire radius chosen here, the MRR is very small at $E_k = \omega_{\mathrm{LO}}$, but large either side of this value. The conclusion is, therefore, that an electron injected at the bare LO-phonon energy will have a large mean free path, whilst one injected with energies either side of his value will be much smaller.

In figure 2(c), the room temperature ($T = 300$ K) calculations are presented, and in this case the results are similar to those obtained by assuming bare LO phonons, although the details are different, especially for $E_k \leqslant \omega_{\mathrm{LO}}$. In particular, the many-body calculation of the MRR always yields positive values for $E_k \leqslant \omega_{\mathrm{LO}}$, in contrast to that obtained via bare LO phonons which is negative as predicted by Riddoch and Ridley [18]. This is due, in the many-body case, to the contribution of the plasmon-like mode which is now highly damped. What our calculations demonstrate further is the difference between the low-temperature and the room temperature MRR. In the latter, the bare LO phonons provide a reasonable approximation, whilst in the former the inclusion of the plasmon interaction is crucial for an adequate description of the many-body transport properties.

The last numerical results which are illustrated in figure 2(d) are those for the electron mean free path, l_k, at $T = 0$ for two different carrier densities. The results obtained for $n = 5 \times 10^5$ cm^{-1} correspond to figure 2(b) and confirm the conclusion that at $E_k = \omega_{\mathrm{LO}}$ the mean free path is very large, whereas either side of this value it is at least two orders of magnitude smaller. For the higher density, the minima in l_k (corresponding to the thresholds in the MRR) are at higher values of E_k as expected. We have included in the above calculations an LO-phonon lifetime of 7 ps, phenomenologically.

We finally remark on the current experimental feasibility of hot-electron transport in Q1D systems. The growth technology for Q1D systems is still in its infancy in terms of producing long wires of small cross-sectional area and uniform thickness, and lags behind that of Q2D structures. Nevertheless, the importance of this area of semiconductor research is such that it is anticipated that in the not too distant future such wires will be produced, and will be suitable for the experimental determination of predictions presented here. The recent experimental work by Maciel *et al* [19] on hot-electron relaxation in 'V-groove' quantum wires suggests that movement in this direction is indeed taking place.

In conclusion, the momentum relaxation rate has been calculated within the Born approximation and RPA with both electron–electron and electron–phonon interactions included on an equal footing. At low temperatures and for typical doping, peaks in the MRR due to the 'plasmon-like' mode and the 'phonon-like' mode are predicted. The peaks are very pronounced at the threshold due to the singular nature of the 1D density of states. As the temperature increases, the two peaks are reduced, broaden, and come closer together. For the carrier concentrations considered here, the room temperature results of the many-body approach are close to those calculated via Fermi's Golden Rule assuming only uncoupled LO phonons, although the MRR is never negative in the many-body case.

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