Many-Body Effects in a Nonequilibrium Electron-Lattice System: Coupling of Quasiparticle Excitations and LO Phonons

J. K. Jain, R. Jalabert, and S. Das Sarma
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742
(Received 20 November 1987)

The coupling of quasiparticle excitations in an electron gas to the LO phonons gives rise to novel phonon modes with energies below $\lesssim qv_F$. We propose that these low-energy "phonon" modes, in addition to the usual plasmon-phonon coupled modes, are responsible for a large *(by orders of magnitude)* enhancement of the hot-electron energy-loss rate to the lattice at low electron temperatures, as observed in several recent experiments. Experimental conditions are outlined for an unambiguous observation of this predicted many-body effect.

PACS numbers: 72.10.Di, 63.20.Ls, 71.38.+i, 72.20.Dp

Interaction of an electron with longitudinal optical (LO) modes of solids is an old[1] and very well-studied[2] subject. In polar materials this interaction results in a carrier mass renormalization,[3] leading to the concept of a Fröhlich "polaron" which is an electron dressed with virtual LO phonons. The LO phonons also couple to the collective modes (plasmons) of the electron gas (EG), and these plasmon-phonon coupled modes[4] have been studied extensively.

In this Letter we present yet another manifestation of this interaction, namely, the coupling of LO phonons to quasiparticle excitations (QPE) of the EG, and indicate experiments where the influence of these modes can be observed. The QPE–LO-phonon coupling has so far been neglected in the literature (in contrast to the well-studied plasmon-phonon coupling) on the basis of the belief that the macroscopic electric-field–carrying LO-phonon field couples only weakly to microscopic quasiparticle excitations. We show in the Letter that there are experimental situations where the many-body renormalization induced by QPE–LO-phonon coupling gives rise to very large quantitative and novel qualitative effects. The QPE–LO-phonon coupling shows up clearly in Fig. 1 where we plot the spectral function of the dressed phonon, whose propagator is given by ($\hbar=1$)

$$D(q,\omega)=\frac{2\omega_{\mathrm{LO}}}{\omega^2-\omega_{\mathrm{LO}}^2-2\omega_{\mathrm{LO}}M_q^2\chi(q,\omega)} . \tag{1}$$

Here ω_{LO} is the LO-phonon frequency, M_q is the Fröhlich coupling constant, and $\chi(q,\omega)$ is the reducible polarizability which we calculate in the random-phase approximation (RPA). RPA is expected to be well valid because of the low r_s values and the fact that for QPE–LO-phonon coupled modes the relevant wave vectors are small compared to the Fermi wave vector. In this work we will always choose parameters appropriate for GaAs: $\omega_{\mathrm{LO}}=36.8$ meV, high-frequency dielectric constant $\epsilon_\infty=10.9$, low-frequency dielectric constant $\epsilon_0=12.9$, and effective mass $m=0.07m_e$. Equation (1) includes phonon self-energy corrections due to its interaction with the EG in the RPA approximation of summing the "bubble" diagrams due to electron-hole pair excitations. We mention that the phonon spectral weight can be directly probed in a Raman-scattering experiment.[4] Besides a peak near the bare phonon energy, ω_{LO}, the LO phonon also acquires weight at the plasmon energy ($\omega_p\simeq 14$ meV) due to plasmon-phonon coupling and in the QPE region ($\lesssim qv_F$) due to QPE-phonon cou-

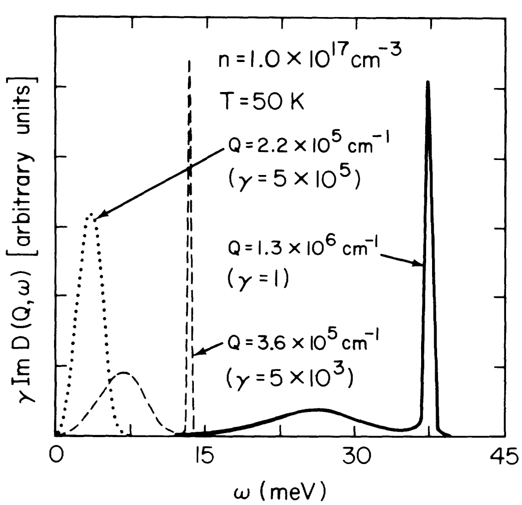

FIG. 1. Phonon spectral function for three wave vectors in a 3D EG at an electron temperature of $T=50$ K ($T_L=0$). For $Q=2.2\times10^5$ cm^{-1}, the QPE branch extends from 0 to 7 meV, and there are δ-function peaks near the plasmon energy ($\omega_p\simeq14$ meV) and the phonon energy (36.8 meV) which are *not* shown explicitly in order to avoid too much detail. For $Q=3.6\times10^5$ cm^{-1} the QPE branch extends up to $\simeq13$ meV, the plasmonlike phonon is visible at $\simeq14$ meV, and there is again a δ-function peak (not shown) at ω_{LO}. For $Q=1.3\times10^6$ cm^{-1} the plasmonlike phonon is Landau damped and the QPE-like phonons extend all the way up to ω_{LO}. The electron density is 10^{17} cm^{-3} giving a Fermi wave vector of 1.4×10^6 cm^{-1}.

pling. We shall refer to these three branches of the dressed LO-phonon spectrum as the bare phonon, the plasmonlike phonon, and the QPE-like phonon, respectively.

One might intuitively feel that the broadness of the QPE-like phonon spectrum and their small spectral weight make then unimportant in any physical phenomenon. We find, however, that these modes play a very significant quantitative role under certain conditions in the physics[5] of hot-electron relaxation in polar semiconductors. A thorough understanding of hot-electron relaxation in polar semiconductors is important in its own right since most transistors and optoelectronic devices work under highly excited (or hot) conditions. Recently, sophisticated experimental techniques have been developed,[5] based on time-resolved optical excitation or steady-state electric-field heating, to probe the cooling of the hot electrons via the phonon emission process.

We work with a model (the so-called "electron temperature" model) in which the EG and the lattice are separately in equilibria at different temperatures T and T_L $(T > T_L)$, respectively. This model is well valid[5] in the steady-state experiments, as well as in time-resolved experiments after the first few hundred femtoseconds following the excitation. The power loss per carrier (P) of the hot electrons via phonon emission is then given by

$$P = \frac{1}{N}\sum_q \int \frac{d\omega}{\pi}\, \omega\, |M(q)|^2 [n_{T_L}(\omega) - n_T(\omega)]\, \mathrm{Im}\chi(q,\omega)\, \mathrm{Im}D(q,\omega), \tag{2}$$

where $n_T(\omega)$ is the Bose occupation factor at temperature T, and N is the total number of electrons. Equation (2) follows directly from the Fermi "golden rule" with the help of the fluctuation-dissipation theorem, and we refer the reader to Kogan[6] and Senna and Das Sarma[6] for a complete derivation. If one ignores the phonon self-energy correction and takes D to be the bare phonon propagator, then Eq. (2) reduces in a straightforward manner to the well-known formula[7]

$$P = (\omega_{\mathrm{LO}}/\tau)\exp[-\omega_{\mathrm{LO}}/k_B T], \tag{3}$$

for $T \gg T_L$ (we will take $T_L = 0$ from now on) and $\omega_{\mathrm{LO}} \gg k_B T$. This follows because as a result of energy conservation the lower limit of the ω integral is ω_{LO} which immediately yields the important temperature dependence to be $n_T(\omega_{\mathrm{LO}}) \simeq \exp[-\omega_{\mathrm{LO}}/k_B T]$. A full calculation must be performed to obtain the prefactor, or the electronic relaxation time τ, but it is expected to be only weakly temperature dependent, which is also corroborated by numerical calculations.[8,9]

The presence of the Bose factor $n_T(\omega)$ in Eq. (2) means that the power loss into high-energy phonon modes is suppressed exponentially. This merely represents the fact that the number of electrons energetically capable of emitting a mode of energy ω goes down exponentially as ω is increased at a given temperature. On the other hand, the oscillator strength, $\mathrm{Im}D(q,\omega)$, favors power loss to the bare phonon mode as the oscillator strength in the QPE-like or plasmonlike modes is smaller by many orders of magnitude. Interesting physics arises from the competition between these two opposing effects. At high temperatures the oscillator strength dictates the power loss, whereas at low enough temperatures the Bose factor takes over, so that the plasmonlike and/or the QPE-like branches become dominant. We now show the results of our numerical calculations to determine exactly at what temperature this crossover from the bare phononlike behavior occurs.

In Fig. 2 we plot the logarithm of power loss per carrier as a function of inverse temperature for both three-

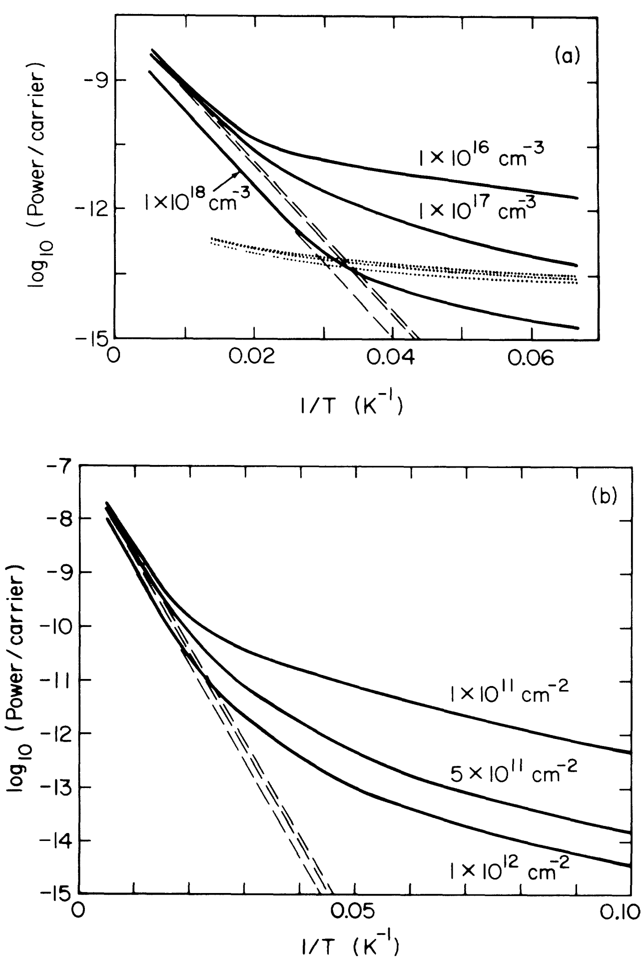

FIG. 2. $\log_{10}(P)$ as a function of the inverse electron temperature for both (a) 3D and (b) 2D for several electron densities (solid lines). The dashed lines correspond to power loss to the bare LO phonons only. In (a) we also show the power loss to acoustic-phonon modes by dotted curves; the uppermost curve is for 10^{18} cm^{-3}, the middle one for 10^{16} cm^{-3}, and the lowest one for 10^{17} cm^{-3}. $T_L = 0$ and P is expressed in watts/carrier.

dimensional (3D) and two-dimensional (2D) EG systems for various electron densities. The dashed lines represent the power loss into the bare phonon mode and are straight according to Eq. (3). The QPE-like and the plasmonlike branches become important when the total power loss deviates from the dashed lines—which happens at 30–80 K depending on the density. The large deviation of the total power loss from these straight lines at low T shows the quantitative importance of the inclusion of the other phonon branches. The effect is most spectacular at lower electron densities where the total power loss differs from the power loss into the bare LO phonon by *several orders of magnitude.*

The relative importance of the three phonon branches is shown in Fig. 3 where we plot power-loss spectra $I(\omega)$, defined by $P=\int d\omega I(\omega)$, at various temperatures. At high temperatures most of the power is lost into the bare phonon mode. As the temperature decreases the exponential (Bose) factor becomes more and more effective in the elimination of the higher-energy modes: First the plasmonlike phonon mode shows up, and at still lower temperatures almost all the power loss occurs into

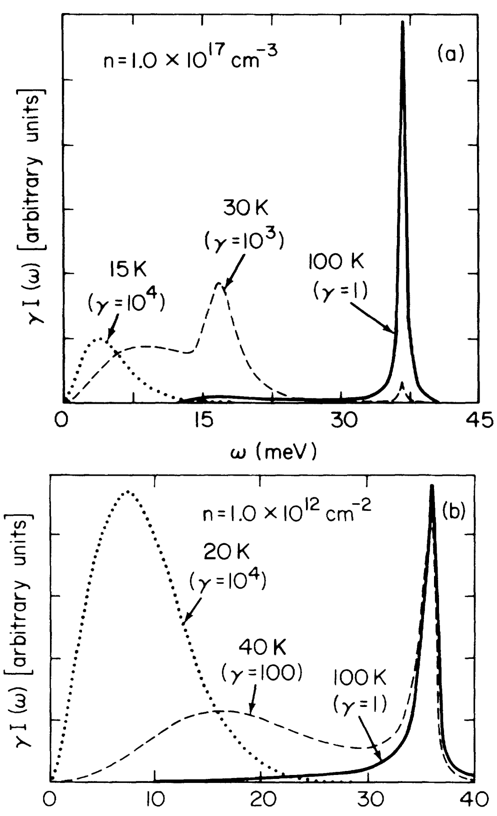

FIG. 3. Power-loss spectrum for (a) a 3D density and (b) a 2D density. At the electron temperature 100 K the bare phonon dominates the power loss, while the QPE-like modes dominate at the lowest temperature shown [15 K in (a) and 20 K in (b)]. The lattice temperature $T_L=0$.

the QPE-like phonon modes. This shows up clearly in 3D where the plasmon energy is essentially independent of the wave vector. In 2D, on the other hand, the plasmon energy is a rapidly varying function of q ($\omega_p \sim q^{1/2}$ for small q), and therefore the power losses into the plasmonlike mode and into the QPE-like modes do not show up distinctly in the plot of $I(\omega)$. We have, however, looked carefully at $I(q,\omega)$, defined by $P=\sum_q \int d\omega I(q,\omega)$, and found that at low temperatures the important loss modes are indeed the QPE-like phonon modes.

Now we come to the experimental status. A bending (i.e., deviation from a straight line) of $\log_{10}(P)$ against $1/T$ at low temperatures is a ubiquitous phenomenon in hot-electron energy-loss experiments,[5,10,11] and is usually ascribed uncritically to the acoustic-phonon modes. There have, however, also been suggestions[12] of the existence of some "missing" energy relaxation mechanism at low temperatures, since the calculations including only the acoustic and *bare* LO phonons could not account for the total observed power loss. We have shown here that the many-body renormalization of the LO phonons also results in a substantial enhancement of the low-temperature power loss, which shows up as a bending in Fig. 2. We also show our calculated power loss to acoustic phonons by dotted curves in Fig. 2(a), and it is obvious that the dressed LO phonons remain the dominant energy-loss mechanism for arbitrarily low T for low electron density. For example, for $n=10^{16}$ cm^{-3} an extrapolation of the curves shows that the dressed LO phonons dominate down to 2K. (Remember that $T_L=0$.) This is in sharp contrast to the popular wisdom which took LO phonons to be unimportant below $\simeq 50$ K. Thus the message is that the acoustic phonons become important not when the data deviate from a straight line (as is widely believed) but when the data deviate from the solid curves in Fig. 2. The experiments which can test these predictions are *steady-state photoexcitation or electric-field heating experiments on low-density n-doped semiconductors at low electron temperatures.* To the best of our knowledge such experiments have not been done in 3D. In 2D, a preliminary comparison[9] with some of the data[10] shows excellent qualitative and reasonable quantitative agreement down to 30 K without recourse to acoustic phonons. At this time a detailed and direct quantitative comparison between our calculations and most of the existing time-resolved photoexcited measurements[11,12] is difficult because the experimental parameters (e.g., carrier density, the fraction of energy contained in the excited carriers, etc.) are often not well known. Also the presence of real holes (in the valence band) in many experiments complicates the situation substantially because the hole band structure is complex and hole-phonon couplings are, in general, not known. We hope that this work will further stimulate systematic experimentation both in 3D and 2D.

We must point out here that we have thus far ignored the possibility of phonon reabsorption (or the "hot-phonon effect"[13]) for simplicity. This effect arises as a result of the finite LO-phonon lifetime and makes important quantitative changes for power loss to bare LO phonons,[8-10,13] but is much less important for power loss to the QPE-like phonons because of their expected short lifetime (from analogy with acoustic phonons). Thus we expect the hot phonons to make a quantitative change only in the bare-phonon–dominated high-temperature region, but not in the QPE-like-phonon–dominated low-temperature region, which is our main interest here. The hot-phonon effect for bare LO phonons has been extensively studied in the recent literature.[5,8,9,13]

In conclusion, we find that many-body phonon renormalization has a drastic effect on the relaxation of hot electrons in polar semiconductors at low electron temperatures and densities leading to an enhancement of the power loss by many orders of magnitude. In particular, we find that for low enough temperatures, the hitherto ignored branch of the phonon spectral function, namely the QPE-like branch, dominates the energy-loss process, and makes important quantitative changes.

The work is supported by the U.S. Army Research Office (US-ARO), the Department of Defense (DOD), and the University of Maryland Computing Center.

[1]H. Fröhlich, Adv. Phys. **3**, 325 (1954).

[2]See, for example, G. Mahan, *Many Particle Physics* (Plenum, New York, 1981), and references therein.

[3]R. P. Feynman, Phys. Rev. **97**, 660 (1955); S. Engelsberg and J. R. Schrieffer, Phys. Rev. **131**, 993 (1963); D. C. Tsui, Phys. Rev. B **10**, 5088 (1974); B. A. Mason and S. Das Sarma, Phys. Rev. B **31**, 5223 (1985).

[4]A. Mooradian and G. B. Wright, Phys. Rev. Lett. **16**, 999 (1966); G. Abstreiter, M. Cardona, and A. Pinczuk, in *Light Scattering in Solids IV*, edited by M. Cardona and G. Güntherodt (Springer-Verlag, New York, 1986), p. 5, and references therein.

[5]J. Shah, IEEE J. Quantum Electro. **22**, 1728 (1986); S. A. Lyon, J. Lumin. **35**, 121 (1986): J. Shah, Solid State Electron. **21**, 43 (1978), and J. Phys. (Paris), Colloq. **42**, C7-445 (1981); P. Leheny *et al.*, Solid State Commun. **31**, 809 (1979).

[6]Sh. M. Kogan, Fiz. Tverd. Tela (Leningrad) **4**, 2474 (1962) [Sov. Phys. Solid State **4**, 1813 (1963)]; J. R. Senna and S. Das Sarma, Solid State Commun. (to be published).

[7]E. Conwell, *High Field Transport in Solids* (Academic, New York, 1963).

[8]W. Cai, M. C. Marchetti, and M. Lax, Phys. Rev. B **12**, 8573 (1986).

[9]S. Das Sarma, J. K. Jain, and R. Jalabert, Phys. Rev. B (to be published).

[10]J. Shah, A. Pinczuk, A. C. Gossard, and W. Weigmann, Phys. Rev. Lett. **54**, 2045 (1985): C. H. Yang, J. M. Carlson-Swindle, S. A. Lyon, and J. M. Worlock, Phys. Rev. Lett. **55**, 2359 (1985).

[11]H. Lobentanzer *et al.*, Solid State Commun. **62**, 53 (1987); M. J. Polland *et al.*, Phys. Rev. B **35**, 8273 (1987): D. J. Westland *et al.*, in Proceedings of the Fifth International Conference on Hot Carriers in Semiconductors, Boston, Massachusetts, 1987, Solid State Electron. (to be published); Kai Shum *et al.*, *ibid.*; M. Tatham *et al.*, *ibid.*

[12]R. Ulbrich, Phys. Rev. B **8**, 5719 (1973); M. J. Barlow, B. K. Ridley, M. J. Kane, and S. J. Bass, to be published.

[13]P. Kocevar, Physica (Amsterdam) **134B**, 164 (1985); P. J. Price, Physica (Amsterdam) **134B**, 155 (1985); S. M. Goodnick and P. Lugli, Phys. Rev. Lett. **59**, 716 (1987).