Hot-electron relaxation in GaAs quantum wells

S. Das Sarma, J. K. Jain, and R. Jalabert
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742
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Theoretical results are obtained for the energy loss of hot electrons to longitudinal optical phonons in quasi-two-dimensional semiconductor systems for carrier temperatures between 25 and 200 K. Quantum statistics, dynamical screening, plasmon-phonon coupling, Landau damping, hot-phonon effects, and quantum-well-width corrections are included in a many-body calculation. The results are in good agreement with experiments. We resolve an important controversy in the experimental literature, as well as show that the theory applies to a much wider range of temperature than what was thought earlier.

This work has been motivated by two sets of experiments, performed by Shah *et al.*[1] and Yang *et al.*,[2] in which they study hot-electron energy loss in GaAs quantum wells using steady-state field-induced heating techniques. While both these experiments are in general qualitative agreement with the existing theoretical calculation, there are some gross order-of-magnitude discrepancies in their quantitative description, which ought to be properly understood, as these experiments constitute a direct probe of a very fundamental interaction in the solid-state physics, namely, the electron-phonon interaction. Various mechanisms such as degeneracy, dynamical screening, and hot-phonon effect have been invoked,[3,4] but no clear quantitative picture has emerged. In this paper we provide a theoretical study of hot-electron energy loss to LO phonons in polar semiconductors, including all the relevant physics. Since power loss to acoustic phonons is negligible compared with that to LO phonons, except at sufficiently low temperatures, our theoretical results can be compared directly with the experiments, and we provide such a critical comparison. We find that the numerical results produce a satisfactory description of the experiments. Not only have we been able to reconcile the results of two experiments, thus resolving an important controversy in the literature, but we have also shown that the theory is valid in a much wider range of temperature than what was thought earlier. The systematic deviation of the experimental points from the earlier theories at lower temperatures no longer persists in our calculations and we obtain quantitative agreement between theory and experiment in a wide temperature range, 25 $\text{K} \lesssim T \lesssim 200$ K. Below 25 K acoustic phonons may play an important quantitative role.

Before we come to the experimental differences, it would be useful to give a brief outline of the theory. This would also serve to familiarize the reader with the essential terminology. First of all, we make several approximations, all of which we expect to be rather well valid in the actual physical situation. We assume, as is suggested by the photoluminescence experiments, that the hot-electron gas is in equilibrium with itself so that it may be described by a temperature T (which is assumed to be much larger than the lattice temperature, which is taken to be zero for our numerical work). We assume that a single-phonon lifetime τ_{ph} (which we take to be an empirical parameter of the theory) describes the thermal relaxation of the LO phonons completely. We also make the standard finite-temperature random-phase assumption (RPA) to describe electronic response. Besides these essential assumptions, we make some minor (and removable) assumptions, such as the use of approximate subband wave functions to describe the quantum-well-width effect, and the neglect of LO-phonon dispersion and band nonparabolicity. All these approximations are expected to be reasonable in the parameter range of our interest.

For simplicity of presentation, we ignore mode coupling effects at first, and, with the use of the golden rule, write the power loss per carrier (see Ref. 5 for details) as

$$P = -\sum_q \int_0^\infty d\omega\, \hbar\omega M_q^2 n_T(\omega)[2\,\text{Im}\chi(q,\omega)]\delta(\omega-\omega_q)\ , \tag{1}$$

where $n_T(\omega)$ is the Bose occupation factor, M_q is the bare ("Fröhlich") electron-phonon coupling strength, χ is the finite-temperature reducible RPA polarizability for the electron gas, and ω_q is the phonon frequency, q being its wave vector. After doing the ω integral, this equation can be rewritten as

$$P = \sum_q \hbar\omega_q R_q n_T(\omega_q)\ , \tag{2}$$

$$R_q = -2\hbar^{-1} M_q^2\, \text{Im}\chi(q,\omega_q)\ , \tag{3}$$

where R_q is the scattering rate. In these formulas, quantum statistics and dynamical screening are included through χ and the finite-quantum-well-thickness corrections are included through the subband form factor which enters, in a standard manner,[6] in the definitions of M_q^2 and χ. Since LO phonons have a finite lifetime, in the steady-state experiment, there is a finite number of phonons present in the system, altering the power loss considerably, as they can be reabsorbed. This is termed the hot-phonon effect. Following the usual procedure,[3]

if the phonon occupation number is N_q, then we have

$$\frac{dN_q}{dt} = R_{\rm em}(N_q+1) - R_{\rm abs}N_q - N_q/\tau_{\rm ph} ,$$

which must be zero in the steady state. Here $R_{\rm em}$ and $R_{\rm abs}$ are the emission and absorption scattering rates, respectively, which are related to R_q as $R_{\rm em} = n_T(\omega)R_q$ (fluctuation-dissipation theorem) and $R_{\rm ab} - R_{\rm em} = R_q$ (principle of detailed balance). The dissipated power, i.e., $\sum_q \hbar\omega_q N_q/\tau_{\rm ph}$, is then given by

$$P = \sum_q \hbar\omega_q \frac{R_q}{1+\tau_{\rm ph}R_q} n_T(\omega_q) , \tag{4}$$

which is identical to (2) for vanishing phonon lifetime ($\tau_{\rm ph}=0$).

Now we come to the experiments. We choose one sample each from Refs. 1 and 2 for our numerical calculation with values for the quantum-well-widths $d=260$ and 137 Å and electron densities 7×10^{11} and 2.5×10^{11} cm^{-2}, respectively. In Fig. 1 we plot the experimental data points from Ref. 1, and in Fig. 2 from Ref. 2. The bold solid lines show the results of numerical calculations [Eq. (4)] with $\tau_{\rm ph}=3$ ps, whereas the light solid lines are obtained ignoring hot-phonon effect ($\tau_{\rm ph}=0$ ps). One finds that in Fig. 1 the experiment suggests $\tau_{\rm ph}\sim3$ ps, except at low temperatures ($T<50$ K). On the other hand, in Fig. 2 the experiment agrees with the theory in a very small temperature range (75 K $< T <$ 100 K) but with $\tau_{\rm ph}=0$ ps, i.e., no hot-phonon effect. This is the discrepancy that inspired this work. At lower temperatures there is a systematic deviation of both sets of experimental points from the theoretical curves—the theory grossly underestimates the power loss. This has been thought to indicate that this theory, which considers only energy loss to LO phonons, is not applicable at lower temperatures, because LO phonons do not remain the dominant mechanism, and power loss to other channels like acoustic phonons must also be considered.

We shall now show that not only can both the experiments be reconciled to a great extent, but also that power loss to LO phonons remains the important physical process down to much lower temperatures (until 25 K in Fig. 2). In order to do this we invoke an important piece of physics that was left out in the earlier theories—namely, the plasmon-phonon coupling or the phonon self-energy correction. Due to its coupling with plasmon, the LO phonon gains some spectral weight near the plasmon energy—thus creating a new channel to which the electrons can lose energy. We find that incorporation of this possibility substantially changes the results at low densities and low temperatures. The modification in the earlier equations is as follows: The δ function in Eq. (1), which is nothing but the spectral function (or, the density of states) of the unrenormalized LO phonon, is to be replaced by $-(1/\pi)\,{\rm Im}D^0(\omega_q,q)$, where D^0 is the bare phonon propagator. In the presence of the electron gas the phonon propagator would be renormalized in the standard way and would now have

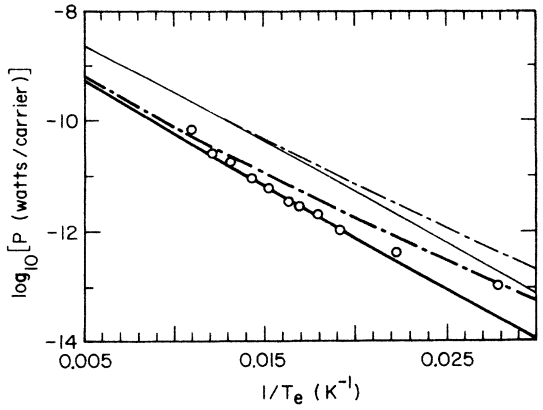

FIG. 1. Power loss by hot electron to LO phonons in a GaAs quantum-well structure plotted as a function of inverse electron temperature. Circles are experimental points from Ref. 1 with sample parameters: $N_s=7\times10^{11}$ cm^{-2} and $d=260$ Å. Bold dashed line gives the theoretical result when plasmon-phonon coupling is included, while the bold solid line gives the theoretical result when plasmon-phonon coupling is not included. For these lines we take $\tau_{\rm ph}=3$ ps. The light lines are the same but with $\tau_{\rm ph}=0$ ps, i.e., they omit the hot-phonon effect. Lattice temperature is low (<10 K).

two poles at the coupled plasmon-phonon frequencies. Thus one needs to include phonon self-energy correction in the theory. The power is now dissipated through these coupled modes. In the expression for the renormalized phonon propagator D (given by $2\omega_q D^{-1} = \omega^2 - \omega_q^2 - 2\omega_q M_q^2 \chi$), we use the finite-temperature plasmon-pole approximation[7] for χ in calculating the renormalized D, and include the effects of Landau damping by using the bare phonon propagator in the Landau-damped region (where the plasmon is not a

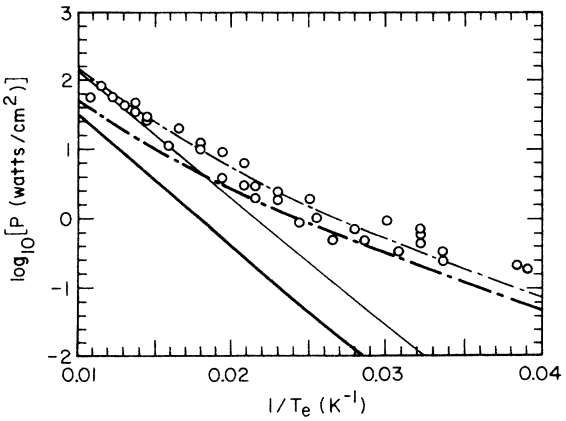

FIG. 2. Power loss by hot electrons to LO phonons plotted as a function of the inverse electron temperature. Circles are experimental points from Ref. 2 with sample parameters: $N_s=2.5\times10^{11}$ cm^{-2} and $d=137$ Å. Bold dashed (solid) line gives the theoretical result when plasmon-phonon coupling is included (excluded), with $\tau_{\rm ph}=3$ ps. The light lines are the same but with $\tau_{\rm ph}=0$ ps. Lattice temperature is low (<10 K).

well-defined RPA mode). These approximations are controlled and fairly accurate. (We have also verified the approximate validity of the plasmon-pole approximation by doing full RPA calculations.) Thus we get two δ functions in place of one in Eq. (1), which finally leads to two terms in the expression for power. We only mention that we make the simplest assumption of using the same τ_{ph} for either coupled mode.

The numerical results after including plasmon-phonon coupling are plotted in Figs. 1 and 2 with dashed lines—the bold one using $\tau_{ph}=3$ ps and the light one using $\tau_{ph}=0$ ps. We find that the bold dashed line produces reasonable agreement with *both* of the experiments[1,2] in the *whole* temperature range of the experiments. In Fig. 1 the agreement worsens a little bit at higher temperatures but becomes much better at lower temperatures. In Fig. 2 our theory shows much better agreement compared to earlier theories in the range 75 K $< T <$ 100 K, thus resolving the aforesaid discrepancy, in part. Moreover, the agreement spectacularly persists almost all the way down to 25 K. At these low temperatures, the earlier theories differed from the experimental points by several orders of magnitude. The bending of the experimental curve at low-electron temperatures seems to be very well described by our renormalized theory.

In summary, we have shown that it is very important to include the physics of plasmon-phonon coupling in the theory of hot-electron energy loss to LO phonons in polar semiconductors. We have resolved the controversy in which two different groups had to use two significantly different LO-phonon lifetimes (namely, $\tau_{ph} \gtrsim 5$ ps and $\tau_{ph} \approx 0$ ps) to explain their data, by showing that the complete renormalized theory is in reasonable agreement with both experiments using a single value for the phonon lifetime. Another significant finding of our calculation is that our results are in agreement with the data down to a much lower temperature ($T \gtrsim 25$ K) than was expected based on the earlier theories.

We have carried out similar calculations for three-dimensional polar semiconductors, which also show good agreement with experiments. The results of the three-dimensional calculations will appear in a future publication.

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