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Effects of stimulated optical phonon decay on hot carriers in GaAs

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Abstract

We have considered energy transfer from highly nonequilibrium electron gas to crystal lattice via emission of high-frequency longitudinal optical (LO) phonons and their subsequent transformations. At high intensity of electron excitation, the daughter LA phonons resulting from LO-phonon decay accumulate in considerable numbers and cause the LO-phonon decay to be a stimulated process. The stimulated decay effectively decimates the LO phonons and thus prevents their reabsorption by the electrons. These effects being incorporated in description of the electron–phonon kinetics, we have obtained considerable intensification of energy transfer from the electron subsystem. We also qualitatively discuss the effects of stimulation for alternative channels of LO-phonon decay.

Keywords: Stimulated phonon decay; Electron cooling

1. Introduction

In polar semiconductors, highly excited electrons transfer their energy to the crystal lattice primarily by emission of longitudinal optical (LO) phonons. This process is known to be quite fast, having characteristic times of the order of 0.1 ps. In contrast, the further transformations of these LO phonons are relatively slow, being determined by the weak process of anharmonic decay into lower-energy phonons. At low lattice temperature, the characteristic time of this decay is about 10 ps [1]. As a result of this discrepancy, at high level of electron excitation the LO phonons tend to accumulate and to be reabsorbed by the electrons, thereby slowing down the electron cooling [2].

Thus, energy transfer from the electrons to the lattice depends substantially on the time of LO-phonon decay. This characteristic time can be considerably decreased due to feedback of the decay products. In Ref. [3] we have analyzed this effect for the case of the so-called Klemens channel of the decay, $LO \rightarrow LA_1 + LA_2$, where LA_1 and LA_2 are short-wavelength daughter LA phonons having energy about half of the LO-phonon energy. We have shown that accumulation of the daughter LA phonons effectively stimulates the LO-phonon decay and decrease the LO-phonon lifetime.

In this work, we address effects of the LO-phonon decay stimulation on the process of energy

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transfer from the electron subsystem. In Section 2 we derive equations describing self-consistently the kinetics of electrons, LO phonons, and LA phonons, and solve these equations numerically for various values of the system parameters. In Section 3, we discuss these results and consider qualitatively their modification for alternative channels of LO-phonon decay.

2. Equations of electron–phonon kinetics and their solution

In steady state, the energy balance equation for energy transfer from the electrons to the lattice reads:

$$P_{\rm input} = -\int {\rm d}E\, E St\{f(E), N_q\}. \quad (1)$$

Here $P_{\rm input}$ is power input into the electron subsystem; E is electron energy; $St\{\cdots\}$ is the electron–LO phonon collision integral; $f(E)$ and N_q are the electron and LO-phonon distribution functions, respectively. We assume these distribution functions to be isotropic in momentum space and, moreover, $f(E)$ to be instantly thermalized by electron–electron collisions. Under these assumptions, the right-hand side of Eq. (1) is a functional of LO-phonon distribution function and a function of electron temperature T.

At low lattice temperature, equilibrium population of LO phonons is negligible. So, N_q is determined by competition of LO-phonon emission and anharmonic decay,

$$(1 + N_q)P_q^{\rm (em)} = N_q P_q^{\rm (ab)} + N_q/\tau_q. \quad (2)$$

Here $P_q^{\rm (em,ab)}$ are the probabilities of the LO-phonon emission and absorption by electrons and τ_q is LO-phonon lifetime due to the anharmonic decay. The latter can be expressed as [3]

$$\frac{1}{\tau_q} = \frac{1}{\tau_{\rm sp}}\left(1 + \frac{1}{q}\int_{k_0 - q/2}^{k_0 + q/2} {\rm d}k(n_k + n_{2k_0 - k})\right). \quad (3)$$

Here $\tau_{\rm sp}$ is characteristic time of *spontaneous* LO-phonon decay, n_k is the distribution function of the daughter LA phonons. The characteristic wave vector of these daughter phonons is $k_0 = \omega_0/(2s)$, ω_0 being the LO-phonon frequency and s being longitudinal sound velocity.

Finally, the population of the product LA phonons is controlled by their generation by the decaying LO phonons, on the one hand, and their own anharmonic decay, on the other [3]:

$$\frac{n_k}{\tau_{\rm a}} = \frac{2(1 + n_k + n_{2k_0 - k})}{k_0^2 \tau_{\rm sp}} \int_{2|k - k_0|}^{2|k_0|} {\rm d}q\, q N_q, \quad (4)$$

where $\tau_{\rm a}$ is lifetime of LA phonons.

We have solved the self-consistent system of Eqs. (1)–(4) numerically. The calculations were performed for GaAs parameters and for an electron density of $10^{18}\,{\rm cm}^{-3}$, using the standard Hamiltonian of electron–polar LO-phonon interaction. The resulting dependence of the electron temperature on the input power is presented in Fig. 1. Different curves correspond to different values of the dimensionless parameter $\alpha = \tau_{\rm a}/\tau_{\rm sp}$ characterizing the intensity of LA phonon feedback. (The case $\alpha = 0$ corresponds to purely spontaneous decay of LO phonons in the absence of the LA phonon accumulation.)

These results clearly demonstrate that LA phonon accumulation growing with increase of the ratio $\tau_{\rm a}/\tau_{\rm sp}$ leads to substantial intensification of energy transfer from the electrons. Though the LO-phonon mediated processes per se cannot provide power dissipation higher than a certain

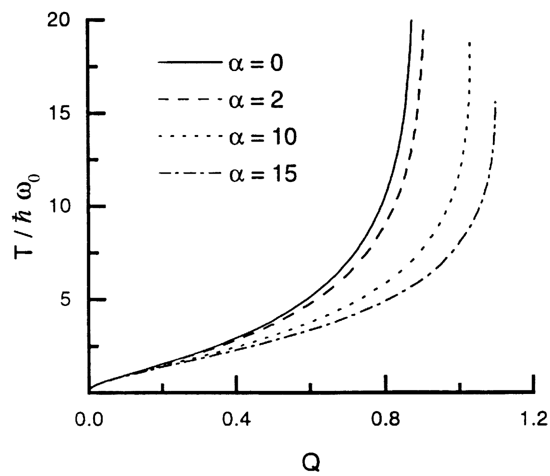

Fig. 1. The dependence of electron temperature on input power density in steady state for several values of parameter $\alpha = \tau_{\rm a}/\tau_{\rm sp}$.

maximum level, this maximum dissipated power grows and gets achieved at higher electron temperatures.

In regard to these results, two points should be mentioned. First, exact values of the short-wavelength LA-phonon lifetime, being very sensitive to the details of particular phonon spectrum, still evade close experimental study and remain unknown. According to our model calculations [3], τ_a can range from tens to hundreds of picoseconds. Second, the above consideration is valid until most of the electrons populate the Γ-valley of the conduction band. At very high electron temperatures, for the electrons being transferred to the higher X- and L-valleys, the interaction with long-wavelength LO phonons is no longer the main mechanism of electron energy transfer to the lattice.

3. Discussion

We have demonstrated that at high levels of electron excitation, the LO-phonon anharmonic decay becomes stimulated, and this gives rise to considerable intensification of energy transfer from electrons. The numerical estimates show that sufficient level of electron heating can be provided by an electric field of about 3 kV/cm [4]. This means that stimulated decay of LO phonons can manifest itself in high-field electron transport in the real semiconductor structures and devices.

It is worth discussing here qualitatively some possible modifications of the considered electron–phonon kinetics.

First, in our consideration we assumed that the electron and phonon distribution functions are isotropic. In real structures they become anisotropic because of applied electric field, anisotropy of the probabilities of phonon–phonon interaction, etc. Since we deal with strongly nonlinear stimulated processes, this anisotropy can result in shrinkage of the phonon distributions to very small regions of momentum space. This should lead to even stronger reduction of the LO-phonon lifetime and further intensification of the electron cooling.

Second, in some semiconductor materials the channels of LO-phonon decay are different from the Klemens channel. In particular, in InP the decay of LO phonons into TO and LA (or TA) phonons was reported [5]. For this decay channel, the daughter TO and LA (TA) phonons are all long-wavelength phonons. Therefore, they are concentrated in relatively small regions of momentum space. As a result, their population numbers can reach considerably higher values than those we obtained for the Klemens channel. In addition, the lifetimes of long-wavelength acoustic phonons are much longer than those of short-wavelength phonons, which also helps to enhance the accumulation of daughter phonons. Both of these factors should lead to more pronounced manifestation of the stimulated decay of LO phonons for alternative decay channels.

In conclusion, we have shown that stimulating feedback of daughter LA phonons on LO-phonon decay in the Klemens channel results in substantial intensification of power transfer from the hot electron gas at high levels of electron excitation. The effect should be observable in modern electronic and optoelectronic devices and promises to be even more pronounced for alternative channels of LO phonon decay.

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