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Stimulated Optical Phonon Decay in GaAs/GaAlAs Heterostructures

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We consider processes determining the steady-state population of longitudinal optical (LO) phonons being intensively produced in the quantum well ($\sim 100\mathring{A}$ width) of a GaAs/GaAlAs heterostructure by electrons accelerated by a strong external electric field. The emitted LO phonons are confined in the well layer [1,2] and transfer their energy to acoustic phonon system through anharmonic decay into longitudinal acoustic (LA) phonons. The latter, in the first approximation, emerge almost monoenergetically and distributed homogeneously in an infinitely thin spherical layer of radius $k_{l0} \approx \omega_o/2v_l \approx 0.6 \times 10^8\ cm^{-1}$ in the reciprocal space, here ω_o is the frequency of LO phonon, and v_l is the group velocity of LA phonon [3].

To demonstrate stimulated feedback of LA phonons on the LO decay processes, we have to trace the stages of decay and propagation of these resulting LA phonons, to obtain the LA phonons density in the near vicinity of the well, and to find the occupation numbers of individual phonon $\boldsymbol{k}$-states.

Using simple analytical functions to model LA and TA dispersion laws, $\omega_l(k) = v_l k$ and $\omega_t(k) = \omega_t \tanh(k/k_0)$ — where $\omega_t = 1.48 \times 10^{13}\ sec^{-1}$ is the edge frequency of the TA phonons, and $k_0 = 4.43 \times 10^7\ cm^{-1}$ is fitting parameter — we have calculated the rates of the main inelastic processes involving in high-frequency LA phonon propagation, $LA \rightarrow LA + TA$ and $LA \rightarrow TA + TA$ decays (see Fig. 1, a and b). The pronounced hierarchy of these processes allows us to neglect the first process altogether and to simplify significantly the general kinetic equation for the LA phonon distribution function $n_l(x, \omega, \theta)$. The only elastic scattering process which matters in the relevant frequency range, LA $\rightarrow$ LA, has the rate $\gamma_l(\omega) = 4\pi G_e \alpha^3 \tilde{\omega}^4$, with coefficient $G_e = 5.59 \times 10^6 sec^{-1}$, $\alpha = 0.59$ being transverse-to-longitudinal-velocity ratio. We assume the operating temperature to be zero and use the natural boundary conditions of absolute absorption at zero-temperature sink, $n_l(L, \omega, \theta) = 0$ for $\cos\theta < 0$. On the other hand, we take into account the phonon generation in the quantum well at $x = 0$ and the specular reflection of the phonons impinging on this plane from the bulk by imposing the other boundary condition, $\cos\theta(n_l(0, \omega, \theta) - n_l(0, \omega, \pi - \theta)) = (2g_0/v_l\omega_t)\delta(\omega - \omega_o/2)$, where g_0 is the LA phonon generation rate (in the further numerical estimates we will take $g_0 = 2 \times 10^{25}\ cm^{-2} sec^{-1}$).

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Finally, we obtain an integral equation for angle-averaged function $\bar{n}_l(x,\omega)$ in the high-frequency range in the form

$$\bar{n}_l(x,\omega) = \frac{g_0}{v_l\omega_t}\delta\left(\omega - \frac{\omega_0}{2}\right)G(\beta x) + \frac{\alpha\gamma_l}{2}\int_0^L dx'\bar{n}_l(x',\omega)\Big(G(\beta(x+x')) + G(\beta \mid x-x' \mid)\Big);$$

$$G(y) = \int_0^1 \frac{d\xi}{\xi}\exp\left(-\frac{y}{\xi}\right) = -Ei(-y)$$

is the exponential-integral function [4], $\beta = \alpha(\gamma_l + \Gamma_{ltt})/v_l$.

We have solved this equation numerically and obtained, therefore, the LA phonon density versus distance to the well. The pronounced concentration of LA phonons in the nearest vicinity of the well, compared to diffusive run-off in the case of usual thermoconductivity, enables these phonons to effectively cause feedback in LO phonon decay.

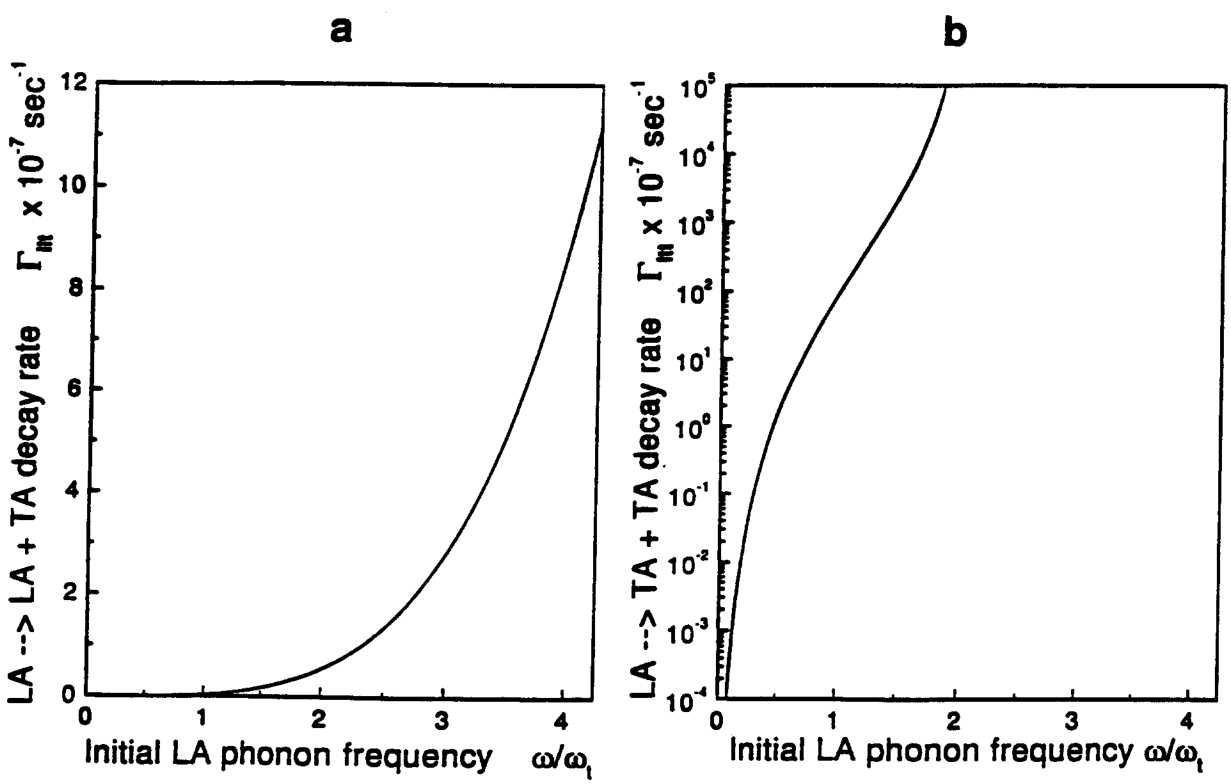

Fig. 1. a) Total decay rate due to LA → LA + TA process.
b) Total decay rate due to LA → TA + TA process. We use a log scale because of the gigantic divergence of Γ_{ltt} at LA phonon frequencies twice the cut-off frequency of the TA spectrum.

To find "partial" population numbers of these near-well LA phonons in individual $\boldsymbol{k}$-modes, $n_{\boldsymbol{k}}$, we need to distribute n_l LA phonon modes over all the accessible values of $\boldsymbol{k}$; in this way we take into account the broadening of the above-mentioned spherical layer in the reciprocal space. The main broadening mechanism determining the actual thickness of this layer, Δk, is the uncertainty of the phonon momentum in the direction normal to the well. This uncertainty is just the width in k-space of the LA-phonon wave packet due to the localization of the wave function of the initial LO phonon: $\Delta k \sim \pi/L$. For a well width of $L = 100$ Å, this gives $\Delta k \sim 3 \times 10^6$ cm^{-1}.

To find the number, p, of accessible LA modes, we take into account all the states covered by the broadening of the previously-mentioned spherical layer in reciprocal space. The mean radius of the layer is $k_{l0} \approx \omega_o/2v_l$, and we suppose it to be inhomogeneously broadened by Δk in the x direction in accordance with the principal broadening mechanism. Multiplying the volume of this layer, $2\pi k_{l0}^2 \Delta k$, by the density of phonon states in $\mathbf{k}$-space, $1/(2\pi)^3$, we obtain the required number:

$$p \approx \frac{k_{l0}^2 \Delta k}{4\pi^2} \approx \frac{\omega_o^2}{16\pi^2 v_l^2} \Delta k \approx \frac{\omega_o^2}{16\pi v_l^2 L}. \tag{1}$$

Given Eq. (1), the average occupation numbers, $n_{\mathbf{k}}$, of LA phonons, which stimulate the decay process, is expressed as,

$$n_{\mathbf{k}} = \frac{\bar{n}_l}{p} = \frac{4\pi^2 \bar{n}_l}{k_{l0}^2 \Delta k} = \frac{16\pi^2 v_l^2 \bar{n}_l}{\omega_o^2 \Delta k} = \frac{16\pi v_l^2 L \bar{n}_l}{\omega_o^2}. \tag{2}$$

where $\bar{n}_l$ is the LA phonon density, $\bar{n}_l(x, \omega)$, averaged over the quantum well. Substituting into Eq. (2) the result of our numerical solution for $\bar{n}_l$, we get the average phonon population numbers $n_{\mathbf{k}} = 1.72 \geq 1$. This means that the LO phonon decay essentially becomes a stimulated process.

The first consequence of this effect must be a considerable enhancement of the decay rate; indeed, such an enhancement may be as large as a factor of 3 or 4. To experimentally verify that LO phonon decay is a stimulated process, one can use a time-resolved coherent anti-Stokes Raman scattering technique [5] and trace the evolution of anti-Stokes signal versus probe delay time curve with increasing excitation intensity. The higher the intensity, the steeper should be slope of the curve. Such an experiment could be crutial for detecting the non-linearity of LO phonon decay.

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