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Hot electrons and nonequilibrium LA phonons in δ-doped GaAs

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The behavior of emitted LA phonons when an electric field is applied to δ-doped $\langle 001\rangle$ GaAs is investigated by the time-of-flight method. The characteristics show peculiar features due to specific interaction processes involved, i.e., direct emission by heated carriers as well as resonance absorption of nonequilibrium LA phonons besides decay and conversion processes of high-energy phonons. The latter contributions are in accordance with Monte Carlo simulations.

The time-of-flight method does not only allow us to investigate the kinetics of phonon fluxes (see for instance Refs. 1–3), but also to draw conclusions with respect to their emission by hot carriers.[4–6] These reports describe electrons confined in GaAs/Al$_x$Ga$_{1-x}$As quantum wells heated by applied electric fields and the phonons emitted from these sources and propagating through the substrate to the bolometer. In the present paper such investigations are performed for δ-doped GaAs layers, in which the electrons are confined to V-shaped quantum wells in thermal equilibrium, and attention is essentially paid to comparatively weak yet heating electric fields. By fabricating a very sensitive bolometer it has become possible to study the role of various electron-phonon interaction processes in contrast to strong electric fields, for which, on account of a high emission rate of optic phonons, the decay and conversion processes of phonons play the dominant role as exhibited in our recent publication.[7] The investigation of the LA mode as a function of carrier heating can be performed in contrast to Refs. 4–7. It should be emphasized that this is the first time to our knowledge that the LA mode along the defocusing $\langle 001\rangle$ direction has been investigated in detail, up to now it was merely detected in GaAs (Ref. 1) and in Si,[3] respectively, by thermalization of photoexcited electron-hole pairs.

The investigation concerns GaAs grown on 3.4 mm thick substrates by molecular beam epitaxy (MBE) and containing two δ-shaped layers in a distance of 100 nm doped with 1.35 and 1.2×10^{12} cm^{-2} Si atoms, respectively, as earlier described in Ref. 7. Contacts of Au:Ge were alloyed in a distance of 250 μm. In contrast to the measurements in Ref. 7 now an In bolometer was evaporated meanderlike on the backside of the substrate in order to enhance the sensitivity. The samples were immersed in liquid He of 2 K. Rectangular voltage pulses were applied with a duration between 30 and 100 ns and a repetition rate up to 500 cps.

Concerning the donor concentration, the average distance within a δ plane is small enough to form quantum wells. While in the absence of an external excitation the electrons are mainly in the ground level as well as the first excited level and concentrated close to the dopant layer, therefore, by applied electric fields the electrons in the neighborhood of the Fermi level become rapidly transferred to more extended states and even to the space between the δ layers.[8,9]

The charge carriers balance their energy gained in the electric field by the emission of acoustic and optic phonons. The time-of-flight spectra integrated over time exhibit a linear behavior as a function of input power as well as of the duration of the applied voltage pulses. The time-of-flight spectrum in Fig. 1 for 37 V/cm shows two well pronounced peaks corresponding to the arrival of longitudinal and transverse acoustic phonons (LA, TA) due to propagation along $\langle 001\rangle$ with main contributions by phonons with group velocities of 5.1 and 3.3×10^5 cm s^{-1}, respectively. In spite of the latter, because of the defocusing of this mode with regard to the neighborhood of $\langle 001\rangle$ the LA phonons can only be detected above 20 V/cm. Therefore, no conclusions can be drawn with respect to this electron-phonon interaction process at lower applied fields, whereas the TA phonon peak due to self-focusing can be observed down to 5 V/cm. As expected on account of the increase of phonon emission with rising

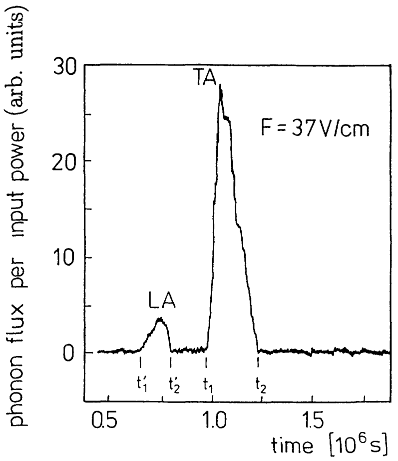

FIG. 1. Time-of-flight spectrum of nonequilibrium phonons at 2 K for an applied field strength of 37 V/cm and a pulse duration of 30 ns. The bolometer signals are divided by the electric input power into the two δ layers in GaAs.

carrier heating the amplitudes of the LA as well as the TA peaks rise with field strengths. As the cross talk from the electric connections rises stronger than the LA flux with increasing applied voltage the relatively small LA signal becomes drowned in the noise for fields above 600 V/cm and cannot be detected for higher fields in contrast to the TA signal, which remains very pronounced.

It is well known that optic phonons decay into lower energetic phonons within some 10^{-11} ns and those in their turn decay with a probability proportional to ν^5 (with ν denoting the phonon frequency). The phonon propagation is accompanied by isotope scattering proportional to ν^4, leading to a transverse mode with a probability of 90% and to a longitudinal mode with a probability of 10% according to the densities of the regarded final states. Therefore, phonons emitted with high energy do not propagate ballistically up to the bolometer, but quasidiffusively and form a long tail in the time-of-flight spectra above 40 V/cm consequently.

The phonon signals according to Fig. 1 are integrated over time in the intervals $t_1' - t_2'$ and $t_1 - t_2$, respectively, and shown as functions of field strengths in Fig. 2. For the TA peak a change of the slope can be observed at about 60 V/cm, i.e., just above the field strength, for which the formation of a tail becomes apparent in the spectra. Therefore, we assume that the stronger slope of the characteristics for medium fields is connected with the contribution of decay products of optic phonons.[5] However it should be pointed out that for the LA mode the increase of the slope becomes remarkable at somewhat higher fields only. A further peculiarity is observed in the time integrated LA signal at above 200 V/cm, when the amplitude appears to remain almost constant, but then to rise again.

In order to elucidate the situation, the propagation of phonons is simulated by the Monte Carlo (MC) method[10] including isotope scattering and decay processes. A total number of 10^5 starting phonons is simulated. On account of their short decay times not only the optical phonons but the first generation of decay products, too, are still in the immediate neighborhood of the δ layers, and we start the MC simulation with a phonon of 1.7×10^{12} cps only. Calculations were performed for a decay time of $\tau_0 \approx 50$ ns according to Ref. 11 as well as of $\tau_0/3$. The latter choice, leading to a diminished isotope scattering on account of the reduced frequency after the decay and, therefore, to a less pronounced diffusive character, well reflects the experimentally observed spectrum. Thus such simulations reflect details of the anharmonic decay process as already earlier mentioned in Ref. 3.

Assuming the MC result to be a justified approximation irrespective of the simplified model—an isotropic sphere with a radius given by the distance between the source (i.e., the δ layers) and the bolometer—it can be concluded that 10% of the quasidiffusively propagating phonons contribute to the narrow TA phonon peak between t_1 and t_2 and 0.5% to the LA phonon peak between t_1' and t_2'. Having such ratios in view and subtracting the according parts of the signal integrated over time for $t > t_2$ from the signals integrated over the intervals of the narrow peaks, the remaining fluxes are presented in Fig. 3. As can be seen these corrected data points can be described by a straight line with a single slope for the TA mode in contrast to Fig. 2 with two different slopes below and above 60 V/cm, respectively. Regarding the LA mode, however, the correction is too small to achieve a behavior according to a straight line, and the corrected flux in Fig. 3 rises more strongly above 100 V/cm than the extrapolation of the linear spline obtained for the weak field branch. Therefore, we conclude that an additional channel with respect to the emission of longitudinal phonons is opened. Whereas scattering between electrons and acoustical phonons is allowed for both modes in case of piezoelectric interaction, the contribution by the deformation potential is forbidden with respect to the TA mode. This can be a hint to the origin of the different behavior observed for TA and LA

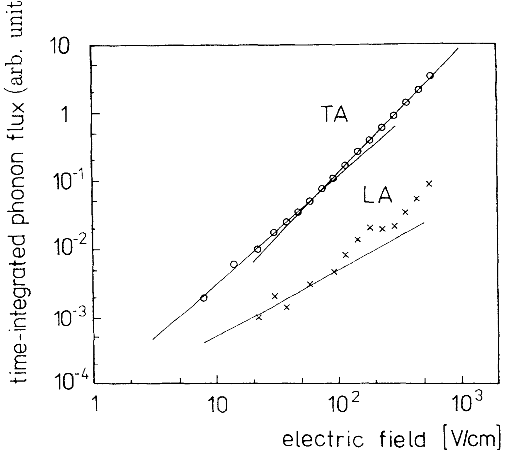

FIG. 2. Time integrated phonon flux as functions of the electric field strength for a pulse duration of 100 ns. Experimental points ○ concern the TA and × the LA signals in the intervals $t_1 - t_2$ and $t_1' - t_2'$, respectively, the indicated lines are a guide for the eye (according to the splines in the various regions of field strength for the straight sections).

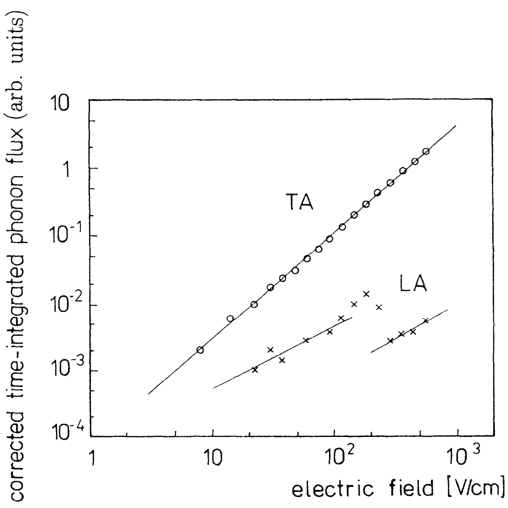

FIG. 3. Time integrated ballistic phonon fluxes of the LA and TA peak, respectively, data from Fig. 2 are corrected with regard to the quasidiffusively propagating phonons according to our Monte Carlo simulations.

phonons. As known[5,12] the energy relaxation by interaction with deformation potential is stronger than by piezoelectric interaction and should, therefore, dominate the LA phonon emission, yet the observation of the increase above 100 V/cm only cannot be explained by a different set in of the two interaction processes regarding intraband scattering,[9] but demonstrates the appearance of an additional channel, such as emission processes connected with intersubband transitions (including transitions between confined and extended states).

The peculiarity of the LA phonon characteristics around 250 V/cm to be seen in Fig. 2 becomes still more pronounced after subtracting the contribution of the quasidiffusively propagating flux. We propose that the drop of the ballistic signal has resonance character and reflects either reabsorption of LA phonons in an electron transfer between two excited subbands in the quantum well or a second order transition including the simultaneous emission of a LA phonon by an electron heated in the lower subbands and absorption by an electron in a higher subband with a transition to the next higher one. Besides the presence of a significant amount of LA phonons with an energy equal to the distance between both regarded higher subbands such a transfer demands a sufficient population of the lower of the two levels involved in the absorption process. Irrespective of the thermal population of the two lowest subbands this becomes realized for the higher subbands on account of carrier heating. It should be stressed once more that a similar effect is not observed for the TA mode.

Summarizing the experimental results and their analysis, it can be stated that the time-of-flight spectra allows us to distinguish the phonons emitted directly by hot electrons from those generated in a cascade of decay and conversion processes. It is the first time to our knowledge that for the ⟨001⟩ direction due to a very sensitive bolometer LA phonons could be extensively studied. Furthermore, the conclusion can be drawn that a part of the nonequilibrium LA phonons effect an intersubband transfer of electrons. A theory with regard to the resonance process has to be developed.

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