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1994 J. Phys.: Condens. Matter 6 7955

(http://iopscience.iop.org/0953-8984/6/39/016)

J. Phys.: Condens. Matter 6 (1994) 7955–7962. Printed in the UK

Hot electrons and non-equilibrium TA and LA phonons in δ-doped GaAs

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Received 28 February 1994, in final form 19 July 1994

Abstract. Phonons emitted by the application of an electric field to δ-doped (001) GaAs are investigated by the time-of-flight method. Using a sensitive bolometer and an accumulation of up to 10^5 signals we investigate TA and LA phonons, as well as the decay products of optical phonons. Concerning the latter contributions the experimental results are in agreement with Monte Carlo simulations. The peculiar features of the LA spectrum are discussed.

1. Introduction

Phonon emission by carrier heating can be investigated by the time-of-flight method. The spectra permit one to draw conclusions about acoustic phonons directly emitted by electrons as well as those generated in a cascade of decay and conversion processes starting from an optical phonon emitted by the hot carriers. Such measurements have been performed for GaAs/AlGaAs quantum wells [1–4]. In [4], the dependence on the direction of phonon propagation between source and bolometer was accentuated. For V-shaped QW formed by δ-doping with an average donor distance within this layer smaller than the effective Bohr radius, we recently studied pronounced phonon signals of the transverse mode [5, 6], while our present investigations emphasize the region of comparatively weak electric fields, in which the longitudinal mode can be detected with a sufficiently sensitive bolometer. Time-of-flight measurements can not only be performed in order to investigate phonons emitted by hot carriers; the method has also been applied to study the interaction of carriers with non-equilibrium phonons generated by a heat pulse [7].

2. Experiments

A GaAs structure was grown on a 3.4 mm thick isolating substrate (containing no Cr) by molecular beam epitaxy. Onto a 1 μm thick buffer layer two planes δ-doped with Si were incorporated into the GaAs in a distance of 100 nm and covered by a spacer and a cap layer as described in more detail in [5]. Due to a donor concentration of 1.35 and $1.2 \times 10^{12}\,\mathrm{cm^{-2}}$, respectively, the quantum wells contained four subbands with energies at the in-plane wavevector equal to zero of -35.5, -12, and about -5.3 and -2 meV, respectively, as obtained by the solution of the Poisson and Schrödinger equations [8]. In thermodynamical equilibrium (at 4.2 K) the ground state contains about 72% of the

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electrons; the excited states are populated by about 21% and 6%, respectively, the latter already appreciably extending in the growth direction, whereas the electrons in the fourth subband will even accumulate in the interlayer space if they become excited (in the presence of an electric field, for example).

The samples were supplied with 2 mm wide Au:Ge contacts at a distance of 250 μm. A meander-shaped In bolometer was evaporated on the back of the substrate covering a surface of 1×1 mm^2 opposite to the current-carrying layers. The measurements were performed in liquid He at 2 K, the transition temperature to the superconducting state of the bolometer. The input power to the δ layers was supplied by rectangular voltage pulses of 11–150 ns duration and 500 Hz repetition rate. The carriers lose a part of the energy gained in the electric field by emission of acoustical and optical phonons. The total time-integrated phonon flux arriving on the bolometer, compiled from 10^4–10^5 measurements for each field strength, demonstrates a linear behaviour as a function of input power into the δ-layers, and scales with the duration of the applied pulses, as shown in figure 1.

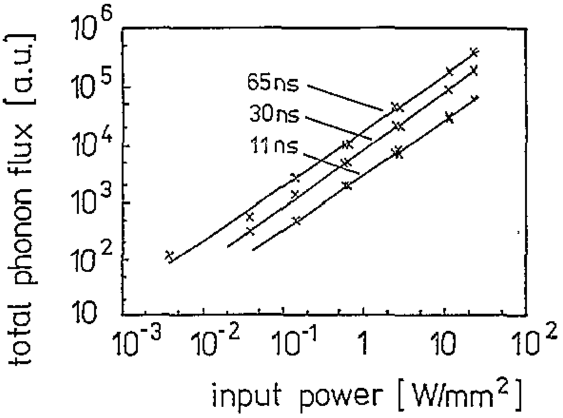

Figure 1. Total phonon signals against input power into two δ-doped layers at 2 K for pulse durations of 30, 65 and 100 ns.

3. Results

At low electric fields the time-of-flight spectra show two peaks (figure 2) according to the group velocities of the LA and TA phonons collected in a cone around the ⟨001⟩ direction equal to 5.1 and 3.3×10^5 cm s^{-1}, respectively. The value for the LA modes reflects some average of 4.7 and 5.4×10^5 cm s^{-1}, corresponding to propagation exactly along the ⟨001⟩ and ⟨111⟩ directions, respectively, because of the small distance between the bolometer and the source as well as their comparatively large extensions in the present sample. On the other hand, the TA group velocity deviates only insignificantly from the value for the ⟨001⟩ direction due to self-focusing [7, 9]. The rise times of the peaks are influenced by the response time of the bolometer and the rise time of the electric pulse as well as the arrival of phonons in a wide cone. Of course, the decay times of the signals are determined by scattering processes on isotopes [10] as well as additional contributions from a cascade of decay and conversion processes originating from optical phonons emitted by hot electrons. The propagation of these high-energy phonons has a quasi-diffusive character, therefore leading to long tails in the time-of-flight spectra. Furthermore, one should keep in mind that in the measurements of phonon generation by hot carriers the significant crosstalk

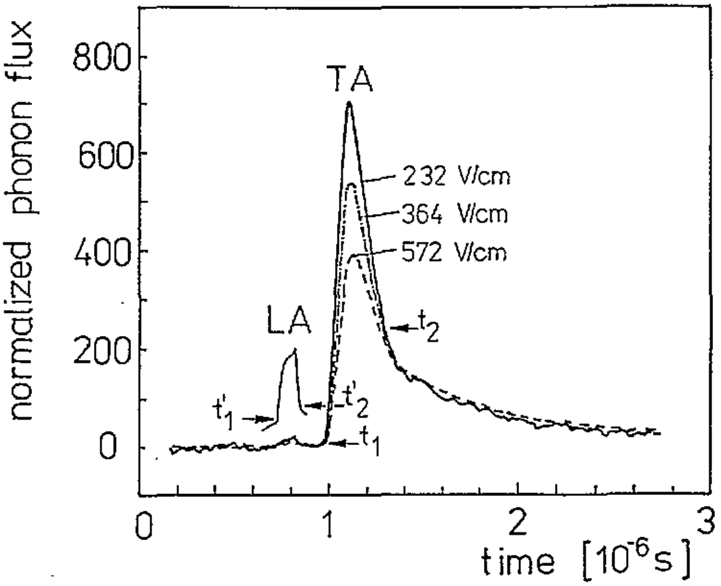

Figure 2. Time-of-flight spectra of non-equilibrium phonons at 2 K for applied field strengths of 232 (full curve), 364 (chain curve) and 572 V cm^{-1} (broken curve) and a pulse duration of 100 ns. The bolometer signals are normalized to their tails. The LA signal for 232 V cm^{-1} is shown magnified by a factor of ten.

between the electric connections for power supply to the sample and the connections to the bolometer causes the comparatively small LA signal to perish in the noise for fields above 600 V cm^{-1}. Because of the very small focusing factor of the LA mode [9] and the resulting small signal for detailed investigations, particularly of this mode, a higher amplification is used. The obtained data are easily reproducible, however, due to the high accumulation rate. This concerns the results with respect to the same sample cycled to low temperatures several times as well as the particular features repeated for another structure of similar type.

In figure 2 results are presented for three different comparatively high field strengths. The data are normalized to the contributions of the tails in order to demonstrate a feature important on its own: within the accuracy of our measurements the time dependence of the fluxes coincides for the whole region of times longer than the arrival times of the ballistically propagating phonons. This reflects the fact that, for this region of applied electric fields, the spectrum of high-energy phonons emitted by heated carriers does not change since the arriving decay products would differ. For 232 V cm^{-1} the signal corresponding to the ballistically propagating LA phonons is shown magnified by a factor of ten.

Integrating the non-normalized signals over time in the indicated intervals $t_1' - t_2'$, $t_1 - t_2$ and $t > t_2$, respectively, we collect the fluxes of both the ballistic LA and TA phonons and the quasi-diffusively arriving phonons. Dividing these time-integrated signals by the input power into the δ-layers we observe a distinct behaviour for the different branches in dependence on input power per electron, as demonstrated in figure 3. In the low-field region the TA and the LA peaks diminish according to a power law with increasing input power up to a value of about 1.6×10^{-12} and 2.8×10^{-12} W per electron, respectively. In the same region the signal from the quasi-diffusively propagating phonons (the tail integrated over $t > t_2$) becomes remarkable. We had already noticed earlier [6] that the TA signal as a function of field strength changes its slope in this region, indicating an increasing contribution of decay

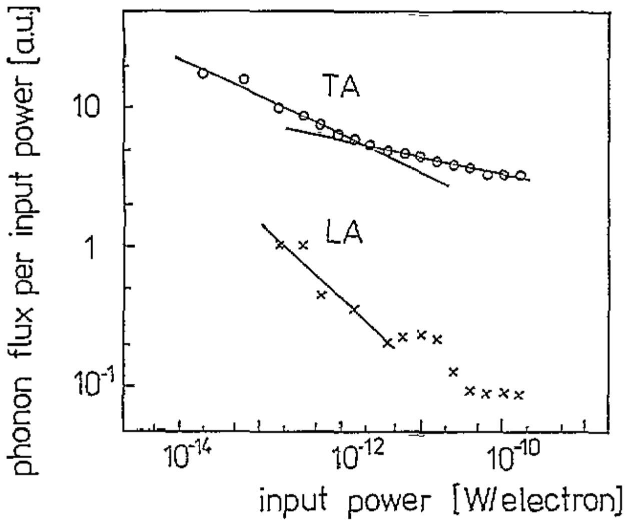

Figure 3. Time-integrated phonon flux divided by the input power into the two δ-doped layers as a function of the electric power per electron for a pulse duration of 100 ns. Experimental points: o, TA signals in the interval $t_1 - t_2$; ×, LA signals in the interval $t'_1 - t'_2$; •, the tail signal. The lines are a guide for the eye according to linear splines in the various regions of field strength.

products. On the other hand, the LA mode exhibits a stronger deviation than expected if, similarly to the results for the TA mode, an extrapolation is made from the dependence for low input power. Therefore, we conclude that an additional channel of LA phonon emission now contributes to the signal. This assumption is confirmed by the value of the power, for which a kink in the curve shown in figure 3 appears. It is shifted to a somewhat higher power (2.8×10^{-12} W per electron) than would be expected from the set in the tail signal (1.6×10^{-12} W per electron).

A further peculiarity is to be seen at about 2×10^{-11} W per electron in the case of the LA mode, which is not observed in the TA signal. There appears a sudden drop of the signal, demonstrating that the LA phonon signal per input power diminishes.

4. Discussion

The experimental investigations were accompanied by Monte Carlo simulations [11] of the diffusively propagating phonons. Assuming that the time of decay of optical phonons into LA phonons is of the order of 10^{-11} s and the decay time τ_d of high-energy LA phonons to be between 1.35 and $0.77 \times 10^{54}\nu^{-5}$ s according to different values of the third-order elastic constants involved [12], the first generation of decay products is still in the surrounding δ-layers. Due to conservation of momentum and energy the two LA phonons originating from the emitted optical phonons can later decay into LA + TA or two TA phonons within 1 ns according to τ_d, and we start the Monte Carlo simulation with these phonons only. During their propagation the phonons experience isotope scattering characterized by $\tau_s = 1.35 \times 10^{41}\nu^{-4}$ s for the LA mode [13]. With respect to the Monte Carlo procedure at the start, random numbers for the probabilities of any event (scattering or decay process), being proportional to $\exp[-t(\tau_s^{-1} + \tau_d^{-1})]$, and for the actual type of this event are determined. In the case of later isotope scattering, it must be fixed whether this process is connected with a conversion of modes. According to the time interval t until any event happens, the distance from the origin is obtained, and then the random numbers for the polar and azimuthal angle of the new direction of propagation are determined. This procedure is repeated until the initial phonons or their decay products cross a sphere of

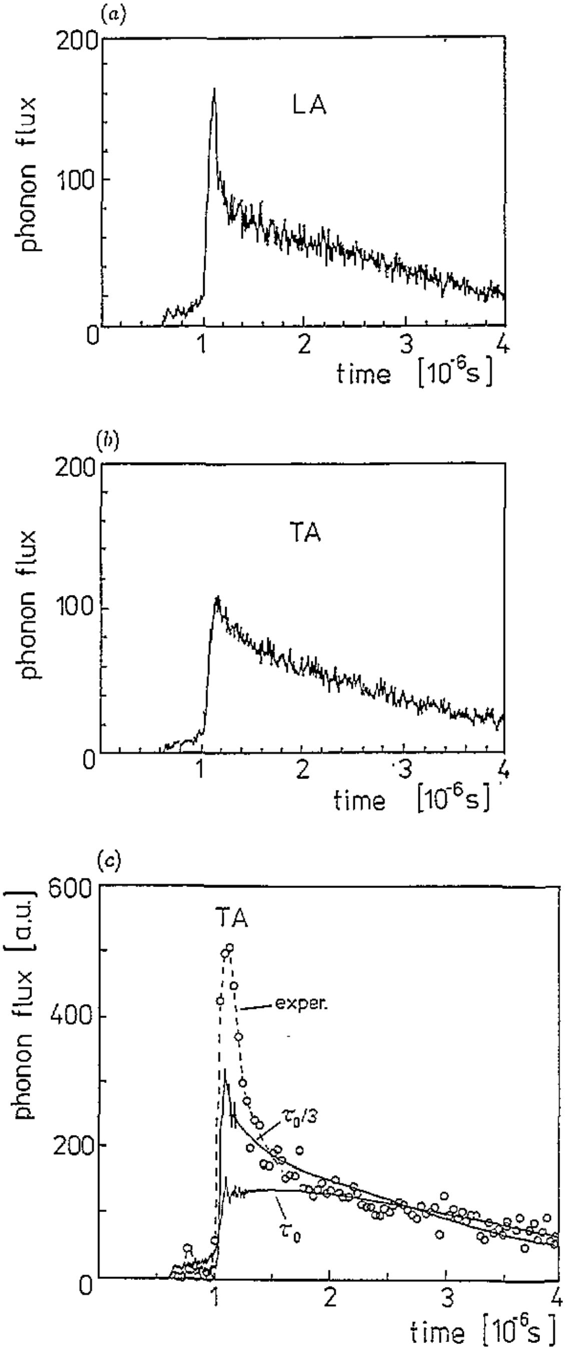

Figure 4. Numerical results for quasi-diffusively propagating phonons simulated with the Monte Carlo method for a LA (*a*) and a TA phonon (*b*) as initial modes, respectively, and for the sum of one LA and three TA modes (*c*) calculated for a decay time $\tau_0/3$ with τ_0 according to [12].

radius given by the real geometry of the sample by the distance between the δ-layer and the bolometer. Between 10^5–10^6 phonons are included in the simulation.

Despite the simplification with regard to the geometry, and the assumption of an isotropic crystal, we assume that the results mirror the main features of propagation. The data are shown in figure 4 for (*a*) LA phonons and (*b*) TA phonons as initial modes with a frequency of 1.7×10^{12} Hz (according to a high state density in ⟨111⟩), and (*c*) the joined spectrum of one LA and three TA phonons. While the scattering time is well established, the decay times given in the published data disagree by more than an order of magnitude. We used an even lower value than the interval given in [10], because in comparison to $\tau_0 = 95$ ns obtained for the cited upper limit $\tau_0/3$ yields a better fit to the experimental data shown for 583 V cm^{-1}. A better agreement is due to the resulting lower frequency after a decay process and the consequently weaker influence of the isotope scattering after such an event. Therefore in the tail of the spectrum the maximum, which is commonly characteristic for diffusive propagation, is shifted to the trailing edge. This is in accordance with classical motion with a diffusion constant equal to $\tau_0 v^2/3$. Comparing the obtained spectra it is seen that an initial longitudinal phonon yields a higher signal of ballistically propagating TA phonons (narrow peak) following the small step connected with the time corresponding to the ballistic arrival of LA phonons. This is due to the predominance of the TA mode in the decay products of an LA phonon. Since the combined spectra of one LA and three TA phonons assumed for the initial situation reflect the experimental time-of-flight spectra for $t > t_2$, we can conclude from figure 4 that the contributions in the experimentally obtained fluxes during $t_1' - t_2'$ as well as $t_1 - t_2$ are about 0.5% and 10% of the total flux *originated by the high-energy phonons and their decay products, respectively. Subtracting* such amounts of the signal integrated over the tail from the ballistic signals, the corrected curves of ballistically arriving phonons are shown in figure 5.

With respect to the TA signal the corrected results as a function of power per electron are described by a single straight line with a slope that is characteristic for the low power branch in figure 3. Regarding the LA signal, there remains a significant deviation from an extrapolation of the straight line obtained below 2.8×10^{-12} W per electron, as already expected given the *discussion of figure 3. Of course, one has to remember that only a* small percentage of a big signal was used for the correction, and on the other hand the LA signal presents a small fraction of the TA signal. Despite this, we assume that the kink in the corrected LA phonon flux per input power reflects an experimental situation and consequently we have to think about a possible physical origin of the different behaviour. Although the total number of electrons remains constant during carrier heating, their distribution among the sublevels changes with heating and the probabilities of phonon emission are expected to differ with respect to intraband scattering in different subbands. For instance, in a simplified model [10, 14] taking into account only one quantized subband (ground state) and one extended level for a multiquantum well structure, significant differences were obtained for the phonon emission by both subgroups of electrons. A more precise treatment of the present case, taking into consideration excited but still confined states, could give a definitive answer. However, this should concern both types of modes, if they refer to the same interaction process with electrons. As is well known (see, for example, [14] and references therein) the deformation potential interaction is allowed in zeroth order between electrons and LA phonons, in contrast to piezoelectric coupling, which is allowed for both modes. Therefore it is reasonable to assume that this is the cause of the experimentally observed peculiarity. This is supported by conclusions drawn from investigations of electron temperature and phonon emission [2] accentuating the energy loss by the deformation potential interaction in spite of the TA mode observed in their time-of-flight spectra only.

Furthermore, the drop of the LA phonon signal at about 2×10^{-11} W per electron becomes still more pronounced in the corrected presentation of figure 5. At present it is not possible to decide whether the observed effect is due to a subsequent reabsorption of an emitted phonon exciting an electron from one of the higher subbands to the next, or to an interaction process of second order, in which one electron loses energy that simultaneously transfers another electron to a higher subband. Since the restrictions to initial and final states can be

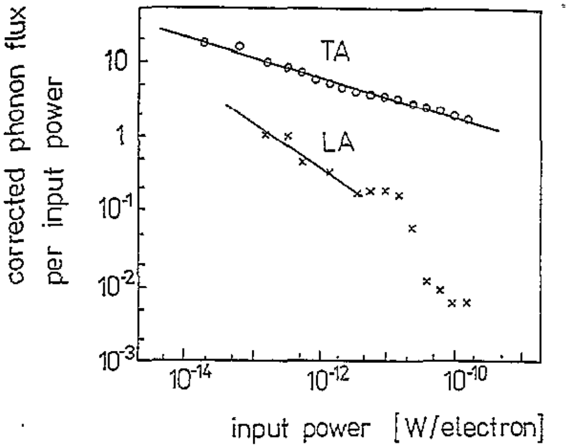

Figure 5. Time-integrated ballistic phonon fluxes of the LA and TA peak, respectively. Data from figure 3 are corrected with regard to the quasi-diffusively propagating phonons (cf. figure 4).

implemented only with more difficultly for interband transitions than for intraband processes, this can result in an apparent resonance character. Because the effect is observed in a comparatively small region of applied electric fields, we assume such a possibility exists. As this effect could only be observed for the LA phonons it can again be a hint of the predominant deformation potential interaction.

5. Summary

Non-equilibrium phonons emitted by the electron gas of a double quantum well created by two δ-doped layers in (001) MBE-grown GaAs have been examined in detail. With the help of a very sensitive meander-like bolometer it became possible to investigate time-of-flight spectra of the phonons even down to comparatively weak electric input power into the δ-layer system in contrast to our previous measurements. The low ratio of LA to TA phonons detected by the bolometer for our ⟨001⟩ orientation is due to defocusing and self-focusing of both the modes, respectively [9]. The decay products of initially high-energy phonons can be separated from the ballistically arriving phonons. These quasi-diffusively propagating contributions to the spectra are in accordance with results of Monte Carlo simulations. The corrected TA phonon signals due to directly emitted acoustic phonons when divided by the input power into the electron gas seem to decrease by a power law with respect to the input power as to be seen in the double logarithmic presentation in the investigated region from 10^{-14}–10^{-10} W per electron. The LA mode exhibits a weaker decrease above 2.8×10^{-12} W per electron and a sudden drop at about 2×10^{-11} W per electron. One might suggest that this peculiarity of the LA mode is connected with electron–phonon interactions on deformation potential, as this process is forbidden for transverse phonons and could therefore explain the absence of the effect for the TA mode. The observation of a drop in a very narrow region of supplied power indicates a resonance character, which can be connected with intersubband transitions in comparison to intrasubband scattering of the electrons.

Acknowledgments

We wish to express our thanks to I Obuchov for the Monte Carlo program used in this work, and to Professor O G Sarbey for his interest in the investigations and especially the discussion with respect to a possible resonance reabsorption or a second-order process.

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