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Phonon emission by hot electrons in δ-doped GaAs

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Abstract. Simultaneous measurements of current–voltage characteristics and time-of-flight spectra of emitted phonons were performed for δ-doped GaAs at 2 K. The phonon flux consists of two parts: a narrow signal due to the ballistic arrival of the acoustic phonons and a broad signal arising from the decay products of optical phonons emitted by hot electrons. An increase in conductivity and a decrease in the time-integrated narrow signal divided by the input power are observed at moderate field strengths. Both features are explained by the real-space transfer of electrons from the quantum wells to extended states. At high fields the conductivity decreases whereas both phonon fluxes per input power increase. These effects are suggested to be due to the transfer of hot electrons from the Γ band edge to the L valleys assisted by the deformation potential interaction with phonons. The dependence of the position of the maximum of the narrow signal on the duration of the voltage pulses at constant input energy indicates the presence of inelastic phonon–phonon interactions and the formation of the hot spot.

1. Introduction

As is well known the mean energy of carriers heated by an electric field is dominated by the interaction with phonons rather than by other scattering mechanisms, because the energy gain is balanced by the loss due to phonon emission. Therefore, the phonon spectra of hot electrons reflect the kinetics of these processes. Such effects were found in epitaxial layers of GaAs [1], GaAs/Al$_x$Ga$_{1-x}$As quantum wells [2, 3] and Si inversion layers [4]. In all cases the measurements were performed at comparatively low heating fields. Measurements at more elevated electron temperatures were only performed with electron–hole pairs excited by laser radiation, as reviewed in [5]. The aim of the present paper is to investigate the phonon spectra of hot electrons as functions of carrier heating produced by electric fields in δ-doped GaAs:Si.

2. Experiments

2.1. Sample preparation

The layers grown by molecular beam epitaxy were deposited on semi-insulating GaAs substrates 3.4 mm thick in order to distinguish signals due to ballistic phonons from that due to background phonon diffusion. Onto a buffer layer 1 μm think, two δ-dopings with 1.35×10^{12} and 1.2×10^{12} Si atoms cm^{-2}, respectively, were made separated by an undoped

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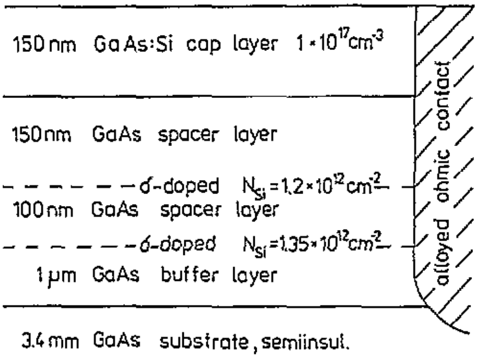

Figure 1. Schematic presentation of the vertical layout.

GaAs layer 100 nm thick and followed by a cap layer consisting of 150 nm undoped and 150 nm Si-doped (1×10^{17} cm^{-3}) GaAs (figure 1).

At normal growth conditions the substrate temperatures for GaAs and δ-like silicon dopant deposition were 500 °C and 520 °C and the growth was interrupted before and after the δ-doping for 120 s and 60 s, respectively. The samples 2 mm wide were equipped with current contacts at a distance of 0.25 mm by alloying Au:Ge at a temperature of 430 °C for 4 min in a N_2–H_2 atmosphere. The smallness of the contact resistance was checked by four-point measurements on analogous samples. The bolometer was fabricated by evaporating In at 300 °C on the back side. A low bolometer sensitivity was chosen to ensure a linear rise up to the highest electric field excitation of δ-layers.

2.2. *Experimental arrangement*

The measurements were performed by immersing the sample in superfluid helium at 2 K. The voltage was applied in the form of rectangular pulses with a duration τ_c of 65, 30 or 11 ns. The current was recorded by the voltage drop on a 50 Ω load resistor connected right next to the sample, in order to reduce the influences of all connections to the electronic system. In the whole region of applied electric fields, from 10^{-1} to 8×10^{3} V cm^{-1}, the shape of the observed current pulses coincided with that of the voltage pulses and was independent of the duration time τ_c.

The phonon signals were accumulated up to 10^4 repetitions in order to obtain a sufficiently high signal-to-noise ratio; however, at fields below 250 V cm^{-1} the sensitivity was not high enough to reach the desired resolution.

2.3. *Experimental results*

Figure 2 displays the current–voltage characteristics for 11 and 30 ns pulse durations. Both these characteristics as well as that for the 65 ns pulse coincide with each other except at the highest applied voltage, which shows a slightly greater current for longer pulse duration. specific features are observed at about 10 V cm^{-1} and 1 kV cm^{-1}, appearing as an increase and a shoulder, respectively; of course, they are more pronounced in a conductivity or differential conductivity plot. Figure 3 shows a strong increase in conductivity at 10 V cm^{-1}, its saturation at about 1 kV cm^{-1} and a strong drop on further increasing the field.

Two time-of-flight spectra are shown in figure 4. The bolometer signals are normalized to input power. A sharp pronounced front appears 1 μs after the electric field was applied to the sample, indicating the arrival of ballistic phonons. This behaviour is unlike that observed in heterostructures [2], which has already been discussed in [3]. From the delay time t_1,

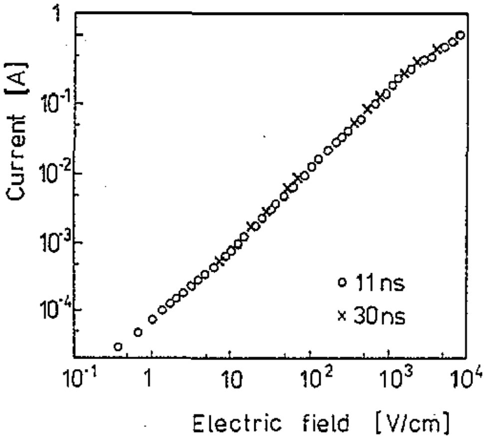

Figure 2. Current–voltage characteristics in a δ-doped GaAs structure at 2 K for pulse durations of 11 and 30 ns.

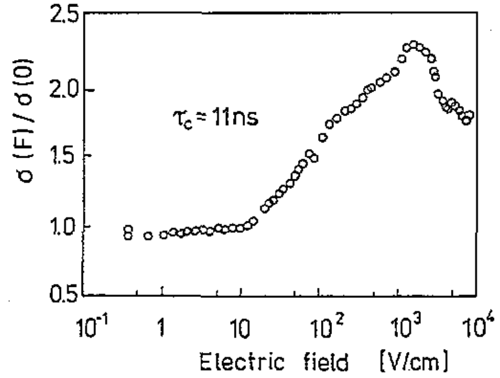

Figure 3. Dependence of the normalized conductivity on electric field derived from data represented in figure 2.

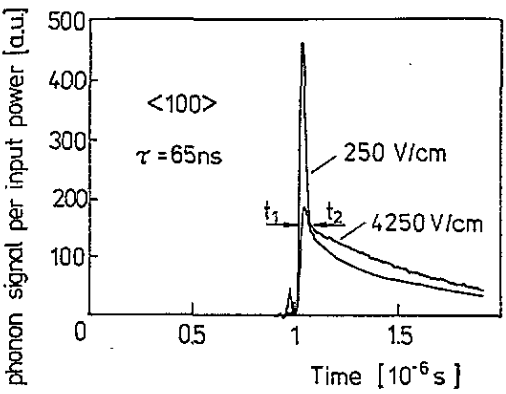

Figure 4. Time-of-flight spectra of non-equilibrium phonons at different electric fields (a.u., arbitrary units). The bolometer signals are divided by the input electrical power to the δ-structure.

the thickness of the sample and the known phonon velocities along the ⟨001⟩ direction we derive that the peak between t_1 and t_2 arises from phonons of the TA mode, whereas the phonons of the faster LA mode are not focused along this direction [6]. They cannot be observed even if phonons of this mode interact with the electrons of the δ-layers. The steep decrease in the phonon pulse at t_2 overlaps with a broad spectrum. We attribute this feature to acoustic phonons produced by multiple decay of high-energy phonons and conversion processes [7] by which optical phonons originally emitted by hot electrons are converted to acoustic phonons with frequencies below 0.6 THz. These phonons can propagate from the region of the layers carrying the current to the bolometer without being scattered by isotopes. All these phonons contribute to the signal between t_2 and a certain upper limit time depending on

(i) the number of decay and conversion processes,
(ii) the velocity of the ballistically propagating phonons and
(iii) the distance travelled.

This distance extends over a certain interval bearing in mind the angle covered by the bolometer and the possible reflection from the top surface. However, the integrated phonon flux of this broad interval might not include the slowest phonons if the signal has already been lost in the noise before their arrival.

The integrated phonon fluxes of the narrow and broad intervals (lower and upper curves, respectively) divided by the input power are shown in figure 5 as functions of the heating electric field for 11, 30 and 65 ns pulse durations. Sets of curves with different pulse durations were measured with different amplifications of the bolometer signal. However, for each set it was verified that the response was linear to the power over the whole range. Up to 1 kV cm^{-1} the normalized values of the narrow peaks slightly decrease with increasing heating field, whereas the broad-band signal remains almost constant. At higher field strengths depending on the duration of the voltage pulse, all the fluxes exhibit a marked increase followed by saturation for the broad-band signals. The behaviour of the narrow phonon peaks above 1 kV cm^{-1} is more complicated. At these field strengths the phonon fluxes increase to a maximum, the position of which depends on the duration of the voltage pulse, and decrease subsequently.

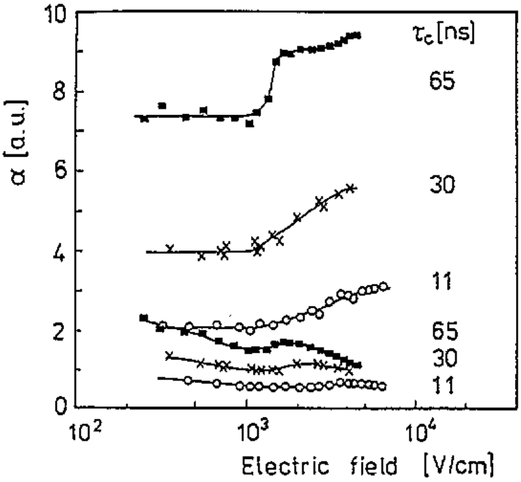

Figure 5. The time-integrated phonon signal divided by the input power as a function of electric field for different pulse durations τ_c (a.u., arbitrary units). The upper three curves refer to the broad signal and the lower three to the narrow signal.

3. Discussion of the results

3.1. Phonons generated at moderate fields

Let us approximate the electron system in the confined quantum states in the V-shaped potential wells formed by δ-doping and those outside these wells by the models of a two-dimensional (2D) and a three-dimensional (3D) electron gas, respectively. We assume that the 2D electrons being heated to the energy of the barrier height of the quantum wells move in extended states later (3D behaviour). The ratio of 3D to 2D electrons increases with increasing field strength, of course.

Although the 2D electrons emit phonons as soon as they are heated by the electric field strongly enough to have the necessary energy and a free final state for the concerned process becomes available, too, it was not possible to detect the phonons at field strengths below 200 V cm^{-1} for the given bolometer sensitivity, as mentioned above. Therefore, the data from the time-of-flight measurements are normalized to their values at 250 V cm^{-1}. The change γ in such a normalized phonon flux per input power as a function of the electric field is shown in figure 6.

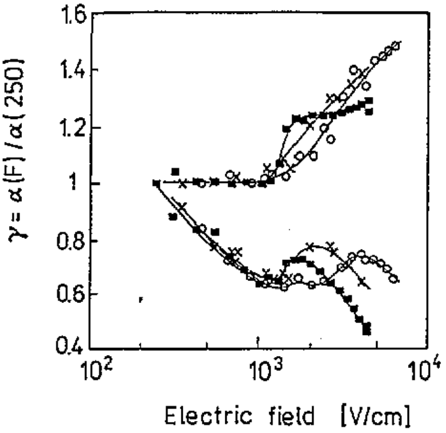

Figure 6. The ratio γ of the time-integrated phonon signal per input power normalized to its value at 250 V cm^{-1} as a function of electric field F for different τ_c: O, 11 ns; X, 30 ns; ■, 65 ns. The upper three curves refer to the broad signal and the lower three to the narrow signal.

To explain the unusual decrease in the narrow signal (lower curves) as the carrier heating proceeds, the following features have to be taken into consideration: low-frequency TA phonons can be emitted directly by electrons or created by the decay of optical phonons, which are initially emitted by hot electrons already at electric fields of about 10 V cm^{-1} (in analogy to [9] for a somewhat lower doping concentration). The time necessary for the decay of the optical phonon, conversion and a repeated decay process into high-frequency acoustic phonons, which are able to propagate ballistically through the sample, is estimated to be about 20 ns [8]. Therefore, the peak observed between t_1 and t_2 can also contain such phonons besides the TA phonons emitted directly by electrons.

The recording of phonons transverse to a quantum well has been under discussion, for instance in connection with the measurements in III–V heterostructures [2, 3]. One has to keep in mind that the electron momentum in the confinement direction need not be conserved in the electron–phonon interaction process. Therefore, phonons in a large range of transverse wavevector components can contribute to the signal, which is collected in a narrow cone perpendicular to the layers. This feature of the 2D electron–phonon interaction is in contrast with the emission by 3D carriers and has been considered for instance in [10] for deformation potential interaction.

Furthermore in the present case, because the doping concentration is slightly above 10^{12} cm^{-2}, the quantum well contains more than one confined state and transitions between different subbands are possible.

As already mentioned earlier, we assume that carriers are heated by the electric field up to extended states, in which they move predominantly in a space where ionized impurities, *acting as scattering centres*, are *rare. Consequently, they are more mobile and heated* more strongly by the applied electric field than are the carriers confined to the wells. As shown in [9], because of this, the electrons in the 3D states dissipate their energy gain predominantly to optical phonons, while the less heated 2D electrons preferentially emit acoustic phonons for moderate electric field strengths and this contribution can even exceed significantly the energy loss to acoustic phonons by 3D electrons. The unusual drop in the narrow TA phonon flux per incident power with increasing field strength can be explained by the diminishing fraction of 2D electrons as carrier heating progresses and their decreasing contribution transferred to emitted acoustic phonons, consequently. Provided that the fraction of TA phonons emitted by 3D electrons and the constituents originating from emitted optical phonons increase only weakly, this proposed transfer of electrons from 2D to 3D states can account for the observed unexpected behaviour.

3.2. Phonons generated at high electric fields

It is shown in figure 6 that for electric fields above 1 kV cm^{-1} the normalized phonon flux per input power increases for the broad as well as for the narrow bands. This effect must be connected with opening a new channel of phonon emission by hot electrons. The observed critical field strengths, especially for short pulse durations, is close to the value known for carrier transfer between Γ and L conduction band edges in GaAs and this new phonon burst is accompanied by a pronounced decrease in the conductivity (compare figure 3); for that reason we suggest that this phonon-assisted carrier transfer from Γ to L valleys takes place in the present experiments. We assume that again optical phonons, generated this time by hot carriers with a deformation potential interaction, decay into acoustic phonons, thus evoking the marked rise in γ in the high-field region.

It should be noted that the increase in γ is shifted to lower electric fields with increasing pulse duration and that γ saturates at lower values of τ_c for the broad-band signal, whereas it decreases again for the narrow band. Such a limitation can be caused by the formation of a 'hot spot' [11], when the density of non-equilibrium high-frequency acoustic phonons reaches a critical value determined by the non-elastic phonon–phonon interaction. It was shown in [12] that such a hot spot in GaAs develops by photon excitation at an absorbed energy density of 3 μJ mm^{-2}. When γ is depicted as a function of power (figure 7), the peaks of the narrow-band phonons are displayed at energy densities of 2.5 μJ mm^{-2}, 2.7 μJ mm^{-2} and 2.8 μJ mm^{-2} for 11 ns, 30 ns and 65 ns pulse durations, respectively. Probably this inelastic phonon–phonon scattering effect influences the broad-band phonon spectrum likewise (upper curves in figure 6).

4. Conclusion

The measured time-of-flight spectra involve acoustic phonons emitted directly by hot electrons (giving rise to a signal peak in a narrow interval of arrival times) and those

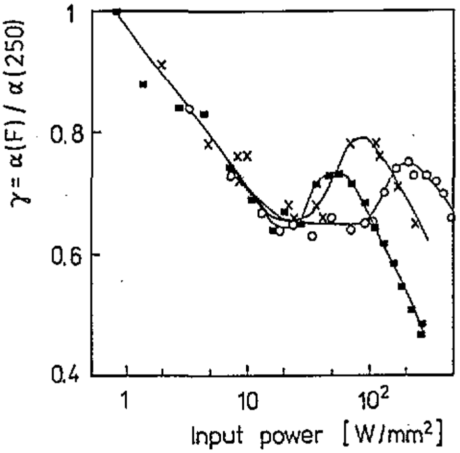

Figure 7. The ratio γ of the time-integrated narrow peak normalized to its value at $F = 250$ V cm^{-1} versus electric input power per unit sheet for different τ_c: O, 11 ns; X, 30 ns; ■, 65 ns.

phonons created by repeated decay and conversion processes from optical phonons emitted by hot electrons (responsible for a signal in a broad interval of arrival times). These spectra normalized to the power converted in the sample reflect the following general behaviour of carrier heating as well as specific features associated with the consequent semiconductor structure.

(i) The drop in the phonon flux divided by the input power for the narrow peak is not compensated by a corresponding increase in the signal in the broad interval; thus this may indicate a decrease in the carrier density, creating the narrow band. Therefore we propose a real-space transfer of 2D electrons from the layers to extended states having a higher mobility.

(ii) The increase in the normalized phonon flux above 1 kV cm^{-1} and the simultaneous decrease in conductivity are explained by transitions of electrons from Γ to L valleys by deformation potential interaction.

(iii) Furthermore, the influence of the duration of the voltage pulses on the increase in the normalized phonon fluxes in the high-field region of decreasing conductivity and on the subsequent saturation indicates the presence of an inelastic phonon–phonon interaction. Its plot as a function of input power verifies this assumption, since these results agree with the formation of a hot spot in optically excited GaAs.

Acknowledgments

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