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Hot electrons and nonequilibrium phonons in a multiple δ-layer-doped GaAs structure

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Time-of-flight spectra of nonequilibrium phonons emitted by hot carriers in quantum-well systems reflect the electron-phonon interaction not only for intraband processes but allow conclusions to interband transitions of the electrons also. We report investigations in multiple quantum wells in GaAs created by δ doping with 5×10^{11} cm^{-2} Si atoms per layer. The present results demonstrate peculiarities ascribed to carrier interband transitions. Our proposals concerning the involved interaction processes are supported by measurements of the differential electrical conductivity as well as by results of a Monte Carlo simulation.

Recently it became feasible to investigate longitudinal acoustical (LA) phonons, which are emitted by hot electrons in a (001)-orientated V-shaped quantum-well structure in GaAs, by time-of-flight spectroscopy, in addition to the well-pronounced transverse acoustical (TA) phonon fluxes.[1,2] This achievement was due to the fabrication of a very sensitive In bolometer obtained by using a meander shape instead of a square shape.[3,4] Comparing the signals of both phonon modes propagating ballistically from the source to the bolometer two peculiarities in the LA signal as a function of the electric field applied to the two-dimensional electron gas were detected. Firstly, besides the usually decreasing phonon flux per input power observed for the piezoelectric interaction between electrons and phonons an additional flux compared to the regularly decreasing one is observed above a certain field strength. Secondly, a strong decrease of the flux per input power (a saturation behavior of the time integrated signal) is measured with further increasing field strength in a narrow adjacent field region. The first feature should be due to a channel for phonon emission in addition to the interaction processes between electrons and LA as well as TA phonons, which we previously connected with interaction processes of the electrons in the confined states with the LA phonons by the deformation potential.[3,4] It was assumed that the second peculiarity is caused by a phonon assisted intersubband carrier transition. In order to confirm that intersubband processes were observed in emitted phonon spectra, it is desirable to repeat the investigations for a quantum-well system with different doping level. An altered concentration of donors in a δ-doping plane changes the energies of the sublevels in such a V-shaped potential well, the Fermi energy, and the corresponding filling factors of the sublevels as well as the carrier mobilities corresponding to impurity scattering and screening. As a consequence the form of the signals will be changed and the characteristic regions of electric field strength with regard to the above-mentioned peculiarities will be shifted. For this purpose in the present paper a multiple δ-layer system (MQW) with 5×10^{11}-cm^{-2} Si atoms per layer is investigated in contrast to the double layer structure with 1.25 and 1.3×10^{12} cm^{-2}, respectively, in previous papers.[3,4]

Furthermore, in addition to the time-of-flight phonon spectra, direct measurements of the differential conductivity were performed on the same sample as the time-of-flight measurements in order to elucidate the situation in more detail.

The MQW structure was grown by molecular-beam epitaxy on a 3.5-mm-thick substrate depositing a 1-μm-thick buffer layer and then seven Si doped layers 100 nm from one another. The sample was supplied with Au:Ge contacts a distance of 2 mm from each other and a width of 0.2 mm alloyed at 420 °C for 4 min. The measurements were performed in pumped helium at 3.5 K according to the transition into the superconducting state of the In bolometer. Square pulse voltages with 55–150-ns duration and a repetition rate between 100 and 500 c.p.s. were applied and the current was determined by the voltage drop on a 50-Ω resistor connected right next to the sample in the cryostat. In order to measure the differential conductivity of the hot carriers the sequence of the applied voltage pulses was modulated by a small a.c. voltage of 3–5 % of the pulse voltage and a frequency of about 20 times less than the repetition rate of the pulses. The direct determination of the differential conductivity seems to be advantageous in comparison to numerical differentiation of the current voltage characteristics[5] in order to detect subtle differences as a function of field strength.

In time-of-flight spectra the propagation of the LA mode in a defocusing orientation had been detected in the case of thermalization of optically excited electron hole pairs,[6,7] whereas in our preceding papers this flux was investigated for electrically heated electrons. In order to obtain the highest possible signal to noise ratio, the bolometer signal was accumulated up to 5×10^4 repetitions. The time-of-flight spectrum is shown for a field strength of $F=4.5$ V/cm in Fig. 1. Taking into account the distance of 3.5 mm between the δ layers and the bolometer as well as the sound velocities of 5.1 and 3.3×10^5 cm/s for the LA and TA modes along ⟨001⟩, respectively, the peaks are caused by the ballistical arrival of LA and TA phonons. The maximum energy of phonons, which can ballistically propagate the distance of 3.5 mm between their source, i.e., the δ layers, and the bolometer, is limited by isotope scattering and equals 3.4 and 3

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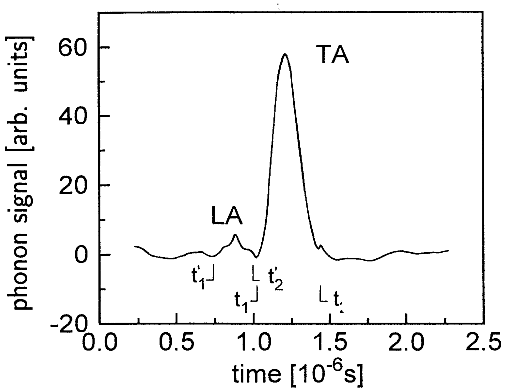

FIG. 1. Time-of-flight spectra of nonequilibrium phonons at 3.7 K for applied field strengths of 4.5 V/cm for a pulse duration of 55 ns. The intervals of arrival of ballistically propagating phonons are indicated.

meV, respectively, for the LA and TA modes. Since the maximum phonon wave vector is about $2k_F$, the maximum energy of emitted phonons is about 1 meV in the present sample, in which the Fermi energy is 15 meV above the bottom of the ground state according to $5\times10^{11}\text{-cm}^{-2}$ carriers. Therefore, at low carrier heating the confined electrons emit a flux of LA as well as TA phonons, which propagate purely ballistically. When the heating electric field is higher than 6.5 V/cm a tail of quasidiffusively arriving phonons is detected for $t>t_2$.

In order to analyze the field dependence of the phonon flux due to different processes of phonon emission we use the same procedure as previously and integrate the phonon signals over the time intervals $t'_1-t'_2$ and t_1-t_2 indicated in Fig. 1 as well as over the tail for $t>t_2$. This procedure can be used because the time integrated signals divided by the duration of the applied electric pulses do not depend on the pulse duration as demonstrated in Fig. 2. The obtained results are shown as functions of the field strength in Fig. 3. Lines are presented as a guide for the eye in order to facilitate the discussion. The special features of the phonon spectrum described in Refs. 3 and 4 are exhibited in the results presented in Fig. 3 also: the abrupt appearance of phonons,

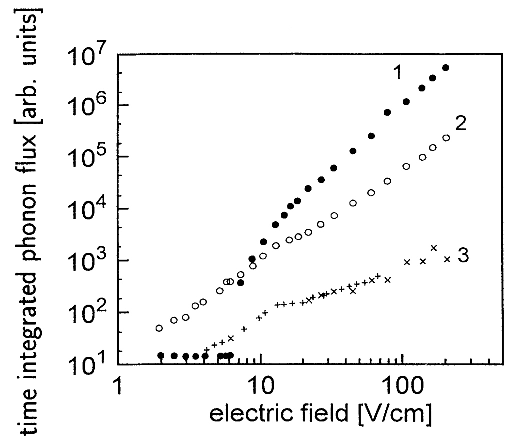

FIG. 3. Time integrated phonon flux as functions of the electric field for a pulse duration of 55 ns. Experimental points refer to ○, the TA and ×, the LA signals in the intervals t_1-t_2 and $t'_1-t'_2$, respectively, and ●, the decay products of high energy phonons in the tail of the signal.

which arrive in times $t>t_2$, and the plateau of the LA phonon signal in a certain region of field strength preceded by a more pronounced increase of the flux in comparison to the slight increase in the weak field limit. In the region of the well-pronounced plateau of the time integrated LA phonon flux a flattening of the slope of the TA curve can be seen.

The observed threshold for the appearance of the tail in the phonon spectrum demonstrated in Fig. 3 agrees with the fields for the steep slope of the differential conductivity (Fig. 4). As discussed in previous papers,[5,8] this strong rise of the differential conductivity is mainly caused by the changes in the concentration as well as in the drift velocity of those electrons that were transferred to the extended states. Since the electrons between the doping layers acquire a higher energy from the field, they preferentially emit optical phonons in contrast to the confined electrons that mainly lose their energy to acoustic phonons in the low field region. The numerical results obtained by a Monte Carlo simulation performed for a simplified two level system of a MQW (Ref. 9)

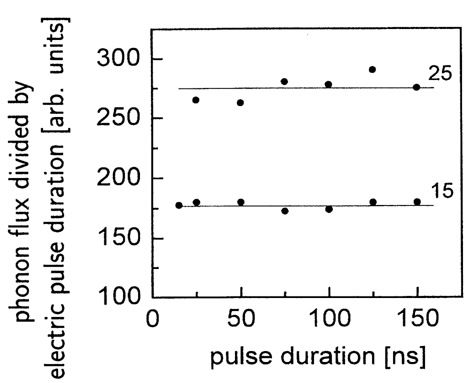

FIG. 2. Time integrated LA phonon flux divided by the duration of the applied electric field pulse as a function of the pulse duration for fields of 15 and 25 V/cm, respectively.

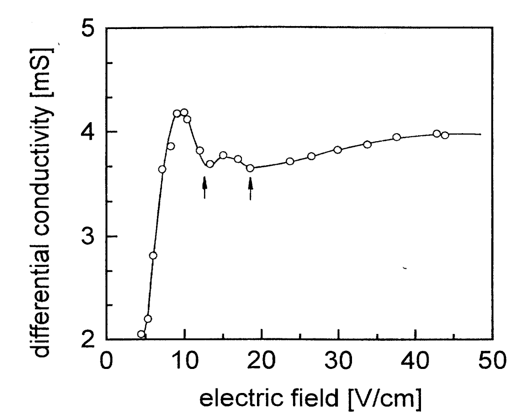

FIG. 4. Differential conductivity as a function of field strength. The region of assumed intersubband transitions discussed in the text is marked by arrows.

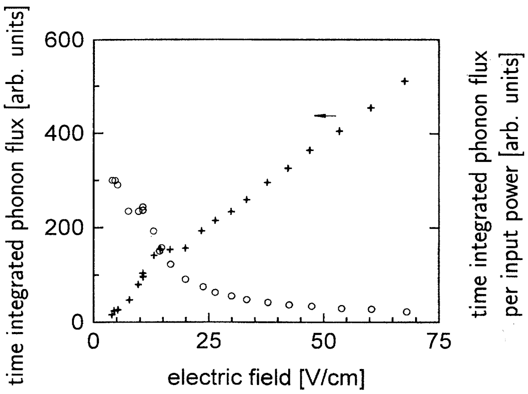

FIG. 5. Time integrated LA phonon flux (+) as function of the electric field for a pulse duration of 150 ns (left scale) and its values divided by the input power to the MQW (○) (right scale).

are in good agreement with the present data, since the experimentally determined threshold for the long time tail is now shifted to 6.5 V/cm in contrast to 37 V/cm observed in the previous highly doped double quantum well. A cascade of repeated decay and conversion products of optical phonons then leads to the observed tail in the spectrum.

The region of field strength, in which the interesting peculiarities of LA phonons are observed, was investigated in more detail. The number of accumulated phonon signals was chosen to be larger and the duration of the heating electric pulse was enhanced from 55 to 150 ns, because the magnitude of the LA signal is much smaller than those of the other modes. The results of the measurements with 150-ns pulse duration are shown in Fig. 5 for the time integrated flux as well as for its values divided by the input power to the MQW (in a linear presentation in contrast to the logarithmic one in Fig. 3). The latter curve shows a well-pronounced shoulder between 7 and 12 V/cm, which reflects the additional phonon flux more clearly than the time integrated flux itself. As stated above, at about 7 V/cm we have the strongest increase in the carrier transfer rate to the extended states with their higher mobility[8,9] and therefore an increase of optical phonon emission is expected. However, it can be estimated that a contribution from the decay products of the originally emitted optical phonons to the signal of the ballistically propagating LA phonons—in contrast to that of the TA phonons—is negligible as concluded from Monte Carlo simulations for the formation of the tail of the spectrum for the previous higher doped double quantum well.[3,10] Yet it seems to be reasonable to connect the observed increase in the LA flux with the direct acoustical phonon emission by carriers redistributed among the subbands.

At about 12 V/cm this enhanced increase happens to stop. Above 12 V/cm the curve sharply drops, whereas the initial curve concerning the time integrated signal exhibits saturation behavior, until at 18 V/cm the LA phonon flux again increases with rising field strength. This behavior repeats the features observed for the more strongly doped double quantum well, but is again shifted to lower field strength due to the weaker impurity scattering. In order to elucidate the effect further, the results concerning differential conductivity as a function of field strength will again be explored (see Fig. 4). Beyond the strong maximum in the differential conductivity the severe influence of optical phonon emission leads to an almost constant differential conductivity.[5,8,9] The slightly higher differential conductivity in the very region (marked by arrows in Fig. 4), in which the saturation of the LA phonon signal is observed proves that "additional" electron transitions into states with higher mobility take place. Therefore we assume that they might be connected with reabsorption of nonequilibrium phonons as proposed in Refs. 3 and 4. We think that the limitation of the field region, in which the saturation of phonon emission is observed, is associated with the necessary conservation of momentum and energy.

Summarizing, we state a very good agreement of both data sets in accordance with the different doping levels and carrier confinements consequently. With regard to the field strengths, for which the peculiarities are observed, the shifts to lower values in the present MQW are expected on account for the reduced impurity scattering and the stronger carrier heating consequently. We state that the observed peculiarities in the phonon spectrum are typical for shallow multiple quantum wells as created by δ doping and the carrier redistribution between the confined and extended subbands.

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[1] P. Hawker, A. J. Kent, O. H. Hughes, and L. J. Challis, Semicond. Sci. Technol. B **7**, 29 (1992).

[2] J. K. Wigmore, M. Erol, M. Sahraoui-Tahar, C. D. W. Wilkinson, J. H. Davies, M. Holland, and C. Stanley, Semicond. Sci. Technol. **6**, 322 (1993).

[3] B. Danilchenko, A. Klimashov, S. Roshko, and M. Asche, Phys. Rev. B **50**, 5725 (1994).

[4] B. Danilchenko, A. Klimashov, S. Roshko, M. Asche, R. Hey, and H. Kostial, J. Phys. Condens. Matter **6**, 7955 (1994).

[5] H. Kostial, Th. Ihn, P. Kleinert, R. Hey, M. Asche, and F. Koch, Phys. Rev. B **47**, 4485 (1993).

[6] B. Stock, M. Fieseler, and R. G. Ulbrich, in *Proceedings of the 17th International Conference on the Physics of Semiconductors,* edited by J. D. Chadi and W. A. Harrison (Springer, New York, 1985), p. 1177.

[7] M. E. Msall, S. Tamura, S. E. Esipov, and J. P. Wolfe, Phys. Rev. Lett. **70**, 3463 (1993).

[8] M. Asche, R. Hey, M. Höricke, T. Ihn, P. Kleinert, H. Kostial, B. Danilchenko, A. Klimashov, and S. Roshko, Semicond. Sci. Technol. **9**, 835 (1994).

[9] P. Kleinert and M. Asche, Phys. Rev. B **50**, 11 022 (1994).

[10] B. Danilchenko, D. Kozakovtsev, and I. Obuchov, Zh. Eksp. Teor. Fiz. **106**, 1439 (1994) [JETP **79**, 777 (1994)].