Photoconductivity of $In_xAl_{1-x}As$ parabolic quantum wells in the optical-phonon regime

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We present far-infrared photoconductivity (PC) measurements for a two-dimensional electron gas (2DEG) in an $In_xAl_{1-x}As$ parabolic quantum well grown on a GaAs substrate. By applying a magnetic field, we observe a response in the longitudinal resistance of the 2DEG caused by the bolometric effect of the cyclotron resonance (CR). We can tune the CR across the optical phonon regimes of both $In_xAl_{1-x}As$ and GaAs. In this regime, we observe both optical effects from the multilayered structure and effects of the coupling between the 2DEG and the longitudinal optical phonons. We compare our results to dielectric calculations and find that the PC signal arises from the absorption in the 2DEG but not from the total absorption of the multilayers.

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I. INTRODUCTION

Both the experimental and theoretical study of charge excitations of two-dimensional electron gases (2DEGs) in the regime of optical phonons in semiconductor multilayered structures is currently of high interest with results remaining controversial.[1–4] There are several effects to be taken into account for the analysis of the behavior of the optical modes in the regime of the longitudinal optical (LO) and transverse optical (TO) phonons. First, the microscopical coupling between the cyclotron resonance (CR) and the LO phonon, e.g., the polaron effect,[5] yield an anticrossing around the LO energy by tuning the magnetic field.[6–11] In addition, there are also macroscopical effects arising from the dielectric properties, which vary strongly in the vicinity of the optical phonons. These effects lead to an absorption by the lattice at the TO energy and therefore to a damping of the CR.[12] In a multilayered structure, interference effects play also an important role. The interferences strongly depend on the frequency. Therefore, a careful comparison between the experimental results and theoretical dielectric calculations is required for the interpretation of the observed effects.

There are experimental difficulties in the study of charge excitations in the regime of the optical phonons arising from the reduced transmission in the reststrahlen band. In earlier works, the electron-phonon interaction was studied by far-infrared (FIR) reflection measurements.[13] In recent works, the FIR transmission was studied in both GaAs (Refs. 1–3) and $In_{0.75}Ga_{0.25}As$ (Ref. 4) quantum wells where the substrate was etched to thin the sample. The results are compared to dielectric calculations. From this comparison, new questions raised concerning the physical nature of the electron-phonon interaction. Instead of the polaron coupling, an interaction of the CR with both the TO phonon and a hybrid LO-phonon intersubband mode is assumed. The latter effect is of pure dielectric origin.

We have recently developed FIR photoconductivity (PC) spectroscopy using the 2DEG directly as the detector. This technique is a very powerful tool for the study of charge excitations in the regime of the optical phonons, since the charge excitations are detected via the sample resistance change instead of by transmission. The basic mechanism for the PC is the bolometric effect[14–17] where the absorbed radiation causes a heating of the electron gas which leads to a change in the longitudinal resistance of the 2DEG. However, in the optical phonon regime the open question remains whether this technique is only sensitive to the absorption of the electron gas or also to the lattice excitations, similar to the optical phonons. The former case means that only the direct heating takes effect on the 2DEG. In the latter case, a resistive change can also be induced by an indirect heating where a heat transport from the lattice to the 2DEG occurs.

In recent works, the FIR photoconductivity response of a conducting In-doped CdTe layer on a semi-insulating GaAs substrate was studied.[18] In this system, the PC spectra were compared to the total absorption of the whole structure.

In this paper, we present FIR-PC measurements on a 2DEG in an $In_xAl_{1-x}As$ parabolic quantum well grown on a GaAs substrate. Such a structure is also interesting for spintronics devices[19,20] due to the tunable spin effects.[21] We observe the CR which can be tuned across the reststrahlen bands of both $In_xAl_{1-x}As$ and GaAs by changing the magnetic field. Due to the ternary alloy of our parabolic quantum well, the CR is relatively broad which is helpful for our experiment focusing on the optical response of the system in the reststrahlen band regimes. Inside the reststrahlen bands, we observe a strong deviation from the Lorentzian line shape. We have used a dielectric model to calculate both the total absorption of the multilayered structure and the absorption of the electron gas only. From the comparison, we can trace back the deviations of the line shape to macroscopical optical effects[12] arising from the multilayered structure. We found that the PC signal in our 2DEG structure can be explained by the direct absorption of the electron system only.

An additional splitting in the vicinity of the LO phonon of the $In_xAl_{1-x}As$ layers can be observed in our experiments. This splitting cannot be explained by the dielectric effects but arises from the microscopical electron-LO-phonon coupling.[6–11]

II. THEORY

A. Bolometric model

In a photoconductivity spectroscopy experiment, ohmic contacts are prepared on the sample and the dependence of

the longitudinal resistance R_{xx} on the incident FIR photon frequency is monitored. By absorbing the far-infrared photon, the total energy of the electron system increases. In a single-particle picture, one electron is excited to a higher energy level. By electron-electron interaction, this energy dissipates in the whole electron system. Within the bolometric model,[14–17] the 2DEG can be described with a steady state at a higher temperature. The change of the longitudinal resistance R_{xx} of the electron system is given by[17]

$$\Delta R_{xx} = \frac{\partial R_{xx}}{\partial T}\frac{P(\omega)\tau_e}{C_e}. \tag{1}$$

Here, $P(\omega)$ describes the power of the absorbed radiation, τ_e the energy relaxation time, and C_e the heat capacity of the electron gas determined by[22]

$$C_e = \pi^2 k_B^2 T \mathcal{D}(E_F,B)/3, \tag{2}$$

where $\mathcal{D}(E_F,B)$ is the electron density of states and T the temperature of the electron gas. The photoconductivity intensity strongly depends on the Landau filling factor and also on the sample temperature. Energy relaxation processes, especially their time constants, are significant for the PC.

B. Dielectric calculations

The photoconductivity signal is proportional to the absorbed radiation. Therefore, macroscopic dielectric effects are important to analyze the PC spectra. In this work, we have used the Fresnel equations to calculate both the total absorption of the multilayered structure and the absorption of the electron system. In the following, we present the basic formalism. Similar calculations have been performed in earlier works.[23] As we will see later, it is of interest to calculate the absorption which occurs in a single layer of the multilayered structure. To present this special technique, it is helpful to reproduce the following equations.

The influence of the optical phonons is included in the dielectric function of the crystal given by[24]

$$\kappa(\omega) = \kappa(\infty)\prod_{\mathrm{i}}^{N}\frac{\omega_{\mathrm{LO_i}}^2 - \omega^2 - \mathrm{i}\omega\Gamma_{\mathrm{LO_i}}}{\omega_{\mathrm{TO_i}}^2 - \omega^2 - \mathrm{i}\omega\Gamma_{\mathrm{TO_i}}}. \tag{3}$$

Here, Γ describes the damping of the phonons. The product is taken over all phonon modes of the material. In the ternary mixed crystal of $In_xAl_{1-x}As$, there exist two optical phonon bands. The lower energy band is called InAs-like and the higher energy band AlAs-like. Between ω_{TO} and ω_{LO} the real part of $\kappa(\omega)$ is negative. The transmittance is reduced between these frequencies. This region defines the reststrahlen band.

To describe the absorption of the 2DEG, the dielectric function can be expanded to[25]

$$\kappa_{\mathrm{2DEG}}(\omega) = \kappa(\omega) + i\frac{\sigma}{\omega\epsilon_0 d_j}, \tag{4}$$

where d_j is the thickness of the electron gas which is assumed to be small compared to the wavelength of the FIR radiation. σ is the high-frequency conductivity of the electrons with

$$\sigma_{\pm} = \frac{N_S e^2 \tau}{m^*}\frac{1}{1 + i(\omega \mp \omega_c)\tau}. \tag{5}$$

Here, N_S is the 2D density of the quantum well, m^* the effective mass of the electrons, τ the scattering time and $\omega_c = eB/m^*$ the cyclotron frequency.

For each interface $(i-j)$ one has to calculate the complex reflection (r_{ij}) and transmission (t_{ij}) coefficients by the Fresnel equations

$$r_{ij} = \frac{k_{z,i}/\kappa_i - k_{z,j}/\kappa_j}{k_{z,i}/\kappa_i + k_{z,j}/\kappa_j},$$

$$r_{ji} = -r_{ij},$$

$$t_{ij} = 1 + r_{ij},$$

$$t_{ji} = 1 + r_{ji}, \tag{6}$$

where $k_{z,i} = \sqrt{\kappa_i\omega^2 - \omega^2\sin^2\theta}/c$ describes the z component of the wave vector in the ith layer, κ_i the dielectric function in the ith layer, and θ the angle of the incident radiation.

For a multi-interface system, one has to calculate the reflection and transmission coefficient by a recursive expansion taking into account the phase difference that is collected by transfer through each layer. For instance, the reflection coefficient for the transition from the layer $n-1$ to $n+m$ can be calculated from the corresponding results of the reflection coefficients for the transitions from the layer $n-1$ to n and n to $n+m$ by solving a geometrical series

$$r_{n-1,n+m} = \frac{r_{n-1,n} + r_{n,n+m}\exp(2ik_{z,n}d_n)}{1 + r_{n-1,n}r_{n,n+m}\exp(2ik_{z,n}d_n)}, \tag{7}$$

where d_n is the thickness of the nth layer.

The absorption in a single layer of a multilayered structure can be calculated from the amplitudes of the incoming and outgoing electromagnetical waves at both sides of the layer. These values can be extracted from the components of the electric and magnetic field. If we define the x and y direction in a way that $E_y = 0$ $(H_x = 0)$, the field components $E_x(z)$ and $H_y(z)$ are given by $E_x(z) = E_0\tilde{E}_x(z)$ and $H_y(z) = H_0\tilde{H}_y(z)$, respectively, where E_0 and H_0 are the amplitudes of the incident wave. The relative field components are given by

$$\begin{aligned}\tilde{E}_x(z) = {} & \frac{ck_{z,n}}{\kappa_n\omega}\frac{t_{0,n}}{1 - r_{n,0}r_{n,N}\exp(2ik_{z,n}d_n)} \\ & \times\{r_{n,N}\exp(2ik_{z,n}d_n)\exp[ik_{z,n}(z - z_{n,\max})] \\ & - \exp[-ik_{z,n}(z - z_{n,\max})]\},\end{aligned}$$

$$\begin{aligned}\tilde{H}_y(z) = {} & \frac{t_{0,n}}{1 - r_{n,0}\cdot r_{n,N}\cdot\exp(2ik_{z,n}d_n)} \\ & \times\{r_{n,N}\cdot\exp(2ik_{z,n}d_n)\cdot\exp(ik_{z,n}(z - z_{n,\max})) \\ & + \exp(-ik_{z,n}(z - z_{n,\max}))\},\end{aligned} \tag{8}$$

where N is the index of the lower half space. $z_{n,\max}$ is the z

coordinate at the top of the nth layer. Then, the absorption in the nth layer is given by

$$A_n = \left| \frac{\tilde{E}_x(z_{n,\max} - d_n) + \tilde{H}_y(z_{n,\max} - d_n)}{2} \right|^2 - \left| \frac{\tilde{E}_x(z_{n,\max} - d_n) - \tilde{H}_y(z_{n,\max} - d_n)}{2} \right|^2 + \left| \frac{\tilde{E}_x(z_{n,\max}) - \tilde{H}_y(z_{n,\max})}{2} \right|^2 - \left| \frac{\tilde{E}_x(z_{n,\max}) + \tilde{H}_y(z_{n,\max})}{2} \right|^2. \quad (9)$$

The total absorption is given by

$$A_{\text{tot}} = \sum_n A_n = 1 - |r_{0,N}|^2 - |t_{0,N}|^2 \sqrt{\frac{\kappa_0}{\kappa_N}}. \quad (10)$$

Now we can define $A_{2\text{DEG}}$ as the absorption of the layer which contains the electron gas [Eq. (9)]. For our PC measurements we find that only the absorption in the electron gas is important.

III. SAMPLE STRUCTURE AND MEASUREMENT TECHNIQUE

Our sample is grown by molecular beam epitaxy on a GaAs substrate. To compensate the lattice mismatch between GaAs and $In_xAl_{1-x}As$, a metamorphic buffer was grown with continuously increasing In content up to $x=0.75$. The total thickness of this buffer is about 1.2 μm. A Si doped layer and a spacer follows with a thickness of 10 and 20 nm, respectively. The parabolic quantum well is composed by first increasing the In content up to $x=1$ and second decreasing it down to $x=0.75$. The total thickness of the quantum well is about 100 nm. The sample is capped with a 20-nm-thick $In_{0.75}Al_{0.25}As$ layer. The back side of the sample is wedged by an angle of 3° to suppress interference effects.

In our dielectric calculations, a GaAs substrate with a thickness of 30 μm is assumed with the phonon frequencies of 273.3 and 297.3 cm^{-1} for the transversal optical (TO) and longitudinal optical (LO) phonon mode,[26] respectively. In this layer, the dynamic dielectricity is $\kappa(\infty)=10.9$. The wedged interface to the lower half space is taken into account by defining the reflection and transmission coefficients to be $r_{ij}=0$ and $t_{ij}=1$, respectively. The metamorphic buffer of $In_xAl_{1-x}As$ is taken into account by 16 layers with linearly varying[27] values for the phonon frequencies and $\kappa(\infty)$. For the In contents of $x=0.0$, 0.5, 1.0 the parameters are given in Table I.

The parabolic quantum well is described by five layers with different In contents. Because of the fact that the total thickness of the quantum well of 100 nm is much smaller compared to the wavelength of interest (above 20 μm) and the thicknesses of the buffer (1.2 μm) and the substrate (30 μm), we neglect the detail of the charge distribution of the 2DEG in the quantum well. We assume that it is located in the center layer with $x=1.0$ and a width of 0.6 nm. The dielectric properties of this layer are described by Eq. (4). In this thin layer, the absorption of the optical phonons is weak and one can interpret the result of $A_{2\text{DEG}}$ described by Eq. (9) as the absorption of the 2DEG.

TABLE I. Values of the parameters for the metamorphic buffer of $In_xAl_{1-x}As$ for different In contents x.

x	$\omega_{\text{TO,InAs}}$	$\omega_{\text{LO,InAs}}$	$\omega_{\text{TO,AlAs}}$	$\omega_{\text{LO,AlAs}}$	$\kappa(\infty)$
0.0	243.3 cm^{-1}	243.3 cm^{-1}	360 cm^{-1}	402 cm^{-1}	8.16
0.5	231.1 cm^{-1}	243.3 cm^{-1}	350 cm^{-1}	371 cm^{-1}	10.21
1.0	218.9 cm^{-1}	243.3 cm^{-1}	340 cm^{-1}	340 cm^{-1}	12.25

The phonon damping parameters Γ are chosen to be 10 cm^{-1} for the metamorphic buffer and 2 cm^{-1} for the other layers. The carrier density and mobility of our sample are determined by magnetotransport measurements to be 4×10^{11} cm^{-2} and 20 000 cm^2/V s, respectively. The effective mass of the electron gas is determined by the CR at lower magnetic fields to be $m^*=0.033m_e$.

To increase the photoconductivity signal, a meandering Hall bar was fabricated by chemical wet etching. The Hall bar has a thickness of $W=75$ μm and a total length of $L=5$ cm. Ohmic contacts were prepared by evaporating AuGe alloys followed by annealing.

The sample is mounted in a variable temperature insert of a liquid He cryostat in the center of a superconducting solenoid which allows us to perform measurements for temperatures down to $T=1.5$ K and for external magnetic fields up to $B=12$ T. The FIR measurements are carried out using a Fourier transform spectrometer with a broadband Hg lamp. For the PC measurements, the sample itself is used as the detector. By applying a dc current through the source and drain contacts, the voltage drop between two probes is ac coupled to a broadband preamplifier and recorded as an interferogram. All data reported here were obtained in Faraday geometry.

IV. RESULTS

Figure 1(a) shows the photoconductivity spectrum of a parabolic $In_xAl_{1-x}As$ quantum well for a magnetic field of $B=8$ T at a sample temperature of $T=1.5$ K. The spectrum was taken by applying a dc current of 450 nA. The dashed vertical lines indicate the positions of the TO phonon modes of both $In_xAl_{1-x}As$ and GaAs. In addition, the frequency of the InAs-like LO phonon mode is shown.

In Fig. 1(c) the calculated total absorption A_{tot} of the whole multilayered structure is shown [Eq. (10)]. In (b) the absorption of only the electron gas $A_{2\text{DEG}}$ is plotted [Eq. (9)]. By comparison of the calculated absorption spectra and the experimental PC spectrum, one can see the strong similarity between the absorption of the electron gas and the photoconductivity response. In the calculated spectrum of the electron gas, only the cyclotron resonance is responsible for the absorption. At $B=8$ T the CR mode is expected at $\omega_c = 226$ cm^{-1} indicated by the arrow in Fig. 1(b). The absorp-

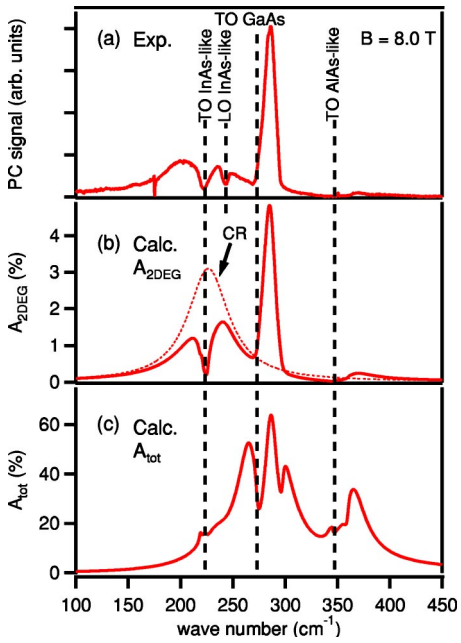

FIG. 1. (Color online) (a) Experimental photoconductivity spectrum of the parabolic quantum well structure for a magnetic field of 8 T. (b) Calculated spectrum of the absorption of the electron gas (A_{2DEG}). (c) Calculated total absorption spectrum (A_{tot}). The vertical lines indicate the positions of the TO phonon modes of $In_xAl_{1-x}As$ and GaAs and the InAs-like LO phonon mode of $In_xAl_{1-x}As$. The dotted curve in (b) shows the absorption of the CR mode at this magnetic field without including the phonon modes.

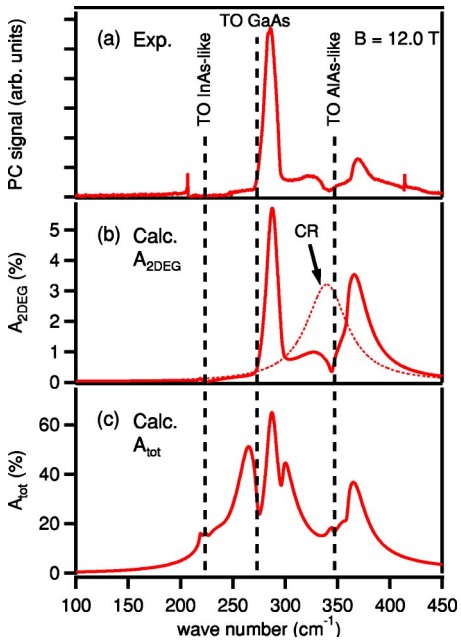

FIG. 2. (Color online) (a) Experimental photoconductivity spectrum of the parabolic quantum well structure for a magnetic field of 12 T. (b) Calculated spectrum of the absorption of the electron gas (A_{2DEG}). (c) Calculated total absorption spectrum (A_{tot}). The vertical lines indicate the positions of the TO phonon modes of $In_xAl_{1-x}As$ and GaAs. The dotted curve in (b) shows the absorption of the CR mode at this magnetic field without including the phonon modes.

tion of the electron gas A_{2DEG} without including the phonon modes $[\kappa(\omega)=\kappa(\infty)]$ is shown in Fig. 1(b) as the dotted line. For the result with including the phonon modes, one can see the strong deviation from the Lorentzian line shape which indicates the interference feedback of the multilayered structure with optical phonon modes. The strongest response in both the calculated absorption and the PC measurement can be found at $\omega=285$ cm^{-1} inside the reststrahlen band of the GaAs substrate.

A significant deviation between the calculated absorption of the electron gas and the experimental result can be found at the InAs-like LO phonon mode of $In_xAl_{1-x}As$. In the experiment, a reduced response is observed which shows an anticrossinglike behavior by switching the B field. This effect reflects the microscopical electron-LO-phonon coupling[6–11] which is not taken into account in our dielectric calculations.

In Fig. 2, the corresponding results for a magnetic field of $B=12$ T are shown. At this magnetic field, the CR mode is expected at $\omega_c=340$ cm^{-1} [arrow and dotted curve in (b)]. By comparing the experimental PC measurement (a) to the calculated absorption A_{2DEG} of the electron gas (b), one finds an excellent agreement. The only deviation can be found for frequencies above 350 cm^{-1}. In this region, the intensity of the FIR radiation is reduced by the experimental setup. In the calculations, a constant intensity is assumed.

The total absorption A_{tot} of the whole multilayered structure seems to be nearly independent of the external magnetic field [see Fig. 1(c) and 2(c)]. The total absorption is dominated by the absorption of the optical phonons mainly from the substrate layer and the metamorphic buffer. By comparing these calculated results to the measurement, one can see that the absorption of the lattice has no significant influence on the photoconductivity in our structure. This indicates that the PC in such a structure is dominated by the direct heating of the electron gas. Indirect heating processes by absorption in the bulk followed by heat transport to the electron gas seem to be very weak.

In Fig. 3, we have plotted the peak positions of the photoconductivity spectra. In addition, the results of the dielectric calculations (A_{2DEG}) are shown as solid lines. The gray areas represent the regions of the TO phonon modes in $In_xAl_{1-x}As$. The dashed lines depict the positions of the LO phonon modes and the TO phonon of the GaAs substrate.

By comparing the experimental data to the results of the dielectric calculations, one finds an excellent agreement except for the region around the InAs-like LO phonon mode. Here, the electron-LO-phonon coupling occurs which is not taken into account in our calculations.

The strong photoconductivity response inside the reststrahlen band of the GaAs substrate can be observed for a large magnetic field regime. In the regime of the InAs-like TO phonons, a strong splitting can be found which can be well described by the theory. The response above the AlAs-like TO phonons can also be observed for a large range of B. Here, the signal amplitude is much lower than for the mode at 285 cm^{-1} [see Fig. 1(a)]. Therefore, it cannot be spectrally resolved for magnetic fields below 8 T.

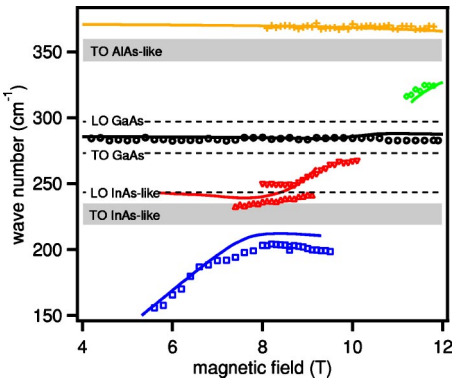

FIG. 3. (Color online) Magnetic field dispersion of the resonance peaks of the FIR-PC spectra measured on the parabolic quantum well structure. The solid lines show the results of the dielectric calculations. The gray areas indicate the regions of the TO phonon modes in $In_xAl_{1-x}As$. The dashed lines represent the LO phonon modes and the TO phonon mode of the GaAs substrate.

Note that in the theory only the absorption of the cyclotron resonance is calculated. The CR leads to a single absorption process whose energy is proportional to the magnetic field. The strong modulation of the dielectric properties and the interference effects of the multilayered structure yield the multi-peak behavior with splittings around the TO phonons which require no microscopic electron-phonon-coupling mechanism.

V. SUMMARY

In summary, we have shown photoconductivity spectra of a 2DEG in a parabolic quantum well of $In_xAl_{1-x}As$ grown on a GaAs substrate. By applying an external magnetic field, we have tuned the cyclotron resonance across the reststrahlen bands of both $In_xAl_{1-x}As$ and GaAs. In the vicinity of the optical phonon frequencies, strong deviations from the Lorentzian line shape are observed. We have performed dielectric calculations by solving the Fresnel equations of the whole multilayered structure. Within these calculations, we extract the theoretical expected absorption of the whole sample and the absorption of the electron system only. By comparing the results of our measurements to the calculations, we find that the PC response can be well described by the absorption of the electron gas. Therefore, the photoconductivity signal in such a structure is dominated by the heating resulting from the absorption of the electron gas. No evidence for an indirect heating arising from the absorption of the bulk and heat transport to the electron gas are found in our measurements.

In both the experiment and the theory, we find that the CR excitation is damped in the vicinity of TO phonon modes. This damping can be explained by the strong influence of the TO phonons on the dielectric properties. In contrast, we find an enhancement of the CR inside the GaAs- and AlAs-like reststrahlen bands. This behavior can be well explained by the interference effects of the multilayered structure which lead to a reflection of the FIR radiation by the buffer and substrate.

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