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Bolometric effect in the far-infrared response of a conducting layer on a semi-insulating substrate

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Far-infrared photoconductivity measurements were performed on In-doped CdTe layers grown on a semi-insulating GaAs substrate. A thin layer of ZnTe was usually grown between the CdTe and GaAs. The photoconductivity spectra exhibited an extremely rich structure. Some of the peaks were identified as intradonor transitions, while others, whose energy does not change with magnetic field, were more difficult to allocate. To explain the spectra, calculations of the complete far infrared optical response of the CdTe/ZnTe/GaAs structures were performed and compared with the photoconductivity results. The mathematical model was formulated in terms of the dynamic dielectric function of the structure, and calculations were done by means of the transfer matrix method. A physical model is proposed, linking the absorption of light by the crystal lattice with the observed photoconductivity. The same effect is observed in similar measurements performed on other materials, such as GaN and GaAs. [S0163-1829(99)06239-6]

I. INTRODUCTION

Measurements of far-infrared photoconductivity are a well known and extremely efficient tool for examining shallow donor transitions (e.g., Refs. 1 and 2). The photoconductive response at low temperature is much more sensitive than absorption measurements, as the photogeneration of even a relatively small number of conducting electrons can lead to large changes in the resistance of a sample. Moreover, the photoconductive method may be used even in the Reststrahlen region of a semiconductor, where the transmission of a typical sample is practically zero. This allows observations of the resonant polaron effect in a very wide range of energies.[3] However, as will be shown in this paper, care should be taken in interpreting the photoconductivity spectra of thin conducting samples on semi-insulating substrates. Especially in and near the Reststrahlen region, which falls in the far-infrared for most semiconductors, the transmission of light through a multilayered semiconductor structure can be an extremely complicated process. The optical properties of the component layers change rapidly with the wavelength, and the effects due to consecutive reflections, absorptions and transmissions can lead to quite startling phenomena in optical spectra. Such effects are known to significantly affect line positions or line shapes[4–6] in transmission measurements. Strange features have also been reported in photoconductivity studies of *n*-type GaAs layers[7]. In this paper we show results of photoconductivity measurements performed on CdTe layers on GaAs substrates and suggest a physical mechanism to explain the strange features found in the spectra. We also find that the same mechanism appears to be at work in samples of *n*-doped GaN on a sapphire substrate.

II. SAMPLES

A series of CdTe layers doped with indium were investigated. Details of sample growth are given elsewhere.[8] The thicknesses of the CdTe layers varied between 1 and 7.5 μm. Prior to the deposition of the CdTe film, the GaAs substrate was covered with an undoped ZnTe buffer. This ZnTe layer was used to reduce the strong mismatch between CdTe and GaAs and to stabilize growth in the (100) direction. In some samples an additional layer of undoped CdTe was grown before the deposition of the In doped layer. The thickness of the substrate GaAs layer was 400 μm. The thicknesses of the different layers for the samples used in the study are listed in Table I.

Identical measurements were performed on a sample consisting of a 1-μm-thick *n*-type GaN layer on a sapphire substrate. A more detailed description of this series of samples has been given elsewhere.[9]

TABLE I. CdTe samples used in the study.

Sample name	6225A	6275C	6275B	6235B
CdTe thickness (μm)	7.5	3	3.5	1
ZnTe thickness (μm)	0.001	0.001	0	0.15

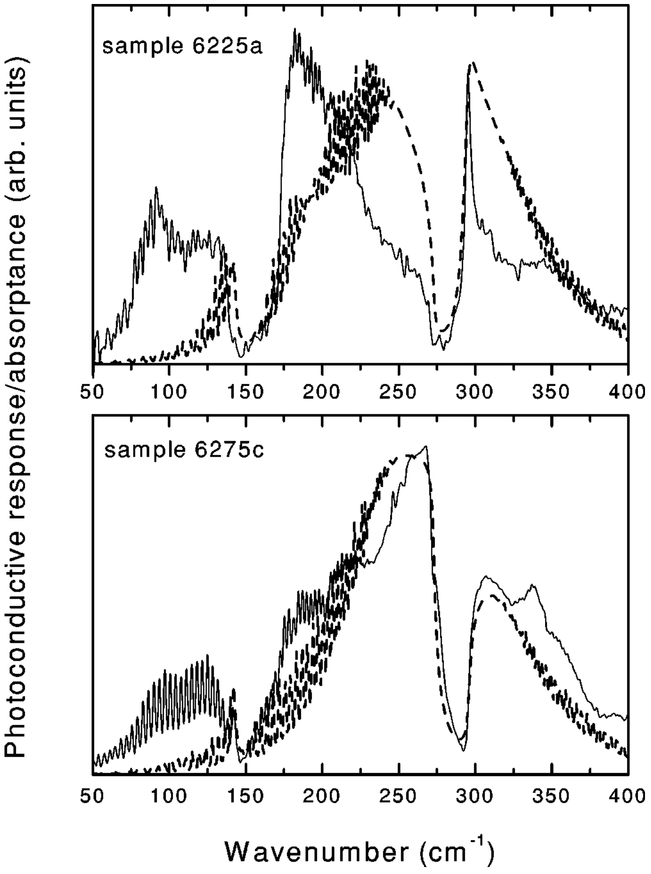

FIG. 1. Far-infrared photoconductivity spectra of CdTe samples (solid lines) and absorptance calculated for each sample (dotted lines).

III. MEASUREMENTS IN CdTe

Photoconductivity (PC) measurements were made with a constant voltage applied across sample connections which were approximately 5 mm apart. The resistance of the samples was larger than 70 MΩ at 4.2 K. The measurements were carried out at temperatures between 2 and 9 K. A 5 MΩ load resistor was connected in series with the sample and measurements were performed in the Ohmic region of the current density—electric field characteristics of the sample. PC spectra were recorded in the spectral range of 50–350 cm^{-1} using a fast-scan Fourier-transform spectrometer (Bruker IFS 113v). A resolution of 1 cm^{-1} was used.

Typical PC spectra at zero magnetic field for four different samples are shown in Figs. 1 and 2. It may be seen that the shape of the spectrum depends strongly on the sample—that is, on the thickness of the CdTe layer. A common feature of all the spectra is the dip around 150 cm^{-1}, which corresponds to the Reststrahlen band in CdTe. Very little light penetrates into the sample at this wavelength, because of the strong reflection coefficient. A small but distinct peak can be seen in some samples at 144 cm^{-1}—the energy of the TO phonon in CdTe. The second feature occurs at energies between 270–300 cm^{-1}, which in turn is the Reststrahlen band of GaAs. There is either a peak in the general region of the TO phonon of GaAs (sample 6275C) or very near the LO phonon energy (samples 6225A, 6235B). It should be noted that the positions of these features do not change with magnetic field.

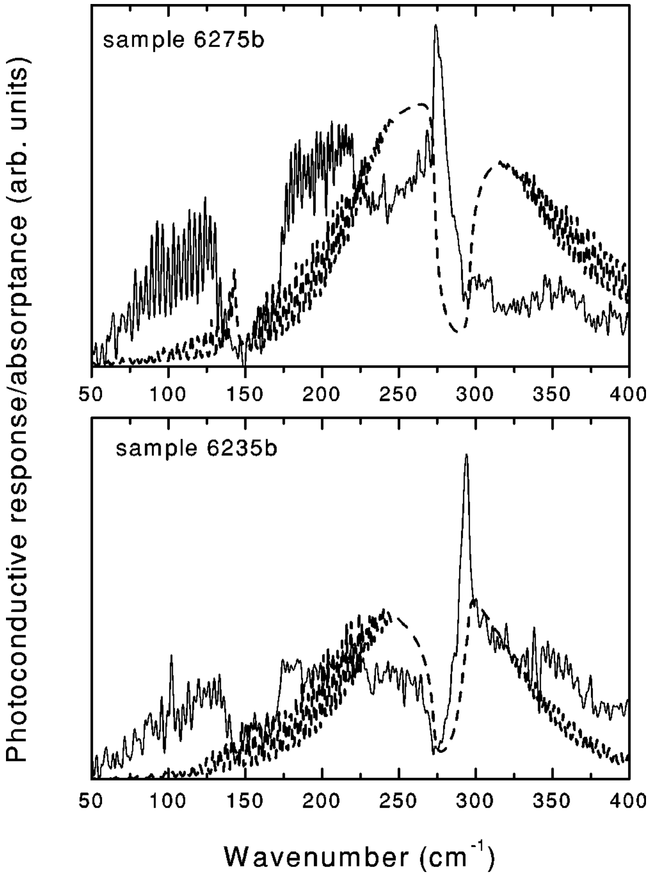

FIG. 2. Far-infrared photoconductivity spectra of CdTe samples (solid lines) and absorptance calculated for each sample (dotted lines).

IV. THE PHYSICAL MODEL

The conductivity of an *n*-type semiconductor layer at low temperatures is usually strongly temperature dependent. In fact, transport measurements performed on the same samples as those used in these experiments have shown[10] that at low temperatures their resistivity is temperature-activated with an activation energy $\triangle E \approx 1$ meV:

$$R = R_0 \exp\left(\frac{\triangle E}{kT}\right).$$

This means that with a resistance of the order of 100 MΩ at 4.2 K, an increase of the temperature by as little as 10 mK will lead to a relative change of the resistance of about 0.8%, which is readily detectable.

This sensitivity to temperature means that such a doped layer, placed on a semi-insulating substrate, can act as a bolometer, detecting changes in the temperature of the substrate and of the layer itself. This process must be taken into account in the analysis of photoconductivity spectra, since light incident on a sample is absorbed by the lattice, leading to heating of the sample. This is especially true for wavelengths close to the TO phonon energy. This heating changes the resistance of the layer, i.e., is detected by the bolometer, and shows up in its photoconductive response although, properly speaking, it is not due to photoconductivity.

In order to explain the observed photoconductivity spectra, we calculated the absorptance of a sample composed of a

CdTe layer, a ZnTe layer and a GaAs substrate. We assumed that the temperature change of the sample will be proportional to the absorbed energy. Thus, the energy absorbed in the CdTe layer, the ZnTe layer and the GaAs substrate causes an increase of the temperature of the sample. This increase in turn leads to a change of the resistivity of the CdTe:In layer, observed in the photoconductivity. The doped CdTe layer, being an integral part of the structure, thus acts as a bolometer, detecting the energy absorbed in the sample.

V. THE MATHEMATICAL MODEL

The reflection, transmission and absorption of light in a semiconductor can be described in terms of its complex refractive index $n^*(\omega)$. This in turn is connected to the (complex) dynamic dielectric function ϵ^* by the relation

$$(\epsilon^*)^{1/2}=n^*=n+ik. \tag{1}$$

The lattice contribution to the dielectric function, described by a single oscillator model and taking into account the Lyddane-Sachs-Teller relation[11] is given by

$$\epsilon_l^*(\omega)=\kappa_\infty+\frac{\omega_{TO}^2(\kappa_0-\kappa_\infty)}{\omega_{TO}^2-\omega^2+i\gamma\omega},$$

where ω_{TO} is the frequency of the transverse optical phonon, κ_0 and κ_∞ are the low frequency and optical (high frequency) dielectric constants, respectively, and γ is a damping parameter.

This may be rewritten for clarity as

$$\epsilon_l^*(\omega)=\kappa_1-i\kappa_2,$$

where

$$\kappa_1=\kappa_\infty+\frac{\omega_{TO}^2(\kappa_0-\kappa_\infty)(\omega_{TO}^2-\omega^2)}{(\omega_{TO}^2-\omega^2)^2+\gamma^2\omega^2},$$

$$\kappa_2=\frac{\omega_{TO}^2(\kappa_0-\kappa_\infty)\gamma\omega}{(\omega_{TO}^2-\omega^2)^2+\gamma^2\omega^2},$$

and the real and imaginary parts of the complex refractive index are then

$$k=\frac{1}{\sqrt{2}}[(\kappa_1^2+\kappa_2^2)^{1/2}-\kappa_1]^{1/2},$$

$$n=\frac{1}{\sqrt{2}}[(\kappa_1^2+\kappa_2^2)^{1/2}+\kappa_1]^{1/2}.$$

Having these values, the response of a semiconductor system composed of N layers may be described by means of a complex 2×2 matrix[12] linking the incident $(\vec{E}_I)$, transmitted $(\vec{E}_T)$ and reflected $(\vec{E}_R)$ waves by means of the relation

$$\begin{pmatrix}\vec{E}_I\\ \vec{E}_R\end{pmatrix}=\mathcal{M}\begin{pmatrix}\vec{E}_T\\ \vec{0}\end{pmatrix}. \tag{2}$$

The transfer matrix $\mathcal{M}$ of the whole system is a product of the transfer matrices of the component layers, $\mathcal{M}=\mathcal{M}_1\mathcal{M}_2,\ldots,\mathcal{M}_N\mathcal{M}_{N+1}$. The expressions for these may be derived from a consideration of the boundary conditions for the electromagnetic waves at the interfaces. Assuming the incident wave to be monochromatic, the layers to be homogeneous and the response function to be local, the expressions for the individual matrices can be written as

$$\mathcal{M}_i=\begin{pmatrix}\frac{(n_i^*+n_{i-1}^*)}{2n_{i-1}^*}e^{-i(\frac{\omega}{c})n_{i-1}^*d_i} & \frac{(n_i^*+n_{i-1}^*)}{2n_{i-1}^*}e^{-i(\frac{\omega}{c})n_{i-1}^*d_i}\\ \frac{(n_i^*+n_{i-1}^*)}{2n_{i-1}^*}e^{-i(\frac{\omega}{c})n_{i-1}^*d_i} & \frac{(n_i^*+n_{i-1}^*)}{2n_{i-1}^*}e^{-i(\frac{\omega}{c})n_{i-1}^*d_i}\end{pmatrix}. \tag{3}$$

The index i denotes the ith layer, and d is the thickness of the layer. The complex reflection and transmission coefficients of the system [from Eq. (2)] are written as $r=\mathcal{M}_{21}/\mathcal{M}_{11}$ and $t=1/\mathcal{M}_{11}$, respectively. The absorptance, i.e., the energy absorbed in the sample, is then given by

$$A=1-rr^*-tt^*. \tag{4}$$

This value should be distinguished from the absorption coefficient α, usually defined in terms of the imaginary part of the refractive index as $\alpha=4\pi\omega k/c$. The wavelength-dependent absorption coefficient describes the probability of absorbing a photon at a given wavelength, while the absorptance gives the total energy absorbed by the system, and depends on the sample dimensions and its reflectivity. Thus the spectral dependence of the two may be completely different. This approach takes into account the multiple reflections and refractions of light in the multilayered structure.

VI. CALCULATIONS

The spectrum of the incident light was approximated by a Gaussian function, fitted to the response of the spectrometer measured with a DTGS detector, a mercury lamp and the same beam splitter as used in the measurements. The absorption spectrum $A(\omega)$ was then calculated from Eq. (4). No adjustable parameters at all were used, and of course we do not assume that absorption and photoconductivity are the same thing. However, as we will show in the next section, already such an extremely crude model provides a surprisingly good description of the complicated spectra observed in the photoconductivity measurements.

The absorption spectra were calculated for layer thicknesses corresponding to those of the measured samples. The material parameters used in the calculations are given in Table II. The data for CdTe and ZnTe are taken from Ref. 13, while those for GaAs are given after Ref. 14. The same model, with a modified dielectric function accounting for four phonon modes in sapphire,[15] was used to calculate the absorptivity of a GaN layer on a sapphire substrate. The parameters in this case were taken from the above-mentioned work.

VII. RESULTS

The PC spectra for all samples, together with the calculated absorption spectra, are shown in Figs. 1 and 2. It can be

TABLE II. Material constants used in the calculations.

Material	κ_0	κ_∞	ω_{TO} (cm^{-1})	γ (cm^{-1})
CdTe	10.23	7.21	144.7	2
ZnTe	9.86	7.28	180.0	2
GaAs	12.41	10.60	173.1	2
GaN	9.49	5.35	560.0	17
Sapphire	10.25	3.08	386.2	1.4
			440.2	1.5
			568.9	3.2
			636.1	3.8

observed that in most cases the calculated absorption spectra recreate the characteristic features of the photoconductivity spectra in such a way as to validate the mechanism of signal generation described in the previous section. It should again be noted here that the relationship between the absorptance and the photoconductive response is not expected to be direct and straightforward, for several reasons:

(1) Other photoconductive mechanisms, e.g., photothermal ionization of shallow donors, are also present—the calculation takes into account only the absorption by the lattice and the resultant heating.

(2) The bolometric response does not necessarily have to be linear, therefore the relative signal strength does not have to follow the calculated curve exactly.

(3) The calculation takes no account of the imperfections which must exist at the interfaces.

In spite of all this, the shapes of the calculated absorptance spectra reproduce the behavior of the photoconductive response in a very reasonable way. A dip is observed in the Reststrahlen band of CdTe, usually preceded by a small peak, also visible in most PC spectra. Its energy is close to that of the TO phonon in CdTe. For samples with a 1-μm thick layer of CdTe (6235B) the spectrum is then flat up to the Reststrahlen band in GaAs, where another dip is visible. A peak whose energy usually coincides closely with that of the LO phonon in GaAs follows. Sample 6275C, with a CdTe thickness of 3 μm, shows a maximum at about 270 cm^{-1} followed by a dip in the Reststrahlen band of GaAs. The thickest sample (6225A) exhibits an increase of absorption, then a dip at the GaAs Reststrahlen band and a peak at the GaAs LO-phonon energy.

Deviations from the remarkable similarity between the calculated absorption curves and the measured PC signal may be observed for sample 6275B, where the shape of the spectrum is similar but the position of the maximum is different. The position of the main maximum in the spectrum is rather sensitive to the thickness of the CdTe layer, which might be different from the nominal one, although it must be admitted that there is no thickness which allows the experimental position to be reproduced in the calculation. A possible explanation is that in sample 6275B, which has no buffer ZnTe layer, the lattice mismatch and resulting strain strongly influence the local lattice parameters. Misfit strain is known to change the phonon energies in semiconductor structures.[16] The photoconductive signal at around 100 cm^{-1}, which is larger than the calculated absorptivity for all samples, is due to the electronic shallow donor $1s$-$2p_+$ transitions, as demonstrated by magnetic field measurements.[3]

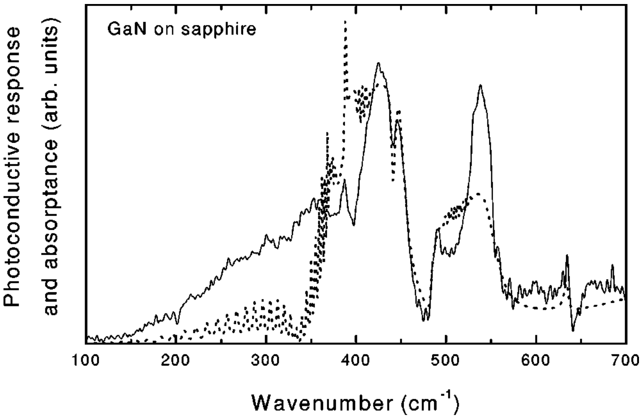

FIG. 3. Far-infrared photoconductivity spectra of a GaN layer on a sapphire substrate (solid lines) and absorptance calculated for this sample (dotted lines).

The resemblance between the calculated absorptivity spectrum and the measured photoconductivity is also striking for the GaN sample (Fig. 3): all of the most important features in the range 300–700 cm^{-1} are recreated, and the general form is remarkably similar. As before, the photoconductive signal at low energies is due to intradonor transitions.[17]

VIII. CONCLUSIONS

A physical mechanism is proposed to explain the complex photoconductivity spectra of In-doped CdTe layers grown on GaAs substrates. According to this model, changes observed in the photoconductivity of the CdTe:In layer arise from a bolometric-type detection of the heating of the structure due to lattice absorption by the structure components. The local increase of temperature affects the conductivity of the doped layer, which acts as a bolometer integrated with the sample. The intricate and surprising shape of the observed spectra are due to multiple reflections in the multilayered structure. Simple calculations of the absorptance of such a system, performed in the formalism of the dynamic dielectric function, show good qualitative agreement with observed photoconductivity spectra for most of the samples, indicating that the model suggested to explain the origin of the signal is correct. It should also be added that a similar ‘‘strange’’ feature, notably a peak in the photoconductivity at the LO-phonon energy, has also been observed in PC measurements of thin weakly n-type GaAs layers.[7] This feature can perfectly well be recreated using the model presented above.[18] The model is also very efficient in recreating the extremely complicated PC spectra of n-type GaN layers on sapphire substrates. It appears therefore that the bolometric effect described above is a general phenomenon which should always be taken into account when analyzing far-infrared photoconductivity experiments performed on thin conducting layers.

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