Cyclotron-phonon resonance with phonon absorption in *n*-InSb

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Peaks have been discovered in the magnetic-field dependence of the photoconductivity of *n*-InSb in fields up to 400 kOe at $T > 80$ K. The positions of these peaks along the field scale and their temperature dependence provide evidence that this is the first observation of a cyclotron-phonon resonance involving an absorption of phonons.

The cyclotron-phonon resonance predicted by Bass and Levinson[1] has been studied in several semiconductors.[2,3] Since the experiments have been carried out at (or slightly above) $T = 4.2$ K, the only processes which have been observable are those involving the emission of one or two[4] phonons. At higher temperatures, by analogy with the magnetophonon resonance,[5] and in accordance with the theoretical predictions of Ref. 1, processes involving an absorption of phonons may occur. In other words, there may be a resonant absorption of radiation of frequency ω under the condition

$$\hbar\omega = E_N - E_0 - \hbar\omega_{LO}, \qquad (1)$$

where E_N and E_0 are the energies of Landau levels, and ω_{LO} is the frequency of a longitudinal optical phonon.

Such resonances will be shifted up the magnetic-field scale from the cyclotron resonance and its harmonics. The amplitudes of these resonances should increase with increasing temperature within a certain range.

A study of quantum magnetooptic effects at $T \geqslant 77$ K will obviously require significantly stronger magnetic fields and, correspondingly, radiation frequencies higher than in low-temperature measurements.

In this letter we report a study of the photoconductivity of *n*-InSb excited by a CO_2 laser in pulsed magnetic fields up to 400 kOe in the temperature interval 77–160 K. We will show that resonances satisfying condition (1) occur under these conditions.

Composite filters[1)] are used to select two lines, with the wavelengths $\lambda_1 = 10.62$ μm and $\lambda_2 = 9.57$ μm, from the beam from an LG-705 laser. This light is brought to the sample, in a cryostat, by a lightguide (a hollow nickel-silver tube terminating in a focusing optical fiber). The cryostat is placed in the induction coil of a pulsed-magnetic-field generator, which generates a field $H_{\max} = 400$ kOe. The lobed diaphragm camera shutter synchronized with the triggering of the magnetic-field generator transmits the laser light exclusively during the magnetic-field pulse ($t_p = 4$ ms). The photocon-

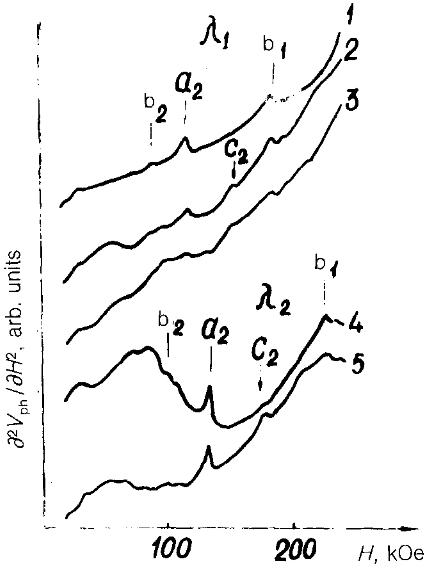

FIG. 1. Experimental curves of $\partial^2 V_{ph}(H)/\partial H^2$ in magnetic fields 0–250 kOe. $\lambda_1 = 10.62$ μm: 1—77 K; 2—88 K; 3—150 K. $\lambda_2 = 9.57$ μm: 4—81 K; 5—98 K.

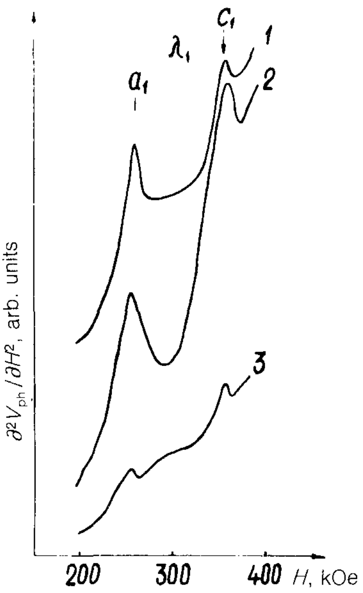

FIG. 2. Experimental curves of $\partial^2 V_{\rm ph}(H)/\partial H^2$ in magnetic fields 200–400 kOe for $\lambda_1 = 10.62$ μm. 1—93 K; 2—120 K; 3—155 K.

ductivity signal $V_{\rm ph}(H)$ from the potential probes on the sample is sent through a differentiator (an RC circuit) to the input of the IV14 amplifier of an S8-13 storage oscilloscope. The second derivatives $\partial^2 V_{\rm ph}(H)/\partial H^2$ are displayed on the screen.

Figures 1 and 2 are experimental curves for an n-InSb sample with a carrier density $n = 9 \times 10^{13}$ cm^{-3} and a mobility $\mu = 4.5 \times 10^5$ cm^2/(V·s) at $T = 77$ K. The curves in Fig. 1 were recorded in magnetic fields up to 225 kOe. Figure 2 shows experimental curves of $\partial^2 V_{\rm ph}(H)/\partial H^2$ over the magnetic-field interval 200–400 kOe. Curve 1 in Fig. 1, recorded at 77 K, has the maxima (marked by the lines) which were observed previously on recordings of the photoconductivity in n-InSb in magnetic fields up to 200 kOe at low temperatures (8–32 K) and which lie very close to λ_1, the wavelength of the exciting light[6] (10.59 μm). Peak a^2 is a harmonic of the cyclotron resonance (the $0^+ \to 2^+$ transition), while peaks b_1 and b_2 are harmonics of a cyclotron resonance involving the emission of an $LO(G)$ phonon [the transitions $0^+ \to 1^+ + LO(\Gamma)$ and $0^+ \to 2^+ + LO(\Gamma)$, respectively]. The positions of the lines correspond to the calculated values ($H^{\rm theo}_{\rm res}$) of the magnetic field at which these resonances should occur at $T = 80$ K and at photon energies $h\lambda_1/c = 116.76$ meV and $h\lambda_2/c = 129.57$ meV. The Landau energy levels were calculated from the formula given in Ref. 7 with the following values for the band parameters: $E_g = 228$ meV (Ref. 8), $m_c = 0.01393\, m_0$ (Ref. 9), and $\Delta = 810$ meV (Ref. 7). We assigned the energy $\hbar\omega_{LO}$ the value of 24.4 meV. As the temperature is raised from 80 K to 150 K, the calculated values of $H^{\rm theo}_{\rm res}$ vary less than 0.8%; this variation could not be seen experimentally.

In addition to these resonances (a_2, b_1, and b_2) we see a peak on curves 2–5 in Fig. 1, i.e., at $T > 77$ K, at the magnetic field $H^{\rm expt}_{\rm res} = 150 \pm 5$ kOe, marked by arrow c_2.

On the curves in Fig. 2 we see two resonances over the magnetic-field interval 200–400 kOe at λ_1 and $T > 80$ K: a large peak, a_1 at $H_{\text{res}}^{\text{expt}} = 260 \pm 8$ kOe c_1 at $H_{\text{res}}^{\text{expt}} = 350 \pm 11$ kOe. With increasing temperature, the height of peak c_1 increases with respect to that of peak a_1, while their positions along the magnetic-field scale remain the same (within the error, of about 3%), in the determination of $H_{\text{res}}^{\text{expt}}$.

Peak a_1 is a cyclotron resonance (the 0^+–1^+ transition), for which the theoretical field is $H_{\text{res}}^{\text{theo}} = 263.7 \pm 1.3$ kOe at $T = 80$ K and at an incident-photon energy of 116.76 meV.

The positions of the arrows in Figs. 1 and 2 correspond to the calculated values of $H_{\text{res}}^{\text{theo}}$ at $T = 80$ K for a cyclotron-phonon resonance caused by the absorption of an $LO(\Gamma)$ phonon. Specifically, peak c_1 corresponds to the transition $0^+ \to 1^+ - LO(\Gamma)$, and c_2 to the transition $0^+ \to 2^+ - LO(\Gamma)$. The values of $H_{\text{res}}^{\text{theo}}$ for these resonances are 354.2 ± 1.7 kOe and 154.1 ± 0.7 kOe, respectively. We see that the positions of peaks c_1 and c_2 along the magnetic-field scale coincide well (within the experimental error) with the values of $H_{\text{res}}^{\text{theo}}$ for the fundamental mode of the cyclotron-phonon resonance due to the absorption of an $LO(\Gamma)$ phonon. The effect of the temperature on the heights of these peaks also agrees with their interpretation as resonances caused by the absorption of a phonon.

In summary, these results furnish grounds for suggesting that we have observed a cyclotron-phonon resonance involving the absorption of a longitudinal optical phonon. Our studies show that the cyclotron-phonon resonance involving the absorption of phonons can be utilized to determine the parameters of the band structure of semiconductors at comparatively high temperatures.

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[1)] The filters were fabricated at the Central Design Bureau of the Academy of Sciences of the Belorussian SSR.

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