MAGNETOPHONON RESONANCE IN n-InAs

D. V. Mashovets, R. V. Parfen'ev, and S. S. Shalyt
Institute of Semiconductors, Academy of Sciences, USSR

Submitted 18 March 1965

It was shown in several experimental papers [1] that magnetophonon resonace causes the field dependence of the magnetoresistance and magneto-thermal emf of n-InSb to acquire an oscillating character under certain conditions. The physical nature of this new effect, theoretically predicted by Gurevich and Firsov [2], is connected with the fact that inelastic scattering of the electrons by optical phonons in a strong magnetic field ($uH/c >> 1$) becomes more intense when the distance between the Landau levels

$$\epsilon_N = (N + \frac{1}{2})\hbar\frac{eH}{m^*c} \qquad (1)$$

becomes equal to the energy of the optical phonons $\hbar\omega_0$. The formula derived from this condition

$$(H_{N_i} - N_j)^{-1} = \frac{1}{\omega_0}\frac{e}{m^*c}(N_i - N_j) \qquad (2)$$

determines a series of magnetic field values at which magnetophonon resonace takes place. Taking into account the spin splitting of the Landau levels, the resonant reciprocal field (2) can either remain unchanged or increase or decrease by an amount $g\mu_B/\hbar\omega_0$.

In the present study we investigated the longitudinal magnetoresistance of polycrystalline samples of n-InAs ($n = 1.25 \times 10^{16}$ cm^{-3}, $U_{90°K} = 6 \times 10^4$ cm^2/V-sec).

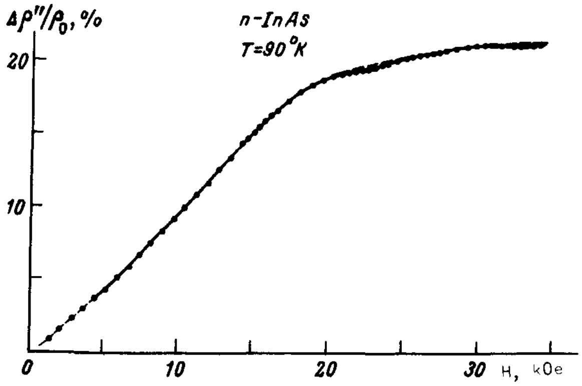

Fig. 1. Dependence of the magnetoresistance of n-InAs on the intensity of the magnetic field at 90°K.

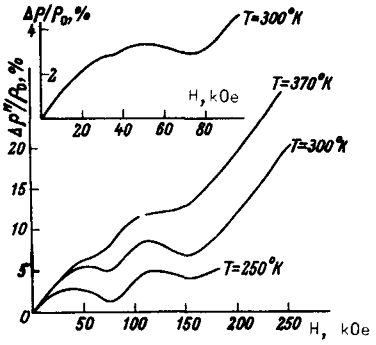

Fig. 2. Dependence of the magnetoresistance of n-InAs on the intensity of the longitudinal pulsed magnetic field at various temperatures.

Figure 1 shows the experimental curve obtained in stationary fields at T = 90°K. The two weakly pronounced minima on this curve at H = 22 and 33 kOe can be related to transitions between unsplit Landau levels $N = 0 \rightleftarrows N = 3$ (H_{0-3}= 21 kOe) and $N = 0 \rightleftarrows N = 2$ (H_{0-2}= 32.5 kOe). The limiting frequency of the longitudinal optical oscillations for InAs was assumed to be $\omega_0 = 4.6 \times 10^{13}$ sec^{-1} [3]. A clearer picture of the oscillations of longitudinal magnetoresistance was obtained by investigating n-InAs in stronger pulsed fields at higher temperatures. The experimental curves (Fig. 2) show three maxima at H = 38, 78, and 150 Oe.

The first of these maxima can be related to the already considered transition $N = 0 \rightleftarrows N = 2$, and its shift (33 → 38 kOe) can be attributed to the increased temperature of the experiment. The temperature shift of the minimum can be explained within the framework of the theory of the longitudinal effect.

The second experimental minimum at $H \approx 78$ kOe can be related to the transition $N = 0 \rightleftarrows N = 1$. In calculating the resonant field for this transition, it is important to take into account the dependence of the effective mass of the electrons in the InAs conduction band on the energy, and consequently on H. Taking into account the dependence m*(H) obtained in cyclotron resonance experiments [4], we obtain H_{0-1} = 71 kOe (the dependence m*(H) was taken into account above in the same manner).

As a sequel to the foregoing conclusions we can attempt to relate the next experimental minimum ($H \approx 150$ kOe) with the transitions $N = 0^- \rightleftarrows N = 0^+$ or $N = 0^+ \rightleftarrows N = 1^-$. If we estimate the g-value from the theoretical formula derived in [5] ($|g(0)| = 15 - 18$), then the resonant value of the field $H_{0^+-0^-}$ lies in the 300 - 350 kOe region. In connection with this result, we have further investigated the longitudinal magnetoresistance of n-InAs at 200 - 400 kOe and observed no noticeable deviation from a smooth variation. Thus, the minimum at H = 150 kOe must be connected with the second possible transition $N = 0^+ \rightleftarrows N = 1^-$. If we recognize that according to our data the experimental minima shift by 10 - 15%, and if we assume for a resonant field $H_{0^+-0^-}$ = 130 kOe and $|g| = 14$ (at H = 130 kOe), then we obtain for the effective mass in such a field the reasonable value $m^*/m_0 = 0.032$.

If we use for the theoretical determination of the resonant conditions the formula derived by Lax et al. [6] for the energy spectrum of the electrons in the magnetic field with allowance for non-parabolicity, then we obtain the following values of the magnetic field: H_{0-3}= = 22.5 kOe, H_{0-2} = 34.5 kOe, H_{0-1} = 72 kOe, $H_{0^+-1^-}$ = 94 kOe, and $H_{0^--0^+}$ = 510 kOe. The first three values, calculated without account of spin splitting, are in good agreement with the experimental data. The fourth value (H = 94 kOe), obtained with allowance for spin splitting of the Landau levels, has found no clear-cut manifestation in the experiment.

The foregoing discussion of the experimental results represented in Fig. 2 is an approximate estimate for the following reasons: 1) In the theory of magnetophonon oscillations of the longitudinal magnetoresistance (unlike the transverse magnetoresistance), the position of the resonant values of the field relative to the extrema of the experimental curve is not defined, since it depends in a complicated manner on the relative role of the inelastic scattering mechanism. Only at sufficiently low temperatures does the resonance cause a minimum to appear. 2) We are analyzing non-periodic oscillations, which are connected with the spin splitting of the lower quantum Landau levels in a band with a non-quadratic dispersion law. The influence of the latter circumstance on the spin splitting of the levels and on the transitions between them has not yet been fully treated in the theory.

An investigation of the transverse magnetoresistance of n-InAs in the same region of temperatures and fields disclosed no noticeable oscillations.

[1] Parfen'ev, Shalyt, and Muzhdaba, JETP 47, 444 (1964), Soviet Phys. JETP 20, 294 (1965); Muzhdaba, Parfen'ev, and Shalyt, FTT 6, 3194 (1964), Soviet Phys. Solid State 6, 2554 (1965); Mashovets, Parfen'ev, and Shalyt, JETP 47, 2007 (1964), Soviet Phys. JETP 20, 1348 (1965); Tsidil'kovskii, Aksel'rod, and Sokolov, FTT 7, 316 (1965); Soviet Phys. Solid State 7 (1965).
[2] V. L. Gurevich and Yu. A. Firsov, JETP 40, 199 (1961) and 47, 734 (1964), Soviet Phys. JETP 13, 137 (1961) and 20, 489 (1965).
[3] M. Hass and B. W. Henvis. J. Phys. Chem. Solids, 23, 1099 (1962).
[4] Palik, Teitler, and Wallis, J. Appl. Phys. Suppl. 32, 2132 (1961).
[5] Roth, Lax, and Zwerdling, Phys. Rev. 114, 90 (1959).
[6] Lax, Mavroides, Zeiger, and Keyes, Phys. Rev. 122, 31 (1961).

HARD VAVILOV-CERENKOV RADIATION IN A SINGLE CRYSTAL

L. A. Rivlin

Submitted 18 March 1965

1. The classical condition for the occurrence of Cerenkov radiation, $v = (c/n)\cos^{-1}\theta \equiv u < c$ (c is the velocity of light in vacuum, v the electron velocity, θ the angle between its vector and the photon emission direction, and n the refractive index of the medium) [1], cannot be satisfied in the x-ray band, where $n \lesssim 1$, so that it is customary to assume that "radiation in this region is impossible" [2], page 29). This statement is valid only so long as it is permissible to describe the properties of the medium with the aid of a single macroscopic parameter - the refractive index n.

2. When considering the propagation of x-rays in a single crystal, the monochromatic wave field of radiation can be represented as a sum of an infinite number of spatial harmonic components of a three-dimensional Fourier series of the same frequency ν, but with different directions and propagation velocities of the phase $u_{k\ell m}$ [3]. Among the set of spatial harmonics, there exist some for which $u_{k\ell m} < c$.

3. The quantity u which enters in the synchronism condition (Sec. 1) is essentially the rate of displacement of the phase of electromagnetic wave in the direction of electron motion. Therefore, if the velocity v of an electron moving in the single crystal coincides in magnitude and direction with the velocity $u_{k\ell m} < c$ of one of the sapatial harmonics ($v = u_{k\ell m}$), then we can expect Cerenkov radiation to occur in the x-ray band.

4. It can be shown [4] that for electromagnetic oscillations of x-ray frequency propagating in a single crystal there exist resonant modes represented by the same point on the boundaries of the Brilluoin zones [3], where the gradient of the frequency with respect to the