INDIRECT TRANSITIONS IN GERMANIUM IN CROSSED ELECTRIC AND MAGNETIC FIELDS

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Submitted 23 March 1971
ZhETF Pis. Red. 13, No. 9, 483 - 487 (5 May 1971)

In the investigation of magnetoabsorption by the usual integral methods, the spectrum in the region of the indirect transitions constitutes a series of steps corresponding to transitions between different Landau levels from the valence band to the conduction band [1]. Even under the most favorable conditions, at sufficiently low temperatures and in strong magnetic fields, it is possible to observe a small number of transitions, owing to the blurring of the steps by relaxation processes [2, 3]. The use of the piezomodulation method has made it possible to increase the measurement sensitivity. Transitions between Landau levels in the spectrum were represented in the form of sharp peaks and could be observed at sufficient depth in the band [4].

Aronov and Pikus [5] investigated theoretically the absorption of light in the region of indirect transitions in crossed electric and magnetic fields. They have shown that for indirect transitions in crossed fields the transition energy should shift towards shorter wavelengths in proportion to the square of the electric field, whereas for direct transitions it shifts into the long-wave region [6, 7]. The centers of the steps in the integral spectrum are then displaced. As indicated in [5], the use of the electromodulation method makes it possible to observe in place of the steps sharp maxima whose positions shift with the electric field. Investigations in crossed fields are useful also for the identification of the levels between which the transitions take place. For the indirect transitions, such an identification is practically impossible in the absence of an electric field, owing to the absence of selection rules in terms of the number n of the Landau level. For semiconductors with a degenerate valence band, as shown in [8], different levels in the valence band shift differently with changing electric field, making it possible to distinguish between different levels.

We have investigated indirect transitions with emission of an αA phonon in crossed electric and magnetic fields. The measurements were made with an electromodulation (differential) procedure (see, e.g., [9]) on samples of compensated germanium at 77°K. The magnetic and electric fields were applied to the sample in the [100] directions. A field $E_0 + E_1 \cos \Omega t$ (E_0 is the static electric field) was applied to the sample and the detection was at the frequency Ω. E_0 was always 10 times larger than E_1.

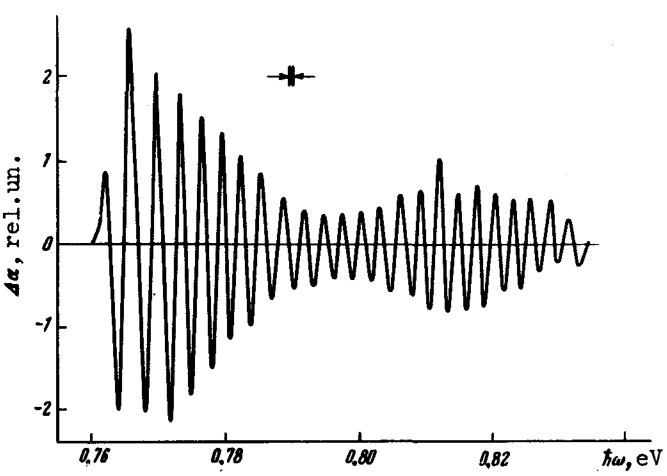

Fig. 1. Variation of the absorption coefficient of light $\Delta\alpha$ with the photon energy: H = 34.6 kOe, E_1 = 50 V/cm, E_0 = 0.

Measurements of the magnetopptical spectrum were also performed at $E_0 = 0$. Since the change of the absorption coefficient $\Delta\alpha$ is an even function of the electric field [5], the detection in this case was at the doubled frequency 2Ω. Figure 1 shows the dependence of the change of the absorption coefficient $\Delta\alpha$ on the energy $\hbar\omega$ at H = 34.6 kOe, E_1 = 50 V/cm, and E_0 = 0.

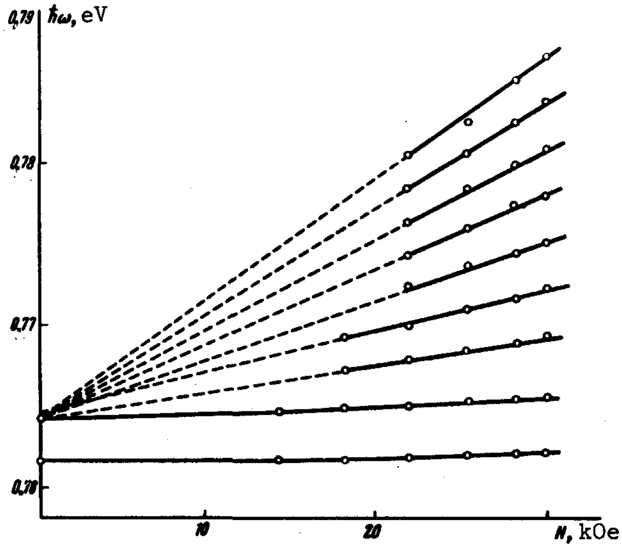

Fig. 2. Dependence of the position of the maxima of Δα on the magnetic field intensity, E_1 = 50 V/cm, E_0 = 0.

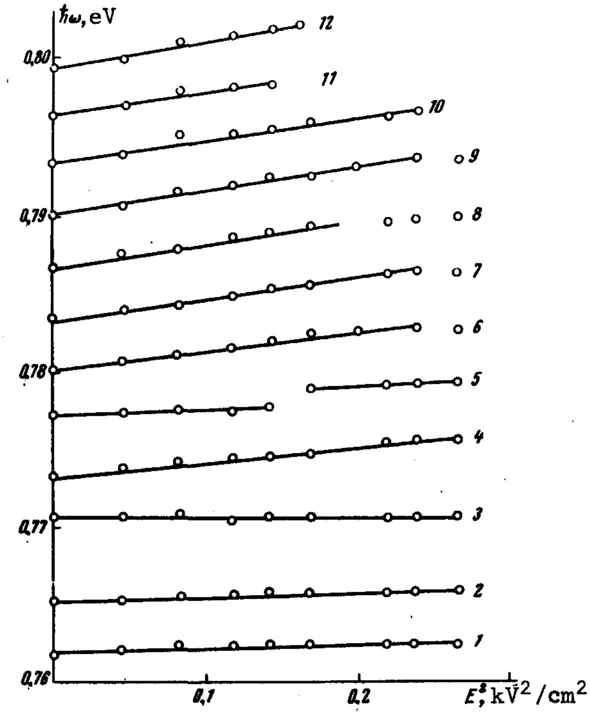

Fig. 3. Dependence of the position of the maxima of Δα on the equare of the electric field intensity, H = 30 kOe.

A comparison of the experimental spectrum with the theoretical one [10] does not make it possible to classify the observed transitions, owing to the large number (more than a thousand) of the possible transitions. However, it is apparently possible to conclude that the spectrum is due to transitions from one or several close Landau levels in the valence band to succeeding levels in the conduction band. It is then obtained that the effective mass of the electrons in the conduction band is $m^* = (0.13 \pm 0.01)m_0$. The dependence of the intensity of the peaks of Δα on the photon energy, shown in the figure, is still unclear to us.

The values of the energy at the maxima of the curve of Fig. 1 are determined by the Landau levels whose position depends on the magnetic field intensity. These dependences are shown in Fig. 2[1]. The position of the first two peaks present in a zero magnetic field depends nonlinearly on the magnetic field. These peaks correspond to transitions to the ground state of the exciton and to the continuum [11]. The positions of the remaining peaks depend linearly on the magnetic field, within the limits of experimental error. The straight lines converge to a point corresponding to the continuous spectrum of the exciton. The exciton binding energy obtained by us is $\mathcal{E}^{ex}$ = 2.7 MeV.

Figure 3 shows the dependence of the position of the maxima of Δα on the

1) The position of the Landau levels does not coincide with the top of the peak in the differential spectrum [5]. However, when the magnetic field is changed, the peaks shift without a change in the line shape, and therefore the shift of the Landau levels coincides with the shift of any point of the differential spectrum. This was verified against the shift of the minima of the differential spectrum, and the relation obtained agrees with Fig. 2.

electric field. We have taken into account the fact that a Hall field is produced in crossed fields besides the applied field E_0. The Hall field was measured for all the investigated values of the electric and magnetic fields, and the effective field E was taken to be the vector sum of the applied and Hall fields. According to theoretical estimates [5], the shift of the Landau levels in a parabolic conduction band should be of the order of 10^{-4} - 10^{-5} eV at the electric and magnetic fields employed by us. Therefore the experimentally observed shifts of $\sim 10^{-3}$ eV can be due only to the shift of the Landau levels in the valence band, which is much larger, owing to the complex structure of the valence band of germanium [12].

The displacements of the first five peaks differ from one another, but starting with the sixth peak, the dependence on E^2 remains the same with increasing number of the maxima. This indicates that for $n \geq 6$ the spectrum is formed by transitions from one level in the valence band to succeeding levels in the conduction band. Comparison with the theory [12] shows that these are most likely to be transitions from the $\mathcal{E}_2^+(0)$ level in the valence band (the notation is that of [12]). The singularities in the behavior of the third, fourth, and fifth peaks (non-equidistance at E = 0, long-wave shift of the third peak, and jump in the position of the fifth peak) are apparently due to singularities in the behavior of the Landau level in the valence band when the electric field is varied.

It should be noted that the theoretical calculations used by us were made by Shindo for $E \parallel [100]$. In our case, the resultant Hall field was comparable in magnitude with the applied field, and therefore the total electric field was not directed along [100]. A final comparison with the theory will be made after completion of measurements on a sample cut in such a way that the resultant field is not directed along [100].

In conclusion, we are grateful to A.G. Aronov for constant interest in the work, for a discussion of the results, and for valuable remarks.

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