Oscillations of the photoconductivity of germanium in a magnetic field under monochromatic impurity illumination

V. N. Zverev

Institute of Solid State Physics, USSR Academy of Sciences
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Oscillations of the photoconductivity in a magnetic field were observed under monochromatic impurity illumination of germanium at helium temperatures; these oscillations are due to the nonmonotonic field dependence of the impurity magnetoabsorption coefficient. The period of the oscillations yields data on the nonparabolicity of the energy bands of germanium.

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The photoconductivity in a transverse field was investigated under monochromatic impurity illumination of germanium samples of *n*- and *p*-type at helium temperatures. The experiments were performed on samples doped with arsenic with concentration $N_{\mathrm{As}}=4\times10^{14}$ cm^{-3} and on samples doped with gallium with concentration $N_{\mathrm{Ga}}=2\times10^{14}$ cm^{-3}. The samples were rectangular plates measuring $4\times4\times0.3$ mm, and the normal to the surface of most samples was parallel to the [100] axis of the crystal. Several *p*-type samples had a surface normal parallel to the [110] axis. After chemical polishing, contacts were placed on the *p*-Ge samples by welding-on gold wires of 80 μm diameter, and on the *n*-Ge samples by fusing-in an In–As alloy. The distance between contacts was approximately 1 mm.

The samples were placed in superfluid helium at the center of a superconducting solenoid that produced a field up to 100 kOe, and the photocurrent J was measured as a function of the reciprocal magnetic field H^{-1} by a procedure described in detail in[1].

The optical pumping source was a CO$_2$ laser ($\lambda = 10.6$ μm, quantum energy $hc/\lambda = 0.118$ eV), whose beam was incident on the sample after passing through a ZnSe window in the upper flange of the cryostat. The laser power was approximately 5 W, but in the experiment it was reduced with filters to approximately 0.1 W.

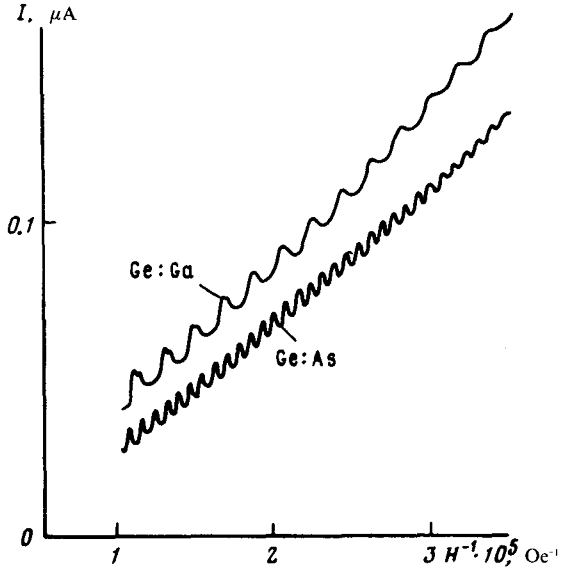

FIG. 1. Photocurrent oscillations in n- and p-Ge samples. Electric field intensity 3 V/cm, $T = 1.5$ K $\mathbf{H}\|[100]$. The ordinate scale pertains to the upper curve. The amplification for the lower curve is 8 times larger.

Figure 1 shows plots of $J(H^{-1})$ for germanium samples doped with gallium and arsenic. As seen from Fig. 1, the samples contining both donor and acceptor impurities have $J(H^{-1})$ curves with oscillations that are periodic in the scale of the reciprocal magnetic field. In the n-Ge samples the oscillation period P was equal to 7.7×10^{-7} Oe at $\mathbf{H}\|[100]$ and depended on the orientation of the vector **H** relative to the axes of the crystal. This dependence, which could be traced at small deviations of the vector **H** from the [100] axis, corresponded to the anisotropy of the cyclotron mass of the electrons in germanium.

In the p-Ge samples the period was 1.9×10^{-6} Oe for both $\mathbf{H}\|[100]$ and $\mathbf{H}\|[110]$. The absence of a noticeable anisotropy of the period is evidence that the oscillations observed for p-Ge are connected with quantization of the energy spectrum of the light holes in the magnetic field. The curve in Fig. 1 corresponding to Ge:Ga has a splitting of several extrema in the region of strong magnetic field. This splitting is approximately the same for different extrema and equals $\sim 0.15\,P$. No such splitting occurred at $\mathbf{H}\|[110]$.

The experimentally observed oscillations can be explained in the following manner.

In a magnetic field $\mathbf{H}\|z$ the carrier spectrum takes the form $\epsilon = E_n + (\hbar^2 k_z^2/2m^*)$, where $n = 1,2,3,\ldots$, and m^* is the mass that characterizes the translational motion along H. Under these conditions the light absorption coefficient in the region of the impurity absorption oscillates when the magnetic field changes, and rises steeply whenever the nonequilibrium carriers are produced near the bottom of the Landau subband, i.e., with energy $\epsilon \approx E$.[2] The periodicity of these oscillations is given by the relation

$$E_0 = E_n, \tag{1}$$

where $E_0 = (hc/\lambda) - E_i$, and E_i is the impurity ionization energy (see Fig. 2). Relation (1), just as the analogous relation for the de Haas—van Alphen effect, describes oscillations with an H^{-1} period equal to[3]

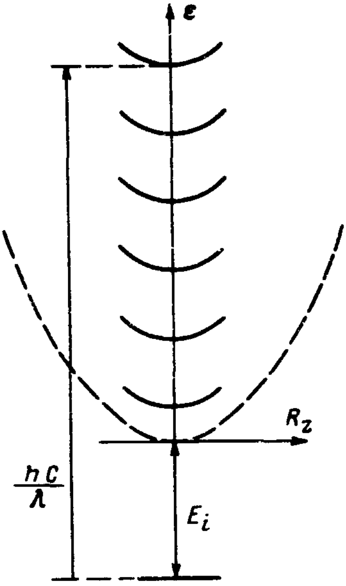

FIG. 2. Energy diagram that illustrates the transition, in a magnetic field, of the carriers with the impurity into the band under the influence of light. The dashed curve shows the $\epsilon(k_z)$ relation at $H = 0$.

$$P = 2\pi e/c\hbar S\,. \tag{2}$$

Here S is the k-space area of the experimental intersection of the equal-energy surface $\epsilon = E_0$ and a plane perpendicular to **H**.

Under the conditions of our experiment the sample thickness was much less than the reciprocal of the light absorption coefficient, so that oscillations occurred not only in the absorption coefficient but also in the total number of carriers produced in the sample by the impurity illumination. It is obvious that this was in fact the cause of the photoconductivity oscillations.

Thus, the described experiments permit measurements of the intersections of the equal-energy surfaces of both electrons and light holes at considerable distances from the bottom of the conduction band and the ceiling of the valence band. Such measurements can therefore be used to investigate the nonparabolicity of energy bands.

For electrons in germanium at $\epsilon \simeq 0.1$ eV the deviations of the dispersion law from quadratic are small[4] and therefore we can confine ourselves to the linear term of the dependence of the electron cyclotron mass on the energy, and write

$$m_e(\epsilon) = m_e(0)(1 + \alpha\epsilon). \tag{3}$$

Since $m=(\hbar^2/2\pi)(\partial S/\partial\epsilon)$, it follows from (2) and (3) that

$$\alpha = \frac{2}{E_0}\left(\frac{e\hbar}{m_e(0)cPE_0} - 1\right) \tag{4}$$

Substituting in (4) the experimentally measured value of P, as well as the values $m_e(0)=0.135m_0$ and $E_0=(hc/\lambda)-E_{\mathrm{As}}=0.104$ eV (we use here the value $E_{\mathrm{As}}=14.04$ meV),[5] we obtain $\alpha=1.4$ eV^{-1}, which agrees satisfactorily with the value 1.6 eV^{-1} obtained in[4].

Experiments on p-Ge yield for S_h a value 5×10^{13} cm^{-2}, which exceeds by 33% the value that would be obtained for a parabolic band with cyclotron mass $m_h=0.043m_0$. This is evidence of strong nonparabolicity of the light-hole band, as expected on the basis of the calculation of[6]. Unfortunately, a quantitative comparison with theory is difficult, since there is no analytic expression in[6] for the dispersion law at such a distance from the ceiling of the valence band.

The splitting of the extrema on the $J(H^{-1})$ plot, observed for p-Ge, is probably due to the fact that the light-hole spectrum in $k_z=0$ comprises two series of Landau levels, shifted relative to each other. It is clear that transitions to different "ladders" of light holes should correspond to two series of extrema, shifted relative to each other, on the $J(H^{-1})$ plot.

Estimates show that we take into account in (1) the energies of the bound states of the carriers produced in the band by the Coulomb field of the ionized impurity,[2] and also take into account the $E_i(H)$ relation, we obtain for S_e and S_h corrections that lie within the limits of the experimental error, which does not exceed 1–2%.

In conclusion, the author thanks V.F. Gantmakher for interest in the work, and G.E. Pikus and S.V. Meshkov for useful discussions.

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