Oscillatory Magneto-Absorption of the Direct Transition in Germanium*

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(Received December 26, 1956)

Infrared transmission of intrinsic germanium was examined at wavelengths from 1.4μ to 1.6μ in constant magnetic fields up to 36 000 gauss. The magneto-absorption showed oscillatory behavior at photon energies greater than that of the direct transition. The energy gap of the direct transition was determined experimentally to be 0.803 ± 0.001 ev at room temperature. The effective mass of the electron in the Γ_2^- conduction band was found to be $\approx 0.042m_0$. Anisotropy of the oscillations was observed as a function of the orientation of the sample in the magnetic field.

IN a previous communication[1] we reported fine structure of the magneto-band effect of the direct transition in germanium. The present note is intended to describe more fully this new phenomenon, which we shall call the *oscillatory magneto-absorption effect*.[2] The effect was studied at room temperature by observing the transmission of infrared radiation at wavelengths near the direct transition[3] absorption edge of germanium in the presence of a dc magnetic field. The samples[4] were thin single crystal specimens $\sim$0.240 inch in diameter and $\sim 4\mu$ thick, as estimated from the percent transmission. The magnetic field was parallel to the sample surface which had an arbitrary orientation relative to the crystal axes. The magnetic field, B, was kept constant at selected values up to 36 000 gauss, and the wavelength region was carefully scanned from about 1.4μ to 1.6μ by using a monochromator with a dense flint prism to obtain maximum resolution. The tungsten lamp source was stabilized so that successive measurements containing the oscillatory magneto-absorption traces could be compared directly with the zero-field trace and to one another. Such superimposed transmission traces are shown in Figs. 1 and 2. Note that with increasing B there is a shift to higher energies of the absorption edge of the direct transition and that a pronounced minimum occurs at the foot of the transmission curve, indicating an absorption at that energy greater than that for $B=0$. This minimum corresponds to the transition from the highest Landau level of the Γ_{25}^+ valence bands to the lowest Landau level of the Γ_2^- conduction band.[5,6] There are also other minima at higher photon energies, corresponding to transitions between higher Landau levels for quantum numbers $n>0$ in the conduction and valence bands. It is apparent that the amplitude, spacing, and number of the observable oscillations increase with magnetic field. The spacings between the minima are unequal, indicating the presence of "quantum effects" predicted by Luttinger and Kohn.[7] They suggested a nonuniform energy spectrum of the Landau levels in the degenerate valence bands for low

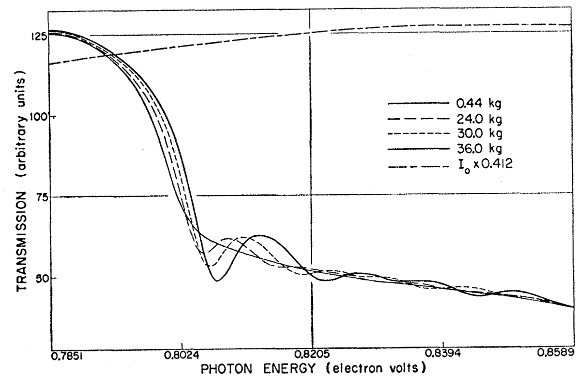

FIG. 1. Transmission *versus* photon energy for several values of B through a 4μ-sample of intrinsic germanium. The trace for the intensity of the incident radiation, I_0, has been scaled down by a factor of 0.412.

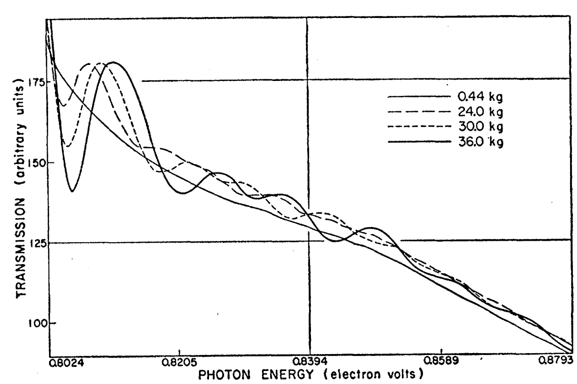

FIG. 2. Enlarged traces showing the oscillatory magneto-absorption at energies above the direct transition absorption edge in germanium.

* The research reported in this document was supported jointly by the Army, Navy, and Air Force, under contract with the Massachusetts Institute of Technology.

[1] Zwerdling, Keyes, Foner, Kolm, and Lax, Phys. Rev. **104**, 1805 (1956).

[2] A similar effect observed in InSb by the Naval Research Laboratory group was reported by E. Burstein concurrently with our report of this effect in germanium at the Semiconductor Symposium, October 1956, Washington, D. C.

[3] The threshold for direct transition has been measured by W. C. Dash and R. Newman, Phys. Rev. **99**, 1151 (1955), to be 0.81 ev at 300°K and 0.88 ev at 77°K.

[4] Mounted polished samples were prepared at General Electric Research Laboratories, Schenectady, New York, and generously provided by W. C. Dash.

[5] F. Herman, Phys. Rev. **95**, 847 (1954).

[6] Dresselhaus, Kip, and Kittel, Phys. Rev. **98**, 368 (1955).

[7] J. M. Luttinger and W. Kohn, Phys. Rev. **97**, 869 (1955).

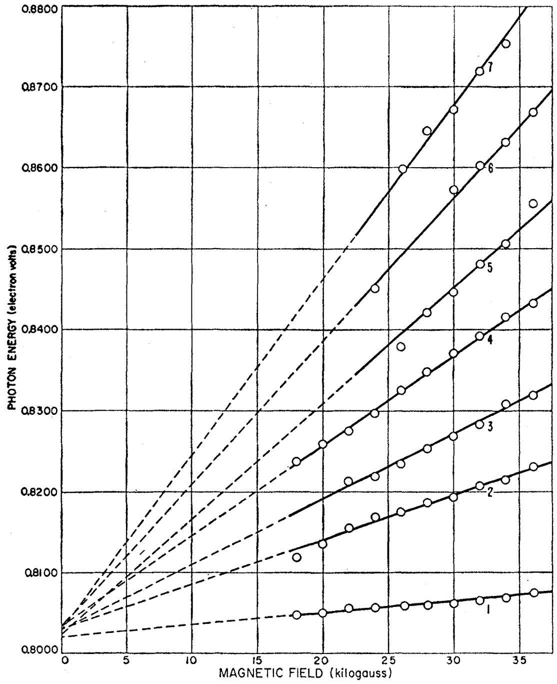

FIG. 3. Energies of the consecutive transmission minima as a function of magnetic field. Curve 1 corresponds to transitions between Landau levels with $n=0$; the successive curves correspond to transitions between higher quantum states of both conduction and valence bands.

quantum numbers. Laura M. Roth of our laboratory has obtained semiquantitative correlation between the level structure observed and the calculations, using the modified theory given by Luttinger.[8] Furthermore, these calculations indicate the existence of fine structure associated with each minimum, which apparently has not been resolved by the present measurements.

Figure 3 shows a plot of the positions of the consecutive minima in terms of photon energy as a function of magnetic field. The figure shows a series of straight lines through the experimental points, converging to a single point at $B=0$. The significance of these curves is that the bands are quadratic in k for the range of B up to 36 000 gauss and that all the Landau levels which are linear in B collapse to the bottom of the band at $B=0$. This appears to be an accurate method for measuring the gap spacing at $k=0$ and gives a value of 0.803 ± 0.001 ev at 24°C. The change in the gap energy at $k=0$ with magnetic field is given by $\Delta E=\frac{1}{2}\hbar(\omega_{c1}+\omega_{c2})$, where ω_{c1} is the cyclotron frequency for the conduction band and ω_{c2} that for the valence band at $k=0$. We shall assume that for the latter the Landau level for $n=0$ corresponds approximately to that of the large hole mass, $m_v\approx 0.33m_0$. This leads to $1/m^*=1/m_c+1/m_v$, where $m^*\approx(0.038\pm0.003)m_0$ is the mass determined from the slope of the magneto-gap shift. Since $m_v\gg m^*$, $m_c\approx m^*(1+m^*/m_v)\approx 0.042m_0$. This value is in reasonable agreement with the theoretical estimate of $\sim 0.034m_0$ by Dresselhaus, Kip, and Kittel[6] from cyclotron resonance data.† These results and the relative shape and position of the absorption edge curves suggest why the data previously obtained[1,9] from iso-transmission lines gave estimates of the gap shift which were too low and estimates of effective masses which were too high. The gap shift is actually represented by the motion of the first transmission minimum.

Experiments are now in progress to search for the possible fine structure of the oscillations and to obtain quantitative correlation with theory. Anisotropy of the oscillatory magneto-absorption has been observed with B in the (110) plane. In order to sharpen the lines, experiments are being performed at 77°K and 4°K. Finally, magneto-absorption of the interband transitions between the three valence bands is being investigated in 0.06 ohm-cm p-type germanium, at wavelengths from 3μ to 25μ. At these wavelengths the resolution and anisotropy of the magneto-absorption spectrum should be enhanced.

We should like to thank J. P. Theriault and P. C. Hohenberg for assistance with the experiments. We have benefited from discussions with L. M. Roth, R. J. Keyes, and H. J. Zeiger. We are grateful to W. C. Dash for providing us with the thin samples of single crystals of germanium.

[8] J. M. Luttinger, Phys. Rev. **102**, 1030 (1956).

[9] Burstein, Picus, Gebbie, and Blatt, Phys. Rev. **103**, 826 (1956).

† *Note added in proof.*—Since this article was submitted, another theoretical estimate of the conduction band electron effective mass at $k=0$ has been published by Dumke [W. P. Dumke, Phys. Rev. **105**, 139 (1957)]. He finds a value of $m_c\sim 0.037m_0$, which is in closer agreement with the present experimental value than that of DKK[6]. The theoretical estimates neglect the influence of higher conduction bands at $k=0$ which, according to Herman [F. Herman (private communication)], decreases the curvature of the Γ_2-band and should improve the agreement between theory and experiment.