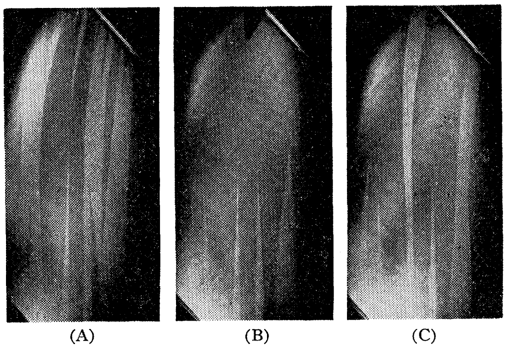
(A) (B) (C)

FIG. 2. Domain behavior in a portion of the film as the S pole of a small compass needle is brought up to the film edge and then removed. The needle end can be seen at the top of (B).

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Observation of Quantum Effects in Cyclotron Resonance

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NEW cyclotron resonance lines associated with the valence band of germanium have been resolved. These are believed to be the experimental confirmation of the predictions of Luttinger and Kohn,[1] who showed that, when a crystal band edge is degenerate, a quantum mechanical treatment of the cyclotron resonances predicts a nonuniform spacing between the lower energy levels. Thus, if these levels can be preferentially populated by going to low enough temperatures, new cyclotron resonances should appear.

Measurements were made at 23.5 kMc/sec at temperatures from 4.2 to 1.3°K. For this latter temperature the Boltzmann factor, $e^{h\nu/kT}$, is 2.5, which should be large enough to provide a significant population of the lower levels. Carriers of both signs were introduced into the germanium lattice by illumination with white tungsten light. In order to study holes in the presence of much larger electron resonances, a circular cavity was used which gave circular polarization. A series of measurements was made on three slices cut from a single-crystal ingot (8×10^{12} cm^{-3} excess donors) in the three principal directions. Final alignment of the sample in the magnetic field was accomplished by rotating the sample until the appropriate electron resonances merged.

In Fig. 1 there is displayed a reproduction of the heavy-hole resonance at both 4.2°K and 1.3°K for the three directions. These reproductions represent a smoothed-out composite of a number of recorder tracings for each case. All the curves are normalized to unity at their maximum. As can be seen, new resonances appear at 1.3°K which are not present at 4.2°K in all three directions. In two instances [$m^*=0.332$ in the (111) direction and 0.262 in the (110) direction] the extra resonances were also seen at 4.2°K. The reason why these have escaped detection previously is presumably a combination of too high a microwave power (possibly raising the average electron energy to the high-energy levels) and too short mean-free-time (broad lines).

The resonances with question marks are somewhat uncertain because of proximity to other lines or because of residual electron lines arising from imperfect circular polarization. This latter also causes an appreciable effect on the shape and position of the strong line at $m^*=0.360$ in the (110) direction. The extra line in the (100) direction at $m^*=0.593$ is unmistakable at 1.3°K but vanishes at 4.2°K. No comparable line was found in the other directions.

The light-hole resonance did not display the same kind of structure. It was measured to have the values

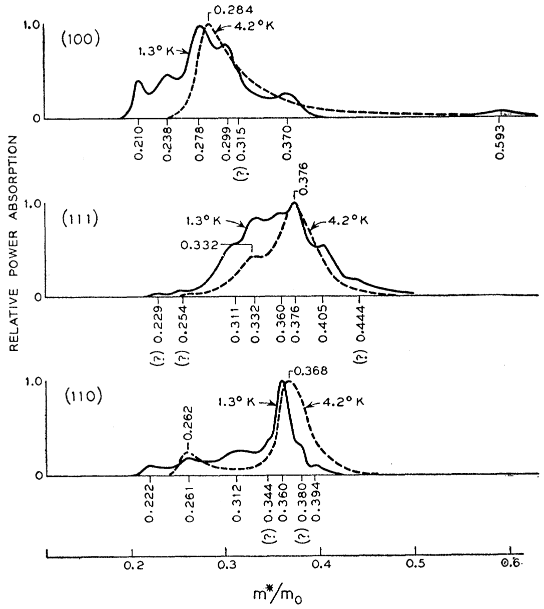

FIG. 1. Heavy-hole resonances at 4.2°K and 1.3°K in the three major crystal directions using circular polarization. The appearance of extra resonances at the lower temperature is believed to be the quantum effect.

0.0437, 0.0421, and 0.0425, in the (100), (111), and (110) directions respectively, the same at both 4.2°K and 1.3°K. Its line width was narrower than any previously reported, $\Delta H/H \doteq 0.04$ between half power points at 1.3°K, corresponding to $\tau=3\times10^{-10}$ sec. In one direction, (100), a weak extra line was observed at $m^*/m_0=0.057\pm0.002$, down a factor of twenty from the main line. Although this line did not suffer a large change in intensity relative to the main resonance as the temperature was varied from 4.2° to 1.3°, it probably is also associated with quantum effects.

The ratio of the intensity of the hole resonances to the electron resonances has been found to depend critically on the sample, the temperature, the microwave power level, and the light intensity. This suggests that temporary hole traps are probably present. It is believed that these traps may have been responsible for earlier failure[2] to observe hole resonances at 1.3°K.

Because of the observed electron resonances at 1.3°K in this sample have an $\omega\tau=80$, almost an order larger than has been previously reported,[3] it seems worthwhile reporting these measurements: $m^*/m_0=0.1341$ for (100); 0.0814 and 0.206 for (111); 0.0983 and 0.361 for (110). These five measurements form a consistent determination of the two constants of the energy ellipsoid: $m_t=0.0813\pm0.002$ and $m_l=1.600\pm0.008$. These agree with previous observations within[3] their expressed accuracy.

We are indebted to W. Kohn and J. M. Luttinger for their continual interest and stimulating discussions during the course of these measurements, to H. W. Dail for experimental assistance, to F. J. Morin and T. H. Geballe for the loan of crystals, and to H. R. Moore and W. H. Brattain for the design and loan of the mechanical chopper and synchronous detector.

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Cyclotron Resonance in Metals: Bismuth

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We have observed the cyclotron resonance[1] behavior of metallic bismuth at 24 000 Mc/sec under conditions such that the steady magnetic field was along the trigonal axis. So far as we are aware, this is the first time such observations have been made successfully on a metal. The (00·1) face of a single crystal of bismuth was made to act as part of one wall of a microwave cavity, and our data consist of observations of the variation of energy absorbed in the cavity at resonance as a function of the dc magnetic field applied normal to this wall. Considerable care and effort were required to obtain clean, strain-free (00·1) surfaces of bismuth.

The experimental arrangement is diagrammed in Fig. 1. A degenerate circular cavity of coin silver in the shape of a pillbox was excited from one end through a coupling window in such a way as to produce a circularly polarized field near the axis of the cavity. The excitation of circular polarization was achieved by proper placement of the coupling window on the broad face of a rectangular wave guide, and by the adjustment of dielectric vanes inside the cavity. The bismuth sample covered a hole in the wall at the end opposite the coupling window, thus forming the cavity wall in an area where circularly polarized radiation impinges upon it. A sample of calcium copper acetate hexahydrate was in the cavity near the bismuth at all times. It was possible to establish the degree of circularity of our polarization by observing the ratio of the intensities of paramagnetic resonance in this salt when observed with the dc magnetic field in opposite directions. A ratio of at least 10 to 1 between the intensities of the two circular polarizations was maintained in taking our data.

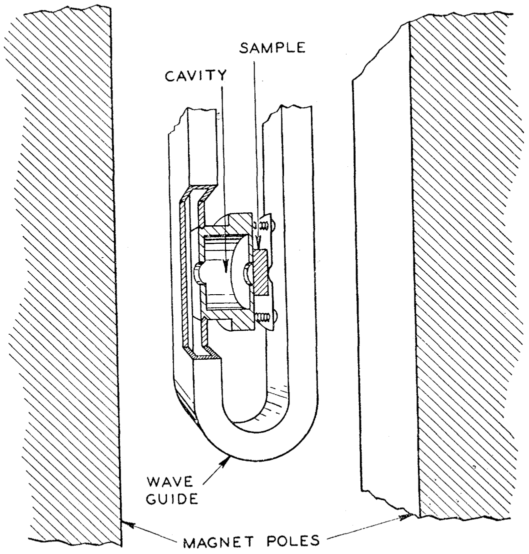

Fig. 1. Diagram of experimental geometry for cyclotron resonance experiments in bismuth. The cavity can be moved back and forth across the broad face of the wave guide so that the coupling window accepts the best approximation to circular polarization. The magnet pole faces are oriented parallel to the ends of the cavity. The sample covers a hole in one end of the cavity and thus forms part of the cavity wall at the center of this end.

The power absorption coefficient of our best sample of bismuth varied with the dc magnetic field as shown in Fig. 2 at 4.2°K. The direction of increased power absorption was established by observation of the para-