the order of 0.5 millivolt, so that the sensitivity of this pulse method of determining sample resistance is about 10^4 times less than the dc method used by Kunzler.

We have made an estimate of eddy current heating in the sample during the field pulse. Above the lambda point (2.17°K) the sample might warm by as much as 1°K. Below the lambda point the high heat transfer rate to superfluid helium should restrict the temperature rise to less than 0.5°K. The temperatures indicated in Fig. 2 are those of the helium bath. The shift in critical field from just above to just below the lambda point indicates that heat exchange to the bath has a measurable but not important effect on the data.

The attenuation of the pulsed field through the niobium sheath can be calculated from equations given by Kosevich.[2] It turns out to be the order of 1 gauss and so is completely negligible.

The great interest in Nb_3Sn wire is, of course, for use in superconducting magnets. In this application it is necessary to know the critical field transverse to the current flow, rather than parallel to it as in our experiment. For a "soft" perfectly diamagnetic specimen the transverse critical field (which restores the first trace of resistance) is one half of the longitudinal critical field. For a hard superconductor, in which flux penetration is nearly complete, these two critical fields are nearly the same. The measurements reported here certainly set an upper limit on the critical field for transverse measurements on this specimen. Kunzler[1] reports that the critical current in their samples scales with diameter in a manner intermediate between that of soft and that of hard superconductors. We are continuing our measurements, and hope to obtain transverse critical fields in the near future.

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[1]J. E. Kunzler, E. Buehler, F. S. Hsu, and J. H. Wernick, Phys. Rev. Letters 6, 89 (1961).

[2]A. M. Kosevich, J. Exptl. Theoret. Phys. U.S.S.R. 33, 735 (1958) [translation: Soviet Phys.–JETP 6, 564 (1958)].

ULTRASONIC CYCLOTRON RESONANCE IN GALLIUM

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Mikoshiba[1] suggested that a cyclotron resonance of metallic electrons could be induced by ultrasonic waves in which the attenuation of the sound waves should be a maximum whenever the frequency of the sound wave is an integral multiple of the cyclotron frequency, $\omega = n\omega_c$. This type of resonance has been seen in the semimetal bismuth[2] but not in any true metal, because the condition required–that $\omega\tau$ be greater than unity–has not been met. This requirement makes severe demands on metal purity; for example, at 100 Mc/sec an electron mean free path of approximately one cm is required to obtain $\omega\tau = 5$.

Single crystals of the metal Ga, kindly prepared and supplied by Kramer and Foster,[3] have been shaped by careful machining techniques into oriented ultrasound specimens about 1 cm in thickness. The electronic grade Ga from which the crystals were grown had a room temperature to 4.2°K resistivity ratio of about 50 000 determined by dc four-probe methods.

Standard ultrasonic pulse techniques[4] were used with a single transducer for transmission and detection. The bonding agent was a silicone fluid with viscosity of 20 000 centistokes.

In Fig. 1 the reflected pulse amplitude is plotted as a function of field for a longitudinal, 115-Mc/sec sound wave traveling along the c_0 axis at 1.6°K. Two types of resonance behavior are present. The first consists of a geometric resonance with a maximum (indicated by a minimum in the pulse amplitude) at 80 oe and additional members of the series occurring at equal intervals of $(1/H)$. About 30 maxima have been ob-

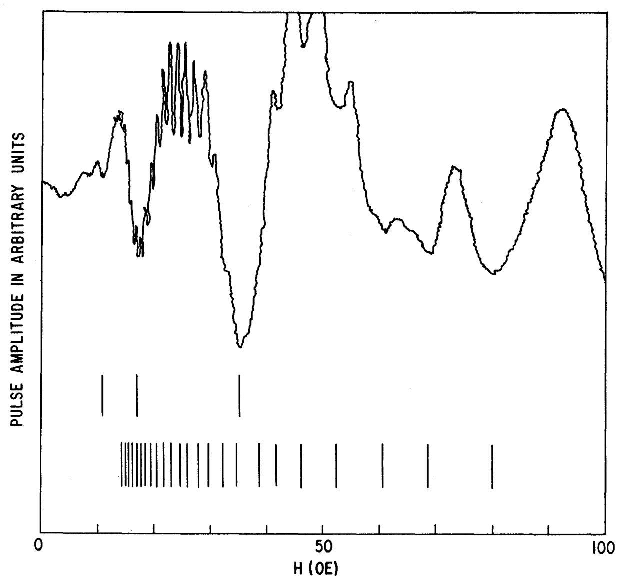

FIG. 1. Reflected ultrasound pulse in Ga as a function of magnetic field. $f = 115$ Mc/sec. $T = 1.5°K$. Upper reference marks indicate ultrasonic cyclotron resonance maxima. Lower reference marks indicate observed geometric resonance maxima.

served, including those which exist above 80 oe. Geometric resonance occurs when the electron orbit dimensions match the sonic wavelength and subsequent maxima are predicted nearly by $\Delta(1/H) = (\lambda/2)(e/c)(1/\hbar k)$, where $\hbar k$ is the electron momentum. The unusually large number of maxima observed in this experiment indicate that the resonance arises from a well-defined extremal portion of the Fermi surface and that electrons in the material have an unusually long mean free path.

The second resonance behavior, the cyclotron resonance, has maxima indicated at 35, 17, and 11 oe. A smoothed curve through the cyclotron resonance maxima but ignoring the geometric resonance maxima is shown in Fig. 2(b); the data here are plotted as attenuation relative to the attenuation at $H = 0$, and they are compared with the predictions of Cohen, Harrison, and Harrison[5] in Fig. 2(a). Both the experimental and theoretical curves are for longitudinal ultrasonic waves, the theoretical curve for $\omega\tau = 10$ and the experimental one for $\omega\tau \sim 5$. Marked similarity exists, although the third maximum is less pronounced in the experimental observations, probably because of the lower $\omega\tau$.

In order to verify that the maxima attributed to the cyclotron resonance and those attributed to the geometric resonance were actually due to those causes, the experiment was repeated with a shear wave produced with an AC-cut quartz transducer. The frequency of the shear wave (116 Mc/sec) was approximately equal to that of the longitudinal, but because its velocity is only 2.4×10^5 cm/sec compared to the longitudinal velocity of 4.7×10^5 cm/sec, the wavelength of the transverse waves was less than that of the longitudinal. The first two maxima of the cyclotron resonance were found to persist at the same H values, while marked changes occurred in the geometric resonance.

The presence of the maximum at only 11 oe in the cyclotron resonance series indicates an orbit circumference of about mcv_f/eH or 0.8 cm, where v_f is the Fermi velocity. Also, if we consider the requirements for the geometric reso-

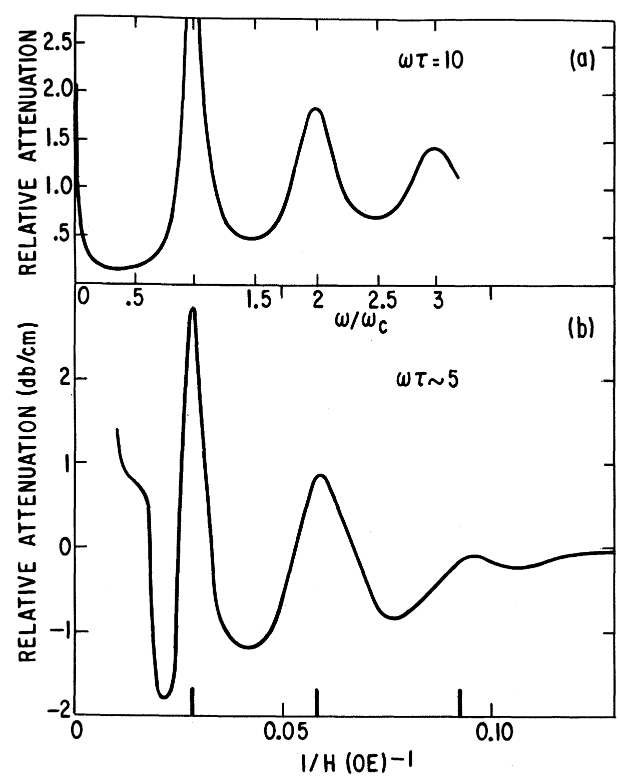

FIG. 2. (a) Predicted relative attenuation for ultrasonic cyclotron resonance after Cohen, Harrison, and Harrison.[5] (b) Observed curve in Ga single crystal derived from data in Fig. 1.

nance series with about 30 maxima, we find that the orbit circumference must be about $30\pi\lambda = 0.4$ cm. The maxima of both phenomena sharpened and the background attenuation shifted as the temperature was reduced from 4.2°K to 1.5°K, suggesting that the resistivity of the Ga was changing. Using these measurements and extrapolating the resistivity measurements of Olsen-Bär and Powell,[6] one finds that $\rho_{1.5°K}$ must be of the order of 10^{-12} ohm cm. Recent measurements by Weisberg and Josephs[7] also indicate that very low resistivity values may occur in Ga samples at 1.26°K. These four observations suggest that a mean free path, l, of order 1 cm is obtained in these Ga crystals at 1.5°K. Associated values of $\omega\tau \sim 5$ and $ql \sim 1500$ follow, where q equals $2\pi/\lambda$. The condition for geometric resonance is $ql > 1$ and is much less stringent than the condition for observing cyclotron resonance.

The topology of the Fermi surface is yet to be established, but the geometric resonance presented here suggests an extremal dimension (1.3×10^{-20} g cm/sec) consistent with regions of electrons in the seventh zone as predicted by the nearly free electron model.[8] The effective electronic mass, m^*, derived from the cyclotron resonance for the same orientation is $0.8_4 m_0$.

Further study of the Ga Fermi surface topology and related effective masses is under way.

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[1]N. Mikoshiba, J. Phys. Soc. Japan 13, 759 (1958).
[2]D. H. Reneker, Phys. Rev. 115, 303 (1960).
[3]R. A. Kramer and L. M. Foster, Alcoa Research Laboratories, New Kensington, Pennsylvania.
[4]B. W. Roberts, Phys. Rev. 119, 1889 (1960).
[5]M. H. Cohen, M. J. Harrison, and W. A. Harrison, Phys. Rev. 117, 937 (1960).
[6]M. Olsen-Bär and R. W. Powell, Proc. Roy. Soc. (London) A209, 548 (1951).
[7]L. R. Weisberg and R. M. Josephs, Bull. Am. Phys. Soc. 5, 430 (1960).
[8]W. A. Harrison, Phys. Rev. 116, 555 (1959).

GENERATION-RECOMBINATION NOISE IN p-TYPE GOLD-DOPED GERMANIUM

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Preliminary estimates of the capture cross sections of free holes by the 0.041-ev donor level and the 0.145-ev acceptor level in p-type gold-doped germanium have been obtained from measurements of the generation-recombination noise spectrum in the range 10^4-10^7 cps. At 97°K the Fermi level of the sample studied was located midway between the two gold levels, such that the noise spectrum simultaneously exhibited relaxation times characteristic of both levels. A two-impurity level model appropriate to the gold-doped germanium system was employed to predict the observed noise in terms of the capture cross sections. Good agreement was obtained between theory and experiment, using values for the total cross sections of $\sigma_A = 1.55 \times 10^{-12}$ cm^2, $\sigma_D = 3.75 \times 10^{-18}$ cm^2. To our knowledge this work represents the first experimental observation of two-level generation-recombination noise in gold-doped germanium and the development of a theory capable of accounting for all of the observed noise in interacting two-level systems of this type.

Generation-recombination noise in semiconductors arises from the modulation of the conductivity by the random thermal fluctuation of charge carriers between the valence (or conduction) band and the impurity levels. Thus, for an extrinsic semiconductor the time-dependent second moment $\langle \Delta J(0) \Delta J(t) \rangle$ of the current fluctuations is simply related to the corresponding moment $\langle \Delta p_V(0) \Delta p_V(t) \rangle$ of the fluctuations in the valence band population:

$$\langle \Delta J(0) \Delta J(t) \rangle = (J^2/p_V{}^2) \langle \Delta p_V(0) \Delta p_V(t) \rangle, \quad (1)$$

where J is the average current and p_V the equilibrium valence band population. The generation-recombination noise spectrum $G(f)$ is the Fourier transform of Eq. (1).

Van Vliet[1] has developed a general prescription for obtaining the free carrier fluctuations in multilevel systems by computing the linear