for investigating possible anisotropy in oriented crystals. The preliminary data agree in order of magnitude with the results deduced by Jones[6] and Blackman[7] from the magnetic susceptibility experiments. However, their ellipsoidal models do not appear to explain our data. The interpretation of our results for multiple carriers is quite involved, particularly for the magnetic field parallel to the metal surface.[8] The simplest situation occurs for transverse H and circular polarization,[9] which would also permit the distinction between holes and electrons. More complicated cases involving ellipsoidal models are being analyzed. The theory which excludes the phenomenon of anomalous skin effect will have to be further refined.

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† Now at the Department of Physics, University of Wisconsin, Madison, Wisconsin.
[1] Lax, Zeiger, and Dexter, Physica **20**, 818 (1954); and Dresselhaus, Kip, and Kittel, Phys. Rev. **98**, 368 (1955).
[2] This crystal of pure bismuth was supplied by Dr. E. I. Salkovitz of the U. S. Naval Research Laboratory, Washington, D. C.
[3] R. G. Chambers and A. B. Pippard, Proc. Phys. Soc. (London) **A65**, 955 (1952).
[4] Dresselhaus, Kip, and Kittel, Phys. Rev. **100**, 618 (1955).
[5] This crystal of bismuth was prepared by Mr. P. L. Moody of Lincoln Laboratory. The highly pure bismuth was kindly contributed by the American Smelting and Refining Company, Central Research Laboratories, South Plainfield, New Jersey, and was zone-refined 60 times.
[6] H. Jones, Proc. Roy. Soc. (London) **147**, 396 (1934).
[7] M. Blackman, Proc. Roy. Soc. (London) **166**, 1 (1938).
[8] B. Lax and L. M. Roth (to be published).
[9] A. F. Kip, Physica **20**, 813 (1954).

Cyclotron Resonance in Ge-Si Alloys*

G. Dresselhaus, A. F. Kip, Han-Ying Ku, and G. Wagoner,
Department of Physics, University of California, Berkeley, California

and

Schuyler M. Christian, *RCA Laboratories, Princeton, New Jersey*

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We have observed cyclotron resonance at 4°K and at 24 000 and 48 000 Mc/sec in four alloys prepared by the RCA Laboratories: in atomic percent, 0.4 and 0.75 Ge in Si; 0.8 and 5.4 Si in Ge. The experimental technique generally has been described earlier,[1] but the 6-mm apparatus is new and utilizes a transmission cavity; the power is produced as the second harmonic from a germanium crystal point-contact rectifier, with a K-band klystron as primary source. The striking feature of the results is that it is possible to resolve cyclotron lines with as much as 5% Si in Ge, whereas 10^{-5}% of trivalent or pentavalent substitutional impurities makes resolution difficult. The resolution we have obtained is not really good enough in conjunction with the present uncertainties in crystal orientation to encourage the examination of the differences in mass parameters between the alloys and the pure crystals.

Results for 0.8% Si in Ge are shown in Fig. 1. The calculated curves are drawn for ⟨111⟩ spheroidal electron energy surfaces with $m_l=(1.59\pm0.05)m$, $m_t=(0.086\pm0.002)m$, as compared with $m_l=1.58m$, $m_t=0.082m$ for pure Ge. The alloy electron relaxation times are 2 to 4×10^{-11} sec. The energy surfaces for the holes are two fluted spheres: the curves are drawn for $A=-11.8\pm0.1$, $|B|=7.4\pm0.1$, and $|C|=10.5\pm0.4$, all in units of $\hbar^2/2m$; the constants for pure germanium[1] are

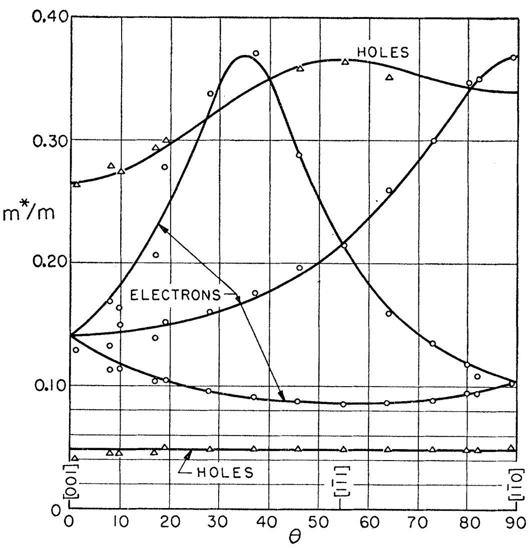

FIG. 1. Variation of effective masses for electrons and holes in the Ge-rich alloy 0.8% Si in Ge with the angle that the magnetic field makes with a [001] crystal direction; frequency 48 000 Mc/sec. The solid line represents the best fit to the experimental points with the parameters $m_t=0.086m$, $m_l=1.59m$ for electron constant-energy surfaces which are ⟨111⟩ spheroids and the fluted energy surface parameters $A=-11.8$, $|B|=7.4$, and $|C|=10.5$, all in units of $\hbar^2/2m$.

$A=-13.0$, $|B|=8.9$, and $|C|=10.3$. For 5.4% Si in Ge, only the electron resonances were resolved, with $m_l\cong(1.5\pm0.1)m$, $m_t\cong(0.10\pm0.01)m$, and $\tau\approx1\times10^{-11}$ sec.

The Si-rich alloys showed only electron resonances: a large nonresonant background absorption suggests that for the holes $\omega\tau\ll1$. For 0.75% Ge in Si, we found $m_l\cong(1.10\pm0.1)m$; $m_t\cong(0.20\pm0.01)m$; $\tau\approx1\times10^{-11}$ sec. The constants for pure Si are: $m_l=0.97m$; $m_t=0.19m$. For 0.4% Ge in Si: $m_l\cong(0.83\pm0.2)m$; $m_t\cong(0.18\pm0.02)m$; $\tau\approx1\times10^{-11}$ sec; this alloy was measured only at 24 000 Mc/sec; all the results on the other alloys refer to 48 000 Mc/sec.

There are theoretical reasons for believing that the mass parameters should not vary rapidly with compo-

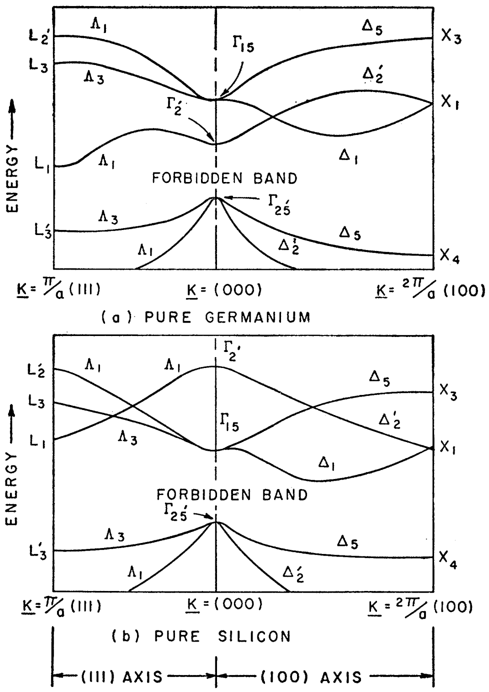

FIG. 2. Schematic diagrams of the energy band contours in perfect Ge and Si crystals along [111] and [100] axes in the reduced zone as suggested by Herman.[2] The removal of the degeneracy by spin-orbit interaction is not shown.

sition. If the conduction band minima are a Δ_1 state in Si and an L_1 state in Ge, as suggested by Herman,[2] then perturbation theory about the minimum gives

$$E=\frac{\hbar^2}{2}\left(\frac{k_1^2}{m_l}+\frac{k_2^2+k_3^2}{m_t}\right), \tag{1}$$

where for the Δ_1, $\mathbf{k}=k(100)$, minimum:

$$\frac{m}{m_l}=1+\frac{2}{m}\sum_{l=\Delta_1}{}' \frac{|(\Psi_{100}{}^0|p_x|\Psi_{100}{}^l)|^2}{E_0-E_l}; \tag{2}$$

$$\frac{m}{m_t}=1+\frac{2}{m}\sum_{l=\Delta_5} \frac{|(\Psi_{100}{}^0|p_y|\Psi_{100}{}^l)|^2}{E_0-E_l}. \tag{3}$$

For the L_1, $\mathbf{k}=(\pi/a)(111)$, minimum:

$$\frac{m}{m_l}=1+\frac{2}{3m}\sum_{l=L_2'} \frac{|(\Psi_{111}{}^0|p_x+p_y+p_z|\Psi_{111}{}^l)|^2}{E_0-E_l}; \tag{4}$$

$$\frac{m}{m_t}=1+\frac{2}{3m}\sum_{l=L_3'} \frac{|(\Psi_{111}{}^0|p_x+\omega p_y+\omega^2 p_z|\Psi_{111}{}^l)|^2}{E_0-E_l}, \tag{5}$$

where $\omega^3=1$.

Herman's[2] explanation (Fig. 2) of the optical gap change observed by Johnson and Christian[3] does not show a Δ_1 level in Si or an L_2' level in Ge sufficiently close to the conduction band minimum to have a profound effect on m_l. The data for holes on the Ge-rich side indicate that the levels at $\mathbf{k}=0$ are separating in an orderly fashion.

There was some suggestion in the results at 24,000 Mc/sec that alloy scattering processes may tend to mix the different ellipsoids together, producing less anisotropy in the observed electron mass parameter. Such an effect, if it exists, would be most effective under conditions of low resolution ($\omega\tau\approx 1$). Our present practice for crystal orientation involves certain resonance degeneracy checks *in situ*, and such a procedure does not work effectively when the resolution is poor.

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[1] Dresselhaus, Kip, and Kittel, Phys. Rev. **98**, 368 (1955).
[2] F. Herman, Phys. Rev. **95**, 847 (1954).
[3] E. R. Johnson and S. M. Christian, Phys. Rev. **95**, 660 (1954).

Rapid Passage Effects in Electron Spin Resonance

A. M. PORTIS
Sarah Mellon Scaife Radiation Laboratory and Physics Department, University of Pittsburgh, Pittsburgh, Pennsylvania
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RELAXATION effects which have been observed in electron spin resonance from F centers in alkali halides[1] and from donor states in silicon[2] are interpreted here in terms of the rapid passage theory of Bloch.[3] The distinguishing feature of the two cases in which these effects have been observed is that the line broadening is of the inhomogeneous type,[4,5] arising from hyperfine interaction.

In Fig. 1 we show the dispersion signal obtained at room temperature from a sample of LiF irradiated with

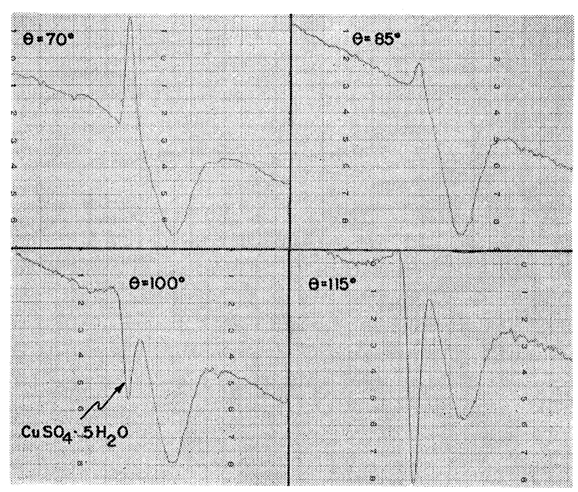

FIG. 1. Dispersion signal in LiF as a function of magnetic field for several values of θ, the phase angle between modulation field and reference signal.