calculated by Kane, and E_g is the energy gap of 0.25 ev at helium temperature.[5] Zwerdling, Lax. and Roth[1,6] have observed magneto-optical transitions to the lowest Landau Level ($l=0$) in the conduction band which gave the value of $\mu=26\mu_B$.[1]

In the present experiments the shift of the g value with concentration is also believed to be associated with the increasing mass of the electrons. Table I shows the close agreement between the observed g's and those calculated by using Eq. (1). The values of m^* were calculated from the known Fermi energy in the samples.[7] All samples were degenerate at helium temperatures with the purest sample having a degeneracy temperature of 11°K. Since the only electrons which participate in the resonance absorption belong to the highest occupied Landau level, the amplitude of the signal does not increase with the concentration of electrons. We were unable to observe resonance in a sample with 10^{16} electrons/cm^3. This is probably due to the progressive broadening of the lines with concentration (Table I).

I would like to thank C. Lee and R. Logan for the InSb samples, G. Feher for the use of the X-band spectrometer and B. Szymanski and E. Gere for help with the experiments.

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[2]Dresselhaus, Kip, and Kittel, Phys. Rev. 100, 618 (1955).
[3]Dresselhaus, Kip, Kittel, and Wagoner, Phys. Rev. 98, 556 (1955).
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[5]For a review, see Semiconductors, edited by N. B. Hannay (Reinhold Publishing Company, New York, 1959), Chapters IX and X.
[6]Zwerdling, Lax, and Roth, Phys. Rev. 108, 1402 (1957).
[7]Moss, Smith, and Taylor, J. Phys. Chem. Solids 8, 323 (1959).

MILLIMETER CYCLOTRON RESONANCE IN SILICON*

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A cavity spectrometer operating at 2.1 mm (136 kMc/sec) has been constructed and cyclotron resonance absorption experiments have been performed on high-purity n-type silicon from 1.2°K to about 50°K.

About 50 microwatts of 2.1-mm microwave energy are generated as the second harmonic from a crossed guide crystal harmonic generator which is fed with 4-mm fundamental power from a Philips DX 151 klystron. The harmonic output is transmitted through an oversized waveguide to a circular TM_{015} cavity located at the bottom of a helium Dewar. The sample, which is about 0.020 in. diameter and about 0.040 in. long, is coupled to the high electric field region of the cavity through a small axial hole beyond cutoff in the end wall of the cavity. The sample is fastened to a quartz rod which extends to the top of the Dewar and serves to position the sample in the cavity and as a light pipe for carrier excitation. Temperature is monitored with a carbon resistance thermometer fastened to the top of the cavity. The cavity, waveguide, and quartz rod are encased in a shield to prevent direct contact with liquid helium, thus eliminating noise due to bubbling of liquid helium in the system. A low pressure of He gas inside the shield provides heat transfer from the cavity and sample to the helium bath. Stabilization of the klystron frequency is accomplished by applying a small 1-kc/sec signal to the reflector of the klystron, and feeding back the synchronously detected signal to the reflector. Resonance lines are observed as a function of the static magnetic field in the standard way by modulating the carrier density with a light chopper at a low audio frequency and synchronously detecting the signal as the magnetic field is swept.

Very pure n-type silicon (3000 ohm cm at room temperature) has been used to obtain the effective-mass parameters of the constant energy ellipsoids associated with the conduction band minima. Orientation data were taken to obtain experimental values for the sum $1/m_1^2+1/m_2^2+1/m_3^2$ (see Fig. 1) which is constant for all orientations and is given by

$$\frac{1}{m_1^2}+\frac{1}{m_2^2}+\frac{1}{m_3^2}=\frac{3}{(m^{*2})_{[111]}}=\frac{1}{m_t^2}+\frac{2}{m_l m_t}. \quad (1)$$

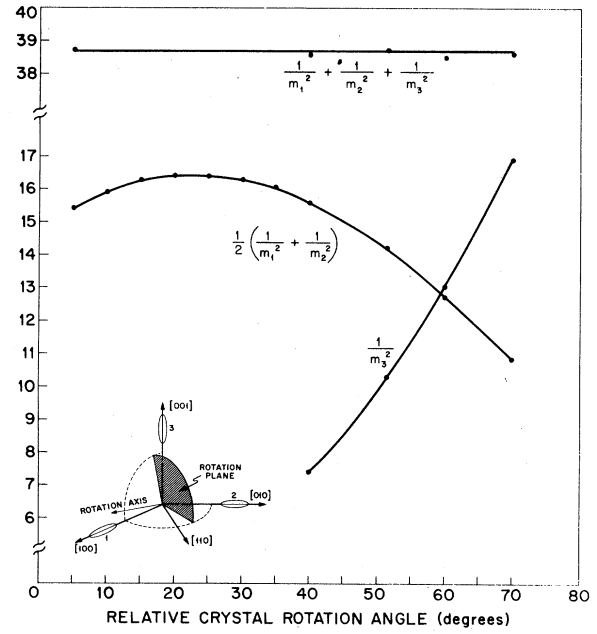

FIG. 1. Experimental values of $1/m_1^2+1/m_2^2+1/m_3^2$, $\frac{1}{2}(1/m_1^2+1/m_2^2)$, and $1/m_3^2$ (in normalized mass units) as a function of sample orientation at 4.2°K.

Here m_1, m_2, and m_3 are the effective masses measured for the individual ellipsoids in the conduction band of Si; m_t and m_l are the transverse and longitudinal components of the ellipsoids, and $m^*[111]$ is the effective mass in the [111] direction. The maximum of the sum $\frac{1}{2}[1/m_1^2+1/m_2^2]$ as a function of orientation yields the effective mass $m^*[110]$ given by

$$\frac{1}{2}\left[\frac{1}{m_1^2}+\frac{1}{m_2^2}\right]_{\max}=\frac{1}{(m^{*2})_{[110]}}=\frac{1}{2}\left(\frac{1}{m_t^2}+\frac{1}{m_l m_t}\right). \quad (2)$$

In addition, an extra relation is found by plotting the experimental values of $\frac{1}{2}(1/m_1^2+1/m_2^2)$ and $1/m_3^2$ as a function of orientation. Where the two curves intersect, the following holds:

$$\left[\frac{1}{m_3^2}\right]_{\text{intersection}}=\frac{1}{(m^{*2})_{[111]}}=\frac{1}{3}\left(\frac{1}{m_t^2}+\frac{2}{m_t m_l}\right). \quad (3)$$

Figure 1 shows experimental curves of $1/m_1^2+1/m_2^2+1/m_3^2$, $\frac{1}{2}(1/m_1^2+1/m_2^2)$, and $1/m_3^2$ as a function of sample orientation at 4.2°K. Using the appropriate values from the curves in Fig. 1 with Eqs. (1), (2), and (3), the self-consistent values $m_t=(0.192\pm0.001)m_0$ and $m_l=(0.90\pm0.02)m_0$ are obtained, where m_0 is the free electron mass.

Our value of m_t agrees with previously reported values; however, our m_l lies outside the limits of error of the values previously reported.[1] At present no explanation of this discrepancy can be given.

Measurements of the effective mass and line width were also made as a function of temperature from 1.2°K to 50°K with the crystal oriented so that the static magnetic field was approximately along the [100] direction. No indication of a change in mass was observed. $\omega\tau$ as a function of temperature measured at low light intensities is shown in Fig. 2. ($\omega\tau=2H_0/\Delta H$, where H_0 is the field at resonance and ΔH is the line width.) Values of $\omega\tau$ approaching 200 were observed, corresponding to a "cyclotron mobility" of the order of 1.5×10^6 cm^2/volt-sec.

Also shown in Fig. 2 is a curve of $m^*\omega\mu/e$, where m^* is given by $1/m^*=\frac{1}{3}(1/m_l+2/m_t)$ and $\mu=4.0\times10^9T^{-2.6}$ cm^2/volt-sec is the high-temperature conductivity mobility for conduction electrons given by Morin and Maita.[2] Our experimental results could be extrapolated to the straight line $m^*\omega\mu/e$. However, we were unable to obtain data at temperatures higher than 50°K due to the masking of the light-excited carriers by intrinsic carriers.

It is hoped that the improved resolution (about 6 times that of a K-band system) and high sen-

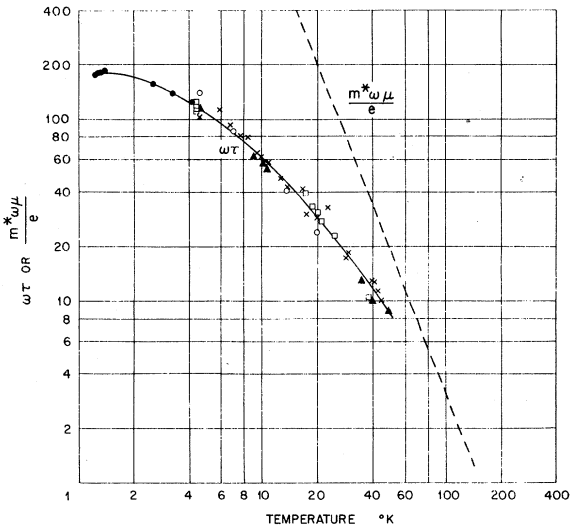

FIG. 2. $\omega\tau$ as a function of temperature for cyclotron resonance absorption in high-purity n-type silicon at 135.95 kMc/sec. The observations were made on the low-field electron resonance with the magnetic field approximately along the [100] axis. (The different symbols refer to different runs.) Also shown is a curve of $m^*\omega\mu/e$, where μ is the high-temperature conductivity mobility for electrons.

sitivity of the 2-mm spectrometer will permit the observation of cyclotron resonance in other materials.

We wish to thank Dr. Benjamin Lax for his continued interest in this work.

*This work was performed with the joint support of the U. S. Army, Navy, and Air Force.

[1]Dexter, Zeiger, and Lax, Phys. Rev. 104, 637 (1956), give the values $m_t = (0.19 \pm 0.01)m_0$ and $m_l = (0.98 \pm 0.04)m_0$. Dresselhaus, Kip, and Kittel, Phys. Rev. 98, 368 (1955), give $m_t = (0.19 \pm 0.01)m_0$ and $m_l = (0.97 \pm 0.02)m_0$.

[2]F. J. Morin and J. P. Maita, Phys. Rev. 96, 28 (1954).

THRESHOLD ENERGY FOR LATTICE DISPLACEMENT IN α-Al_2O_3

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Seitz[1] has estimated that the threshold energy, E_d, for displacement of an ion or atom in a tightly bound solid should be about 25 ev. Experiments have been carried out on metals[2-5] and semiconductors[6,7] which yield displacement energies of 10 to 30 ev. This Letter reports the first direct determination of E_d for a nonconducting material, i.e., α-Al_2O_3.

Levy and Dienes[8] have shown that reactor irradiation of α-Al_2O_3 causes the growth of an optical absorption band at about 204 mμ which cannot be generated by x-rays or γ irradiation. This band is presumed to arise from the trapping of charges at defects which occur when atoms are displaced.

In the present experiment, 0.0635-cm thick samples of α-Al_2O_3 (Linde) were irradiated at 77°K with fast electrons from a Van de Graaff accelerator and the resulting optical absorption was measured at 77°K without intervening warm-up with a Cary Model 14M spectrophotometer. In Fig. 1 are shown the absorption features induced by irradiation with 2-Mev electrons at 77°K and by a fast-neutron irradiation[9] at pile temperature (Oak Ridge X-10 reactor). As previously reported by Levy and Dienes,[8] absorption bands were found at 205, 230, and 255 mμ in neutron-irradiated material. The only band observed after electron irradiation was at 205 mμ. The absorption on the long-wavelength side of the 205-mμ band in the electron-irradiated sample bleached when the sample was warmed to room temperature, and a slight increase in absorption took place at 205 mμ. No bleaching of the 205-mμ absorption occurred when the samples were irradiated and held at 77°K. A very slow bleaching of this band took place when held at room temperature after the low-temperature irradiation. Irradiation at 77°K produces many more centers than does a comparable irradiation at room temperature, the ratio of the yields at these two temperatures being at least ten.

The growth of the 205-mμ band with increasing electron flux was qualitatively similar to that found by Levy and Dienes[8] for neutron irradiation, i.e., a rapid initial increase followed by a linear growth. No dependence on rate or crystallographic orientation with respect to the electron beam was found.

The formation of the 205-mμ centers as a function of electron energy was determined at a constant incident flux (0.945×10^{17} e/cm^2). This flux gives absorption values on the rapidly rising portion of the growth curve. The energy absorbed in the sample, E', is obtained from

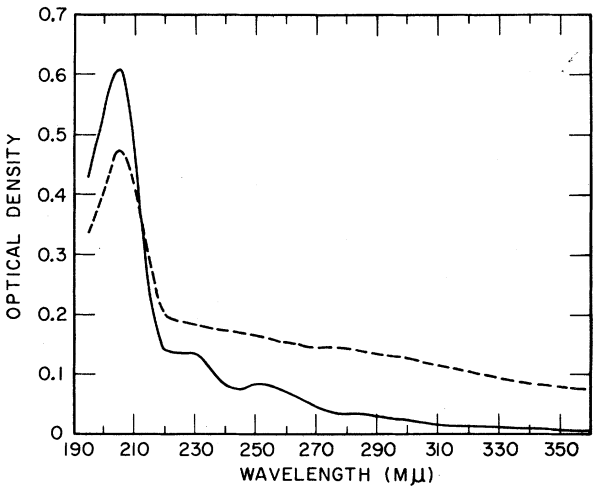

FIG. 1. Optical density vs wavelength in mμ for α-Al_2O_3. Background prior to irradiation has been subtracted. —— 10^{17} nvt (fast), pile temperature. --- 2-Mev electrons, 9.45×10^{16} e/cm^2, 77°K. Measurements made at 77°K.