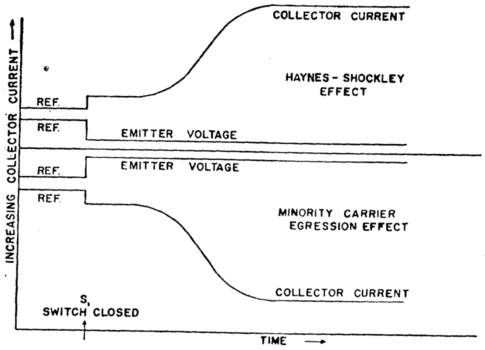

FIG. 2. Haynes-Shockley effect compared with minority carrier egression.

an oscilloscope sweep is synchronized with $S_1$ to give a repetitive presentation. The collector is biased negatively to attract positive holes. Positive holes in excess of the equilibrium density cause an increase in collector current which appears as an increased voltage across resistor $R_1$. This voltage is presented on the oscilloscope. A sweeping voltage $V_1$ causes positive holes to go from the emitter to the collector.

In Fig. 2, the upper trace is the Haynes-Shockley effect compared with the emitter voltage appearing across $R_2$ to show the switching instant. The lower trace appears when switch $S_2$ is reversed. In this case, the leakage current of the collector is decreased after a time delay for propagation of the effect and remains depressed as long as the emitter bias remains. It is to be noted that the sweeping voltage $V_1$ has the same polarity in both cases.

The phenomenon of electron egression has implications in the physical mechanism of the operation of transistor devices.

[1] J. R. Haynes and W. Shockley, Phys. Rev. **75**, 691 (1949).

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## Effective Masses of Electrons in Silicon*

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THE original cyclotron resonance experiments on germanium were made possible by virtue of rf ionization of carriers by the microwave electric field.[1] This technique could not be used on silicon because of the relatively large trapping energies for carriers. Recent experiments by the groups at Berkeley and at Lincoln Laboratory have used optical excitation of carriers.[2] We report here the independently obtained results of the two laboratories on the effective mass $m^*$ of electrons in silicon. The principal values of $m^*$ agree within the experimental error. The experiments were carried out on single crystals at liquid helium temperature. Microwave frequencies were in the 23-kMc/sec region.

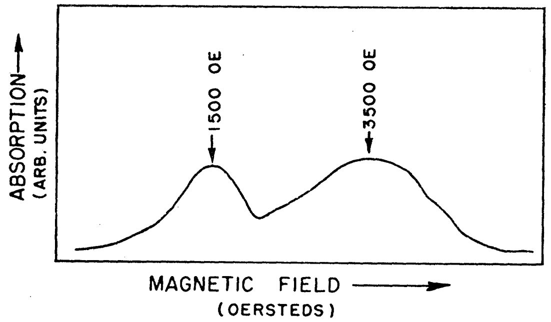

FIG. 1. Cyclotron resonance absorption of electrons in silicon as a function of magnetic field $H$ when $H$ is parallel to the [001] direction.

The resonance peaks were observed when the magnetic field was parallel to the [001] and [110] directions and one peak was observed when the magnetic field was along the [111] axis. This suggests that the constant energy surfaces at the bottom of the conduction band in silicon can be represented by six ellipsoids of revolution along the cubic axes in the Brillouin zone, in agreement with the conclusions drawn from magnetoresistance[3] and piezoresistance[4] experiments.

The principal values of the mass tensor are conveniently obtained from the peak positions when the magnetic field is along the [001] direction. An absorption trace for this orientation is shown in Fig. 1; the peaks correspond to effective masses $m_2$ and $(m_1m_2)^{\frac{1}{2}}$. These data indicate a transverse mass $m_2=0.19\,m_0$ and a longitudinal mass $m_1=0.98\,m_0$, where $m_0$ is the free electron mass.[5] The average effective mass for these values is $\bar{m}^*=3\,m_1m_2/(2\,m_1+m_2)=0.26\,m_0$. The ratio $m_1/m_2=5.2$ is consistent with the value estimated from the magnetoresistance effect.[3] By using these values of $m_1$ and $m_2$, following Shockley,[6] two theoretical curves for $m^*/m_0$ as a function of $\theta$ were computed, where $\theta$ is

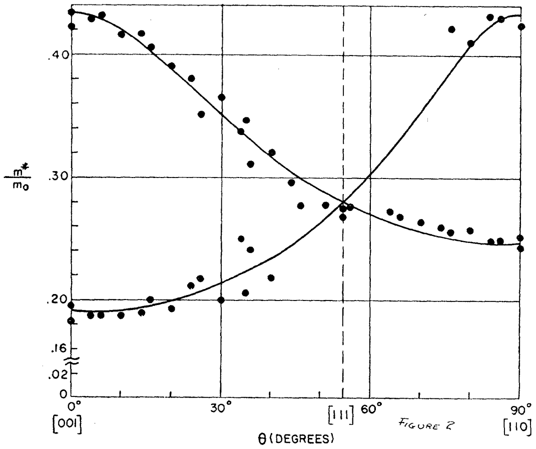

FIG. 2. Effective mass of electrons in silicon as a function of magnetic field orientation in the $(\bar{1}10)$ plane.

the angle between the [001] direction and the magnetic field in the ($\bar{1}10$) plane. These curves are shown in Fig. 2 in comparison with experimental points obtained with several samples.

The half-widths of the resonance lines were of the order of 1000 oersteds. From this fact it was estimated that the mean collision time was about $2\times10^{-11}$ sec. This is approximately $\frac{1}{3}$ the collision time found for pure Ge at 4°K.

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[1] Dresselhaus, Kip, and Kittel, Phys. Rev. **92**, 827 (1953); Lax, Zeiger, Dexter, and Rosenblum, Phys. Rev. **93**, 1418 (1954).

[2] Dexter, Zeiger, and Lax, Phys. Rev. **95**, 557 (1954).

[3] G. L. Pearson and C. Herring, Physica (to be published), paper presented at the International Conference on Semiconductors, Amsterdam, Netherlands, June 30, 1954.

[4] C. S. Smith, Phys. Rev. **94**, 42 (1954).

[5] The estimated error in the mass values is about ±5 percent.

[6] W. Shockley, Phys. Rev. **90**, 491 (1953).

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# Effective Masses of Holes in Silicon*

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Cyclotron resonance experiments have been carried out on *p*-type silicon at 23 kMc/sec and 4°K. Carriers were excited by infrared light as described for germanium.[1] The beam from the light source was chopped at 900 cps, with a resulting amplitude modulation of the absorption signal. High sensitivity was achieved by a phase-sensitive detection method.[2] The reference signal for the detector was obtained from a phototube in the chopped beam.

Two resonance peaks were observed corresponding to effective masses $m_1^*$ and $m_2^*$. The effective masses measured in the principal directions are summarized in Table I; $m_0$ is the free electron mass. From these data, by means of simple statistics, the approximate average effective mass of holes was calculated to be $0.39m_0$.

Table I.

| Magnetic field parallel to: | [001] | [111] | [110] |
|---|---|---|---|
| $m_1^*/m_0$ | 0.171 | 0.160 | 0.163 |
| $m_2^*/m_0$ | 0.46 | 0.56 | 0.53 |

The observations are consistent with the model used for germanium,[1,3] in which the top of the valence band occurs at $k=0$ and in which the constant energy surfaces in the Brillouin zone can be represented by two sets of warped surfaces centered about the origin. For these surfaces, the energy $E$ is given as a function of the wave vector $\mathbf{k}$ by

$$E=(-\hbar^2/2m_0)\{ak^2\pm[b^2k^4-c(k_x^4+k_y^4+k_z^4)]^{\frac{1}{2}}\}, \quad (1)$$

where $a$, $b$, and $c$ are constants. The approximate theoretical calculation of the resonance frequency and the effective mass at resonance was carried out as previously described[1,4] but a more exact expansion of the radical was used. The result is

$$1/m^*=(1/m_0)[A_\pm+B_\pm(1-3\cos^2\theta)^2], \quad (2)$$

where $A_\pm=a\pm b'\pm(c/12b')$, $B_\pm=\mp c/32b'$, $b'=(b^2-\frac{2}{3}c)^{\frac{1}{2}}$, and the plus and minus signs refer to the effective masses $m_1^*$ and $m_2^*$, respectively. The constants can be determined from the values for $m_1^*$ at $\theta=0$ and for $m_2^*$ at $\theta=0°$ and 55°. The result for silicon is: $a=4.0$, $b^2=8.1$, and $c=6.5$. By using these values in Eq. (2), a theoretical curve was calculated for $m_2^*$ and plotted in Fig. 1.

According to the perturbation theory[3] which describes the valence band structure of germanium around $\mathbf{k}=0$, three degenerate bands are split by spin-orbit interaction into the two bands described by Eq. (1) and a lower band for which the energy is

$$E_3=-E_0-(\hbar^2ak^2/2m_0)=-E_0-(\hbar^2k^2/2m_3^*), \quad (3)$$

where $E_0$ is the splitting at $\mathbf{k}=0$.[5,6] If this expression is correct for silicon, $m_3^*=0.25m_0$. We have not been able to detect holes in this normally filled band.

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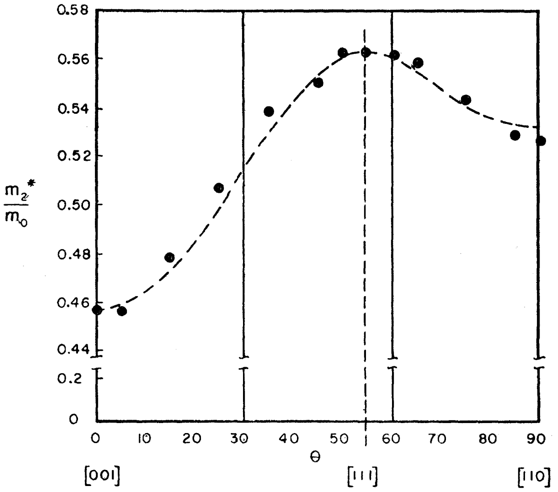

Fig. 1. The effective mass $m_2^*$ of the heavy holes in silicon is plotted as a function of $\theta$, the angle between the [001] direction and the magnetic field in the (110) plane. The points are experimental, and the curve is theoretical.