de Haas–van Alphen Oscillations in the Magnetoresistance of Heavily Doped Germanium

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The existence of de Haas-van Alphen oscillations in the magnetoresistance of degenerately doped n- and p-type germanium is reported. Transverse and longitudinal magnetoresistance measurements were performed on a number of selected samples of various crystal orientation at 4.2°K in dc magnetic fields up to 110 kOe. In p-type germanium distinct oscillations were observed only in the longitudinal magnetoresistance. In n-type germanium oscillations could be seen only in the transverse magnetoresistance, the magnitude of the effect being enhanced by the use of antimony as dopant and by aligning $H \parallel [111]$. In each sample studied the period of the oscillations can be related to the motion of Landau levels with respect to the Fermi level, when the appropriate cyclotron mass is introduced. The magnetic field dependence of the amplitude of the oscillations yields in each case a value of $\omega\tau$ in reasonable agreement with that obtained from analysis of conductivity data. As expected, no oscillatory behavior could be detected in the magnetoresistance of degenerately doped silicon.

IN this article we report on the existence of de Haas–van Alphen oscillations in the magnetoresistance of degenerately doped n- and p-type germanium at 4.2°K in dc magnetic fields up to 110 kOe. Such oscillations have been observed previously in a number of compound semiconductors.[1] However, no de Haas–van Alphen type oscillations have been reported in heavily doped germanium, presumably because of the relatively large effective masses and short relaxation times encountered.

Nevertheless, it is possible to obtain $\omega\tau$ sufficiently >1 in degenerate germanium to yield significant magnetoresistance oscillations over more than one complete period in $1/H$. To achieve this, one must carefully select the appropriate magnetic field direction, crystal orientation, and doping. Figure 1 presents calculations of $\omega\tau/H$ versus impurity concentration at 4.2°K for the light hole band in gallium-doped p-type germanium and for various crystal orientations with respect to H in arsenic-doped n-type germanium. The relaxation time τ for p-type material was obtained from an analysis of the conductivity on the basis of the actual valence band structure.[2] For n-type material, the relaxation time was derived from measured conductivities, assuming isotropic scattering in the multiellipsoid conduction-band model.[3,4] For a particular impurity concentration and crystal orientation, $\omega\tau$ in antimony-doped germanium is greater by a factor $\simeq 1.5$ than that shown for arsenic doping in Fig. 1. According to this figure, a magnetic field along the [111] direction in antimony-doped material provides the most favorable conditions for the observation of de Haas–van Alphen oscillations in n-type germanium.

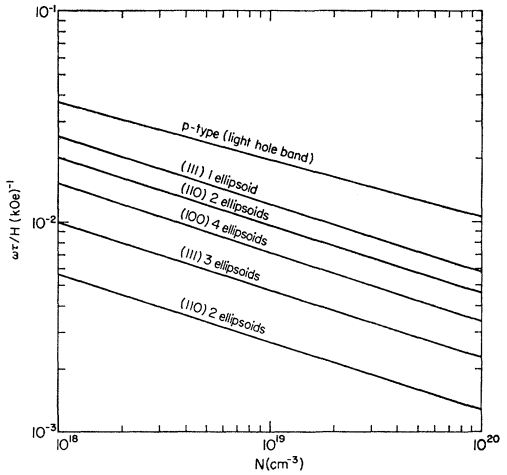

FIG. 1. Concentration dependence of $\omega\tau/H$ for the light hole band in gallium-doped germanium and for various magnetic field directions in arsenic-doped germanium. Note that $(\omega\tau/H)_{Sb} = 1.5(\omega\tau/H)_{As}$.

The experiments were carried out at the MIT National Magnet Laboratory. Oscillations were observed in the longitudinal magnetoresistance of p-type germanium in the impurity concentration range from 2.1×10^{18} to 1.9×10^{19} cm^{-3} and in the transverse magnetoresistance of n-type germanium in the impurity concentration range from 3.0×10^{18} to 4.6×10^{18} cm^{-3}.

Figure 2 presents longitudinal magnetoresistance versus $1/H$ for a [100] oriented p-type sample doped to a gallium concentration of 1.2×10^{19} cm^{-3}. According

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[2] W. Bernard, H. Roth, and W. D. Straub, Phys. Rev. **132**, 33 (1963).

[3] C. Herring, Bell System Tech. J. **34**, 237 (1955).

[4] G. Dresselhaus, A. F. Kip, and C. Kittel, Phys. Rev. **98**, 368 (1955).

to Fig. 1, $\omega\tau=1$ at $H=52$ kOe for this sample. The semilogarithmic portion of Fig. 2 shows distinct oscillations superimposed on a monotonically increasing magnetoresistance component. In order to examine the de Haas–van Alphen behavior in greater detail, we have fitted the amplitude of the oscillations to the equation due to Dingle[5]

$$(\Delta\rho/\rho)_{\text{amp}} \propto H^{1/2} e^{-(2\pi^2 kT/\hbar\omega)} e^{-(2\pi/\omega\tau)}, \quad (1)$$

where $\omega=eH/m^*$. The second exponential takes into account collision broadening of the Landau levels. The experimental value of $\omega\tau/H$ thus obtained is 0.030 $(\text{kOe})^{-1}$ as compared to the value of 0.019 $(\text{kOe})^{-1}$ predicted from Fig. 1. The oscillatory component of the magnetoresistance is plotted alone in the linear portion of Fig. 2.

The reciprocal field at which the nth Landau level in the light hole band passes through the zero-field Fermi level ϵ_f is given by

$$1/H=(n+\tfrac{1}{2})(e\hbar/m^*\epsilon_f). \quad (2)$$

As indicated in Fig. 2, the period of the oscillations predicted by Eq. (2) is in reasonable agreement with experiment. In all p-type samples studied, both the amplitude and period of the oscillations decreased with increasing impurity concentration as required by the τ dependence in Eq. (1) and the Fermi-level dependence in Eq. (2). As expected from the approximate spherical symmetry of the light hole band only small variations in the period with crystal orientation were evident. Oscillations in the transverse magnetoresistance could be detected only in the lowest doped sample studied. However, the amplitude of these oscillations was an order of magnitude smaller than that observed in the longitudinal direction.

Figure 3 shows the transverse magnetoresistance

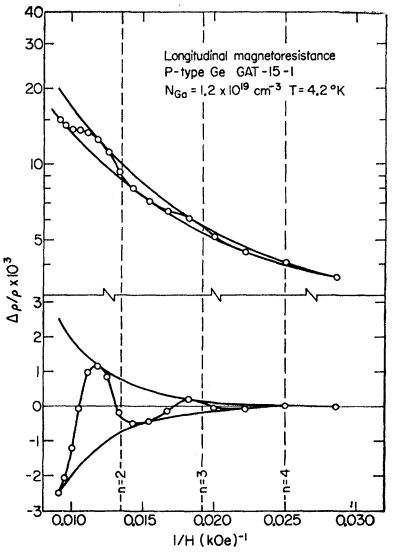

FIG. 2. Longitudinal magnetoresistance versus $1/H$ for a degenerate gallium-doped germanium sample. The linear portion of the figure shows the oscillatory component.

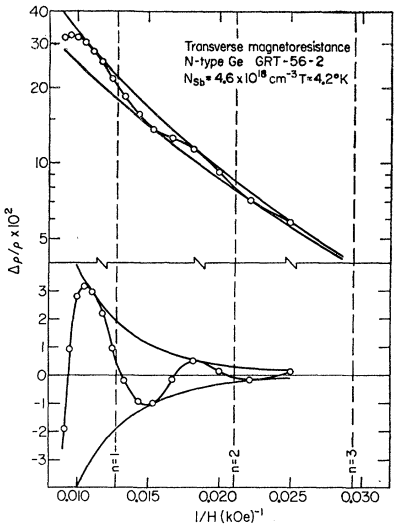

FIG. 3. Transverse magnetoresistance versus $1/H$ for a degenerate antimony-doped germanium sample. The linear portion of the figure shows the oscillatory component.

versus $1/H$ for a sample doped with 4.6×10^{18} antimony impurities cm^{-3}, with H along a [111] crystal axis. According to Fig. 1, $\omega\tau=1$ at $H=43$ kOe for this sample. Again the amplitude of the oscillations has been fitted to Eq. (1), and the oscillations alone have been replotted in the linear portion of the figure. The experimental value of $\omega\tau/H$ obtained by fitting the amplitude to Eq. (1) is 0.035 $(\text{kOe})^{-1}$ as compared with the value of 0.023 $(\text{kOe})^{-1}$ predicted on the basis of Fig. 1. The period is again seen to be in reasonable agreement with Eq. (2).

Oscillations have been observed in the transverse magnetoresistance of both arsenic -and antimony-doped samples, with H along the [110] and [111] crystal axes. The periods are in agreement with Eq. (2) when the appropriate cyclotron mass is inserted. In contrast to the case of p-type material, no oscillations could be detected in the longitudinal magnetoresistance of any n-type sample studied.

There are two distinct processes due to Landau level formation which can contribute to the magnetoresistance oscillations in a multiband semiconductor: Transfer of carriers between high- and low-conductivity bands, and modulation of the conductivity within a given band. In p-type germanium the motion of the Fermi level will be negligible since the heavy hole band serves as an effective particle reservoir, and the population transfer should be relatively independent of field direction owing to the approximate spherical symmetry of the light hole band. Thus, the difference between the transverse and longitudinal magnetoresistance oscillations must be attributed to a corresponding dependence of the high-field quantum transport properties of the light hole band on magnetic field direction.[6] The situation is somewhat more involved in n-type germanium, where population transfer will be accompanied by appreciable motion of the Fermi level and where

[5] R. B. Dingle, Proc. Roy. Soc. (London) **A211**, 517 (1952).

[6] P. N. Argyres, Phys. Rev. **117**, 315 (1960).

crystal as well as field orientation must be taken into account.

We have also considered the possibility of observing magnetoresistance oscillations in silicon, where $\omega\tau$ is smaller by a factor ~ 3 than that in germanium owing to the larger cyclotron masses. Preliminary magnetoresistance measurements performed on heavily doped silicon samples in magnetic fields up to 110 kOe exhibited, as expected, no oscillatory behavior.

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Electron Cyclotron Resonance in CdS*†

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Electron cyclotron resonance has been observed in single-crystal CdS platelets at temperatures below 4.2°K. The single resonance seen in all orientations is consistent with a single-ellipsoid conduction-band model for CdS. The cyclotron effective masses measured with the crystal c axis parallel and perpendicular to the magnetic field are $m^*_{c\|B}/m_o=0.171$ and $m^*_{c\perp B}/m_o=0.162$, implying that the constant-energy surfaces near the conduction-band minimum are oblate spheroids having transverse and longitudinal effective masses $m_t^*/m_o=0.171$ and $m_l^*/m_o=0.153$. The effective mass values determined from cyclotron resonance are 15% lower than those measured in other experiments. The difference cannot be due to depolarization or optical polaron effects, but can be accounted for in terms of an electron self-energy correction resulting from the piezoelectric electron-phonon interaction in CdS. Electron collision times of order 10^{-11} sec were calculated from the 70-Gc/sec cyclotron resonance data taken between 1.25 and 4.2°K. The magnitude and temperature dependence of the collision times are best described by the theoretical predictions for piezoelectric scattering along with possibly a small neutral-impurity scattering contribution.

INTRODUCTION

OPTICAL[1–3] and galvanomagnetic[4,5] experiments have indicated that the conduction band of cadmium sulfide is characterized by a single, nearly spherical, constant-energy surface with an electronic effective mass about one-fifth of the free electron mass. Preliminary cyclotron resonance experiments reported by Dexter[6] proved to be nonreproducible, and the tentative effective mass values quoted then are erroneous. This article describes the observation of reproducible electron cyclotron resonance at 72 Gc/sec and liquid-helium temperatures in several CdS platelets obtained from two separate sources. Recently, Sawamoto[7] has reported cyclotron resonance of both electrons and holes in CdS in one orientation. The present study was undertaken to measure directly the effective mass tensor of electrons in CdS and to gain information on the scattering mechanisms important at low temperatures through a determination of the electronic collision times from the widths of the cyclotron resonance peaks.

EXPERIMENTAL

Successful cyclotron resonance experiments were carried out using CdS single-crystal platelets grown from the vapor phase under the direction of D. C. Reynolds at the Wright-Patterson Aeronautical Research Center and high resistivity platelets supplied by J. E. Powderly of the Eagle-Picher Company. The Wright-Patterson platelets were of dimensions 1×1×0.02 mm, while 1-×1-×0.2-mm samples were cleaved from somewhat larger Eagle-Picher platelets. No etching or other surface treatment was employed. Resonances were not seen in Eagle-Picher "high purity" or

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‡ National Science Foundation Predoctoral Fellow.

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