Magnetic Susceptibility of Indium Antimonide

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The magnetic susceptibility of both *n*- and *p*-type InSb has been measured by the Faraday method from 65°K to 650°K. The carrier contribution has been obtained by subtracting the lattice component in both the intrinsic range and the extrinsic range. These data indicate that the energy gap at 0°K is 0.262 ev and that the electron effective mass is 0.028 m_0. The hole contribution to the susceptibility in the extrinsic range for the *p*-type specimen used was too small to permit a determination of the effective mass of holes.

THE magnetic susceptibility of several *n*- and *p*-type single crystals of InSb[1] have been measured by the Faraday method from 68°K to 650°K. The results of these measurements[2] are shown in Fig. 1. In specimen *N*-1 the extrinsic electron concentration $n_0 = 1.6\times10^{16}$ cm^{-3}, in *N*-2 $n_0 \simeq 4\times10^{14}$ cm^{-3}, and in *P*-1 the extrinsic hole concentration $p_0 = 1.1\times10^{16}$ cm^{-3}.

It can be shown[3] that the susceptibility of a semiconductor can be written as the sum of three components: the diamagnetic lattice contribution χ_L, the paramagnetic contribution of impurity atoms χ_I containing unpaired electrons, and the contribution of the carriers χ_c. Since the impurity content of the specimens is too small to contribute significantly to the susceptibility, we are concerned here only with χ_L, which is usually only slightly temperature dependent, and χ_c. In the range of classical behavior,

$$\chi_c = (\beta^2/3\rho kT)n(3-f_e^2) \quad (1)$$

for electrons, a similar expression holding for holes. Here, β is the Bohr magneton, ρ the density of the crystal, n the electron concentration, and $f_e = m_0/m_e^{(M)}$, where m_0 is the electron rest mass and $m_e^{(M)}$ is the effective electron mass averaged appropriately for motion in the magnetic field.[4] In the case of appreciable carrier degeneracy Eq. (1) gives too large a value for χ_c. For classical intrinsic behavior the carrier contribution is

$$\chi_c = CT^{\frac{1}{2}}\left[\frac{m_e^{(N)}m_h^{(N)}}{m_0^2}\right]^{\frac{3}{4}} e^{-E_g/2kT}[6-f_e^2-f_h^2], \quad (2)$$

where $C = 2\beta^2(2\pi m_0)^{\frac{3}{2}}k^{\frac{1}{2}}/3\rho h^3$ and $E_g = E_g^0 + BT$.

In view of Eq. (2), the rapid increase in diamagnetism above 200°K exhibited by the curves in Fig. 1 is attributed to intrinsic ionization. The maximum at 600°K is probably due to two effects: (1) the onset of carrier degeneracy which in itself would not cause a maximum and (2) a temperature dependence of χ_L similar to that observed in Ge[5] and Si,[6] i.e., decreasing diamagnetism with increasing temperature. From Eq. (2), it is evident that a plot of $\log(\chi_c/T^{\frac{1}{2}})$ *vs* $1/T$ should yield a straight line of slope $E_g^0/2k$. Such a plot is shown in Fig. 2 for *N*-2. In order to obtain χ_c, it was assumed that χ_L is temperature independent and is given by the low-temperature value of χ in Fig. 1. The curve is indeed linear over most of the range with a slope corresponding to $E_g^0 = 0.262$ ev, in reasonable agreement with values obtained from electrical measurements.[7,8] Because of the assumption concerning χ_L, this value may be somewhat small.

The curve for *N*-1 in Fig. 1 shows the extrinsic contribution at low temperature (<200°K). Because of

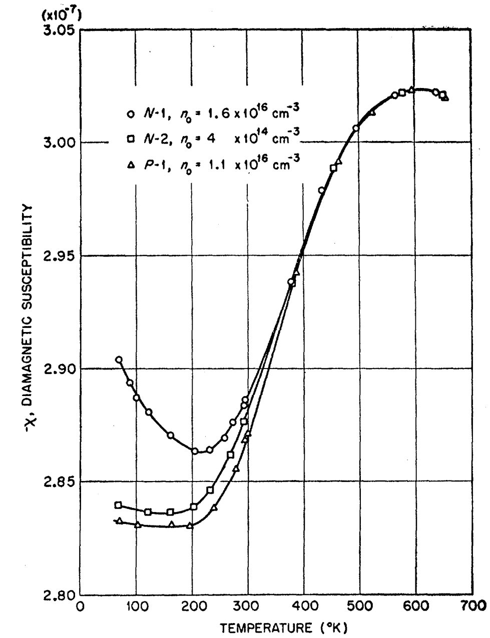

FIG. 1. Diamagnetic susceptibility as a function of absolute temperature for three specimens of InSb.

[1] We are indebted to H. J. Hrostowski and M. Tanenbaum of Bell Telephone Laboratories for these specimens.

[2] The relative precision of points on a given curve is better than ±0.1 percent. The absolute precision, relative to the reported value of O_2 gas at N.T.P. is not better than ±0.5 percent. For comparison purposes the curves were adjusted to correspondence at 600°K.

[3] G. Busch and E. Mooser, Helv. Phys. Acta **26**, 611 (1953).

[4] $m^{(M)}$ becomes identical with the density of states mass $m^{(N)}$ only when the energy surfaces are spheres in *K*-space and the bands are nondegenerate.

[5] D. K. Stevens and J. H. Crawford, Jr., Phys. Rev. **92**, 1065 (1953).

[6] D. K. Stevens (unpublished data).

[7] M. Tanenbaum and J. P. Maita, Phys. Rev. **91**, 1009 (1953).

[8] Breckenridge, Blunt, Hosler, Frederikse, Becker, and Oshinsky, Phys. Rev. **96**, 571 (1954).

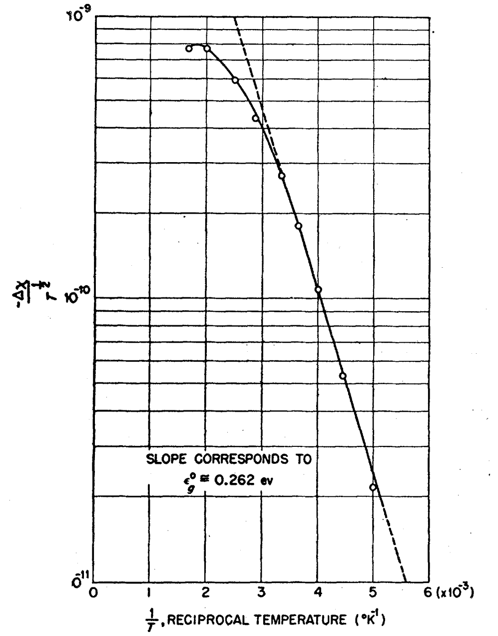

FIG. 2. Carrier susceptibility divided by $T^{3/2}$, $(\Delta\chi T^{-3/2})$, as a function of reciprocal temperature in the intrinsic range for sample N-2.

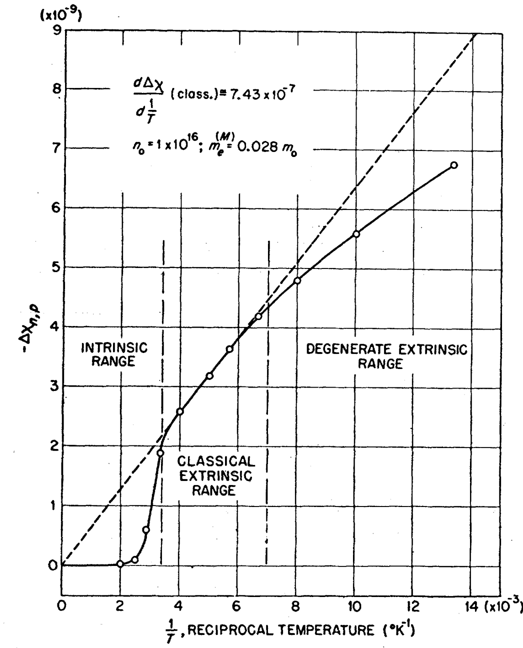

FIG. 3. $-\Delta\chi_{n,p} = (\chi_{P\text{-}1} - \chi_{N\text{-}1})$ as a function of reciprocal temperature.

the smaller temperature dependence of χ_c and the expected temperature dependence of χ_L, χ_c cannot be obtained in this case as was done for the intrinsic contribution. However, because of the larger hole mass,[9] the extrinsic contribution of N-1 is given to a good approximation in the extrinsic range by the difference in the curves for N-1 and P-1. This difference is plotted as a function of $1/T$ in Fig. 3. Three ranges of behavior are evident: (1) the intrinsic range in which the extrinsic difference between the two specimens is reduced by intrinsic ionization, (2) the approximately classical extrinsic range due only to N-1, and (3) the extrinsic range in which degeneracy becomes appreciable. It is evident from Eq. (1) that the slope of the χ_c *vs* $1/T$ curve is proportional to $m_e^{(M)}$ in the classical extrinsic range. From Fig. 3, this corresponds to $m_e^{(M)} = 0.028m_0$. This value is somewhat smaller than that determined electrically.[8] A similar analysis was made for the difference between N-1 and N-2, yielding $m_e^{(M)} = 0.032m_0$. Because of the higher purity of N-2 than P-1, the intrinsic range extended to a much lower temperature. Consequently, the slope was obtained on a portion of the curve deeper in the degenerate range which would give too small a slope and too large a value of $m_e^{(M)}$. Hence the first value is the most reliable.

[9] The reported mobility ratio of 85 in this material (reference 7) indicates that the contribution of holes in P-1 is perhaps no greater than 2 percent of the electron contribution in N-1.