Hall Effect and Conductivity of InSb

H. J. HROSTOWSKI, F. J. MORIN, T. H. GEBALLE, AND G. H. WHEATLEY
Bell Telephone Laboratories, Murray Hill, New Jersey

(Received August 19, 1955)

Hall coefficient and conductivity of single-crystal InSb have been measured from 1.3°K to 700°K. Impurity band conduction and an acceptor ionization energy of 7×10^{-3} ev have been observed in p-type InSb at low temperature. Variation of R_H with H indicates a complicated valence band structure. Effective masses of $0.015m$ for electrons and approximately $0.17m$ for holes are consistent with mobility and low temperature Hall effect data. Lattice scattering mobilities are proportional to $T^{-1.68}$ for electrons and approximately $T^{-2.1}$ for holes. The intrinsic carrier concentration product is given by $np=3.6\times10^{29}T^3\exp(-0.26/kT)$ above 200°K. E_g at 0°K is between 0.26 and 0.29 ev.

1. INTRODUCTION

ALTHOUGH many investigations of InSb have been reported,[1] most of the information about this compound has been obtained from relatively impure material in which the total impurity concentration, N_I, was unknown. The present work was designed to determine semiconducting properties of InSb from 1.3°K to 700°K from measurements of Hall coefficient and conductivity on single-crystal samples of rather definite, low impurity content. Since degeneracy[2] and other effects[3] complicate the interpretation of data obtained from highly doped InSb, only samples of the highest purity obtainable were studied.

2. EXPERIMENTAL

Samples were cut from single crystals pulled[4] from melts of InSb purified by extensive zone refining.[5] Measurements were made on oriented bridge shape[6] samples using indium alloyed contacts below 300°K and platinum 10 percent rhodium wire pressure contacts above this temperature. For high-temperature measurements the samples were heated in an atmosphere of N_2.

TABLE I. Electrical properties of InSb samples at 78°K.

Sample		N_d-N_a (cm^{-3})[a]	$R_H\sigma$ (cm^2/volt sec)
n-type	1	7.7×10^{14}	3.75×10^5
	2	9.8×10^{14}	3.70×10^5
	3	1.2×10^{15}	2.30×10^5
	4	8.8×10^{14}	3.80×10^5
p-type	A	2.9×10^{14}	9.5×10^3
	B	4.4×10^{14}	1.0×10^4
	C	1.8×10^{15}	8.1×10^3
	D	1.1×10^{15}	9.3×10^3

[a] Obtained from $n=(3\pi/8)(1/eR_H)$; $H=3080$ gauss for all cases except Samples 3 and C where $H=750$ gauss.

Table I gives the extrinsic electrical properties of the samples used.

Above 500°K acceptors were introduced during the measurements. The effects were small and generally did not change the extrinsic properties by more than 10 percent. At 300°K the changes were not detectable unless the sample had been heated above 650°K. Different samples of comparable carrier concentration were used for the high- and low-temperature regions because of this and the low melting point of indium in the alloyed contacts.

3. VARIATION OF HALL COEFFICIENT WITH MAGNETIC FIELD

The Hall coefficient, R_H, was measured as a function of magnetic filed strength, H, for a number of samples using fields ranging from 250 to 4300 gauss. In n-type InSb, R_H is independent of H up to 4300 gauss at 300°K. At 78°K, R_H decreases linearly with increasing H. The decrease of R_H over this range of H is dependent on electron concentration and varies from sample to sample. It amounted to less than 5 percent for the samples investigated.

For p-type InSb, R_H varies with H in a manner somewhat similar to that observed for p-type germanium.[7] Figure 1, which shows the behavior of samples A and B at several temperatures, indicates that the variation of R_H with H depends on acceptor concentration as well as temperature.[8]

The field dependence of R_H in p-type germanium has been successfully interpreted[7] by assuming the presence of a small percentage of high-mobility holes in addition to the usual positive charge carriers. Recent cyclotron resonance experiments[9] on InSb show the existence of two anisotropic holes with effective masses of approximately $0.18m$ and $1.2m$. Analysis of low-temperature Hall effect data (see Sec. 4) gives an average effective mass of $0.17m$ which is very close to the lower cyclotron

[1] O. Madelung and H. Weiss, Z. Naturforsch. **9a**, 527 (1954), give a comprehensive review of the literature.
[2] Harman, Willardson, and Beer, Phys. Rev. **93**, 912 (1954).
[3] Hrostowski, Wheatley, and Flood, Phys. Rev. **95**, 1683 (1954).
[4] G. K. Teal and J. B. Little, Phys. Rev. **78**, 647 (1950).
[5] W. G. Pfann, Trans. Am. Inst. Mining Met. Engrs. **194**, 747 (1952).
[6] P. P. Debye and E. M. Conwell, Phys. Rev. **93**, 693 (1954).
[7] Willardson, Harman, and Beer, Phys. Rev. **96**, 1512 (1954) and references cited there.
[8] Harman, Willardson, and Beer, Phys. Rev. **95**, 699 (1954), find little field dependence of R_H in the extrinsic range for samples with 2×10^{16} acceptors per cm^3.
[9] Dresselhaus, Kip, Kittel, and Wagoner, Phys. Rev. **98**, 556 (1955).

resonance value. This result indicates that the heavy holes are considerably less abundant. Since these would be expected to influence R_H only at relatively high fields it appears that the observed behavior of R_H below 4300 gauss results primarily from a complicated valence band structure.

The Hall coefficient is given by the relation $R_H = (\mu_H/\mu)(1/ep)$, where μ_H/μ, the ratio of Hall to conductivity mobility, is strongly dependent on magnetic field. Although μ_H/μ cannot be determined exactly without independent measurements of drift mobility,[10] approximate values ranging from 1.5 to 1.8 can be obtained from the ratio of the low- and high-field values of R_H since $(\mu_H/\mu)_{H=\infty}=1$. Thus,

$$R_{H=0}/R_{H=\infty}=\mu_H/\mu. \quad (1)$$

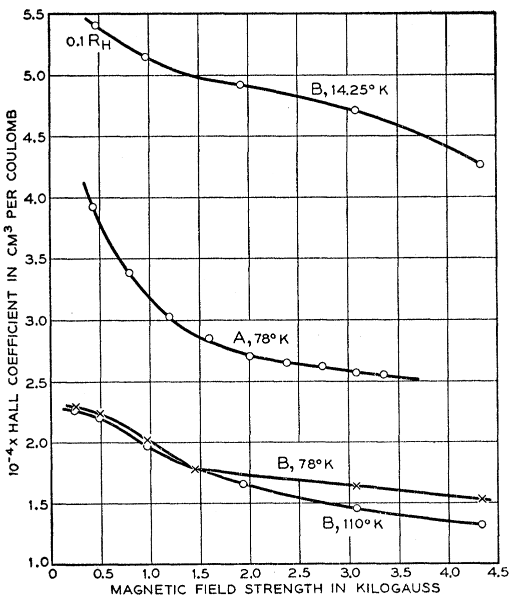

FIG. 1. Variation of Hall coefficient with magnetic field for p-type InSb.

These values are much greater than $3\pi/8$, the value for spherical energy surfaces. They are also somewhat approximate because of the onset of impurity scattering, which influences μ_H/μ at liquid nitrogen temperatures.

4. LOW-TEMPERATURE RESULTS

Figures 2 and 3 show, respectively, the temperature dependence of the Hall coefficient (for $H=3080$ gauss) and conductivity, σ, for two samples of low extrinsic carrier concentration. Measurements were taken to 1.3°K in both cases.

There is no evidence of donor ionization in Sample 2 in the temperature range studied. An effective electron mass, m_n, of $0.015m$ (see Sec. 6), where m is the free

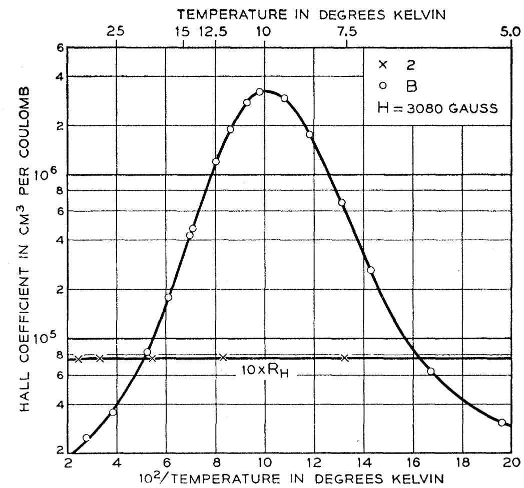

FIG. 2. Hall coefficient below 50°K *vs* reciprocal temperature for Samples 2 and B.

electron mass, gives a degeneracy temperature[11] of 28°K for this sample. This is in reasonable agreement with the observed temperature dependence of the conductivity. The donor ionization energy calculated from the hydrogen-like model for impurity centers is 10^{-3} ev for a dielectric constant[12] of 16. Ionization from this level would be observable in Hall effect measurements on nondegenerate samples ($n \approx 10^{13}$ cm^{-3}) around 2°K.

The data for p-type sample B show ionization of acceptors with increasing temperatures above 10°K and impurity band conduction[13,14] below this tempera-

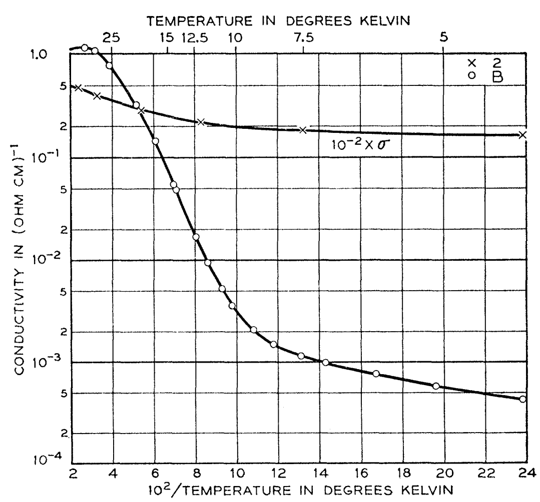

FIG. 3. Conductivity below 50°K *vs* reciprocal temperature for Samples 2 and B.

[10] The lifetime of holes in InSb is apparently too low to measure drift mobilities by existing techniques.

[11] W. Shockley, *Electrons and Holes in Semiconductors* (D. Van Nostrand and Company, Inc., New York, 1950).

[12] Briggs, Cummings, Hrostowski, and Tanenbaum, Phys. Rev. **93**, 912 (1954).

[13] C. S. Hung and J. R. Gliessman, Phys. Rev. **96**, 1226 (1954).

[14] Impurity band conduction in p-type InSb has also been observed recently by H. Fritzsche and K. Lark-Horovitz, Phys. Rev. **98**, 1532(A) (1955).

ture. The value obtained for E_a, the acceptor ionization energy, from the slope of the curve between 10°K and 20°K, is $(7\pm1)\times10^{-3}$ ev.

Because of the dependence of R_H on H, exact values for the effective hole mass, m_p, and the donor concentration, N_d, cannot be obtained from these data. The results vary with the temperature for which they are calculated and the assumptions regarding the definition of R_H. Hole concentration, p_e, in the extrinsic range where p_e is constant was calculated by assuming that $R_{(H=0)}=(3\pi/8)(1/ep_e)$. Then μ_H/μ was determined as a function of temperature by using the expression $\mu_H/\mu = p_e eR_{(H=3080)}$ and extrapolated into the impurity ionization region. With these values of μ_H/μ and the Hall coefficient data for 3080-gauss carrier concentration was calculated as a function of reciprocal temperature and analyzed to give average values of $m_p = 0.17m$ and $N_d=8\times10^{14}$ cm^{-3}. The estimated uncertainty of the values is less than 50 percent.

Below 10°K, impurity band conduction is observed in p-type InSb. A Hall coefficient maximum similar to that reported for germanium by Hung and Gliessman[13] is observed. This maximum occurs at a higher temperature and impurity band conduction occurs at lower impurity concentrations than for germanium because of the smaller effective hole mass in InSb. Although the mobility of the acceptor band carriers can be estimated to be 1 cm^2/volt sec, analysis of these results is not justified without a clearly defined R_H. Furthermore, the acceptor centers are residual impurities and were not introduced in a controlled manner. Thus, it is possible that there are several chemically different acceptor centers with different ionization energies.

5. HALL EFFECT AND CONDUCTIVITY ABOVE 78°K

Hall effect and conductivity as functions of T^{-1} are shown in Figs. 4(a), 4(b), 5(a), and 5(b), respectively, for temperatures from 78°K to 700°K. The data for n- and p-type samples merge into common intrinsic curves around 300°K. The curvature in the conductivity and Hall effect curves at high temperature has been attributed to degeneracy by several investigators.[1,2] The shift in the optical absorption edge with increasing electron concentration, however, indicates that the effective electron mass is increasing with increasing population of the states in the conduction band.[3] The conductivity, which is most sensitive to these effects, is an exponential function of T^{-1} up to 465°K, the Hall coefficient up to 535°K. Therefore the intrinsic behavior does not appear to be seriously affected by these phenomena below 500°K in samples of this purity.

6. ELECTRON MOBILITY

Since R_H is relatively independent of H for n-type InSb, we assume that $\mu_n=(8/3\pi)(R\sigma)$. Figure 6 shows the observed variation of μ_n with temperature. Also

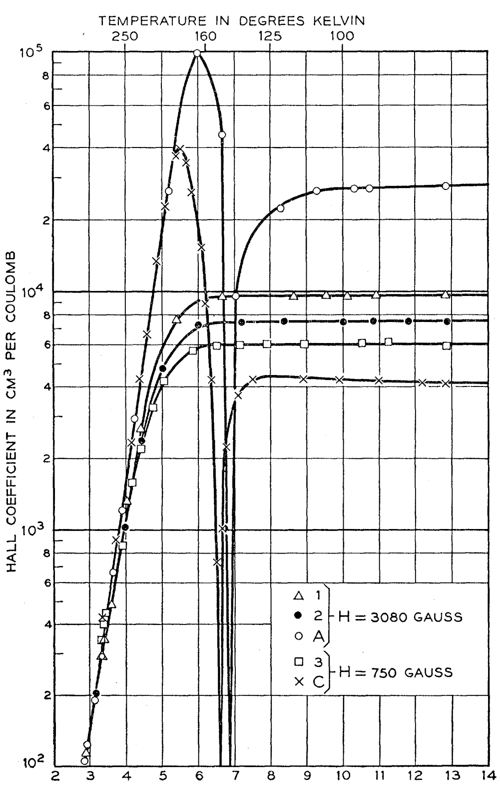

FIG. 4(a). Hall coefficient *vs* reciprocal temperature from 78°K to room temperature.

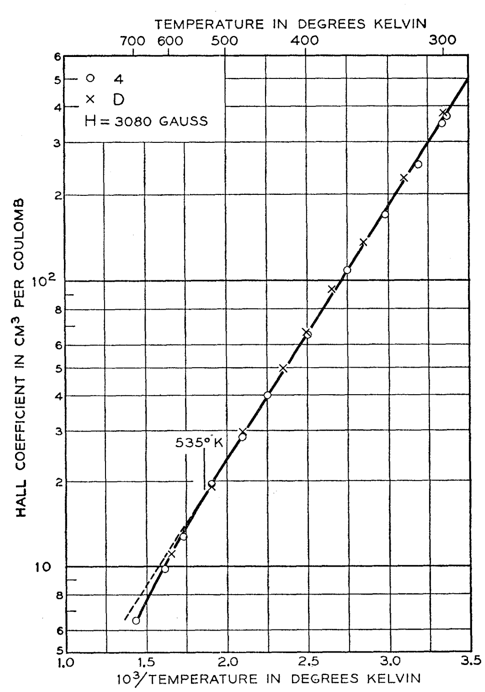

FIG. 4(b). Hall coefficient *vs* reciprocal temperature in the intrinsic range.

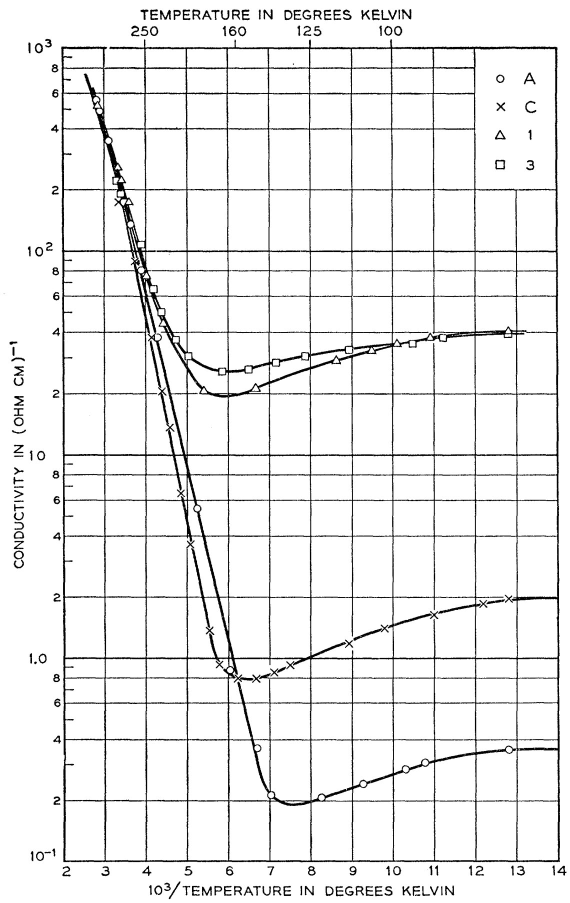

FIG. 5(a). Conductivity *vs* reciprocal temperature from 78°K to room temperature.

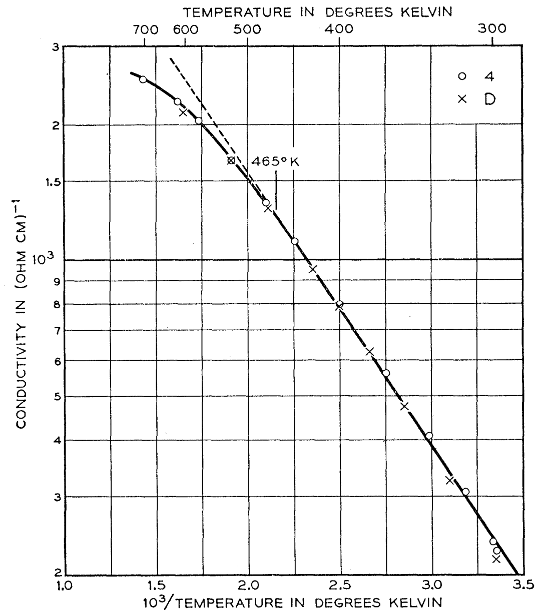

FIG. 5(b). Conductivity *vs* reciprocal temperature in the intrinsic range.

shown are values of μ_I, the impurity scattering mobility calculated from the Brooks-Herring formula[15] for an effective electron mass of $0.015m$. It is apparent that samples 1 and 2 have approximately the same total impurity concentration. Assuming $N_I \cong N_d - N_a = 9.8 \times 10^{14}$ cm^{-3} for sample 2, the electron lattice scattering mobility, μ_{Ln}, was calculated by the method of Conwell[16] by adjusting m_n to give the best straight line over the temperature range from 50°K to 400°K. A value of $m_n = 0.015m$ gives a significantly better result than $0.01m$ or $0.02m$. This value of m_n is very close to that determined from cyclotron resonance experiments.[9] The calculated lattice scattering mobility shown in Fig. 6 can be described by the equation

$$\mu_{Ln} = 1.09 \times 10^9 \ T^{-1.68}. \qquad (2)$$

The experimental results for sample 3 give good agreement with this equation for $N_I = 3.6 \times 10^{15}$ cm^{-3}.

The curvature of μ_n above 465°K is somewhat similar to that observed in germanium[17] at comparable intrinsic carrier density and attributed to electron-hole scattering. The dashed curve in Fig. 6 shows the calculated temperature dependence of μ_{Ln} including μ_{np}, the electron-hole scattering mobility, obtained by using the intrinsic carrier concentration determined in Sec. 8 and the effective masses given above. Since the inclusion of electron-hole scattering gives a result which is not in accord with the experimental data, it is concluded to be an unimportant scattering mechanism in InSb. Degeneracy and the increasing effective electron mass can qualitatively account for the observed deviation of the experimental mobility from the calculated lattice scattering mobility above 465°K.

The temperature dependence of electron lattice scattering mobility is almost identical to that of germanium where the deviation from a $T^{-1.5}$ dependence has been attributed to scattering by optical modes or intervalley scattering.[17]

7. HOLE MOBILITY

Experimental values of $R_H\sigma$ are shown in Fig. 7 along with impurity scattering mobility calculated for a range of values m_p and N_I obtained from the low-temperature data for sample *B*. Although the exact relation of $R_H\sigma$ to conductivity mobility is not clear, these probably differ by less than 20 percent above 50°K for $H = 3080$ gauss. The temperature dependence of lattice scattering mobility, μ_{Lp}, can be estimated from impurity scattering mobility and the conductivity data using hole densities obtained from the Hall coefficients. Results of these calculations indicate that the temperature dependence of μ_{Lp} is approximately $T^{-2.1}$. Impurity scattering, low temperature effects and the variation of R_H with H

[15] This is discussed in reference 6.
[16] E. Conwell, Proc. Inst. Radio Engrs. **40**, 1331 (1952).
[17] F. J. Morin and J. P. Maita, Phys. Rev. **94**, 1529 (1954).

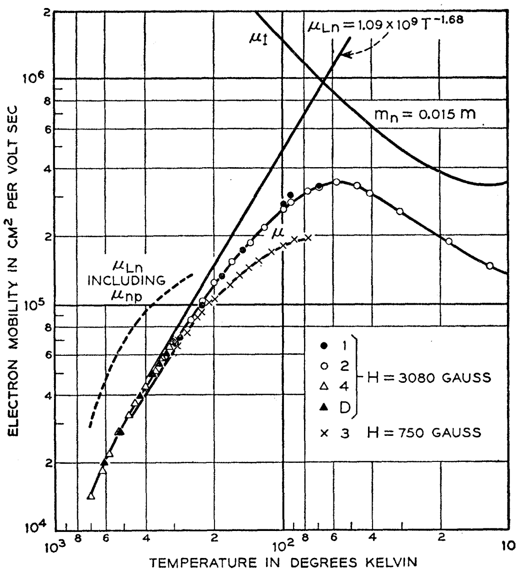

FIG. 6. Electron mobility *vs* temperature.

make it difficult to draw more quantitative conclusions.

8. CARRIER CONCENTRATION

Intrinsic carrier concentration has been determined from conductivity using measured electron mobility and extrinsic carrier concentration obtained from the Hall coefficient in the saturation range. The method is similar to that used by Morin and Maita[17] except that the contribution of holes has been neglected because

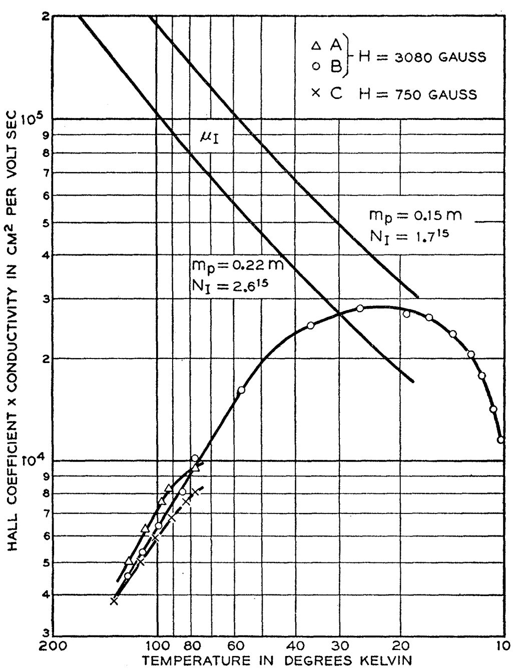

FIG. 7. Hole "mobility" *vs* temperature.

of the high ratio of electron to hole mobility.[18] The results are shown in Fig. 8. Between 200°K and 600°K they can be described by the empirical relation:

$$np = 3.6\times10^{29}T^3\exp(-0.26/kT). \qquad (4)$$

They do not differ greatly from results obtained on less pure samples.[1,18] Because of degeneracy[1] the true energy gap, E_g, at 0°K is somewhat higher than 0.26 ev, the exponent in (4). However the varying effective electron mass and possible electrostatic interaction of charge carriers[17] also influence these data and make the value of E_g rather uncertain.

With the effective masses obtained above and the theoretical expression[11] for carrier concentration in the intrinsic range the calculated temperature coefficient

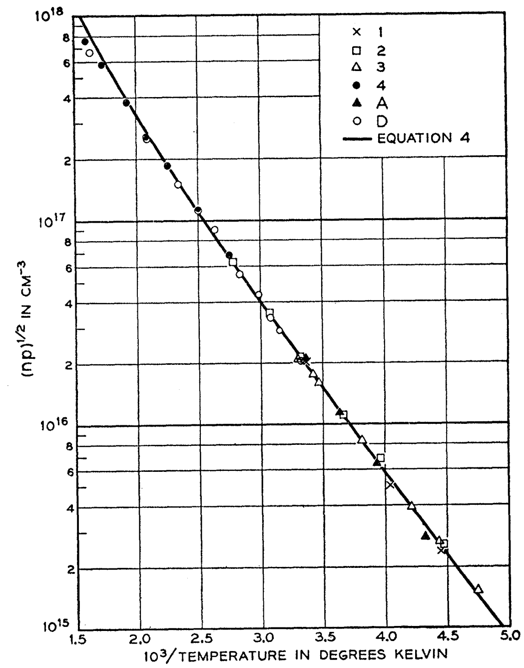

FIG. 8. Square root of the product of electron and hole concentration *vs* reciprocal temperature in the intrinsic range.

of E_g is $(-3.9\pm0.3)\times10^{-4}$ ev/°K if a linear temperature dependence is assumed. Combining this with $E_g=0.17$ at 300°K, a value obtained from optical measurement[19] on "pure" InSb, E_g at 0°K is 0.29±0.005 ev. Although this is probably an upper limit to the true value, it indicates the over-all consistency of these results.

ACKNOWLEDGMENTS

We are indebted to J. P. Maita and W. L. Feldman for assistance with some of the measurements. We wish to thank Professor C. Kittel for informing us of the results of the cyclotron resonance experiments before publication and Dr. M. Tanenbaum for assistance and encouragement during the early phases of this work.

[18] M. Tanenbaum and J. P. Maita, Phys. Rev. **91**, 1009 (1953).
[19] L. N. Hand and H. J. Hrostowski (to be published).