of data in the literature; the true value is probably closer to one watt cm^{-1} deg^{-1}. The largest possible value of $|x| = 5\times 10^{-10}$ was found for crystal 40 by assuming intrinsic conductivity at 300°K. For crystal 104 the largest $|x| = 4\times 10^{-5}$ was obtained when impurity scattering in the low temperature region was arbitrarily assumed, and an even smaller value was found for lattice scattering.

A check on these calculations may be obtained by means of a phenomenological argument. It may be shown that the fractional Ettingshausen error in the Hall voltage is equal to QP/R_i, where Q is the thermoelectric power of the semiconductor-metal junction and P is the Ettingshausen coefficient. The classical free-electron theory for a single carrier gives $R_i/P = 4k/e = 345$ microvolts/deg if the thermal conductivity is all electronic.[23] To take into account the lattice conductivity this value must be multiplied by the ratio (r) of total thermal conductivity to electronic thermal conductivity.[24] A most pessimistic estimate of the error in boron was made by considering crystal 104 (Fig. 3) at 500°K. The Wiedemann-Franz ratio of $2k^2/e^2$ (classical statistics) was used to estimate the electronic contribution to the thermal conductivity. This estimate gave $r = 10^5$. Using $Q = 600$ microvolts/deg from Fig. 4, we found the largest fractional Ettingshausen error to be the order of 2×10^{-5} for crystal 104 (and many orders of magnitude smaller for crystal 40). A formula[25] for P which takes into account carriers for both signs gives essentially the same results.

It is concluded that for our Hall measurements the fractional error from the Ettingshausen effect cannot possibly exceed 10^{-4} no matter what type of scattering and conductivity are assumed. The smallness of the error is a direct consequence of the fact that the scarcity of carriers produces a high ratio of lattice thermal conductivity to electronic thermal conductivity.

ACKNOWLEDGMENT

We wish to thank R. D. Redin for a helpful study of classical thermomagnetic phenomena.

[23] A. Sommerfeld and N. Frank, Revs. Modern Phys. **3**, 1 (1931).

[24] L. Stilbans, Zhur. Tekh. Fiz. **22**, 77 (1952) (in Russian), abstracted in Physics Abstr. **55**, Sec. A, No. 8177 (1952).

[25] A. Johnson and K. Lark-Horovitz, Phys. Rev. **73**, 1257(A) (1948).

PHYSICAL REVIEW VOLUME 107, NUMBER 2 JULY 15, 1957

Thermal Conductivity of Indium Antimonide

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(Received March 1, 1957)

The thermal conductivity of indium antimonide of varying purity has been measured by a comparative method from 40°C to 425°C. The electronic component of the conductivity has been calculated for each specimen and hence the lattice thermal conductivity has been deduced. Within the limits of experimental error InSb appears to behave according to conventional theory.

USING a comparative method previously described,[1] measurements of the thermal conductivity of single crystals of indium antimonide of varying purity have been made from 40°C to 425°C. The results shown in Fig. 1 represent the average of several measurements on each sample and have an estimated accuracy of $\pm 10\%$.

In the temperature range considered, specimens A and C were essentially similar to specimens $P-N-A_2$ and $P-N-C_2$ for which electrical conductivity and thermoelectric power data have already been given.[2] Specimen B was "n"-type and contained 10^{17} extrinsic electrons/cc. Specimens A and B are weakly degenerate over the temperature range and specimen C strongly so near room temperature. The kinetic energy transport K_E in the three samples has been calculated according to the expression

$$K_E = S(k/e)^2\sigma T,$$

where the symbols have their usual meaning and S is a

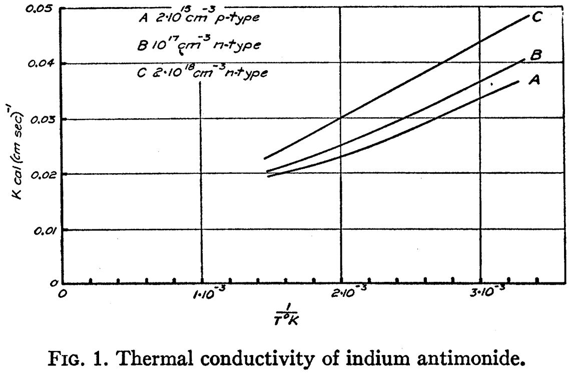

FIG. 1. Thermal conductivity of indium antimonide.

[1] A. D. Stuckes and R. P. Chasmar, *Report of the Meeting on Semiconductors* (The Physical Society, London, 1956), p. 119.

[2] Antell, Chasmar, Champness, and Cohen, *Report of the Meeting on Semiconductors* (The Physical Society, London, 1956), p. 99.

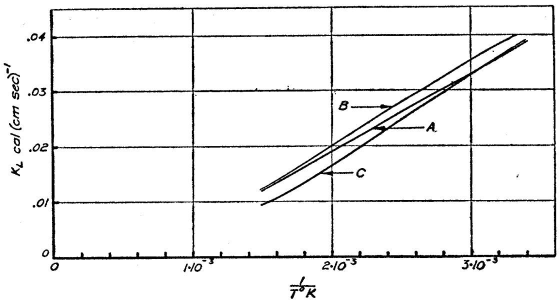

FIG. 2. Estimated lattice thermal conductivity of indium antimonide.

coefficient having the following limiting values:

$S=2$, classical, lattice scattering;

$S=\pi^2/3$, degenerate, any scattering;

$S=4$, classical, impurity scattering.

In specimens A and B where lattice scattering predominates, a value for S between 2 and $\pi^2/3$ appropriate to the degree of degeneracy has been used, but in specimen C the value $\pi^2/3$ has been employed over the whole range since although it is only weakly degenerate at high temperatures, the impurity scattering present will raise the value of S.

Calculation shows that transport of ionization energy as discussed by Price[3] and Thuillier[4] is negligible in the present temperature range owing to the high ratio of electron to hole mobility, but should become appreciable at higher temperatures in the pure specimen.

The calculated value of K_E has been subtracted from the measured value K and the lattice thermal conductivity K_L deduced (Fig. 2). Since the Debye temperature for InSb (202°K) is well below the temperature range of the experiments, the lattice thermal conductivity should be independent of free-electron scattering[5] while impurity scattering should yield a constant resistance contribution. If three-phonon processes predominate, the lattice conductivity should be inversely proportional to the absolute temperature.[6] Owing to the limits of experimental accuracy, the dependence of the lattice conductivity on purity indicated in Fig. 2 may not be significant, but K_L clearly does not vary as $1/T$. The lattice thermal resistance W_L is plotted logarithmically against temperature in Fig. 3; it appears that at the lower temperatures W_L is tending towards proportionality with T, but at the higher temperatures there is a trend towards a T^2 dependence. It should be noted that if four-phonon processes predominate, it would be expected that the thermal resistance would be proportional to the square of the absolute temperature.[6]

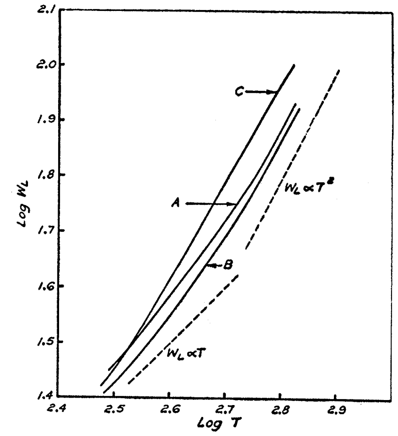

FIG. 3. Estimated lattice thermal resistance of indium antimonide.

Measurements of thermal conductivity of InSb have been reported by Busch and Schneider[7] which are quite different to those given here, both in magnitude and temperature dependence. In their analysis of their results, they assume the lattice thermal conductivity to be inversely proportional to the temperature over the whole range and hence deduce the electronic component, finding a value which is about fifteen times too high. No such anomalous rise in thermal conductivity has been observed here, and within the limits of experimental error, InSb would appear to behave according to conventional theory.

The author wishes to thank the Radar Research Establishment and the Services Electronics Research Laboratory for supplying the indium antimonide crystals and to thank Mr. R. P. Chasmar for much valuable discussion and Mrs. B. Brooks for carrying out many of the measurements. The author also wishes to thank Dr. Willis Jackson, F.R.S., M.I.E.E., Director of Research and Education, and Mr. B. G. Churcher, M.Sc., M.I.E.E., Manager of the Research Department, Metropolitan-Vickers Electrical Company Limited, for permission to publish this article.

[3] P. J. Price, Phil. Mag. **46**, 1252 (1955).

[4] J. M. Thuillier, Compt. rend. **22**, 2633 (1956).

[5] R. Stratton, Phil. Mag. **2**, 422 (1957).

[6] R. E. Peierls, *Quantum Theory of Solids* (The Clarendon Press, Oxford, 1955), p. 51.

[7] G. Busch and M. Schneider, Physica **20**, 1084 (1954).