Thermal Conductivity of Nb_3Sn*

G. D. CODY and R. W. COHEN
RCA Laboratories, Princeton, New Jersey

Measurements have been made of the thermal conductivity κ of two samples of Nb_3Sn over the temperature range 2.6°K to 28°K. The samples, in the form of thin strips approximately 3 cm by 1 cm by 0.04 cm, were obtained by vapor deposition.[1] Some characteristics of these samples are given in Table I. In this paper only the data obtained for FS 14 are presented as this sample had near ideal stoichiometry, and a very narrow transition width. Although sample GS 53 was off stoichiometry and had a broad superconducting transition, it is noteworthy that below the transition temperature (T_c) the two samples had essentially identical thermal conductivities.

The thermal conductivity was measured in a conventional manner.[2] One-tenth W Allen Bradley 360 Ω resistors were used as thermometers. Both the heater and the carbon resistors were glued with GE 7031 varnish into copper tubes which were soldered with indium to nickel-plated tabs on the specimen. The lower end of the specimen was in turn soldered to a copper plate, which was in thermal contact with a gas thermometer. Resistor and heater leads were of 1.5 mil diam Advance wire. These leads were brought into thermal contact with the gas thermometer before being brought to a thermal junction in contact with the surrounding helium bath.

A double, equal arm, Wheatstone bridge[2] was used with a Leeds Northrup dc amplifier to measure resistance. The power level in the carbon resistors was kept at, or below, 10^{-8} W. Three lead connections were made to each resistor in order to compensate for lead resistance. The carbon resistors were calibrated with respect to the gas thermometer above 4.2°K, and with respect to the vapor pressure of liquid helium below 4.2°K. At each temperature, with no heat applied, the resistances of each resistor was recorded, as was the pressure of the gas thermometer. With power into the heater, the new resistance values were recorded at equilibrium. The calibration pionts made with exchange gas in the sample container at 4.2°K and below, agreed well with the results of the above procedure. A two-parameter equation[3] was used to determine resistance as a function of temperature for each resistor, and temperature differences, when heat was applied, were determined by the individual calibrations for each resistor.

The major source of error in the present measurements is the existence of parallel conduction paths. The choice of lead material kept possible errors due to lead conductance to well below 1%. A more significant source of error, and one that is enhanced by the sample geometry is the conductance due to gas remaining in the sample container as a result of either adsorption or (possibly) a small leak. Although it is difficult to measure the gas pressure in the vicinity of the specimen it was estimated to be better than 10^{-6} mm. Thus, for these measurements the error due to gas conductance was less than two % at the lowest temperatures. The relative accuracy of the present measurements are of the order of ±3%.

The enormous fields required to quench superconductivity in Nb_3Sn (230 kG at 4.2°K[4]), limit the region over which one can obtain normal thermal conductivity data, to temperatures close to T_c. Nevertheless, the recent work of Dubeck *et al.*[5] leads one to expect sizeable changes in κ at temperatures as low as one half the transition temperature for fields where flux penetration is large. For this reason measurements were made on the thermal conductivity of GS53 in fields up to 6500 G at temperatures of 8.0°K and 11.2°K. No effect of magnetic field on κ was found for this sample. This result should be contrasted with magnetization measurements on vapor deposited Nb_3Sn,[6] which indicate that at 4.2°K field penetration starts at about 400 G, and in fields of 5000 G only about 10% of the external field is excluded from the samples. The failure of modest fields to restore normal conductivity has made it impossible to present the usual comparisons of κ_s with κ_n below T_c.[7] Fortunately, significant information can be obtained from κ_s itself.

Figure 1 gives the measured thermal conductivity

* The research reported in this paper was sponsored by the Electronic Technology Laboratories, Aeronautical Systems Division, Air Force Systems Command, Wright Patterson Air Force, Ohio, under contract AF33(657)7733.

[1] G. W. Cullen (to be published); see also J. J. Hanak, in *Metallurgy of Advanced Electronic Materials*, edited by G. E. Brock (Interscience Publishers, Inc., New York, 1963), p. 161.

[2] R. Berman, in *Experimental Cryophysics*, edited by F. E. Hoare, L. C. Jackson, and N. Kurti (Butterworths Scientific Publications, Ltd., London, 1961), p. 327.

[3] R. P. Hudson, in Ref. 2, p. 214.

[4] W. H. Cherry (private communication, 1963).

[5] L. Dubeck, P. Lindenfeld, E. A. Lynton, and H. Rohrer, Phys. Rev. Letters **10**, 98 (1963).

[6] P. Brown (private communication, 1963).

[7] J. Bardeen, G. Rickayzen, and L. Tewordt, Phys. Rev. **113**, 982 (1959).

Table I. Characteristics of Nb_3Sn samples.

Sample	ρ (300°K) ($\times 10^{-5}$ Ω-cm)	ρ (77°K) ($\times 10^{-5}$ Ω-cm)	ρ (27°K) ($\times 10^{-5}$ Ω-cm)	T_c (°K)	ΔT_c (°K)	wt.% Nb (%)
GS53	10.1	5.9	...	16.8	2	72.0 ± 0.5
FS14	8.1	3.9	1.5	18.3	0.04	70.5 ± 0.5

for sample FS14 as a function of temperature from 28°K to 2.6°K. A measurement made at 86°K is also included to give an indication of the high temperature behavior of Nb_3Sn. One notes that below T_c the data is in fair agreement with a $T^{2.6}$ temperature variation. In the normal state there are indications of a slight maximum in κ.

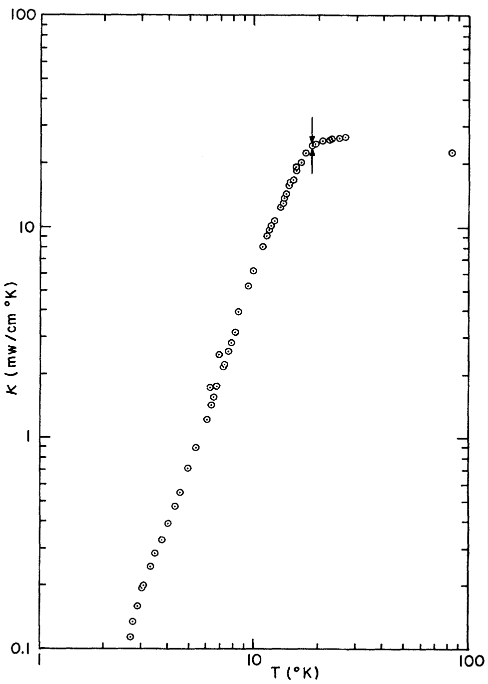

Fig. 1. Thermal conductivity of Nb_3Sn (sample FS14) as a function of temperature.

A more illuminating way of plotting the data is shown in Fig. 2 which is a semi-log plot of κ as a function of T_c/T. One notes that there is a good fit to the function $\kappa \propto e^{-(1.60 T_c/T)}$ over the range 18.3°K to about 6.5°K. Using the expression of Bardeen, Rickayzen, and Tewordt (BRT)[7] for the impurity limited electronic thermal conductivity, this dependence would imply a band gap at $T = 0$°K of $2\epsilon_0 = 3.56\ kT_c$. Below 6.5°K the temperature dependence departs from an exponential. The dashed curve in Fig. 2, labeled κ_{GS}, was obtained by subtracting the extrapolated exponential from the experimental curve. At low temperatures the resultant function has a maximum and then falls as T^3 as can be seen in Fig. 3 where κ_{GS} is plotted as a function of T^3.

It should be clear from the above paragraph that the data can be interpreted on the basis of a simple model. From 18.3°K to 6.5°K, the thermal conductivity is dominated by an electronic component that is impurity limited. By 6.5°K the number of normal electrons has been so reduced that the phonon contribution rises rapidly only to be limited by boundary scattering with a constant mean free path and a T^3 temperature dependence characteristic of the low temperature specific heat.

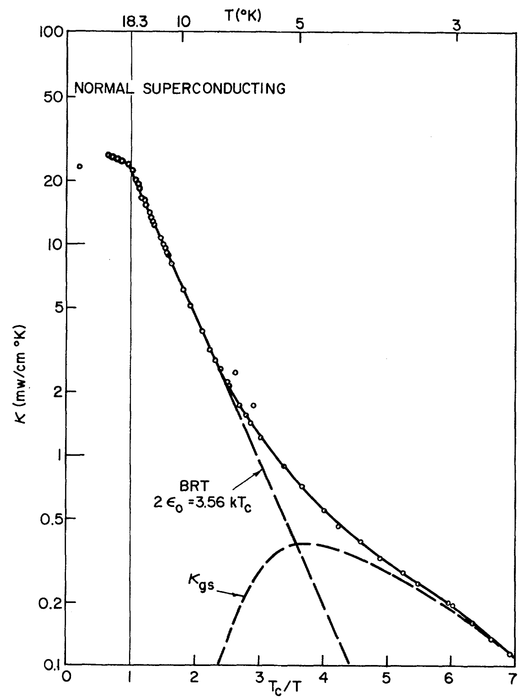

Fig. 2. Thermal conductivity of Nb_3Sn (sample FS14) as a function of the inverse reduced temperature T_c/T.

The validity of the above model is at present difficult to estimate in the absence of data for κ_n below T_c. One can use the simple one-band theories of electronic thermal conductivity, for example, to estimate the relative magnitudes of phonon and impurity scattering.[8] Based on a lattice constant of 5.29 Å, a valence of 4.75, a Debye temperature of 290°K[9] and the resistivities of Table I, one obtains a ratio of impurity scattering to phonon scattering at T_c of the order of 0.1. Moreover, the phonon conductivity in the normal state can similarly be estimated and can be shown to be small. Such estimates would certainly ensure the validity of using the BRT theory to derive the band gap from the experimental curves for κ_s.[10] However, the anomalous resistivity of Nb_3Sn[11] makes any simple application of the theory of metals to Nb_3Sn suspect without further experimental data.

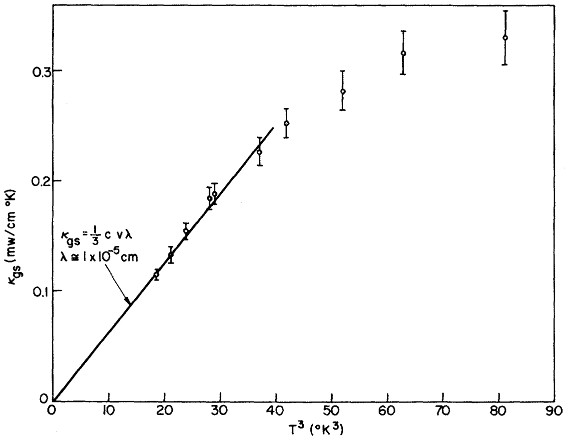

FIG. 3. Phonon contribution to the thermal conductivity as a function of T^3.

The postulated phonon contribution at low temperatures is on a firmer basis. Preliminary electron-microscopic examination of sample FS14 showed that the microstructure consists of oriented platelets 1μ and 10μ in diameter and from 200 Å to 2000 Å in thickness.[12] It is apparent that this structure could account for the 1000 Å boundary size derived from the T^3 region of Fig. 3.

In summary, the thermal conductivity of two samples of vapor deposited Nb_3Sn has been measured at 86°K, and in detail from 28°K to 2.6°K. The thermal conductivity in this region ranges from 27×10^{-3} W/cm °K to 0.14×10^{-3} W/cm °K. Below T_c, the thermal conductivity drops with a temperature dependence characteristic of a band gap of $2\epsilon_0 = 3.56\, kT_c$, if one assumes the conductivity to be electronic and impurity limited. This model can be shown to be in reasonable agreement with the properties of the present samples of Nb_3Sn. Below 6°K, one can interpret the data in terms of an additional conductivity in parallel with the electronic conductivity, which rises exponentially and then falls with a T^3 law characteristic of a boundary limited phonon conductivity. The size of the boundary, ≈1000 Å, is of the same order as the thickness of the platelet structure characteristic of vapor deposited Nb_3Sn.

Although magnetization measurements indicate large field penetrations for fields of 5000 G at 4.2°K, no effect on the thermal conductivity of one sample was observed when a field of 6500 G was applied at 8.0°K and 11.2°K.

The band gap obtained in the present measurements differs by about a factor of 3 from that obtained by Goldstein[13] through tunneling measurements on similar material. Possible explanations for this discrepancy will be discussed in a subsequent paper.

Note added in proof. Since this paper was presented, thermal conductivity measurements were made on sample FS 14 in a longitudinal field of 6500 G at 15.0°K and 17.5°K. The change in κ with field was less than 2% at both temperatures.

ACKNOWLEDGMENTS

The authors are grateful to J. Cooper for transition temperature measurements and to F. R. Nyman of the Superconducting Materials and Devices Laboratory for kindly furnishing one of the samples. The advice and assistance of T. Seidel in the early stages of this experiment is gratefully acknowledged.

8 K. Mendelssohn and H. M. Rosenberg, in *Solid State Physics*, edited by F. Seitz and D. Turnbull (Academic Press, Inc., New York, 1961), Vol. 12, p. 223.
9 F. J. Morin and J. P. Maita, Phys. Rev. **129**, 1115 (1963).
10 L. P. Kadanoff and P. Martin, Phys. Rev. **124**, 670 (1961).
11 G. D. Cody, J. J. Hanak, and G. T. McConville, Bull. Am. Phys. Soc. **6**, 146 (1961). See also, Technical Documentary Report No. ASD-TDR-62-1111.
12 T. Barnard (private communication, 1963).
13 Y. Goldstein, Rev. Mod. Phys. **36**, 213 (1964).