THERMAL CONDUCTIVITY OF SODIUM CHLORIDE AT HELIUM TEMPERATURES

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Abstract

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THERMAL CONDUCTIVITY OF SODIUM CHLORIDE AT HELIUM TEMPERATURES

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It is known that various defects in a crystal lead to phonon scattering. Theoretical calculations of phonon scattering by defects were carried out by Klemens (^{1}) and Ziman (^{2}). They showed that, in the region of helium temperatures, the dependence of the thermal conductivity on the dislocation density and temperature has the form

$$K_d = CT^2/N, \tag{1}$$

where C is a constant for the given substance, and N is the density of immobile dislocations.

Measurements by Sproull, Moss, and Weinstock (^{3}), performed on lithium fluoride, and by Inshoka and Suzuki (^{4}), on sodium chloride at a dislocation density of the order of 10^6 cm^{-2}, showed that the thermal-conductivity coefficient differs from that calculated by formula (1) by 2–3 orders of magnitude. However, it should be borne in mind that, for the crystals studied at helium temperatures, phonon scattering, generally speaking, may be determined not only by dislocations, but also by point defects, to which there corresponds the thermal-conductivity coefficient

$$K_a = B/T, \tag{2}$$

where B is a constant depending on the concentration of point defects, and by the crystal boundaries—the thermal-conductivity coefficient

$$K_c = AT^3, \tag{3}$$

where A is a constant.

In the present communication we present the results of measurements of the thermal conductivity of sodium chloride single crystals as a function of the

Fig. 1. Thermal conductivity of NaCl crystals with different dislocation density as a function of temperature at $N = 5 \cdot 10^4$ cm^{-2} (1), $2.4 \cdot 10^5$ cm^{-2} (2); $3.1 \cdot 10^6$ cm^{-2} (3); $9.3 \cdot 10^6$ cm^{-2} (4); $5 \cdot 10^7$ cm^{-2} (5)

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dislocation density in the interval $5 \cdot 10^4 \div 5 \cdot 10^7$ cm^{-2} and in the temperature interval $4 \div 20$°K.

The thermal conductivity was measured by the steady-state heat-flow method (^{5}). The specimen was in a vacuum of $10^{-5} \div 10^{-6}$ mm Hg. Carbon resistors (Allen Bradly, 45 ohm, 0.25 watt) were used to measure the temperature difference, making it possible to measure temperature with an accuracy of up to 0.01°. The distance between the resistors was 1.5 cm. The specimens were cut from a single-crystal block along the (100) plane and had dimensions $7.5 \times 7.5 \times 55$ mm. The increase in dislocation density was produced by compression. The dislocation density was taken as the average over the surface of the specimen, without taking into account dislocations in slip lines. (For an average density $N = 5 \cdot 10^4$ cm^{-2}, the local density varied within the limits $2 \cdot 10^4$–$7 \cdot 10^4$ cm^{-2}.) The sodium chloride crystals contained impurities (wt.%): Ca 0.001; Mg 0.001 –0.0001; Mn 0.001–0.0001; Fe 0.001–0.0001; Al 0.0001; Si 0.001–0.0001.

Figure 1 presents the measurement results. The dotted curve in this figure represents a result borrowed from (^{4}).

Adopting Matthiessen' s rule, the total thermal resistance, in accordance with formulas (1)–(3), can be expressed in the form

$$1/K = N/CT^2 + T/B + 1/AT^3, \tag{4}$$

where K is the actual coefficient of thermal conductivity. The thermal resistance due to phonon-phonon scattering is not taken into account here, because of its smallness at the temperatures of the experiment.

From the curves of Fig. 1 the thermal resistance $1/K = f(T)$, shown in Fig. 2, was calculated. The results shown in Fig. 2 were then processed by the method of least squares according to formula (4), from the minimum temperatures up to the extremal values of the function $f(T)$, and in this way the coefficients A, B, C were determined. The portions of the curves lying beyond the extrema were not processed, since they already belong to the temperature region where phonon-phonon scattering begins to play a noticeable role.

Fig. 1. Thermal conductivity of NaCl crystals with different dislocation density as a function of temperature at $N = 5 \cdot 10^4$ cm^{-2} (1), $2.4 \cdot 10^5$ cm^{-2} (2); $3.1 \cdot 10^6$ cm^{-2} (3); $9.3 \cdot 10^6$ cm^{-2} (4); $5 \cdot 10^7$ cm^{-2} (5)

Fig. 2. Thermal resistance of NaCl crystals with different dislocation density as a function of temperature at $N = 5 \cdot 10^7$ cm^{-2} (1), $3.1 \cdot 10^6$ cm^{-2} (2); $2.4 \cdot 10^5$ cm^{-2} (3); $5 \cdot 10^4$ cm^{-2} (4)

Figure 2: Fig. 2. Thermal resistance of NaCl crystals with different dislocation density as a function of temperature at $N = 5 \cdot 10^7$ cm^{-2} (1), $3.1 \cdot 10^6$ cm^{-2} (2); $2.4 \cdot 10^5$ cm^{-2} (3); $5 \cdot 10^4$ cm^{-2} (4)

Fig. 2. Thermal resistance of NaCl crystals with different dislocation density as a function of temperature at $N = 5 \cdot 10^7$ cm^{-2} (1), $3.1 \cdot 10^6$ cm^{-2} (2); $2.4 \cdot 10^5$ cm^{-2} (3); $5 \cdot 10^4$ cm^{-2} (4)

As a result it was found that at a density $N = 5 \cdot 10^4$ cm^{-2} dislocations make a negligibly small contribution to the thermal resistance, and it is expressed by formula (4) without the first (dislocation) term on the right-hand side. The dashed curve shows the thermal resistance of a sodium chloride crystal calculated theoretically, without allowance for scattering by dislocations, which occurred at the impurity concentrations and geometrical dimensions of the sample.

For crystals with a dislocation density of 10^5 cm^{-2} and higher, the third (boundary) term loses its significance, and the total thermal resistance is expressed by formula (4) without this term. As for the thermal-conductivity coefficients, the impurity value $K = 50/T$ W/cm · deg proved to coincide with that calculated theoretically according to (1) (within the limits of the errors caused by the uncertainty in the values of the -

of the quantities entering the coefficient B of formula (2)). The dislocation thermal-conductivity coefficient K_d was found to be $1.53 \cdot 10^5 T^2/N$ W/cm • deg. This result confirms the theoretical dependence on the dislocation density N, given by Klemens (^{1}); however, the numerical coefficient obtained experimentally is in fact two to three orders of magnitude smaller than the theoretical one, in agreement with work (^{4}).

Thus, for sodium chloride at a dislocation density $N = 10^5$ cm^{-2} and higher, the latter play a determining role in phonon scattering at helium temperatures. At the same time, the theory of phonon scattering by dislocations is justified only as regards the general dependence of thermal conductivity on dislocation density; in numerical values, however, it differs from experiment by 2–3 orders of magnitude. This fact undoubtedly deserves special theoretical consideration. In this connection it is interesting to note that a similar situation exists also in the dislocation theory of the Mott-Nabarro yield point. According to work (^{6}), the dislocation vibration frequency appearing in this theory is 8 orders of magnitude lower than its theoretical value, while the time dependence of the yield point is nevertheless confirmed.

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