THE THERMAL RESISTIVITY AND THERMAL MAGNETORESISTIVITY
OF POTASSIUM*

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July 1972

Report #1839

Issued by the Materials Science Center

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Recent experimental measurements and calculations have shown that the zero-field electrical resistivity of potassium can be well understood using semiclassical ideas provided umklapp scattering processes are considered.^{1,2} On the other hand, no suitable, widely acceptable explanation has been found that enables one to understand the observed linear high-field electrical magnetoresistance.³ We have undertaken a study of the thermal resistance W , and thermal magnetoresistance (TMR) $W(H)$, in an attempt to determine if similar problems exist in the thermal case. Both W and $W(H)$ have been measured in single and polycrystalline potassium specimens having residual resistance ratios (RRR) ranging from 1800 to 6500 with measurements of W extending down to a RRR of 195. W was measured between 1.5 and 15K and $W(H)$ was measured in fields up to 18kG at many temperatures between 2 and 9K.

Many experimental problems are encountered when one attempts to measure the thermal resistance of a soft, reactive material such as potassium. A detailed description of the experimental apparatus including mounting procedures, sample preparation

and methods of data acquisition and analysis are given elsewhere.⁴ As a general check of our apparatus and measurement technique, we measured the thermal resistance of indium. Using an experimental procedure identical to that used for potassium, we obtain excellent agreement with previous measurements even though the thermal contacts between the sample and thermometers were, by choice, very bad.

The expression generally used to describe the electronic thermal resistivity of a metal is

$$W = \frac{A}{T} + BT^2 \quad (1)$$

where A/T is the electron-impurity scattering term and BT^2 represents the electron-phonon scattering contribution.

Figure 1a shows the temperature dependence of W , plotted as WT vs. T^3 , for three potassium samples of purity ranging from $RRR = 195$ to $RRR = 6100$. A smooth extrapolation of the data to $T = 0$ gives $A = (WT)_{T=0}$. For comparison with other work on potassium, the thermal conductivity $\kappa = 1/W$, for the same three samples is shown in Figure 1b.

The temperature dependent portion of the thermal resistance times temperature can be written as $W_T T = WT - (WT)_{T=0}$; the last term is temperature independent. We can compare W_T with recent theoretical work.⁵ Figure 2 shows W_T/T^2 as a function of temperature for both an impure ($RRR = 195$) and a pure ($RRR = 6100$) specimen. The solid and dashed curves represent the

theoretical thermal resistance due to electron-phonon scattering as calculated by Ekin⁵; as indicated in the caption, each curve corresponds to a different pseudopotential. Effects of electron-phonon umklapp processes are included specifically and phonon drag effects are neglected. The Kohler variational method using the standard relaxation-time trial function is used to calculate the curves in Figure 2a while a modified trial function containing a second order energy dependent term is used to calculate the curves in Figure 2b.

Data plotted in this manner emphasize deviations from the simple Bloch theory of thermal conductivity. If only normal processes are important, then the thermal resistivity should increase as T^2 at low temperatures; such behavior corresponds to a straight, horizontal line in Figure 2.

Good quantitative agreement is obtained between our measurements on the impure specimen shown in Figure 2a and the calculated values, even though a very simple trial function is used to calculate the electron-phonon contribution to the thermal resistivity. This is expected, since it can be shown that if a particular scattering mechanism is dominant and can be described by a relaxation time, then the relaxation-time trial function can be used to obtain the temperature dependence of those scattering mechanisms that cannot be described by a relaxation time.⁴ In the impure specimen, impurity scattering

is dominant and can be described by a relaxation time. One expects calculations using the simple trial function to become increasingly less accurate as electron-phonon scattering becomes more important in relation to impurity scattering. Figure 2b shows results on a pure specimen; at low temperatures the experimental values lie 10 to 20% below the calculated values even though a potentially better trial function was used.

What appears to be excellent agreement between theory and experiment at high temperatures for the impure specimen is not quite that good. Sample K-15 is sufficiently impure so that above 6K the lattice thermal conduction is appreciable. This makes the thermal resistance lower than that due to electronic processes alone. When lattice conduction is taken into account, the measured temperature dependence for the impure sample at high temperatures is in poor agreement with the calculated dependence shown in Figure 2a.

The experimental results for pure specimens at high temperatures also show a temperature dependence that differs considerably from the calculated values. Possible reasons for this behavior in both the pure and impure specimens are discussed in detail elsewhere.⁴ Briefly, it may be due to the choice of the trial function and/or deviations from Matthiessen's rule (over the range of purity studied here, about a 50% deviation from Matthiessen's rule is observed in the low temperature data).

In the temperature interval 4 to 7K, umklapp scattering contributes as much as 50% to the total thermal resistivity.⁵ The observed temperature dependence at low temperatures and the reasonably good agreement as to the magnitude of the thermal resistivity show quite clearly that umklapp scattering plays an important role in determining the thermal resistivity. Even so, the resistivity is represented quite closely by a T^2 dependence. It is a curious coincidence that just when the thermal resistivity due to normal processes begins to deviate below a T^2 dependence, the resistivity due to umklapp processes increases in nearly the correct proportion to give a total thermal resistivity having a quadratic temperature dependence. This should be contrasted with the electrical resistivity where no simple power law is sufficient to describe the low temperature results.

Our results are in reasonable quantitative agreement with those of MacDonald, White and Woods whose measurements were done on specimens encapsulated in glass capillaries.⁶ Contrary to the observations of Stauder and Mielczarek,⁷ we find no evidence for any anomalous contribution to the thermal resistance of potassium in any specimens that we have measured. Possible reasons are discussed elsewhere;⁴ we conclude that the anomalous behavior reported by Stauder and Mielczarek is not a property of potassium.

Preliminary data on the thermal magnetoresistivity of potassium has been obtained in fields up to 18kG. Figure 3 shows the TMR at a number of temperatures between 2.5 and 6.0K. W(H) is nearly linear in H at the higher temperatures. The curvature increases rapidly for temperatures below 4K. As shown in Figure 3b, TMR curves for different temperatures cross. That is, at some high field, the low temperature TMR will decrease initially with increasing temperature. Higher temperature data show a tendency to cross at fields above 20kG. Such effects are observed in all pure ($R_{RR} > 1800$) specimens.

It is interesting to compare these results with the electrical magnetoresistance (MR). Under conditions for which the data in Figure 3a were taken, the electrical MR would increase nearly linearly with H above a few kilogauss. If the Wiedemann-Franz law were obeyed, one would expect a similar behavior for the TMR. Clearly this is not the case. This is quite surprising since it is at low temperatures where the scattering is most likely to be elastic that one expects the Wiedemann-Franz law to be obeyed. It is difficult to draw any firm conclusions from our magnetic field results until the work is extended to higher fields.

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- * This work was supported partly by the United States Atomic Energy Commission under contract number AT(11-1)-3150, technical report number COO-3150-6 and partly by the Advanced

Research Projects Agency through the Materials Science Center at Cornell University, MSC Report #1839.

† Alfred P. Sloan Research Fellow.

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Figure Captions

Figure 1: The temperature dependence of (a) the thermal resistance, and (b) the thermal conductivity of three potassium specimens: K-16, polycrystalline, RRR = 195; K-15, single crystal, RRR = 1095; K-9, polycrystalline, RRR = 6130. The curves in Figure 1b are calculated using Eq. (1) ($\kappa = 1/W$) where A and B are determined, respectively, from the intercept and slope of the data in Figure 1a.

Figure 2: The temperature dependence of W_T for the three specimens shown in Figure 1. The curves are theoretical values calculated by Ekin using different pseudopotentials: solid line (—), Bardeen pseudopotential; double broken line (— - —), Ashcroft pseudopotential and broken line (-----), Lee-Falicov pseudopotential. The relaxation time trial function was used for calculations in (a) and the modified trial function for curves in (b).

Figure 3: The thermal magnetoresistance for a single crystal specimen of potassium having a RRR = 4140; note the crossing of the TMR curves in (b). Specimen size is 1 x 3 x 40 mm.

Figure 1

Figure 2

Figure 3