

Manifestation of hydrodynamic effect in the thermal conductivity of tungsten

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We have investigated the thermal conductivity of pure single-crystal tungsten in the interval 2-120°K.

An anomalous temperature dependence of the thermal conductivity is observed in the temperature region 15-40°K, where the normal electron-phonon processes predominate and conditions exist for the establishment of the hydrodynamic transport mechanism.

In very pure metals at low temperatures, the normal electron-phonon scattering processes may turn out to be predominant. Then a local-equilibrium drift distribution is formed in the electron-phonon system, and the hydrodynamic transport mechanism sets in. A distinguishing feature of compensated ("even") metals with closed Fermi surfaces is in this case the appearance of a hydrodynamic regime in the heat-conduction process

(in the absence of an electric current). An analysis of this situation, carried out by Gurzhi and Kontorovich,^[1] has led to the following result for the total thermal conductivity:

$$\kappa = C_e v_F l_{en} + C_e v_F \left(\frac{T}{T_0} \right)^6 l_u, \quad (1)$$

where the first term corresponds to the diffusion-elec-

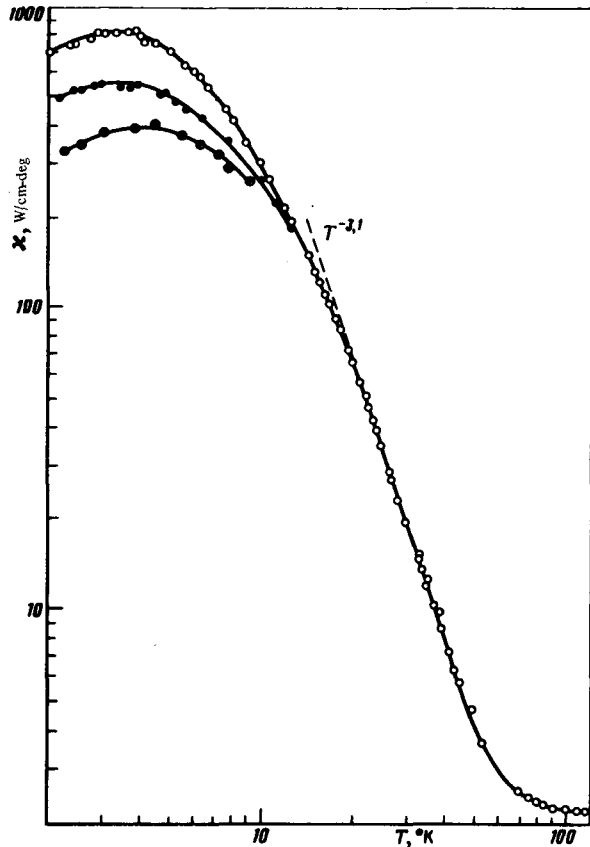


FIG. 1. Temperature dependence of the thermal conductivity of tungsten. ○) Initial single crystal, $d=3.2$ mm; ●) the diameter reduced in succession by electric etching to 1.4 mm; ⊕) further reduction to $d=0.8$ mm.

tron thermal conductivity (according to the Bloch-Wilson theory, $l_{en} \sim (T_0/T)^3$ in electron-phonon scattering), while the second term constitutes the contribution of the drift motion; C_e is the electronic specific heat, $T_0 = sp_F$ (s is the speed of sound and p_F is the momentum at the Fermi level), and l_u is the electron mean free path for processes with loss of quasimomentum. Equation (1) does not include Poiseuille flow and it is assumed that $T_0^2 \gg T^2 > T_*^2 \equiv T_0^3/\epsilon_F$. As the temperature rises, the length l_u is limited mainly by electron-phonon Umklapp processes, i.e., $l_u \sim \exp[\beta(\theta/T)]$. The conclusion that the thermal conductivity of a compensated metal has an exponential temperature dependence is contained also in a paper by Flerov.^[2] A suitable object with which to verify this conclusion is tungsten, which can be obtained in very pure form.

The presently available experimental data on the thermal resistance of pure tungsten pertain only to helium temperatures (1.5–6°K),^[3] where the principal role in carrier scattering is played by interelectron and impurity scattering. To answer the question of interest to us, the thermal resistance of tungsten should be measured in the region $T > 20^\circ\text{K}$, where electron-phonon interaction plays the principal role in the sample investigated by us. This circumstance was revealed experimentally in an investigation of the resistivity ρ of this sample, which varies in the region 20–50°K like

$\rho \approx BT^5$, and B depends little on the impurity concentration.^[4]

We measured the thermal conductivity of a tungsten single crystal with diameter 3.2 mm and ratio $\rho_{273^\circ\text{K}}/\rho_{4.2^\circ\text{K}} = 86000$ in the temperature region 2–120°K. It follows from estimates based on a study of the influence of the magnetic field on the thermal conductivity that in a strong field, i.e., when the drift regime is disturbed, the heat transfer at $T < 40^\circ\text{K}$ is mainly via the carriers. To answer the question of interest to us it was therefore necessary to determine the temperature dependence of the total thermal conductivity, and to compare it in the section 20–40°K with the results of Bloch-Wilson theory.¹⁾ To extend this temperature interval to lower temperatures it was necessary to take into account other scattering mechanisms at $T < 20^\circ\text{K}$. To this end we separated from the total thermal resistance n the additive terms corresponding to the interelectron scattering (aT^2) and to the impurity scattering $[(WT)_0]$, and plotted the function $WT - (WT)_0 - aT^2 = f(T)$. The coefficients a and $(WT)_0$ were determined from the dependence of WT on T^2 in the region of lowest temperatures (2–6°K), where this dependence is linear and it is therefore possible to neglect the electron-phonon scattering. It is seen from Fig. 1 that in the 20–40°K section of the plot of the total thermal conductivity the slope is -3.1 , which is much higher in absolute magnitude than the value -2 corresponding to the Bloch-Wilson theory. Separation of the contribution of the interelectron scattering increases the slope to -3.4 , and greatly extends the region of the anomalous temperature dependence of the thermal conductivity into the low-temperature region (Fig. 2). According to preliminary data,

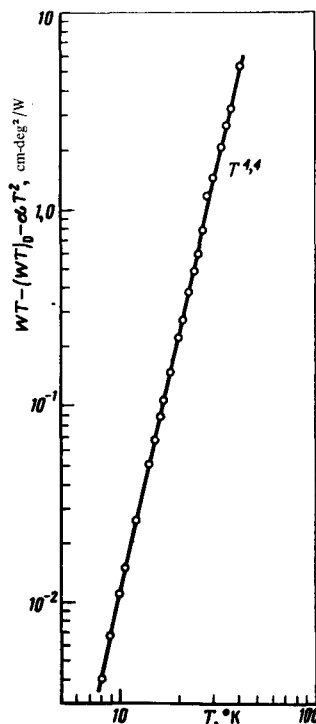


FIG. 2. Temperature dependence of the quantity WT after eliminating the interelectron scattering (aT^2) and the impurity scattering $[(WT)_0]$.

the dependence of the thermal resistance of "dirty" samples is close to $W \sim T^2$.

According to (1), the hydrodynamic contribution to the total thermal conductivity $\Delta\kappa$ depends on the temperature at least like $\kappa_{\text{exp}} \sim T^{-3.4}$ and corresponds to a much steeper dependence of l_u (at least like $l_u \sim T^{-10}$), which means in practice the realization of an exponential dependence of the mean free path l_u . The influence of the size effect, which is shown in Fig. 1, demonstrates that the energy mean free path of the carriers in the investigated tungsten single crystal exceeded the transverse dimensions of the crystal at low temperatures, i.e., the scattering by impurities was indeed very small. Allowance for the influence of the carrier scattering by the surface can only increase the slope of interest to us in the region $T < 12^\circ\text{K}$, but in our case this was immaterial. With increasing temperature, processes with quasimomentum loss begin to predominate in the phonon system itself, and the hydrodynamic flow of the electron-phonon gas is disturbed.

It can thus be taken as experimentally proved that in

a compensated metal the temperature dependence of the thermal conductivity in the region of the mutual electron-phonon scattering can be caused to a considerable degree by the appearance of the hydrodynamic regime, i.e., by the effect of mutual dragging.

¹On going from the diffusion regime to the drift regime, the relative contributions of the electronic and lattice thermal conductivities are significantly altered:

$$\left. \frac{\kappa_e}{\kappa_p} \right|_{\text{dif}} = \left(\frac{T_0}{T} \right)^4 \gg 1, \quad \left. \frac{\kappa_e}{\kappa_p} \right|_{\text{drift}} = \frac{T_0^2}{T^2} \lesssim 1.$$

¹R. N. Gurzhi and V. M. Kontorovich, *Fiz. Tverd. Tela* **11**, 3109 (1969) [*Sov. Phys.-Solid State* **11**, 2524 (1970)].

²V. N. Flerov, *Fiz. Tverd. Tela* **16**, 55 (1974) [*Sov. Phys.-Solid State* **16**, 33 (1974)].

³D. K. Wagner, I. C. Garland, and R. Boners, *Phys. Rev.* **B3**, 3141 (1971).

⁴A. B. Batdalov, V. I. Tamarchenko, and S. S. Shalyt, *Fiz. Tverd. Tela* **16**, No. 10 (1974) (in press) [*Sov. Phys.-Solid State* **16**, No. 10 (1975)].