Thermoelectric power in high-purity tin

A. A. Altukhov and N. V. Zavaritskiĭ

Institute of Physics Problems, USSR Academy of Sciences
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We determine the change of the thermoelectric power in the transition region from impurity to
phonon scattering of electrons. The role of nonadditivity of the scattering processes in the character
of the change of the thermoelectric power is explained.

We consider in this paper the dependence of the thermoelectric power of tin on the impurities. The published data on this question[1,2] are insufficient and contradictory. The onset of the thermoelectric power α is due, according to calculations by Gurevich[3] to two mechanisms: 1) direct action of the temperature gradient on the electrons, and 2) dragging of the electrons by the phonon flux produced by the temperature gradient.
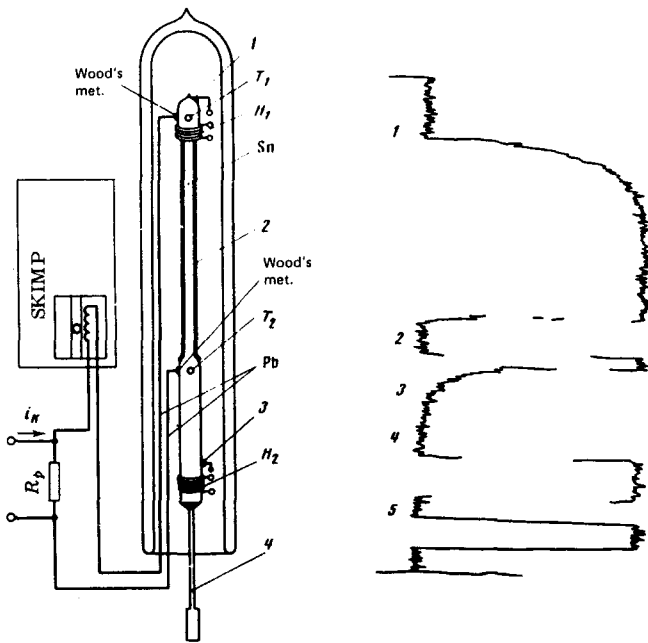
FIG. 1. Left—schematic diagram of the thermoelectric-power measurement apparatus: 1, 3—current leads for the measurement of the sample resistance, Pb—lead leads for the measurement of the voltage drop across the sample. T_1, T_2—thermometers, H_1, H_2—heaters, 2—glass capillary, 4—copper rod. Right—typical time trace of SKIMP apparatus reading, 1, 3—heater turned on and off, 2—compensating voltage turned on, 4—control spin turned on, 5—current through sample turned on.

Accordingly, at low temperatures we have

$$a = aT + bT^3 , \tag{1}$$

where the first and second terms are due to the electron and phonon contributions, respectively. We determine the change that occurs in the coefficients a and b on going from electron scattering by impurities to electron scattering by lattice vibrations.

A diagram of the instrument used for the measurements is shown in Fig. 1. The temperature gradient is produced along a narrow cylindrical part of the sample, of 2 mm diameter. This part of the sample is protected against possible additional deformation by a thin-wall glass capillary. The thermometers are placed in openings produced electrolytically in thicker sections of the sample. The sample is thermally insulated from the surrounding liquid helium by a Dewar vessel. The thermoresistor 4 and the heater H_2 are used for measurements above 4.2 °K. Superconducting leads, in which there is no thermoelectric power, are used for the measurement circuit. The voltage drop across the sample was determined by a null method with the SKIMP installation[4] as the null-reading instrument. At $R_N = 10^{-5}$ Ω, the sensitivity of the apparatus was 10^{-13} V. On the right side of Fig. 1 is shown a typical time trace of the SKIMP readings. The temperature gradient in the principal measurements, along the sample, was $\sim 10^{-2}$ °K.

The objects of the investigation were tin single crystals grown along the [110] direction. The residual resis-

tivity ρ_0 of the samples was 10^{-10} Ω-cm—10^{-10} Ω-cm, and was varied by introducing In and Sb impurities in the tin.

The measurement results have shown that the transition of the tin to the superconducting state at 3.72 °K is accompanied by an abrupt vanishing of the thermoelectric power without any precursor of the transition[5] at temperatures above T_c. The transition interval was ~ 0.01 °.

In the normal state, from 3.72 to 7.2 °K, relation (1) describes quite satisfactorily the temperature variation of α. The results of the measurements are shown in Fig. 2 in the form of a plot of α/T against T^2. The only exceptions were samples with the smallest amount of impurities. The slope of the curves and the values of the constant b decrease somewhat when the sample lattice becomes distorted. This may be the cause of the lower values of b obtained in[2] for samples along [110].

The constants a and b in (1) depend on the number of impurities introduced into the sample or, equivalently, on ρ_0 (Fig. 3). At $\rho_0 \approx 10^{-8}$ Ω-cm a change is observed in the dependences of a and b on ρ_0. This change is probably due to the transition from the region where the principal role is played by collisions between the electrons and impurities or defects, to a region where a noticeable role is played by electron-phonon collisions. Indeed, if we denote by τ_{imp}, τ_{phE}, and τ_{php}, the relaxation times for electron scattering by impurities, by phonons with change of energy (τ_{phE}), and by phonons with change of momentum (τ_{php}), then $\tau_{imp} \sim \tau_{phE}$ (8 °K) at $\rho_0 \approx 10^{-8}$ Ω-cm and $\tau_{imp} \sim \tau_{php}$ (4°), at $\rho_0 \approx 10^{10}$ Ω-cm (τ_{phE} and τ_{php} were determined by us from data on the temperature dependence, thermal conductivity, and electric conductivity of Sn). The value of b is determined principally by the inelastic interaction of the
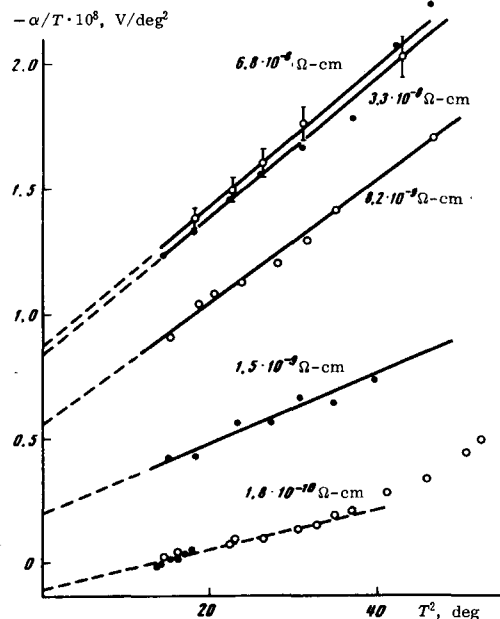

FIG. 2. Dependence of α/T on T^2 for tin samples with indium impurity. Dashed—linear extrapolation to $T = 0$°K. The curves are labeled with the residual resistivity.
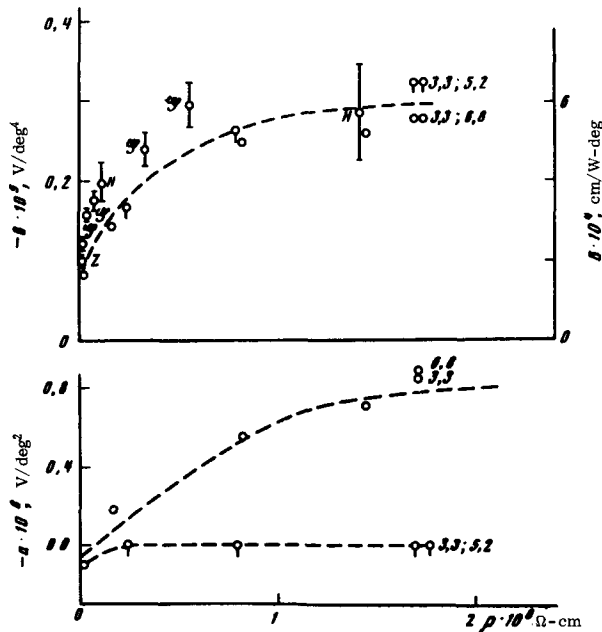
FIG. 3. Dependence of the coefficients b and a from (1) and B from (2) on the residual resistivity of the samples: B—Φ Z, G, H—data of[6-8]; b and a—Sn with Sb impurity; $\bigcirc$—Sn with In impurity. For samples with $\rho_0 > 2 \times 10^{-8}$ Ω-cm, the corresponding point is labeled by the value of ρ_0.

electrons with the phonons (τ_{phE}) and depends on the ratio $\tau_{\mathrm{imp}}/_{\mathrm{phE}}$. In the region of electron-impurity scattering ($\tau_{\mathrm{imp}}/\tau_{\mathrm{phE}} \ll 1$), the value of b remains practically constant (Fig. 3), and on going into the phonon-scattering region, b decreases several fold.

A similar effect was observed by us earlier[6] and later on[7] in an investigation of the thermal conductivity K. As is well known

$$TK^{-1} = \frac{\rho_0}{L_0} + BT^3, \qquad (2)$$

where $L_0 = 2.45 \times 10^{-8}$ W-Ω/cm-deg, and B is a mea-

sure of the effective interest to us, that of electron-phonon scattering. The changes of b and B proceed in similar fashion (Fig. 3), thus additionally confirming the relation between the electron dragging by phonons and electron scattering by phonons.

The value of τ_{phE} varies with temperature like T^{-3}, and $\tau_{\mathrm{imp}}/\tau_{\mathrm{phE}}$ changes by a factor of 7 in the measurement interval 3.8—7.2°K. One should therefore expect the deviation from relation (1) to be larger the purer the sample. This may be the cause of the observed deviations in our measurements (Fig. 2) and the term $\sim T^4$ observed in the thermoelectric power of high-purity gallium.[9]

As is well known, the electronic term of the thermoelectric power is

$$a \sim \left(\frac{\partial \ln \sigma}{\partial E}\right)_{E_F} \sim \left(\frac{\partial \ln S_F}{\partial E} + \frac{\partial \ln \tau}{\partial E}\right)_{E_F},$$

where S_F is the Fermi-surface section. We assume that the change of $\partial \ln \tau / \partial E$ plays the principal role in the $a(\rho_0)$ dependence. At $\tau_{\mathrm{imp}} \ll \tau_{\mathrm{phE}}$, the coefficient a becomes constant and is determined by the character of the electron scattering by the lattice-field distortions due to the particular type of impurity. In this region, a is extremely sensitive to the type of impurity, with $a_{\mathrm{In}} = -8.5 \times 10^{-9}$ V/deg^2 and $|a_{\mathrm{Sb}}| < 0.5 \times 10^{-9}$ V/deg^2 for In and Sb in tin, respectively.

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