THERMAL CONDUCTIVITY OF BISMUTH AT LOW TEMPERATURES

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We discuss here the results of measurements of the thermal conductivity of perfect Bi single crystals at low temperatures.

Interest in this research is due primarily to the fact that in Bi the concentration of the free carriers is small ($\sim 10^{-5}$ per atom) and the heat transfer at low temperature is effected mainly by the phonons, making it possible in principle to estimate the contribution made to the thermal conductivity by different mechanisms of phonon scattering (phonon-phonon and phonon-electron interaction, scattering by the boundaries). However, the results given in [1 - 3] for measured thermal conductivity of Bi at low temperatures differ noticeably.

Thus, according to the measurements of Shalyt et al. [1], the thermal conductivity of samples with diameter d = 2.5 mm reaches a maximum at a temperature $T \simeq 4°K$, and decreases with decreasing temperature like $K \sim T^{2.6}$ (Fig. 1, curve 1). At the same time, according to the data of Bhagat et al. [2] in the temperature interval 1.3 - 2°K the temperature dependence of K is close to $K \sim T^{3.1}$ (Fig. 1, curve 2). In addition, at 2°K the thermal conductivity is twice as large than in [1] at the same temperature.

We investigated the thermal conductivity of Bi at T = 1.3 - 6°K. The samples (d = 2.5 mm, ℓ = 50 mm) were grown in a dismountable graphite mold. The thermometers were curved resistances. The accuracy of the measurement of T was 1%, and the error in the determination of K did not exceed 2%. The results of our measurements are shown in Fig. 1 (curve 3). At $T \geq 4°K$, our data coincide with the results of [1], but the maximum value of K exceeds the maximum thermal conductivity of the best of the known samples of other authors, and the position of the maximum is shifted towards lower temperatures. In the interval 1.3 - 2.5°K we have $K \sim T^{3.15 \pm 0.07}$, i.e., the temperature dependence of K is close to that observed in [2] for the sample having the same crystallographic orientation.

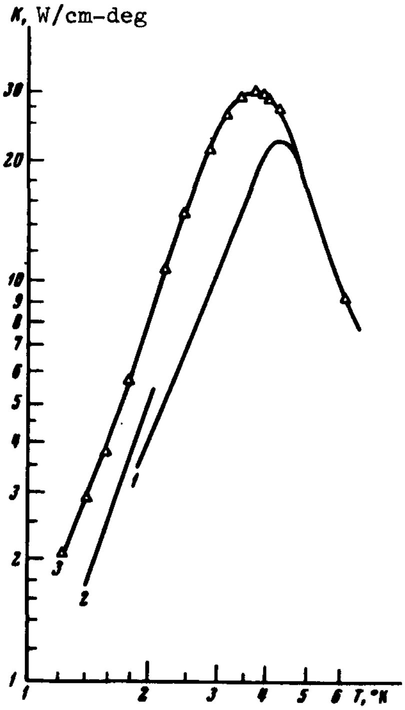

Fig. 1. Temperature dependence of the thermal conductivity: 1 - data of [1], 2 - data of [2], 3 - results of our measurements ($\nabla T \perp C_3$ for all curves).

In the estimate of the influence of different mechanisms of phonon scattering on the heat-transport processes in the crystal lattice, it is convenient to consider the temperature dependence of the effective length of the mean free path of the phonons ℓ_{eff} (Fig. 2) determined by the formula

$$K = 1/3\, C s \ell_{eff},$$

where $C = 5.5 \times 10^{-5}\, T^3$ J/cm^{3}deg is the specific heat per unit volume, and $s = 1.1 \times 10^5$ cm/sec is the Debye speed of sound in Bi.

From a theoretical analysis [4] it follows that at the lowest temperatures, when the thermal resistance of the lattice is due to scattering of

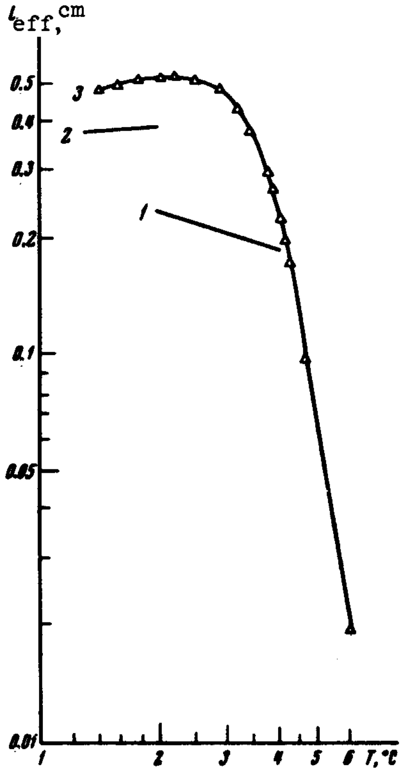

Fig. 2. Temperature dependence of the mean free path (the symbols are the same as in Fig. 1).

phonons by the boundaries, ℓ_{eff} does not depend on the temperature ($\ell_{eff} \simeq d$, where d is the characteristic dimension of the sample). With increasing temperature, when inelastic scattering of the phonons in the volume of the sample becomes significant (the scattering is by phonons, by electrons, and by the crystal-structure defects), ℓ_{eff} decreases with increasing temperature.

The small decrease of ℓ_{eff} calculated in accordance with data [1] (curve 1) with increasing T in the interval 2.5 - 4°K can be attributed to scattering of the phonons by imperfections of the crystal lattice.

It is much more difficult to explain the growth of ℓ_{eff} at T = 1.4 - 2.5°K, observed in our measurements and in [2]. The authors of [2] connect the increase of ℓ_{eff} with increasing T with the influence of phonon-electron interaction on the thermal conductivity. The mean free path of the phonons in Bi when they are scattered by electrons, ℓ_{pe}, can be estimated by using the results of measurements of the temperature dependence of the mean free path of the electrons ($\ell_{ep} \approx 1.5/T^2$ cm) [5] and by using the ratio $n_p/\tau_{pe} = n_e/\tau_{ep}$ (it is assumed here that the scattering of the phonons by electrons and of the electrons by the phonons is equally effective, since at $T \leq 2$°K the dimensions of the phonon sphere and of the Fermi ellipsoid are of the same order): $\ell_{pe} \approx 0.15\ T^2$, $\ell_{ep} = 0.15$ cm. Thus, $\ell_{pe} \approx d$ and does not depend on the temperature, making it impossible to explain the observed growth of ℓ_{eff} with the temperature.

On the other hand, from the data of [1], the relaxation time in normal collisions between the phonons in Bi is $\tau^N_{pp} \approx 10^{-9}$ cm at 8°K and increases like $\sim T^{-4}$ with decreasing temperature. Hence at 2°K the effective mean free path of the phonons in normal collisions is smaller by approximately one order of magnitude than the diameter of the sample ($\ell^N_{pp} \approx 0.02$ cm) and all the characteristic phonon lengths.

In dielectric crystals, in the case when the thermal resistance is due to scattering of the phonons by the boundaries of the sample ($d \ll \ell^R$, where ℓ^R is the mean free path of the phonons between collisions in the volume with loss of quasimomentum), frequent normal collisions ($\ell^N_{pp} \ll d$) lead to the occurrence of hydrodynamic flow of the phonon gas ($\ell_{eff} \simeq d^2/\ell^N_{pp} \gg d$), which is manifest in the change of the magnitude and of the temperature dependence of the thermal conductivity. From the foregoing estimates it follows that in Bi at helium temperatures $\ell^N_{pp} \ll d \sim \ell_{pe}$, i.e., an appreciable growth of ℓ_{eff} is prevented by the scattering of the phonons by electrons. Thus, the stronger-than-cubic dependence of the thermal conductivity on the temperature observed in our experiments at $T \leq 2.5°K$ (and accordingly the growth of ℓ_{eff} in the interval 1.3 - 2.5°K) can be attributed to the influence of frequent normal collisions between the phonons in the volume of the sample.

It is interesting to note that inasmuch as the condition $\ell_{pp}^{N} << \ell^{R}$ is sufficiently well satisfied for perfect samples of Bi at helium temperatures, "second sound" (i.e., weakly damped temperature waves) can propagate in principle in such crystals in the phonon gas. We are presently carrying out investigations in this direction.

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INFLUENCE OF LASER RADIATION ON INSTABILITY IN YTTRIUM IRON GARNETS WITH PARALLEL PUMPING

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We report here the results of an investigation of instabilities arising in yttrium iron garnets acted upon simultaneously by parallel pumping and by laser radiation of wavelength $\lambda = 1.06\ \mu$.

We used in the experiment a sample of $Y_3Fe_5O_{12}$ in the form of a disk of 5 mm diameter and 1.9 mm thickness. If the sample is placed in a constant field H_0 and in an alternating magnetic field parallel to it $h_{\sim}$ (a rectangular resonator in the H_{012} mode is used), applied in the plane of the disk, spin-wave instability sets in at a microwave power exceeding the critical value [1]. The frequencies of the parametrically-excited spin waves $\omega_c = \omega/2$ and the magnitude and the direction of the wave vectors vary in wide limits. Further increase of the microwave-signal power leads to the occurrence of low-frequency oscillations of magnetization. The threshold curves of the spin-wave instability h_{cr} and of the low-frequency oscillations for our sample are shown in Fig. 1.

With simultaneous action of parallel pumping and laser radiation, we registered the variation of these instabilities. The laser beam was propagated normal to the plane of the disk. The laser-signal power density on the front face of the disk (the beam was focused on the rear face of the sample) could be varied with the aid of calibrated neutral filters. Both signals - pump with duration $\tau_p = 300$ μsec and laser with $\tau_L = 120$ μsec - were synchronized to act simultaneously. Typical oscillograms of the processes observed by us are shown in Fig. 2.