Singularities in the phonon thermal conductivity of deformed lead crystals at temperatures below 2 K

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The thermal conductivity of perfect and of plastically deformed lead crystals were measured at temperatures down to 0.5 K. The effective transport mean free path of the phonons l_p in the deformed sample, calculated from the thermal conductivity, increases exponentially with decreasing temperature, reaches a maximum at $T=2$ K, and then decreases rapidly, becoming weakly dependent on the temperature at $T<0.9$ K. The inflections on the $l_p(T)$ curve at $T\leq 2$ K may be connected with resonant scattering of phonons by dislocations introduced into the sample.

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The investigation was devoted to the temperature dependence of the thermal conductivity of lead crystals made of S-0000 high-purity metal from the Chimkent copper plant by multiple zone melting of freely lying cylindrical blanks in vacuum.[1] It is known[2] that at helium temperatures in a zero magnetic field the thermal conductivity of lead is determined mainly by the phonon component κ_p. The maximum value of κ_p of the prepared samples with average diameter $d=0.4$ cm was higher by one order of magnitude than the published values, and was limited at temperatures $T\leqslant 2$ K by the phonon scattering from the sample surface. The effective phonon transport mean free path l_p calculated from the thermal conductivity at $T\leqslant 4$ K increased exponentially with decreasing temperature, reached values $l_p\approx d$ at $T=2$ K, and from there on was practically independent of the temperautre (upper curve in Fig. 1).

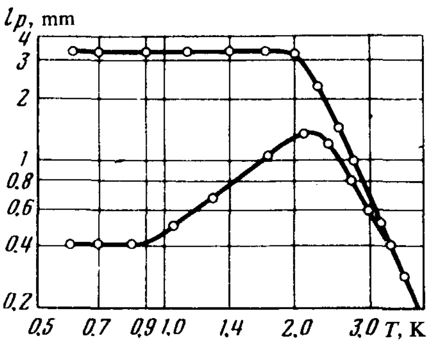

FIG. 1.

It was of interest to observe phonon scattering by dislocations introduced into the volume by plastic deformation of the sample. We first deformed the crystal by bending at room temperature, in analogy with our earlier procedure in the study of thermal conductivity of Bi crystals.[3] It turned out, however, that the rate of motion of the defects in Pb is so high that the samples have time to become annealed during the assembly of the instrument (several hours at temperatures 80–20 °C). The thermal conductivity of bent Pb samples, in contrast to Bi, turned out to be close to the initial value. The deformation procedure was therefore modified. The initial measurements of the thermal conductivity were made on a sample lying loosely in a horizontal vessel (segment of stainless-steel pipe coated with teflon film) and soldered on one side to the cold finger. The second end of the sample was then soldered to the end face of the vessel with Wood's alloy, and the measurements were repeated. On cooling from room temperature to helium temperature, owing to the large difference between the coefficients of the thermal compression of steel and lead, the sample was stretched (the relative elongation of the sample is estimated[4] at 0.3%).

The thermal conductivity of the deformed sample was several times lower than κ_p of the initial sample, and the temperature dependence $\kappa_p(T)$ also changed. In the interval $T=0.9$–2 K it turns out to be closer to $\kappa_p(T)\sim T^5$, and $T=0.9$ K we have $\kappa_p \sim T^3$. This is clearly seen from the plot of $l_p(T)$–the lower curve in Fig. 1. There is no doubt that the inflections on this curve are due to resonant scattering of phonons by dislocation structures produced when the sample is deformed.

For any other mechanism of phonon scattering by the defects, l_p increases or remains constant with decreasing temperature: $l_p \sim T^{-4}$ for scattering by point defects, $l_p \sim T^{-1}$ for scattering by the stress fields around immobile dislocations, and $l_p = \text{const}$ for scattering by grain boundaries or crystals.[5] The decrease of the phonon mean free path may be the consequence of the resonant scattering of the phonons by the vibrating dislocations (the flutter effect) or by statistically ordered grids of dislocations[5] which accumulate in the walls along the slip planes of the crystal as the sample becomes deformed.

Let us examine the first mechanism. In the simplest string model of the dislocation, the distance L between the dislocation pinning points and the characteristic dislocation oscillation frequency ν are connected by the relation $\nu=v/3L$ (v is the speed of sound, $\sim 10^5$ cm/sec), and the effective mean free path of the thermal phonons in the region of the resonance (the minimal value of l_p) is given by $l_p = 2\nu/Nv$, where N is the dislocation density.[6] The thermal phonons that dominate at the temperature T have a frequency $\nu \approx 3.8\, kT/h = T\times 10^{11}$ Hz. Assuming that l_p reaches a minimum at $T=0.7$ K, we obtain $\nu=0.7\times 10^{11}$ Hz, an average distance $L=5\times 10^{-7}$ cm, and $N=3\times 10^7$ cm^{-2}. Thus, the obtained values of the dislocation density and of the characteristic lengths of freely vibrating sections of dislocation loops are perfectly reasonable.

If the second scattering mechanism predominates, then the average distance between the walls should be $\sim 5\times 10^{-2}$ cm, and the characteristic dimensions of the cell made up of intersecting dislocation loops is $\sim 10^{-6}$ cm. The shapes of the $l_p(T)$ curves have not been investigated theoretically in either model. It is clear from general considerations that in scattering by vibrating dislocations l_p should increase with decreasing temperature, up to values $l_p \approx d$, and in scattering by a grid of dislocations it should remain practically constant. It would therefore be of interest to continue the measurements at the temperatures $T \ll 0.7$ K.

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