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THERMAL CONDUCTIVITY OF NORMAL AND SUPERCONDUCTING LEAD ALLOYS*

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The thermal conductivity of lead specimens containing 3% indium, 6% indium, and 6% bismuth has been measured in the normal and superconducting states. The data are shown in Fig. 1. Their analysis shows that the addition of impurity leads to an increase in thermal resistance in both states, but that near 2°K the ratio of increase in the resistance to lattice heat transport is 40 times greater in the normal state than in the superconducting state. Since in superconducting lead, at 2°K and below, the electronic conductivity and the effect of the electrons on the lattice conductivity are expected to be negligible, it is seen that the large change in lattice thermal resistance with impurity in the normal state depends on the presence of the electrons.

In the normal state the electronic thermal conductivity is equal to αT, where the coefficient α is related to the residual electrical resistivity ρ_0 by the Wiedemann-Franz law, $\alpha = L_0/\rho_0$ ($L_0 = 2.445\times10^{-8}$ volt^2/deg^2).[1] At sufficiently low temperatures the lattice conductivity is equal to βT^2. The total thermal conductivity $K = \alpha T + \beta T^2$ is most easily separated into its components graphically, on a plot of K/T versus T which will then be a straight line. In Fig. 2 the experimental data for the normal state have been plotted on such a graph. For each specimen the intercept α has been calculated from a measurement of the electrical resistance near 4.2°K, and a straight line drawn through this point and through the low-temperature thermal conductivity points. The slope β of each line is shown in Table I. In addition Table I lists the values of ρ_0 for our specimens and of β and ρ_0 for a specimen of lead with 0.7% bismuth measured by Montgomery.[2] The deviation of the data from the straight lines at higher temperatures is likely to be caused by the increased importance of impurity scattering at these temperatures.

The effect of adding impurity may be calculated roughly by comparing the thermal resistances of specimens containing different amounts of impurity. The lattice resistances at 2°K are

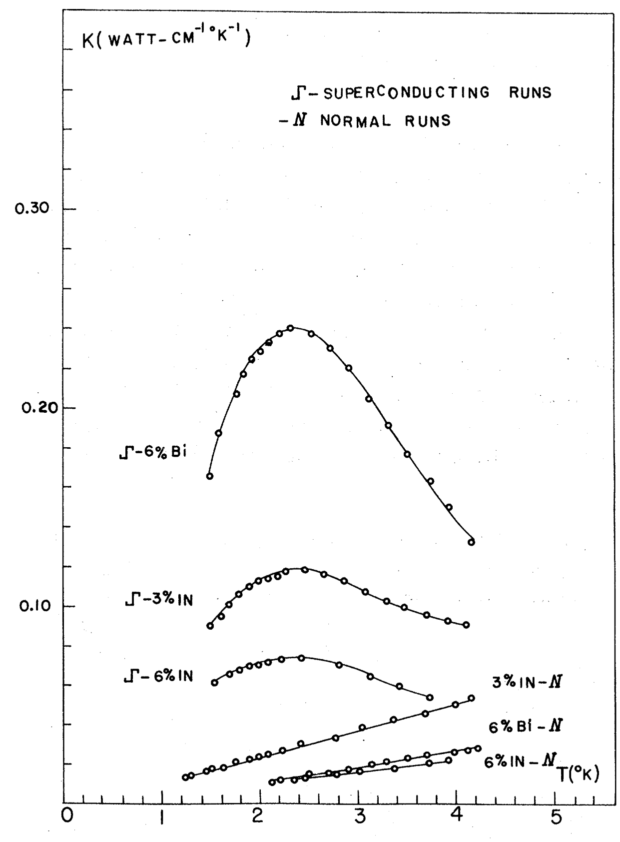

FIG. 1. Thermal conductivity of lead alloys versus temperature.

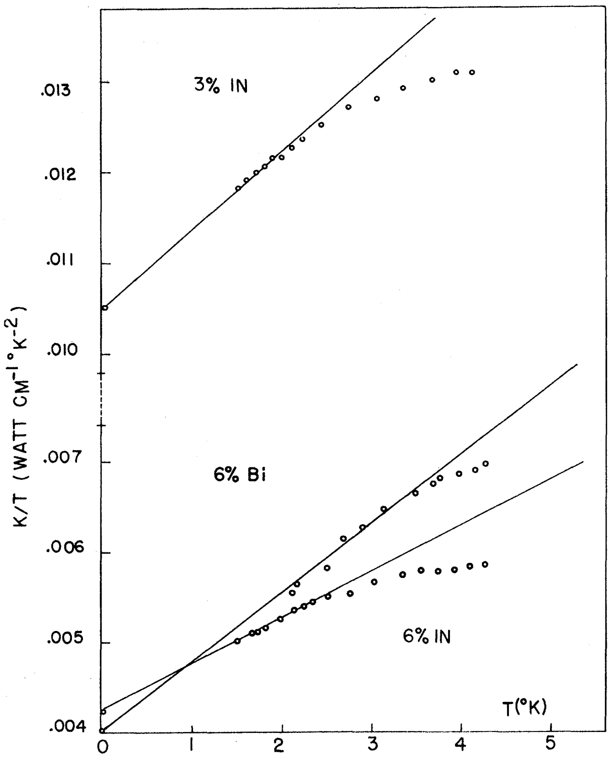

FIG. 2. Normal state thermal conductivity divided by temperature versus temperature.

listed in Table II. It is seen that the extra resistance of the 6% indium specimen compared to the 3% indium specimen is 190 cm-deg/watt in the normal state, and 4.9 cm-deg/watt in the superconducting state; i.e., the extra resistance is 40 times as large in the normal state as in the superconducting state. If the resistances of the 6% bismuth and 0.7% bismuth specimens are compared in the two states, the same ratio between the extra resistances is obtained. Supporting evidence may be inferred from a comparison of Montgomery's data with those of Olsen[3] for a specimen of lead with 10% bismuth.

The results for the superconducting state are similar to those found in insulating crystals where boundary and point defect scattering predominate. The difference between the effects of indium and bismuth may be at least partially accounted for by the difference in the mass of the impurity atoms. On the high-temperature side of the maximum, conduction and scattering by electrons will, of course, begin to affect the conductivity.

That the lattice conductivity in normal metals decreased in an anomalously strong fashion with increasing impurity content has been known from work on other metals.[1] The present measurements underscore our previous conclusion[4] that this change is not related to a large change in dislocation density since this would be expected to affect the conductivity in both states in the same way. The measurements show that the large increase in resistance with added impurity depends on the presence of the electrons, since it is greatly reduced in the superconducting state.

This added resistance could, in principle, be caused by a change in the electronic density of states or the electron-phonon interaction. It seems more reasonable, however, that the presence of the electrons as scattering centers leads to an interference between impurity scattering and electron scattering similar to that discussed for a different case by Berman et al.[5] In that case the interference between isotope scattering and phonon scattering was such that the process of smaller magnitude turned out to dominate the thermal resistance. If a similar enhancement can occur for impurity scattering in metals, the anomalously large effect of impurities on lattice conduction in lead as well as in other metals might be explained.

Table I. Values of lattice conductivity coefficient β and residual resistivity ρ_0.

	β (watt/cm-deg^3)	ρ_0 (ohm-cm)
6% In	0.52×10^{-3}	5.77×10^{-6}
3% In	0.86×10^{-3}	2.33×10^{-6}
6% Bi	0.77×10^{-3}	6.09×10^{-6}
0.7% Bi [a]	1.3×10^{-3}	0.750×10^{-6}

[a]See reference 2.

Table II. Lattice resistance at 2°K in the normal state ($1/K_{gn}$) and in the superconducting state ($1/K_{gs}$).

	$1/K_{gn}$ (cm-deg/watt)	$1/K_{gs}$ (cm-deg/watt)
6% In	480	13.7
3% In	290	8.8
6% Bi	320	4.4
0.7% Bi [a]	190	1.1

[a]See reference 2.

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DIRECT OBSERVATIONS OF ION DAMAGE IN CADMIUM

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Pashley and Presland[1] have recently found that, during the normal operation of the Siemens electron microscope, the filament gives off negative ions (of unknown origin) which are accelerated and strike the specimen. The measured flux density at the specimen ranged between 10^7 and 10^9 ions/cm^2 sec. They studied the effect of these ions on a number of metal films, particularly gold,[2] and observed microstructural defects similar to those produced by fast neutron irradiation,[3] namely, tiny dot-like features which were sometimes resolvable as dislocation loops.

This Letter reports evidence that ion damage in cadmium crystals irradiated in the electron microscope results in the nucleation and growth of vacancy-type dislocation loops. Dislocation-free platelets of cadmium, thin enough ($\lesssim$2000 A) to be transparent to 100-kv electrons, were grown from the vapor[4] and examined in transmission in the Siemens Elmiskop I, on a cold stage, at temperatures in the range +25° to -100°C. After a few minutes at high beam current, tiny, isolated dislocation loops appeared and began to grow in the region illuminated by the beam. They were first detectable as dots of about 40A diameter (the minimum size resolvable by the transmission technique). At low temperature the rate of formation was high and the growth rate of individual loops was low, leading to a defect distribution like that in Fig. 1, which is a transmission electron micrograph, taken at -90°C about five minutes after the dots began to appear. At room temperature the rate of production was low, but those loops formed grew quite rapidly and eventually intersected one another to form dislocation networks. Figure 2 shows a typical distribution of loops (a) 5 minutes and (b) 10 minutes after the beginning of irradiation of the same area at +25°C.

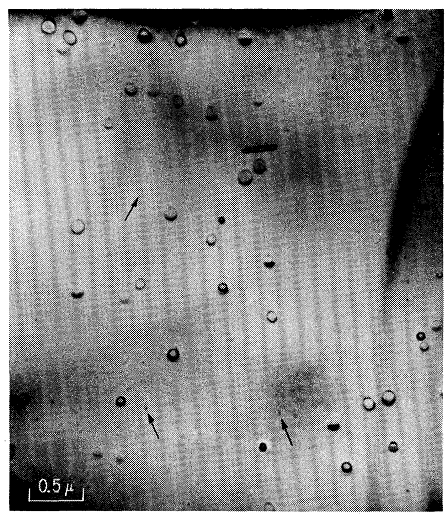

FIG. 1. Vacancy-type dislocation loops due to ion damage in cadmium at -90°C. Several of the smallest loops, clearly visible on the original micrograph, are indicated by arrows.

The nature of the loops was determined by tilting a specimen and obtaining selected area diffraction patterns from individual loops in several different reflecting conditions. Virtually all of the loops were circular and oriented in the basal plane, which was parallel to the large platelet faces and perpendicular to the beam.