Letters to the Editor

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Structural Defects in Copper and the Electrical Resistivity Minimum

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THE observation of de Haas, de Boer, and van den Berg[1] that a minimum in the electrical resistivity of polycrystalline gold wires occurred in the vicinity of liquid helium temperatures resulted in considerable interest as this raised some doubt as to the validity of Matthiessen's rule. Since that experiment, many others have been performed with the result that not only has the effect been verified in gold, but a similar minimum has been found in many other metals. Several explanations and suggestions to account for this anomalous behavior have been advanced. While many of these comments have attributed the anomalous behavior to the presence of chemical defects, particularly ferromagnetic impurities, Lane[2] on the basis of Meissner's[3] data suggested that grain boundaries might play a predominate role in the phenomena. It is the purpose of this note to discuss the role of structural defects, especially grain boundaries, in the electrical minimum found in copper.

In the course of investigating the effect of plastic deformation[4] on the residual resistivity of high-purity copper single crystals,[5] several factors arose which seemed to suggest that a substantial fraction of the residual resistivity observed during the investigation of the resistance minimum arose from the interaction of conduction electrons with structural defects (especially grain boundaries). It has generally been assumed that the residual resistivity was determined by the scattering of conduction electrons by chemical defects. The suggestion of the importance of structural defects arose from the observation that the annealed single crystals had a resistivity many times lower than the usual values reported for polycrystalline materials; that severe tensile deformation could increase the resistivity to the order of that usually observed in polycrystalline materials; and that recrystallization of the worked crystals by annealing in high vacuums (10^{-5} mm or better) at 1000°C only slightly reduced the resistivity. This situation, which was observed in many crystals, is typified by the data of crystal 304*C* in Table I.

TABLE I. The resistivity of copper (in ohm-cm) at various temperatures. The values are multiplied by 10^8.

Temperature °K	4.2	3.4	2.7	1.67	1.60
	Sample 305*D*				
Annealed single crystal	0.080				
Worked single crystal	1.308	1.310	1.308		1.306
After recrystallization	0.908				0.933
	Sample 305*C*				
Annealed single crystal	0.036	0.035	0.035		0.035
Worked single crystal	1.099				1.101
	Sample 304*C*				
Annealed single crystal	0.080				
Worked single crystal	1.140				
After recrystallization	0.830			0.846	0.847
	Sample 305*F*				
Annealed single crystal	0.090				
Worked single crystal	0.720				
After recrystallization	0.636			0.648	0.650

If then a substantial fraction of the residual resistivity is associated with grain boundaries, as the above observations suggest, it would seem that the minimum in the resistivity may arise as a result of the scattering or trapping properties of the grain boundaries. A survey-type experiment was then made to examine this hypothesis. The effect of temperature in the region from 1.6°K to 4.2°K on the electrical resistivity was determined on single crystals of copper as well as polycrystalline copper. The results are shown in Table I. The results for crystal 305*D* are of particular interest in that the resistance minimum was not found until recrystallization had occurred. The data of Table I, while only of a survey nature, would seem to indicate that grain boundaries are one type of defect which can result in a negative temperature coefficient of resistance in metals. It would seem to be especially significant that the defects introduced by the deformation, presumably dislocations (apparently the vacant lattice sites have been annealed out), scatter in a normal fashion until they have been polygonized to form grain boundaries. Whether impurity atoms, especially those which are ferromagnetic, can cause similar effects as measurements on polycrystalline metals seem to show, is open to question. It would, however, seem that the apparent indications of the influence of impurity atoms on the resistance minima should be re-examined in terms of grain boundary scattering, especially with regard to the effect of the impurities on the grain size. In the case of the results described here it would, however, seem to be difficult to ascribe the negative temperature gradient in any way to the presence of chemical defects as the magnitude of the effect is in excess of the residual resistivity of the annealed single crystals.

It may be pertinent to point out that the magnitude of the residual resistivity of single copper crystals is in good accord with the data of Meissner's values for gold and zinc single crystals. Meissner, however, found polycrystalline wires of these metals to have a residual resistivity of the same magnitude. In neither of these samples was a resistance minimum found. It may be that the grain size of Meissner's samples were large compared with the wire diameter so that the contribution of grain boundary scattering to the total residual resistivity was small.

In conclusion, it may be stated that the manner in which the conduction electrons and the grain boundaries interact is not clear. It would appear that suitable experiments, possibly Hall constant measurements, should be made to distinguish between the scattering and trapping properties of the grain boundary.

[1] De Haas, De Boer, and Van den Berg, Physica **1**, 1115 (1934).
[2] C. T. Lane, Phys. Rev. **76**, 304 (1949).
[3] W. Meissner, Z. Physik **38**, 647 (1926).
[4] To be published.
[5] The sample preparation and experimental technique used is similar to that described previously. See T. H. Blewitt, Phys. Rev. **91**, 1115 (1953).

Interaction of Beta Particles with Matter

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THE back-scattering of beta particles[1] and positrons[2] from various elements has shown a marked dependence upon atomic number or atomic weight. When the results are confined to a few elements, widely distributed over the whole range of Z, it is possible to represent them fairly simply by a $Z^{\frac{1}{3}}$ relationship. It is only when more detailed information is obtained that significant discontinuities become apparent.

A systematic study has been made of the back-scattering of 2.0-Mev betas from Y^{90} by samples of infinite thickness for 32 elements ($Z=4$ to $Z=83$) and 22 compounds. It is definitely established that the relative back-scattering is a discontinuous