Threshold Measurements and the Production of Radiation Damage in the Noble Metals*

J. W. CORBETT AND R. M. WALKER
General Electric Research Laboratory, Schenectady, New York
(Received September 10, 1959)

We have measured the electrical resistivity changes induced by bombarding Cu, Ag, and Au at ~10°K with 1.5-Mev electrons. It is inferred that the threshold energy T_d for radiation damage production in Cu, Ag, and Au is 22, 30, and ≥ 40 ev, respectively. The fact that the T_d values are not the same for this homologous series of metals requires reconsideration of the comparison of deuteron radiation damage theory and experiment. This shows that even beyond the different T_d values, the damage process parameters in these materials are not identical.

WE report here measurements of the electron irradiation induced changes in the electrical resistivity of Cu, Ag, and Au samples cooled with liquid He. The results indicate that the threshold energy for damage production increases with atomic number.

The experimental apparatus has been previously described.[1,2] We estimate that the sample temperatures were <10°K. The average energy of the bombarding electrons was inferred by heating measurements and theory to be 1.41±0.05 Mev. The most probable energy was 1.51 Mev. The samples were one-mil thick strips made from the following materials: Cu—American Smelting and Refining Company, 99.999% purity; Ag—Handy-Harmon, Inc., 99.9+%; Au—Sigmund Cohn, 99.99%.

The following resistivity changes, $\Delta\rho_e$, were observed: Cu—8.3×10^{-27}, Ag—5.3×10^{-27}, and Au—$\leq 2.5\times10^{-29}$—in units of ohm cm per elec/cm^2. The total dose was 2.2×10^{17} elec/cm^2. The change in Au is too small to be significant.[3] The recovery of the damage in Cu is consistent with that previously published. The Ag recovery is similar to that observed after deuteron bombardment by Magnuson, Palmer, and Koehler.[4]

The resistivity change is given by $\Delta\rho_e=\sigma\cdot\Delta\rho_f$, where σ is the damage cross section and $\Delta\rho_f$ is the resistivity per atomic concentration of defects (assumed Frenkel pairs). At a fixed bombarding energy the σ's are functions of the threshold. If the atoms are in a square well potential[5] of height, T_d, Seitz and Koehler[6] give an explicit relationship between σ and T_d. We have previously measured $T_d=22$ ev in Cu by varying the energy of the bombarding electrons. Using this in the cross-section relationship and making an assumption about the ratio of the $\Delta\rho_f$, we can infer threshold values for Ag and Au. Only a lower limit can be set in Au.

The resistivity, $\Delta\rho_f$, can be written as the product of the lattice parameter, a_0, and a function of phase shifts, $V(\delta_l)$. It can be shown,[7] that when the defect is replaced by a square well potential with a radius equal to the atomic cell volume and a depth adjusted to give appropriate screening, the function $V(\delta_l)$ is constant (Born approximation). We therefore expect $\Delta\rho_f\propto a_0$ as a first approximation. The detailed calculations of Abelès[8] and Jongenburger[9] bear this out. On this basis we find $T_d=30$ ev in Ag and $\gtrsim 40$ ev in Au. Using a constant $\Delta\rho_f$ as given by Dexter[10] does not alter the results substantially.

In a study of the deuteron induced damage in the noble metals, Cooper, Koehler, and Marx[11] showed that the measured ratio of the resistivity changes were closely predicted if the following quantities were assumed equal: (a) the threshold energies, (b) the resistivity of Frenkel pairs per *unit volume*, and (c) $\bar{\nu}$,

TABLE I. Ratios of the resistivity change in Ag and Au relative to that in Cu for a given deuteron bombardment. Various assumptions are made concerning the resistivity of Frenkel pairs per atomic concentration, $\Delta\rho_f$, and T_d, the threshold energy. n_0 is the number of atoms/cm^3. a_0 is the lattice constant. C is an arbitrary constant.

Assumptions				Ratios	
	T_d				
$\Delta\rho_f$	Cu	Ag	Au	Au/Cu	Ag/Cu
Cn_0 [a]	25	25	25	1.67[b]	1.07[b]
Cn_0	22	30	40	0.92[b]	0.78[b]
C	22	30	40	1.12[c]	1.05[c]
Ca_0	22	30	40	1.27[c]	1.19[c]
	Experimental values[a]			1.71	1.19

[a] See reference 11.
[b] $\bar{\nu}$, the average number of secondaries per primary displacement, assumed constant.
[c] Variation of $\bar{\nu}$ with T_d and Z included.

* The research reported in this paper has been sponsored by the Electronics Research Directorate of the Air Force Cambridge Research Center, Air Research and Development Command.

[1] J. W. Corbett, J. M. Denny, M. D. Fiske, and R. M. Walker, Phys. Rev. **108**, 954 (1957).
[2] J. W. Corbett, R. B. Smith, and R. M. Walker, Phys. Rev. **114**, 1452, 1460 (1959).
[3] We have previously been informed by J. Brinkman of Atomics International, Canoga Park, California, that this group's measurements at 80°K showed no damage produced in Au.
[4] G. D. Magnuson, W. Palmer, and J. S. Koehler, Phys. Rev. **109**, 1990 (1958)
[5] Considering more realistic potentials does not alter the substance of the ensuing discussion.
[6] F. Seitz and J. S. Koehler, in *Solid State Physics* (Academic Press, Inc., New York, 1956), Vol. 2, pp. 307–442.
[7] W. A. Harrison (private communication).
[8] F. Abelès, Compt. rend. **237**, 796 (1953).
[9] P. Jongenburger, Appl. Sci. Research **B3**, 237 (1953).
[10] D. L. Dexter, Phys. Rev. **87**, 768 (1952).
[11] Cooper, Koehler, and Marx, Phys. Rev. **97**, 599 (1955).

the average number of secondaries per primary displacement. The observed agreement was interpreted by Cooper, Koehler, and Marx as an indication that both the basic theory and the specific assumptions outlined above were essentially correct. In view of the present work, we feel that these conclusions need to be modified.

The present situation is summarized in Table I where the predicted ratios are tabulated for several different assumptions on the thresholds and resistivities. Following Seitz and Koehler the resistivity change per incident deuteron is taken proportional to $\bar{\nu}Z^2\cdot\Delta\rho_f/T_dM$ where Z and M are, respectively, the atomic number and atomic weight of the bombarded metal. If assumptions (b) and (c) above are retained, the present thresholds predict values in substantial disagreement with experiment. However, if instead of (b) we assume either $\Delta\rho_f=C$ or $\Delta\rho_f=CA_0$, agreement is to some extent restored. While the agreement is satisfactory for Ag, the situation for Au is much worse. We therefore conclude that while the basic theory predicts the proper general trend, the noble metals are not identical as regards the damage process. It is necessary to consider each metal separately.

ACKNOWLEDGMENTS

We wish to acknowledge valuable discussions with W. A. Harrison.

PHYSICAL REVIEW VOLUME 117, NUMBER 4 FEBRUARY 15, 1960

Electrical Resistivity of Dysprosium Single Crystals*

P. M. HALL, S. LEGVOLD, AND F. H. SPEDDING
Institute for Atomic Research and Department of Physics, Iowa State University, Ames, Iowa
(Received September 8, 1959)

Resistivity measurements are reported on two single crystals of hcp dysprosium metal in the temperature range 1.3°K to 400°K. The two magnetic transitions at 90°K and 175°K are very evident in the resistivity. Significant anisotropy is observed only above 175°K, which is the paramagnetic range; at 400°K, $\rho_\perp/\rho_{\parallel}=1.5$. A prediction for the resistivity of polycrystalline dysprosium based on these measurements is seen to be in good agreement with the resistivity of a polycrystalline sample.

INTRODUCTION

THE electrical resistivity of a hexagonal single crystal sample, in which the current flows at an angle ϕ with the c axis, is given by[1]

$$\rho(\phi)=\rho_{\parallel}\cos^2\phi+\rho_\perp\sin^2\phi. \quad (1)$$

One can estimate the resistivity of a polycrystalline sample by averaging $\rho(\phi)$ over-all solid angles. The result is

$$\bar{\rho}=(2\rho_\perp+\rho_{\parallel})/3. \quad (2)$$

Now for dysprosium, we assume the additivity of three contributions to the resistivity,

$$\rho=\rho_{\rm res}+\rho_{\rm ph}+\rho_{\rm mag}. \quad (3)$$

This assumption has been made by Kasuya[2] and by de Gennes and Friedel,[3] and has been verified by Anderson and Legvold[4] and Kondorsky et al.[5] The first term in Eq. (3) is assumed temperature independent. It is the resistivity extrapolated to 0°K. The second term is due to phonon scattering and theoretically is essentially linear in temperature when $T>0.5\theta$, where θ is the Debye temperature. The third term is due to magnetic, or "magnon" scattering. It increases with the magnetic entropy, which is temperature independent above the highest magnetic ordering temperature.

Part of the interest in dysprosium (and in many of the other rare earths) is due to its three magnetic states.[6] Below 90°K (the Curie point), it is ferromagnetic. Between 90°K and 175°K it is antiferromagnetic, and above 175°K (the Néel point), it is paramagnetic. However, it is felt that in the region 90–175°K the application of a magnetic field can cause a spin flip from antiferromagnetic to ferromagnetic alignment. Also, it has been found that dysprosium is magnetically very anisotropic in all three magnetic states, the hard direction being the c axis. Below 110°K there is anisotropy in the basal plane also, it being easier to magnetize along an a axis than along a direction 30° away from an a axis and in the basal plane. It was of interest, then, to see what anisotropy would occur in the magnetic resistivity, and how it would change as the sample goes from one magnetic state to another.

* Work was performed in the Ames Laboratory of the U. S. Atomic Energy Commission.
[1] W. Boas and J. K. Mackenzie, Progr. in Metal Phys. **2**, 90 (1950).
[2] T. Kasuya, Progr. Theoret. Phys. Kyoto **16**, 58 (1956).
[3] P. G. de Gennes and J. Friedel, J. Phys. Chem. Solids **4**, 71 (1958).
[4] G. S. Anderson and S. Legvold, Phys. Rev. Letters **1**, 322 (1958).
[5] E. Kondorsky, O. S. Galkina, and L. A. Tchernikova, J. Appl. Phys. **29**, 243 (1958).
[6] D. R. Behrendt, S. Legvold, and F. H. Spedding, Phys. Rev. **109**, 1544 (1958).