Production Rates of Electrical Resistivity in Copper and Aluminum Induced by Electron Irradiation*

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Polycrystalline copper and aluminum were bombarded below 6°K with monoenergetic electrons with energies in the range 0.15 to 2.1 MeV. The production rates of electrical resistivity were measured and the threshold energies for atom displacement were found to be 19±3 eV for copper and 16±2 eV for aluminum. The results indicate that the probability function for atom displacement is not a single step for either copper or aluminum. More complex functions are considered, and multiple displacements appear to be important for both metals for the energy range studied.

THE rates of production of radiation-induced electrical resistivity per electron as a function of electron energy were investigated from 0.15 MeV up to 2.1 MeV. A simple step probability displacement function cannot account for the results in either copper or aluminum. More complex functions are considered below and the onset threshold energies determined. The recovery spectra of copper[1] and aluminum[2] after electron irradiation have been reported.

The only threshold value reported for aluminum previous to the present work was that of Lucasson and Walker.[3] They obtained a much higher value (32 eV) than the present result,[4] but also reported some uncertainties in their experiments. Previous results for copper production determinations[5] were carried out at electron energies below 1.1 MeV and the threshold found agrees with the result reported here. No previous studies involving multiple displacements at beam energies above 1.5 MeV have been reported for copper.

The stated purity of the starting material was 99.999% for copper and 99.9999% for aluminum. The ratio of the resistivity at room temperature to that at 4.2°K was 540 for copper and 1870 for aluminum, without correction for the surface-scattering contribution. Zig-zag–shaped specimens 50-μ thick with a total irradiated length of 8 cm were used. A monoenergetic electron beam was used over the range 0.15 to 2.1 MeV. There were no intervening foils between the electron source and the specimens. In order to obtain a uniform electron density over the collimated area, the beam was scanned with an electronic circuit and a TV yoke. The near-threshold detection limit of resistivity production was better than 5×10^{-30} Ω cm/electron/cm^2.

In Figs. 1 and 2, examples of the production at one energy (2.0 MeV) as a function of dose are shown. The

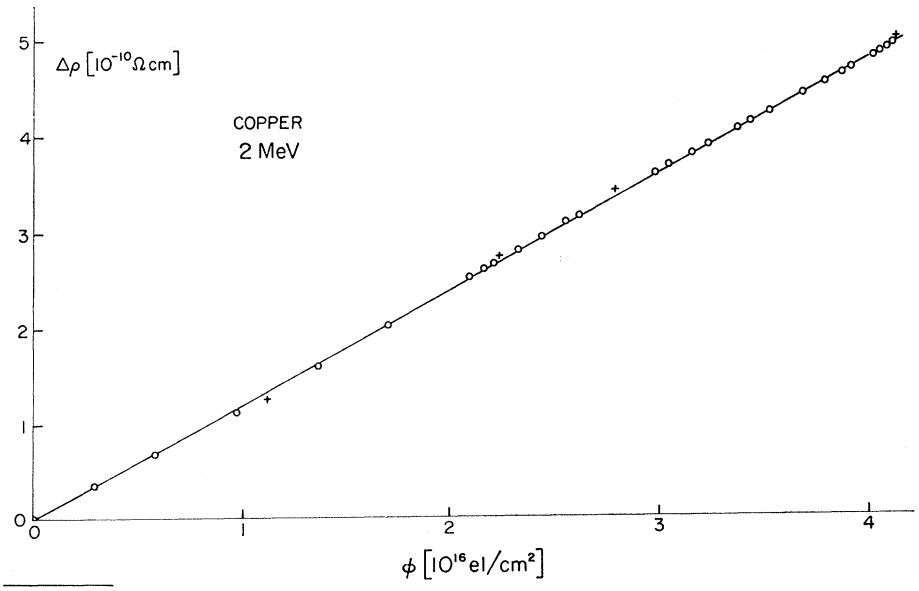

FIG. 1. Production of electrical resistivity in copper as a function of electron dose at 2.0 MeV. The circles are points measured during bombardments and the crosses were measured with the beam off.

* Supported in part by the U. S. Atomic Energy Commission.
[1] G. W. Iseler, H. I. Dawson, A. S. Mehner, and J. W. Kauffman, Phys. Letters **17**, 212 (1965).
[2] H. I. Dawson, G. W. Iseler, A. S. Mehner, and J. W. Kauffman, Phys. Letters **18**, 247 (1965).
[3] P. G. Lucasson and R. M. Walker, Phys. Rev. **127**, 485 (1962).
[4] A. S. Mehner, G. W. Iseler, H. I. Dawson, and J. W. Kauffman, Bull. Am. Phys. Soc. **10**, 690 (1965).
[5] W. Bauer and A. Sosin, Phys. Rev. **135**, 521 (1964); J. Appl. Phys. **35**, 703 (1964).

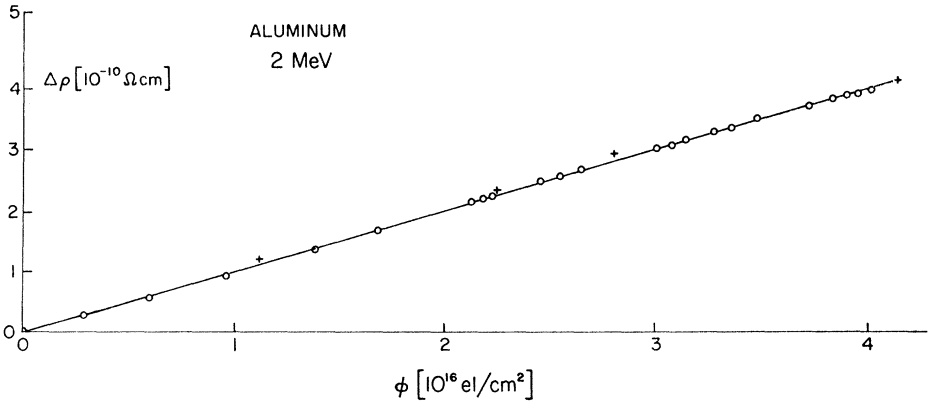

FIG. 2. Production of electrical resistivity in aluminum as a function of electron dose at 2.0 MeV. The circles are points measured during bombardment and the crosses were measured with the beam off.

circles are data taken while the beam was bombarding the specimens and the crosses are taken with the beam off. The fact that both types of data lie on the same line indicates that the specimen temperature during irradiation was below 6°K. Up to 3.5×10^{17} electrons per cm² (the highest dose used) no consistent deviations from linearity were found.

Production rates as a function of electron energy from 0.15 to 2.1 MeV are shown in Figs. 3 and 4. Here the circles and the triangles represent data for two different specimens with different collimator arrangements. The data have been corrected for energy degradation and angular deviation. The onset threshold energy for resistivity production was obtained by extrapolation to zero production rate. The value of the threshold energy obtained does not depend to any appreciable degree on the method of extrapolation as is evident from the data. The threshold energy for atom displacement is 19±3 eV for copper. This value is in agreement with results obtained by others.[3,5] Bauer and Sosin[5] observed nonzero production rates for subthreshold energies in copper. For run I we also observed nonzero rates below the 19-eV threshold energy for copper (see Fig. 3). These rates[6] were below 0.2×10^{-27} Ω cm/electron cm². In run II, however, which was performed with more care and with a more pure specimen, subthreshold production rates were unobservable. Production below the threshold energy of 19 eV may be due to transfer of energy to a copper atom via a lighter impurity atom, as suggested by Bauer and Sosin.[5]

The threshold for aluminum was found to be 16±2 eV in agreement with subsequent work by Neely.[7]

Theoretically,[8] the resistivity $\Delta\rho_F$ produced by an integrated electron flux Φ is

$$\Delta\rho=\Delta\rho_{FC}=100\Phi\Delta\rho_F\int_{T_t}^{T_m(E)}P(T)\frac{d\sigma}{dT}dT,$$

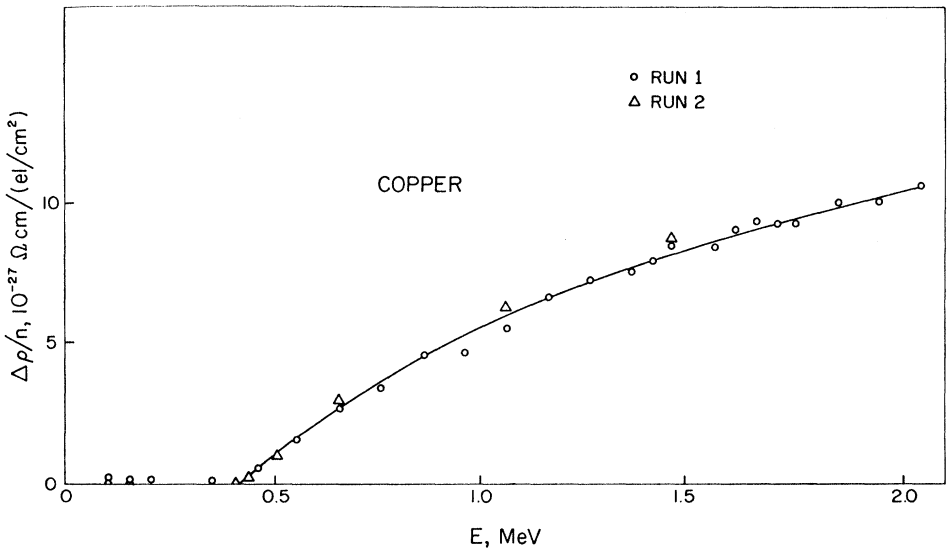

FIG. 3. Rates of electrical resistivity production in copper as a function of electron energy.

[6] These rates have been corrected for angular deviation of the electron beam in the specimen according to Yang's method which is outlined in Ref. 3.

[7] H. H. Neely, Bull. Am. Phys. Soc. **19**, 1179 (1965).

[8] F. Seitz and J. S. Koehler, in *Solid State Physics*, edited by F. Seitz and D. Turnbull (Academic Press Inc., New York, 1956), Vol. 2, p. 305.

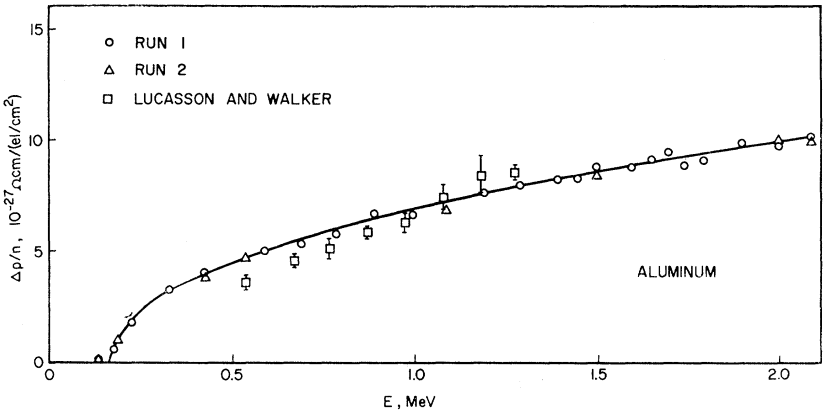

FIG. 4. Rates of electrical resistivity production in aluminum as a function of electron energy.

where c is the Frenkel pair concentration, and $\Delta\rho_F$ the resistivity of a 1% concentration of Frenkel pairs. $T_m(E)$ is the maximum energy that can be transferred to an atom by an electron with energy E. $P(T)$ and $d\sigma$ are the displacement probability function and the differential cross section for atom displacement. For aluminum and copper, one can use the McKinley-Feshbach approximation to the Mott formula for $d\sigma$.[8] The simplest choice that can be made for the displacement probability function $P(T)$ is a unit step at the threshold energy. The result of a calculation using this simple step is shown in Figs. 5 and 6. The calculated production rates have been adjusted to fit the data points at low energies, and in this case the measured production rates at higher energies are higher than indicated by the calculated curve. Therefore, the Kinchin-Pease (KP) model which takes secondary-defect production into account was used. The probability function in this case is

$$P(T)=1 \quad \text{for} \quad T_t \leq T \leq 3T_t,$$

and

$$P(T)=\tfrac{1}{2}(T/T_t-1) \quad \text{for} \quad T>3T_t.$$

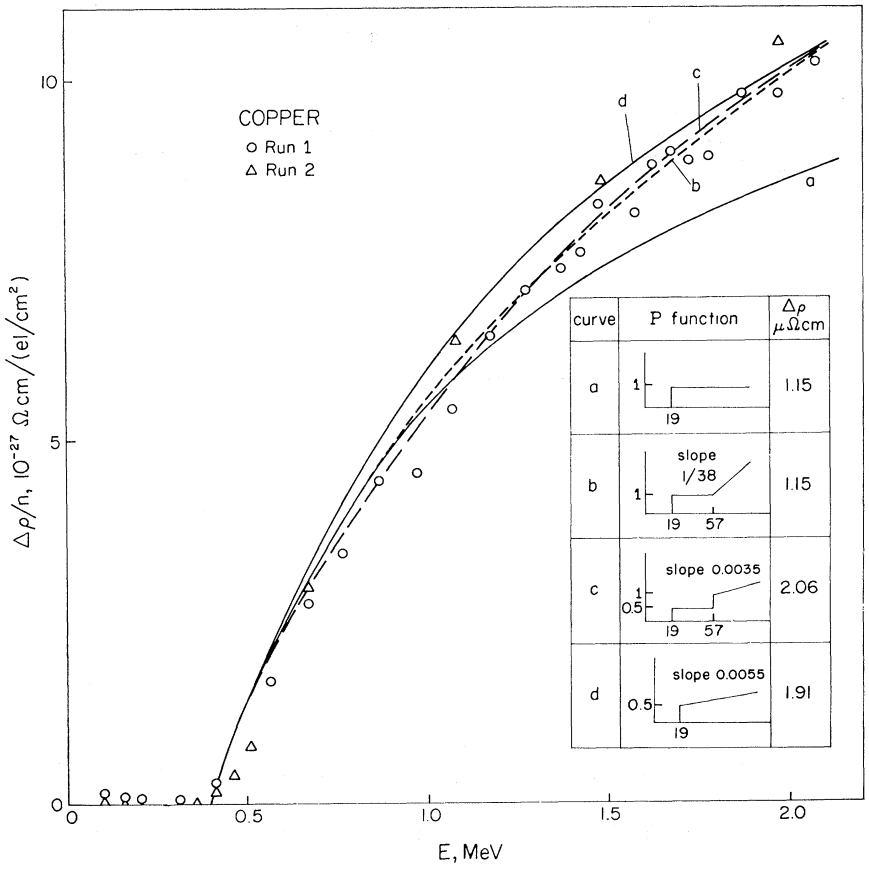

FIG. 5. Comparison of calculated production curves with experimental points for copper. Curve b corresponds to the Kinchin-Pease model.

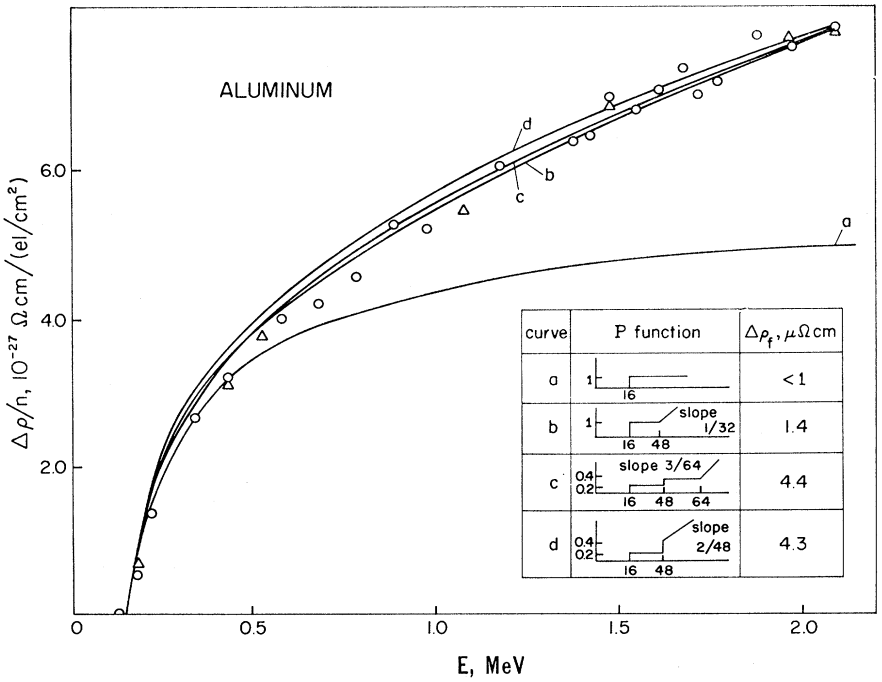

FIG. 6 Comparison of calculated production curves with experimental points for aluminum. Curve b corresponds to the Kinchin-Pease model.

The results of this calculation are given in Figs. 5 and 6 together with the corresponding values of $\Delta\rho_F$, which are small compared to values reported for the resistivity for 1 at.% of lattice vacancies.[9] It is seen that a good fit between the calculated curves and the experimental points is obtained. It is, however, difficult to estimate the significance of the fit because an equally good fit can be obtained by using other, somewhat arbitrarily chosen functions for $P(T)$. For illustrative purpose, this is also shown in Figs. 5 and 6 (curves c and d). For these curves, $\Delta\rho_F$ is higher than for the KP model. Of course, a higher $\Delta\rho_F$ can be obtained if the probability function in the KP model is scaled towards lower probabilities.

The conclusions are:

(1) The threshold energy for atom displacement is 19±3 eV for copper and 16±2 eV for aluminum.

(2) A single-step displacement probability function does not fit the production data for either copper or aluminum.

(3) The Kinchin-Pease model fits the data for both copper and aluminum. However, other somewhat arbitrarily chosen probability functions fit as well. $\Delta\rho_F$ values obtained from the KP model appear to be small as compared to other results for individual vacancies.

[9] See, for a general discussion, A. C. Damask and G. J. Dienes, *Point Defects in Metals* (Gordon and Breach Science Publishers, Inc., New York, 1963).