namely, $N = 2.4$, $\tau = 1.2 \times 10^{-15}$ sec, for which a Drude-type model was used also.

A more complete discussion of the results and a description of the methods used to treat the data, including procedures used to unfold the natural absorption profile, will be communicated elsewhere.

The authors wish to thank Dr. L. Marton, Chief, Electron Physics Section, for his encouragement; Dr. Howland Fowler and Mr. Nils Swanson for permission to use their unpublished data; and Mr. Benjamin Furst for providing the computational program for the unfolding procedure.

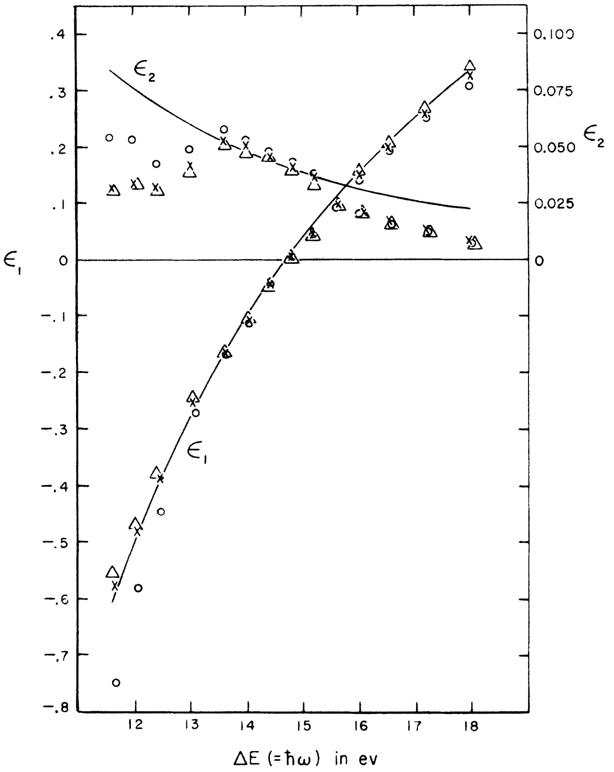

FIG. 1. The real part ϵ_1 and the imaginary part ϵ_2 of the complex dielectric constant for aluminum; ×, from the experimental electron energy loss absorption spectrum; o, from the experimental electron energy loss absorption spectrum plus the 5 % contribution at 7 eV; Δ, from the experimental electron energy loss absorption spectrum plus the 10 % contribution at 30 eV; ——, the Drude-type model $\epsilon_1 = 1 - \omega_p{}^2\tau^2/(1+\omega^2\tau^2)$, and $\epsilon_2 = (1/\omega\tau)[\omega_p{}^2\tau^2/(1+\omega^2\tau^2)]$, with $N = 2.6$ and $\tau = 1.1 \times 10^{-15}$ sec.

---

*This work was done during the tenure of a National Research Council-National Bureau of Standards Research Fellowship grant.

[1] L. Marton, L. B. Leder, and H. Mendlowitz, Advances in Electronics and Electron Physics, edited by L. Marton (Academic Press, Inc., New York, 1955), Vol. 7, p. 183.

[2] J. Hubbard, Proc. Phys. Soc. (London) A68, 441 (1955); H. Fröhlich and H. Pelzer, Proc. Phys. Soc. (London) A68, 525 (1955).

[3] H. Fowler and N. Swanson (unpublished).

[4] P. H. Berning, G. Hass, and R. P. Madden, J. Opt. Soc. Am. 50, 586 (1960).

[5] R. deL. Kronig, J. Opt. Soc. Am. 12, 547 (1926); Ned. Tijdschr. Natuurk. 9, 402 (1942); H. A. Kramers, Estratto Dagli Atti Del Congresso Inter. de Fisici Como (1927). A more recent review of the application of the Kronig-Kramers dispersion relation has been given by F. Stern, Suppl. J. Appl. Phys. 32, 2166 (1961).

[6] U. Fano, Phys. Rev. 103, 1202 (1956), Eq. 56.

[7] One of the authors (RL) would like to acknowledge helpful discussions with Dr. J. Becker.

[8] G. Hass and J. E. Waylonis, J. Opt. Soc. Am. 51, 719 (1961); H. Mendlowitz, Proc. Phys. Soc. (London) 75, 664 (1960).

FISSION-FRAGMENT TRACKS IN METAL AND OXIDE FILMS*

K. L. Merkle
Argonne National Laboratory, Argonne, Illinois

(Received June 25, 1962)

Transmission electron microscope studies on the interaction of energetic fission fragments with thin films have yielded some interesting results. The outstanding feature observed in fission-fragment-irradiated thin films[1-4] has been the appearance of tracks which are indicative of the removal of material from a region of the order of 100 Å around the path of the fission fragment. The tracks are thought to be the result of localized heating and vaporization, but it is not understood why the lattice reaches a high enough temperature to cause vaporization. The present study presents a model of track formation and experimental evidence based on observations on Au and Al.

Single crystalline and polycrystalline (100Å average grain size) Au films of approximately 50Å thickness and polycrystalline (100Å average grain size) Al films, 20 and 50Å thick, were irradiated with fission fragments from a U-foil.

After irradiation none of these films showed fission-fragment tracks.

Fast-moving fission fragments lose energy mainly by electronic excitations. If one considers the rate of energy transfer from these electrons to the lattice and the rate of diffusion of these electrons, it can be shown that the maximum temperature attained by the lattice along the path of the fission fragment is not high enough to cause vaporization.[5-7] This is in agreement with the experimental results reported here. If, however, the specimen consists of isolated particles rather than a continuous film, different results can be expected. A fission fragment passing through one of these particles will excite electrons along its path. As in the case of the continuous film, the cylindrical region of excitation will be approximately 10^{-7} cm in diameter and the electrons will be excited to a mean energy of the order of 20 eV[8] and will transfer energy very rapidly to neighboring electrons, the mean free path being of the order of 10^{-8} cm. However, the physical dimensions of the particle will restrict the diffusion distance of the electrons and in effect concentrate energy to the dimensions of the particle. The excited electrons can escape from the surface of the particle if their energy is greater than the work function ϕ. Electrons of lower energy have only a small probability of escaping to a neighboring particle by a tunneling process. Thus, the majority of the excited electrons whose energy is less than that of the work function will be trapped in the particle, raising the lattice temperature to a value determined by the number and mean excitation energy of the electrons and the size of the particle. If one assumes reasonable values for the work function and heat of vaporization, namely, 5 eV and 4 eV, respectively, it can be seen that one excited electron per atom with an average energy of 4 eV is sufficient to cause vaporization. Although the work function generally exceeds the heat of vaporization/atom, this is not a limiting factor because generally more than one electron can be excited. It should be noted that the escaping electrons will cause a potential difference between the particle and the surroundings and will therefore increase the potential barrier above the value of the work function. The electrostatic charges will also cause the material to be preferentially redeposited in the vicinity of the track.

Some modifications in the model are required if the voids between the particles are the metal oxides. If the layer is thick enough and if there is sufficient periodicity to permit the use of a band model, the determining factor for retaining electrons in the metal is not ϕ, but the energy difference between the Fermi surface in the metal and the bottom of the conduction band in the oxide. If there are only a few atomic layers of oxide, the isolated-particle model might be a better approximation, but the influence of the dipole moment of the oxide layer on the value of ϕ has to be considered.

Let us now consider electron excitations in insulators and semiconductors. In this case only transitions from the valence band to the conduction band are allowed, thus resulting in a higher mean energy of the excited electrons. The excited electrons will spread out much in the same way as in a metal, but initially there will be a large fraction of the valence electrons removed in a cylinder of ~10Å diameter around the path of the fragment. Thereby direct transfer of energy to the lattice atoms is possible, provided the time lag between electron excitation and electron capture is large enough ($\geq 10^{-13}$ sec). If we apply the isolated-particle model to non- or semiconductors we find that vaporization will be favored in materials where the energy gap δ between valence and conduction band is small and where $\phi-\delta$ is large.

Figures 1 and 2, consisting of isolated islands of Au on a carbon backing, clearly show the importance of particle size in track formation. The films were irradiated with 6×10^{10} fission fragments per cm^2 from a U foil. The larger particles in Fig. 1 are too big to be vaporized. Therefore only the smaller and medium-sized particles have been removed by passing fission fragments. In Fig. 2 even the largest particles are small enough to be vaporized when passed by a high-energy fission fragment. Therefore "tracks" are visible in Fig. 2. Not only the particles in the immediate path of the fragment have been vaporized but also adjacent particles, due to the action of secondary electrons.

Previous investigators have been puzzled by irregular and tapering track widths. In each instance of this, however, the particle diameters were smaller than the track widths. It would seem that the isolated-particle model suggested here is applicable in these cases and would explain the observed anomalies.

We would like to thank T. H. Blewitt, R. K. Hart, and D. Van Ostenburg for valuable discussions, and we are grateful to L. R. Singer

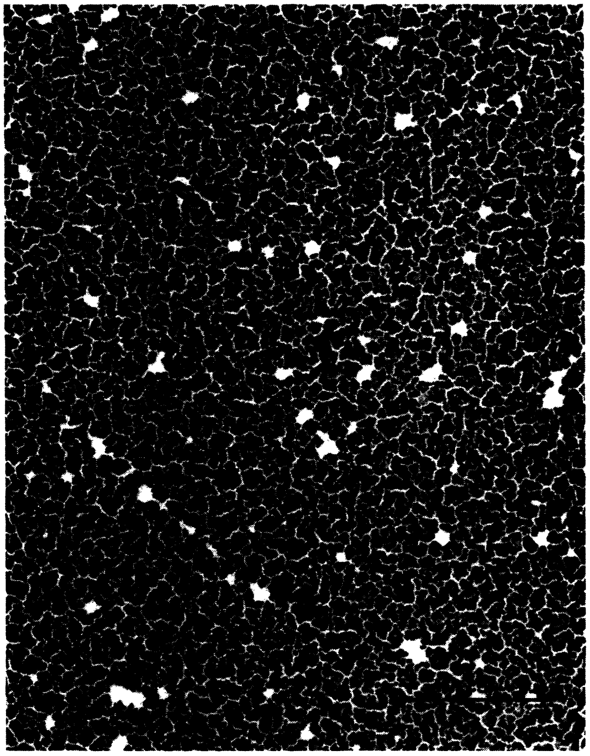

FIG. 1. Fission-fragment damage in film of noncoherent gold particles on carbon backing. Thickness of Au particles is approximately 35 Å. The white spots were occupied by gold particles prior to irradiation.

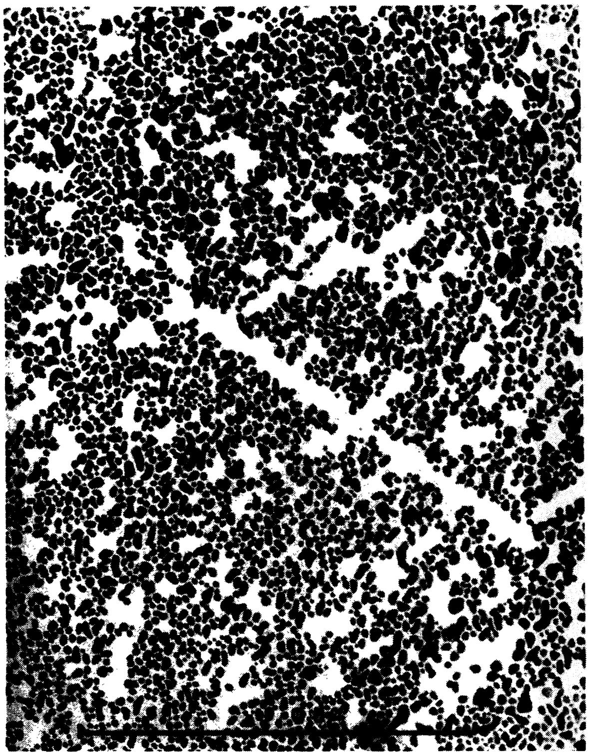

FIG. 2. Fission-fragment tracks in "film" of isolated particles of Au on carbon backing. Particle thickness approximately 20 Å.

for his assistance in performing the experiments.

---

*Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] T. S. Noggle and J. O. Stiegler, J. Appl. Phys. 31, 2199 (1960).

[2] T. K. Bierlein and B. Mastel, J. Appl. Phys. 31, 2314 (1960).

[3] J. J. Kelsch, O. F. Kammerer, A. N. Goland, and P. A. Buhl, J. Appl. Phys. 33, 1475 (1962).

[4] T. S. Noggle and J. O. Stiegler, J. Appl. Phys. 33, 1726 (1962).

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

[6] J. Ozeroff, U. S. Atomic Energy Commission Report AECD-2973, 1949 (unpublished).

[7] I. M. Lifshits, M. I. Kaganov, and L. V. Tanatarov, J. Nuclear Energy 12, Part A, 69 (1960).

[8] J. Ozeroff gives a value of 90 eV; however, this value is too high according to our calculations.

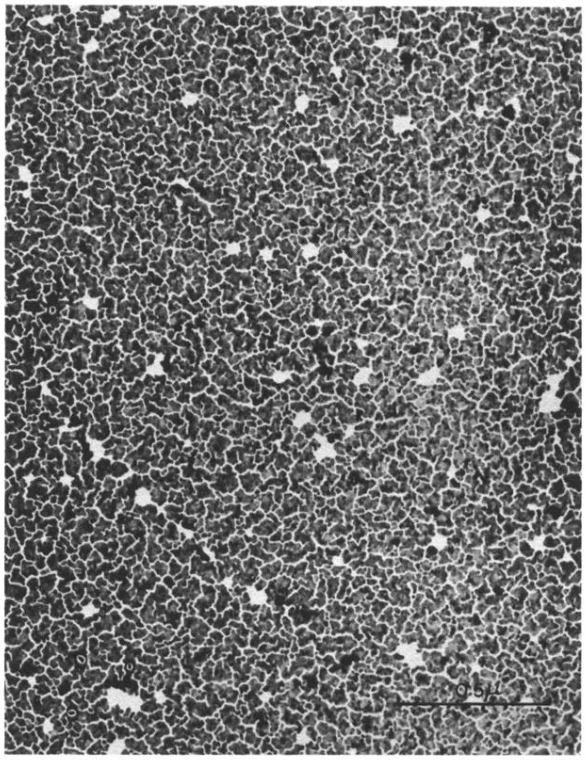

FIG. 1. Fission-fragment damage in film of noncoherent gold particles on carbon backing. Thickness of Au particles is approximately 35 Å. The white spots were occupied by gold particles prior to irradiation.

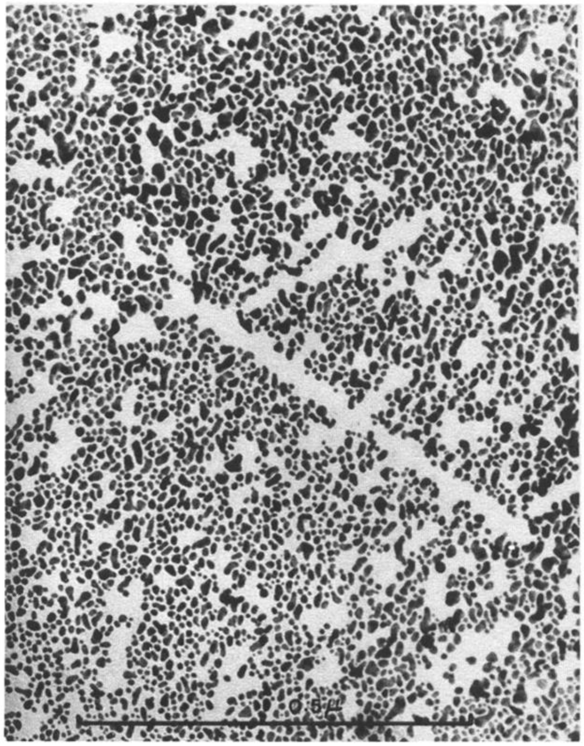

FIG. 2. Fission-fragment tracks in "film" of isolated particles of Au on carbon backing. Particle thickness approximately 20 Å.