Electron Mean Free Path near 2 keV in Aluminum†

H. KANTER
The Aerospace Corporation, El Segundo, California 90045
(Received 30 October 1969)

From beam-attenuation measurements on evaporated films 125–185 Å thick, mean free paths for elastic scattering (37 and 26 Å) and for plasmon production (88 and 70 Å) were determined at 2 and 1.5 keV, respectively.

RECENTLY, we reported measurements of electron beam attenuation by free-standing thin metal films at energies slightly above the work function value.[1] Since the electron scattering cross section at a few electron volts increases rapidly with energy, attenuation at larger energies became strong enough to prevent collection of unscattered beam electrons that had penetrated the films. With further increase in energy the electron scattering cross section passes through a maximum and approaches, at still higher energies, a near-E^{-1} dependence. By increasing the beam energy of our apparatus to 2 keV, we were able to observe unscattered "high-energy" electrons after penetration of aluminum films and could perform attenuation measurements of the type previously reported. The energy resolution was sufficient to determine the cross section for plasmon production. The data are reported here since cross-sectional measurements in this energy range are scarce; in fact, we extend experimental "high-energy" data for aluminum by about an order of magnitude to lower energies. We find the mean free path for plasmon production in reasonable agreement with Quinn's prediction[2] and obtain, after subtracting the plasmon contribution from the total collision mean free path, a lower limit for elastic scattering (on screened atoms) that is larger by nearly a factor of 2 than the prediction by Wentzel's scattering formula.[3]

The experimental method was identical to that for aluminum films described in Ref. 1. An electron beam produced by a simple diode gun was accelerated between apertures before entering the target region which was free of electrical fields. After traversing the aluminum films between 125 and 185 Å thick, the electrons were decelerated between an aperture and a flat soot-covered collector. An axial magnetic field (100 Oe) served to collimate the beam electrons in the low-energy regions. At beam energies between 1.4 and 2 keV, collector current versus retarding potential curves indicated the pressence of unscattered beam electrons. A typical plot for retarding potentials near cathode potential is shown by the inset of Fig. 1. A well-defined current step (or peak in the differential spectrum) I_0 is observed representing electrons which have passed through the film with no energy loss. A second step, I_1, at 15 eV below I_0, comprises electrons that have suffered a characteristic energy loss. The width of step I_1 is wider than that of I_0, but the height above background can be measured with reasonable accuracy.

The width of the primary step I_0 of nearly 2 eV, which was found independent of energy, results from the energy spread (~0.5 eV) of the beam, the angular spread of the beam electrons (flat collector), and momentum deflections at the oxide-covered film surfaces. We estimate from the step width a maximum angular spread of I_0 of about 2°. From the flat portion of the retarding curve adjacent to I_0, we conclude that no appreciable number of electrons are scattered into the immediate vicinity of the primary cone. (Using Lenz's formula for plural scattering, a most probable scattering angle of at least 20° is estimated.[4]) We may thus assume that I_0 consists essentially of primary electrons unscattered by the interior of the film. In support of this

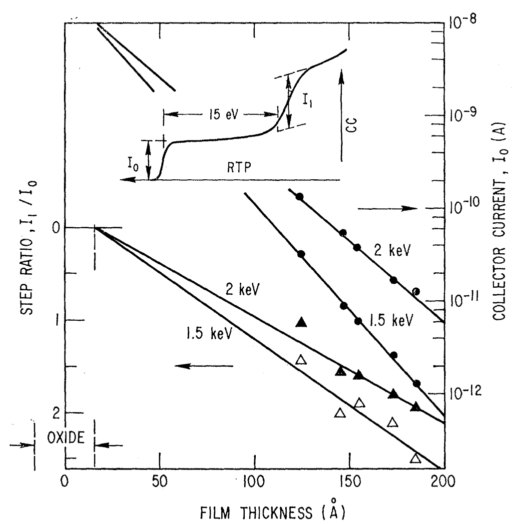

FIG. 1. Collector current I_0 (right) and step ratio I_1/I_0 (left) versus film thickness. The oxide does not contribute to the step ratio since its characteristic loss is a broad line near 23 eV. The inset shows a typical collector current (CC) versus retarding potential (RTP) plot. Only about 20 eV within full retarding potential (or beam energy) are displayed. I_0 and I_1 comprises electrons which have suffered no loss or a characteristic loss, respectively. I_1 was taken as the difference between the dashed extrapolations of the measured curve at an energy value midway between the points of maximum curvature.

† Work supported by the U. S. Air Force under Contract No. FO4701-69-C-0066.

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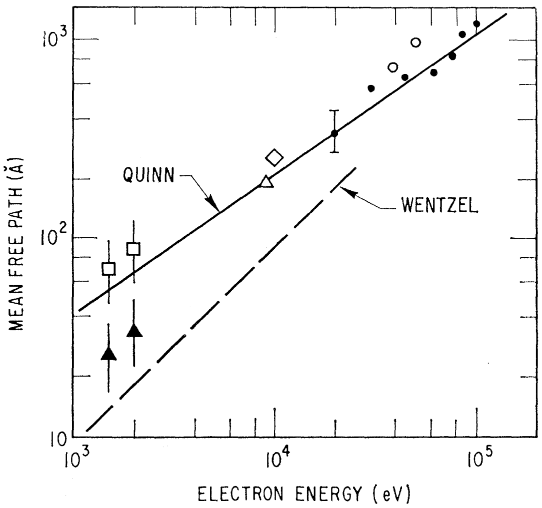

FIG. 2. Mean-free-path measurements for collective excitations in aluminum, together with Quinn's theoretical prediction (solid line). The dashed line indicates an extrapolation of the mean free path for elastic scattering using Wentzel's formula and experimental data at 20 keV by Cosslett and Thomas. The investigators (Ref. 6) are as follows: ● Blackstock *et al.*; ○ Kunz; △ Klemperer and Shepherd; barred close circle Swanson and Powell; ◇ Jull. Our data are marked open squares with slash for characteristic losses and closed triangle with slash for elastic scattering.

assumption is the fact that we observe an exponential collector current-thickness relation typical for a ballistic scattering process (Fig. 1). An exponential relation would otherwise only be obtained for electrons in the state of diffusion, which is unlikely to be reached after only five to ten collisions in a low-Z material. We find an attenuation length $L\sim 26$ Å at 2 keV and $L\sim 19$ Å at 1.5 keV, which we consider representative of the total scattering cross section for inelastic collisions and elastic collisions leading to deflections larger than 2°. Data for other energies between 1.4 and 2 keV are consistent and of similar scatter as in Fig. 1. The slopes of the lines could be determined with $\sim 7\%$ accuracy, to which the uncertainty in film thickness of 5% has to be added to arrive at the experimental accuracy of L.

The mean free path for plasmon production, λ_c, was determined from the variation of the step ratio I_1/I_0 with film thickness D: $I_1/I_0=\lambda_c^{-1}D$. Since the method has been used extensively and is described in the literature, we do not repeat it here.[5] Suffice it to say that the expected mean angular deflection for characteristic losses at 2 keV in aluminum is near 1°, with a cutoff angle near 3°. Our collector geometry permitted collection up to a maximum deflection of 7°. Therefore, collection of all electrons scattered by a characteristic loss from I_0 into I_1 was assured. (Total angular range of $I_1\sim 2°+3°$.) Deflections due to other processes should affect both I_0 and I_1 similarly. From the slope of the lines in I_1/I_0-versus-thickness plots (Fig. 1), we find $\lambda_c\sim 88$ Å at 2 keV and 70 Å at 1.5 keV, where allowance has been made for the oxide layers. The mean-square deviation of the data points was $\pm 20\%$, resulting in a total uncertainty of $\pm 25\%$.

Our data for λ_c are shown in Fig. 2, together with mean free paths found by other investigators. The solid line presents the mean free path for characteristic losses in aluminum according to Quinn's theory.[2] Our observed energy dependence agrees with that of Quinn's theory and the general trend of the experimental data. Deviation of the absolute value from the theoretical prediction is not larger than that of most previous investigators.[6] Our data may be considered in support of Quinn's theory.

Also shown in Fig. 2 is the mean free path λ_s for all scattering processes other than characteristic losses, obtained by subtracting the characteristic loss contribution from the attenuation length, with $\lambda_s^{-1}=L^{-1}-\lambda_c^{-1}$. We find $\lambda_s\sim 37$ Å at 2 keV and $\lambda_s\sim 26$ Å at 1.5 keV. Since little is known quantitatively about other inelastic contributions except that they do not appear to be negligible in this energy region,[7] we consider λ_s representative of a lower limit of the elastic scattering mean free path and compare it with the prediction by Wentzel's scattering formula. Wentzel's formula has been found by Cosslett and Thomas[3] to be reasonably accurate for electrons at 20 keV if the proper screening angle (or "atomic radius") is used. The dashed line in Fig. 2 is an extrapolation of their experimental result valid at 20 keV to lower energies. We find that the extrapolation underestimates the mean free path below 2 keV by a factor of nearly 2. The most likely reasons for the discrepancy are relatively stronger screening and failure of the Born approximation at the lower energies.

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