

Energy Dissipation and Secondary Electron Emission in Solids

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Experimental evidence is presented for the proportionality between secondary electron yield and the energy dissipated by electrons near the surface of a solid. Using measurements of the energy carried away by electrons transmitted and reflected from thin foils of aluminum and carbon, the energy dissipated in an incremental layer at the exit surface was obtained. Simultaneous measurements of the secondary electron yield showed a close proportionality between the number of secondaries produced and the energy dissipation density near the surface independent of the incident electron energy between 1 and 10 kev. By subtracting the contribution of the backscattered electrons to the yield at the front surface of a thick aluminum target, the yield of secondaries was found to be proportional to the rate of energy loss calculated from the Bohr-Bethe theory over the energy range investigated.

INTRODUCTION

IN recent theoretical studies of secondary electron emission under electron¹ and fast-ion bombardment,² the assumption is made that the number of secondaries produced within a volume element of the solid is proportional to the energy dissipated in that volume element by the incident particles. Direct experimental evidence for the proportionality between energy loss and ion or secondary electron production has heretofore been obtained only for gases.³ In this paper, the proportionality between secondary production and energy dissipation is confirmed experimentally for solids, using Al and C films and electron energies from 1 to 10 kev. It is shown that the secondary electron yield is directly related to the density of energy dissipation at the emitting surface and that the observed rate of energy loss for kev electrons agrees with Bethe's stopping theory.⁴

The escape depth of secondary electrons from metals is known to be of the order of tens of angstroms.^{1,5-7} In order to obtain the energy dissipation density of the primary electrons for thicknesses of this magnitude, the energy dissipation was measured as a function of film thickness in thin films of aluminum and carbon. By measuring the gradient of the curve showing energy dissipation vs film thickness, the energy dissipation density at the exit surface (back surface) was determined for certain film thicknesses. This was then compared with the secondary electron yield from the exit side of the films.

EXPERIMENTAL PROCEDURE

The energy dissipation for films of various thicknesses was determined from the difference between the total energy input and the fraction of the energy carried away by the transmitted and backscattered electrons. These quantities were determined from measurements of the average energy and the relative number of transmitted and backscattered electrons. The initial energy, E_p , was varied between 1 and 10 kev.

The fraction of transmitted or backscattered electrons and their energy distribution were measured using a spherical collector arrangement as shown in Figs. 1(a) and 1(b), respectively. In order to determine transmitted currents [Fig. 1(a)], the inner grid, tied electrically to the surrounding electrodes, served as a collector. With a collector potential of 45 v negative with respect to the target only scattered primaries were collected, the slow secondaries being returned to the target. The ratio of the collector current to the initial current gave the transmitted fraction of electrons. With a positive collector potential, both scattered primaries and secondary electrons were measured. The secondary electron yield, δ , was calculated from the difference of these two measurements.

In order to determine energy distributions, the inner grid was tied electrically to the target. Thus the region immediately in front of the target was kept field free.

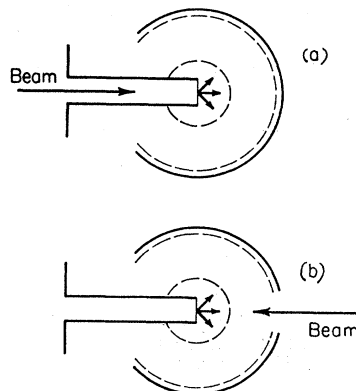


FIG. 1. Collector structures.

¹ See review articles by A. J. Dekker, in *Solid-State Physics*, edited by F. Seitz and D. Turnbull (Academic Press, New York, 1958), Vol. 6, p. 251. O. Hachenberg and W. Brauer, in *Advances in Electronics and Electron Physics*, edited by L. Marton (Academic Press, New York, 1959), Vol. 11, p. 413.

² E. J. Sternglass, *Phys. Rev.* **108**, 1 (1957).

³ See for instance: J. M. Valentine and S. C. Curran, *Reports on Progress in Physics* (The Physical Society, London, 1958), Vol. 21, p. 1.

⁴ H. A. Bethe, *Ann. Physik* **5**, 325 (1930).

⁵ H. Goldschmidt and H. Dember, *Z. Tech. Phys.* **7**, 137 (1926).

⁶ E. J. Sternglass and M. M. Wachtel, *Phys. Rev.* **99**, 646 (A) (1955).

⁷ I. M. Bronshtein and R. B. Segal, *Soviet Phys.—Solid State* **1**, 1365 (1960).

The retarding potential was applied between the inner and outer grid. Those electrons which were able to pass the retarding field were collected by the outer spherical electrode. This electrode had a potential of 45 v positive with respect to the outer grid, thus preventing secondary electrons formed on the collector wall from flowing back to the target. The average energy of the transmitted electrons was obtained from the integral energy spectrum, given by the collector current as a function of the retarding potential between the inner and outer grid. A more detailed description of the experimental technique may be found in a previous paper.⁸

Measurements on backscattered electrons were carried out by the same technique but with the beam direction reversed [Fig. 1(b)]. The solid angle subtended by the beam apertures was less than 0.16 steradian. Tests were carried out to ensure that the retarding potential inside the collector had no defocusing action on the primary beam.

Thin films of aluminum were prepared by evaporation onto nitro-cellulose support films, which were subsequently baked away in air at 200°C.⁹ The thickness was determined by interferometry on films deposited simultaneously on microscope slides.¹⁰ Using the density of bulk material, the film thickness was converted to mass per unit area. The thickness was corrected for the formation of an oxide layer during the bake-out procedure. Since the stopping power of Al_2O_3 is essentially the same as that for Al referred to in $\mu\text{g}/\text{cm}^2$, the data on energy dissipation, presented in the following, should not be appreciably affected by oxidation. The accuracy of the thickness determination is believed to be within $\pm 10\%$ or $\pm 2 \mu\text{g}/\text{cm}^2$, whichever is the greater.

Carbon films were evaporated onto microscope slides covered with a thin layer of KCl.¹¹ The films could thus be transferred to a water surface where the KCl was dissolved away, and picked up with a frame and mounted on the target holder. The thickness of each film was determined by extrapolating the transmission vs energy curve to zero transmission. The relation between the energy thus obtained and the film thickness is simply the range-energy relation. Since it has been shown that range-energy relations when plotted in mass per unit area do not vary appreciably with the atomic number,^{8,12} the thickness of the carbon films was determined using the range-energy relation for aluminum. For a more detailed description of the thin film techniques, see reference 8.

⁸ H. Kanter, Phys. Rev. **121**, 681 (1961).

⁹ M. Garbuny, T. P. Vogl, and J. R. Hansen, Westinghouse Research Laboratories, Report 71F189-R7-X (unpublished).

¹⁰ See for instance: G. D. Scott, T. A. McLaughlan, and R. S. Sernet, J. Appl. Phys. **21**, 843 (1950).

¹¹ D. E. Bradley, J. Appl. Phys. **27**, 1399 (1956); G. Dearnaley, Rev. Sci. Instr. **31**, 197 (1960).

¹² J. E. Holliday and E. J. Sternglass, J. Appl. Phys. **30**, 1428 (1959).

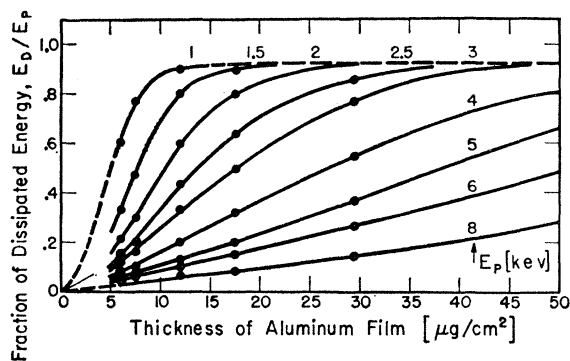


FIG. 2. Fraction of dissipated energy vs thickness of Al films for various initial energies. Data extend to 80 $\mu\text{g}/\text{cm}^2$.

RESULTS AND DISCUSSION

The fraction of the incident energy dissipated in the film as a function of film thickness was calculated using the detailed results on the transmitted electrons published earlier.⁸ Corrections due to the energy carried away by the backscattered electrons were applied in each case. For thick films, the backscattering coefficient, η_B , was found to approach 8% for carbon and 15% for aluminum, in good agreement with results by Palluel¹³ and Sternglass¹⁴ obtained for bulk material. The average energy of the backscattered electrons was always close to one-half the initial electron energy. As a result, the correction for the "backscattered energy" was always less than 5% of the input energy for carbon and less than 8% for aluminum.

The results for the case of aluminum are presented in Fig. 2, for the case of carbon in Fig. 3.¹⁵ Because the E_D/E_P values were obtained from the difference between energy input and the sum of transmitted and backscattered energy, the accuracy of the data varies with the absolute value of E_D/E_P . The transmitted and backscattered energies are derived from the product of

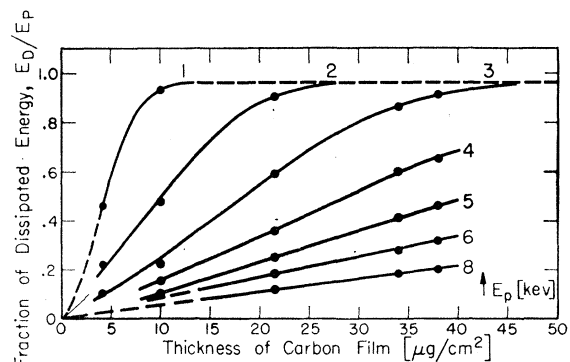


FIG. 3. Fraction of dissipated energy vs thickness of C for various initial energies.

¹³ P. Palluel, Compt. rend. **224**, 1492 (1947).

¹⁴ E. J. Sternglass, Phys. Rev. **95**, 345 (1954).

¹⁵ Similar results obtained on aluminum oxide films have been published by J. R. Young, J. Appl. Phys. **28**, 524 (1957).

intensity and mean energy, each of which is determined with an average accuracy of about $\pm 2\%$, and could therefore only be determined to within $\pm 4\%$. The percent error in E_D/E_p is therefore very large for small E_D/E_p values, but decreases for larger values.

No data could be obtained for film thicknesses less than $6 \mu\text{g}/\text{cm}^2$ for aluminum and less than $4 \mu\text{g}/\text{cm}^2$ for carbon. However, inspection of Figs. 2 and 3 shows that the curves for $E_p=8$ kev can be readily extrapolated to the origin. The curve for $E_p=1$ kev was then extrapolated to meet the origin with a slope determined from Bethe's theory in the following way. In the limit of very small film thicknesses the electrons will pass through the film in a nearly straight path. Thus the energy dissipation will be proportional to the average rate of energy loss along the path. The slope at the origin of the curve for $E_p=1$ kev was chosen to be larger than that of the curve with $E_p=8$ kev in proportion to the relative increase in the rate of energy loss as calculated with Bethe's stopping power formula. While this formula is strictly correct only for E_p large compared to the K -shell binding energy of the scattering material (1.6 kev for aluminum and 0.3 kev for carbon), it still provides a sufficiently good approximation for somewhat smaller energies. Since the stopping power of carbon is only slightly larger than that of aluminum referred to in $\mu\text{g}/\text{cm}^2$, the energy dissipation curves for these two materials do not differ greatly from each other.

In general, it is not possible to determine the energy dissipation density in a solid from the slopes of energy dissipation curves obtained from a series of thin films. This arises from the fact that such measurements do not take into account the contribution due to electrons backscattered from the deeper layers. This contribution can be considerable and will be largest for the layer near the entrance surface. Here, the average energy of the backscattered electrons is at its lowest value relative to the primaries, resulting in the highest rate of energy loss along the path. Direct experimental evidence as to the magnitude of this effect is presented in a separate paper.¹⁶

Under certain conditions, however, the actual energy dissipation density for the layer near the exit surface of thin films can be determined from the slope of the energy dissipation curves at any particular film thickness. This method applies in the case when the energy of the electrons backscattered from a thin layer a few tens of angstroms thick at the exit surface is negligible compared to the energy dissipated by the transmitted electrons in that layer. This consideration is met to a high degree of approximation for materials of low atomic number such as aluminum and carbon, provided that the initial energy is well in excess of two times the minimum energy for penetration of the film. For such

¹⁶ H. Kanter, following paper [Phys. Rev. 121, 681 (1961)]; see also reference 7.

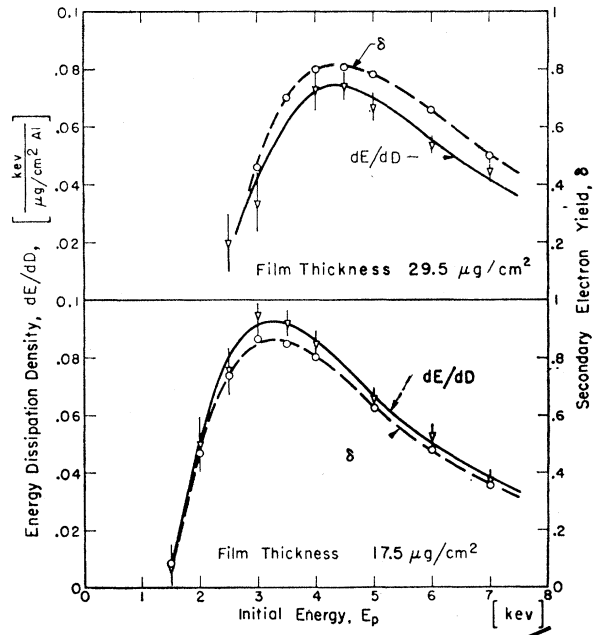


FIG. 4. Comparison of energy dissipation density and secondary electron yield at the exit surface of Al films.

energies, the backscattering coefficient of a thin film is well below that of the bulk material.¹⁷ Under this circumstance, the incremental increase in energy dissipated in the material upon a small increase in thickness occurs almost entirely within the added layer. At lower electron energies, however, the fraction of energy carried away from the layer by the backscattered electrons can become considerable, so that the energy dissipation density determined from the slopes of the curves in Fig. 2 and Fig. 3 tends to be larger than the actual value.

The variation of the energy dissipation density with initial energy near the exit surface, obtained from the slopes of the energy dissipation curves for aluminum films $17.5 \mu\text{g}/\text{cm}^2$ and $29.5 \mu\text{g}/\text{cm}^2$ thick is shown in Fig. 4. Equivalent results for a carbon film $21.5 \mu\text{g}/\text{cm}^2$ thick are shown in Fig. 5. The shape of these curves

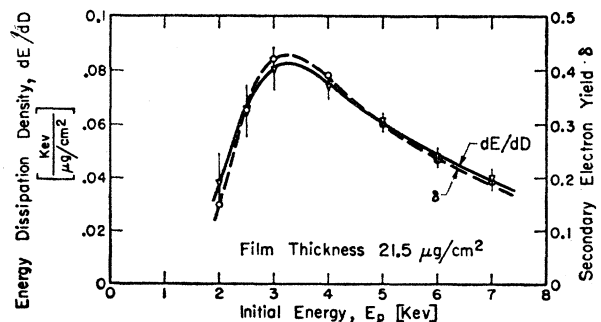


FIG. 5. Comparison of energy dissipation density and secondary electron yield at the exit surface of C films.

¹⁷ See, for instance, Fig. 2 in reference 16.

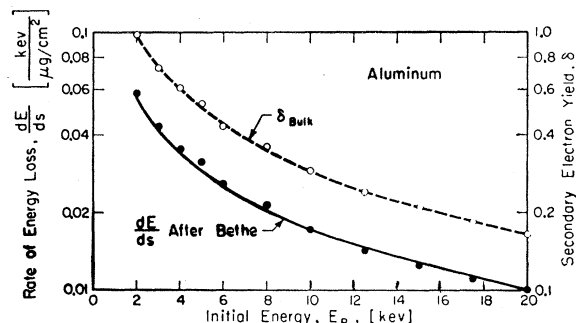


FIG. 6. Comparison of secondary electron yield on bulk Al with the rate of energy loss of the primaries as calculated with Bethe's stopping-power formula.

may be compared with that of the secondary electron yield observed at the exit surface of the films, also shown in Figs. 4 and 5. As can be seen, a direct relation exists between the energy dissipation density dE/dD near the surface and the secondary yield, δ , which is independent of initial energy for sufficiently high incident energies. For smaller energies, small deviations from proportionality are observed. In this case, however, the slope cannot be measured with the same accuracy as obtained at higher energies, where the energy dissipation curves are nearly straight lines. In the estimation of the errors, indicated in Figs. 4 and 5 for the dE/dD values, account was taken of the uncertainty of the slopes in Figs. 2 and 3 due to the fact that the data points are relatively far apart. The absolute value of the yield for the thicker Al film is somewhat larger with respect to dE/dD than that of the thinner film. The difference is believed to be caused by a slight difference in the surface conditions. Quantitatively, an average energy dissipation density required to obtain one escaping secondary electron of $\nu = 100 \text{ eV}/(\mu\text{g}/\text{cm}^2)$ was found for aluminum and of $\nu = 210 \text{ eV}/(\mu\text{g}/\text{cm}^2)$ for carbon.

It should be mentioned that although surface contaminating layers were undoubtedly present, the accuracy of the dE/dD determination is not appreciably affected for the following reason. The presence of a thin layer of contaminant shifts the energy dissipation curves to larger film thicknesses, but it does not change the slopes of the curves from which the dE/dD values are obtained. The absolute value of the yield observed in the experiments will, however, depend on the surface properties of the material. The influence of the surface conditions on yield is not well known even for clean surfaces, and the surfaces of the films used in these experiments cannot be considered clean. The films were handled in air, and particularly the aluminum surfaces were covered with an oxide layer due to the bake-out procedure during the film preparation. Because it is well known that the secondary electron yield of con-

taminated surfaces and oxides is generally higher than that of clean metal or carbon surfaces, the numerical values of ν stated above can only be considered as lower limits. As a result, it is impossible to obtain a reliable value for the energy \bar{E}_0 required to form a secondary electron in the bulk material from these measurements, even if the escape depth were known accurately. One can only say that the magnitude of ν is not inconsistent with the values assumed in recent theories.^{1,2}

The relation between the energy dissipation density and the secondary electron yield was further tested by measurements on bulk material. In Fig. 6, the yield for bulk aluminum is plotted as a function of E_p . A thin aluminum film was stretched across the surface of the target in order to provide the same surface conditions as in the previous experiments. As shown by measurements reported separately,¹⁶ the backscattered electrons from bulk aluminum produce about 40% of the observed number of secondaries for energies in the energy range under consideration here. Therefore, 60% of the secondary yield (solid circles in Fig. 6) results from the energy dissipation of the incident primaries.

Because the scattering of the primaries in the thin escape region of the secondary electrons is negligibly small, the energy dissipation density of the incident primaries equals their average rate of energy loss along the path. This rate, calculated by Bethe's stopping-power formula, is represented by the solid line in Fig. 6. The rate of energy loss was actually calculated for aluminum oxide, since the oxide layers formed on the surface during film preparation are comparable in thickness to the escape depth of the secondaries. However, practically the same result is obtained for aluminum when the thickness is measured in mass per unit area. The same ratio is obtained between energy dissipation density and secondary yield which was observed for the exit side of thin films. This can be considered as direct experimental evidence for the applicability of Bethe's stopping-power formula for aluminum down to energies in the order of the *K*-shell binding energy (1.6 keV). The latter conclusion is in agreement with that of Young, based on his range-energy measurements,¹⁸ and with the underlying assumption of recent theories of secondary emission under electron and ion bombardment.^{1,2}

The principal result emerging from these experiments is that for energies between 1 and 10 keV, direct proportionality exists between the energy dissipation density near the surface of secondary emitters and the observed secondary yield. Furthermore, it is found that the rate of energy loss agrees with that given by the Bohr-Bethe theory for free atoms down to at least 2 keV in aluminum. For gases, the proportionality between energy dissipation and secondary production had previously been established from a few kilovolts up

¹⁸ J. R. Young, Phys. Rev. **103**, 292 (1956).

to energies in the megavolt region.³ Since for higher energies the details of the outer electronic structure become increasingly less important, it is to be expected that this proportionality will also be preserved for solids at higher energies. Secondary electron emission may accordingly be used to measure the relative

energy-dissipation density at the surface of solids over a wide range of energies.

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Contribution of Backscattered Electrons to Secondary Electron Formation

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It is shown experimentally that backscattered electrons emitted from solids under electron bombardment contribute significantly to the observed secondary yield, even for the case of low backscattering coefficients. Thus, it was found that in Al with a backscattering coefficient of only 0.14, about 40% of all secondaries are produced by backscattered electrons for initial energies from several kev to several tens of kev. The large contribution of backscattered electrons to secondary formation even for materials of low atomic number agrees approximately with what one would expect from the larger rate of energy loss and the greater path lengths of the backscattered electrons in the secondary electron escape region compared to that of the incoming primaries.

INTRODUCTION

THE secondary electron emission properties of solids are strongly dependent on the scattering process of the primary electrons¹⁻³ for which any detailed theory does not as yet exist. The problem is somewhat simplified in the case where the penetration depth of the primaries is much larger than the escape depth of the secondary electrons. Under this condition, the primaries pass through the escape region along a nearly straight path. The backscattered electrons, diffusing back from the interior of the material, emerge through the escape region with reduced energy, following a cosine distribution.⁴ Therefore, the rate of energy loss and the path lengths of the backscattered electrons in the secondary escape region are larger compared to that of the incoming primaries. Thus, the total energy dissipation in the escape region due to backscattered electrons can be comparable to that of the primary electrons even when the backscattering coefficient is relatively small. Since the energy dissipation close to a surface is proportional to the observed secondary yield as confirmed experimentally and reported in the preceding paper, backscattered electrons can contribute considerably to secondary formation.

The large contribution to secondary yield of the backscattered electrons was first noticed by Stehberger.⁵ More recently, Dobretsov and Matskevich⁶ determined the fraction of slow secondaries formed by the incident primary while passing through the secondary escape region from existing data on the yield. Generally, data on secondary electron yield in the literature refer to the total number of electrons re-emitted by the material,^{2,3} including both fast backscattered electrons and slow secondaries, the latter being formed by incident as well as backscattered electrons. In order to find the yield of slow secondaries due to the incident primaries, δ_p , Dobretsov and Matskevich used the formula

$$\delta_p = (\delta_{\text{tot}} - \eta) / (1 + \beta\eta), \quad (1)$$

where δ_{tot} is the observed total yield including backscattered and slow secondary electrons, and η is the backscattering coefficient. β accounts for the increased efficiency of the backscattered electrons in forming secondaries.

The quantities, δ_{tot} and η , in Eq. (1) have been measured over a large range of energies for a large variety of materials. Very little, however, is known about β . While Dobretsov and Matskevich tried to determine the limits of β under specific assumptions with regard to the scattering process, Bronshtein and Segal⁷ very recently reported direct experimental

¹ E. J. Sternglass, Westinghouse Research Laboratories, Scientific Paper No. 1772, 1954 (unpublished).

² A. J. Dekker, in *Solid-State Physics*, edited by F. Seitz and D. Turnbull (Academic Press, New York, 1958), Vol. 6, p. 251.

³ O. Hachenberg and W. Brauer, in *Advances in Electronics and Electron Physics*, edited by L. Marton (Academic Press, New York, 1959), Vol. 11, p. 413.

⁴ H. Kanter, *Ann. Physik* **20**, 144 (1957).

⁵ K. H. Stehberger, *Ann. Physik* **86**, 825 (1928).

⁶ L. N. Dobretsov and T. L. Matskevich, *J. Tech. Phys. U.S.S.R.* **27**, 734 (1957) [translation: *Soviet Phys. (Tech. Phys.)* **2**, 663 (1957)].

⁷ I. M. Bronshtein and R. B. Segal, *Soviet Phys.-Solid State* **1**, 1365 (1960).