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 electrons[1-3] 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 Matskevich[6] 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

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

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 Segal[7] very recently reported direct experimental

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[2] A. J. Dekker, in *Solid-State Physics*, edited by F. Seitz and D. Turnbull (Academic Press, New York, 1958), Vol. 6, p. 251.
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[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)].
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results on β from the observed relation between secondary electron yield and backscattering coefficient in Be, Ag, and Bi. These authors made measurements on thin layers of various thicknesses, deposited on solid substrates. The backscattering and secondary emission characteristics of the substrates differed widely from those of the surface layers (Be on Pt, Ag or Bi on Be). By variation of the initial electron energy between 0.1 and 3.6 kev, the effective backscattering coefficient of the target could be changed and the corresponding change in yield was observed. Unfortunately, the condition that the primary penetration depth must be much larger than the escape depth of the secondaries is satisfied for only the largest energy values used by these authors. A systematic trend of β with energy, therefore, could not be established.

It was the purpose of the work described in the present paper to determine the value of β for aluminum for energies in the kev region. The result gives quantitative evidence as to the importance of backscattering in the secondary emission process of a low-Z material and can thus serve to guide the development of a detailed theory of secondary emission. Furthermore, the information is of interest for a stopping power experiment on Al described in the preceding paper.

EXPERIMENTAL PROCEDURE

The objective of the work was to measure the secondary electron yield from a front surface in the presence and absence of backscattered electrons. In order to reduce backscattering, the measurements were carried out on thin films. The observed backscattered fraction and secondary yield were compared with the backscattered fraction and secondary yield obtained on bulk material. The experimental technique used is illustrated schematically in Fig. 1. Because the secondary yield is influenced by the surface condition of the target, it was found necessary to prepare a single film which covers the whole target area, one-half of which is backed with bulk material. For the free and backed film areas, the backscattering coefficient and the yield of slow secondaries were measured. By varying the primary electron energy, the ratio of the effective backscattering coefficients for the free and backed film areas could be changed and a corresponding change in yield ratio could be observed.

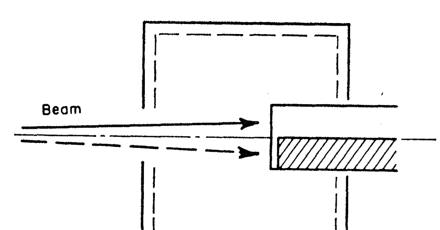

FIG. 1. Collector structure and film arrangement.

The target was bombarded with an electron beam of the order of 10^{-8} amp and about 1 mm in diameter. The beam spot could be positioned on the free or backed portion of the film. The total useful target diameter was 8 mm. The target was surrounded by a cylindrical collector provided with an aperture for the electron beam. A grid with wide open area and a potential negative with respect to the collector served to suppress secondaries emitted by the collector electrode. The collector surface was covered with soot to reduce electron emission further. Currents flowing back from the collector to the target when the latter was made positive were always smaller than 0.5% of the collector current. The angle subtended by the aperture was smaller than 0.12 steradian. No corrections for the escape of electrons through the aperture were made.

The total electron emission from the target including secondaries was measured with the collector tied electrically to the grid and held 20 v positive with respect to the target. The total yield, δ_{tot}, was obtained

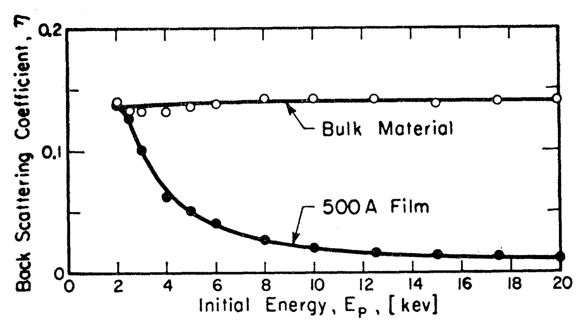

FIG. 2. Backscattering coefficient for Al film and bulk Al vs initial energy.

from the ratio of collector current to input current. The backscattering coefficient was measured with a grid potential of -100 v and a collector potential of -50 v with respect to the target, thus repelling all electrons with less than 50-ev energy. The yield of slow secondaries, δ, could be determined as the difference between these two quantities. Because δ_{tot} showed small fluctuations across the film area, the accuracy in the yield determination is limited to $\pm 4\%$.

Thin films of aluminum were prepared by rapid evaporation in vacuum onto nitro-cellulose films, which were subsequently baked away in air.[8] The film thickness was determined from the value of E_p at which the backscattering coefficient begins to fall below the value for bulk material. The practical range of the electrons for this energy is approximately twice the film thickness.[9] The thickness of the films determined in this manner was 500 A and 1900 A.

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[9] J. E. Holliday and E. J. Sternglass, J. Appl. Phys. 28, 1189 (1957).

RESULTS

The backscattering coefficient, η, of aluminum as a function of E_p for the free and the supported film 500 A thick is shown in Fig. 2. The backscattering coefficient, η_{bulk}, for the film backed by the bulk layer is seen to be 0.14 in reasonable agreement with published data for bulk material.[9,10] For the thin film, a rapid change of η is observed for E_p in excess of 2 kev. At 20 kev the backscattering coefficient of the thin film has decreased to about 1/20 of the backscattering coefficient of bulk material.

The secondary yield, δ, as a function of E_p is plotted in Fig. 3. The yield of the thin film is smaller than that of the bulk material by an amount which represents an increasing fraction of the total yield for bulk aluminum as the primary energy is raised. A plot of the observed yield ratio $\delta/\delta_{\text{bulk}}$ as a function of the ratio of the backscattering coefficient η/η_{bulk} is shown in Fig. 4. This plot makes it possible to determine the secondary yield for the limiting case of zero backscattering.

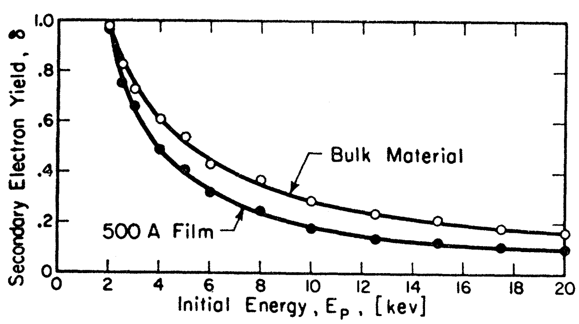

FIG. 3. Secondary electron yield for Al film and bulk Al vs initial energy.

It should be noted that the data points for the film 500 A thick in Fig. 4 were obtained at various primary energies, E_p. In order to check whether any appreciable effect of the primary energy exists, the measurements were repeated on a second film greater in thickness by nearly a factor of 4. For the heavier film a given value of η/η_{bulk} occurs at about 3 times the primary energy for the thinner film. It is seen that to within the accuracy of the present measurements, no observable influence of primary energy appears to exist over the range of energies investigated. A single straight line can be fitted to the data for the two aluminum films used, which can be extrapolated to a value of $\delta/\delta_{\text{bulk}} \sim 0.59$ for the limiting case of $\eta/\eta_{\text{bulk}}=0$.

One is therefore led to the conclusion that for the energy range from a few kev to several tens of kev, close to 40% of all secondaries from the front surface of a thick aluminum target was formed by the backscattered electrons. Since the number of backscattered electrons in this material represents only 14% of the incident electrons, it follows that the backscattered electrons are 4.9 times as effective in forming secondaries as the incoming primaries, i.e., $\beta=4.9$. This value for β is of the same order as the β values found by Bronshtein and Segal[7] for Be ($4.2<\beta<4.5$) and for Bi ($\beta\sim3.9$).

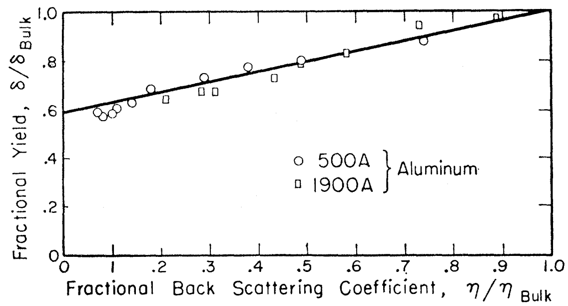

FIG. 4. Relation between fractional change in yield and fractional change in backscattering coefficient for Al.

DISCUSSION

The somewhat surprising result that the backscattered electrons contribute a relatively large fraction of the observed secondary electron yield even for a material of relatively low backscattering coefficient such as aluminum, can be explained in terms of the relative contribution of incident and backscattered electrons to the energy dissipation density near the surface.[11] The rate of energy dissipation for each of these groups can be estimated from the respective rates of energy loss along the path and the average path length in the secondary electron escape zone.

The penetration depth of the incident primaries with $E_p \geq 2$ kev in aluminum is larger than 700 A and thus much larger than the escape depth of the secondaries, which is only a few tens of angstroms. Thus, the energy and direction of the primaries remain practically constant throughout the secondary escape zone. The rate of energy dissipation of the primary within the escape zone is therefore equal to the initial rate of energy loss along the path and can be calculated using Bethe's stopping-power formula,[12]

$$dE/dX = FE^{-1}\ln(E/I), \qquad (2)$$

where F and I are factors depending only on the material. This formula has been found to apply quite accurately in solids down to electron velocities in the order of the orbital velocity of the K-shell electrons, (1.6 kev for aluminum).[13]

Backscattered electrons from bulk aluminum emerge with an average energy of about half the initial energy.[4,14] Since the logarithmic term in Eq. (2) varies only slowly with energy, the rate of energy loss of the

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backscattered electrons is roughly twice as large as that of the primaries. Furthermore, since the backscattered electrons escape with a cosine distribution in angle, the average path lengths of the backscattered electrons in the secondary escape zone can be shown to be twice the zone depth. Therefore, the ratio between the rate of energy dissipation of the backscattered and incident electrons near the surface is roughly 4. A more accurate estimate using the known energy distribution of backscattered electrons as a weight function leads to a ratio of 4.3 at $E_p=10$ kev. This is in reasonable agreement with the experimentally observed value of $\beta=4.9$.[15]

Thus, both theory and experiment indicate that even for materials of low atomic number, the backscattered electrons make an important contribution to secondary electron emission from solids. Therefore, as pointed out by Sternglass[1] and more recently by Dekker and Lye,[16] any theory of the secondary electron emission under electron bombardment must take into account the diffusion and backscattering of the incident electrons.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to Dr. E. J. Sternglass for helpful discussions and to Mr. R. Matta for preparing the thin films.

[15] It should be pointed out that if the average energy of the backscattered electrons were a constant fraction of the initial energy, the ratio between the rate of energy dissipation of the backscattered and incident electrons would increase somewhat with increasing initial energy due to the logarithmic term in Eq. (2). However, as shown in reference 4, the average energy of the backscattered electrons also increases continuously relative to the incident energy with increasing E_p. As a result, the ratio of the rate of energy dissipation for backscattered and incident electrons changes less rapidly than would be expected on the basis of Bethe's formula alone. Since the backscattering coefficient of aluminum does not vary with the incident energy, it follows that the ratio between the energy dissipation density or secondary electron production of incident and backscattered electrons is about constant with energy, in agreement with the results obtained for the two different aluminum films.

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Excess Tunnel Current in Silicon Esaki Junctions

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At low forward biases, a high current flows in Esaki junctions due to band-to-band tunnelling. At sufficiently high biases the current flows by normal forward injection. Between these two bias ranges, the current is unexpectedly high and has been called the excess current. A comprehensive experimental study has been made of this excess current in silicon junctions. It is shown that the properties of the excess current observed so far can be accounted for by a mechanism originally suggested by Yajima and Esaki, in which carriers tunnel by way of energy states within the forbidden gap. Based on this model, the following expression for the excess current, I_x, is proposed:

$$I_x \sim D_x \exp\{-(\alpha_x W_1 \epsilon^{\frac{1}{2}}/2)[\epsilon - eV_x + 0.6e(V_n+V_p)]\},$$

where D_x is the density of states in the forbidden gap at an energy related to the forward bias, V_x, and the Fermi energies on the n and p sides are V_n and V_p, respectively, e is the electron charge, ϵ is the energy gap, W_1 is the junction width constant, and α_x is a constant containing a reduced effective mass, m_x. This formula describes the observed dependence of I_x (i) on D_x, observed by introducing states associated with electron bombardment, (ii) on ϵ, studied by the temperature variation of the diode characteristics, (iii) on V_x, verified from semilogarithmic plots of the forward characteristics, and (iv) on W_1, tested by using junctions of different widths. From these experiments, $m_x=0.3m_0$ to within a factor of 2.

The origins of the states in the band gap are not known for certain though they are most likely the band edge tails inherent to heavily doped semiconductors. It is probable that the tunnelling-via-local-states model for the excess current in silicon is applicable to excess currents in other materials.

INTRODUCTION

THE occurrence of so-called excess current in Esaki junctions[1] is now well known.[2] It occurs at forward biases in the range where the electrons in the degenerate donor levels in the n side have been raised to energies greater than those of the degenerate acceptor levels on the p side. Ideally, tunnelling of electrons from the conduction band to the valence band in a single energy-conserving transition should then be impossible and only the normal diode current due to the forward injection of minority carriers should flow. In practice, as Yajima and Esaki first noted,[2] the actual current at such biases is considerably in excess of the normal diode current; hence the term, excess current.

It was apparent that the excess current is primarily a tunnelling process since its behavior generally parallels that of the peak current; the peak and excess currents exhibit much the same dependence on pressure,[3] on temperature,[4] and on the donor and acceptor concentra-

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