PHYSICAL REVIEW VOLUME 93, NUMBER 5 MARCH 1, 1954

The Mechanism of Secondary Electron Emission

A. O. BARUT
Swiss Federal Institute of Technology, Zurich, Switzerland, and University of Chicago, Chicago, Illinois

(Received July 24, 1953; revised manuscript received Novermber 9, 1953)

It is shown that a simple theory based on the constant energy loss per unit path length of primary electrons accounts quantitatively for the variation of secondary electron emission yield below its maximum value. The theory can be extended formally to include a Bethe-type energy loss at high primary energies. An attempt was made to clarify the present situation concerning the relationship between the secondary electron emission and the atomic structure of the elements, and some new relations are indicated. The mechanism of the secondary emission of insulators and semiconductors is also discussed.

1. INTRODUCTION

THE secondary electron emission of solids when bombarded by electrons (of moderate energies) is a complex phenomenon involving several single events: (1) the slowing down of primary electrons (PE) in the solid, (2) the production of excited "internal secondary electrons (SE)" through the interaction of PE with the lattice electrons, (3) absorption of internal SE within the solid or the possible production of tertiary electrons by energetic SE, (4) the escape of internal SE from the surface of the solid, and (5) the reflection and backscattering of PE.

There exist in the literature various assumptions and calculations for these single processes,[1–9] but a satisfactory quantitative agreement with the experiments on secondary emission has not yet been reached.

The interaction of PE with the electrons of the solid, which is the fundamental process, depends strongly upon the energy E_p of PE. For small energies it is clear that only an interaction with the outermost electrons of the atoms of the solid or with the free electrons of a metal is possible. If, however, the primary energy is greater than the ionization potential of the electrons of the K shell, then the atom as a whole takes part in the interaction process and absorbs energy. Furthermore there are for these higher energies other types of radiations from the solid under electron bombardment and therefore the proportionality between energy loss of PE and the production of SE will depend on E_p. This is the reason why we have made a distinction between the processes (1) and (2).

2. THE SECONDARY EMISSION YIELD BELOW ITS MAXIMUM VALUE

The Coulomb interaction of a fast primary electron with the electrons in the periodic field of the lattice has been calculated by several authors.[10,3–5,7,8] For free electrons the energy loss per unit path length of PE is inversely proportional to the energy of PE;[4] for bound electrons the result is given by Bethe's well-known ionization formula[10] for fast electrons. The Wooldridge approximation of the interaction with weakly bound lattice electrons[3] which gave an energy loss independent of E_p has been shown by Marshall[9] to be incorrect for sufficiently high energies. Marshall showed that a correct treatment yields Bethe's formula for sufficiently high primary energies. There seems to be at present no other information concerning the energy loss and the production of internal SE by low-energy primaries, which is of prime interest here.

It has been found that a constant energy loss can explain quantitatively, for all elements, the variation of secondary emission yield up to its maximum value. A constant energy loss in the form

$$-dE/dx=A \tag{1}$$

gives, for the penetration depth of PE,

$$X=E_p/A. \tag{2}$$

Such a linear increase of the penetration depth for slow PE has been observed experimentally by Copeland.[11] It will be assumed that the production of SE per unit path length is proportional to Eq. (1) (i.e., that it is also constant and equal to KA) and that the absorption of SE in the solid is according to an exponential law. If p denotes the probability that an internal SE will escape the surface of the solid (p is nearly independent of x, where x is the coordinate in the direction of the primary beam normal to the surface), then the true secondary emission yield can be expressed as

$$\Delta=\int_0^X KAe^{-\alpha x}dx=\frac{KAp}{\alpha}[1-\exp(-\alpha E_p/A)]. \tag{3}$$

This is the same as the result obtained by Baroody in a paper correcting Wooldridge's result.[5] The observed secondary electron emission yield can then be written

$$\delta=\Delta(E_p)+\eta, \tag{4}$$

---

[1] H. Bruining, *Sekundarelektronenemission fester Körper* (J. Springer, Berlin, 1942) p. 60 ff.
[2] J. L. H. Jonker, Philips Research Repts. **7**, 1 (1952).
[3] D. E. Wooldridge, Phys. Rev. **56**, 562 (1939); **58**, 316 (1940).
[4] E. M. Baroody, Phys. Rev. **78**, 780 (1950).
[5] E. M. Baroody, Phys. Rev. **83**, 857 (1951), **86**, 915 (1952).
[6] O. Hachenberg, Ann. Physik **2**, 404 (1948).
[7] H. Schlechtweg, Naturwiss. **31**, 204 (1943).
[8] A. J. Dekker and A. van der Ziel, Phys. Rev. **86**, 775 (1952).
[9] J. F. Marshall, Phys. Rev. **88**, 416 (1952).
[10] H. Bethe, Ann. Physik **5**, 325 (1930).
[11] P. L. Copeland, Phys. Rev. **58**, 604 (1940).

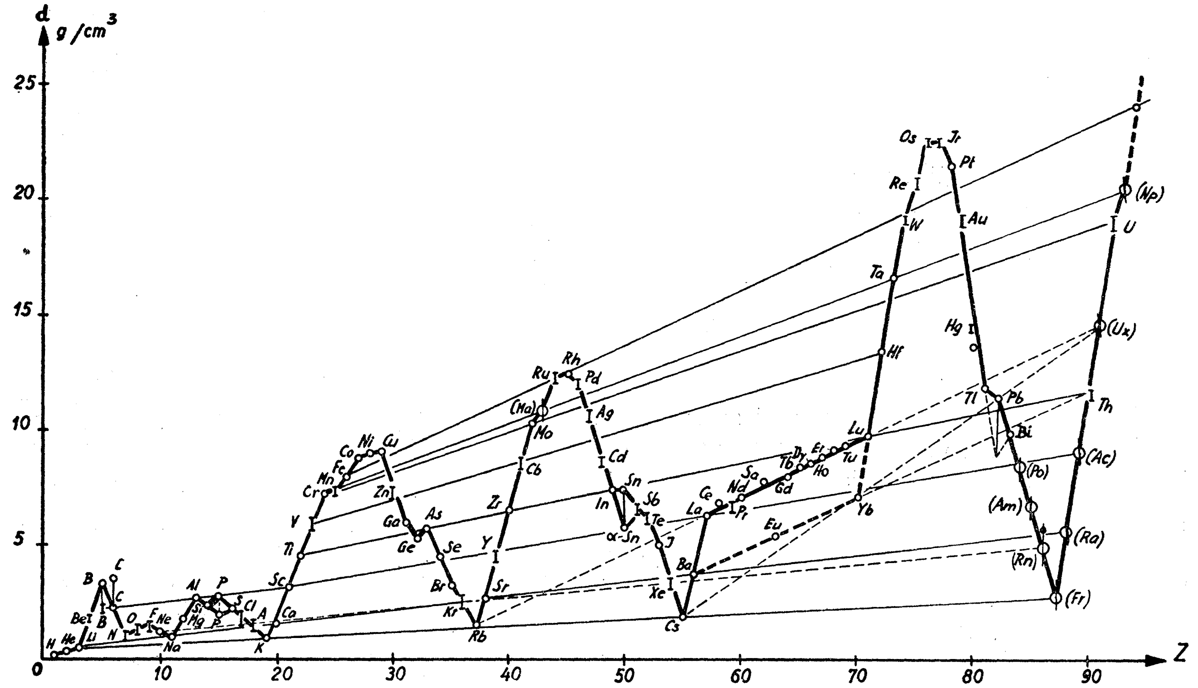

FIG. 1. Plot of the density *d versus* the atomic number *Z*.

where η is the proportion of reflected and backscattered PE and is only very slowly dependent on E_p for the range considered.

Experimentally it has been found that one obtains a universal secondary emission yield curve by plotting the yield relative to its maximum value, namely δ/δ_m *vs* E_p/E_m.[4] Identifying Δ_m with $\Delta_\infty=KAp/\alpha$, one gets

$$\delta/\delta_m\approx\Delta/\Delta_\infty=1-\exp[(-\alpha E_m/A)E_p/E_m]; \qquad (5)$$

this expression is exactly the experimental universal curve if one puts

$$E_m=5A/\alpha. \qquad (6)$$

Then

$$\Delta_m=\Delta_\infty=KpE_m/5=KpA/\alpha. \qquad (7)$$

The right-hand side of Eq. (5) has only two constants, the absorption coefficient α and the "energy loss constant" A. In the constant K, on the other hand, the possible production of tertiary electrons is included; if all internal SE have the same initial energy E_0, then $K\cong 1/E_0$.

Geyer[12] had found empirically that the logarithm of the derivative of the yield curve below its maximum, considered as a function of the primary energy, gives a straight line for all elements and has tried to give physical meanings to the slope and the intersection of this line with the ordinate. From Eq. (3) it follows that

$$\log(\partial\Delta/\partial E_p)=\log K_p-\frac{\alpha}{A}E_p=\log\frac{5\Delta_m}{E_m}-\frac{5}{E_m}E_p, \qquad (8)$$

or, from Eq. (5),

$$\log[\partial(\Delta/\Delta_m)/\partial(E_p/E_m)]=\log 5-5E_p/E_m. \qquad (8')$$

Geyer's empirical relations find here their natural analytical form. We shall turn now to a discussion of the absolute value of the yield and of the constants.

3. SECONDARY ELECTRON EMISSION AND PERIODIC SYSTEM OF ELEMENTS

According to Eq. (7) the ratio of Δ_m to E_m does not depend on the ratio A/α. It will be shown, by examination of the changes of Δ_m and E_m in practical measurements that the separation of Δ_m into two factors (Kp) and (A/α) is of real interest. An examination of the experimental values shows that, in general, to large values of δ_m (or Δ_m) there correspond large values of E_m (this is seen by simply plotting δ_m *vs* E_m); this shows that (Kp) varies slowly, as one should expect. Kp (essentially equal to Δ_m/E_m) is almost the same in each period of the atomic table and decreases linearly with the quantum number of the outermost electron shell, n.

It is seen furthermore from Eq. (6) that E_m has a simpler physical meaning than δ_m; it is, apart from the factor 5 which arose from the mathematical approximation, the ratio of the two constants A and α [also the slope of Eq. (8)]. Unfortunately the experimental values of E_m have been determined up to now only very roughly. It is believed that an exact determination of E_m might give important new information. However, even with the known less reliable values of E_m one obtains a well-defined periodic curve if one plots E_m

---

[12] K. H. Geyer, Ann. Physik 42, 337 (1942–43).

vs atomic number Z. It must be pointed out that there are many ways of correlating the secondary electron emission with the atomic structure; in fact, attempts have been made to compare δ_m or some related quantity of the δ curve with the atomic number Z,[13,14] or with other properties of solids such as work function[4,15] or density.[15] Many investigations, especially those on complex targets,[16] indicate that the depth to which primary electrons penetrate is the most important factor for the secondary emission; in fact a close relation has been found to exist between density on one hand and the secondary emission constants on the other. Figure 1 shows the density of the elements as a function the atomic number Z. The previously mentioned $E_m=f(Z)$ curve (not given here) has a very similar shape to this curve.

If one further plots either δ_m or Δ_m against the density d, a striking proportionality is found for the elements in the first half of each period (Fig. 2). Comparing Figs. (1) and (2), it follows that in each period where the density increases linearly with Z, Δ_m (or δ_m) increases linearly with density and therefore also linearly with Z. No simple correlation is found for the other elements from the existing data. This fact explains partly the correlation reported by Sternglass,[13] where Δ_m increases linearly with Z in each half-period. However, it must be remarked that there is no reason to assume that Δ_m also increases linearly with Z for the elements of the second half of each period (where d decreases with Z), namely elements $Z=30$–36, 48–54, and 79–86, as Sternglass implicitly did. Moreover, the values of Δ_m for Au, Sb,[17] and the recent values for Pb, Hg, Ga, and Bi[18] would not agree with his representation.

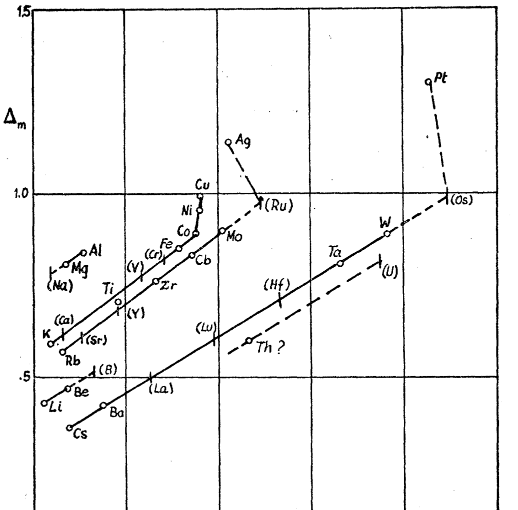

FIG. 2. Plot of the maximum true secondary-emission yield Δ_m *vs* the density d. The circles represent experimental points; the vertical bars give predicted values.

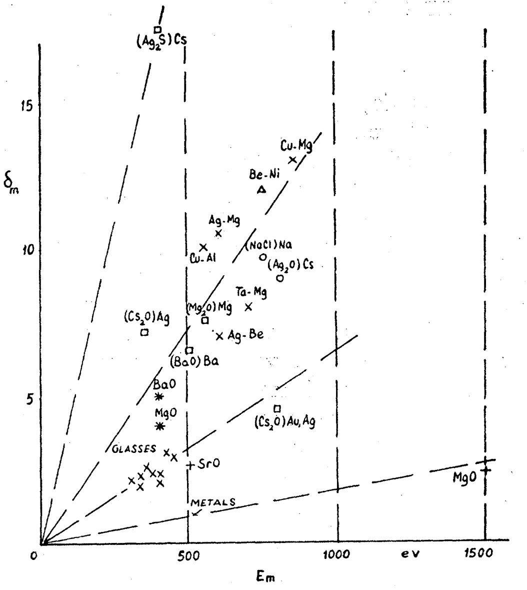

FIG. 3. The secondary emission yield δ_m of different materials as a function of E_m, the primary energy at which δ_m occurs. × H. Salow, Z. tech. Phys. **21**, 8 (1950); ○ G. Maurer, Z. Physik **118**, 122 (1941); △ Gille, Mathes, Z. tech. Phys. **22**, 228, 232 (1941); □ Timofeew, Physik. Ber. **23**, 1070, 1071 (1942); + K. H. Geyer, Ann. Physik **42**, 241 (1942); ✱ H. Bruining and J. H. de Boer, Physica **5**, 17 (1938).

Similar curves to those in Fig. 2 are obtained in each period, if Δ_m is plotted against the work function φ instead of d (though these have larger deviations from straight lines). This is because φ is also related to the density of the elements.[19] However, a universal relationship between δ_m and $\varphi^{4,15}$ does not seem to exist.

If the constants introduced here turn out to be useful, the best way of expressing the above relationships would be in terms of these constants like one considers the variation of the work function or the ionization potential with the atomic number Z. There are two ways of determining the constants (A/α) and (Kp): one from the maximum values Δ_m and E_m according to Eqs. (6) and (7), and the other from the δ curve $\delta=f(E_p)$ according to Eq. (8). If further the penetration depth can be determined, then A and α can be separated. If the factor p can be calculated approximately (Sec. 4) then the constant K can be evaluated. It must be remarked that other factors like the surface conditions or deviations from ideal crystal structure have not been treated explicitly here; their effect is included in the other constants.

---

[13] E. J. Sternglass, Phys. Rev. **80**, 925 (1950).

[14] P. L. Copeland, Phys. Rev. **46**, 167 (1934).

[15] K. G. McKay, *Advances in Electronics* (Academic Press, Inc., New York, 1948), Vol. 1, p. 69.

[16] P. L. Copeland, Phys. Rev. **48**, 96 (1935); R. Truell, Phys. Rev. **62**, 340 (1942).

[17] P. Görlich, Physik. Z. **43**, 121 (1942).

[18] J. J. Brophy, Phys. Rev. **83**, 534 (1951).

[19] F. Rother and H. Bomke, Z. Physik **86**, 231 (1933).

4. THE SECONDARY ELECTRON EMISSION OF NONMETALS

The considerations of Sec. 2 hold also for insulators and compounds; in particular, the same universal curve (5) is found for all materials.

With the help of Eq. (7) one can derive some information regarding the origin of high secondary emission of certain materials. For this purpose the known values of δ_m are simply plotted as a function of E_m (Fig. 3). The lines from the origin correspond to $Kp=$ const. and the parallels to the ordinate to $A/\alpha=$ const. [Eqs. (6, 7)]. There follows the interesting result that in general all materials have A/α values of the same order of magnitude as that of metals, whereas Kp of some compounds may be as much as 15 times larger.

If the average energy of a secondary electron below the surface is $\bar{\epsilon}$, then for metals p can be calculated from the number of SE which have a normal component of energy greater than the work function φ of the surface. This gives

$$p=\tfrac{1}{2}\{1-[(\varphi+\xi)(\bar{\epsilon}+\xi)]^{\frac{1}{2}}\}, \tag{9}$$

where ξ is the Fermi-energy; p does not depend strongly on ϵ, so that the average over the distribution function of ϵ can be replaced by $\bar{\epsilon}$.

In the case of insulators and semiconductors, electrons which have been excited to the conduction band can only escape the surface if the conduction band lies higher than the vacuum level. In this case, if W denotes the breadth of the conduction band and χ the energy difference between the lower end of conduction band and the vacuum level, then p is essentially given by the following expression:

$$(1-\chi/W). \tag{10}$$

This factor is responsible for the high Kp values found experimentally. One can see now why the intrinsic semiconductors B, Ge, Si or the defect semiconductors (e.g., SnO_2, Cu_2O, Ag_2O, MoO_2, $\cdots$) with χ of the order of 4 ev are poor secondary emitters in comparison with, for example, alkali halides with $\chi\approx 0-1$ ev. This consideration strongly supports the qualitative view of Bruining and deBoer[20] concerning the mechanism of the secondary emission of compounds rather than the other view that the high secondary emission is due to the absence of absorption of internal SE due to the conduction electrons.[21] Furthermore it follows that for excess semiconductors (e.g., activated semiconducting layers) the enhanced secondary emission is not due to the emission of active centers itself but due to the decrease of χ by these centers.

5. HIGH PRIMARY ENERGIES

For high primary energies, Eq. (1) does not hold and one should have [8–10]

$$-dE/dx=(B/E)\log(E/E_i), \tag{11}$$

where B and E_i are characteristics of the medium. The variation of the logarithmic term is very slow and one gets a penetration depth which tends to a quadratic curve with increasing E_p in accordance with experiment.[11] Also the initial energies of the internal SE are different than in low-energy region.

Formally, taking a combination of (1) and (11) and writing the total number of SE in the form

$$dn/dx=kA/(1+D^2E_p^2)^{\frac{1}{2}}, \tag{12}$$

one obtains exactly the entire experimental curve by adjusting only the constant D. However, because of its empirical character, this calculation is not given here. For $E_p>E_m$ the result has the simple form

$$\frac{\delta}{\delta_m}\cong\frac{4}{(15+E_p/E_m)^{\frac{1}{2}}}. \tag{13}$$

6. CONCLUSION

Since the secondary electron emission process consists of a finite number of elementary collision acts (a very small number for low energies), the quantitative agreement obtained by using classical methods such as an exponential absorption law and the energy loss equation is the maximum that can be expected. In this sense the only question not settled seems to be the derivation of Eq. (1) and the physical meaning of the constant A.

---

[20] H. Bruining and J. de Boer, Physica 6, 834 (1939).

[21] H. Salow, Ann. Physik. 5, 417 (1950).