THE BACKSCATTERING OF $10 \div 120$ keV ELECTRONS FOR VARIOUS ANGLES OF INCIDENCE

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The object of this investigation is to define the backscattering coefficient as a function of the angle of electron incidence for various materials together with a theoretical model of backscattering at various angles of incidence and to experimentally test this model.

1. Introduction

The backscattering of an electron beam is one of the processes connected with electron penetration in solid materials. The backscattering coefficient is the probability that an electron incident on a semiinfinite specimen will leave it again. It is a function of electron incidence (α), the specimen atomic number (Z) and the electron beam energy (E_0). There are many experimental [5–8, 14, 15] and theoretical works [1, 2, 9–11, 13] about backscattering for normal incidence, but only few of them for various angles of incidence. And there is no theory of backscattering for various angles of incidence, as well. Due to the absence of this theory, only an empirical relationship between the backscattering coefficient and angle of incidence have been published so far [3, 7].

This paper is concerned with the theoretical model of backscattering for various angles of incidence and an experimental test of this model. This problem may be useful in connection with electron probe microanalysis, scanning electron microscopy and electron beam micromachining.

2. Backscattering for various angles of incidence

In order to find the relation between the backscattering coefficient and angle of incidence of the electron beam the theory at normal incidence was chosen. One of the more universal is that of Kanaya and Okayama [10] but at normal incidence only. Starting

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from Lindhard's theory [12] for a stream of ions penetrating into solid targets they proposed the fundamental theory of electron scattering (containing transmission of electrons in amorphous solid targets, backscattering and energy loss of electrons). Kanaya and Okayama did not take into account the angle of electron incidence.

The model proposed by Kanaya and Okayama assumed that incident electrons are travelling straight into the target and then on the maximum energy dissipation depth they are moving in all directions in such way that their overall paths are equal to the maximum range [1, 10, 12]. That model is similar to Archard's model [1] where the centre of the rphere is located at the depth of complete diffusion [1, 12].

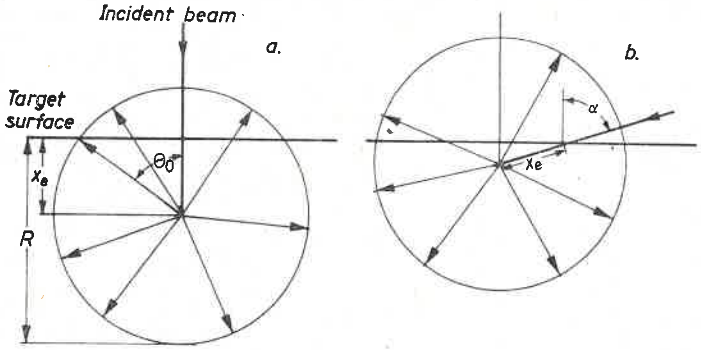

Fig. 1. The modified diffusion model of electron beam penetration in a target (a — at normal incidence, b — at angle of electron incidence equal to α)

Kanaya and Okayama model cannot be applied for various angles of electron incidence. It follows from this model that the centre of the sphere and the sphere itself go towards surface if the angle of incidence increases (Fig. 1). So, for angles of incidence equal 90° the electron beam scatters in a layer of thickness equal to the ray of that sphere. In practice that thickness decreases towards zero.

It is necessary to introduce the function of angle of incidence which modifies the maximum range. The function cos α is proposed in consideration of the experimental results, limit conditions, etc.

The thickness of the layer (x_α) and maximum range (R_α) for angular incidence of electron beam on the material will therefore be

$$x_\alpha = x \cdot \cos \alpha, \qquad R_\alpha = R \cdot \cos \alpha, \tag{2.1}$$

where x and R — the thickness of the layer and the maximum range for normal incidence.

From Kanaya and Okayama's theory follows that the fractional backscattering may be expressed by [10]

$$\frac{d\eta_B}{dy} = -\frac{d\eta_T}{dy} \cdot D(y) \cdot P(\theta), \tag{2.2}$$

where η_B — the backscattering coefficient, η_T — the transmission coefficient, $D(y)$ — the diffusion loss function of backscattered electrons,

$$P(\theta) = \frac{\int\limits_0^{\theta_0} \frac{\sin\theta d\theta}{(1+\cos\theta)^{11/6}}}{\int\limits_0^{\theta_0} \frac{\sin\theta d\theta}{(1+\cos\theta)^{11/6}}} = n \int\limits_0^{\theta_0} \frac{\sin\theta d\theta}{(1+\cos\theta)^{11/6}}$$

— the probability of leaving the specimen by backscattered electrons from material, $y = x/R$ — the reduced depth.

By substituting η_T, $D(y)$, $P(\theta)$ [10] we obtain for normal incidence

$$\frac{d\eta_B}{dy} = \frac{\gamma_B}{(1-y)^2} \exp\left(\frac{-\gamma_B y}{1-y}\right) \int\limits_0^{\theta_0} \frac{\sin\theta d\theta}{(1+\cos\theta)^{11/6}}, \tag{2.3}$$

where $\gamma_B = n\gamma$ — the absorption factor for backscattering, γ — the absorption factor for transmission.

With $\cos\theta_0 = y/(1-y)$, this leads to

$$\frac{d\eta_B}{dy} = \frac{6}{5} \frac{\gamma_B}{(1-y)^2} \exp\left(\frac{-\gamma_B y}{1-y}\right) [(1-y)^{11/6} - 2^{5/6}]. \tag{2.4}$$

At various angles of electron incidence on the material the relationship of η_T, $D(y)$ will be expressed by

$$\eta_T = \exp\left(-\frac{\gamma y \cos\alpha}{1-y}\right) \tag{2.5}$$

$$D(y) = \exp\left(\frac{\gamma y (n-1)\cos\alpha}{1-y}\right). \tag{2.6}$$

In such a way the fractional backscattering coefficient for various angles of electron incidence $d\eta_{B\alpha}/dy$ becomes

$$\frac{d\eta_{B\alpha}}{dy} = \frac{\gamma_B \cos\alpha}{(1-y)^2} \exp\left[-\frac{\gamma_B y \cos\alpha}{1-y}\right] \int\limits_0^{\theta_0} \frac{\sin\theta d\theta}{(1+\cos\theta)^{11/6}}. \tag{2.7}$$

After some transformations we obtain another form of that equation

$$\frac{d\eta_{B\alpha}}{dy} = \left\{\frac{\gamma_B(1-\cos\alpha)}{(1-y)^2} \exp\left[\frac{\gamma_B y}{1-y}(1-\cos\alpha)\right]\right\} \cdot \left\{-\exp\left(\frac{-\gamma_B y}{1-y}\right) \int\limits_0^{\theta_0} \frac{\sin\theta d\theta}{(1+\cos\theta)^{11/6}}\right\}$$

$$+\left\{\exp\left[\frac{\gamma_B y}{1-y}(1-\cos\alpha)\right]\right\}\cdot\left\{\frac{\gamma_B}{(1-y)^2}\exp\left(\frac{-\gamma_B y}{1-y}\right)\int_0^{\theta_0}\frac{\sin\theta d\theta}{(1+\cos\theta)^{11/6}}\right\}$$

$$=\frac{dA}{dy}B+A\frac{d\eta_B}{dy}. \tag{2.8}$$

It is necessary to test, is B an expression for the backscattering fraction η_B at normal incidence of the electron beam or not. We can do it by differentiating B.

$$\frac{dB}{dy}=\frac{6}{5}\frac{\gamma_B}{(1-y)^2}\exp\left(\frac{-\gamma_B y}{1-y}\right)\left[\tfrac{5}{6}(1-y)^{11/6}+(1-y)^{5/6}-2^{5/6}\right]. \tag{2.9}$$

A comparison of expression (2.9) and (2.4) shows that they differ from each other only in

$$\frac{5}{6\gamma_B}(1-y)^{11/6}. \tag{2.10}$$

Since $(1-y)<1$, $\gamma_B>1$ and power of (2.10) is approximately twice as large as the other ones it may be assumed that the component (2.10) is to be neglected. So

$$\frac{dB}{dy}=\frac{d\eta_B}{dy} \tag{2.11}$$

and by integration we obtain

$$B(y)+C=\eta_B(y). \tag{2.12}$$

Now equation (2.8) may be expressed by

$$\frac{d\eta_{B\alpha}}{dy}=[B(y)+C]\frac{\gamma_B(1-\cos\alpha)}{(1-y)^2}\exp\left[\frac{\gamma_B y}{1-y}(1-\cos\alpha)\right]$$

$$+\frac{d\eta_B}{dy}\exp\left[\frac{\gamma_B y}{1-y}(1-\cos\alpha)\right]. \tag{2.13}$$

By integration (2.13) from 0 to y the backscattering fraction from layer of thickness y and for various angles of incidence can be obtained. In order to obtain the backscattering coefficient for bulk material it is necessary to integrate at a thickness where backscattering becomes fixed. From the spherical model of electron scattering one can conclude that diffusion and backscattering reaches their values which are subsequently constant at greater depths, at the depth of maximum energy dissipation.

Therefore, the backscattering coefficient for various angles of electron incidence is as follows

$$\eta_{B\alpha}=\eta_B\exp[A_0(1-\cos\alpha)]$$

with

$$A_0=\frac{\gamma_B x_e}{R-x_e}. \tag{2.14}$$

The expression (2.14) seems to be very versatile because it was obtained from a model which is in good agreement with experiments over the energy range (10÷1000 keV) and the atomic number range.

The expression (2.14) is similar to Bruinning relation [6] which was obtained for the emission of secondary electrons and was applicable to backscattering. They differ from each other in parameter A_0 only (according to Bruinning $A_0 = \mu l$, where μ — absorption factor and l — diffusion depth).

3. *Experimental procedure*

In order to verify the theoretical results of the backscattering coefficient, the measurements were made for a wide range of electron energy (10÷120 keV), atomic number (14÷92) and angle of incidence (0÷80°). The system shown on Fig. 2 was used to measure the electron backscattering coefficient. The shield net was biased to −50 eV so low energy secondary electrons returned to the specimen. High energy backscattered electrons however could reach the grounded cage walls. The beam current was determined by the

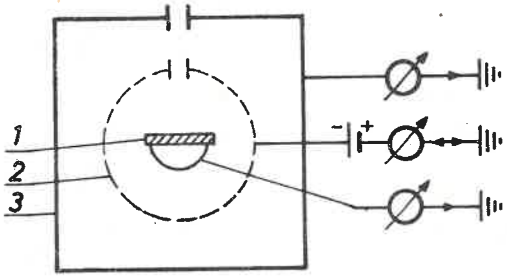

Fig. 2. The system to measure the backscattering coefficient (*1* — the specimen holder, *2* — the shield net, *3* — collector of backscattered electrons)

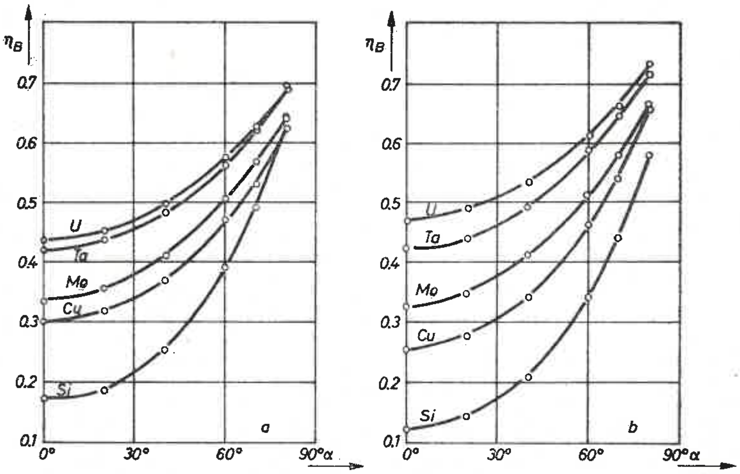

Fig. 3. Backscattering coefficient η_B as a function of angle of beam incidence α at 10 keV (a) and 100 keV (b

addition of all currents measured in that system. This method of measuring the backscattering coefficient was also devised by Bronshtain [3] and Bruinning [4]. The measurements were made at a pressure of $5 \cdot 10^{-5} \div 5 \cdot 10^{-6}$ Tr. From experiments and published data it follows that this pressure was sufficient. The specimens of silicon, copper, molybdenum, tantalum were chemically and uranium mechanically polished before using. For accurately measuring the backscattering coefficient three or four specimens of the same material were measured. Figure 3 shows the experimental results for all materials.

4. The comparison of theoretical and experimental results

The comparison of theoretical and experimental results will be made in coordinates [$\lg \eta_{B\alpha}/\eta_B$; $1 - \cos\alpha$]. Equation (2.14) predicts a straight line relation in these coordinates. From gradient of curves a value of parameter A_0 can be obtained. Figures 4 and 5 show theoretical and experimental graphs for all elements. It can be seen that results for copper

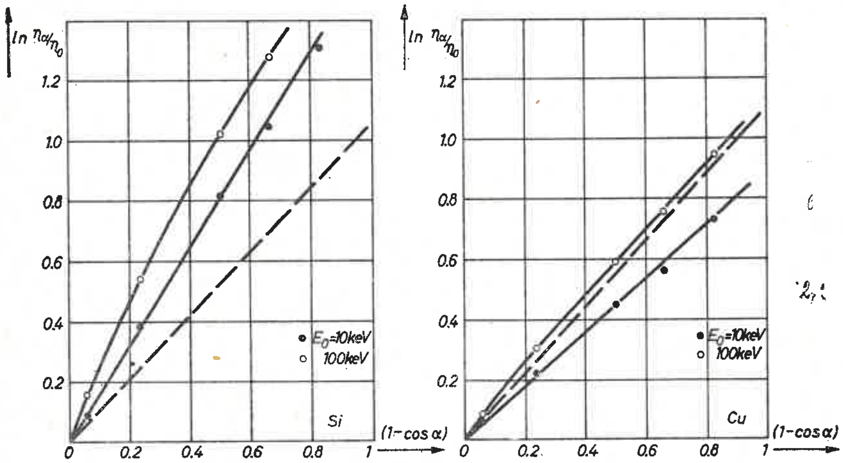

Fig. 4. $\lg \eta_{B\alpha}/\eta_B$ as a function of $(1 - \cos\alpha)$ for Si and Cu (broken curves calculated from Eq. (2.14))

and molybdenum are in a good accordance with practice. For silicon the equation (2.14) gives a smaller value of A_0 than the experimental results but for tantalum and uranium this value is larger. The differences for Si and U are equal to 100%. By usage of theoretical value of parameter A_0 and experimental value of η_B at normal incidence in Eq. (2.14) the exactness of the evaluation of the backscattering coefficient for electron incidence at various angles is equal about 25%. It is the error originating in the proposed modification of Kanaya and Okayama's model for various angles of electron incidence. If a value η_B at normal incidence issuing from Kanaya and Okayama's theory is used, the error of estimation of $\eta_{B\alpha}$ will increase to about $50 \div 100$%. The increase in error comes from an inexact accordance between the experimental function $\eta_B = f(Z)$ at normal incidence and that predicted by Kanaya and Okayama.

The performance of measurements of the backscattering coefficient at various angles of incidence made it possible to find the reasons for the difference between theory and experiment. One of those reasons is probably an incorrect evaluation of depth of the maximum energy dissipation. That parameter influences η_B and A_0. The better agreement

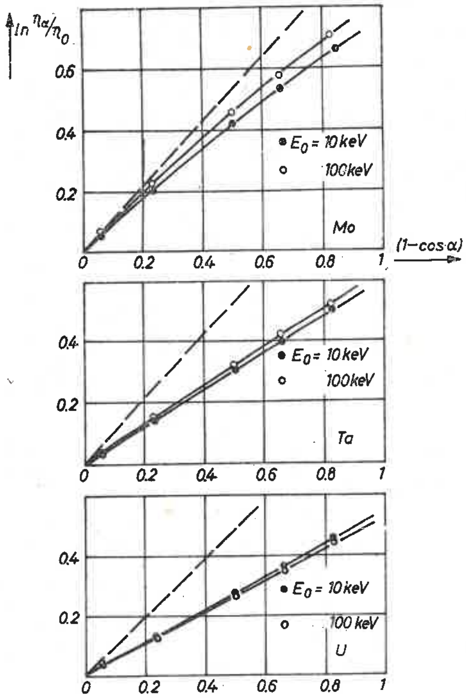

Fig. 5. Lg $\eta_{B\alpha}/\eta_B$ as a function of $(1 - \cos\alpha)$ For Mo, Ta and U (broken curves calculated from Eq. (2.14))

of the theoretical value of η_B and A_0 with experiment can be obtained by a suitable modification of x_e.

It should be pointed out that both Kanaya and Okayama's model and the modification proposed in this paper may be used in a wide energy range (10÷1000 keV), for all materials and over the entire range of angles of incidence.

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