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PHYSICS

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THE RANGE OF SLOW SECONDARY ELECTRONS IN A METAL AND THE ROLE OF INELASTICALLY REFLECTED ELECTRONS IN SECONDARY ELECTRON EMISSION

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1. It may be assumed approximately that the spectrum of secondary electrons consists of slow secondary electrons with energies $0 \div 50$ eV and of inelastically and elastically reflected primary electrons; moreover, the fraction of elastically reflected electrons at primary energies $E_p > 100$ eV amounts to only a few percent. The coefficient of total secondary emission is $\sigma = \delta + \eta$, where δ and η are, respectively, the emission coefficients of slow secondary electrons (among which $\sim 70\%$ have energies $E_2 \ll 10$ eV) and of fast inelastically and elastically reflected electrons.

Existing theories of secondary emission (^{1}) usually do not take into account the role of inelastically reflected and scattered primary electrons in the creation of slow secondary electrons and assume that all slow secondary electrons are knocked out of the target by primary electrons as they move into the depth of the substance. In this case, if the range of the slow secondary electrons is denoted by λ_2, and that of the primary electrons by l, it follows that at small E_p, $l < \lambda_2$, and at large $l > \lambda_2$, while $l \simeq \lambda_2$ corresponds to $\sigma_{\max}$, i.e., the depth of the "escape zone" of the secondary electrons, λ_2, is approximately equal to the range of primary electrons with energies $E_p \sim 300 \div 800$ eV.

L. N. Dobretsov and T. L. Mashkevich (^{2}) pointed out that a substantial part of the slow secondary electrons (in individual cases up to 50%) may owe its origin to inelastically reflected electrons. The aim of the present work is the experimental clarification of the role of η in the creation of slow secondary electrons (δ), as well as an estimate of the range λ_2, i.e., the depth of the "escape zone" of slow secondary electrons.

2. The measurements were carried out in an apparatus of the spherical-condenser type with an antidynatron grid. To determine η, a potential

of −50 V relative to the target was applied to the grid. In a vacuum of the order of $5 \cdot 10^{-8} \div 10^{-7}$ torr, thin layers of different metals were successively evaporated onto a target with a constant, preliminarily calibrated rate. Measurements of σ and η of these thin layers were made in the energy interval $E_p = 0.1 \div 3.6$ keV.

3. The coefficients σ and η for Be are several times smaller than the same quantities for Pt, Ag, and Bi. Therefore, when Pt, Ag, and Bi are evaporated onto a beryllium substrate, it may be regarded approximately as "zero." As the layer thickness changes at $E_p =$ const, the coefficients δ and η increase simultaneously. In Fig. 1 are given the dependences $\delta(\eta)$ when thin films of Bi and Ag are evaporated onto a beryllium substrate, and Be onto a platinum substrate. The substrate temperature was $t = -180°$. It is seen that for small energies ($E_p \simeq 600$ eV) these dependences are represented by a single straight line, whereas for large energies ($E_p = 3600$ eV) by a broken line consisting of two rectilinear segments. With increasing E_p from 600 to 3600 eV, straight lines 1, 3, 5 gradually pass into broken lines 2, 4, 7, respectively, the break for each metal always occurring

at one and the same thickness. As an example, one intermediate curve 6 is given.

For $E_p =$ const, the limiting values δ and η, corresponding to the massive layer of the deposited metal, are reached simultaneously, at one and the same layer thickness d.

A qualitative explanation of the dependences $\delta(\eta)$ shown in Fig. 1 for Bi and Ag films may be as follows. We shall assume that the essential part of δ is due to η. Then, as the film thickness d increases, while $d < \lambda_2$, δ increases owing to an increase in: 1) the number of slow secondary electrons produced directly by the primary electrons; 2) the number of inelastically scattered and inelastically reflected electrons (η); and 3) the "effectiveness" of each inelastically scattered electron, which is proportional to d. With a further increase in film thickness ($d > \lambda_2$), only the second factor is operative, i.e., the increase in the number of electrons inelastically scattered at thicknesses $d > \lambda_2$, while their "effectiveness" in the λ_2 zone (at $E_p =$ const) changes only slightly. It is clear that for $d < \lambda_2$ the dependence of δ on η must be steeper than for $d > \lambda_2$. Sections a of lines 2 and 4 correspond to thicknesses $d < \lambda_2$, sections b to thicknesses $d > \lambda_2$, and the points of break correspond to $d = \lambda_2$ (for Bi, $d = \lambda_2 \approx 7$ atomic layers; for Ag, $d = \lambda_2 \approx 20$ atomic layers). Straight lines 1, 3 have no noticeable break, since here all secondary emission (both δ and η) proceeds mainly from the λ_2 zone: at thickness $d \approx \lambda_2$, the σ corresponding to $E_p = 600$ eV is established. The slope of section b characterizes the "effectiveness" of scattered electrons in producing slow secondary electrons in the zone $d \approx \lambda_2$. With increasing E_p, this slope decreases.

Fig. 1. Relation between δ and η for thin films of Bi (curves 1, 2), Ag (3, 4), and Be (5, 6, 7). 1—$E_p = 600$ eV; 2—3600 eV; 3—600 eV; 4—3600 eV; 5—400

Fig. 1

Figure 1: Fig. 1

Fig. 2

Figure 2: Fig. 2

eV; 6—1200 eV; 7—3600 eV. The arrows indicate the direction of increasing film thickness.

4. The course of curves 5, 6, 7 for Be films on a platinum substrate is explained in the following way. Pt has high coefficients δ and η, and the spectrum of inelastically reflected electrons has a maximum in the region $E_2 = 0.9E_p$ (3). Thus, the platinum substrate may be regarded as a kind of "mirror." During the deposition of thin Be films ($d < \lambda_2$), absorption occurs mainly of the group of slow electrons emerging from Pt, with a small change in η. At thicknesses $d > \lambda_2$, when the slow electrons emerging from Pt are already completely absorbed by the beryllium film, δ decreases owing to a decrease in η. The thickness corresponding to the break point on line 7 (and also 6) is the range of slow electrons in Be (i.e., the "escape zone" of them from Be), $d = \lambda_2 = 12$ atomic layers. The slope of section *b* decreases with increasing E_p.
5. To determine the range of slow secondary electrons, one may also use an "equivalent" substrate, i.e., select a pair layer—substrate such that they have the same η and different σ. Such a pair is, for example, Bi and Pt.

Since, during deposition on an "equivalent" substrate, η does not change, the coefficient σ can change only owing to changes in: 1) the "effectiveness" of the primary and inelastically reflected electrons η in the λ_2 zone and 2) the width

of the zone itself, λ_2. Thus, the coefficient σ should be established over a thickness $d \approx \lambda_2$.

Figure 2 shows the dependences $\sigma(E_p)$ when Bi is deposited on a platinum substrate (substrate temperature $t = -180°$), and Fig. 3 shows analogous dependences for platinum films on a bismuth substrate (substrate temperature $t = 50°$). It is seen that all the curves shift in parallel and reach the limiting value σ_{B} simultaneously for all E_p already at

Fig. 2. Curves of the dependence $\sigma(E_p)$ when Bi is deposited on a platinum substrate. 1—pure Pt; 2—$d = 2.5$ atomic layers; 3*a*—$d = 7.5$, 3*b*—$d = 12.5$

Fig. 3. Curves of the dependence $\sigma(E_p)$ when Pt is deposited on a bismuth

Fig. 3

Figure 3: Fig. 3

substrate. 1—pure Bi; 2—$d = 1.1$ atomic layers; 3—$d = 2.2$; 4—$d = 3.3$; 5—$d = 5.5$; 6—$d = 7.7$; 7—$d = 10$; 8—$d = 11$

a thickness $d = \lambda_2 = 7.5$ atomic layers of Bi, while σ_{Pt}—at $d = \lambda_2 = 10$ atomic layers of Pt. The point here is not that $\Delta\sigma = \sigma_{\mathrm{Pt}} - \sigma_{\mathrm{Bi}}$ ($1.55 - 1.07 = 0.48$ at $E_p = 3000$ eV) is relatively small [4], since when Pt was deposited on a beryllium substrate a Pt layer thickness $d \sim 150$ atomic layers was required in order to change σ from 1.05 to 1.5 at $E_p = 3000$ eV.

Thus, the "equivalent" and "zero" substrate methods give identical values of λ_2 for Bi.

The values of λ_2 of the order of 10 atomic layers given for Bi, Pt, Ag, and Be are perhaps nevertheless overestimated because of the insufficient continuity and homogeneity of such thin layers, even those obtained at $t = -180°$.

6. From the experimental data obtained, partly presented in this paper, it follows that the mechanism of secondary electron emission may be represented as follows. The primary electron, upon entering the metal, directly creates a small number of secondaries. The penetration depth l of the primaries is many times greater than the escape zone of the secondaries, λ_2. For example, for $E_p = 3000$ eV, $l_{\mathrm{Be}} > 1000$ atomic layers, $l_{\mathrm{Pt}} > 200$ atomic layers. As the primary electrons move into the depth of the metal, an increasing number of inelastically scattered electrons arises, some of which (η) emerge to the outside. Slow secondary electrons ($E_2 \lesssim 10 \div 15$ eV) emerge from a thin near-surface layer λ_2, of the order of 10 atomic layers, and are generated chiefly by inelastically scattered electrons, i.e., in essence they are "tertiary."

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Note: Figure translations are in progress. See original paper for figures.