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# PHYSICS

I. M. BRONSTEIN and B. S. FRAIMAN

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## Abstract

## Full Text

PHYSICS

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# ON CERTAIN REGULARITIES OF SECONDARY ELECTRON EMISSION OF THIN LAYERS OF METALS AND SEMICONDUCTORS

(Presented by Academician A. F. Ioffe, 22 VI 1960)

1. In [1] certain characteristics of the secondary electron emission of Be, Bi, Ag, and Pt were given. With the aid of “equivalent” substrates and of the diagrams  $\delta-\eta$ , the path lengths  $\lambda$  of slow secondary electrons and the efficiency  $S$  of inelastically reflected electrons in the formation of slow secondaries in the escape zone of the latter were determined. In this way two types of  $\delta-\eta$  diagrams were obtained ( $\delta$  and  $\eta$  are the coefficients of secondary electron emission of slow secondary and fast inelastically and elastically reflected electrons): 1) when Bi and Ag are deposited on a beryllium substrate, and 2) Be on a platinum substrate (Fig. 1, curves of the type *AMO* and *CNO*, respectively). It can be shown, however, that these two types of curves  $\delta(\eta)$  do not exhaust the possible cases of the dependence of  $\delta$  on  $\eta$  in the adsorption of layers of one substance on a substrate of another. In fact, let a layer of the substance under investigation of thickness  $d > \lambda$  correspond to the dependence  $\delta(\eta)$  represented by the straight line *MN*. Then the remaining part of the  $\delta-\eta$  diagram will be determined by the values of  $\delta$  and  $\eta$  of the substrate, and the diagram as a whole will be characterized by curves of the type *CNO*, *BMO*, *AMO*, *DNO*, *LNO*, *KMO*, *FO*, and *EO*.

**Fig. 1.** Possible types of dependences  $\delta(\eta)$  when thin layers of one substance are deposited on a substrate of another substance. The arrows indicate the direction of increase of the layer thickness.

Fig. 2. Dependence  $\sigma(d)$  upon deposition of thin Ba layers on a silver substrate.  $a$ — $p = 5 \cdot 10^{-9}$  torr, the apparatus was under continuous pumping;  $b$  —the same,  $p \approx 10^{-7}$  torr;  $v$ —the apparatus was baked out,  $p = 5 \cdot 10^{-9}$  torr

Figure 2: Fig. 2. Dependence  $\sigma(d)$  upon deposition of thin Ba layers on a silver substrate.  $a$ — $p = 5 \cdot 10^{-9}$  torr, the apparatus was under continuous pumping;  $b$  —the same,  $p \approx 10^{-7}$  torr;  $v$ —the apparatus was baked out,  $p = 5 \cdot 10^{-9}$  torr

Let us consider the conditions that determine one or another type of dependence  $\delta(\eta)$ . Since, beginning with  $E_p \gtrsim 1$  keV, for an adsorbed-layer thickness  $d \ll \lambda$  the  $\eta$  of the substrate practically does not change, then

$$\delta_\lambda = \delta_{0c} + S_c \eta_p, \quad (1)$$

where  $\delta_\lambda$  is the coefficient of secondary electron emission of slow secondary electrons of a layer of thickness  $\lambda$ ;  $\delta_{0c}$  and  $S_c$  are the efficiencies of the direct and reverse electron fluxes in the escape zone of the deposited substance;  $\eta_p$  is the coefficient of electrons inelastically reflected from the substrate. For the substrate, respectively, we have:

$$\delta_p = \delta_{0p} + S_p \eta_p. \quad (2)$$

The form of the curve  $\delta(\eta)$  (the presence or absence of an extremum, a rectilinear course) will be determined by the conditions

$$\eta_p \gtrsim \eta_c, \quad \delta_\lambda - \delta_p \gtrsim 0,$$

i.e.,

$$\eta_p \lesssim \eta_s, \quad \delta_{0s} - \delta_{0p} + \eta_p(S_s - S_p) \lesssim 0, \quad (3)$$

the combinations of which, as is easy to see, give all possible types of the  $\delta - \eta$  diagrams shown in Fig. 1 by solid lines.

Adsorption of monatomic layers of alkali or alkaline-earth metals leads to a lowering of the work function and, consequently, to a change in the form of the curves  $\delta(\eta)$  (dashed lines, Fig. 1). An analogous change takes place also when these metals serve as substrates and layers of metals with a larger work function are deposited on them; in this case, for thicknesses  $d \approx 1-3$  atomic layers, the work function also decreases noticeably (apparently owing to the formation of patch fields), as was established by measuring the photocurrent simultaneously with measuring the secondary-electron-emission coefficient  $\sigma$ .

Fig. 3

Figure 3: Fig. 3

**Fig. 2.** Dependence  $\sigma(d)$  upon deposition of thin Ba layers on a silver substrate.  $a-p = 5 \cdot 10^{-9}$  torr, the apparatus was under continuous pumping;  $b$ —the same,  $p \approx 10^{-7}$  torr;  $v$ —the apparatus was baked out,  $p = 5 \cdot 10^{-9}$  torr.

The aim of the present work is the experimental elucidation of all possible types of relation between  $\delta$  and  $\eta$  when thin layers of one substance are deposited on a substrate of another.

2. The apparatus and measurement procedure are described in detail in <sup>(1)</sup>. The target temperature was  $t = -180^\circ$ . The vacuum during the measurements was  $\sim 5 \cdot 10^{-8}$  torr. Control experiments carried out in a vacuum of  $4-5 \cdot 10^{-9}$  torr (when the time for depositing the layer and recording the curve  $\sigma(E_p)$  was much shorter than the time for adsorption of a monolayer of residual gases) during the deposition of Ba on Ag (Fig. 2) showed that both the curves  $\sigma(E_p)$  for massive Ba and Ag layers and the dependence  $\sigma(d)$  during adsorption of Ba and Ag agree well with the results obtained in a vacuum of  $\sim 10^{-7}-5 \cdot 10^{-8}$  torr. The coefficient of inelastic reflection of electrons  $\eta$  depends on the vacuum conditions considerably less than  $\delta$ . All this apparently indicates that the investigation of the secondary electron emission of thin layers in the energy range  $E_p > 50 \div 100$  eV can be carried out in a vacuum of  $\sim 5 \cdot 10^{-8}$  torr.
3. Figure 3 presents some of the dependences  $\delta(\eta)$  obtained during evaporation of Pb onto aluminum foil and Si (1, 2), Ti onto Be and Ag (3, 4), and Si onto Ti (5). Curves 1 and 5, which have extrema at layer thicknesses of Pb and Si  $d \approx \lambda$ , are similar to the corresponding curves **BMO** and **DNO** in Fig. 1. In the upper part of Fig. 3 the dependences of  $\sigma$  and  $\eta$  on thickness are given. It is seen that the curves  $\eta(d)$  are monotonic, whereas the curve  $\sigma(d)$  for Ti on Si has a minimum at layer thickness  $d = \lambda \approx 10-12$  atomic layers, and the curve  $\sigma(d)$  for Si on Ti has a maximum at  $d = \lambda \approx 20$  atomic layers. Such a character of the dependence  $\delta(\eta)$ , and consequently also of  $\delta(d)$  and  $\tau(d)$ ,

when Si is deposited on Ti is explained by the larger efficiencies of the forward and reverse fluxes in Si than in Ti. Thus, for example, for Si,  $\delta_0 = 0.15$ ,  $S = 1.1$ , while for Ti, respectively, 0.13 and 0.8 ( $E_p = 1.2$  keV). It is clear that, when Ti is evaporated onto a silicon substrate, the curve  $\delta(\eta)$  must have a minimum. The behavior of the curve  $\delta(\eta)$  when Pb is evaporated onto aluminum foil can be explained in the same way. The explanation of the monotonic behavior of curves 2, 3, and 4 is given in <sup>(1)</sup>.

**Fig. 3.** Relation between  $\delta$  and  $\eta$ : for layers of Pb on aluminum foil (1) and Si (2); for layers of Ti on Be (3) and Ag (4); for layers of Si on Ti (5),  $E_p = 3$  keV. The arrows indicate the direction of increasing layer thickness. At the top are

Fig. 4

Figure 4: Fig. 4

shown the curves  $\delta(d)$  and  $\eta(d)$  for Si on Ti (6, 9) and Ti on Si (7, 8),  $E_p = 1200$  eV.

Figure 4 presents the curves of the dependence  $\delta(\eta)$  for evaporation of Ca onto Be (1), Be onto Ca (2), Ba onto Ti (3), and Ti onto Ba (4). These curves are similar to the corresponding curves  $B'MO$  and  $D'NO$  of Fig. 1. The behavior of curves 1 and 3 is easily explained as follows. Upon adsorption of approximately a monolayer of Ca or Ba, the work function of the substrate is substantially reduced, as a result of which  $\delta$  rises sharply, while  $\eta$  remains unchanged. With a further increase in layer thickness, while  $d < \lambda$ , the effect of the decrease in work function disappears, and the contribution of the Ca and Ba layers to the formation of  $\delta$  increases, as a result of which  $\delta$  decreases sharply, reaching a minimum at  $d = \lambda$ . The rectilinear portions of these diagrams determine the efficiencies of inelastically reflected electrons in Ca and Ba, respectively. As can be seen, at the minimum  $\delta_c < \delta_p$ , which is explained by the smaller efficiencies of the forward and reverse fluxes in the layer than in the substrate.

When Be is deposited on Ca and Ti on Ba, the increase in  $\delta$  is due both to a decrease in the work function and to the large efficiencies of the fluxes in Be and Ti. The break points  $A$  on the  $\delta$ - $\eta$  diagram correspond to layer thicknesses equal to the escape depth  $\lambda$  of slow secondary electrons from Be and Ti. If there were no effect of a decrease in the work function, the transition from Ca to Be on the  $\delta$ - $\eta$  diagram up to the break point  $A$  would proceed along the dashed line. Thus, with the aid of the  $\delta$ - $\eta$  diagram it is possible to separate the effect of the influence of a change in work function on the secondary-electron emission coefficient  $\sigma$  from the effect caused by a change in the efficiencies of the direct and reverse electron fluxes in the layer.

**Fig. 4.** Relation between  $\delta$  and  $\eta$  for thin layers of Ca on Be (1), Be on Ca (2), Ba on Ti (3), Ti on Ba (4),  $E_p = 2$  keV. At top, the curve  $\sigma(d)$  for deposition of Ca on Be.

Curve 5 presents the dependence  $\sigma(d)$  on thickness during deposition of Ca on Be;  $\sigma_{\max}$  corresponds to  $d \simeq 1$  atomic layer, and  $\sigma_{\min}$ ,  $d = \lambda \simeq 10$  atomic layers.

It follows from the diagrams presented here that, knowing the efficiencies of the deposited substance and of the substrate, one can predict in advance the course of the dependence  $\delta(\eta)$ , and consequently also the thickness dependence of the secondary-electron emission coefficient  $\sigma(d)$ .

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