

## Secondary Electron Emission in Thin Layers of Silver

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The effects of the underlying surface on the emission depth of the secondary electrons are examined for the experimental method which uses deposits of the investigated metal on a metal base. A real emission depth  $d$  of secondary electrons from silver is determined. It is shown that in the region of 100-600 eV the emission depth depends linearly on the energy of the primary electrons. It is established that, for adsorption of approximately monatomic layers of silver on nickel and beryllium, displacements of the maxima of the energy distribution curves of the secondary electrons take place for increasing thickness. The maximum of the curve for Ag on Ni is displaced to the left and that for Ag on Be to the right. This fact points to an influence of the work function of the base on the energy distribution function of the secondary electrons.

### 1. INTRODUCTION

SEVERAL papers have been devoted to the investigation of secondary emission from thin layers of silver and to the determination of the effective emission depth of the secondary electrons from silver. In several cases<sup>1,2</sup> silver was deposited on oxidized aluminum and dielectric surfaces such as mica<sup>2</sup> and glass<sup>3</sup>. At other times metals such as platinum<sup>4</sup> and nickel<sup>5</sup> were used. Even though in all of these experimental determinations of the emission depth of secondary electrons the wedge-like silver layer was deposited by the same technique on the base, the obtained values of the emission depth turned out to be very different from each other. Furthermore, the dependence of the emission depth on the energy of the primary electrons has a different character for the wedge method than for our work: in our case<sup>2</sup> a linear dependence of the emission depth  $d$  on the energy of the primary electrons  $E_p$  was found, while in the second case<sup>3</sup> this dependence was absent.

It should be noted in connection with these facts that the conductivity of thin metallic layers adsorbed on dielectric surfaces depends very substantially on the thickness of the metallic layer. For thicknesses less than 8  $\mu$  the conductivity of the metallic layers is extraordinarily

small. Such layers are closer in their properties to semiconductors and dielectrics than to metals<sup>6</sup>. Only at thicknesses of about 50  $\mu$  does the conductivity of the layers become approximately equal to the conductivity of a massive specimen. Therefore, a doubt arises as to the feasibility of obtaining the correct values of the coefficients for secondary electron emission from thin metallic layers deposited on dielectric surfaces. Indeed, as shown by Haas and Scott<sup>7</sup>, the resistance of a silver layer approximately 20  $\mu$  thick is still very large (about  $10^8$  times larger than the normal value). Under such conditions the coefficient of secondary electron emission of a layer should be approximately equal to the coefficient of secondary emission for a free electron, i.e., unity.

Experimental investigation proved the latter conclusion to be correct. Instead of a metallic target a glass base was placed onto the apparatus described previously<sup>5</sup>. The sides of the glass base were covered with thick layers of silver that served as electrodes. The layer of silver on which the experiments were carried out was about 18  $\mu$  thick and was obtained by 2 minutes of evaporation from a red-hot tungsten filament. The measurements showed that the coefficient of secondary electron emission of this silver layer was practically equal to unity through the entire energy range of 50 - 1500 eV of primary electrons. The resistance of the layer was about  $10^{10} \Omega$ .

It was shown previously<sup>8,9</sup> that the correct

<sup>1</sup> I. F. Pesiatskii, Zh. Tekhn. Fiz. 9, 188 (1939).

<sup>2</sup> M. M. Vudynskii Dokl. Akad. Nauk SSSR 82, 705 (1952).

<sup>3</sup> N. D. Morgulis and N. D. Nakhodkin, Dokl. Akad. Nauk SSSR 94, 1029 (1954).

<sup>4</sup> A. E. Hastings, Phys. Rev. 57, 695 (1940).

<sup>5</sup> I. M. Bronshtein, Zh. Tekhn. Fiz. 13, 176 (1943).

<sup>6</sup> I. D. Konozenko, Uspekhi Fiz. Nauk 52, 561 (1954).

<sup>7</sup> G. Haas and N. Scott, J. Phys. Radium 11, 394 (1950).

<sup>8</sup> A. E. Kadyshevich, J. Exper. Theoret. Phys. USSR 15, 651 (1945).

<sup>9</sup> I. M. Bronshtein and T. A. Smorodin, J. Exper. Theoret. Phys. USSR 27, 215 (1954).

Emitter	$\sigma_{max}$	$E_{p\ max}(ev)$	$\varphi (ev)$
Ag . . . . .	1.56	800	4.4
Ni . . . . .	1.27	500	5.0
26-atomic layer of Be on Ni . . . . .	0.61	300—1500	3.9

values of the effective depth of the secondary electron emission may be obtained only if the coefficient of secondary emission  $\sigma_1$  of the metallic layer differs greatly from the coefficient  $\sigma_b$  of the base. This basic condition was not satisfied in any of the cited experiments and generally the effect of the base was not taken into account. This fact apparently explains the differences in values of the effective emission depth obtained by various authors.

It was found earlier<sup>10</sup> that it is possible to exclude entirely the effect of the base and determine the real emission depth of secondary electrons by depositing layers of one metal on various bases which have increasing or decreasing values of  $\sigma_b$ . The present work is devoted to an investigation of this question; the role of the base is explained and a real emission depth of secondary electrons from Ag is determined. Thin layers of Ag were deposited on Ni, Be and on a Be layer 26 atoms thick adsorbed on Ni. In the table above the values of  $\sigma_{max}$ ,  $E_{p\ max}$  and the work functions of the emitters are given.

As is apparent from the table,  $\sigma_{max}$  for Ag differs from  $\sigma_{max}$  for Ni by 0.3 and from  $\sigma_{max}$  of Be by unity. Also, Ag is electropositive relative to Ni and electronegative relative to Be. This circumstance allows us to clarify the influence of the difference between the work functions of the base and the metallic layer on the regularity of the change in the secondary emission.

Techniques and methods used in the present experiments were described previously<sup>5,9,10</sup>. As criteria of the accuracy of the apparatus and purity of the experimental conditions the following curves were used for Ni, Ag and Be:  $\sigma = f(E_p)$  and  $\frac{d\sigma}{dE_{sec}} = f(E_{sec})$  where  $E_{sec}$  is the energy of the secondary electrons. The results of the measurements were repeatedly reproducible with a great degree of accuracy.

2. RESULTS OF THE MEASUREMENTS

Figures 1 - 3 present the curves of the dependence of  $\sigma$  on  $E_p$  for silver atoms adsorbed on Ni, Be and 26 atomic layer of Be on Ni. In Fig. 4 analogous results are shown as obtained by one of the authors<sup>5</sup> for adsorption of silver on irreversibly altered nickel surface with  $\sigma_{max} = 1.43$ .

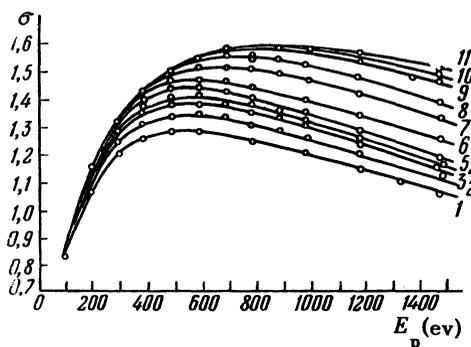


FIG. 1. Curves  $\sigma = f(E_p)$  for adsorption of atoms of Ag on Ni. 1 - Ni ( $\Theta = 0$ ,  $\sigma_{max} = 1.27$ ); 2 -  $\Theta = 0.7$ ; 3 -  $\Theta = 1.4$ ; 4 -  $\Theta = 2$ ; 5 -  $\Theta = 4$ ; 6 -  $\Theta = 7$ ; 7 -  $\Theta = 14$ ; 8 -  $\Theta = 24$ ; 9 -  $\Theta = 42$ ; 10 -  $\Theta = 56$ ; 11 -  $\Theta \geq 70$  atomic layers ( $\sim 20 m\mu$ ).

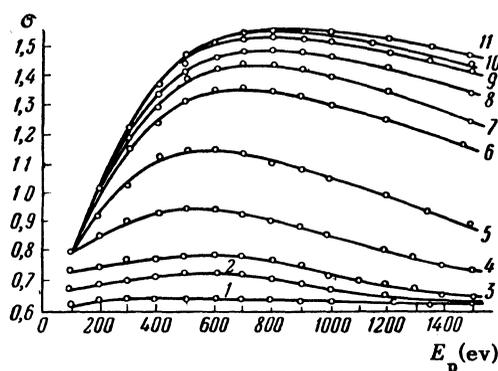


FIG. 2. Curves  $\sigma = f(E_p)$  for adsorption of atoms of Ag on 26-atomic layer of Be on Ni. 1 - curve of dependence of  $\sigma$  on  $E_p$  for the nickel base with beryllium layer approximately  $6 m\mu$  thick; 2 -  $\Theta = 0.7$ ; 3 -  $\Theta = 2$ ; 4 -  $\Theta = 4$ ; 5 -  $\Theta = 8$ ; 6 -  $\Theta = 21$ ; 7 -  $\Theta = 28$ ; 8 -  $\Theta = 42$ ; 9 -  $\Theta = 56$ ; 10 -  $\Theta = 70$ ; 11 -  $\Theta \geq 84$  atomic layers ( $\sim 24 m\mu$ ).

<sup>10</sup> I. M. Bronshtein and T. A. Smorodinov, J. Exper. Theoret. Phys. USSR 27, 495 (1954).

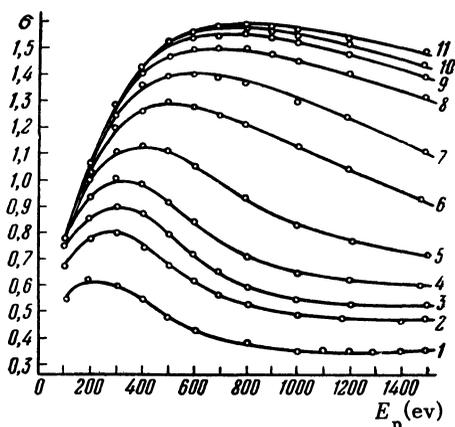


FIG. 3. Curves  $\sigma = f(E_p)$  for adsorption of  $Ag^z$  on Be. 1 - Be ( $\Theta = 0$ ); 2 -  $\Theta = 1$ ; 3 -  $\Theta = 2$ ; 4 -  $\Theta = 4$ ; 5 -  $\Theta = 8$ ; 6 -  $\Theta = 17$ ; 7 -  $\Theta = 28$ ; 8 -  $\Theta = 49$ ; 9 -  $\Theta = 70$ ; 10 -  $\Theta = 84$ ; 11 -  $\Theta \geq 98$  atomic layers ( $\sim 30 \mu m$ ).

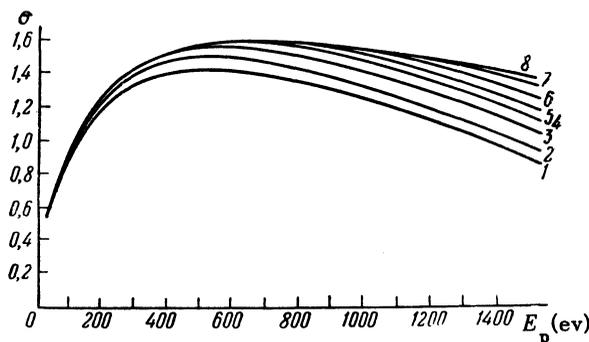


FIG. 4. Curves of dependence of  $\sigma$  on  $E_p$  for thin deposits of Ag on irreversibly altered Ni surface<sup>5</sup>. 1 - Ni,  $\sigma_{max} = 1.43$ ; 2 -  $\Theta = 0.7$ ; 3 -  $\Theta = 1.4$ ; 4 -  $\Theta = 2.1$ ; 5 -  $\Theta = 2.8$ ; 6 -  $\Theta = 4.2$ ; 7 -  $\Theta = 5.6$ ; 8 -  $\Theta = 7$  atomic layers. The latter curve coincides with an emission curve of a massive silver specimen.

From a comparison of the curves it is evident that the general regularity of the variation of the coefficient of secondary emission does not depend on the properties of the base. In adsorption of Ag on various surfaces the coefficient of secondary emission increased monotonically for all values of  $E_p$  to the value of  $\sigma$  for a massive specimen of Ag. The major change in  $\sigma$  ( $\sim 80\%$ ) occurs within the first 20 - 30 atomic layers.

A comparison of the curves in Figs. 1-4 shows that in spite of the fact that  $\alpha_{Ag}$  is greater than  $\alpha_{Be}$  and smaller than  $\alpha_{Ni}$ , there is no additional regularity of change of  $\sigma$ , directly connected with a change in the work function of the base in the adsorption on it of the first layers of Ag.

The curves in Figs. 5-7 show a dependence of  $\sigma$  on  $\Theta$  (where  $\Theta$  is the number of deposited

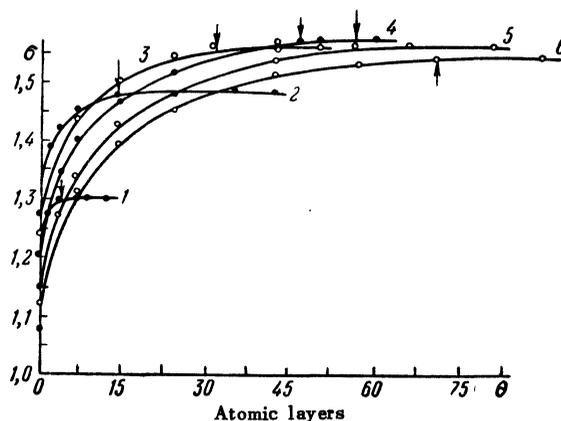


FIG. 5. Curves of dependence of  $\sigma$  on  $\Theta$  for adsorption of Ag on Ni for various  $E_p$ . 1 -  $E_p = 300$ ; 2 -  $E_p = 500$ ; 3 -  $E_p = 700$ ; 4 -  $E_p = 900$ ; 5 -  $E_p = 1100$ ; 6 -  $E_p = 1200$  ev.

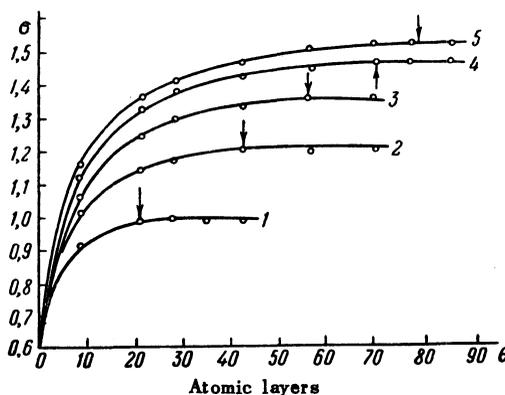


FIG. 6. Curves of dependence of  $\sigma$  on  $\Theta$  for adsorption of Ag on a 26-atomic layer of beryllium on Ni. 1 -  $E_p = 200$ ; 2 -  $E_p = 300$ ; 3 -  $E_p = 400$ ; 4 -  $E_p = 500$ ; 5 -  $E_p = 600$  ev.

atomic layers of Ag) for various  $E_p$ . The arrows point to these values of  $\Theta$  at which  $\sigma$  attains maximum. To these values of  $\Theta$  correspond the values for the maximum depth  $d$  of emission of secondary electrons at a given energy  $E_p$ .

Figures 8 - 11 present the curves of entrapment  $\sigma = f(-V_k)$  and of  $\frac{d\sigma}{dE_{sec}}$  obtained by differentiation

$$\frac{d\sigma}{dE_{sec}}$$

of these curves to show the energy distribution of the secondary electrons. The curves in Figs. 10-11 show that for the adsorption of Ag on Ni ( $\Theta \sim 1$ ) the maximum of the energy distribution curve shifts first to the left (to lower energies) by 1.8 ev, then with increasing  $\Theta$  to the right by 0.8 ev and remains unchanged for any  $\Theta$  thereafter. As an example a curve for  $\Theta = 7$  is shown in Fig.

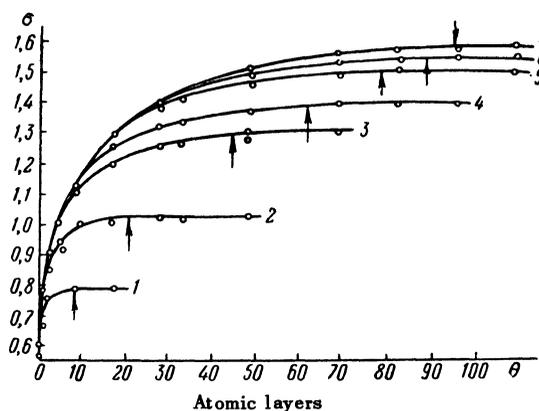


FIG. 7. Curves of dependence of  $\sigma$  on  $\Theta$  for adsorption of Ag on Be. 1 -  $E_p = 100$ ; 2 -  $E_p = 200$ ; 3 -  $E_p = 300$ ; 4 -  $E_p = 400$ ; 5 -  $E_p = 500$ ; 6 -  $E_p = 600$ ; 7 -  $E_p = 700$  ev.

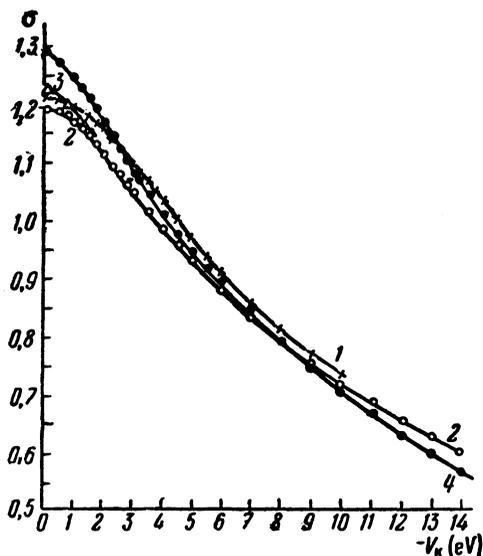


FIG. 8. Curves of dependence of  $\sigma$  on retarding potential of the collecting electrode ( $-V_k$ ) for adsorption of Ag on Ni. 1 - Ni ( $\Theta = 0, E_p = 300$  ev); 2 -  $\Theta = 0.7, E_p = 250$  ev; 3 -  $\Theta = 1.4, E_p = 250$  ev; 4 -  $\Theta = 7, E_p = 300$  ev. For  $V_k \geq 0, \sigma$  was observed to be constant.

10. For adsorption of Ag and Be one observes a different picture: for  $\Theta = 1$  the maximum shifts to higher energies by 0.8 ev, then at  $\Theta = 2$  it shifts to lower energies and thereafter its position remains unchanged and coincides with the position of the maximum of the distribution curve for thick layers of Ag.

The energy distribution curves of the secondary electrons were obtained for various energies of primary electrons. The character of the distribu-

tion curves and also the regularity observed with variation of  $\Theta$  do not depend on the velocities of the primary electrons.

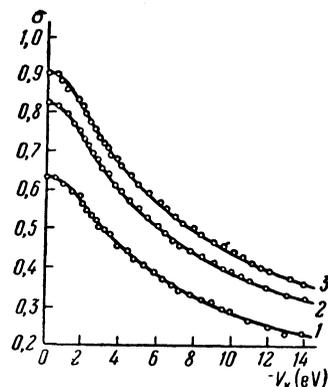


FIG. 9. Curves of dependence of  $\sigma$  on the retarding potential of the collecting electrode ( $-V_k$ ) for adsorption of Ag on Be, 1 - Be; 2 -  $\Theta = 1$ ; 3 -  $\Theta = 2$ . All curves were obtained with  $E_p = 300$  ev. For  $V_k \geq 0, \sigma$  was again observed to be constant.

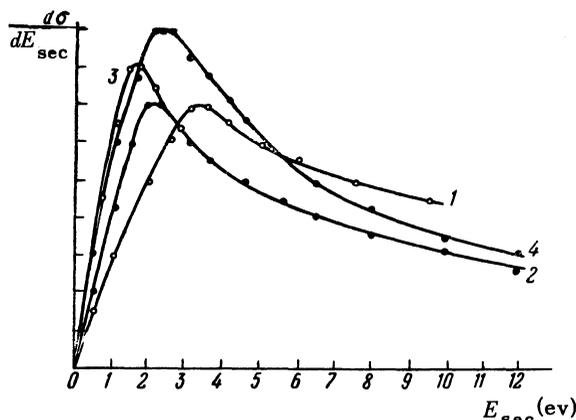


FIG. 10. The variation of the energy distribution curves of secondary electrons for adsorption of atoms of Ag on Ni. 1 - Ni,  $E_p = 300$  ev; 2 -  $\Theta = 0.7, E_p = 250$  ev; 3 -  $\Theta = 1.4, E_p = 250$  ev; 4 -  $\Theta = 7, E_p = 300$  ev.

### 3. EVALUATION OF RESULTS

The curves of Figs. 1 - 7 convincingly demonstrate that it is necessary to take into account the effect of the base in the determination of the effective emission depth of the secondary electrons. However, the role of the base may be eliminated in the final calculations, if the layers of the investigated metal are deposited on various bases whose  $\sigma$  values differ by various amounts from the  $\sigma$  values of the metallic layer. To every base and

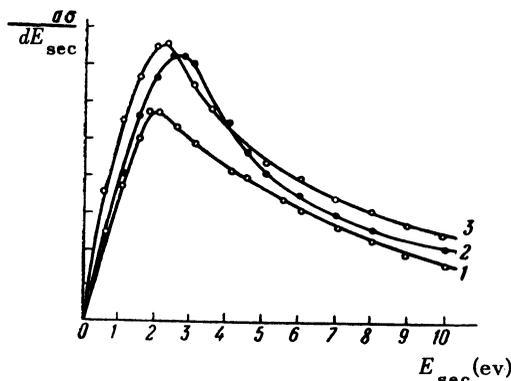


FIG. 11. The variation of the energy distribution curves of secondary electrons for adsorption of atoms of Ag on Be. 1 - Be; 2 -  $\Theta = 1$ ; 3 -  $\Theta = 2$ . All curves were obtained with  $E_p = 300$  ev.

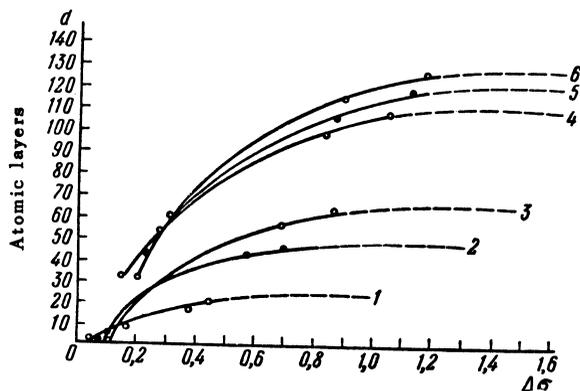


FIG. 12. Curves of the thickness of the layer of Ag at which  $\sigma = \sigma_{Ag}$  vs.  $\Delta\sigma = \sigma_e - \sigma_b$ . 1 -  $E_p = 200$ ; 2 -  $E_p = 300$ ; 3 -  $E_p = 400$ ; 4 -  $E_p = 500$ ; 5 -  $E_p = 600$ ; 6 -  $E_p = 700$  ev. The ordinate of the curves 4, 5 and 6 is displaced relative to the first three curves by 28 atomic layers.

a fixed value of  $E_p$  corresponds a definite value of  $\Delta\sigma = \sigma_e - \sigma_b$  and a specific emission depth  $d$  of the secondary electrons. Our results show that  $d = f(\Delta\sigma)$ . It is evident that the real value of  $d$  will correspond to  $\Delta\sigma = \sigma_e$ .

In Fig. 12 a series of curves obtained in the present work shows the dependence of the emission depth of the secondary electrons on  $\Delta\sigma = \sigma_e - \sigma_b$ . From these curves the real emission depth of secondary electrons may be found by extrapolation to  $\Delta\sigma = \sigma_1$  for a given value of  $E_p$ . The emission depth  $d$  corresponding to the latter value of  $\Delta\sigma$  will be the real emission depth of the secondary electrons.

The dependence of the real emission depth of the secondary electrons on the energy of the primary

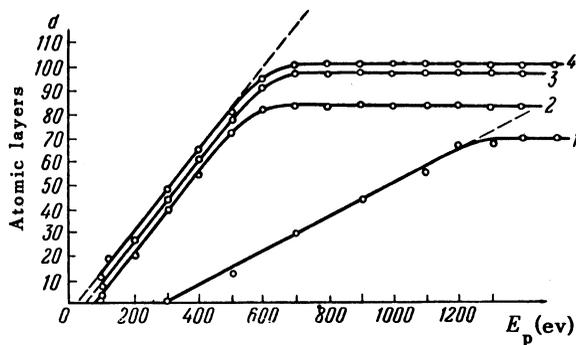


FIG. 13. The dependence of the emission depth of the secondary electrons from silver on the energy of the primary electrons and on the base on which the silver atoms are adsorbed. 1 - Ni base; 2 - base of approximately  $6 \mu$  thick layer of Be adsorbed on Ni; 3 - Be base; 4 - the real emission depth of secondary electrons from silver as a function of the energy of primary electrons  $E_p$ . The effect of the base is eliminated.

electrons is shown in Fig. 13. There the curves  $d = f(E_p)$  are presented for the cases of adsorption of Ag on Ni, Be and on 26 atomic layer of Be on Ni.

It is evident that the values of  $d_{real}$  and  $d_{exp}$  obtained for adsorption of Ag on thick layer of Be, and their dependence on  $E_p$  almost coincide. Therefore, it may be assumed that the effect of the base practically does not appear for the pair Ag - Be. Using the Be base, we may then determine the real emission depth of the secondary electrons from Ag and its dependence on  $E_p$  by depositing on Be base layers of Ag of increasing thickness.

As far as a nickel base is concerned, the corresponding curve of Fig. 13 shows that its effect on the determination of the emission depth of secondary electrons from Ag is by no means negligible:  $d_{real}$  and  $d_{exp}$  obtained by adsorption of Ag on Ni and their dependence on  $E_p$  differ greatly from each other.

The emission depth  $d$  appears to be linearly dependent on  $E_p$  for energies up to  $E_p = 600$  ev. Consequently, it is again possible to form the conclusion that the penetration of primary electrons is linearly proportional to their energies in the region 100 - 600  $ev^{1,1,1,2}$ . It is not possible to say anything about the penetration of the primary electrons of energies above 600 ev since the secondary electrons freed by them are often formed in depths

<sup>1</sup> A. Ia. Viatskii, J. Exper. Theoret. Phys. USSR 20, 547 (1950).

<sup>2</sup> A. J. Dekker and A. van der Ziel, Phys. Rev. 86, 755 (1952).

from which they cannot escape due to elastic and inelastic collisions.

The changes in the work function due to adsorption of Ag on Be apparently are not manifested by changes in  $\sigma$ , since in both cases  $\sigma$  increases linearly with the thickness of the Ag layer. At the same time the energy distribution of the secondary electrons depends on the change in the emitter work function on agreement with the work of Kadyshovich<sup>13</sup>. In spite of the fact that the method of differentiating the curves of entrapment used in the present work is not satisfactorily accurate, the position of the maximum of the energy distribution curve obtained by the method of the retarding potential agrees well with the position of the same maximum obtained by Kollath<sup>14</sup> directly by means of magnetic analysis. This fact and also the good reproducibility of the results lead us to the conclusion that the other curves for various  $\Theta$  obtained by our method of

spherical condensers are also correct. As Figs. 10 - 11 show, the position of the maximum of the energy distribution curve of secondary electrons shifts to lower energies when electropositive atoms are adsorbed (for Ag on Ni at  $\Theta \sim 1$  by 1.8 ev) and to higher energies when electronegative atoms are adsorbed (for Ag on Be at  $\Theta \sim 1$  by 0.8 ev). This effect should apparently increase with an increase in the difference between the work functions of the adsorbed metal and the base, and with an increase in the separations of the maxima of their distribution curves.

To explain more fully the role of the work function in secondary emission it will be necessary to obtain the energy distribution curves by a method which yields directly the energy distribution of the secondary electrons and which allows simultaneous measurement by some means of the change in the work function of the base with a change in  $\Theta$ .

<sup>13</sup> A. E. Kadyshovich, J. Exper. Theoret. Phys. USSR 15, 600 (1945).

<sup>14</sup> R. Kollath, Ann. d. Phys. 39, 59 (1941).

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Translated by M. J. Stevenson  
232