UDC 537.533.9

A.N. Andronov

St. Petersburg State Polytechnical University

SECONDARY ELECTRON EMISSION AT VERY LOW ELECTRON ENERGY

A detailed review of experimental and theoretical studies of secondary electron emission (SEE) at low electron energies performed in the past has been given in this paper. It is shown that some present-day authors' statement on increase of the SEE yield up to unity while the primary electron energy tends to zero does not have sufficient theoretical justification and is inconsistent with the numerous experimental data obtained for various materials.

SECONDARY ELECTRON EMISSION, THERMIONIC EMISSION, LOW PRIMARY ENERGIES, ELECTRON REFLECTION FROM POTENTIAL BARRIER, CONTACT POTENTIAL DIFFERENCE.

I. Introduction

Secondary electron emission (SEE) from solids plays an important role in many areas of science and technology [1]. In the last few years, there has been a substantial renewed interest in the experimental and theoretical studies of SEE. A recent study proposed that the reflectivity of very low energy electrons from solid surface approaches unity in the limit of zero electron energy [2 − 4]. If this were the case indeed, this effect would have a profound impact on the formation of electron clouds in particle accelerators, plasma measurements with electrostatic Langmuir probes, and operation of Hall plasma thrusters for spacecraft propulsion [5, 6]. It turns out that the proposed high electron reflectivity at low electron energies is inconsistent with numerous previous experimental data obtained for secondary electron emission [7].

The goal of this article is to discuss possible causes of these contradictions.

II. Theoretical Description of Secondary Electron Emission in the Limit of Low Energy

A. Electron Reflection from the Surface Potential Barrier

According to quantum-mechanical laws, certain electrons falling on the vacuum-solid interface are reflected from it without penetration into the solid. Strict calculation of the reflection coefficient taking into account the atomistic potential field, the electrons' interaction with each other and inelastic interactions with the crystal lattice is impossible in principle in the framework of quantum mechanics. In this connection all known theories of electron reflection use a one-dimensional model of the real potential (Fig. 1), and consider only the part of the electron kinetic energy that is associated with the velocity component normal to the surface: $E_k = mv_x^2/2$.

In recent years several articles have been published where authors propose to describe the effective potential in the form of an abrupt potential step of height V_i at the interface (see potential *1* in Fig. 1) [1, 2]. Quantum reflectivity R at such a barrier is described by the simple expression

$$R = \left[\frac{E_k^{1/2} - E_s^{1/2}}{E_k^{1/2} + E_s^{1/2}} \right]^2, \qquad (1)$$

where $E_s = E_k + eV_i$ (V_i − internal potential).

The results of relevant calculations are shown in Fig. 2.

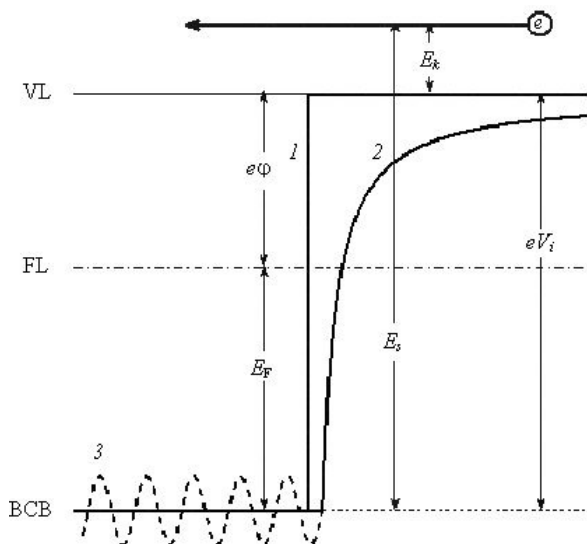Authors of Refs. [2−4] proposed an un-

Fig. 1. One-dimensional approximation
for the effective potential acting on the electron
crossing the metal surface: sharp step barrier (*1*);
barrier of the image force (*2*); Bloch model (*3*);
E_k , E_s − kinetic energies of the electron in vacuum
and inside the metal, respectively; E_F − Fermi energy;
V_i − internal potential; φ − work function; VL, FL −
vacuum and Fermi levels, respectively; BCB −
the bottom of the conduction band

realistically high value for internal potential
(150 eV) to obtain agreement with their own
experimental data (Fig. 2, curve *1*). J. Cazaux
[1] used the same model with a more realistic
value V_i (12.1 V for Cu), and adoption of those
values led to a more rapid decrease in R with
increasing energy (Fig. 2, curve *2*). But in any
case R tends to unity as energy approaches zero
for a sharp step barrier model.

Yet, nearly 100 years ago, W. Schottky
[7] proved that electron interaction with
the real surface of a solid target could not
be described by a potential barrier with a
sharp step. This allowed him to calculate the
dependence of thermionic emission current on
the external electric field, and this result was
very well confirmed by experiment (the so-
called Schottky effect). A similar approach was
used later in a one-dimensional model of the
effective potential near the surface of metal,
and this one is now considered to be the best
approximation to the real conditions.

According to this model an electron
experiences an image force at distances x more

than interatomic one in solids when the metal
surface can be considered as perfectly smooth
and perfectly conducting. At shorter distances
the metal surface cannot be considered as
perfectly smooth, and the work function is
determined by the dipole moments of surface
atoms, preventing the exit of electrons into
vacuum. In this region the potential is nearly
constant and equal to the inner potential V_i
of the solid which depends on material (see
barrier *2* in Fig. 1). In that case the dependence
of the effective potential V in vacuum on the
distance x to the surface in absence of an
external electric field is written as

$$V(x) = \begin{cases} -e^2/4x & \text{at } x \geq x_1; \\ -V_i = -e^2/4x_1 & \text{at } x \leq x_1. \end{cases} \quad (2)$$

Quantum-mechanical reflectivity R of slow
electrons at the barrier of such a form is taken
into account in the Richardson law for the
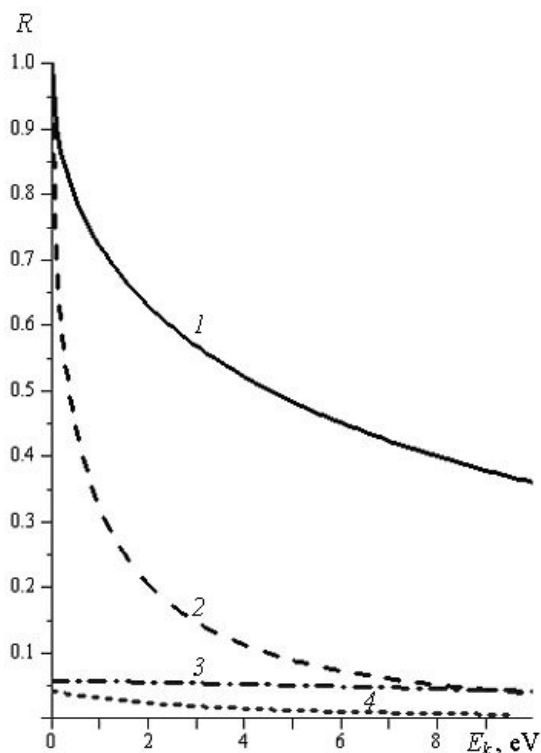thermionic emission current density J [9]:

Fig. 2. The reflection coefficient dependence on
electron energy for different approximate models:
Step Potential (*1*, *2*) at V_i = 150 V (*1*) [2 − 4]
and at V_i = 12.1 V (*2*) [1]; Image Force (*3*, *4*)
using WKB at V_i = 12.0 V (*3*) [10] and numerical
solution (*4*) [13]

$$J = A_0 T^2 D \exp\left(-e\varphi/kT\right), \qquad (3)$$

where A_0 is the Sommerfeld constant, $A_0 = 120.4$ A/cm^{2}K^2; D is the average transparency of the barrier, $D = 1 - R$; φ is a local work function of the sample, k is the Boltzmann constant, and T is an absolute temperature.

The Richardson law has been tested experimentally a lot of times and data obtained indicated that the average reflection coefficient of thermal electrons (energy in vacuum is less than 0.1 eV) did not exceed 10 %.

In the quantum-mechanical methods for the calculation of the barrier transparency the wave function inside the solid is always described by a plane wave. Outside the solid various approaches are possible and then both wave functions are cross-linked at interface.

So in the works [10, 11], the semiclassical Wentzel−Kramers−Brillouin (WKB) approximate solution of the wave equation was applied to problems of the transmission of electrons through potential barriers (Fig. 2, curve *3*). In this case, the reflection coefficient can be described [10] by the expression

$$R = \frac{(eV_i)^4}{16(E_k + eV_i)^3 + (eV_i)^4}. \qquad (4)$$

Here all the energies are in electron-volts.

In a more accurate calculation the wave function outside the solid is described by degenerate hypergeometric functions, and the solution is obtained using numerical methods [12, 13] (Fig. 2, curve *4*).

Thus the results of the most accurate estimations show that the quantum-mechanical coefficient of reflection at the surface potential barrier when $E_k = 0$ is a few percent (< 4.5 % for Cu), but other than unity.

B. Diffraction of Electrons at the Surface Potential Barrier

The Bragg reflection is often cited as the probable cause of the high reflection coefficient of the electrons incident on the surface [22]. This effect is possible if the electron with a certain energy and a direction has no allowed energy states within the solid. In this case, the electron cannot move inside and is to be reflected with a coefficient $R = 1$.

Theoretical description of such reflection in a one-dimensional model needs to take into account the periodicity of potential within the solid and the condition that the potential box with a flat bottom (see barrier *2* in Fig. 1) is replaced with a box (see barrier *3*, ibid.) whose bottom is profiled with the same periodicity (the Bloch theorem) [14]. Theoretical calculations for tungsten performed by this means [15] brought out that Bragg reflection should not take place at any crystallographic orientation of the sample surface. Many other researchers have also found that Bragg reflection could not play a significant role for low-energy electrons due to interference of Bloch waves in solids [22].

One more proof of the small value of the reflection coefficient at low energies is another diffraction effect, namely, periodic deviations from the Schottky law at high primary energies [16, 17]. The cause of this is that the electron waves are scattered both by the solid surface and by the maximum potential in vacuum. The distance between that maximum and that surface depends on the external electric field value and is responsible for resulting interference of these two waves scattered [18]. A detailed theory of this phenomenon [19−21] yielded good agreement with experiment, and in particular showed [22, 19] that the low-energy reflection coefficient is small and of the same order as the data of Ref. [13] (see curve *4* in Fig. 2).

Thus, the diffraction effects discussed above should not lead to a noticeable increase in the reflectivity of primary electrons at very low energies.

C. The Reflection from the Heterogeneous Surface (Fields of Patches)

The actual technological materials are, as a rule, polycrystalline (sometimes amorphous) and also their surface is always covered by adsorbate. This condition can cause the appearance of the surface areas with different work functions, and the contact potential difference arises between them. In certain situations, these contact fields (so-called «fields of patches») can lead to a substantial increase of electron reflection from inhomogeneous surface. This matter was discussed in detail by C. Herring and M.H. Nichols [22] who discovered that in the worst case, the maximum reflectivity at low energies did not exceed 60 %.

D. Backscattering in Volume of Solids

Additional contribution to the elastic reflection is caused by electrons scattered inside a solid target. Incident primary electrons are accelerated by the surface potential barrier to the value

$$E_s = E_k + E_F + e\varphi = E_k + eV_i$$

(see Fig. 1) and then they penetrate the solid target as deep as $50 - 100$ Å [23, 24]. Electrons lose their energy in that act, produce secondary electrons, and are also elastically scattered by atoms of the solid. This scattering can be described as a spherical electron wave, which is usually expanded in series of spherical functions (Legendre polynomials) P_l ($l = 0, 1, 2, ...$) [25]. Each term of this series describes the partial wave with angular momentum

$$\frac{h}{2\pi}\sqrt{l(l+1)},$$

where h is the Planck constant.

At $E_k < 10$ eV the wavelength λ of the electron is much greater than the interatomic distance r_{eff}:

$$\frac{\lambda}{2\pi} = \frac{h}{2\pi p} >> r_{eff}, \qquad (5)$$

where p is an electron momentum.

It means that the product of momentum and effective radius that determines the angular momentum should be subject to the inequality

$$\hbar >> pr_{eff} = \hbar[l(l+1)]^{1/2}, \qquad (6)$$

that could be satisfied only when $l = 0$.

Thus, only one zero term remains in the series expansion (so-called s-scattering). It is an isotropic one, its cross-section is determined by the atomic number of scattering atoms and does not depend on energy. Then only a half of electrons elastically scattered are scattered by an angle of more than $\pi/2$ (back-scattered electrons). These electrons also undergo the elastic and inelastic scattering on their way back to the surface, and only their small fraction reaches the surface with an initial energy $E_s \geq eV_i$. When an electron passes through the surface potential barrier in vacuum, only the electron momentum component normal to the surface changes whereas the parallel one does not. Therefore, if an electron has small kinetic energy E_k in vacuum, this electron

cannot overcome the potential barrier after scattering on atoms unless it scattered exactly backward by 180°. In the limit $E_k \to 0$, the contribution of these back-scattered electrons to the total elastic reflection tends to zero (not to unity). Thus, this process also does not increase the elastic reflection up to a full 100 percent reflection with the kinetic energy of the electrons in vacuum decreasing to zero.

E. True Secondary Electron Emission

It is commonly accepted [7] that the total secondary electron yield σ is only a sum of true secondary emission coefficient δ and the coefficient R of elastic reflection when the primary electrons energy is less than 50 eV (electrons back-scattered inelastically are ignored). The penetration depth of primary electrons with very low energies E_k into a solid is much smaller than the escape depth of secondary electrons excited inside, and because of this fact all such electrons can escape into vacuum with some probability P depending on the properties of the target material. Then

$$\delta = P\frac{E_K + eV_i}{\Delta E} \text{ at } E_k = E_s - eV_i \geq 0, \quad (7)$$

where ΔE is an average energy needed to excite one secondary electron.

Thus $\delta \to 0$ at $E_k \to 0$, and total secondary yield is determined by reflection coefficient only.

In summary, the correct theoretical description of the secondary electron emission in the limit of very low energy reveals that the total secondary electron yield does not exceed 60 % and its value is much less in most cases.

III. Experimental Considerations of the Secondary Electron Emission Yield at Very Low Energy

A. Specific Features and Challenges of Secondary Emission Measurements

Experimental measurements at low incident electron energy, below 1 eV, are extremely challenging. It is very difficult (if at all possible in the present day) to produce a collimated aligned electron beam at such low energy. Another problem is that a monochromatic electron beam is required to obtain the correct experimental data at these energies. In the current state of the art a technique of obtaining

electron beams with the energy spread about 10 meV is being developed; it is used in High-Resolution Electron-Energy-Loss Spectroscopy (HREELS) [26 − 28], but at higher energies of primary electrons (a few electron-volts). In addition, this method allows making only relative, not absolute estimates of the number of secondary electrons.

For this reason, electron thermionic guns without a monochromator are commonly used in experiments to determine SEE yield at very low energies [1]. These guns have a rather broad electron energy spread (a full-width at half maximum (FWHM) is of 0.5 eV at best) which is not negligible with respect to electron energy. This calls into question the experimental data obtained at lower energies. In addition the true energy of primary electrons arriving at the surface of the sample is determined not only by the potential difference between the cathode of the gun and the surface but also by the contact potential difference between them.

Two basic approaches to such measurements have been developed. The first one (hereafter referred to as method 1) is to create an electron-optical system for the electron gun to be stable at energies of 2−5 eV with the proper neutralization effect of parasitic electric and magnetic fields [7]. In another approach (method 2), the accelerating voltage of the electron gun is kept constant (30 V in Ref. [3]) and the incident energy is decreased by an increase of the negative bias of the sample instead of a decrease of the nominal beam energy. Such a bias leads to constant potential surfaces in the vacuum gap on which the incident electrons may be totally reflected and then collected without any contact with the sample surface [1]. It may be wrongly interpreted as an increase of the reflection coefficient from the solid to unity whereas the energy of primary electrons tends to zero.

A similar experimental setup is commonly used to measure a contact potential difference between a cathode and a target with the help of an electron beam (so-called «the Anderson method» [29−31]). In this case it is very important that the primary electrons moving to the target in the nonuniform retarding electric field have to cross its field lines strictly normal

to them all along their way. If this condition is not satisfied electrons deviate from the initial trajectory and acquire a velocity component v_{tang} parallel to the sample surface. Correspondingly, the normal component v_x should be reduced as well. As a result, the initial part of the dependence of the measured secondary emission current from retarding voltage (so-called «retarding curve») could expand up to several electron-volts because of the spread of v_x in the primary electron beam.

It is difficult to say anything with certainty without knowing the details of the experimental adjustment position of the electron beam at the sample surface in Ref. [3], but the effect mentioned above might well be one of the probable causes of the increase of the electron reflection to unity and a rather broad initial part of the curve 1 in Fig. 3. For comparison, this figure shows the results (obtained earlier by method 1) for the copper film deposited and heated in vacuum [32] (see curve 2 in Fig. 3).

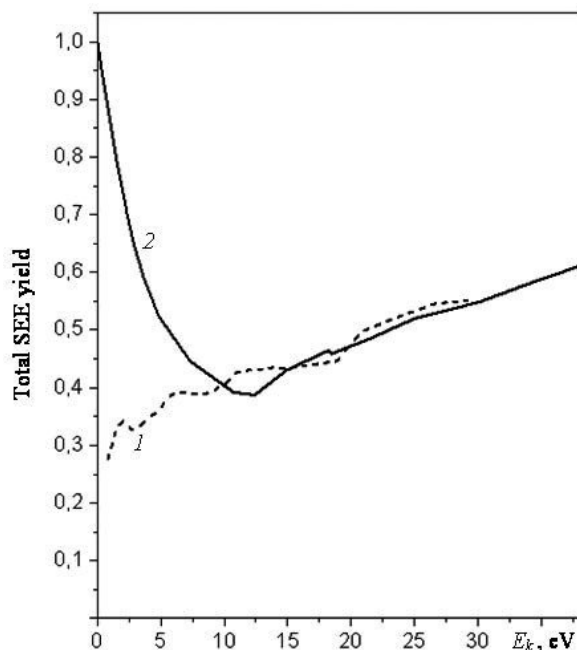It is evident from Fig. 3 that there is sufficiently good agreement between two

Fig. 3. Experimental total secondary electron emission yield of Cu as a function of low primary electron energy E_k, obtained by methods 1 (1) [32] and 2 (2) [3];
samples were heated in vacuum, room temperature (1); were fully scrubbed, $T = 10$ K (2)

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data sets for $E_k > 10$ eV, but there are drastic differences for $E_k < 10$ eV. However, the data of Ref. [3] were taken for a cryogenically cooled target whereas data of Ref. [32] were taken at normal conditions. But we do not know now any convincing arguments why this might lead to such a significant difference in the results.

To conclude this brief overview of the experimental challenges of measuring secondary emission at very low energies we should once again remind that method 2, which is used in most of the works of our time, is very sensitive to all kinds of inaccuracies in the tuning of the experimental equipment. For this reason, there is a very large discrepancy in the experimental data of different researchers. For example, making use of such approach authors of Ref. [33] reported a reflection coefficient of 40 % whereas authors of Ref. [34] reported a reflection coefficient of 100 %.

Therefore, to compare theory with experi-mental data, it is preferable to use the results obtained without the deceleration of electrons on the way from the gun to the sample (method 1). Some of the similar results will be presented in the next section as an example.

B. Experimental Data on the SEE Yield of Some Materials at Low Primary Energies

Most measurements of secondary emission of various materials using low-voltage electron guns (method 1, $E_k > 2$ eV) were made in the middle of the last century in the former Soviet Union (e. g. [7, 35−38 and others]). A very large part of these measurements (though not all of them) was made by the research team of Professor I.M. Bronstein, who was then known as the "Mendeleev of secondary emission" [39].

For illustration the measurement results for secondary emission properties of some materials at low primary energies are given in Fig. 4.

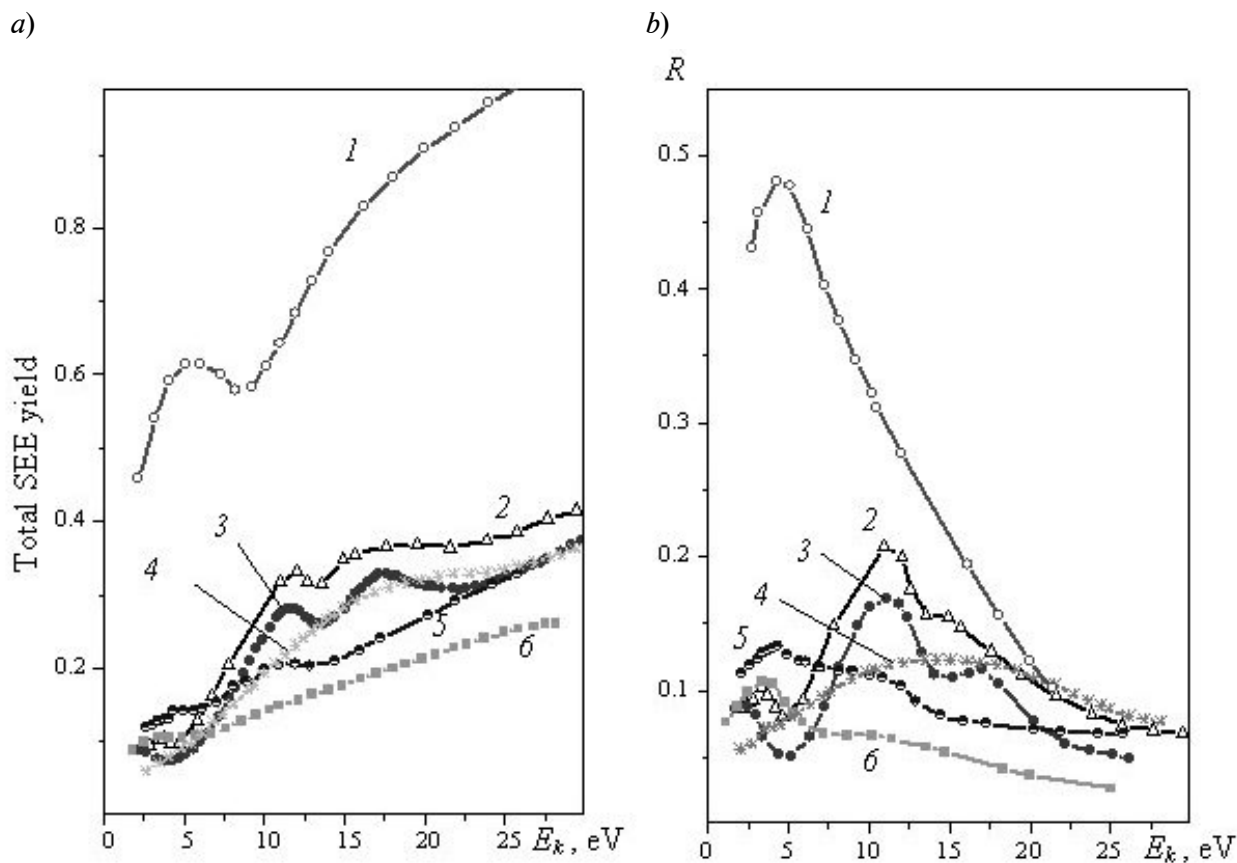Similar results were also obtained for

a) *b)*

Fig. 4. Experimental data on total SEE yield (*a*) and reflectivity (*b*) as a function of low primary energies for MgO (*1*) [38], Au (*2*), Ag (*3*), Al (*5*), Ni (*6*) [32, 35] and Ta (*4*) [36] samples, subjected to thermal cleaning in vacuum
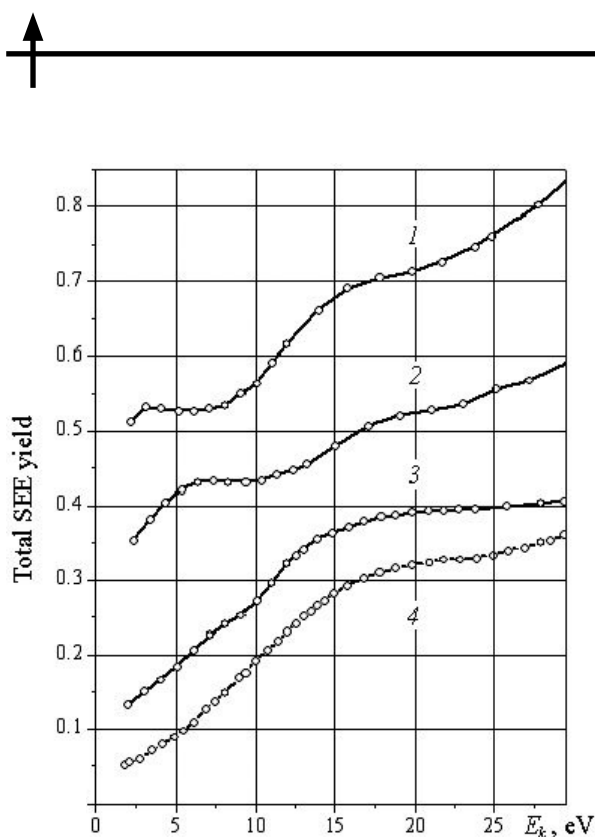
Fig. 5. SEE of tantalum samples as a function of low primary energies at various stages of their thermal cleaning in vacuum [36]: untreated (*1*), $T = 1300$ °C for 2 h (*2*), $T = 2000$ °C for 5 min (*3*), $T = 2300$ °C for 10 h (*4*)

other materials such as Mo [36], Pt and single crystals of Cu [40] and Ge [40, 41], number of refractory metals and alloys [42], different faces of a W single crystal [43, 44], some oxides [45] and alkali-halide compounds [46−48], and that is not a complete list of earlier publications.

Nevertheless, no one received then any reliable experimental evidence that SEE yield tends to increase up to unity at $E_k < 2$ eV.

Another problem seeing a rebirth of interest nowadays [1, 2 − 4, 49] is the influence of surface contamination, adsorbates and previous pre-treatment of the sample surface on secondary emission at low energies.

This question was also highlighted in the past when it was shown that the surface cleanliness was a key factor of correct SEE yield measurement at low energies and that all untreated metals were characterized by their very similar dependences on primary energy [7].

Experimental results dealing with the change of secondary emission properties of tantalum in the process of thermal cleaning in vacuum are presented as an example in Fig. 5.

At the same time the SEE yield of contaminated surfaces is always less than unity when primary energies are low although its value is usually significantly higher than that of the samples subjected to vacuum cleaning.

Thus a lot of experimental data do not support the hypothesis that the total SEE yield should tend to unity when the energy tends to zero.

IV. Conclusion

In summary, we have presented an analysis of some theoretical and instrumental problems which arise when the energy of primary electrons striking the sample is very low. It has been demonstrated that the theoretical model in Refs. [1, 3] is too simplified and leads to an incorrect conclusion about increasing secondary emission yield up to unity in the limit of very low-energy primary electrons. This conclusion is supported by numerous previous experimental studies of secondary emission properties of various materials at low electron energies which have shown that in most cases the value of this coefficient should not exceed a few percent at energies below 1 eV. Therefore we do not see satisfactory arguments in favour of the statement that closeness to unity of secondary emission coefficient at low energies is the main origin of electron clouds in different plasma systems.

Unfortunately, a lot of present-day physicists are not very familiar with the theoretical and experimental results obtained at the beginning of the last century. This publication is trying to remind everyone these results and recall that we should not once again "reinvent the wheel", since it does not always lead to the desired results. "The new is well-forgotten old".

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THE AUTHORS

ANDRONOV Alexander N.
St. Petersburg State Polytechnical University
29 Politekhnicheskaya St., St. Petersburg, 195251, Russia
andronov@rphf.spbstu.ru

Андронов А.Н. ВТОРИЧНАЯ ЭЛЕКТРОННАЯ ЭМИССИЯ ПРИ ОЧЕНЬ НИЗКИХ ЭНЕРГИЯХ ЭЛЕКТРОНОВ.

Приведен подробный обзор выполненных в прошлые годы экспериментальных и теоретических работ по вторичной электронной эмиссии (ВЭЭ) при низких энергиях электронов. Показано, что утверждение ряда современных авторов о возрастании до единицы коэффициента ВЭЭ, когда энергия первичных электронов приближается к нулю, не имеет достаточного теоретического обоснования и противоречит многочисленным экспериментальным данным для различных материалов.

ВТОРИЧНАЯ ЭЛЕКТРОННАЯ ЭМИССИЯ, ТЕРМОЭЛЕКТРОННАЯ ЭМИССИЯ, НИЗКИЕ ЭНЕРГИИ ПЕРВИЧНЫХ ЭЛЕКТРОНОВ, ОТРАЖЕНИЕ ЭЛЕКТРОНОВ ОТ ПОТЕНЦИАЛЬНОГО БАРЬЕРА, КОНТАКТНАЯ РАЗНОСТЬ ПОТЕНЦИАЛОВ

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СВЕДЕНИЯ ОБ АВТОРАХ

АНДРОНОВ Александр Николаевич *− кандидат физико-математических наук, профессор кафедры физической электроники Санкт-Петербургского государственного политехнического университета.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
andronov@rphf.spbstu.ru