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APPLICATION FEATURES OF THE ELECTROSTATIC SYSTEMS FOR MEASURING THE SECONDARY ELECTRON EMISSION YIELD

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The analysis of the experimental systems for research of secondary electron emission during the interaction of electron beams with matter is presented. The three most common and methodologically developed variants of experimental systems are considered. According to their design features and methodological capabilities, they allow for the study of the main parameters of secondary emission depending on the primary electron beam energy and the sample thickness. The evolution of the experimental measuring systems and their improvement from simple to three-electrode systems with pass-through collectors is considered too. The peculiarities of registration of the secondary electrons current emitted from the studied target surface depending on the structural features of the target device are considered too. Application results of the developed three-electrode measuring system for research thin foil emission characteristics have been discussed.

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INTRODUCTION

The study of the phenomenon of secondary electron emission (SEE) during the last century is inextricably linked with the development of technologies not only in the electro technical field (radio and instrument engineering: secondary-electronic, photon-electron multipliers, microchannel plates, etc.), but also a number of fundamental directions that make it possible to conduct comprehensive research in solid-state physics (electron detectors of scanning electron microscopes), plasma physics (formation, development and maintenance of high-frequency discharge and secondary emission discharge in microwave structures), accelerator physics (secondary emission monitors, multifactor discharges, etc.). The acquired knowledge ensures the sustainable development of future technologies, which include space, nuclear and thermonuclear technologies.

At one time, the rapid development of cathode electronics first of all required researchers to conduct experimental research, the purpose of which was to optimize the emission parameters of materials, in particular, to increase the yields of secondary electron emission and reduce the output work. The accumulated experience from the experimental study of secondary electron emission induced by electron beams allowed developing and deepening knowledge about the phenomenon of secondary electron emission during the interaction of various types of ionizing radiation (gamma quanta, neutrons, protons, etc.). At the same time, a comparison of results was carried out, generalization of knowledge, which makes it possible to understand the nature of the phenomenon itself, to predict, to optimize the secondary emission properties of materials according to the tasks or, for example, technical or technological requirements. That is, it is important to know about the emission properties of the material depending on the specific conditions of its use (type and parameters of irradiation, temperature regimes, pressure, etc.).

Among the wide range of available experimental data, one feature should be highlighted: with a sufficiently high rate of development of accelerating complexes of charged and neutral particles, it was possible to conduct research and partial systematization of knowledge on the interaction of ionizing radiation with matter in a wide range of energies of primary particles precisely at the atomic level. To establish and investigate the main processes that occurs when a substance is irradiated, to determine the kinetics of the radiation-stimulated effect, to gain new knowledge about the nature of matter and the peculiarities of its structure.

As is currently known, the phenomenon of secondary emission of electrons plays an important role in the accelerating technique of beams of high-energy electrons, ions, etc. For example, there is a purely applied one: for on-line measurement and observation of accelerated beams in their transport systems, and of course the fundamental one – transportation and retention of high-energy beams during interaction with the residual gas of the vacuum system, development of beam stabilization systems on the main trajectory, etc.

The main goal is demonstration of the experimental systems possibilities for the study of secondary emission outputs on the example of the interaction of electron beams with matter, to generalize knowledge, methods and methods of obtaining data on the main parameters of the distribution of secondary emission depending on the energy of the primary electron beam when using the specified systems.

1. PHYSICAL BASIS OF SECONDARY EMISSION

Well known the low energy secondary electrons emitted out from the surface layer of a solid body, the thickness of which, according to various estimates, does not exceed 10^{-6} cm. The number of ejected electrons depends on the energy and type of particles in the primary beam and the properties of the irradiation material (on the charge of atoms, amorphous or crystalline structure, the presence of impurities or a surface oxide or non-conductive layer, etc.). In general, the secondary emission coefficient value increases as the velocity of the primary particles increases, then reaches a maximum, and finally decreases for very fast particles that penetrate the material to a considerable depth, from where it is difficult for secondary electrons to escape the surface target.

Energy spectra and angular distributions of secondary electrons contain fairly complete information about the basic microscopic characteristics of the surface-composition, structure, electronic state. Also distinguish between electrons diffraction in secondary electron emission, which are divided into two subspecies, namely the diffraction of slow electrons and the diffraction of reflected fast electrons, when using high-energy particles, the primary and secondary particles channeling effects in single-crystalline structures are important too.

In the energy spectra, secondary electrons (SE) are divided into three main groups:

– Low energy electrons with energy up to 50 eV, which are knocked out of the valence zone or conductivity zone;

– High energy δ-electrons with $E_{max}=E_0/2$;

– Auger electrons usually with energy up to 10 keV.

Depending on the requirements of experimental research, the SEE measurement system is set up to registration of one or more energy ranges. Accordingly, obtaining complete information from the distribution of the SEE throughout the energy range is a very technically complex task, so sometimes they focus on which certain area of the energy spectrum when there is an integral yield only.

As mentioned earlier, the SEE yield characteristic has a rather complex dependence versus the energy of the primary electrons, which is caused primarily by the change in the ionization losses of electrons in the material. The corresponding dependence is presented in Fig. 1. It demonstrates a comparison of calculation results (line) and a small amount of experimental data of SEE for aluminum and gold targets, described in details in [1]. For primary electron energy range $E_0 \rightarrow 1$ MeV, the SEE yield (δ_{se}) decreases proportionally to $1/\beta^2$. At $E_0 > 1$ MeV, it increases due to multiple electron scattering, and for ultrarelativistic case, δse increases in proportion to the $ln(E_0)$.

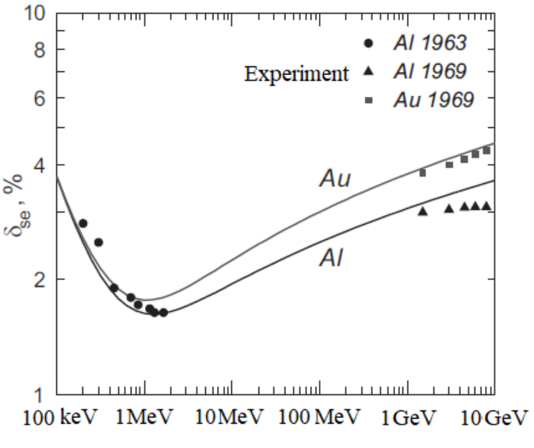

Fig. 1. Comparison of experimental and calculated data on the secondary emission coefficient for Au and Al

For practical application in order to estimate the SEE yield, a number of assumptions are sometimes allowed, which greatly simplify obtaining sufficiently accurate calculation data. Namely, the SEE yield is proportional to the specific energy loss *dE/dx* of primary electrons per unit their path length in the substance, and secondary emission electrons have a characteristic mean free path length. These assumptions make it possible to calculate the secondary emission coefficients in the following form:

$$\delta_{se} \approx \left(dE_0/dx\right) \cdot \Delta x/\varepsilon \cdot \cos(\theta), \qquad (1)$$

where ε is the average energy required to knock out one secondary electron; Δx is the thickness of the near surface layer from which secondary electrons are emitted; θ is the incidence angle of primary particle beam. In the case when the maximum energy of SE is no more than 50 eV, which is significantly less than the energy of the primary beam, then ε and Δx in this approximation should be considered independent of E_0. As follows from expression (1), the SEE increases with an increase in the angle θ. According to formula (1), for *Al*, the ratio $\varepsilon/\Delta x$=90 (MeVμcm^2)/g, and for *Au* - $\varepsilon/\Delta x$=55 (MeV·cm^2)/g.

Electron ionization losses data, namely their dependence on the energy of primary electrons and the density effect contribution, are used for more correct calculations of SEE yields. This makes it possible to consider the phenomenon of secondary emission more broadly, taking into account the characteristics of each energy range [2]. There are the dependences of the total ionization losses and their components (collision losses and delta electron emission), as well as the influence of the density effect factor, are presented too. It should be noted that, on the one hand, for primary electrons require knowledge of total ionization losses depending on their energy and the layer thickness. And absorbed energy and a certain excitation of layer occurred both due to electron-electron collisions and during the interaction of the Coulomb field of the incoming relativistic electron with free conduction electrons (therefore, the influence of the density effect is determined depending on the energy of the primary electrons). On the other hand, the vast majority of secondary electrons after exiting the surface have a maximum energy of about 50 eV. Taking into account their ionization losses causes difficulties. Since there are uncertainties in this range of energies, in addition, their exit is affected by a number of factors related to the passage of the material-vacuum boundary, which is characterized by the presence of a double layer (the so-called Schottky effect).

2. DISCUSSION OF SEE EXPERIMENTAL RESEARCH

The first discussed system considered is the system that allows obtaining yield of secondary electrons depending on the temperature of the samples and the energy of the primary electron beam (up to 2000 eV).

In fact, this is the case when the irradiated surface of a thick target is a source of secondary electrons emitting in the opposite direction from the primary electron beam irradiation [3], which excites a certain near-surface layer of the target. These systems were widely used to study the secondary emission of various cathodes for cathode electronics needs. The Faraday also works according to a similar principle. To ensure the correctness of the measurement of the absorbed current of primary currents, a system of delay or suppression of secondary currents is used, which ensures the effect of complete absorption.

Usually, the energy of the primary electron beam for such measuring system type is several kiloelectronvolt, which makes it possible to distinguish true secondary electrons from backscattered ones in the spectra of secondary electrons with the help of electrostatic analyzers. Expanding the energy range for such systems does not make it possible to increase the secondary electron yield, as total ionization losses and, accordingly, the transfer of energy to secondary electrons decrease.

In Fig. 2 typical dependences of the secondary electron emission coefficient presents depending on the energy of the primary beam for the Cu-Al-Be alloy at different sample heating temperatures. From the presented data, it can be seen that in the temperature range from 20 to 500°C, the maximum of the SEE is in the energy range from 400 to 800 eV of the primary electron beam, and it slightly decreases with increasing temperature.

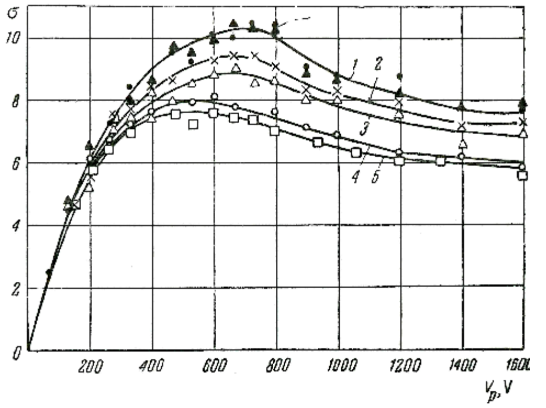

Fig. 2. Dependences of the SEE yield for the Cu-Al-Be alloy for temperatures: 1 – 20 °C; 2 – 100 °C; 3 – 250 °C; 4 – 400 °C; 5 – 500 °C [3] versus primary electron beam energy

Dependencies in Fig. 2 obtained in the regime of the maximum value of the extraction potential on the collector, which makes it possible to estimate the SEE integral yields depending the heating temperature target and the energy of the primary electron beam. As can be seen, in fact, the conditions close to the operation of elements of cathode electronics systems have been repeated. This approach allows conducting not only fundamental research, but also working out the technological aspects of implementation and working out the method of activation of this type of cathodes to ensure optimal conditions for their operation.

In Fig. 3 presented a series of voltage-current characteristics (VAC) measured for the same alloy, respectively, in the indicated temperature regime [3]. Scanning was carried out in the range of potentials from -50 to 100 V. It is characteristic of this type of VAC that in the area of retarding potentials, the coefficient of secondary emission goes to zero. In the region of positive potential values (from 0 to 100 V), there is a change in the behavior of the I-V characteristic depending on the sample temperature. As a result, an increase in the temperature of the studied sample does not greatly affect the spectrum of electrons in the area of retarding potentials, but significantly changes the distribution in the area of extraction potentials, which indicates the existence of a dependence of the saturation yield of secondary extracted electrons on the temperature of the alloy sample.

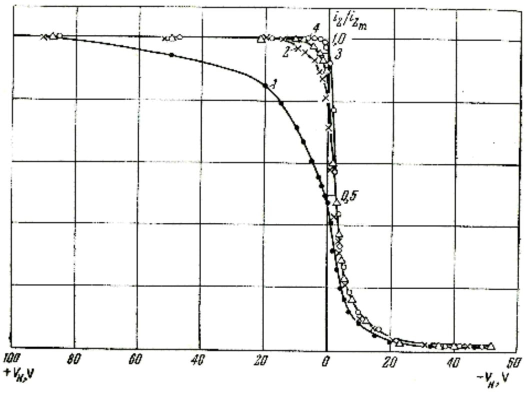

Fig. 3. Typical VAC curves [3] measured by spherical electrostatic analyzer system for Cu-Al-Be allo: 1 – 20 °C; 2 – 250 °C; 3 – 350 °C; 4 – 400°C

Thus, the application of the specified system makes it possible to determine the dependence of the secondary emission coefficient on temperature and the energy of the primary beam directly from the area of sample irradiation. When differentiating the I-V, it is possible to obtain the energy distribution of secondary electrons in the region up to 100 eV.

In contrast to the previous version of the measurement system, systems that allow for a more extensive investigation of the effects associated with SEE are also considered. These systems are used on high-energy beams (from 1 MeV and above). The development of such techniques was facilitated by the need to monitor accelerated beams in on-line mode, namely control of the stability of the accelerated particle beam current during accelerator operation.

The second example is a SEE measuring system that is a combination of three thin films (collector-emitter-collector) and is practically a simple monitor of the primary electron beam (primary beam energy megaelectronvolt range), which makes it possible to study the yield of secondary low-energy electrons from both surfaces of a thin film, in the absence of an opportunity to study the delta electron yield.

The thin film application in the mentioned systems opens up new opportunities for researching the mechanisms of SEE. Since it is possible to study SEE on the beam passing mode, to compare SEE yields from the front and back foil surfaces (prerequisites for determining the influence of the density effect), to conduct in situ relative measurements of SEE according to a standard sample. In addition, to obtain data from the delta electrons yield, which are mainly directed along the trajectory of the primary beam is realized.

When an electron beam passes through a thin film, the current of secondary electrons will consist of three components (for the case when the primary electrons are not absorbed and the background low-energy electronic component that can be absorbed is also absent): n_1 – secondary from the front surface in relation to the direction of movement, the case of [3]; and n_2 – those moving along the direction of the primary beam trajectory and consisting of two components, low-energy and delta electrons. When a negative potential (about -50...-100 V) is applied to the emitter, conditions are created for obtaining data on the maximum SEE yield – the "saturation region". When a positive potential (+50 V) is applied, all low-energy electrons will be retained on the surface sample, the main contribution to the emission current from the film will be the delta electron yield with the maximum energy value $E_0/2$). As can be seen from the peculiarities of the flow of SEE processes on thin films, research using the system presented [3] is only a partial case in comparison with experiments of the beam passing mode.

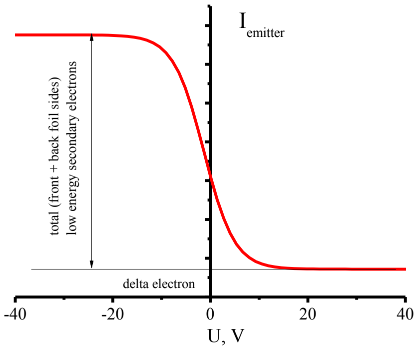

Fig. 4. VAC thin film during high energy electron beam passing

The main advantage of this system is the ability to study the delta electron yield, but it is not possible to obtain data from the secondary electron yield on each surface separately. Since the saturation region (Fig. 4) $I_{emitter}$ – corresponds to the total yield of SEE from both surfaces, and accordingly, the differentiation of I-V makes it possible to obtain only an integral characteristic of the energy spectra of SEE (i.e. $n_1 + n_2$). In addition, the specified system is very sensitive to background conditions; for example, the presence of scattered low-energy electrons in the electron beam transport system will accordingly lead to a distortion of the values of the true currents due to their absorption. An underestimation of the value of the positive current or even a transition into the negative region will be observed in the VAC.

The logical continuation of such a measurement system development was the use of three thin films (sandwich technique), the middle of which is the emitter, and the two extreme ones are collectors. Schematically, the principle of operation of this system is shown in Fig. 5.

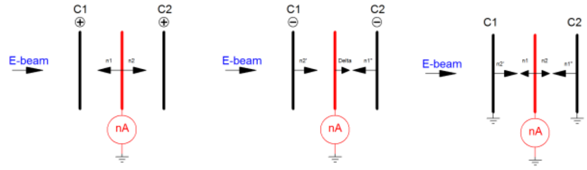

Fig. 5. Scheme of the three foil system, C1 and C2 – collectors, the middle one – emitter, but the test sample is constantly connected at ground potential

Collectors in this case protect the test sample from the influence of background low-energy electrons but have their own shortcomings and difficulties that must be considered when processing the VAC of the measurement system in question.

This version of the SEE measurement system is characterized by the effect of compensating or amplifying the SEE of the emitter due to the additional emission of collectors C1 and C2. But it is already possible to distinguish emission currents from the first and second surfaces separately, provided compensation is taken into account. For the case when C1=C2≥50 V, then $I_{emitter} = n_1+n_2$. When using full blocking when C1=C2 ≥ -50 V, $I_{emitter}=\delta-n_2'-n_1'$ for $U \geq$-50 V, as a result, in the specified region, the VAC has negative current values, since the low-energy emission electrons of C1 and C2 compensate for the emitter current losses due to the emission of delta electrons. And the last mode, but important, is when C1=C2=0, then $I_{emitter}=n_1+n_2-n_2'-n_1'$, which is actually compensation of all emitter charge losses due to the emission of collectors C1 and C2, provided that all three foils are of equivalent thickness relative to the primary beam of accelerated electrons.

The specified system was used in [4] to measure SEE yields, the scheme of which is presented in Fig. 6 and VAC curves were obtained (Fig. 7) when appling a beam of accelerated electrons with an energy of 0.3…1.6 MeV of the Van de Graaff accelerator. The SEE yields of carbon, nickel, and aluminum thin foils were studied. The thickness of the collector foils was 1.8 mg/cm^2.

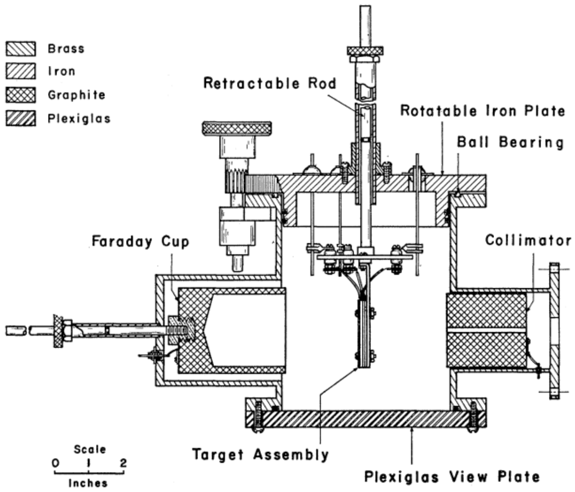

Fig. 6. Experimental chamber for the study of SEE using three thin films (sandwich technique) for beam passing mode

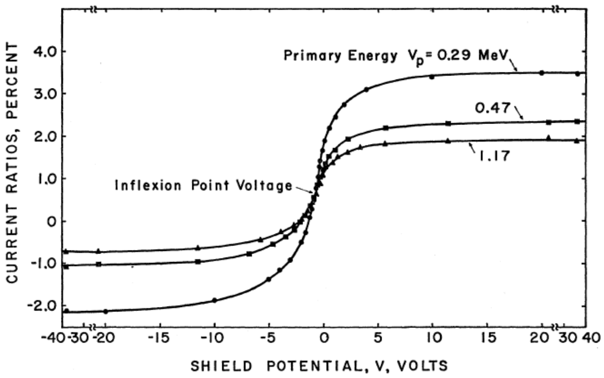

Fig. 7. Typical experimental VAC measured by three foil system for beam passing mode. Primary electron beam energies are 0.29, 0.47, and 1.17 MeV

The experimental chamber was equipped with a collimator, which reduce the influence of the background scattered electrons on the measuring system. The target holder was mounted to goniometer, which enables angular scanning operation only in one plane. The primary beam current was measured using a total absorption Faraday cup.

The specified scheme was also used to study the SEE yields according to the standard foil in the case of applying doubled system for beam passing mode. Schematically, such a system is shown in Fig. 8 [5]. The direct electron current of the primary beam with an energy of 70 MeV was measured using a total absorption Faraday cup.

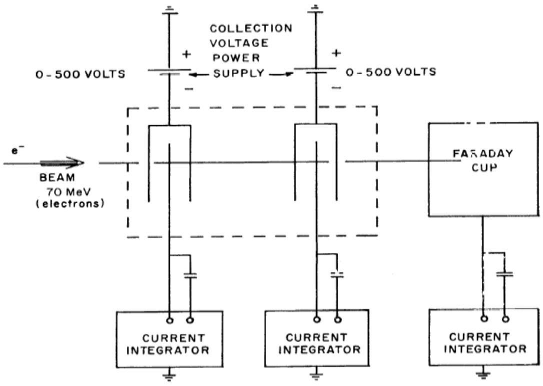

Fig. 8. Schematic diagram of SEE yield measurement with standard foil technique application

Such technique application is possible only on beams of accelerated particles of sufficiently high energy to minimize losses on all foils of the primary beam due to its absorption and scattering. This technique should be considered as auxiliary, since it does not provide an opportunity to measure "pure" VAC.

The third proposed and realized system, in the presence of pass-through collectors and a thin film placed between them, allows researching the integral yield of delta electrons and the low-energy emission yield in the range of collector potentials ±100 V. The main advantage of the latter over the above-mentioned is the possibility of conducting experimental studies of relativistic effects (influence density effect) in a wide range of film thicknesses and, accordingly, primary beam energies (from 1 MeV to GeV range). Because it provides the measure SEE yield from every side of the experimental foil separately.

In the implementation of the scientific research of the IHEPNP NSC KIPT, a multifunctional experimental beamline [6] was developed for the study of the interaction of high-energy electron beams (intermediate – 2 MeV and relativistic energies – 10...30 MeV) with amorphous and single-crystal structures. When using the specified experimental equipment, a series of studies of SEE yields for thin aluminum films (8...100 μm) [7, 8] versus the primary electron beam energy up to 30 MeV were carried out. The scheme of experimental is presented in Fig. 9.

The proposed measurement scheme in terms of the geometrical parameters of the target device is a modification of the previous one, namely, three foils or a sandwich technique. Aluminum disks (1 mm thickness) with 16 mm diameter through hole were used as collectors. The distance between the emitter and the collector is 5 mm. The potential on the collectors is independently adjustable in the range from -100 to +150 V. The photography of the collector is shown in Fig. 10. To equalize the distribution of the electric field in the collector-emitter gap, a thin grid is installed on the collector through-hole of 16 mm, on the one hand, its contribution to the SEE from rods system on the emitter will be minimal, on the other hand, the reduction of VAC distortion due to the uniform distribution of the electric field.

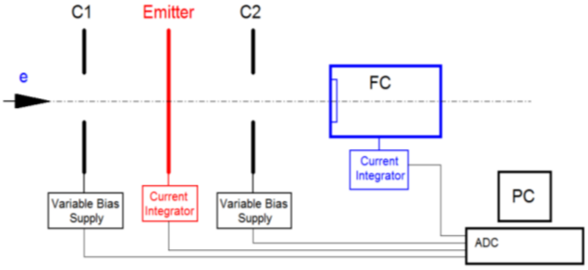

Fig. 9. Experimental scheme of the SEE measurements

Fig. 10. Collector view, it upgraded by AlSi (1%) rod system with 25 μm rod diameter and distance between rods – 1 mm

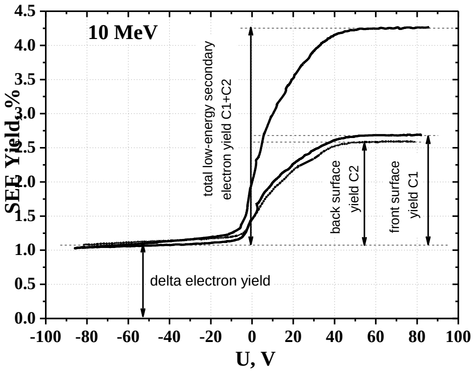

Fig. 11. Typical VAC from 50 μm Al foil, primary electron beam energy 10 MeV

In Fig. 11 the experimental results obtained using the specified system for 50 μm Al foil for primary electron beam energy 10 MeV present. The peculiarity of the modified system is that, in comparison with the other considered ones, it allows a wider study of the SEE phenomenon, namely: the delta electron yield, the SEE from the front foil side (curve C1) and the back (C2), and their summary yield separately (C1+C2). In fact, the system allows to scan the energy of low-energy electrons depending on which side of the target (film) they emit, for this, a retarding potential (about -80 V) is applied to one of the collectors, and scanning is performed in the range of potentials -80...+80 V to the other, then vice versa. When it is necessary to obtain an integral VAC (taking into account the SEE of both surfaces of the investigated foil), the potential on C1 and C2 is given the same and in the specified range of potentials, the dependence of C1+C2 is measured. In addition, it should be noted that this approach allows checking whether there is a contribution from background scattered electrons, since the sum of the experimental values of currents C1 and C2 (in the saturation region corresponding to ~50 V) should be equal to the total experimental yield C1+C2.

CONCLUSIONS

Thus, the evolution of SEE measurement systems during the interaction of primary electron beams with a solid body (peculiarities of processes in thick and thin targets) was presented. It is shown that with an increase in the energy of the primary beam, the design of the measuring system and methodical approaches to conducting SEE studies change accordingly.

The analysis of measurement systems showed the need for mandatory control of the temperature of test samples, to clearly distinguish the contribution of heating and radiation-stimulated influence of a beam of primary particles in the outputs of VEE.

It is necessary to fulfill the requirements for the accelerated particle beams in the experiments for the study of SEE not depending on the energy range, namely the energy spread – because there is a dependence of the low-energy electron yield for primary energies of about 2000 eV, transverse dimensions and angular divergence – because the systems are limited by the geometric dimensions of the targets and collectors, stability over time – storage of the beam parameters during the measurement, for example, three VAC curves: C1, C2, and C1+C2.

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ОСОБЛИВОСТІ ЗАСТОСУВАННЯ ЕЛЕКТРОСТАТИЧНИХ СИСТЕМ ДЛЯ ВИМІРЮВАННЯ ВИХОДУ ВТОРИННОЇ ЕЛЕКТРОННОЇ ЕМІСІЇ

С. Карпусь, І. Шляхов, М. Лящов, В. Борисенко, С. Кочетов, Є. Цяцько, О. Шопен

Проведено аналіз експериментальних систем дослідження вторинної електронної емісії при взаємодії електронних пучків з речовиною. Розглянуто три найбільш поширені та методологічно розроблені варіанти експериментальних систем. За своїми конструктивними особливостями та методичними можливостями вони дозволяють досліджувати основні параметри вторинної емісії залежно від енергії первинного електронного пучка та товщини зразка. Розглянуто еволюцію експериментальних вимірювальних систем та їх удосконалення від простих до триелектродних систем з прохідними колекторами. Розглянуто також особливості реєстрації струму вторинних електронів у залежності від конструктивних особливостей пристрою мішені. Обговорено результати застосування розробленої триелектродної вимірювальної системи для дослідження емісійних характеристик вторинних електронів з тонкої плівки.