Electron spectroscopy methods are widely used in scientific research and for technological purposes. The main element of spectrometers is an analyzer of charged particle beams. Electrostatic mirror systems are widely used due to their simpler practical realization. At their development two purposes were set: to improve the quality of spatial focusing of charged particles or to increase the value of linear energy dispersion. The objects of the study are electrostatic systems characterized by small sizes, simplicity of stabilization and localization of the working field and its shielding from the external electromagnetic disturbances. From all the known types of energy analyzers, suitable for the analysis of solid surfaces, preference is given to those that have good electron-optical properties, are simple in manufacture and operation. Therefore, spherical and cylindrical mirrors, which have become a basic tool for firms producing spectrometers, have been chosen as the object of study. The work solves the problem of expansion of the functional capacities of these systems by, firstly, combining several research methods in one device; and secondly, by solving specific narrower problems. A photoelectron or Auger spectrometer with an increased scanning area is proposed, where the initial angular opening of the beam 4° after passing a cylindrical mirror is increased to 10°, and the image smearing is reduced to 0.05 %. An Auger-electron spectrometer for analysis of rough surface has been developed, which allows to increase the probing depths by more than 5 times. A double filter type energy analyzer is calculated. Energy resolution was improved to 1.37 % by eliminating potential barrier smearing in low energy filter mode. Previously, the energy resolution was limited to 10 % due to this drawback

Keywords: electron spectroscopy, spherical and cylindrical mirrors, energy analyzer

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EXPANSION OF THE FUNCTIONAL CAPACITIES OF ELECTROSTATIC MIRROR ANALYZERS FOR ELECTRON SPECTROSCOPY

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1. Introduction

In the ever-evolving landscape of scientific exploration and technological advancement, staying at the forefront of research is imperative. One such field that continues to gain traction and remains highly pertinent is electron spectroscopy. Electron spectroscopy provides powerful tools for analyzing various materials and systems, allowing to obtain detailed information about their electronic properties, structure and chemical composition. This is important for developing new materials, improving technologies and solving current problems in various fields of science and industry, such as materials science and nanotechnology, microelectronics, biology, ecology and etc.

Electron spectroscopy techniques are constantly developing, and there are many unresolved questions and challenges that require further research. The rapid advancements in technology and the emergence of novel materials have propelled the need for enhanced analytical tools. The urgency to comprehend nanoscale phenomena, intricate molecular structures, and the electronic characteristics of advanced materials mandates the advancement of spectroscopic instruments.

Thus, the expansion of device capabilities, whether through modernizing existing instruments or developing new ones, is crucial to meet the demands of contemporary scientific inquiries.

Nowadays, a set of mutually complementary methods must be used to fully address the problems of solid-state surface studies. Such methods as X-ray photoelectron spectroscopy (XPS) [1, 2] or electron spectroscopy for chemical analysis (ESCA) [3, 4], slow electron diffraction [5, 6], electron Auger spectroscopy (AES) [7, 8], secondary mass spectroscopy [9, 10] in combination allow to obtain complex information about the chemical, energy state and the structure of solid state surface. A special place here is given to the XPS or ESCA methods.

When working with devices with high sensitivity, it is necessary to take into account the problem associated with the separation of signals from the surface and from volume of the sample. From possible variants it is interested in the case when the signal from the volume can be neglected in comparison with the signal from the surface. That is why electron spectroscopy methods are positioned as methods of solid state surface studies, e. g., XPS or ESCA.

The improvement of corpuscular-optical parameters of electron spectrometers has always been an actual and main objective in the development of energy analyzers of charged particle beams, and in present study this objective is complemented by the expansion of their functional capabilities.

2. Literature review and problem statement

There are many well-known types of energy analyzers developed to solve various scientific and technological problems. The widespread application of electron spectroscopy techniques has led to increased requirement for the characteristics of electron spectrometers. These requirements mainly relate to charged particle beam analyzers.

Electrostatic cylindrical (CMA) and spherical mirror (SMA) type analyzers are widely used tools for energy analysis of charged particles. The CMA became the basic device for different electron spectrometers produced by leading instrumentation companies. The CMA provides a second-order focusing and high energy resolution [11].

Further improvement of the energy resolution of CMA went by the way of creation of two-stage and three-stage analyzers, introduction of new electrodes and modifications of the electrode shape. Serially produced the CMA use an emission angle of $42.3068 \pm 4°$ (entrance solid angle 0.5905), which corresponds to the base resolution of 0.4 %. Work [12] shows that the energy resolution of a classical one-step CMA can be made three times better by adjusting its geometrical parameters. For example, the base energy resolution of the optimized CM type analyzer is 0.1 % for an entrance solid angle $\Omega = 0.5905$.

In work [13] a modification has been made to the standard CMA by dividing the inner and outer electrodes into segments and setting the voltages on these segments to obtain the best value for the energy resolution. The segmented cylindrical mirror analyzer has energy resolution of 0.017 % for entrance angles of $42.3 \pm 6°$. This corresponds to more than an order of magnitude improvement in the resolution over that of the standard device.

The electron-optical properties of improved design of the CMA are studied in work [14]. Both external and internal electrodes of the analyzer are divided into three isolated parts, whereby the potentials on the individual parts can be regulated independently from each other. The energy resolution of the improved CMA twice the resolution of a standard CMA at an opening angle of incoming beam $2\alpha = 6°$.

The analyzer, presented in the work [15], uses combination of CMA and face-field configuration but with analyzed electron beam entrance/exit windows made in the inner cylindrical electrode similar to CMA. The data obtained show that the aberration calculated is about 4 times less than that of the standard CMA.

A miniature double-pass cylindrical mirror electron energy analyzer is developed in the work [16]. The analyzer consists of a shield for the electric field, inner and outer cylinders, two pinholes with a diameter of 2.0 mm, and an electron multiplier. The electron-energy resolution of the proposed analyzer was estimated to be $E/\Delta E = 20$. This value is better than that of the miniature single-pass CMA ($E/\Delta E = 12$).

In work [17] the time-of-flight characteristics of a are investigated under conditions of ideal solid-angle focusing for a point source located on the symmetry axis of the spectrometer. It is shown that the time it takes a particle to move from the source to the ideal focus, also located on the symmetry axis, is, to first order, independent of particle direction for directions near the normal to the axis. This time-of-flight focusing realized in this way enables efficient use of the SMA in electron spectroscopy methods in which each emission event is registered separately.

The time-energy dispersion characteristics of a SMA are used to design an unusual electron energy analyzer in [18]. It is shown that time-energy dispersion characteristics of a retarding spherical field in an electron mirror configuration is positive and it increases with the electron kinetic energy. This is due to an increasing penetration of electrons with high kinetic energy in the retarding field and provides the basis for developing a new type of time-of-flight spectrometer. In the case of a 10-cm inner sphere radius (22 cm outer sphere radius) for the electrostatic mirror, the spectrometer is expected to have an energy resolution of about 0.5 eV/ns and an acceptance solid angle of about 2.2 srad for electrons of 75 eV kinetic energy.

All this allows to argue that it is appropriate to conduct a study characterized by the following points. Firstly, the expansion of functional capabilities of electron spectrometers with simultaneous improvement of their characteristics; secondly, the possibility of modernization of existing devices to solve additional scientific and technological problems. One of the positive points is the low cost of modernization of existing electron spectrometers and at the same time the possibility of creating an original device.

Let's consider the calculation of aberrations determining the focusing conditions of a charged particle beam in a corpuscular-optical system. If a beam of particles with an angular spread $\pm\Delta\alpha$ in the axial plane and an energy spread $\Delta\varepsilon = \Delta E/E_0$, then the value of the total trajectory projection L can be expanded into a Taylor series, considering $\Delta\alpha$ both $\Delta\varepsilon$ are small perturbations [11]:

$$L = L_0 + \frac{\partial L}{\partial \alpha}\Delta\alpha + \frac{\partial L}{\partial \varepsilon}\Delta\varepsilon + \frac{1}{2!}\frac{\partial^2 L}{\partial \alpha^2}(\Delta\alpha)^2 + \dots . \quad (1)$$

The first-order angular focusing is realized at $\frac{\partial L}{\partial \alpha} = 0$, the second-order angular focusing is realized under the condition $\frac{\partial L}{\partial \alpha} = \frac{\partial^2 L}{\partial \alpha^2} = 0$. The values $\Delta L = \frac{\partial L}{\partial \varepsilon}\Delta\varepsilon$ and $\varepsilon = \frac{\Delta W}{W}\Delta\varepsilon$ characterize the dispersion properties in the corpuscular-optical system and determine the magnitude of the image displacement when the particle beam energy changes.

Basically, two directions were used in modeling and calculations of corpuscular-optical systems resulting from the following formula $R = \Delta L/D$, where R is energy resolution, $\Delta L = L - L_0$ is image smearing, D is linear energy dispersion. First direction of research was related to the reduction of image smearing, i.e. improving the quality of focusing of the charged particle beam or increasing the focusing order. This direction was exhausted for widely used electrostatic analyzers of the cylindrical mirror (CM) and spherical mirror (SM) type [19], which became the basic tools for many firms producing physical-analytical equipment. The limits and regions of angular focusing for a single CM, SM with external reflection of the charged particle beam (entry and exit of the beam through the outer spherical electrode), and ideal focusing for SM with internal reflection (entry and exit of the beam through the inner spherical electrode) were found.

For further development of this direction it was necessary either to complexify the electrodes forming the field [20–23], or to use additional elements, which was accomplished by a large number of works, for example, [24, 25]. In works [20–23], a non-uniform field was formed by complicating the shape of the outer cylindrical electrode. In [20], its form changed according to the hyperbolic law; in [21], its optimal form is presented. In works [22, 23], the shapes of the outer electrode coincided with the equipotential surfaces of the quadrupole-cylindrical [22] and decapole-cylindrical fields [23]. In works [24, 25], a hyperbolic electrostatic mirror formed between conical and hyperbolic electrodes was used as an additional element. In [24], the entrance of charged particles into and exit from the deflecting field was carried out through a conical electrode, and in [25] – through an

electrode of hyperbolic shape. The feature in these cases is the complexity of manufacturing these electrodes, which requires the creation of original non-serialized electron spectrometers. This leads to a significant increase in the cost of the device and the duration of its manufacture, in contrast to the use of spherical and cylindrical mirrors proposed in this work.

The first direction for improving the operation of energy analysis tools is to modify the deflecting field by changing the shape of the outer cylindrical electrode of the CM. In [20–23] electron-optical schemes of energy analyzers based on multipole-cylindrical fields were proposed. The multipole cylindrical field is formed by superposition of the cylindrical field and circular multipole of different contributions (quadrupole, hexapole, decapole, etc.). The field is created in the space between two axially-symmetric coaxial electrodes, the inner cylindrical electrode of which is under the ground potential, and the outer electrode with a curvilinear profile under the deflecting potential. Profile of outer electrode repeats the equipotential of the multipole-cylindrical field. Proposed schemes have high luminosity and energy resolution, do not require an additional power supply system, is characterized by compactness.

The second direction is related to the increase of value of the linear energy dispersion [24, 25]. The basic principle in this case is the following: an element with increased angular dispersion in energy was used, which was converted into linear dispersion by subsequent cascades in the CM. That is, as in the case of improving the quality of focusing, an example of usage of the additional elements. The second approach using complexification of the electrode shape was also used in this direction.

Firms producing physical-analytical equipment widely use mainly two types of electrostatic analyzers – spherical mirror and cylindrical mirror.

When studying the surface of a solid, there is a need for additional research methods, i.e. the need for complex analysis. Most electron spectrometers do not meet this requirement. This is particularly noticeable when solving narrow technological problems. There are no commercial electron spectrometers for these cases. Many commercial devices have free flanges in high vacuum chambers, which provides an opportunity to solve this problem.

Three moments can be highlighted in all the reviewed works. First, the presence of a point source in all electron-optical schemes. When examining a sample that has extended dimensions, the focus adjustment is disturbed. The focus adjustment also disappears in the case of a rough sample surface, as the source is displaced in two directions. In both cases, the condition of angular focusing of the charged particle beam in an angle of divergence is disturbed, which makes it impossible to qualitatively analyze the object of study. Secondly, the reviewed articles do not take into account the linear longitudinal magnification factor, this is because the most common electrostatic cylindrical mirror has it equal to 1. Thirdly, these works do not emphasize that charged particles of the same kinetic energy are reflected from different equipotential surfaces due to different angles of entry into the field. This leads to a smearing of the potential barrier and significantly limits the energy resolution.

3. The aim and objectives of the study

The aim of this work is to improve the electron-optical characteristics of energy analyzers of charged particle beams and to expand the functional capacities of electron spectrometers based on them.

To achieve this aim, the following objectives are accomplished:

– to develop a system the for design of a photoelectron or Auger spectrometer with an increased scanning area;

– to develop an electron-optical system for Auger-electron spectroscopy of rough surfaces;

– to develop semi-dispersive energy analyzer of charged particles operating in energy filter regime.

4. Materials and methods

The object of study in this work is the combined systems of electrostatic spherical and cylindrical mirrors. The principle of operation of SM and CM separately is well understood. However, using them in a system expands the possibilities of devices based on them. It is expected that the emergence of new free parameters will not only expand the functionality of these systems, but also improve their electron-optical characteristics. The paper does not consider the influence of edge fields at the electrode ends that form the deflecting electrostatic field. The field distortion in the region of the entrance and exit slits, through which the entrance and exit of charged particles is carried out, is also not considered. These issues are usually addressed during the implementation phase of an instrument.

Studies of the electron energy distribution are carried out in special devices called spectrometers. As an example, let's take a commercially available device – an electron spectrometer ESCALAB MK II, Fig. 1 shows its design [26].

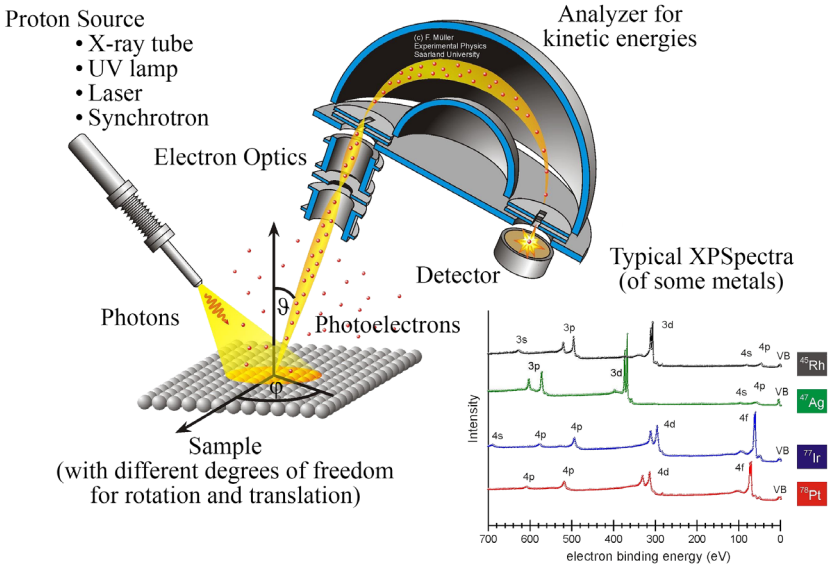

Fig. 1. Schematic drawing of a typical ESCALAB Mk II setup

This paper focuses on issues and features of modeling of the main component of the device – energy analyzer of charged particle beams (in Fig. 1 analyzer of kinetic energy). The wide application of electron spectroscopy and the associated variety of requirements have led to the development of many different types of spectrometers using electric and magnetic fields [27]. Since the limits of energy change in secondary electron spectroscopy methods lie in the range from keV to eV, electrostatic systems are mainly used as energy analyzers. The choice of electrode configurations is dictated by simplicity of manufacturing, small size, and the estimation of the expected electron-optical characteristics of the device.

Basically, specially prepared samples with smooth surfaces and limited dimensions were investigated when using electron spectrometers. However, in materials science, the objectives are sometimes to investigate rough surfaces (e. g., fracture) and specimens under mechanical loading. When using the scanning mode, such as in an Auger spectrometer, there is a need to increase the surface area of the sample.

As a method of study, a perturbation theory approach was used, which allows the image smearing function to be represented as a series of small values of the initial spread in a charged particle beam in terms of divergence angle and energy. The criteria for angular focusing of various orders are formulated in the form of the requirement that the derivatives of the image function with respect to the divergence angle must equal to zero. The criterion for assessing the correctness of the results obtained by the perturbation theory method is their adequacy to the data calculated using exact formulas for the path lengths of charged particles. This means that after integrating the motion equations of charged particles and calculating their trajectories, the points of entrance of particle into deflecting field and exit from it, as well as the point of maximum entry into the deflecting field, were checked for the coincidence.

In the present work, three schemes are considered which are combinations of CM and SM. A special feature of the scheme shown in Fig. 2 is that the entry and exit of the charged particle beam into the deflection field of SM is realized by the inner spherical electrode. In the second scheme considered (Fig. 3), the entry and exit of the charged particle beam into the SM region is realized through the outer electrode. In the third scheme (Fig. 4), a spherical mirror is used in the external reflection mode, as in the second scheme, and the spherical field in the first stage is used as a low-energy filter.

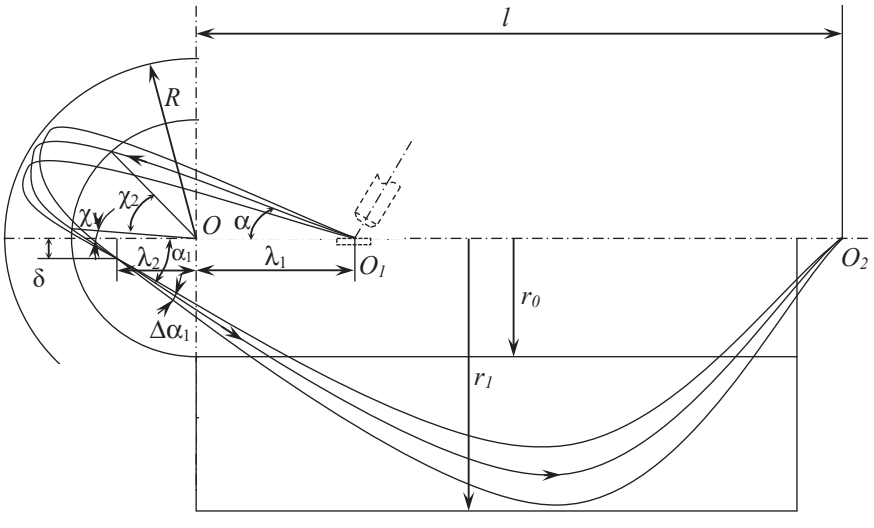

Fig. 2. System of spherical and cylindrical mirrors in which linear reduction of source image is achieved

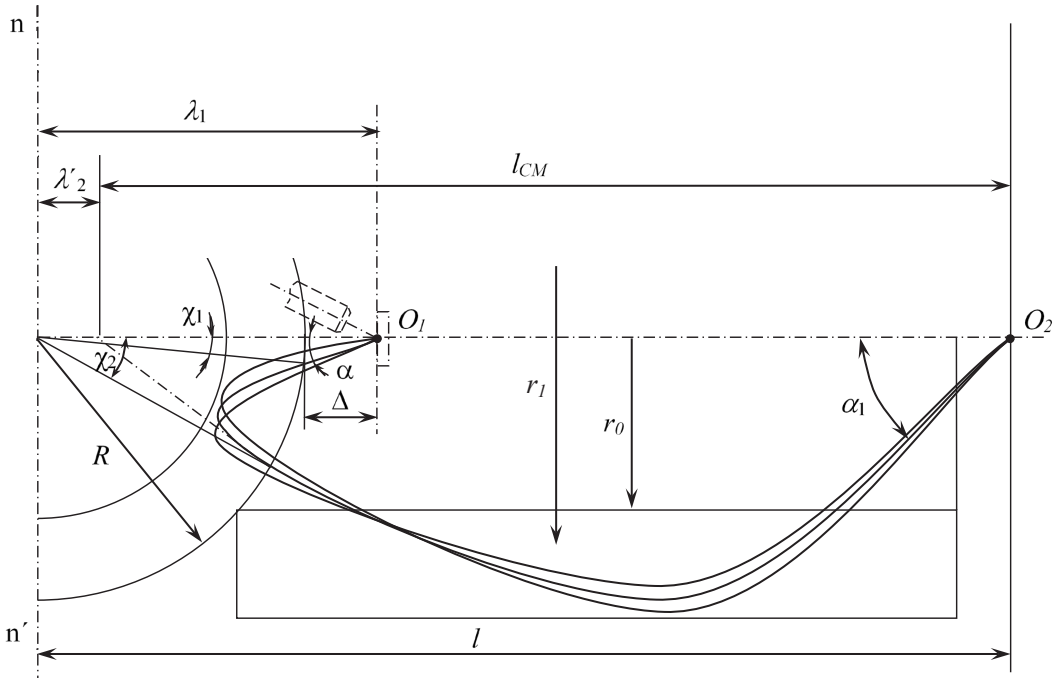

Fig. 3. Electron-optical scheme of electrostatic analyzer based on the cylindrical and spherical mirrors with external beam reflection

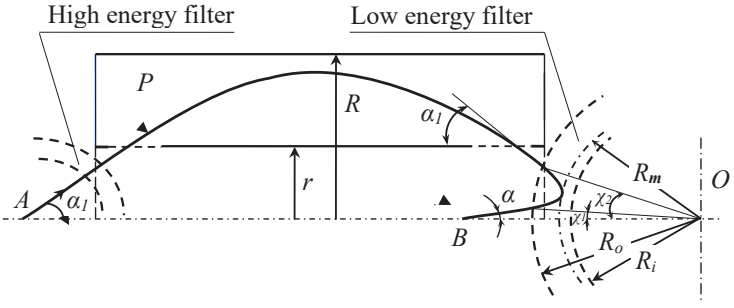

Fig. 4. Semi-dispersive energy analyzer of the double filter type

5. Results of calculations of corpuscular-optical systems

5. 1. System of spherical and cylindrical mirrors for developing a photoelectron or Auger spectrometer with an increased scanning area

Let's consider the system of spherical and cylindrical mirrors (SM+CM system), where the entrance of the charged particle beam is realized through the inner spherical electrode (Fig. 2). To find a set of such schemes that meet requirement of the second-order angular focusing, the values of the following free parameters should be varied: α, α_1, χ_1 (Fig. 2); and then find the reflection parameter $P=\sqrt{\frac{E}{qU}}\ln\frac{r_1}{r_0}\sin\alpha$ of the CM, E is the kinetic energy of the charged particle, q is the charge of the particle, U is the deflecting potential of the CM, $\theta(p)=e^{P^2}\int_0^{P^2}e^{-x^2}dx$ [11], followed by the calculation of the electron-optical parameters of the system, such as the image smearing Δl, the energy resolution R, and the linear energy dispersion D.

A characteristic feature of the SM+CM scheme is that the source O_1 is located outside of the inner spherical electrode, the intermediate image is reduced and for the system as a whole the linear longitudinal magnification factor is $G<1$ (Fig. 2). The calculation is considerably simplified if the second-order focuses of SM and CM are combined in the plane of the intermediate image of the system. Then the number of free parameters of the system is reduced to two, and it is convenient to choose the values of entrance angles to the SM and CM. The system characteristics are found in the following order: let's calculate the parameters of the SM in the second-order angular focusing regime, the input parameter for the calculation of the CM is the angle α_1, which in the conditions of second-order angular focusing is linked to the reflection parameter P by the following relation:

$$\cot^2\alpha_1=\frac{\frac{\theta}{2}+F(P)}{1+2p\theta-F(P)}, \qquad (2)$$

where:

$$F(P)=\frac{1+\frac{\delta}{2}}{2p^2}=\frac{3P+(1+10P^2)\theta+8P^3\theta^2}{5P+2P^3+(3+12P^2+4P^4)\theta}.$$

By defining the value of the reflection parameter P, let's find all the other parameters of the CM and the system SM+CM as a whole. Calculation characteristics of the scheme shown in Fig. 2, in the case of $\alpha=20°$, $\alpha_1=42.29°$ are as follows: $\chi_1=54.66°$, $\chi_2=7.63°$, $\lambda_1=-1.7304$, $\lambda_2=-0.8717$, $\Delta=0.00712$, $S=1.3984$ ($S=\frac{qU}{2E(R_o/R_i-1)}$ is reflection parameter of SM), $P=0.7695$, $\mu=1.040$ $(\mu=R/r_0)$, $l=5.2417$, $D=4.7318$, $G=0.2244$, $d\alpha_1/d\alpha=2.5403$, $R_m=1.4307R$ (radius of maximum entry into the field of the SM), $r_m=1.8078$ (radius of maximum entry into the field of CM). All linear dimensions here are expressed in terms of radius r_0 of the inner cylindrical electrode. If the initial angular opening of the beam is $\Delta\alpha=\pm2°$, then after passing the SM, the angular opening increases to $\Delta\alpha_1=\pm5°$, while the relative image smearing due to the angular cubic aberration does not exceed $(\Delta l)/l=0.0005$.

This scheme is characterized by a high quality of the angular focusing, typical value of the energy dispersion for the SM and CM, and, remarkably, a small longitudinal magnification coefficient of the system as a whole. At the first stage of the system, the SM forms a reduced image of the source in the intermediate focus of the system, which is then transferred to the focus of the CM with a single longitudinal magnification. The scheme can be recommended for the development of a photoelectron spectrometer or Auger spectrometer with an increased scanning area.

5. 2. Scheme of spherical and cylindrical mirrors with external reflection of the charged particle beam for Auger-electron spectroscopy of rough surfaces

Let's consider the scheme of SM+CM with an external reflection of the charged particle beam with the entrance to the SM field through the outer spherical electrode (Fig. 3). The point source is placed on the symmetry axis near the surface of the outer spherical electrode of the SM.

Under second-order angular focusing conditions, three parameters are free, and it is convenient to choose α, $\mu>1$ and $\Delta=\mu[\cos\chi_1-1+\cot\alpha\cdot\sin\chi_1]$ as free parameters. This scheme is characterized by a small absolute value of the longitudinal magnification coefficient $|G|<1$. Let's give the numerical data of the parameters for this system in one of the possible regimes of second-order angular focusing: $\mu=1.6$, $\alpha=10°$, $\alpha_1=43.634°$, $\chi_1=8°$, $\chi_2=24.634°$ (Fig. 3), $P=0.7656$, $S=1.9149$, $\Delta=1.2473$, $l=6.7222$, $l_{CM}=5.9922$, $r_m=1.7970$, $R_m=0.8164$, $\lambda_1=2.8471$, $D=5.1388$, $G=-0{,}0644$. The distinguishing features of this system are the second-order angular focusing combined with large linear energy dispersion and a small longitudinal magnification coefficient. It may be useful for electron Auger spectroscopy of rough solid surfaces, such as fracture surfaces. It is known that the relatively large angle of a secondary electron selection $\alpha=42.3°$ in the traditionally used CM limits the depth of Auger micro-probing of the depressions of a rough solid surface. The depth of the probed depressions is approximately equal to their width.

The peculiarity of the scheme is that the charged particle beam (of the secondary electrons), entering the SM, exits at a small selection angle α. If selection angle α is 10–15°, the depth of the depressions, probed by methods of Auger-electron spectroscopy, increases several times. The small magnitude of the longitudinal magnification of the system preserves the «focus adjustment» over a wide range of variation in the depth of depressions and height of protrusions of the rough surface. The probing depth increase is shown in Fig. 5 and is determined by the following formula:

$$n=\frac{h_2}{h_1}=\frac{\tan 42.3^\circ}{\tan 10^\circ}=5.16. \quad (3)$$

Due to the large energy dispersion, high energy resolution is achieved in the SM+CM scheme. By equipping a standard raster Auger spectrometer with a the SM, it is possible to create an additional measurement channel, which allows to register the Auger electron spectra at individual points of the scanned surface area with high energy resolution. Thus, this system is able to provide deep probing of depressions and can be used to the microanalysis of rough solid surface.

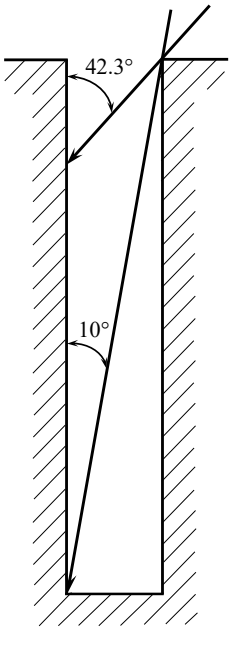

Fig. 5. Probing depth increase

5. 3. Scheme of the double filter type analyzer

Let's consider the scheme of the electrostatic analyzer for the case when imposition of an additional condition in modeling allows to significantly improve the characteristics of the system and expand the functional capacities of energy analysis of charged particle beams.

An electrostatic spherical field created between two concentric spherical mesh electrodes, on which a potential difference is applied, is used as a beam-slowing system at the entrance to the CM. This simple technique significantly improves the absolute resolution of the analyzer. If an additional SM is placed at the exit of the CM in the regime of external beam reflection, this system can be used as a semi-dispersive energy analyzer of charged particles. This setup operates based on the principle of a double filter (Fig. 4).

The function of a filter of high energy charged particles is performed by a system of spherical meshes at the entrance to the CM, between which a retarding field is created. When charged particles pass through this filter, the low-energy part of the spectrum is cut off. Then the filtered beam enters the CM and experiences the dispersing effect of the cylindrical electrostatic field. The second filter, the function of which is performed by the SM, reflects charged particles from a small energy interval adjacent to the low-energy edge of the spectrum separated by the first filter. As a result of the two filters, the energy analyzer extracts a narrow band of the spectral interval.

One of the serious disadvantages of the existing double filter type energy analyzers is related exactly to the operation of the low-energy filter. The disadvantage lays in the fact that during reflection of the beam the trajectory vertices, corresponding to the same kinetic energy but different inclination angles α, fall on different equipotential surfaces of the reflecting field of the filter. Consequently, the theoretical energy resolution is limited as if due to radial smearing of the potential barrier. The radial smearing is defined by $\Delta U=U(\alpha_0-\Delta\alpha)-U(\alpha_0+\Delta\alpha)$, where $U(\alpha_0\pm\Delta\alpha)$ are the potentials on the equipotential surfaces from which the extreme beam trajectories are reflected. This disadvantage sets a limit on the achievable energy resolution, which in some cases is ~10 %.

The equipotential surfaces in the SM are spherical, so the magnitude of the energy aberration is determined by the character of the dependence of the maximum penetration depth $R_m(\alpha_1)$ into the region of the reflecting field of the SM. The system under consideration contains a sufficient number of free parameters (α_1, P, μ, χ_2), giving a possibility to choose them in such a way that the dependence of R_m on α_1 is significantly weakened. This will narrow the resolved energy band of the low-energy filter. Let's require two conditions $dR_m/\alpha_1=0$ and $d^2R_m/\alpha_1^2=0$ for narrowing the potential barrier in this filter and set the value of the CM reflection parameter to $P\geq 0.77034$. Next, let's calculate α_1 and thus set the operating regime of the CM. Then by choosing the value of the coefficient $\mu=R/r$, let's find $\alpha+\chi_1$. In practice, it is convenient to have $\chi_1=0$, then the axial trajectory of the beam leaves the SM field at the point of intersection of the surface of the outer spherical electrode with the symmetry axis. In this case, the receiving diaphragm can be made in the form of a spherical segment of radius R with a central aperture along the width of the registered beam. As a result, it ends up with only two free parameters P and μ, the choice of values of which completely determines the parameters of the double filter schemes and its operation regime.

The double filter scheme for the case of $P=0.85$ and $\mu=2.2$ is calculated. The axial trajectory parameters are as follows: $\alpha_1=44.39°$, $\chi_2=19.38°$, $\alpha=25.01°$, $S=2.066$, $R_m=0.84628$. For the side trajectories bounding the beam at angles $\alpha_1\pm 5°$, the values of R_m are 0.8455553(–) and 0.84711(+), respectively. Then according to the formula $|\Delta E/E|=1.37$ % by changing P and μ, the entrance depth of the beam trajectories to the SM field and the width of the beam at the exit of the field can be adjusted.

6. Discussion of calculation results of electron-optical schemes of the electrostatic energy analyzers

The calculated electron-optical systems can be implemented in practice. Such approach is tested and detailed are available in [28], where the expansion of functional capacities is realized by combining Auger electron spectroscopy and secondary ion mass spectrometry in one compact setup.

This is a promising approach in the development of technological and diagnostic equipment for the production of modern nano- and microelectronic devices. In addition to the basic requirements for diagnostic equipment, such as the magnitude of relative energy resolution of the analyzer and the diameter of the probing electron beam, there are additional requirements. One of the requirements is the small size of the devices to install on the free flange of the CF100 vacuum chamber of the spectrometer. Physical analytical equipment production companies usually equip high-vacuum chambers with additional free flanges, making it possible to use the possibilities described above in practice. Combination of methods of Auger electron spectroscopy and secondary ion mass spectrometry in one embedded analytical module allows to provide rapid non-destructive elemental inspection of surface by method of Auger electron spectroscopy with an acceptable level of sensitivity. To combine these methods in one chamber, the analyzers that allow working with long distances «sample-analyzer» are required. The solution of such a problem imposes strict requirements to the geometry of the analyzers and the mutual arrangement of the system elements. The approach to modeling of corpuscular-optical systems proposed in this article allowed to meet these requirements and expand the functional capabilities of the existing device [28].

The value of longitudinal linear magnification G of the image in CM is equal to one and the influence of this parameter practically was not considered in the development of analyzers of charged particle beams. But in two cases, firstly, in case of extended sizes of the study sample (source) and, secondly, in case of the source displacement due to the roughness of the sample surface, the value of longitudinal magnification should be considered. The limit of sensitivity of impurity detection of 1 % in case of the usual size of the analyzed spot in electron spectroscopy is more than sufficient. However, it should still be noted that there is a limit linking the spatial resolution and sensitivity of the above methods. The smaller the analyzed spot size, the less accurately the quantitative composition of the sample can be determined.

It is established that the image of a point source located on the symmetry axis of the SM in the second-order angular focusing regime is ring, which in practice complicates registration. In the SM+CM system, this limitation is removed. In scheme SM+CM system the main dispersing element is the SM with internal reflection, and a relatively small in size CM corrects the image of the SM, transforming it into a point image, providing in general for the system second-order angular focusing of the «axis-axis» type (Fig. 3). The scheme is characterized by relatively high dispersion, small value of angular aberration, along with this longitudinal magnification of the system is quite large, the scheme can be effectively used for a source of small size in those cases where the product of the source size on the longitudinal magnification is less than or equal to the width of the slit, for example, in microprobe electron spectroscopy.

A characteristic feature of the SM+CM system (Fig. 2) is that the source is placed outside the inner spherical electrode. This scheme is characterized by high quality of angular focusing and small longitudinal magnification factor.

Therefore, the proposed electron-optical systems based on the SM+CM system for developing a photoelectron or Auger spectrometer with an increased scanning area and for Auger-electron spectroscopy of rough surfaces are preferable to the existing ones.

A distinctive feature of the proposed double filter type energy analyzer of charged particle beams is that it is semi-dispersive (Fig. 4). This made it possible to combine in this scheme the advantages of dispersionless and dispersion analyzers. As a consequence, it leads to a sufficiently high luminosity and a high resolution of this energy analyzer of charged particle beams.

The available knowledge allows to positively evaluate the prospects of implementation of the proposed electron-optical schemes for energy analysis of charged particle beams.

The limitations of this study are related to the implementation stage of the proposed schemes into the practice. Since one of the requirements is a low cost of the device, the realization of the proposed electron-optical schemes suggests using them as additional modules in existing devices. However, this approach does not exclude the creation of an independent electron spectrometer based on these schemes. Limitations are determined by the size of the vacuum chamber and the availability of free flanges.

All formulas used in this work were obtained analytically. The results were controlled by trajectory calculations using the exact formulas.

As for the disadvantages of this study, it does not consider the effect of edge fields at the ends of cylindrical electrodes, field sagging at the entrance and exit slits of electrostatic mirrors. This is due to the fact that the technique for eliminating these disadvantages is well developed and applied successfully in many energy analyzers of charged particle beams.

7. Conclusions

1. The electron-optical scheme of CM and SM with the internal reflection of the charged particle beam is developed. The advantages of this system are: the source of secondary electrons is placed outside of the inner spherical electrode; the second-order focuses of both mirrors are combined; the linear longitudinal magnification coefficient is significantly less than 1. The construction of a new device or modernization of an existing device will allow this scheme to be used as a photoelectron spectrometer or Auger spectrometer with an increased scanning area.

2. The electron-optical scheme of CM and SM with external reflection of the charged particle beam is calculated. Its advantages are: high quality of angular focusing of the charged particle beam (second order); high linear energy dispersion; the linear longitudinal magnification coefficient is significantly less than 1 and is equal to –0.0644, which allows to keep the «focus adjustment» for a wide range of depths of depressions and heights of protrusions of rough surface; the selection angle of secondary electrons from the study sample is 10°, which allowed to increase the probing depth in comparison with the CM by more than 5 times. This scheme can be used in the construction of an Auger spectrometer for the study of rough surfaces.

3. The semi-dispersive energy analyzer of double filter type is proposed. Its first stage high energy filter is dispersionless, further the CM and low energy filter are dispersive. The advantages of this system are: the disadvantage of the low energy filter, which limited the energy resolution magnitude, is eliminated; the dependence of the depth of penetration into the field on the entrance angle for the low energy filter is reduced by imposition of the additional conditions. Thus, in the double filter type energy analyzer, the theoretical resolution is improved to 1 % by the narrowing of the

potential barrier in the low energy filter, which is a very good parameter for energy analyzers of this type.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Manuscript has no associated data.

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