PROCEEDINGS OF THE INTERNATIONAL CONFERENCE
NANOMATERIALS: APPLICATIONS AND PROPERTIES
Vol. **2** No 3, 03AET04(4pp) (2013)

Ion Probe with Primary ion Beam Prism Mass Separator

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(Received 19 May 2013; published online 30 August 2013)

It has been considered the ion-optical properties and characteristics of ion microprobe analyzer in which the primary ion beam mass separation is realized by the magnetic prism, and the beam spherical capacitor is used in the secondary ion analyzing system as energy analyzer which form parallel ion beam at the mass analyzer inlet. It has allowed to improve the instrument parameters and to scale down its overall dimension.

Keywords: Ion Probe, Magnetic Prism, Ion Focusing, Energy Analyzer, Mass Analyzer, Electrostatic Lens, Resolution.

PACS number(s): 07.75. + h

1. INTRODUCTION

Among the variety of methods for characterization of solid surfaces, microprobe analysis takes one of the leading places [1,2]. The sensitivity of this method surpasses the one for Auger electron spectroscopy and electron probe analysis, and resolution enables one to observe all the chemical elements and their isotopes. The method allows determining the profiles of particle distribution along the sample depth as well as obtaining the image of impurities distribution at its surface. At the same time, instruments and equipment for practical realization of this method have comparatively high dimension, weight, and price suppressing their wide use. The issue may to some extent be solved if in the system of primary ion beam formation and in the system of secondary ion analysis one will use the magnetic and electric fields of special geometry which will allow to rise the efficiency of separation and focusing of ions at the appropriate parts of their trajectory. In this work the construction and characteristics of such an instrument are given.

2. ION-OPTICAL SCHEME AND OPERATING PRINCIPLE OF THE IMPROVED ION PROBE

In ion probe equipment the primary ion beam has to be separated in order to provide the necessary composition and charge of bombarding ions. At this, the beam expansion in radial plane caused by the discrepancy in the initial energies of ions is eliminated by using the mass separator with achromatic focusing, and in order to maintain the ion beam locality the focusing in axial plane is made stigmatic. Realization of mass separators with such properties is made with a help of sector magnetic fields in combination with electrostatic lenses [3-5]. The resolution of an achromatic mass separator is not high since in such systems only half the magnetic field is used for separation of ion beam by masses, and the other half realizes the dispersion reversing.

Efficiency of the primary ion beam separation could be increased by applying in the separation system the sector magnetic prisms with inhomogeneous field r^{-1} [6] whose dispersion at the same mass separator size is higher than the dispersion of homogeneous magnetic field. This causes an increase in mass separator resolution [7,8]. Further improvement of an ion probe could be achieved by using the analyzing system for secondary ions with parallel ion beam between the electrical and magnetic cascades [9]. In this case, three of four optical arms of ion-optical system of secondary ion analysis could be diminished to zero by the appropriate choice of geometric and physical parameters of energy and mass analyzer, and general scheme of an ion microprobe analyzer will have the view shown in Figure. Let's consider the instrument operation.

From the ion source 1 the primary beam goes to the separation system where it gradually passes the electric field of the collimating lens 2, first half of the prism magnetic field sector 3, aperture of the selection diaphragm 4, then second half of the prism magnetic field sector 5 and electric field of the focusing lens 6. As a result of an influence of electric and magnetic fields of the mentioned elements on ion beam, the separation of ion by masses is made, and focused the-same-mass ion beam comes to the inlet of the aperture diaphragm 7 which is the entrance diaphragm of a microbeam formation system. Geometric and physical parameters of the mass separator elements are chosen in the way the dispersion of the first half of the magnetic prism to be compensated with the dispersion of the second half. In this case the ion focusing will be achromatic and, upon ensuring the ion beam focusing in axial plane, also stigmatic.

After collimation with the diaphragm 7 ion beam is focused with the objective 9 onto the surface of sample under study 10. By means of the beam deflector 8 and the sweep generator 20 the sample surface is scanned with ion beam. Secondary ions knocked on from the irradiated part of a sample are accelerated and focused by the emission lens 11 onto the entrance diaphragm of the secondary ion analyzing system. After that the sec-

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ondary ion beam goes to the mass spectrometer with double focusing which consists of the energy analyzer 13, selection diaphragm 14, mass analyzer 15, secondary ion collector 16, ion current amplifier 17, and mass spectra registration system 18. Mass spectrum retrieved using the mass spectrometer gives information on qualitative and quantitative composition of ions knocked on from the sample. Output signal from the mass spectrometer is used for the viewer brightness modulation in the image registration system 19, whose scanning is synchronized with the sample scanning system with the primary ion beam; as a result, one may observe enlarged image of sample surface in ions of chosen type.

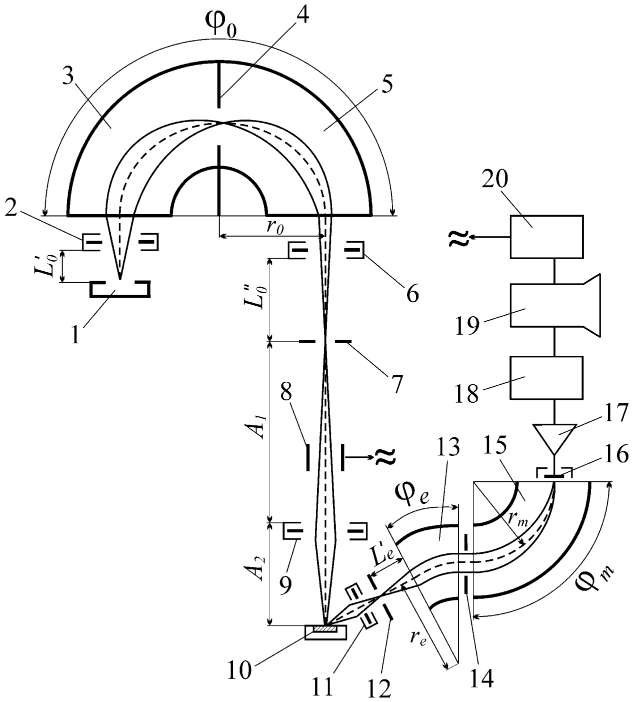

Fig. 1 – Ion-optical scheme of the ion microprobe analyzer with magnetic prisms: 1 – ion source; 2, 6, 9, 11 – electrostatic lenses; 3, 5 – magnetic prisms; 7 – entrance diaphragm of the microbeam formation system; 8 – beam deflector; 10 – sample; 12 – entrance diaphragm of secondary ion analyzing system; 13 – energy analyzer; 14 – selection diaphragm; 15 – mass analyzer; 16 – secondary ion collector; 17 – ion current amplifier; 18 – mass spectra registration system; 19 – image registration system; 20 – sweep generator.

3. ION-OPTICAL PROPERTIES AND CHARACTERISTICS OF THE PRIMARY ION BEAM FORMATION SYSTEM

The primary ion beam focusing system ensures production of homogeneous by mass and charge beam spatially focused on aperture diaphragm of the ion microbeam formation system. It's equipped with mass separator with stigmatic achromatic focusing which is realized by the sector magnetic prisms with the field r^{-1} and electrostatic lens. Since the magnetic prism with linear limits and orthogonal ion beam entry doesn't focus ions in radial plane but only in axial, focal distances of collimating and focusing lenses in radial and axial planes will be different. In this respect, ion-optical properties and characteristics of the primary ion beam separation system are necessary to determine both in radial and axial planes.

For the case when the electrostatic lenses are directly adjoined to the magnetic prism, the conditions of achromatic ion focusing in radial plane are [7]

$$l_0' - \frac{l_0' l_0''}{f_r''} - \frac{l_0'}{f_r'}\left[\left(1-\frac{l_0''}{f_r''}\right)\varphi_0 + l_0''\right] + \left(1-\frac{l_0''}{f_r''}\right)\varphi_0 + l_0'' = 0, \qquad (1)$$

$$\left(1-\frac{l_0''}{f_r}\right)\frac{\varphi_0^{\,2}}{2} + l_0''\varphi_0 = 0, \qquad (2)$$

where $l_0' = L_0'/r_0$, $l_0'' = L_0''/r_0$ – optical arms of the mass separator expressed in units of central ion trajectory radius r_0; φ_0 – ion deflection angle in the magnetic prism; $f_r' = F_r'/r_0$, $f_r'' = F_r''/r_0$ – focal distances of collimating and focusing electrostatic lenses in units of central ion trajectory radius r_0.

From the set of equations (1) and (2) relations for calculation of focal distances for collimating and focusing lenses in radial plane could be determined as

$$F_r' = \frac{r_0\varphi_0 L_0'}{r_0\varphi_0 + 2L_0'}, \quad F_r'' = \frac{r_0\varphi_0 L_0''}{r_0\varphi_0 + 2L_0''}, \qquad (3)$$

or

$$\frac{1}{F_r'} = \frac{1}{L_0'} + \frac{2}{r_0\varphi_0}, \quad \frac{1}{F_0''} = \frac{1}{L_0''} + \frac{2}{r_0\varphi_0}. \qquad (4)$$

The relations derived define the relationship between the lens power and the mass separator geometric parameters at achromatic focusing of ion beam. As one can see from (4), the collimating lens forms real image of ion source slit at a distance $r_0\varphi_0/2$ from the output limit of the first half of magnetic prism sector, so selection diaphragm should be placed at the point of central ion trajectory intersection with the radius traced angularly at $\varphi_0/2$. At a distance of L_0'' from the second half of the magnetic prism sector the focusing lens forms achromatic image of ion source slit containing only the ions of the same mass. Here the aperture diaphragm is placed as the entrance diaphragm of the microbeam formation system. At the mass separator parameter values $r_0 = 0{,}15$ m, $L_0' = 0{,}1$ m, $L_0'' = 0{,}15$ m focal distances of the collimating and focusing lenses in radial plane will be: $F_r' = 0{,}07$ m, $F_r'' = 0{,}09$ m.

In order to prevent the ion beam widening in axial plane it is necessary to ensure the stigmatic beam focusing in the mass separator. Taking into account that magnetic prism with r^{-1} field changes ion trajectories in axial plane, axial focal distances of the collimating and focusing lenses F_z' and F_z'' could be determined from the condition of ion focusing in axial plane which is [7]:

$$l_0'\left(1-\frac{l_0''}{f_z''}\right)\cos\varphi_0 - l_0' l_0''\sin\varphi_0 - \frac{l_0'}{f_z'}\left[\left(1-\frac{l_0''}{f_z''}\right)\sin\varphi_0 + \right.$$

$$+ l_0'' \cos\varphi_0 \Big] + \left(1 - \frac{l_0''}{f_z''}\right) \sin\varphi_0 + l_0'' \cos\varphi_0 = 0 . \qquad (5)$$

To ensure the higher dispersion it is reasonable to choose the angle of ion deflection in the magnetic prism $\varphi_0 = \pi$. At this, the condition (5) will be met when $f_z' = l_0'$ and $f_z'' = l_0''$, i.e. focal distances of the collimating and focusing lenses in axial plane will be as such: $F_z' = L_0'$; $F_z'' = L_0''$ or $F_z' = 0{,}1$ m, $F_z'' = 0{,}15$ m.

The dispersion value determining the efficiency of ion separation by mass for the given variant of ion-optical system will be [7]

$$D_c = \frac{r_0 \varphi_0^{\,2}}{16} = \frac{r_0 \pi^2}{16} . \qquad (6)$$

I.e. dispersion of the prism mass separator is by 18% higher than dispersion of the mass separator with homogeneous magnetic field and the same radius of central ion trajectory. It allows one to increase the resolution of the primary ion beam separation system. Let's evaluate its value. According to the definition, resolution of the mass separator is [10]

$$\frac{m}{\Delta m} = \frac{D_c}{2d} , \qquad (7)$$

where D_c – dispersion of the mass separator, d – ion beam width in the plane of the selector diaphragm place.

In consideration of first-order chromatic aberration

$$d = S_1 + D_c \frac{\Delta U}{U} , \qquad (8)$$

where S_1 – size of the ion source outlet, $\Delta U/U$ – relative energy divergence in a beam.

Than the formula for evaluation of the mass separator resolution will be

$$\frac{m}{\Delta m} = \frac{D_c}{2\left(S_1 + D_c \dfrac{\Delta U}{U}\right)} . \qquad (9)$$

At $r_0 = 0{,}15$ m, $S_1 = 1 \cdot 10^{-4}$ m, $\Delta U = 10$ eV, U =5000 eV dispersion of the prism mass separator $D_c = 0{,}092$ m, and resolution m/Δm = 160.

After the mass separator an ion beam comes to the ion microbeam formation system. It has the following parameters: entrance diaphragm slit diameter $D_1 = 1 \cdot 10^{-4}$ m, distance from the entrance diaphragm to the objective $A_1 = 0{,}8$ m. One may use the single electrostatic lens with focal distance $7.8 \cdot 10^{-4}$ m as the objective. When using the plasma ion source with current density in a beam 1÷10 mA/cm^2 the ion microbeam formation system ensures the probe diameter of about 2 μm.

4. ION-OPTICAL PROPERTIES AND CHARACTERISTICS OF THE SECONDARY ION BEAM FORMATION SYSTEM

Taking into account high energy divergence of secondary ions, for their analysis it is necessary to apply the system with double focusing (directional and velocity). Upon this, it is reasonable to use the spherical capacitor as energy analyzer possessing focusing properties both in radial and axial planes. Let's consider first the radial ion beam focusing. For this let's write the expression for ion beam widening in the plane of double focusing system image

$$y_k = a_{11} y_0 + a_{12} y_0' + a_{13} e_0 + a_{14} \mu_0 , \qquad (10)$$

where y_k – ion deflection value in the image plane in units of central ion trajectory radius in the mass analyzer; y_0, y_0', e_0, μ_0 – initial ion beam parameters at the ion source outlet: initial shift in units of central ion trajectory radius in the mass analyzer, direction and relative change of ion energy and impulse. Relations for the coefficients a_{ij}, included into expression (10), are defined in [9] under the condition that ion beam enters and leaves orthogonal to the limits of both analyzers. Let's use the results of work [9] and define the parameters of ion-optical system which consists of spherical capacitor and mass analyzer with homogeneous sector magnetic field. We will assume that energy analyzer forms parallel beam at mass analyzer inlet. In this case the condition of ion directional focusing will be [10]

$$l_m'' = ctg\varphi_m , \qquad (11)$$

where l_m'' – mass analyzer output arm value in r_m units; φ_m – ion deflection angle in magnetic field of a mass analyzer. From (11) it is seen that when $\varphi_m = 90^{\circ}$ the output arm $l_m'' = 0$. The parameters of spherical capacitor will be defined form the conditions of directional and velocity ion focusing [9]

$$l_e' = ctg\varphi_e , \qquad (12)$$

$$\pm 2 \sin\varphi_e + 1 = 0 , \qquad (13)$$

where l_e' – energy analyzer output arm value in units of central trajectory radius r_e; φ_e – ion beam deflection angle in spherical capacitor.

From the condition of velocity ion focusing (13) taking into account that in energy and mass analyzer the ion beam should be deflected in opposite directions, the angle of ion deflection in spherical capacitor is found as $\varphi_e = 30^{\circ}$, and from the condition of directional ion focusing (12) one can derive the length of energy analyzer output arm $L_e' = r_e\sqrt{3}$. For the case when $r_e = r_m = 0{,}1$ m the parameters of secondary ion mass analyzer will be the following: $L_e' = 0{,}1732$ m, $\varphi_e = 30^{\circ}$, $L_e'' = 0$, $L_m'' = L_m' = 0$, $\varphi_m = 90^{\circ}$. At such values of the ion-optical system parameters the coefficient a_{11}, and thus the system increase, will be equal to 0,5.

Let's determine now the mass spectrometer resolution. Dispersion value for the mass analyzer with parallel beam at the inlet is known to be equal to

$D_m = r_m / 2$, and beam width in the ion collector zone according to (10) will be

$$d_m = 2a_{11}r_m y_0 + 2a_{12}r_m y'_0 + 2\left(2a_{13} + a_{14}\right)\beta , \qquad (14)$$

where $\beta = \Delta\upsilon / \upsilon$ – relative change in ion velocity.

Since in the mass spectrometer with double focusing directional and velocity focusing takes place, i.e. $a_{12} = 0$ and $2a_{13} + a_{14} = 0$, then $d_m = 2a_{11}r_m y_0$. Keeping in mind that $2y_0 = S_2 / r_m$ (S_2 – slit width for the entrance diaphragm of the secondary ion analyzing system), one derives $d_m = a_{11}S_2$, and resolution, excluding second order aberrations, will be:

$$\frac{m}{\Delta m} = \frac{r_m}{2\left(2a_{11}S_2\right)} . \qquad (15)$$

At $r_m = 0{,}1$ m, $a_{11} = 0{,}5$, $S_2 = 1 \cdot 10^{-4}$ m $m / \Delta m = 500$.

Now let's consider the ion-optical properties of the secondary ion mass analyzer in axial plane. Ion beam focusing in this plane is realized by spherical capacitor. Let's write down the expression for the value of axial ion deflection with unrestricted entry conditions from the neutral trajectory in the plane of ion collector slit

$$z_k = b_{11}z_0 + b_{12}z'_0 , \qquad (16)$$

where z_k – value of axial ion deflection in the image plane of energy analyzer field system, expressed in r_m units; z_0 and z'_0 – initial ion beam parameters: axial shift in r_m units and axial ion divergence angle. Relations for the coefficients b_{11} and b_{12} were obtained in [9] and are the following:

$$b_{11} = \frac{r_e}{r_m}\cos\varphi_e - \varphi_m \sin\varphi_e \qquad (17)$$

$$b_{12} = \frac{r_e}{r_m}\left(l'_e \cos\varphi_e + \sin\varphi_e\right) + \varphi_m \cos\varphi_e - l'_e\varphi_m \sin\varphi_e . \qquad (18)$$

According to (16), the ion beam height h_k in the ion collector plane will be

$$h_k = 2r_m\left(b_{11}\frac{h_0}{2r_m} + b_{12}z'_0\right), \qquad (19)$$

where h_0 – slit height for the entrance diaphragm of the secondary ion analyzer.

From (19) one derives

$$h_k = b_{11}h_0 + 2r_m b_{12}z'_0 . \qquad (20)$$

After the calculation of the coefficients b_{11} and b_{12} using the values of the geometric parameters of a mass spectrometer and taking into account that $h_0 = 1 \cdot 10^{-4}$ m, and $z'_0 = 0{,}008$, one can derive the ion beam height in the collector plane: $h_k = 1{,}76$ mm. It should be noted that upon absence of axial ion focusing the beam height in the image plane would be thrice as much. Thus, axial focusing is necessary since it reduces the influence of axial aberrations and allows one to narrow the interpolar magnet gap in the mass analyzer which in turn gives the possibility to increase the magnetic induction in the gap and to enlarge the ion mass registration range.

5. CONCLUSION

Considered physicotechnical peculiarities of the ion microprobe analyzer with sector magnetic prisms, as well as the results of performed theoretical studies of its basic characteristics indicate that suggested improvements will enhance the analytical and operational capabilities of the instrument. Prism mass separators and compact systems for the secondary ion analysis could be applied for development of relatively simple microprobe instruments of technological use.

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