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Off-axis aspherical collector for EUV-lithography and SXR microscopy

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By the method of ion-beam shape correction, a small-sized ion beam formed a non axisymmetric aspherical profile of the collector surface for an extreme ultraviolet radiation source TEUS-S100 with a numerical aperture of $\mathrm{NA} = 0.25$, PV on the surface is — $36.3\,\mu$m microns, the surface shape accuracy by standard deviation is — $0.074\,\mu$m microns, which allowed to obtain a focusing spot with a width of $300\,\mu$m at half-height. To solve the problem, the technological ion source KLAN-53M was upgraded the flat ion-optical system was replaced with a focusing one. The ion-optical system consisting of a pair of concave grids with a radius of curvature of 60 mm provided the following parameters of the ion beam: the ion current is 20 mA, the width at half height is 8.2 mm at a distance of 66 mm from the cutoff of the ion source.

Keywords: EUV radiation, ion beam correction, ion source, aspherics.

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Introduction

The technique of ion-beam processing of optical surfaces has wide possibilities for the formation of elements for systems of soft X-ray (SXR) and extreme ultraviolet (EUV) wavelength ranges. The method is based on the physical phenomenon of sputtering material from the target surface, which allows controlled removal of material with subnanometer accuracy. The method has been actively used since about the end of the 80 s — the beginning of the 90 s of the last century [1–3]. Currently, there are a large number of machines on the world market and in laboratories that process the surface of optical elements with a beam of accelerated ions [4–7].

A wide range of methods of surface treatment with ion beams has been developed, which can be divided into two classes.

1) Surface treatment with high-current quasi-parallel ion beams through the diaphragm forming the beam, the workpiece rotates behind the diaphragm, as a result, the profile specified by the diaphragm is formed on the surface. The diaphragm section is calculated taking into account the ion current distribution in the beam, the local angles of incidence of ions on the sample surface and the required etching profile. It is possible to form axisymmetric aspherics and carry out ion polishing [8] using this method; in this case, the diaphragm section is selected so that a uniform material removal along the radius is made on the surface of the workpiece. A special case of the method is the formation of one-dimensional distributions when the workpiece moves linearly behind the slit ion source [9].

2) Ion-beam correction of local shape errors is realized by scanning with a small-sized low-current ion beam along the surface of the workpiece according to a defined law. In this case, the ion beam removes the elevations on the sample surface due to the specified etching time at the point [10].

A method of deep aspherization (etching depth greater than $36\,\mu$m) is implemented in this paper with scanning along the surface with a small-sized ion beam.

1. Problem formulation

The collector mirror should be an off-axis ellipsoid to implement the X-ray optical scheme (Fig. 1), where F_1 and F_2 — focuses, O — the intersection point of the ellipsoid generatrix and the optical axis, O_1 — mirror center. Due to the geometry of the problem (significantly off-axis radiation drop), in order to ensure the calculated size of the focusing spot of the EUV radiation, it is necessary to compensate for wavefront aberrations having two components — spherical aberration centered at the point O (on the optical axis) and astigmatism depending on the angle α between the mirror normal and the central beam of the incident beam.

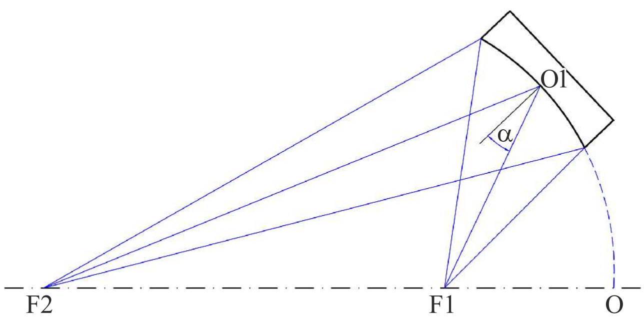

Figure 1. Optical scheme of the collector mirror.

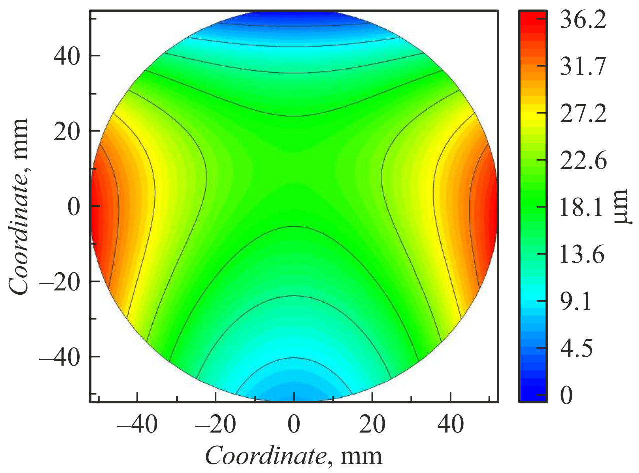

Figure 2. Asphierization profile of the collector mirror.

The asphierization profile, which provides compensation for the aberrations indicated above, was calculated in the Zemax [11] program. Fig. 2 shows the results of simulation for the following optical circuit parameters: mirror diameter — 105 mm, radius of the nearest sphere $R = -679.2$ mm, segment length $F_1O_1 = 401.2$ mm, $F_2O_1 = 2202.3$ mm, $2\alpha = 14.3°$.

As can be seen, the aspherization profile of the collector mirror should be substantially non-axisymmetric with a height span of $PV = 36.3\,\mu$m to realize the calculated dimensions of the EUV radiation focusing spot. Such surfaces are produced using optical machines with a small-sized polyurethane polisher. The resulting products have acceptable parameters for shape accuracy and roughness for the visible and ultraviolet wavelength ranges, but do not provide the accuracy required for the SXR and EUV spectral regions [12]. Ion-beam aspherization with subsequent correction of local shape errors [13] is used to form aspherical surfaces of the SXR and EUV wavelength ranges. However, to implement the aspherical profile presented in Fig. 2, due to the lack of axial symmetry, the methods of forming aspherical surfaces using high-current wide-aperture ion sources described in [13,14] cannot be used, which are implemented by rotating the workpiece behind the forming ion beam with a diaphragm. The paper [15] suggested the possibility of forming a non-axisymmetric aspherical profile using a technique for correcting local shape errors, i.e. by scanning over the surface with a small ion beam, however, due to the small ion current, no practical implementation of the method has been found in the literature. Our estimates using the etching time calculation program „PMC“ [16] showed that the duration of the formation of the aspherical profile shown in Fig. 2 by the ion source KLAN-12M described in [17] (the width of the ion beam at half height ~ 2.5 mm and ion current 1 mA), will be greater than 1000 h.

2. Modernization of the ion source KLAN-53M

It was proposed to modernize the technological source of accelerated ions KLAN-53M to solve the aspherization problem using the example of upgrading the source KLAN-10M [17]. The flat ion-optical system providing a quasi-parallel ion beam was to be replaced with a concave focusing one, which would allow obtaining a high-current ion beam with a small width at half-height. It was expected that the size of the ion beam would be less than 10 mm, which would be less than 1/10 of the dimensions of the collector mirror substrate. As shown in the paper [18], an ion beam with a size of 1/10 of the diameter of the part at a scanning step no worse than 0.5 of the diameter of the ion beam can ensure the accuracy of the shape by the standard deviation of the surface shape from the ideal better than 10 nm.

KLAN-53M source was upgraded taking into account the above. The flat ion-optical system was replaced by a focusing system consisting of a pair of concave grids with a radius of curvature of 60 mm (Fig. 3).

A series of experiments was carried out to determine the size of the ion beam and the density of the ion current. For this purpose, a series of etching craters was made for different values of the ion current, accelerating voltage and distance from the cutoff of the ion source. A typical example of a crater is shown in Fig. 4.

The optimal ratio of ion current and ion beam width at half-height was obtained for the following experimental parameters: ion current — 20 mA, accelerating voltage — 1000 V, distance from the ion source cutoff — 66 mm. The width of the ion beam at half-height was 8.2 mm, which corresponds to the ion current density at the level of 40 mA/cm^2. The etching time was calculated for this beam, using „PMC“ program and amounted to 21 h. The etching time distribution map is shown in Fig. 5.

3. Ion-beam aspherization

Aspherization was performed on a spherical blank of fused quartz with dimensions: Ø 105, radius $R = -672.9$ mm and thickness 25 mm. A test experiment was carried out at the first stage, which comprised etching „of a witness“ (a similar blank) to a depth of about $3.3\,\mu$m. The shape of the surface can be directly measured at such a depth of removal (without the use of additional wavefront correctors) on point diffraction interferometer with a diffraction comparison wave [19]. The surface map after the test etching is shown in Fig. 6.

Having made sure of the applicability of the method, we performed ion-beam aspherization of the substrate collector mirrors. The maximum etching time at the point is more than 15 s as can be seen from Fig. 5. The time was divided into 12 equal segments with a maximum etching time at a point at the level of 1.5 s to prevent overheating of the

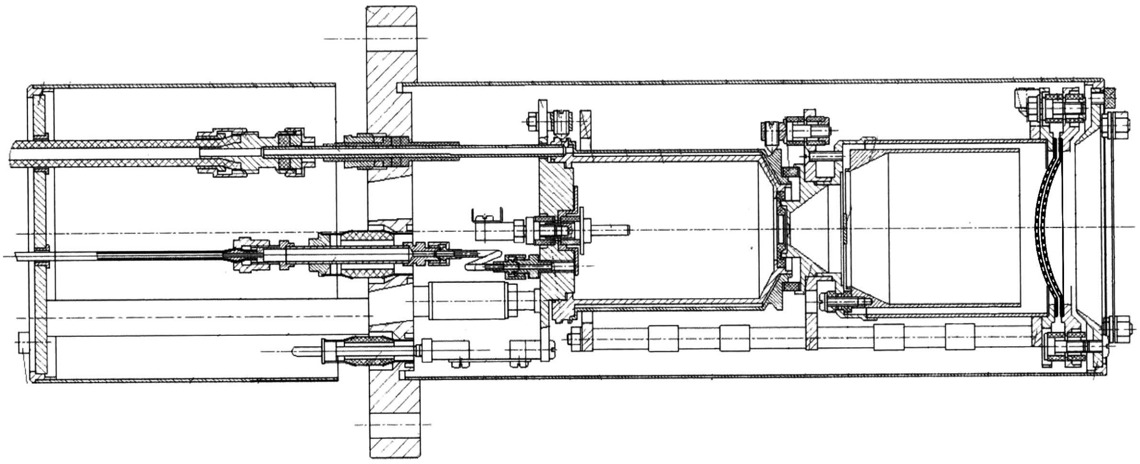

Figure 3. Diagram of the upgraded KLAN-53M source with a focusing ion-optical system.

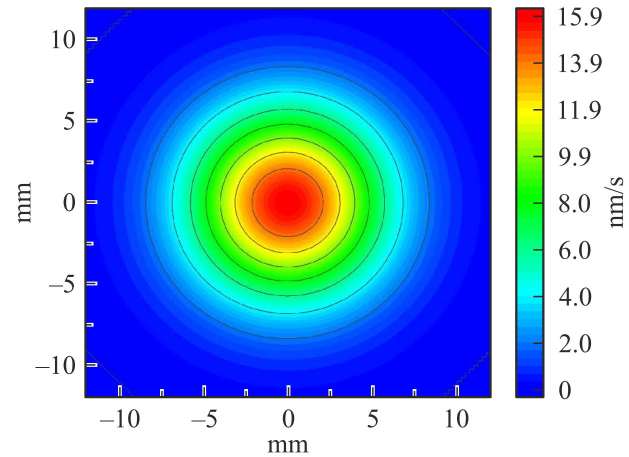

Figure 4. Etching crater of upgraded KLAN-53M source with a focusing ion-optical system.

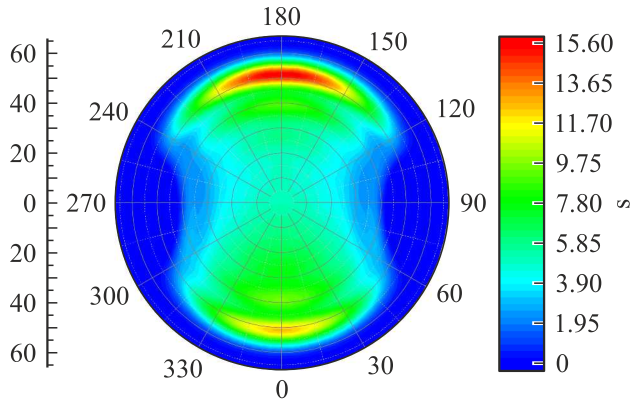

Figure 5. Etching time distribution.

quartz blank (quartz has low thermal conductivity) during asphering which corresponds to standard times when processing surfaces with a KLAN-12M source, also for additional heat removal, the part was planted on an Rose's alloy, and water cooling was applied to the substrate holder. Thus, the total etching time with the source moving relative to the part was 30 h.

After the aspherization procedure, the wave aberrations of the ellipsoid and the size of the focus spot were certified. The wave aberrations, the map of which is shown in Fig. 7, *a*, were measured according to the scheme published in [20].

It is possible to see (Fig. 7, *b*) that the half-width of the focus spot at half-height was 300 μm with a point source in the first focus. A spherical wave source based on an optical fiber narrowed to subwavelength dimensions [21] was used as a point source. The source size was 250 nm. If necessary, correction of local shape errors can be carried out to obtain a smaller spot. The manufactured elliptical mirror will be used to focus the EUV radiation of the TEUS-S100 source with a size of FWHM = 60 μm. The focus spot is 0.33 mm for an ideal elliptical mirror, due to the size of the source and 5.5-fold magnification so its broadening due to

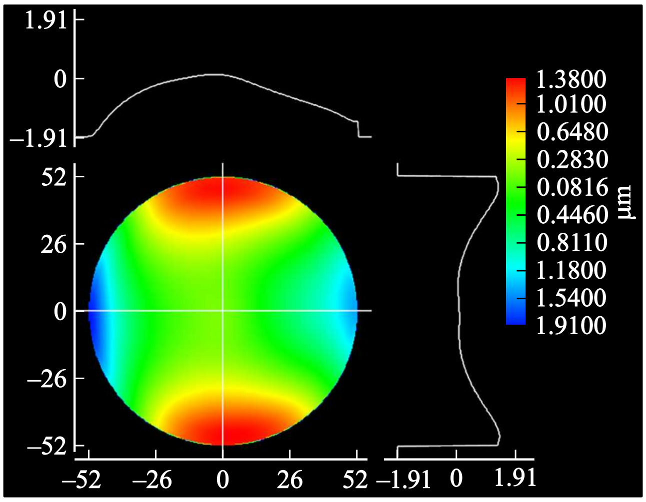

Figure 6. The surface map „of the witness“.

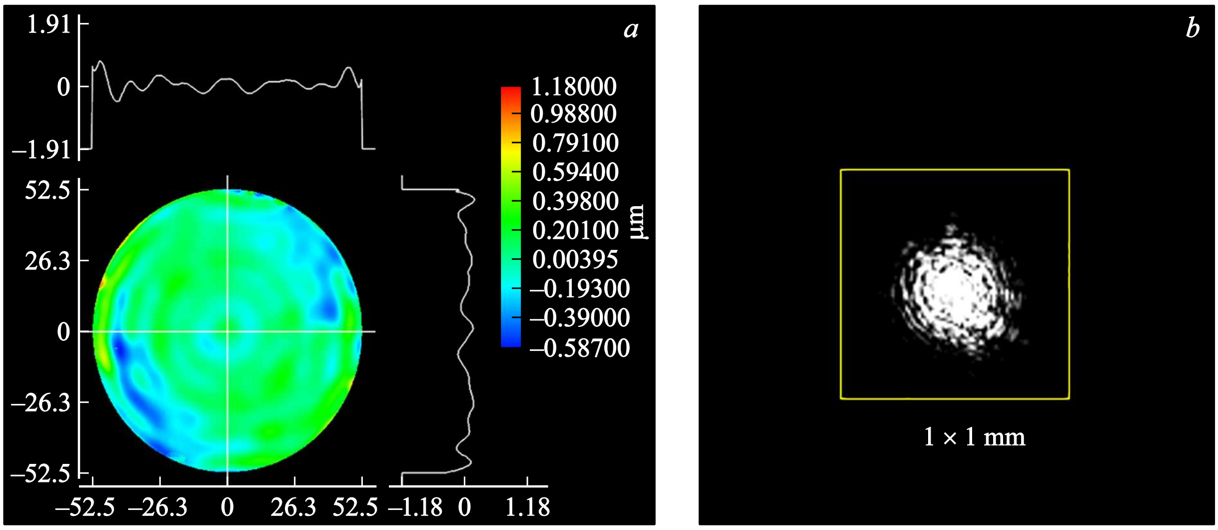

Figure 7. The wave aberration map of the collector mirror (*a*) and the focus spot (*b*) after asphierization.

the residual error of the mirror shape can be estimated as $\sqrt{0.3^2 + 0.33^2} - 0.33 \approx 0.12$ mm.

Conclusion

An ion-beam method of manufacturing aspherical optical elements with a span of surface profile heights greater than 30 μm is implemented in this study. The technological ion source KLAN-53M was upgraded to solve the problem. As a result of modernization, a high-current small-sized ion beam with parameters was obtained: ion current — 20 mA, ion beam width at half height — 8.2 mm, ion current density $\sim$ 40 mA/cm^2, ion energy — 1000 eV, velocity etching at maximum — 1.0 μm/min.

The modernization of the source made it possible to produce a collector with a numerical aperture NA = 0.25, with material removal 36 μm, shape accuracy according to the standard deviation 0.074 μm and a focus spot 300 μm.

It is possible to manufacture collectors in this way with a numerical aperture up to NA = 0.65 for aspherization of which material removal up to 100 μm is required, which can be used in high-performance EUV lithography.

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Conflict of interest

The authors declare that they have no conflict of interest.

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