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Prospects for the use of reactive ion-beam etching of fused quartz with a mixture of tetrafluoromethane and argon for aspherizing the surface of optical elements

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Received April 26, 2022
Revised April 26, 2022
Accepted April 26, 2022

The paper proposes to use the discharge energy for the synthesis of chemically active particles in order to correct the shape and aspherize the surface of optical elements by reactive ion-beam etching. A stand was assembled on the basis of a radio frequency source of accelerated ions KLAN-105M, the design of which allows working with reactive gases. The possibility of increasing the etching rate of fused quartz by more than 5 times compared to ion etching with inert gases by creating a mixture of tetrafluoromethane (CF_4) and argon (Ar) in a ratio of 1 : 1 is shown, while maintaining the initially smooth surface roughness (($\sigma_{\text{eff}} \sim 0.3$ nm) in the range of spatial frequencies $\nu \in [5.0 \cdot 10^{-2}–6.4 \cdot 10^{1}\,\mu\text{m}^{-1}]$.

Keywords: ion etching, reactive ion etching, roughness, surface, X-ray optics.

DOI: 10.21883/TP.2022.08.54574.111-22

Introduction

The development of modern science and technology, in particular, such advanced areas as SXR microscopy, space astronomy and projection EUV nanolithography requires improving the quality of optical elements. The short wavelength (units nm) imposes strict requirements on both the shape and surface roughness. The low reflection coefficients of multilayer X-ray mirrors do not allow the use of multi-mirror optical systems (more than 3 elements), since the intensity of such a system is proportional to $\sim R^n$, where n is the number of elements, and R is the reflection coefficient of mirrors. Thus, in order to reduce the number of elements in the system, they resort to the use of aspherical profiles of complex shapes of optical elements. The maximum deviation of the real surface profile often implies a significant deviation from the nearest sphere (at the level of units–tens μm). To solve the problems of deep aspherization of the surface shape of optical elements of the short-wave spectrum (EUV, BEUV, SXR), the ion-beam etching technology [1–3] is used. However, when creating surfaces with a deviation from the nearest sphere of $10\,\mu$m and more, developers face certain difficulties associated primarily with low etching rates (up to 50 nm/min), which leads to long processing times at which it is possible to change the output parameters of the source accelerated ions. In addition, ion-beam etching with inert gases has a very weak effect on the errors of the surface of the mid-frequency range of the spatial spectrum ($10^{-3}–10^{0}\,\mu\text{m}^{-1}$) [4]. Thus, it is practically impossible to reduce the amplitude of heterogeneity with lateral dimensions of the order of $1\,\mu$m, whereas they play a very important role in achieving the diffraction limit of the spatial resolution of imaging optics.

In order to increase the efficiency of such a promising contactless method as ion beam etching, it is proposed to use the discharge energy for the synthesis of chemically active particles (ChAP) in plasma. Depending on the pressure, energy and available ChAP, the nature of the etching process can vary from purely physical (ion-beam) to purely chemical (reactive). In addition to aspherization and correction of shape errors, reactive ion beam etching can be used to remove the disturbed layer after the procedure of mechanical polishing or turning without penetration of ions into the volume, as well as to clean the surface from contamination. For example, to clean the collector mirror of a laser-plasma source from erosion products due to a laser spark or optical elements of a lithograph from hydrocarbon contamination with photoresist particles [5].

1. Description of the installation and experiments

For this study, a stand was assembled (Fig. 1) consisting of *1* — a vacuum chamber; *2* — a movable flap electrically disconnected from the structural elements, which allowed it to be used as an ion current meter when the accelerated ion source is heated; *3* — motorized linear movement with height movement in the range of 300 mm and with the possibility of inclination within 0–60° (the angle is calculated from the normal); *4* — rotating table for mounting samples; *5* — frames for fixing the diaphragms forming the ion beam profile; *6* — oil-free forevacuum pump; *7* — thermocouple vacuum lamp PMT-6; *8* — magneto-discharge vacuum lamp

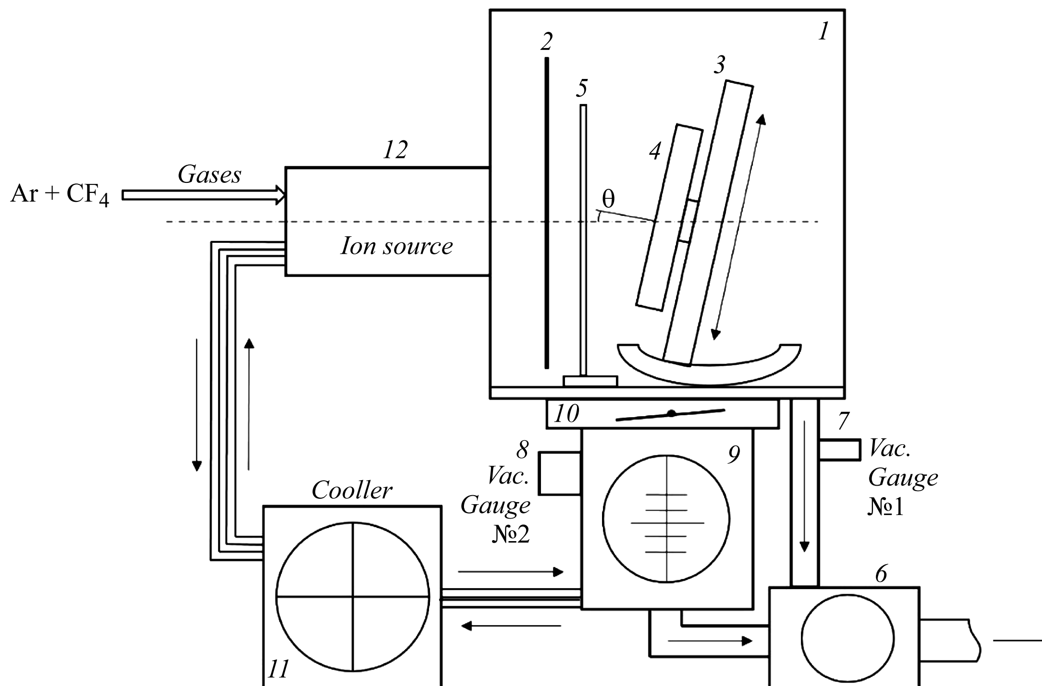

Figure 1. Diagram of the experimental unit.

PMM-32; *9* — turbo molecular pump (TMN); *10* — gate; *11* — chiller with dionized water for cooling the source of accelerated ions and TMN; *12* — the source of accelerated ions KLAN-105M (NTK „Platar“). The pressure of residual gases in the chamber $\sim 10^{-4}$ Pa. Dimensions of the vacuum volume: cylinder Ø 400 mm, height 450 mm.

The KLAN-105 M — radio frequency source (operating frequency 13.56 MHz) accelerated ion source with a flat ion-optical system. Output aperture —Ø 100 mm. Gas consumption — 6–15 cm^3/min. The maximum ion current is up to 300 mA. Ion energy range 0.2–1.5 keV. The working pressure of gases in the chamber $\sim 10^{-2}$ Pa.

Plates of fused quartz of the KV brand were used as samples — initial effective roughness (σ_{eff}) at the level of 0.3 nm in the spatial frequency range $\nu \in [5.0 \cdot 10^{-2}–6.4 \cdot 10^{1}\,\mu\text{m}^{-1}]$. The maximum size of samples is — $200 \times 200 \times 60$ mm. Roughness measurements were performed at the atomic force microscopy (AFM) stand [6], frames 2×2 and $40 \times 40\,\mu$m and the corresponding PSD function (power spectral density) are shown in Fig. 2 and 3, respectively). Restoration of the PSD function from AFM measurements and calculation of the effective roughness was performed according to the procedure described in [6].

As part of this study, all experiments were carried out under normal line to the plane of the sample. The samples were irradiated with accelerated neutralized (the positive spatial charge was compensated by introducing an additional electron source at the output of the ion source) argon ions, as well as a mixture of argon (Ar) and tetrafluoromethane (CF_4). The ion current density was 0.25 mA/cm^2. Part of the sample was covered with a mask to determine the etching depth. The step obtained as a result of etching at the mask boundary was measured using a Talysurf CCI2000 white light interferometer.

2. Results and discussion

A series of experiments were conducted using argon ions mixed with tetrafluoromethane in a ratio of 1 : 1 (the ratio was controlled by the partial pressure of gases in the chamber). The etching depth in all experiments was ~ 200 nm. The obtained dependences of the etching rates and the values of the effective roughness on the ion energy are shown in Fig. 4.

It can be seen that the addition of tetrafluoromethane made it possible to significantly increase the etching rate over the entire ion energy range. Moreover, it can be noted that the dependence of the etching rate on the energy with the addition of ChAP has a downward trend in contrast to the case of pure argon, which indicates different prevailing spraying mechanisms in the etching process at different energies. At low ion energies (up to 300 eV), the main mechanism is reactive etching, and with an increase in ion energy, the depth of penetration of ions under the surface also increases, which leads to the fact that the products of the chemical reaction do not leave the sample volume and the mechanism of physical sputtering becomes predominant. However, even in this case, the etching rate is higher.

The most important parameter when processing the surface of optical elements is the value of effective

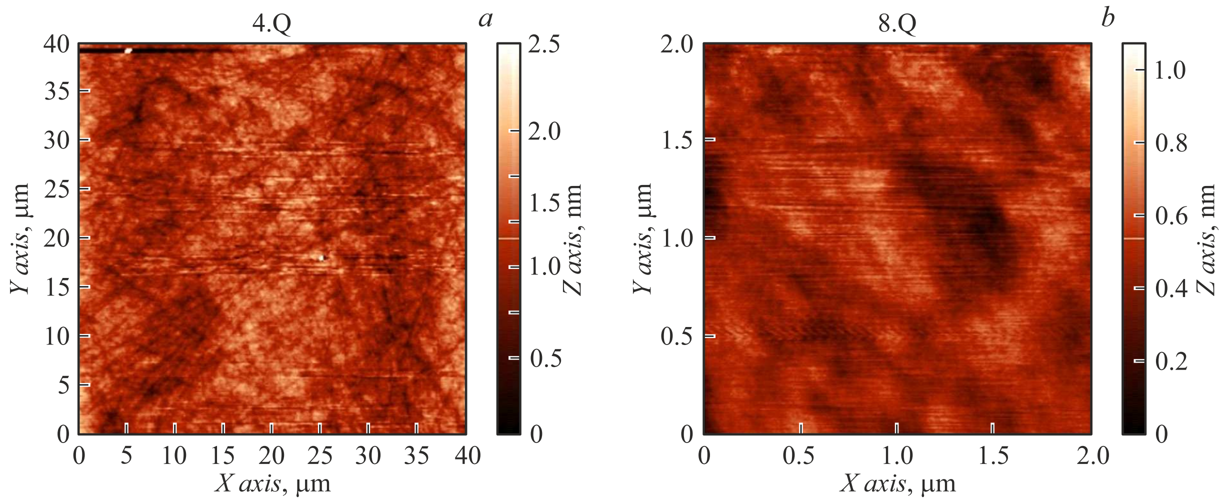

Figure 2. AFM frames of the initial surface of fused quartz.

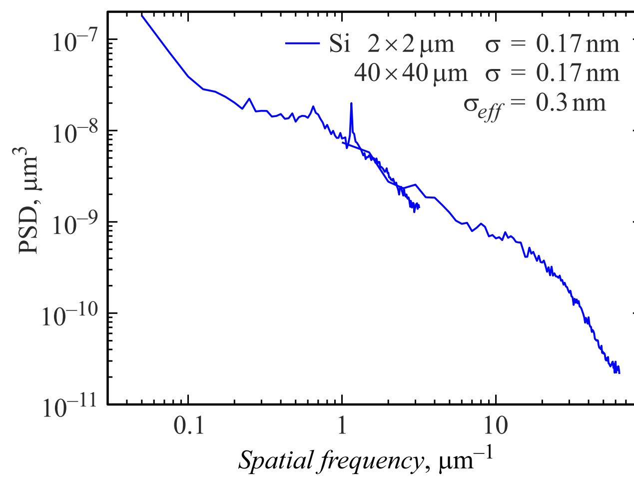

Figure 3. PSD is a function of the initial surface of fused quartz.

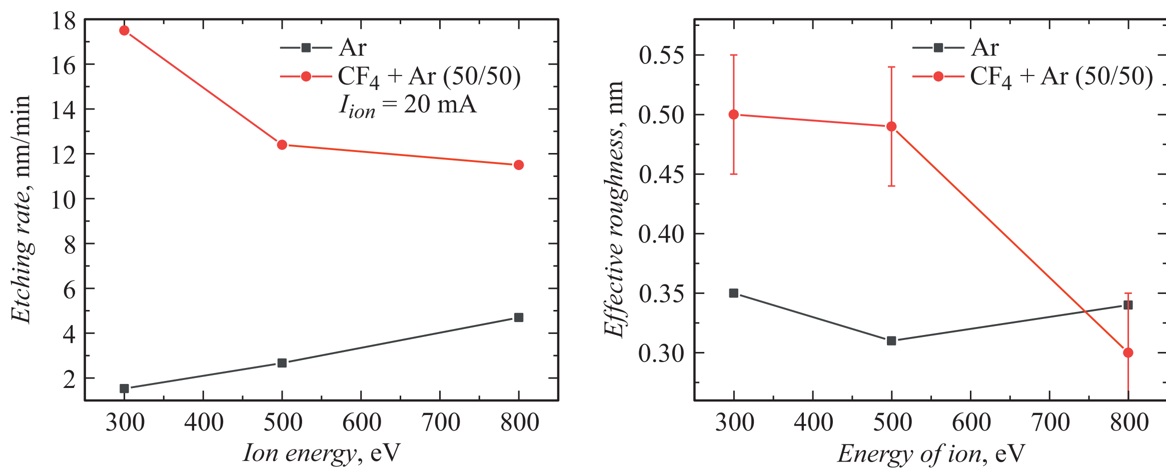

Figure 4. Experimentally obtained dependences of the etching rate (left) and the effective roughness on the ion energy (right).

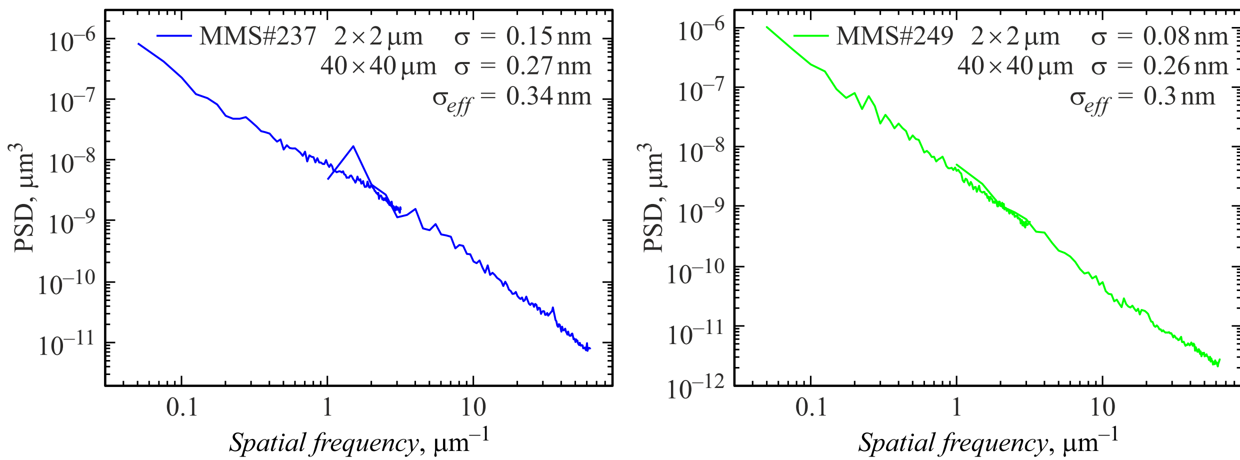

Figure 5. PSD-functions of the surfaces of fused quartz after etching with argon ions (left) and a mixture of argon and tetrafluoromethane ions (right). Ion energy — 800 eV.

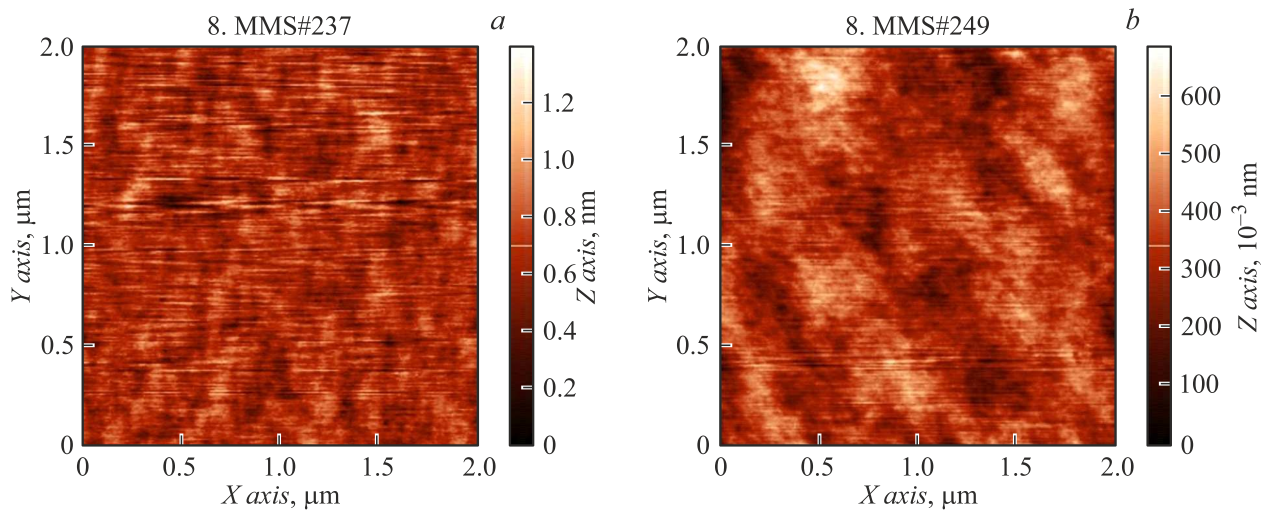

Figure 6. AFM frames $2 \times 2\,\mu m$ of fused quartz surfaces after etching with argon ions (left) and a mixture of argon and tetrafluoromethane ions (right). Ion energy — 800 eV.

roughness. For all experiments, the effective roughness of the sample surface was monitored before and after etching. Fig. 4 shows that the best result (from the point of view of roughness minimization) was obtained at an energy of 800 eV. Below are the constructed PSD functions for samples irradiated with argon ions and a mixture of tetrafluoromethane and argon with an energy of 800 eV, respectively. At such energy, high-frequency heterogeneities $\nu \in [10^0{-}10^3\,\mu m^{-1}]$ smoothed out almost 2 times (Fig. 5), which can be seen on AFM frames $2 \times 2\,\mu m$ (fig. 6).

Thus, the first experiments on reactive ion-beam etching showed the possibility of increasing the etching rate of fused quartz from 2.5 to more than 5 times when tetrafluoromethane ions were added to the beam. The effective surface roughness in the spatial frequency range $\nu \in [5.0 \cdot 10^{-2}{-}6.4 \cdot 10^1\,\mu m^{-1}]$ at the same time remains at the initial level or even smoothing is observed after the etching procedure throughout ion energy range (300–800 eV).

Conclusion

As a result of the study, a stand for aspherization of the surface of optical elements by reactive ion-beam etching was developed and manufactured. The possibility of increasing the etching rate (sputtering coefficient) due to the use of chemically active particles is shown.

It has been experimentally shown that when using tetrafluoromethane and argon gases in a ratio of 1 : 1 as a working mixture (control by partial pressure of gases in the chamber), it is possible to increase the etching rate of fused quartz by more than 5 times compared with pure argon. At the same time, the surface roughness is preserved

or smoothed over the entire range of spatial frequencies $\nu \in [5.0 \cdot 10^{-2}–6.4 \cdot 10^{1}\,\mu\mathrm{m}^{-1}]$.

Acknowledgments

The CUC equipment of the IFM RAS Central Research Center was used.

Funding

The study was carried out with the financial support of the RNF grant № 21-72-30029.

Conflict of interest

The authors declare that they have no conflict of interest.

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