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Features of Ion-Beam Polishing of the Surface of Sapphire

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Abstract—The effect of an argon ion beam on the surface of sapphire is studied at different technological parameters: the ion energy, and the angle α between the sapphire surface and the ion-beam axis. The roughness of the sapphire surface is analyzed before and after ion polishing. The optimum ion-beam parameters are determined, at which the surface roughness after polishing decreases to 0.8 nm. At angles $\alpha = 20°–30°$, the relief of the sapphire surface is found to become wavy. The study of the impact of the ion energy on the roughness of the sapphire surface in the 400–1200-eV range reveals that an increase in the energy of the ion beam to 1200 eV is accompanied with a decrease by 8.8 times in the roughness which falls below the level of 3 nm.

Keywords: ion-beam treatment, roughness of thesapphire surface, Ar ion beam
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INTRODUCTION

The surface polishing of oxide optical materials, such as sapphire, is considered to be the most promising physical method for designing various optical products with amplified characteristics. This is achieved by a pronounced decrease in the surface roughness, which is unattainable by other methods [1–7].

The influence of various factors, such as the incident-particle energy, the weight ratio of the bombarding and emitted particles, the temperature of the target, and the angle of incidence of particles onto the irradiated surface on the roughness of the ion-beam-treated surface attracts the greatest interest. This is especially important for improving the properties of the surfaces of optical components. According to [8], the rate of sputtering reaches a definite maximum at the corresponding angle α between the sapphire surface and the ion-beam axis, which depends on the surface material, energy, species of ions, and others. The sputtering of the target surface at various temperatures was studied in [9], where the optical glasses, molybdenum, quartz, and sapphire were exposed to argon-ion bombardment. It was found that the rate of sputtering remained constant up to a temperature of 700 K. However, the effect of ion bombardment on the roughness of the surface was not discussed in [9].

The influence of ion treatment on superficial defects was elucidated in [10] using electron microscopy. As was shown, the defects were not eliminated, but were smoothed with improving the surface microrelief. Ion polishing becomes essential for the removal of fractured layers of polycrystalline optical materials that are used as active media in the fabrication of lasers (sapphire, ruby, garnet, and others). This evidences the great prospects and the importance of the ion polishing of optically active materials.

Thus, the ion polishing of the surface of optical materials can substantially enhance their microstructural and optical properties, as well as simplify their production technology.

EXPERIMENTAL

To ensure performance of the process, suitable ion current densities at certain energies are highly desirable. The Kaufman source meets these requirements to the greatest extent. Measurements were carried out using a KLAN-53M ion source (Platar Corp.) which is designed to create ion beams of chemically active gases (argon, nitrogen, and their mixture with oxygen) in vacuum [1].

According to passport details, the maximally accessible output beam diameter is 50 mm, and the maximum ion current is 80 mA. The ion-beam energy varies from 150 to 1500 eV, and the output ion current density can reach 4 mA/cm^2.

The vacuum chamber is equipped with a carousel containing the sapphire samples (Fig. 1), each of them is oriented at a definite angle α to the ion-beam axis.

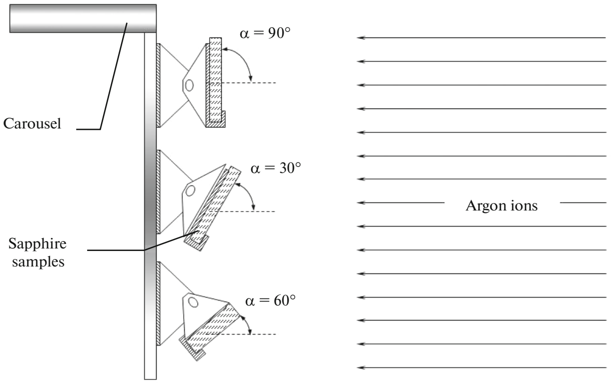

Fig. 1. Schematic of the ion polishing of the sapphire surface.

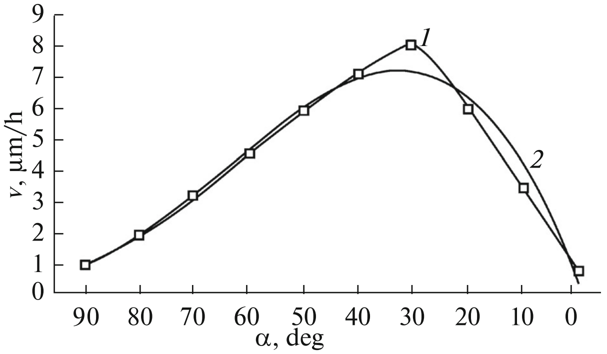

Fig. 2. Rate of sputtering of sapphire v versus angle α between the sapphire surface and the ion beam axis: (*1*) experiment; (*2*) approximation.

The simultaneous loading of sapphire samples in the vacuum chamber allows one to perform ion-beam exposure within a single technological process that ensures the same conditions and considerably reduces the time of experiments.

The argon-ion energy and the angle α between the ion-flux direction and the sapphire surface varied during the measurements, as follows. The argon-ion energy was set over a range of 400–1200 eV at an increment of 400 eV and an accuracy of 5%. Angle α was varied in the range 90°–10° with an increment of 10° and an accuracy of 5% (Fig. 1). The temperature of the sapphire targets was kept constant at around 200°C (accuracy of 2%) that was determined with a chromel–alumel thermocouple. The ion current was maintained at 39 mA, corresponding to a current density of ~2 mA/cm^2 (error of 5%). Since the time of the process was 1 h, then the fluency defined as $\Phi = j\Delta t/e$ equals 7.5×10^{15} cm^{-2}.

The thickness of the etched sapphire layer was measured using an IKD-140 interferometer. The sapphire surface state prior and after ion-beam exposure was controlled in a Versamet 2 optical microscope. The roughness parameters of the sapphire surface were established with an NTEGRA atomic force microscope (AFM).

RESULTS AND DISCUSSION

Pre-polished sapphire substrates with dimensions of 10 × 10 × 3 mm were used in the first stage of the study. The average initial roughness of the surface as the irregularity height was 115 ± 10 nm. First, the rate of sputtering was investigated as a function of the angle α, which is plotted in Fig. 2. For all samples, the energy of argon ions was 1200 eV. The rate of sputtering of the sapphire surface was found to be maximum at α = 30°. It is worth noting that the rates of sapphire sputtering, determined in this work, match those in [2, 10].

Figure 3 displays the optical micrographs with the sapphire surface exposed to argon-ion bombardment at different α angles. As is seen in Fig. 3a, while the

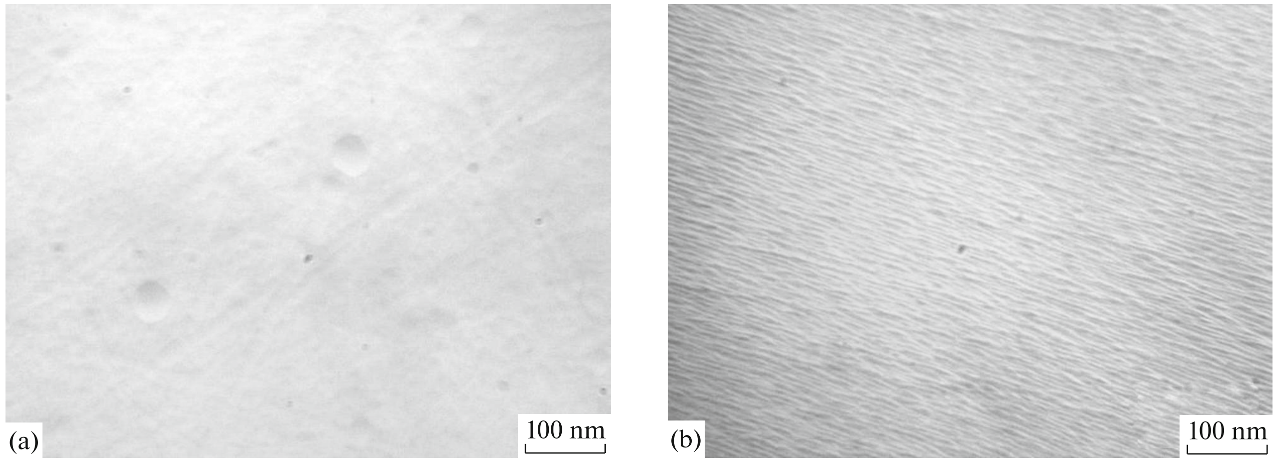

Fig. 3. Sapphire surface after ion polishing (2000× magnification) at different α angles: a — 70°; b — 30°.

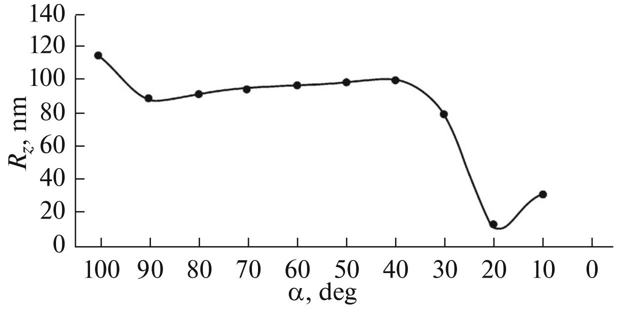

Fig. 4. Roughness R_z as a function of angle α between the sapphire surface and the ion-beam axis.

relief becomes smooth, the surface topology remains unchanged. As follows from Fig. 3b, when the angle α is equal to 30°, the relief is completely modified as compared to the initial sapphire surface and exhibits a wavy structure.

The next stage of the study was to establish the surface roughness of pre-polished sapphire as a function of angle α between the sapphire surface and the ion-beam axis. The results are given as the irregularity height R_z plotted versus the incidence angle α (Fig. 4). It is evident that the roughness at the energy of argon ions of 1200 eV is the minimum at α = 20°, and the irregularity height decreases 8.8 times. Some AFM data on the dependence of the amount of irregularities on their height are illustrated in Fig. 5.

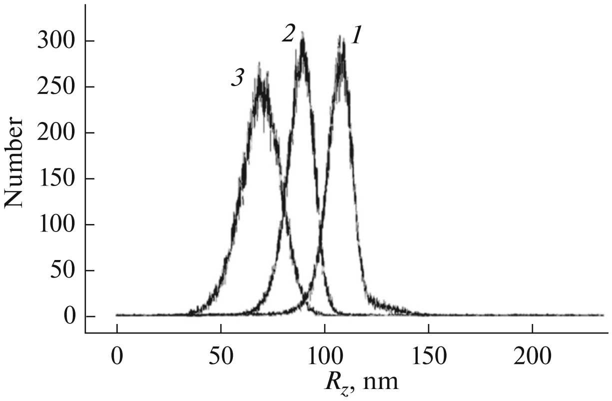

Fig. 5. Number of irregularities of the sapphire surface versus its roughness R_z: (*1*) before polishing; (*2*) after polishing at an angle of α = 90°; (*3*) after polishing at an angle of α = 40°.

The roughness of sapphire was then inspected at various energies of the argon ion beam. Based on previous data on the ion-beam treatment of sapphire, two α angles of 90° and 20° were chosen. The ion-beam energy was varied within a range of 400 to 1200 eV. The roughness of the sapphire surface was probed with AFM. Figure 6 shows the irregularity height R_z versus the ion energy at two α angles. The maximum of the irregularity height is well resolved at an ion-beam energy of 800 eV for both angles between the sapphire surface and the ion-beam axis. The roughness of the sapphire surface exposed to ion bombardment is the lowest at an energy of 400 eV, α = 90°, and at an ion energy of 1200 eV, α = 90° and 20°. Thus, ion-beam treatment of the initial sapphire substrates with the 110–220-nm-high irregularities leads to a decrease in the irregularity height to 33–3 nm.

The last stage of the work was ion polishing of the so-called nanopolished sapphire surface. Figure 7a shows AFM data of the initial wafer of nanopolished sapphire where the maximum height of irregularities is about 3 nm. Figure 7b represents the nanopolished sapphire surface after ion-beam exposure at the optimal technological parameters (the ion energy E = 1200 eV, α = 20°). It is seen that the maximum height of irregularities has fallen to 0.8 nm.

The results of the present study allow one to conclude that 1 hour of the argon ion polishing of nanopolished sapphire (at a fluence of 7.5×10^{15} cm^{-2}) at an ion energy E = 1200 eV and at the angle α = 20° reduces the surface roughness to 0.8 nm. Ion treatment makes the irregularities of the nanopolished sapphire surface 3.75 times lower, which corresponds to the best values reported by other authors [2, 10].

CONCLUSIONS

Based on the results elucidating the effect of ion polishing on the sapphire surface, the following conclusions were drawn. The rate of sputtering of the sapphire surface was found to be maximum at α = 30° at an energy of argon ions of 1200 eV. As was highlighted,

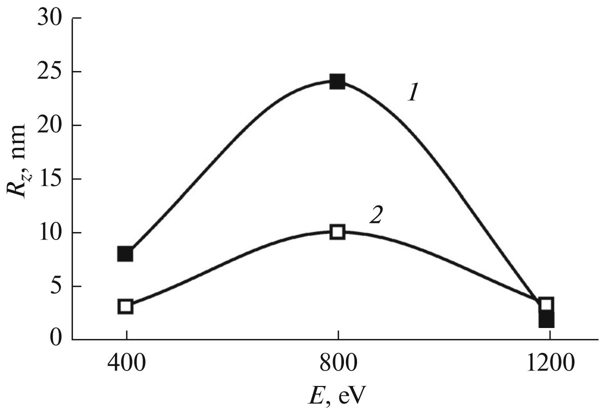

Fig. 6. Roughness R_z as a function of the ion energy E at an angle α between the sapphire surface and the ion beam axis of: (*1*) 90°; (*2*) 20°.

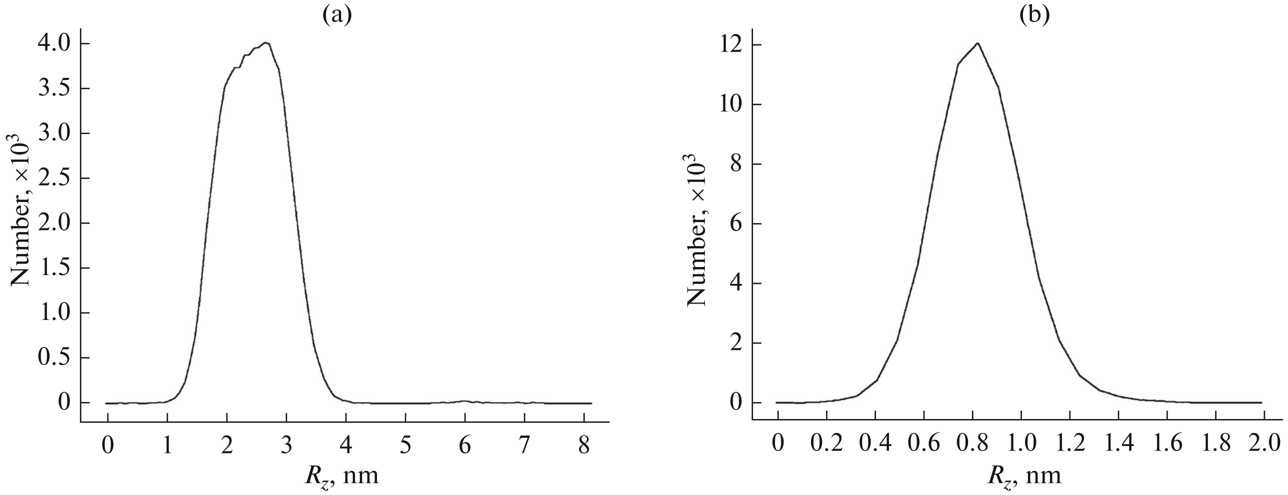

Fig. 7. Number of irregularities of the sapphire surface versus its roughness R_z: (a) before polishing; (b) after ion-beam polishing.

at $\alpha = 20°–30°$ the sapphire surface relief took on a wavy character. The roughness was the lowest at an argon-ion energy of 1200 eV and an incidence angle of $\alpha = 20°$ onto the sapphire surface. The height of the irregularities became 8.8 times smaller and did not reach 3 nm. The height of the irregularities of nanopolished sapphire after ion-beam exposure at $E = 1200$ eV and $\alpha = 20°$ decreased 3.75 times its initial value, reaching the level of 0.8 nm.

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