Fabricating Sapphire Nanostructures by Near-Field Focusing of Ultrafast Laser

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Bio-inspired nanostructures have drawn significant interest and attention due to their attractive electrical, optical, and mechanical properties. One unique effect enabled by bio-inspired nanostructures is surface functionalization, which includes anti-glare, self-cleaning, anti-fogging, and fracture resistance.[1,2] Such applications can be found in conventional materials such as silica-based glass in previous studies.[3] However, the functionalization of sapphire surfaces enabled by these bio-inspired nanostructures has been less explored. This is because its attractive properties, such as high mechanical hardness and chemical stability, which make creating high-density features on the sapphire surface extremely challenging.

In our previous studies, we demonstrated that bio-inspired nanostructures can be obtained either by using a multilayer mask[4] or by applying low radio frequency (RF) power[5] in dry etching processes. Another interesting approach in the past for texturing sapphire surfaces involved using an ultrafast laser to induce morphology changes.[6] By employing direct ultrafast laser writing before the etching process, the etching rate of ultrafast modified regions can be increased. Therefore, in this study, we propose a new approach to create highly dense sapphire nanostructures by using near-field focusing of an ultrafast laser. The fabrication process is illustrated in Fig. 1. Initially, dielectric microspheres are utilized as lenses to form tightly focused laser beams on the sapphire surface, exploiting the photonic nanojet effect.[7] Subsequently, these nanojets alter the crystallinity of sapphire from crystalline to amorphous and polycrystalline forms. Finally, we use chemical or plasma etching to remove the modified regions, thus forming sapphire nanostructures.

The initial results shown in Fig. 2(a) demonstrates that sapphire structures can be created using 9 μm silica particles following ultrafast laser exposure and HF etching for 20 min. A finite-difference time-domain (FDTD) simulation was performed to verify the feature profile by determining the intensity threshold based on the hole diameter observed in SEM images. In Fig. 2(a), the donut shape indicated by an orange arrow corresponds with the simulation result shown in Fig. 2(b). Furthermore, an intensity threshold defined by a particle with 1.7 μm diameter can be used to predict the depth of the sapphire nanostructures, as shown in Fig. 2(b)-(c). Consequently, the simulated depth of 6.4 μm closely matches the actual depth of 6.1 μm. However, the region modified by the near-field ultrafast laser focusing, indicated by a white arrow in Fig. 2(a), does not appear to be completely removed. This is because the nanojet focus lies beneath the surface, as shown in Fig. 2(c), which makes it difficult for the HF etchant to penetrate the amorphous sections. Therefore, smaller silica particles were used to adjust the nanojet focus closer to the surface. The results in Fig. 3 show that sapphire nanostructures with a diameter of 510 nm and a depth of 1120 nm can be created using 4.3 μm silica particles, and sapphire nanostructures with a diameter of 190 nm and a depth of 150 nm can be created using 1.18 μm silica particles.

This approach confirms that highly dense sapphire nanostructures can be fabricated using near-field ultrafast laser focusing. Additional details, including further fabrication results, challenges, and limitations, will be presented.

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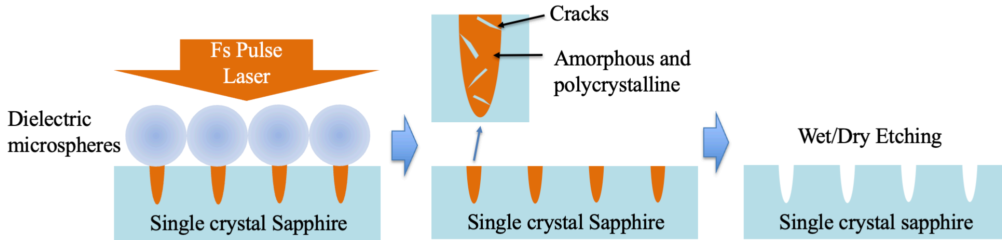

Figure 1. Fabrication processes of proposed technique.

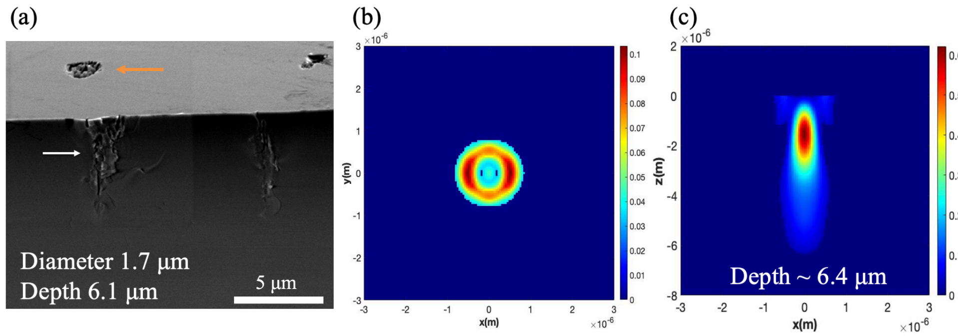

Figure 2. Sapphire nanostructures fabricated by the near-field focusing of ultrafast laser using 9 µm silica particles. (a) Cross-sectional SEM image of sapphire nanostructures. FDTD simulation results: (b) top-view and (c) cross-section.

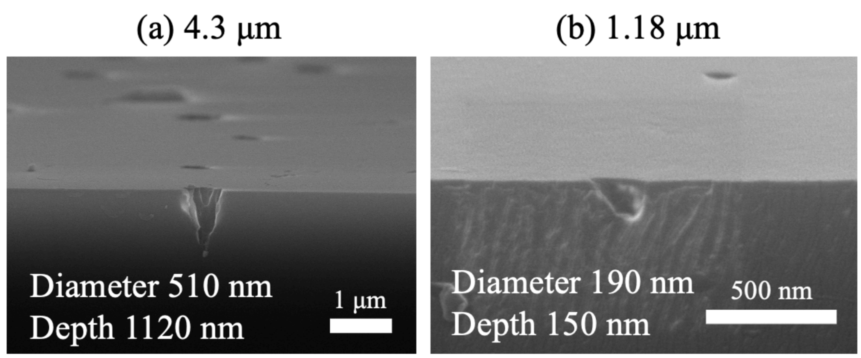

Figure 3. Sapphire nanostructures fabricated by the near-field focusing of ultrafast laser using (a) 4.3 and (b) 1.18 µm silica particles.

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