FEMTOSECOND LASER ABLATION OF SAPPHIRE

Litao Qi¹, Yoshiharu Namba¹, Kazuhiro Nishii², Motohiro Yasui² and Hikoharu Aoki²
¹Department of Mechanical Engineering
Chubu University
Kasugai, Aichi, Japan
²Engineering Department
Brother Industries, LTD
Nagoya, Aichi, Japan

INSTRUCTION
Sapphire is widely used in the field of optical components and micromechanical devices owing to its useful mechanical, optical, and electrical properties. However, sapphire is mechanically and chemically difficult to machine because of its high hardness and chemical stability. The difficulty of machining sapphire has restricted the development of advanced device structures. As sapphire is inert to most types of wet chemical and dry etching, laser ablation has been proposed as a potential machining method. The interaction of laser pulses with sapphire materials has been investigated for many years [1-3]. However, a thermal effect is unavoidable, even in ultraviolet laser processing. Recently, the femtosecond laser ablation of sapphire has been attracting much attention because femtosecond laser ablation can produce precise, well-defined micrometer-sized structures in materials that cannot be processed with nanosecond pulsed lasers. A number of studies on the femtosecond laser ablation of sapphire have been carried out [4-7], and a mechanism for the femtosecond laser ablation of sapphire has been proposed [8-10]. The advanced development of III–V nitride devices such as those of GaN and InGaN [11,12] has prompted research into a suitable method of patterning sapphire. However, further experiments need to be carried out to obtain fine structures on sapphire. In this study, experiments on the femtosecond laser ablation of sapphire were carried out focusing on several aspects including the investigation of laser-induced periodic surface structures (LIPSS) on sapphire, and the relationship between ablation depth and the number of pulses, and a method of improving the surface quality of sapphire. As a result of our investigations, a sample of sapphire with parallel microgrooves on the surface was fabricated.

EXPERIMENTS
In the experiments, we used a commercially available amplified Ti:sapphire laser system that generated 164 fs laser pulses with a maximum pulse energy (E_p) of 1 mJ at a 1 kHz repetition rate and with a central wavelength of \( \lambda = 780 \) nm. The laser beam had a Gaussian profile with a diameter of 6 mm. The incident laser beam was irradiated onto a sapphire sample through a 4 mm aperture positioned normal to the sample and a 10× or 50× microscope objective lens. The sample was placed on a scanning stage and translated at various scanning speeds (v) under computer control during irradiation. The scanning direction was perpendicular or parallel to the laser polarization direction. All experiments were carried out in air at atmospheric pressure and room temperature. After irradiation, the sample was rinsed for 30 minutes with acetone in an ultrasonic cleaner to remove any debris from the ablation process. The morphology of the structures was examined by scanning electron microscopy (SEM). The sample was coated with a gold layer of approximately 22 nm thickness to ensure conduction in the SEM observation. The surface profile was measured by atomic force microscopy (AFM).

RESULTS AND DISCUSSION
The sapphire was first irradiated by different pulse energies and numbers of laser pulses under static irradiation, and then the fabrication of microgrooves on sapphire by femtosecond laser pulses was investigated through line-scanning experiments.

Laser-Induced Periodic Surface Structures on Sapphire
Figure 1 shows an image of LIPSS formed on the sapphire surface when it was irradiated with a pulse energy close to the ablation threshold.
and 20-50 laser shots. The spatial period of LIPSS on the sapphire surface was approximately 340 nm. The orientation of the LIPSS was perpendicular to the polarization direction of the laser beam.

**FIGURE 1.** SEM image of LIPSS formed on sapphire by femtosecond laser pulses with $E_p = 1.95 \mu J$ and 50 laser shots.

The formation of LIPSS on sapphire was caused by interference between the laser-induced plasma and the incident laser beam [13]. Further investigations on the fine nanostructures formed on sapphire by femtosecond laser pulses similar to those that Shinoda et al. obtained on diamond [13] are being carried out because of their potential application to nanotechnology.

**Laser Processing of Sapphire with Different Pulse Energies and Laser Shots**

Upon irradiation with ultraviolet and ultrashort laser pulses, two ablation phases can be observed with increasing number of laser pulses [2,4,5]. One is a ‘gentle’ ablation phase characterized by a low rate of material removal, which has been attributed to particle vaporization. The second phase is characterized by a high rate of material removal and the production of molten droplets, which has been attributed to a phase explosion [2,4,5]. In our experiment, the same results were obtained, in agreement with previous works by Tam et al. [2] and Ashkenasi et al. [5]. Figure 2 shows AFM images of the cross-sectional profile of the crater produced by the irradiation of femtosecond laser pulses with a pulse energy of 3.64 $\mu J$ and different number of laser pulses. During the first 10 pulses, the laser-ablated area is generally smooth, as shown in Figures 2(a), 2(b), and 2(c). After 10 laser shots, rough regions start to form in the ablated area, as shown in Figure 2(d).

**FIGURE 2.** AFM images of cross-sectional profile of the crater produced by irradiation of femtosecond laser pulses with $E_p = 3.64 \mu J$ and different numbers of laser pulses.

Cracks have a negative effect on the applicability of sapphire. The formation of cracks is unavoidable, even in ultraviolet laser processing with long pulses, because of the thermal effect [1]. The sapphire ablated by femtosecond laser pulses is free of cracks under appropriate irradiating conditions. Figure 3 shows SEM images of the craters produced by the irradiation of femtosecond laser pulses with 1000 laser shots and different pulse energies. When the pulse energy was high, cracks were observed around the ablated crater, as shown in Figure 3(a). When the pulse energy decreased, no cracks were observed around the ablated crater, as shown in Figure 3(b).

**Variation of Ablation Depth with Pulse Energy and Number of Laser Pulses**

The ablation depth of the crater is an important parameter for investigating the mechanism of laser ablation and for expanding the range of applications of sapphire. In our experiment, sapphire was first irradiated by femtosecond laser pulses that were propagated through a 50×
Microscope objective lens. The dimensions of the crater were measured by AFM and the ablation depth of the crater was obtained by measuring its cross-sectional profile. The ablation depth as a function of the number of laser pulses is illustrated in Figure 4 for three different pulse energies. The ablation depth of the crater increased with the number of laser pulses up to 100 shots. Above 100 laser shots, the ablation depth remained almost unchanged. The maximum obtainable depth was fixed. The mechanism of the femtosecond laser ablation of sapphire involves the phase explosion [2,5]. Ashkenasi et al. analyzed in detail the occurrence of the phase explosion during the femtosecond laser ablation of sapphire [5]. However, their results were puzzling in that the depth of ablation should be independent of the laser fluence if phase explosion is the main process leading to the removal of materials [5]. Our results may partially clarify this anomaly. Figure 4 shows that the ablation depth of the crater was independent of the pulse energy when the number of laser pulses was smaller than 25. As the number of laser pulses increased to 100, the ablation depth remained almost the same. The results showed that the ablation depth was independent of the laser pulse energy provided it was sufficiently high for phase explosion to occur.

![FIGURE 3. SEM images of the craters produced by irradiation of femtosecond laser pulses with 1000 laser shots and different pulse energies.](image)

(a) $E_p = 16.49 \mu J$

(b) $E_p = 1.33 \mu J$

**FIGURE 3.** SEM images of the craters produced by irradiation of femtosecond laser pulses with 1000 laser shots and different pulse energies.

![FIGURE 4. Relationship between the ablation depth of the crater and number of laser pulses as a parameter of pulse energy (50× objective lens).](image)

**FIGURE 4.** Relationship between the ablation depth of the crater and number of laser pulses as a parameter of pulse energy (50× objective lens).

**Microgroove Fabrication on Sapphire by Femtosecond Laser Pulses**

First, experiments to determine the dependence of the surface quality of the ablated crater on the crystal plane of the sapphire were carried out. Three types of crystal plane, c-plane, a-plane, and r-plane, was considered. The experiments were carried out with different pulse energies and number of laser pulses. The results showed that the surface quality of the ablated crater was higher when femtosecond laser pulses were irradiated on the c-plane, resulting in the fabrication of microgrooves on c-plane sapphire.

![FIGURE 5. SEM images of microgrooves fabricated with different numbers of laser scans by femtosecond laser pulses with $E_p = 1.64 \mu J$ and $\nu = 100 \mu m/s$.](image)

(a) Number of laser scans = 2

(b) Number of laser scans = 10

**FIGURE 5.** SEM images of microgrooves fabricated with different numbers of laser scans by femtosecond laser pulses with $E_p = 1.64 \mu J$ and $\nu = 100 \mu m/s$. 
Second, experiments on the fabrication of microgrooves on sapphire by femtosecond laser pulses were carried out under various conditions of pulse energy, scanning speed, and number of laser scans. The surface quality of the microgrooves was improved when the number of laser scans increased, as shown in Figure 5, although as the number of laser scans increased, the ablation depth of the microgrooves remained almost the same. The finding that the ablation depth of the microgrooves was independent of the number of laser scans was consistent with the results of the static irradiation experiments shown in Figure 4.

Finally, a sample of parallel microgrooves with high surface quality was fabricated on sapphire by femtosecond laser pulses, as shown in Figure 6.

**CONCLUSION**

Experiments on the femtosecond laser ablation of sapphire were carried out. The main conclusions are as follows.

1) Nano- and microstructures were fabricated on sapphire.

2) The craters formed by laser ablation are free of cracks under appropriate irradiating conditions. The removal of materials by femtosecond laser pulses was mainly caused by phase explosion.

3) The finding that the ablation depth of the crater was independent of the laser pulse energy clarified the puzzling phenomenon reported by Ashkenasi et al. that the depth of ablation should be independent of the laser fluence if phase explosion is the main process leading to the removal of materials.

4) The surface quality of the ablated crater was higher when femtosecond laser pulses were irradiated on c-plane sapphire.

5) In the line-scanning experiments, the surface quality of the ablated microgrooves fabricated by femtosecond laser pulses was improved by increasing the number of laser scans.

**REFERENCES**


