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Effect of crystal axis in temperature dependence of laser-induced damage thresholds by nanosecond near-infrared laser

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ABSTRACT

Laser-induced damage thresholds in crystalline quartz were evaluated using a single-mode Nd:YAG laser (wavelength 1064 nm, pulse width 4 ns) at temperatures ranging from 123 K to 473 K. In this experiment, three kinds of crystalline quartz different in the cut direction were prepared. The damage morphologies were coincident with the crystal structure. The laser induced damage thresholds in crystalline quartz differed according to the cutting direction. The laser-induced damage thresholds expect in the case of *Z*-cut sample increased with decreasing temperature. The cutting direction of the *Z*-cut of crystalline quartz was parallel to the crystal axis. A tendency of the temperature dependence was the same with in the case of the glass materials. In contrast, the laser-induced damage threshold of the *Z*-cut sample decreased with decreasing temperature. The difference in the temperature-dependent behaviors of crystalline quartz is explained using physical models. The crystal axis influenced strongly to the electron resistivity and the electron avalanche process in laser-induced damage mechanisms was affected in the result.

1. Introduction

Recent advances in high-power laser systems have accelerated their use in numerous scientific and industrial fields. In these laser systems, output power is determined in several cases by laser-induced damage threshold (LIDT). The LIDT is defined as the minimum fluence of laser irradiation at which laser-induced damage is occurs. The LIDT can be improved by understanding the laser-induced damage mechanisms (LIDMs) that under the conditions encountered in the laser systems. LIDMs have been extensively studied over the last several decades [1]. Temperature plays an extremely important role in determining the LIDM for cryogenically cooled laser systems, which are promising candidates for next-generation high-power laser systems. Cooled Yb:YAG laser medium extremely produces high power with high slope efficiency [2, 3]. Some authors have reported the temperature dependence of LIDT for amorphous glass and coating materials [4–6]. As a typical example of a study on crystal materials, Manenkov evaluated the temperature dependence of LIDT in NaCl crystals in 1978 [7], and observed that the LIDT in these crystals increased with decreasing temperature.

Investigations of laser-induced damage are associated with the study of electric breakdown. The electric breakdown strengths of crystalline quartz and a silica glass at different temperatures were reported in 1941 [8]. The electric breakdown strengths for silica glass increased with decreasing temperature, thereby exhibiting the same tendency as the temperature dependence of LIDT. However, the temperature dependence of the breakdown strengths for crystalline quartz decreased with decreasing temperature. The LIDT in dielectric materials is partially determined by the relationship between the crystal axis and the direction of the optical electric field [9–11], however, the temperature dependence is not well understood. Elucidation of the temperature dependence of the LIDT for dielectric crystals is important in the design of a cooled laser system. In this study, we investigated the temperature dependence of LIDT in crystalline quartz using a single-mode Nd:YAG laser (wavelength 1064 nm, pulse width 4 ns). The experimental results indicated that the cutting direction in these dielectric crystals plays a role in determining their LIDTs. In addition, the experimental results are explained using a physical model.

2. Experimental setup and samples

Fig. 1 shows the experimental layout for measuring the temperature dependence of the LIDT of experimental samples. The incidental laser energy was adjusted by a half-wave plate and a

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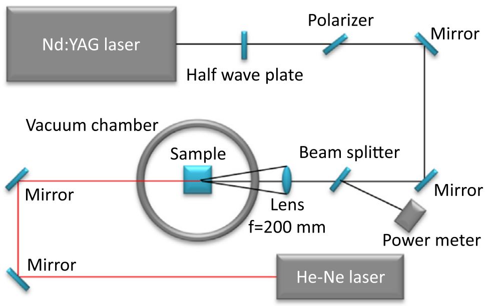

Fig. 1. Experimental setup.

polarizer. The laser pulse was focused onto the experimental sample by a lens with a 200 mm focal length. The focal spot size was measured in air and was defined by the $1/e^2$ peak intensity; the spot size was 70 µm in diameter. The sample was placed in a copper holder and the holder was subsequently placed in a vacuum chamber (~5 Pa) to avoid water condensation at low temperatures. The temperature was controlled with a combination of liquid nitrogen and a heater and was monitored with a platinum resistance temperature detector attached to the holder. We tested the setup using an N-on-1 irradiation scheme. A fixed site was irradiated by laser pulses, and the fluence was gradually increased until damage occurred. The laser-induced damage was detected by scattering on the damage site with a co-aligned He–Ne laser.

As shown in Table 1, three kinds of dielectric crystals were prepared as experimental samples. The cutting direction of the *Z*-cut of crystalline quartz was parallel to the crystal axis. The cutting directions of the *X*- and *Y*-cuts of crystalline quartz were perpendicular to the crystal axis and orthogonal to each other. The concentrations of impurities listed in Table 1 were evaluated by inductively coupled plasma mass spectrometry (ICP-MS) and inductively coupled plasma atomic emission spectrometry (ICP-AES). The three experimental samples were cut from selfsame crystalline quartz and had the qualities as well or better than that of ultra-high purity silica glasses.

3. Experimental results

3.1. Temperature dependence of LIDT

The plots in Fig. 2 shows the temperature dependence of LIDT in crystalline quartz as each plots and these error bars shows the measuring error attributable to the detectors for the input energy and the focal spot size. The LIDT in only *Y*-cut crystalline quartz was measured using two polarizations. The polarizations were adjusted along the crystal axis (0°) and in an oblique direction (45°). The LIDTs in the *X*- and *Y*-cut crystalline quartz increased with decreasing temperature. The temperature dependence of the LIDT exhibited the same trend as that of silica glasses [5], and the LIDT in the *Y*-cut crystalline quartz with 0º polarization was lower compared with 45º polarization. However, the temperature dependence of the LIDT in *Z*-cut crystalline quartz exhibited an opposite trend. The lines in Fig. 2 shows the calculation results of the LIDT and the detail is discussed in Section 4.1.

Table 1
Experimental samples and its concentrations of impurities.

Sample	Cutting direction	Concentration of impurities (ppm)		
		Al	Na	Fe
Crystalline quartz	*X* cut	0.0174	0.0050	0.0024
Crystalline quartz	*Y* cut			
Crystalline quartz	*Z* cut			

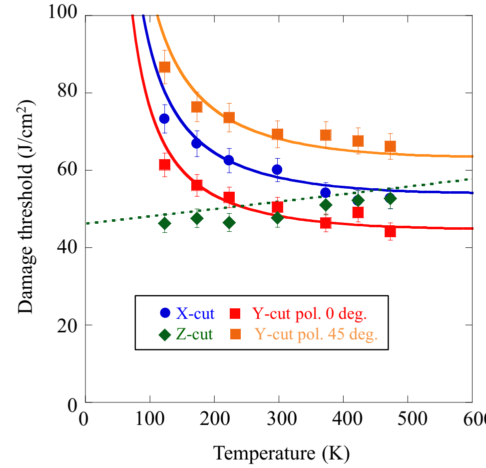

Fig. 2. Temperature dependence of the LIDT in crystalline quartz.

The LIDT in a bulk material can be varied by changing the refractive index, the self-focusing effect, or the thermal stress. Previously, we reported the temperature dependence of the self-focusing effect in a silica glass [12]. Under the temperatures used in our previous study, the refractive index of silica glass is of the order of 10^{-6} K^{-1}[13] and the nonlinear refractive index that causes a self-focusing effect is of the order of 10^{-20} m^2 W^{-1} K^{-1}. The variation of the spot size in the material was estimated to be less than 0.01% using geometric optics theory. Therefore, the variation was too small to change the LIDT and was neglected in this study.

3.2. Damage morphologies

Fig. 3 shows the damage morphologies after LIDT at room temperature in (a) *X*-cut crystalline quartz, (b) and (c) *Y*-cut crystalline quartz, and (d) *Z*-cut crystalline quartz. The arrows in Fig. 3 indicate the direction of the electric field of the incident laser pulse. The effect of thermal stress was also neglected in this study because the geometries and sizes of the sites damaged by LIDT fluence did not change as the temperature was varied. Fig. 4 (a) shows the positions of Si atoms in the crystal structure of dextro-α-quartz. Fig. 4(b) and 4(c) shows the lateral and the elevation views, respectively. The dotted line indicates the direction of the damage morphology. The morphologies were in good agreement with the crystal structure.

4. Discussion

4.1. Theoretical model

Laser-induced damage occurs when the relation

$$n_{cr} \le \beta_{(T)} \tau V n_{(T)} \quad (1)$$

is satisfied [14], where n is the electron number density generated by photoionization, phonon–electron interaction, or multiphoton ionization; $\beta_{(T)}$ is the multiplication rate for impact ionization; τ is the pulse width; T is the lattice temperature; and V is the volume in which free electrons are generated.

The first step during laser-induced damage of a dielectric materials is the generation of free electrons by photoionization [14] and phonon–electron interactions [15] in the case of irradiation with a nanosecond pulse of an infrared laser. Photoionization,