Influence of laser conditioning on defects of HfO_2 monolayer films

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The influence of laser conditioning on defects of HfO_2 monolayer films prepared by electron beam evaporation (EBE) is investigated utilizing the spot-size effect of the laser-induced damage. It is found that the laser-induced damage threshold of HfO_2 monolayer films can be increased by a factor of 1.3−1.6. It is also found that the defects with low threshold can be removed by laser conditioning and defects with higher threshold may be removed partially.

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Laser conditioning is a phenomenon that the laser-induced damage threshold (LIDT) of many optical components for high power lasers can be enhanced after under-threshold pre-irradiation. Several mechanisms have been proposed to explain the observed laser conditioning[1−8], but there is no complete physical explanation. It is well known that the laser-induced damage is induced by the defects in the film under long wavelength and wide pulse duration, so the influence of the laser conditioning on the defects in the film is worth investigating. In this letter, the laser conditioning of HfO_2 monolayer films prepared by electron beam evaporation (EBE) is reported and the transformation of the defects is analyzed using the spot-size effect of LIDT. The samples are prepared by EBE on K9 glass substrates. The wavelength of laser pulse used in laser induced damage tests and laser conditioning process is 1064 nm, and the pulse duration of it is 12 ns.

The experimental setup is built up according to ISO11254[9], as shown in Fig. 1. The Nd:YAG laser system outputs pulse at 1064 nm with pulse width of 12 ns. The laser is focused on the target normally by lens. Three spot-sizes (Gaussian diameters of 650, 313, and 247 μm) are obtained by changing the focal length of the lens. The attenuator and a half wave plate are employed to adjust the pulse energy radiating the sample. The sample is mounted normally to the beam in a step motor, which is used to position different test sites. The online imaging system of 200 magnifications comprised of charge-coupled device (CCD) and microscope is used to observe the radiating area and check whether the damage occurs during 1-on-1 damage test and the laser conditioning scanning process.

Firstly, the 1-on-1 damage tests are done under three laser spot diameters of 650, 313, and 247 μm. The LIDTs of HfO_2 monolayer films under the diameters of the three spots are 7.7, 13.8, and 19.0 J/cm^2, respectively. These data are fitted by[10]

$$I = I_\mathrm{d}P(\omega_0) + I_\mathrm{i}P(\omega_0), \tag{1}$$

$$P(\omega_0) = 1 - \exp\Big[-\frac{1}{8}\pi\ln2(\omega_0/d)^2\Big], \tag{2}$$

to obtain the characteristics of the defects in the films, where I is the threshold of the film, I_d is the threshold of the initiating defects, I_i is the intrinsic threshold of the film, ω_0 is the spot diameter, P is the probability of pulse radiation area containing at least one defect, and d is the average distance between two defects.

$$\sigma^2 = \frac{\sum_{i=1}^{n}(I_\mathrm{fi} - I_\mathrm{ei})^2}{n}, \tag{3}$$

where I_fi is the threshold fitted by Eq. (1), I_ei is the threshold obtained by 1-on-1 damage test, and n is the number of the spot sizes. σ^2 in Eq. (3) is used to judge whether the fitting parameters are optimum or not. When the value of σ^2 reaches the minimum, the fitting parameters are considered to be the characteristics of the initiating defects.

Figure 2 indicates that I_d and d are 7.7 J/cm^2 and 64.6 μm, respectively. The density of the initiating defects of HfO_2 monolayer films could be calculated as 2.40×10^4 cm^{-2}, supposing that the defects distributing in the film evenly.

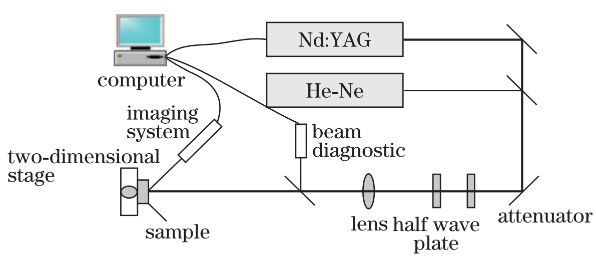

Fig. 1. Experimental setup for laser conditioning and laser damage.

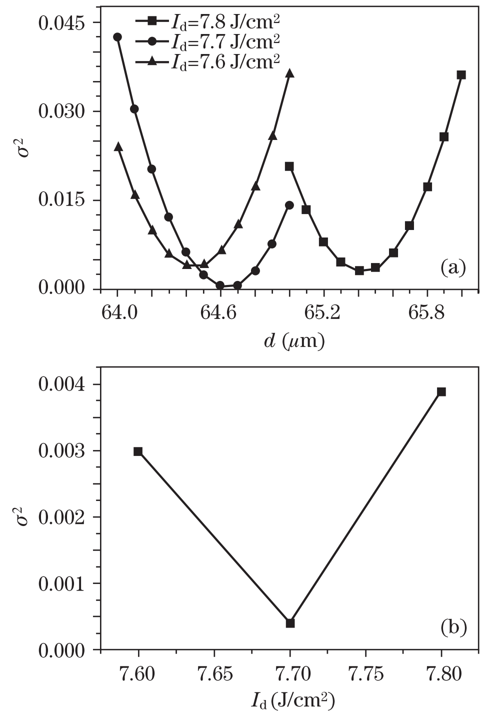

Fig. 2. Fitting results of HfO_2 monolayer films before laser conditioning. (a) Relationship between the values of σ^2 and d; (b) relationship between the minimum values of σ^2 and I_d.

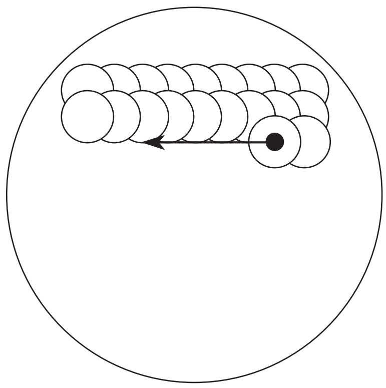

Fig. 3. Schematic of laser conditioning scanning process.

Laser conditioning is conducted by scanning process as shown in Fig. 3. The scanning pulse spot diameter is 650 μm, and the scanning step length is 300 μm, which is a little shorter than the half of the scanning spot size. The scanning pulse energy densities of $0.6I_d$ is chosen.

The 1-on-1 damage test is done after laser conditioning under the same three spot diameters. The 1-on-1 damage results are shown in Table 1, which demonstrates that the damage threshold can be increased by a factor of 1.3−1.8.

These damage data are treated using Eqs. (1) and (3) for fitting to get characteristics of the initiating defects. These fitting results are shown in Fig. 4.

Figure 4 indicates that I_d and d after the laser conditioning are 9.7 J/cm^2 and 81.9 μm, respectively. The density of initiating defects after laser conditioning could be calculated as 1.93×10^4 cm^{-2}, supposing that the defects distributing in the film evenly.

From the data, we can see that the defects with low threshold can be removed by laser conditioning process. Capoulade *et al.* have investigated the density distribution of initiating defects in the film, which follows the Gaussian distribution as[11,12]

$$g(T) = \frac{2\rho}{\Delta T_0\sqrt{2\pi}} \exp\Big[-\frac{1}{2}\Big(\frac{T-T_0}{\Delta T_0/2}\Big)^2\Big], \quad (4)$$

where $g(T)$ is the distribution function of the initiating defects, ρ is the density of initiating defects, T_0 is the average threshold of the defects, T is the threshold of the defects, and ΔT_0 is the standard deviation of the defects threshold.

The Gaussian defect distribution is shown schematically in Fig. 5[11]. It is indicated that when the threshold T is lower than the average threshold T_0, the threshold density should be increasing along with the increase of the defects threshold. In fact, the density of higher defects after the laser conditioning is larger than the density of initiating defects before the laser conditioning. On

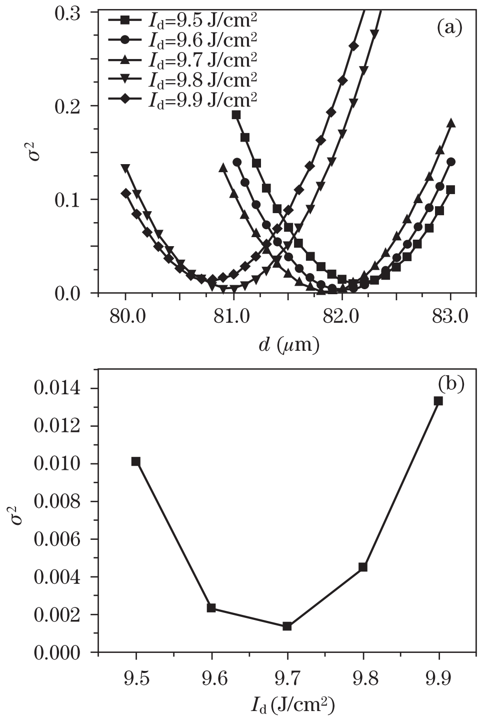

Fig. 4. Fitting results after laser conditioning process. (a) Relationship between the values of σ^2 and d; (b) relationship between the minimum values of σ^2 and I_d.

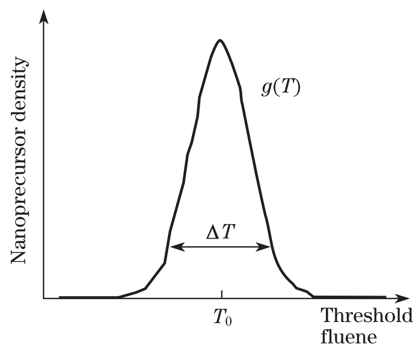

Fig. 5. Gaussian distribution of the initiating defects.

Table 1. Damage Threshold of 1-on-1 Test of the Sample under the Three Selected Spot Diameters after Laser Conditioning

$\omega_0(\mu$m)	650	313	247
LIDT(J/cm^2)	9.9	24.4	33.5

the assumption that the threshold of initiating defects (9.7 J/cm^2) is higher than the average threshold before the laser conditioning, the corresponding threshold symmetrical to the threshold of initiating defects should be larger than T_0 and lower than the threshold of the initiating defects. That is to say, the defects with threshold lower than 9.7 J/cm^2 are all removed, even including the defects whose threshold is larger than T_0. On the other hand, if the threshold 9.7 J/cm^2 is smaller than T_0, the density of the defects should be larger than the density of the initiating defects, but the fact is not. So the defects with threshold of 9.7 J/cm^2 are removed partially.

In conclusion, we have demonstrated the influence of laser-conditioning on the defects in the HfO_2 monolayer films using the spot-size effect of LIDT. The LIDT of the film can be increased by a factor of 1.3−1.6. The defects with lower threshold can be removed from the films after laser conditioning. At the same time, defects with higher threshold may be removed partially.

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