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Femtosecond-laser-induced damage initiation mechanism on metal multilayer dielectric gratings for pulse compression

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ABSTRACT

The femtosecond-laser-induced damage behaviors of metal multilayer dielectric gratings (MMDG) for pulse compression are explored. The grating ridge of this type of MMDG consists of a layer of HfO_2 sandwiched between two SiO_2 layers. The initial damage position is on the HfO_2 layer of the ridge which opposite to the laser beam direction. A theoretical model is constructed to explain the femtosecond-laser-induced damage initiation mechanism on the MMDG, and the model can simulate the evolution of the electron density in the conduction band and the change of the dielectric constants of HfO_2 and SiO_2 in the sandwiched grating structure. The dramatic increase in the imaginary part of the dielectric constant of the middle HfO_2 layer indicates that it strongly absorbs laser energy, resulting in damage to the MMDG. The experimental results and theoretical calculation agree very well with each other.

1. Introduction

Numerous large laser facilities supplying ultrahigh-intensity beams have been developing rapidly in the past decade [1–8]. The chirped pulse amplification (CPA) technique introduced in 1985 by Stickland and Mourou [9] has been applied to these laser systems. This technique strongly impacted the laser field and considerably promoted an enhancement in the fluence of the femtosecond pulse. However, a major critical issue in the compression stage of the CPA technique remains. Diffraction gratings, particularly the final one in the pulse compressor, require further research and improvement. These gratings are exposed to the highest intensity compared with the other optical elements in the laser system. Therefore, to maintain high performance and a stable operation of the femto-laser system, the diffraction gratings in the compressor must possess high diffraction efficiency, a large bandwidth, and a high damage threshold.

A Metal multilayer dielectric grating (MMDG) [10] with a high diffraction efficiency, wide bandwidth and potential high laser damage resistant [11,12] is deemed as the next generation of pulse compression grating (PCG) used in large femtosecond laser facility. Therefore, many researchers have studied MMDG regarding their structural design [13], manufacturing technique [14], and damage behaviors [12]. The recent review article by Bonod and Neauport [15] discusses prior works on metal dielectric hybrid gratings and reports a record 3.5 J/cm^2 LIDT with the pulse duration of 500 fs Our group has studied MMDG for several years, and an MMDG with a high efficiency and broad bandwidth was achieved in 2014 [16]. The adhesion issue of the metal multilayer dielectric film for the MMDG has also been solved by our group, and we have successfully achieved a 200 mm × 400 mm MMDG. However, the laser induced damage threshold (LIDT) of the MMDG which we manufactured is lower than that of the gold grating which we published recently [17]. Therefore, the mechanism—especially the damage initiation mechanism of the MMDG—is very important for improving the damage threshold in future research.

The MMDGs utilized in this study are designed by our group [16] and manufactured by Tsinghua University [18]. The ridge of this type of grating consists of a middle HfO_2 layer sandwiched between two SiO_2 layers with a line density of 1740 l/mm as shown in Fig. 1. For these sandwich-structured MMDGs, the damage initiation has never been reported in detail. In this letter, the location, formation

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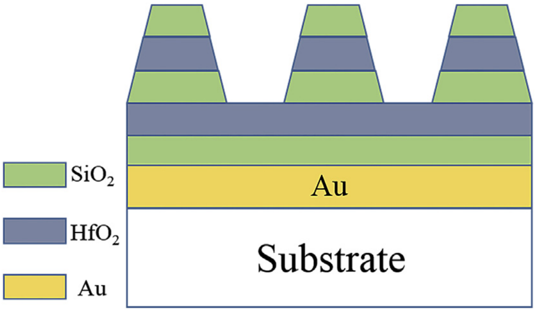

Fig. 1. Structure of the MMDG [16].

and development of the femtosecond laser-induced damage initiation of these MMDGs are analyzed by Scanning Electron Microscope (SEM), Focused Ion Beam (FIB) and theoretical calculation. These results provide a direction for improving the damage threshold of the MMDGs.

2. Experiments and results

In the femtosecond LIDT test system, a commercial Ti:sapphire laser system centered at 800 nm and operated at 1 kHz is used as the laser source, which provides a pulse energy of 4.0 mJ with the pulse duration of 30 fs The samples are mounted on a motorized x–y translation stage and positioned in the front of focal plane of a lens with a focal length of 2.0 m. The effective area of the light spot of the laser beam on the sample in the normal direction is 0.17 mm^2. The online damage detection setup is a CCD, which is focused on the tested area to determine whether the radiation sites are damaged or not, then ascertained by off-line Leica polarizing optical microscope. The s-polarized laser beam is focused onto the sample surface at an angle of 53°. The 1-on-1 LIDT of the MMDGs in beam normal are determined to be 0.30 ± 0.02 J/cm^2 by the damaged area extrapolation method according to the relationship between the damaged area and the logarithm of the laser fluence [19,20]. The uncertainty of the LIDT comes from the fluctuation of the laser energy, the measurement of the light spot on the sample, and the measurement of the damaged area.

The fine morphologies are characterized by SEM and the damage morphologies with different laser fluences are shown in Fig. 2. The position which the MMDG is damaged is located on the grating ridges opposite to the incident wave (see the red dashed frame in Fig. 2(a)). The initial damaged positions are formed ablation lines in the pillars of the MMDG. The grating lines of the MMDG are gradually stripped as the fluence increases, finally resulting in catastrophic damage (see Fig. 2(b) and (c)).

To confirm the initial damage location, the cross-sectional profiles of the damaged spots are observed by FIB, as shown in Fig. 3. The series of pictures in Fig. 3 reflect the evolution of the damage in the sandwiched structure. The initial damage location is on the HfO_2 layer (see Fig. 3(a)) opposite to the incident wave direction obviously. Then, the upper SiO_2 layer and part of the middle HfO_2 layer in the sandwich structure are gradually stripped from the grating pillars as the fluence increases, as shown in Fig. 3(b). When the fluence reaches a higher level of 0.49 J/cm^2 in Fig. 3(c), the upper SiO_2 layer and part of the middle HfO_2 layer are separated from the sandwich structure entirely. Finally, the damage will be extended to the inner layer of the film with the laser fluence continues to rise as shown in Fig. 3(d) and (e). The determination of the initial damaged location and analyzing the cause of formation have a great significance for development of MMDGs.

3. Discussion and analysis

In the short-pulse regime, damage is dominated by plasma formation originating from multiphoton and collisional ionization, which is strongly dependent on the electric field intensity [21]. The normalized electric field intensity (NEFI) of the MMDG is calculated

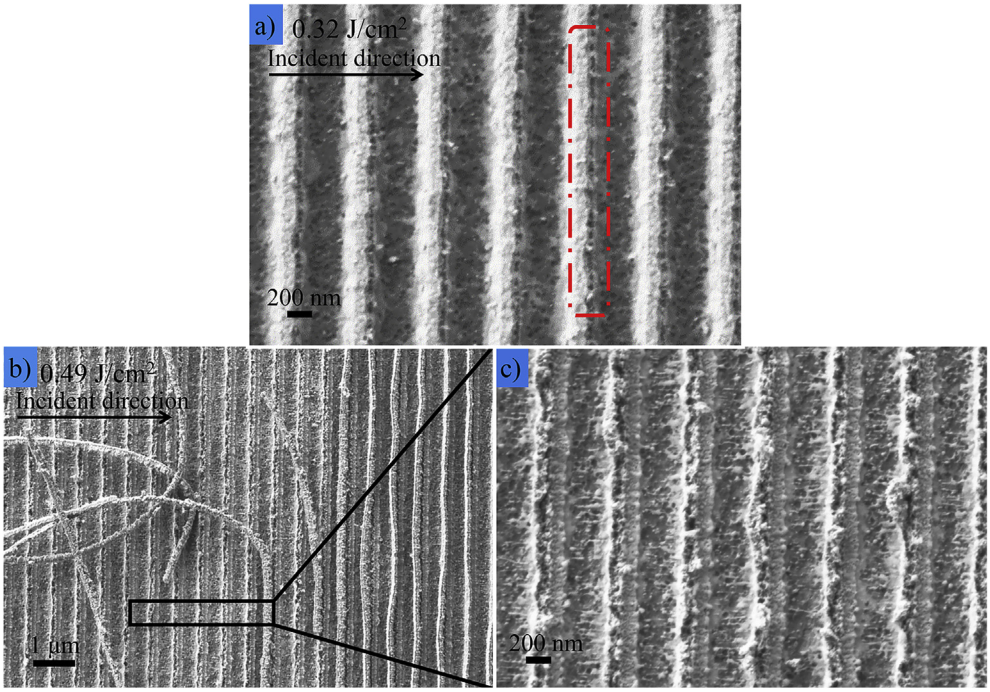

Fig. 2. SEM images of typical damage morphologies. (a) Damage morphology at a fluence of 0.32 J/cm^2 near the damage threshold. (b) Typical damage morphology at a higher fluence of 0.49 J/cm^2. The pillars of the MMDGs are stripped. (c) Local magnification of (b).