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Damage mechanism and morphology characteristics of chromium film in femtosecond laser rear-side ablation

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ABSTRACT

In this paper, damage mechanism and morphology characteristics of chromium film in femtosecond laser rear-side ablation are investigated. The film removing process includes two key sub-processes: the laser ablation dynamic process and subsequent breaking and ejecting dynamic process. Film morphology in rear-side ablation is determined by the interrelation between the laser energy and the film strength. When lower laser energy is used, residual out-layer film is relative thick and tends to break into some large fragments, which results in an irregular ablation shape. While when higher pulse energy is used, thinner residual film with weaker break strength breaks into small fragments, the ablation quality improves correspondingly. Besides laser energy and film property, energy distribution of laser beam also affects the ablation quality. In experiments, this kind of effect is researched by changing the focal position. It is found that ripples, which are familiar nano-structures in front-side ablation, also exist in rear-side ablation. These ripples are formed initially at the interface between quartz substrate and film, and their coverage varies with the energy distribution. Additionally, increasing number of scans is an effective method to shorten the period of ripples.

1. Introduction

In the past two decades, the interaction of femtosecond laser pulses with solid targets such as metals, semiconductors, ceramics, and composite materials as well as biological tissues [1–5] has generated a lot of interest due to the variety of possibilities offered in industrial manufacturing, information and communication technologies, environmental technology and life sciences. It offers completely new possibilities for well-defined ablation threshold, minimal collateral damage and limited heat affected zones [6] in addition to demonstrations of sub-micron machining [7].

Beside of the bulk material ablation, selective ablation of metallic and oxide films with femtosecond laser pulses has been studied widely for their possible applications in the fields of semiconductor manufacturing, solar cells, photoelectrical devices and other new high-technology industries [8–9], for example, the femtosecond laser direct writing of Cr metallic film is a newly emerging and promising technique for fabrication and repair of binary photomask [10–11]. In most of these investigations, films are ablated and removed by laser direct irradiation in film–air interface. This kind of direct irradiation is commonly called laser front-side ablation. The interaction between femtosecond pulsed laser and film in this kind of ablation has been reported in a mass of literatures, and the researches mainly focus on the damage mechanism and ablation model [12–13], the minimum resolvable feature size [14] and the ablation efficiency [15–18], etc.

As is well known, ablations with ultra-fast pulsed lasers such as femtosecond laser have much higher machining quality compared with those long pulse laser ablations. However, the low ablation efficiency in ultra-fast pulsed laser ablation limits their actual applications seriously. How to increase the efficiency is critical and draws more and more research attentions. For example, Sallé et al. compared the ablation efficiency in femtosecond laser and picosecond laser ablations, and found that the ablation efficiency is better for the cases without laser-plasma interactions for pulse durations shorter than 1 ps. With the higher pulse repetition frequency femtosecond laser, Choi et al. achieved the high-efficiency patterning on ITO film. Liu et al. split a parent laser beam into a number of beamlets and to digitally manipulated their position to achieve the high throughput precision patterning of ITO on glass substrate. Guo et al. adopted the near-filed laser parallel nanofabrication process to obtain the arbitrary nanopatterns on a large surface area.

Besides of its application in laser induced forward transfer process, the rear-side film ablation, which directs the laser beam

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through the transparent substrate to remove the film material from the rear side, is also regarded as an effective film material remove method. Beyer et al. have confirmed that the efficiency for the rear-side ablation process is up to two magnitudes higher than that for traditional front-side ablation in nanosecond laser micromachining [19]. It is necessary to point out that, for an high-precision ablation process, the quality and efficiency are equivalent important. Different from the ablation efficiency, which can be enhanced by many methods such as parallel processing, the ablation morphology depends mostly on the material damage mechanism. In rear-side ablation, the material is ablated in a closed boundary, which may result in a different material damage mechanism compared with that in traditional front-side ablation. Thus if rear-side laser ablation can become a high quality and high-efficiency manufacturing method, the involved material removal mechanism and morphology characteristic should be explored firstly.

In this paper, the material damage mechanism and morphology characteristics in femtosecond laser rear-side ablation of Cr film are investigated. The film damage mechanism in rear-ablation is researched via the analysis of interaction between laser effect and film intrinsic properties. In addition, the effects of energy distribution on rear-side ablation quality are discussed in detail.

2. Experimental setup

The sketch of rear-side laser ablation and its difference from the traditional front-side ablation are shown in Fig. 1. Experiments were performed by a Ti:Sapphire laser delivering pulses of 25 fs duration, 1 mJ energy, and 800 nm wavelength at a repetition rate of 1 kHz. A Cr film with the thickness of 150 nm sputtered on a quartz substrate was used as the experimental sample. The sample was mounted on a computer-controlled 3-axes stage with the accuracy of 50 nm, which was used to adjust the position of the laser beam relative to the sample. A continuously variable optical attenuator was introduced in the laser beam path to control the energy at the sample surface. The pulse energy irradiated on the ablated surface was measured by a power meter, which has a measuring range of 1 nW $\sim$ 50 mW and measurement accuracy of 0.001 nW. The laser beam was focused by a 50× microscope objective (NA = 0.5) giving a typical focal spot size around 1.4 μm in diameter. After the experiments finished, the surface morphologies of the ablated areas were inspected by a scanning electron microscope (SEM).

3. Film damage mechanism in femtosecond laser rear-side ablation

The ablation dynamic process of the Cr film induced by femtosecond laser has been researched by experimental and theoretical analysis method in some literatures [20,21]. When Cr film is irradiated by the femtosecond laser, the pump laser pulse delivers energy to the electrons which thermalize rapidly via electron–electron collision and scattering. Because the femtosecond laser pulse is shorter than the electron–phonon coupling time, the electrons can be heated up to a high temperature at first, and then cool down by electron–phonon coupling process. It has been shown that the time scale for the fast electron cooling and a considerable energy transfer to the lattice is on a picosecond time scale, and the heated lattice results in the creation of vapor and plasma phases followed by a rapid expansion.

This material ablation dynamic process is suitable for both front-side ablation and rear-side ablation. The difference is that the material in rear-side ablation is heated in a closed boundary, which would result in a different material ejecting process compared with that in traditional front-side ablation. When the fluence of laser beam exceeds the ablation threshold for the bulk material, a certain amount of materials absorb the laser energy and ablation dynamic process take place. The ablation volume depends on the pulse energy. For a certain beam spot, the fluence distribution obeys Gaussian function along the radial direction of the beam spot, that is, the fluence irradiated on the position x which is the distance to the beam spot center is given by [22],

$$F(x) = F_0 e^{-2x^2/\omega^2} \tag{1}$$

where ω and F_0 are the spot radius and the peak fluence of the Gaussian beam. F_0 and the pulse energy, E_p, are directly related by [23],

$$F_0 = \frac{2E_p}{\pi\omega^2} \tag{2}$$

The ablation rate (ablation depth per pulse), $L(x)$, at the position x is equals to [24]:

$$L(x) = \delta \ln\left(\frac{F(x)}{F_{th}^{\delta}}\right) \tag{3}$$

where δ is the optical penetration depth of material, and F_{th}^{δ} is the ablation threshold of material.

Introducing Eqs. (1) and (2) to Eq. (3), the relationship between the random position x on the film surface and the ablation rate of this position $L(x)$ can be obtained:

$$L(x) = \delta\left[\ln\frac{2E_p}{\pi\omega^2 F_{th}} - \frac{2x^2}{\omega^2}\right] \tag{4}$$

According to Eq. (4), the ablation volume with each pulse in rear-side ablation can de determined. To be detailed, the gaseous Cr produced by laser has a deepest ablation depth at the center of beam, while when the irradiated position is far away from the center, the ablation depth reduces.

In the front-side ablation, gaseous Cr can be ejected quickly, and the dynamic process of material ablation can be used to describe the whole ablation process, as shown in Fig. 2(a). While in the rear-side ablation, ablation is not the whole process. The heated Cr

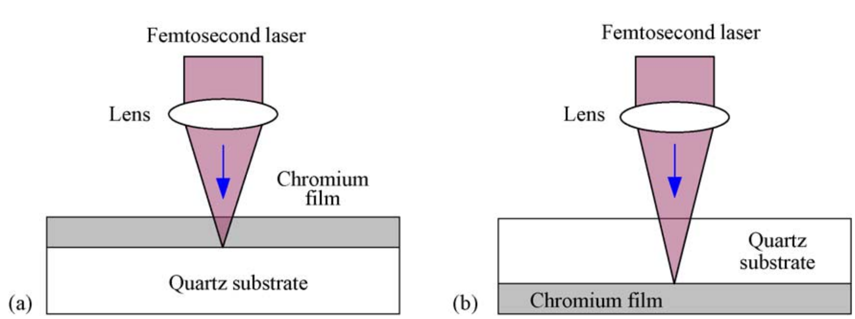

Fig. 1. Illustration of front- and rear-side laser ablations. (a) Front-side ablation; (b) rear-side ablation.