Analysis of surface damage produced by pulsed laser ablation on metal Al and semiconductor Si

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Abstract The surface morphological changes produced by Nd:YAG pulsed laser ablation of metal Al and semiconductor Si were carefully examined and analyzed by using scanning electron microscope. The formation mechanism of the droplets was discussed, and the reasons for formation of the microcracks on the laser irradiated area of the target surface were analyzed by calculating the thermal stress, the vapor pressure and the shock pressure induced by the laser supported detonation.
Keywords Laser damage, Thermal stress, Shock pressure

1 Introduction

Laser induced damage in material has been widely studied by many investigators, since intense laser beams are currently being used in a whole range of new applications from melting and cutting in machinery to surface cleaning and etching in microelectronics. Although a large number of literatures on the laser induced damages have been published, only a few papers[1~3] gave out the descriptions of the topographic changes of the laser irradiated area. The mechanisms of laser induced damages on solid material surface remain to need a further research. In the present work, the surface morphological changes produced by Nd:YAG pulsed laser ablation of metal Al and semiconductor Si were carefully examined by using scanning electron microscope (SEM). In theory, the formation mechanism of the droplets was discussed, and the reasons for formation of the microcracks on the laser irradiated area of the target surface were analyzed by using the thermal dynamics, liquid sputtering and evaporation theory.

2 Experimental

The materials used in the present experiment were metal Al and semiconductor Si samples polished to a mirror-like state. The sample was installed on a sample holder in chamber pumped by a mechanical pump. Residual air in the chamber was used as buffer gas. A Nd:YAG pulsed laser with a pulse duration of 10 ns and a wavelength of 1.06μm was used. The laser energy was measured by an energy meter (OPHIR DGX30A). The laser pulse was focused onto the target surface by a quartz focus lens (f=6.3 cm) in front of the target. The focus of the lens was on the target surface and the spot size of the laser beam was 0.66 mm in diameter measured by a microscope with a resolution of 0.001 mm. The irradiated areas were examined by a SEM.

3 Results and discussion

Fig.1(a)~(d) show the SEM micrographs taken from a single pulse laser irradiated area on metal Al surface at different laser power density and under an atmospheric pressure. From Fig.1(a), it can be observed that a lot of liquid droplets were formed during the ablation process. Therefore, the laser liquid sputtering was presented. However, the vaporizing phenomenon is not very clear. By increasing laser power density, more droplets were formed, as shown in Fig.1(b). When the laser power density was increased to 1.6×10^9 W/cm^2, as shown in Fig.1(c), some tiny holes were observed on the irradiated area, which proves that the vaporizing phenomenon occurred. When the laser power density was increased up to 9×10^9 W/cm^2, as shown in Fig.1(d), the circular holes became greater and the sputtering was weakened, right now, the damage is mainly produced by the vaporizing.

For the laser sputtering, a simple model was given by Kelly.[2] The target surface will be melted when irradiated by pulse laser, and the surface asperities are somehow formed be-

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cause of the inhomogeneity of the surface. The droplets are principally formed during melting and resolidifying of the surface materials. The liquid expansion during heating phase is not counterbalanced by the behavior during the cooling phase follows because the cooling begins at the bottom of the liquid substrate, so that, there is an additional tendency for the droplets to move away from the substrate. The separation of a droplets from the surface will be opposed, for an ideal spherical shape, by a force $f = -\partial(4\pi r^2\gamma)/\partial r = -8\pi r\gamma$, where r is the droplet radius and γ is the liquid surface energy. A necessary condition for expulsion is that the total droplet momenta away from the substrate exceed or equal to the product $f \cdot \Delta t$, i.e.

$$(4\pi r^3\rho_l/3)(\Delta L/\Delta t) \geq 8\pi r\gamma\Delta t \quad (1)$$

where ρ_l is the density of the liquid, ΔL is the total height change of the droplet relative to the substrate, ΔL and Δt can be expressed as, respectively[2]

$$\Delta L = 2r\alpha(T_b - T_m) + 2r(\rho_s - \rho_l)/3\rho_s \quad (2)$$

$$\Delta t = \tau(1 - T_m^2/T_b^2) \quad (3)$$

where α is the linear thermal expansion coefficient of the liquid, T_m, T_b are the melting point and boiling point respectively, ρ_s is the density of the solid.

By using Eqs.(1)~(3), one can get the minimum droplet radius, calculated and experimental results are shown in Table 1.

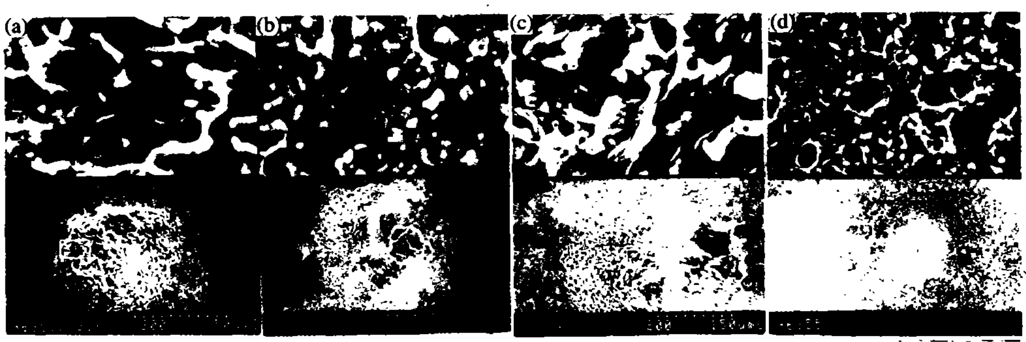

Fig.1 SEM micrographs of Al target surface irradiated by a pulsed laser with a wavelength of 1.06μm and a duration of 10ns. The laser power density is (a) 2.0×10^8 W/cm^2; (b) 7.0×10^8 W/cm^2; (c) 1.6×10^9 W/cm^2; (d) 9.0×10^9 W/cm^2, respectively. The magnification of the upper portion is 10 times of the lower

Table 1 Parameters needed for evaluating the minimum droplet radius

Sample	γ /J·m^{-2}	α /10^{-5}deg^{-1}	ρ_s /g·cm^{-3}	ρ_l /g·cm^{-3}	T_b /K	T_m /K	r_{cal} /μm	r_{exp} /μm
Al	0.866	4.73	2.7	2.39	2714	933	0.91	0.8~1.4
Si	0.73	0.2	2.33	2.53	3540	1683	1.83	1.0~ 1.6

From Table 1, it is obvious that the crude model can give a reasonable explanation to the laser liquid sputtering phenomena by use of the liquid surface tension theory.

In Fig.1(c), the tiny holes on the tiny grains can be observed, and it makes the tiny grain be hollow, so we deduce that the tiny holes on the grains were formed by the breaking up of the bubbles during the laser ablation process. This means that the bubbles are present in the ablation process. So we think that the overheating phenomena are present in the pulsed laser ablation process. However, when the laser power density does not exceed 10^{10} W/cm^2, only is at pressure of an atmosphere, the overheating phenomena can be clearly observed. When the pressure is decreased beneath 1000 Pa, there is no tiny holes on the irradiated surface, as shown in Fig.2. The reason for this result is as followings, the ambient air has a spatial confining effect to the melted material that can absorbed laser energy; this confining effect would bring about more absorption of the laser energy by the irradiated material, and resist the spread of the irradiated material; both of this two respects would cause the increase in the irradiated material temperature. The spatial confinement becomes stronger with increasing the ambient pressure, so the overheating phenomena can be observed at an atmospheric pressure.

In addition, at an atmospheric pressure, when the laser power density is high to 9×10^9 W/cm^2, the laser induced microcracks on the Si surface can be observed clearly, as shown in Fig.3(a). When the laser power density is increased, more serious damage can be observed, as shown in Fig.3 (b).

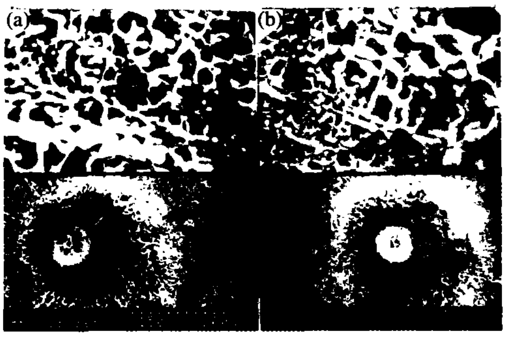

Fig.2 SEM micrographs of Al target surface irradiated by a pulsed laser with a wavelength of 1.06μm and a duration of 10 ns at the laser power density of 5.2×10^9 W/cm^2. The ambient pressure is (a) 1.0×10^3 Pa; (b) 5 Pa. The magnification of the upper portion is 10 times of the lower

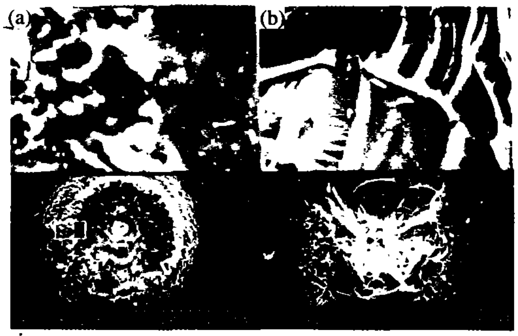

Fig.3 SEM micrographs of Si target surface irradiated by a pulsed laser with a wavelength of 1.06μm and a duration of 10 ns at the ambient pressure of an atmospheric pressure. The laser power density is (a) 9.0×10^9 W/cm^2; (b) 3.0×10^{10} W/cm^2. The magnification of the upper portion is 10 times of the lower

So far, some investigators have paid a great of attentions to the laser induced cracks and fracture. The explanations given by these authors[4~6] are attributed to the thermal stress. We think that it may be valid for the laser induced crack damage in some materials.

According to Xia *et al*[6], the thermal stress is expressed as:

$$\sigma=\frac{\beta E\Delta T}{1-2\nu} \tag{4}$$

where β is the linear thermal expansion coefficient, E is the Young's modulus, ν is the Poisson ratio, ΔT is the temperature increase from the ambient temperature. Kelly *et al*[2] have given the following temperature distribution for a laser heated surface:

$$\Delta T=2\alpha I_0(Mt/\pi K\rho C)^{1/2}\exp(-x^2/4kt)-(\alpha I_0 x/K)\mathrm{erfc}(x/2\sqrt{kt}) \tag{5}$$

where α is the effective optical absorption of the target surface, I_0 is the incident laser intensity, M is the molecular weight, K is the thermal conductivity, C is the heat capacity in J·mol^{-1}K, ρ is the density, x is the distance beneath the surface, and t is time. For simplicity, we use an average temperature difference between the heated layer and the substrate beneath the layer to estimate the maximum thermal stress. For the laser power density of 9×10^9 W/cm^2, the calculated thermal stress in the irradiated Si materials is as high as 1.43×10^9Pa, which exceeds the stress threshold for fracture of Si material, so there will be cracks on the laser irradiated area of Si target.

If the microcracks were induced only by the thermal stress, most cracks would be distributed near the edge of the ablated area, since the temperature gradient is the highest there. But we found that the microcracks are distributed in the whole ablated area. In fact, besides the thermal stress, the vapor pressure and the shock pressure induced by the Laser Supported Detonation (LSD) wave are other two important reasons for cracking or rupture.

According to a vaporization model given by Rosen *et al*[7] the vapor pressure at temperature T is expressed as:

$$P_{\rm v}(T) = 1.06 \times 10^6 \cdot \exp(-\frac{\lambda_{\rm v}}{K_{\rm B}T})/\exp(-\frac{\lambda_{\rm v}}{K_{\rm B}T_{\rm b}}) \qquad (6)$$

where $\lambda_{\rm v}$ is the heat of evaporation per particle, and $K_{\rm B}$ is the Boltzmann's constant.

The vapour temperature T can be obtained from the following equation

$$\frac{\alpha I}{L_{\rm v} + L_{\rm f} + C_{\rm p}(T - T_{\rm b})} = 1.06 \times 10^6 (\frac{M}{2K\pi T})^{1/2} [\frac{\exp(-\lambda_{\rm v}/K_{\rm B}T)}{\exp(-\lambda_{\rm v}/K_{\rm B}T_{\rm b})}] \qquad (7)$$

where $C_{\rm p}$ is the specific heat, I is the average laser power density, $L_{\rm v}$, $L_{\rm f}$ are the latent heats of vaporization and fusion, respectively. By using Eqs.(6) and (7), the vapour pressure can be calculated to be 3.31×10^9 Pa at the laser power density of 9×10^9 W/cm^2.

The laser induced shock wave pressure under the ambient background can be calculated by[8]

$$P_{\rm s} = \frac{\rho_0}{\gamma + 1}(\frac{\gamma + 1}{2\gamma})^{\frac{2\gamma}{(\gamma-1)}}[2(\gamma^2 - 1)\frac{I}{\rho_0}]^{2/3} \qquad (8)$$

where γ is the ratio of the specific heats of the air, ρ_0 is the density of the air. By using the equation, $P_{\rm s} = 3.23 \times 10^8$ Pa was obtained at the laser power density of 9×10^9 W/cm^2.

From above experimental observation and calculation, we suggest that the laser induced microcracks may be caused by the thermal stress, the vapour pressure and the shock pressure induced by LSD wave.

4 Conclusion

A scanning electron microscope was used to examine the surface morphological changes produced by Nd:YAG pulsed laser ablation of metal Al and semiconductor Si. The results show that the laser liquid sputtering is presented, but the vaporizing phenomena is presented only in high laser power density. The appearance of the tiny hole proves that the overheating phenomena are in existence when the laser power density is high. From experimental observation and calculation, we suggest that the thermal stress, the vapour pressure and the shock pressure induced by the laser supported detonation were all the reasons for formation of the microcracks on the laser irradiated area of the target surface.

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