Analysis of the expansion of rear and front-side laser ablation plasmas

L. Escobar-Alarcón, E. Camps
Departamento de Física, Instituto Nacional de Investigaciones Nucleares, Apdo. Postal 18-1027, México D.F. 11801, México;

E. Haro-Poniatowski
Laboratorio de Óptica Cuántica, Universidad Autónoma Metropolitana Iztapalapa Apdo. Postal 55-534, México D.F. 09340, México

M. Villagrán
Centro de Instrumentos, UNAM, México

S. Muhl
Instituto de Investigaciones en Materiales, Universidad Nacional Autónoma de México, Apdo. Postal 364, México DF 01000, México.

With transparent target materials it is possible to get both front-side and rear-side laser ablation. Rear-side laser ablation has been investigated as a new configuration for thin film deposition of transparent materials. In order to study the features of this configuration, the analysis of the propagation of laser ablation plumes of the rear and front-side plasmas was performed. The shock wave associated with rear and front-side ablation plumes were recorded by shadowgraphy and the corresponding velocities were determined in each case. We found a spherical wave front in both cases, with the shock wave of the rear-side plasma having a higher velocity. Optical emission spectroscopy measurements were carried out in order to identify the excited species present in each plasma.

Keywords: Laser ablation; Thin film; Shock wave
PACS: 81.15.Fg; 82.45.Mp; 52.35.T

1. Introduction

Laser ablation has been widely used as a suitable method for thin film deposition of oxides due to its advantages over other techniques, particularly the possibility of growing films under oxygen atmospheres with the purpose to assist the incorporation of this gas in the growing film in order to compensate for some oxygen loss and obtain stoichiometric films [1-3]. It is well known [4] that ablation under high pressure atmospheres results in the formation of a shock wave, which then propagates through the background gas towards the substrate accompanying the plasma plume. However during propagation of the plume, reactions may occur and the velocities and trajectories of ablated species can be modified which gives as a result a change in the plasma parameters. Therefore the study of laser ablation plasmas in presence of a background gas has great importance.

Rear-side laser ablation has been investigated as a new configuration for thin film deposition of transparent materials [5]. In order to study the features of this arrangement, the analysis of the propagation of laser ablation plumes and the shock waves associated with rear and front-side ablation plasmas was performed. Additionally the excited species present in each plasma were identified by optical emission spectroscopy (OES). Recently, Yavas et al [6,7] reported that the shock waves generated by front an rear-side laser ablation of natural calcite at 1064 nm are spherical and planar respectively. However our results seems to indicate a spherical shock wave in both cases.

2. Experimental setup

In this configuration the ablation of the material occurs at the backside of a transparent target and the substrate is positioned at a suitable distance behind it. The experimental set up used to produce front and rear-side laser ablation is presented in figure 1.

There are a number of alternatives to generate the rear-side plasma, for example, by self-focusing of non-linear materials or in a thick target by focusing the laser at the rear side. For thin targets two different ways are possible, changing the energy per pulse or increasing the optical absorption of the backside of the target by roughening [5]. In the present work we have used this last procedure for the thin (2 mm) SiO_2 targets. The plasmas were produced using a Q-switched Nd:YAG laser using the fundamental frequency (λ=1064 nm, pulse duration=28 ns). The energy per pulse was 140 mJ at a repetition rate of 20Hz.

Optical emission spectroscopy was performed using a 0.5 m spectrometer (Spex model 1702/04) equipped with a fast intensified charge coupled device (ICCD) (Princeton Instruments model 1024E) with a 150 ns gate for photon

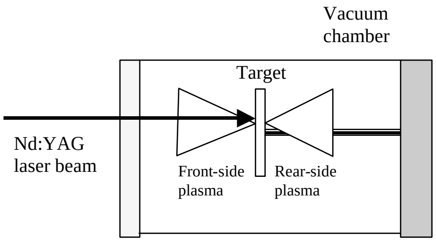

Figure 1. Experimental set up used to produce front and rear-side laser ablation.

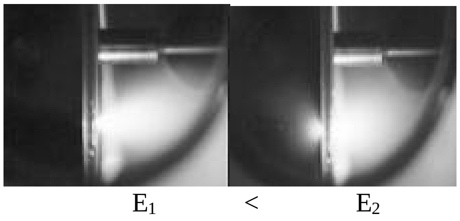

Figure 2. Photographs of the rear and front-side plasmas as function of the energy delivered on the target.

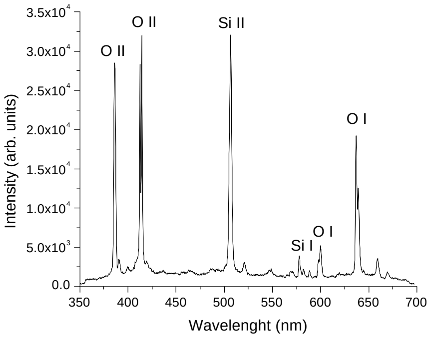

Figure 3. Typical optical emission spectrum of the front side plasma.

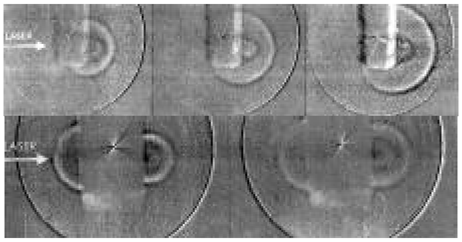

Figure 4. Shadowgraphs of the shock wave fronts of the front and rear-side plasmas at different delay times.

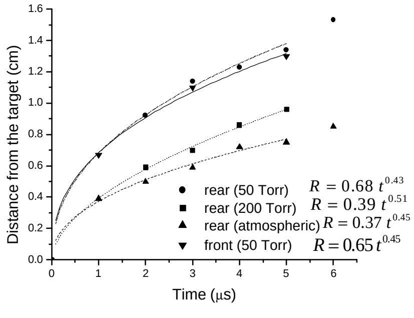

Figure 5. Positions of the wave fronts for the rear and front-side plasmas as a function of time.

detection. The light was collected by an UV-Vis fiber bundle placed at the side window of the vacuum chamber, approximately 15 cm apart from the plasmas. Synchronization between laser pulse and ICCD was ensured using an electro-optical detector. The OES measurements were performed along the axis of the plasma, at different distances from the target surface.

3. Results and discussion

Although the initial setups attempted focusing on the front or back surface, experimental observations revealed that the positioning of the beam waist is not a crucial parameter in order to obtain ablation in the front or back surface. This may be due to the fact that the Rayleigh parameter is often of the order of the target thickness and thus the spatial energy concentration on either surface is very similar. On the other hand, the laser power plays an important role. It is observed that at moderate powers ablation takes place at the back surface, whereas as the power is increased the ablation decreases at the back surface and increases at the front surface, until it is only observed at the front surface. These experimental facts are explained using a based interference model that has been proposed to account front and rear-side laser ablation process [5]. Figure 2 shows the production of the rear an front-side plasmas as function of the energy delivered on the target. As can be observed at moderate powers ablation takes place at the back surface whereas as the power is increased the ablation increases at the front surface. It is worth mentioning that the front plasma exhibits a blue color while the rear-side plasma is orange indicative of two plasmas with different properties.

Optical emission spectroscopy (260-700 nm) of both plasmas reveals the presence of Si I, Si II, O I and O II. A typical OES spectrum is presented in figure 3. Table 1 summarize the more important emission lines present in each plasma. Comparing the emission lines of each plasma is observed that the front plasma is a more rich plasma with more excited species, whereas the rear plasma has less excited species. The most intense emission of the front plasma correspond to the lines 288.15 nm (Si I), 412.14 nm (O II), 414.35 nm (O II) and 504.98 (Si II), therefore the observed color can be attributed to this emission shift to the blue spectral region.

On the other hand in the rear-side plasma the maximum emission observed corresponds to the line 591.52 nm consistent with the orange color observed for the rear-side plasma.

The formation and expansion of the shock wave resulting of the laser ablation process, can be studied using shadowgraphic techniques [8]. Shock wave images corresponding to front an rear-side laser ablation plumes are presented in figure 4. The shape of the shock front is spherical for both plasmas (front and rear) indicating a radial expansion, this behavior can be associated with an explosive process which takes place when the plasma

Table 1.

Front-side plasma	Rear-side plasma
O II (279.66 nm)	O III (285.37 nm)
O II (280.31 nm)	Si I (288.15 nm)
Si I (288.15 nm) *	O II (383.66 nm)
Si II (290.42 nm)	O II (397.32nm)
O II (386.05 nm)	O II (423.32 nm)
Si I (390.55 nm)	O II (430.72 nm)
O II (400.74 nm)	Si II (591.52 nm) *
O II (412.14 nm) *	
O II (414.35 nm) *	
Si II (504.98 nm) *	
Si II (505.59 nm)	
Si I (578.03 nm)	
O I (599.52 nm)	
O I (636.63nm)	
O I (639.17 nm)	

*high intensity lines

density reaches its highest values and the plasma pressure significantly overcomes the background pressure.

The radial position from the target surface to the center of the dark ring was measured at different delay times after ablation in order to study shock wave evolution at different background pressures: 50 Torr, 200 Torr, and atmospheric pressure. The positions of the shock fronts are plotted as a function of time in figure 5 for the rear-side plasma. The obtained plots are indicative of an expansion velocity which decreases with time, due to collisions with the background gas. The expansion of the shock wave can be described by the point source blast wave model for a spherical shock wave given by: [9]

$$R = x_0 (E / r_0)^{1/5} t^{2/5}$$

where R is the distance from the target surface to the shock front, x_0 is a constant, E is the explosive energy, r_0 is the background gas density and t is the time after the ablation.

The experimental points were fitted to an expression of the form:

$$R = C\, t^{a}$$

the values found for the exponent α were 0.51 for 200 Torr, 0.43 for 50 Torr and 0.45 for atmospheric pressure. The α values are close to the corresponding for a spherical shock wave (0.4). Then the expansion is well described by the spherical shock wave model consistent with the shadowgraphic images. Figure 5 also shows the fitted curves. The maximum expansion velocities have been found to be: 8.7 x 10^3 m/s at 50 Torr and 5 x 10^3 m/s at 200 Torr and atmospheric pressure.

For the front-side laser plasma we found similar results. Figure 4 also shows the radial position of the shock front at a pressure of 50 Torr for comparison. The behavior observed for both plasmas is almost identical. This result reveals that front-side laser ablation also produces a shock wave with spherical shape (α = 0.45) with a maximum velocity of 6.4 x 10^3 m/s. Analysis of the fitted curves seems to indicate that the rear-side shock wave expands more rapidly consistent with the shadowgraphic images (figure 3) where a larger displacement for the rear-side front shock for the same time is clearly observed. This is because the explosive energy used to produce the rear-side plasma is higher, according with the interference model proposed for rear-side laser ablation[5].

Conclusions

The present work shows that the shock wave associated with rear and front-side ablation plumes have a spherical wave front in both cases, with the shock wave of the rear-side plasma having a higher velocity The obtained results are consistent with the interference model proposed previously for rear-side laser ablation process. Optical emission spectroscopy measurements reveals that the front plasma has more excited species than the rear plasma. Furthermore the main emission of the two plasmas lays in different spectral regions. This is the first attempt to characterize the expansion and plasma properties of rear and front-side laser ablation plasmas. Thin film deposition under an oxygen atmosphere at high pressure in order to optimize the film quality is underway.

Acknowledgements

The present work has been partially supported by the Consejo Nacional de Ciencia y Tecnología under contracts number 29250-E and 4225-E9405.

References

[1] L. Escobar-Alarcón, E. Haro-Poniatowski, M. Fernández-Guasti, C. N. Afonso, A. Perea; Applied Physics A, **69**, s949 (1999).

[2] D. B. Chrisey and G, K. Hubler, Eds., “Pulsed Laser Deposition of Thin Films” (Wiley, New York, 1994).

[3] L. Ponce, M. Fernández-Guasti, E. Jiménez, E. Haro-Poniatowski, Rev. Mex. Fis. **40**, 798 (1994).

[4] D.B. Geohegan; Appl. Phys. Lett. **60**, 2732 (1992).

[5] L. Escobar-Alarcón, M. Villagrán, E. Haro-Poniatowski, J. C. Alonso, M. Fernández-Guasti, E. Camps; Applied Physics A. **69**, s583 (1999).

[6] O. Yavas, E. L. Maddocks, M. R. Papantonakis, R. F. Haglund, Jr., Appl. Phys. Lett. **71**, 1287 (1997).

[7] O. Yavas, E. L. Maddocks, M. R. Papantonakis, R. F. Haglund, Jr., Appl. Surf. Sci. **26**, 127 (1998).

[8] M. Villagrán, M. Sobral, E. Camps; IEEE, Trans. on Plasma Science. **29**, 613 (2001).

[9] Y.B. Zel´dovich, Y.P. Raiser, in: W.D. Hayes, R.F. Probstein (Eds.), *Physics of shock waves and high temperature hydrodynamic phenomena*, Academic Press, New York (1966).