Proceedings of 10th International Conference on Precision, Meso, Micro and Nano Engineering (COPEN 10)
December 07 – 09, 2017, Indian Institute of Technology Madras, Chennai – 600 036 INDIA

Single Nd^{3+}:YAG laser based pump-probe technique to study the effect of plasma shielding on laser ablation in vacuum ambience

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Abstract

A laser-induced shock wave generated due to high temperature and pressure leads to partial ionization of the evaporated material, consequently an interaction between the incident laser light and the ablated material forms a plasma plume above the target material. The plasma plume tends to absorb the incident laser beam thus significantly influencing the transmitted intensity for laser scribing, pulsed laser deposition and other laser assisted material removal processes. Therefore, it is necessary to understand the influence of various parameters, such as irradiation laser wavelength, laser intensity, pulse width, repetition rate, ambient condition, material characteristics on the plasma shielding effect in order to control the laser material interaction. Plasma shielding phenomenon and its influence on micromachining is studied experimentally for laser wavelengths of 355 nm in vacuum. A time resolved pump-probe technique is proposed and demonstrated by splitting a single nanosecond Nd^{3+}:YAG laser into an ablation laser (pump laser) and a probe laser to understand the influence of plasma shielding on laser ablation of copper (Cu) cladded on polyimide thin films. The proposed nanosecond pump-probe technique allows simultaneous measurement of absorption characteristics of plasma produced during Cu film ablation by the pump laser. Experimental measurements of the probe intensity distinctly show that the absorption by the ablated plume increases with increase in the pump intensity as a result of plasma shielding.

Keywords: Laser Ablation, Plasma Shielding, Laser Micro Machining, Ambience

1. INTRODUCTION

Recently, there is an increasing interest in micro-scribing of Al, Cu, and other material thin films for various electronics, solar and micro-fluidics applications. Various nanosecond pulsed lasers, such as excimer lasers, Nd^{3+}:YAG lasers, are used for such micro-scribing applications, considering low heat affected zone. Irradiation of metallic thin films with high intensity pulsed laser results in laser ablation and material removal. However the plasma produced during the laser ablation absorbs the incoming laser pulse and limits the depth of material removal. Hence in some applications, where the depth of the order of few micrometers has to be attained, it is essential to understand the plasma induced absorption and estimate appropriate laser intensity suitable for the material removal.

The plasma diagnostic techniques during laser ablation process have been reported by various research groups. Laser induced evaporation due to localized heating [1] and the formation of shock waves [2] have also been described by many researchers. A spatially resolved pump-probe technique with a Q-switched Nd^{3+}:YAG laser (532 nm, 10 ns) as a pump laser and a continuous-wave He-Ne laser (632.8 nm) as a probe laser was used to study the laser induced breakdown phenomena. Physical dimensions, propagation velocities and dynamical behavior of the laser-induced breakdown of saline samples were studied using the pump-probe technique [3]. Time resolved optical emission technique to study the plasma plume characteristics after the laser-material interaction was reported [4, 5]. Optical interferometry and laser induced fluorescence techniques was also been reported to study the plasma plume formation during the laser interaction with the material [6, 7]. A "high-speed laser stroboscopic videography" system has been developed for dynamic visualization of laser-induced processes, such as laser induced cavitation bubbles in liquids, change in ablation dynamics during multiple pulse irradiation, in microsecond timescale [8].

However, these diagnostic techniques are mainly towards study of plasma dynamics after the laser ablation. Some of the above measurement techniques provide a quantitative data of plasma dynamics, number density and identifying various species. Nevertheless, it is also essential to understand the interaction of a laser beam and the ablation plume during the laser ablation. In the previous work by the authors [9], A single nanosecond-pulsed Nd^{3+}:YAG laser based pump and probe technique was proposed and demonstrated to study the effect of plasma shielding on the performance of laser micromachining. Experimental and theoretical simulation studies were performed for laser irradiation wavelengths of 355 nm, 532 nm and 1064 nm. Plasma shielding was found to be influenced by laser wavelength as well as laser intensity. It was also observed that with increase in energy, ablation depth was increased, but at a higher input energy, the depth of channel was decreased. This was attributed to the depletion in the laser ablation energy as a result of plasma shielding.

In this paper the influence of the plasma shielding phenomenon on the depth of micro-channel formed when laser micro-scribing of Cu thin film is performed in vacuum is reported. A nanosecond pulsed Nd3+:YAG laser with a wavelength of 355 nm is used for micro-scribing of Cu thin films on polyamide material.

2 EXPERIMENTAL SETUP

Figure 1 shows the experimental setup proposed for the pump-probe measurements. A Q-switched Nd3+:YAG laser source (Quantel, Brilliant B) with a pulse width of 6 ns at full width at half maximum (FWHM) and repetition rate of 10 Hz was used as a source laser. The laser beam was split into two beams, namely a probe and pump laser beam. The pump laser was used for ablating thin film of copper (thickness: 35 µm) deposited on a polyimide substrate (thickness: 50 µm) by

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ISBN: 978-93-80689-28-9

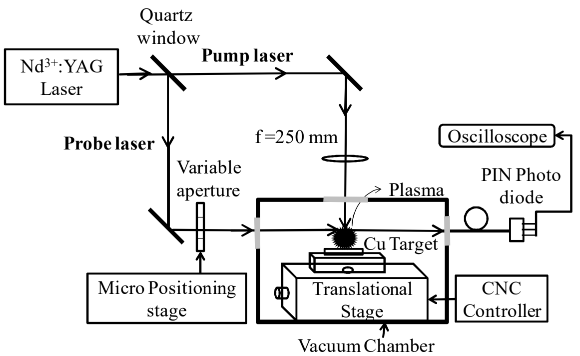

Figure 1: Experimental setup of the pump probe setup in vacuum ambience

focusing on the target with a plano-convex lens (focal length = 250 mm). The probe laser was aligned orthogonally to transmit through the ablated plume formed above the ablated target as shown in figure 1. Laser ablation was performed in vacuum (3 $\times 10^5$ m bar) by mounting the copper coated polyimide thin film on an X-Y translational stage. A variable aperture was used to limit the probe laser beam diameter to ~100 µm in order to align it through the plasma plume. An optical fiber (P300-1-SR, Ocean Optics) was used to couple the probe laser to the fast PIN-photo diode (Hamamatsu Photonics-S3883, resolution ~ 1 ns) and the signal was acquired using a digital storage oscilloscope (Lecroy, 6110A, 1 GHz). The translational stage of the aperture was positioned such that only the essential part of the probe laser beam was transmitted through the ablation plume.

3 EXPERIMENTAL RESULTS

Figure 2 presents the intensity of probe obtained in air ambience for without ablation and during ablation, the first case is the reference intensity where there is no plasma, during ablation indicates the transmitted probe through the plasma i.e plasma formed due to laser ablation. From the figure 2 it is observed that the probe intensity during ablation shown by dotted line depletes after ~ 5 ns. There is a drop in the intensity by ~ 40 %. This indicates a plasma shielding effect where the incident intensity is absorbed by the plasma plume creating a shield between the laser and the workpiece.

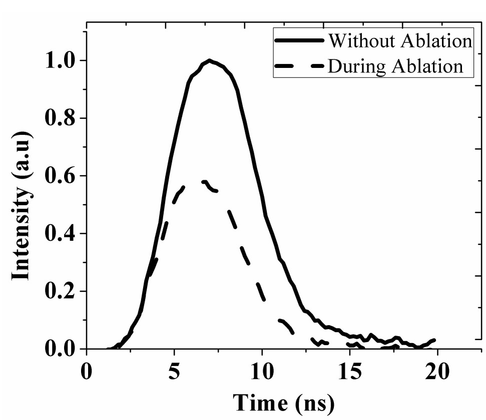

Figure 2: Probe Intensity for laser wavelength of 355 nm in air ambience for a laser intensity of 12 GW/cm^2

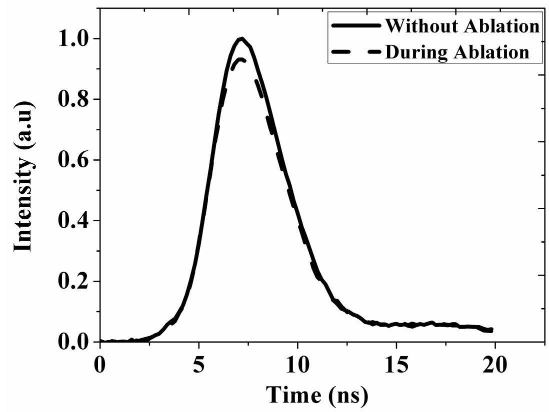

Figure 3: Probe Intensity for laser wavelength of 355 nm in vacuum ambience for a laser intensity of 12 GW/cm^2

Figure 3 presents the probe intensity in vacuum condition. It is seen that the reduction in the intensity of the probe beam is negligible which indicates that there is no shielding effect due to the plasma formation. This can be due to the fast expansion of the plasma plume in vacuum compared to air ambience. This phenomenon is also observed in the case of micro channels scribed in vacuum and air ambience. The diameter of the ablated surface with a single pulse was approximately 500 µm. Figure 4 shows the depth of the micro channels obtained using 95 % overlap of the laser spot diameter in air and vacuum. In the case of air it is observed that the depth of the channel tends to reduce or saturate after 30 mJ of energy where as in the case of vacuum the depth increases. This indicates that the influence of plasma shielding on material removal in vacuum is not as significant as in air medium.

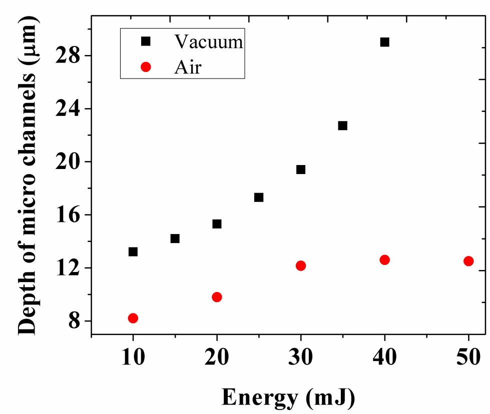

Figure 4: Micro channel depth achieved for 355 nm in 3×10^{-5} m bar vacuum on copper

4 DISCUSSION

A single nanosecond-pulsed Nd^{3+}:YAG laser based pump and probe technique was proposed and demonstrated to study the effect of plasma shielding in air and vacuum on the performance of laser micromachining. As shown in Figure's 2 and 3 it is observed that the plasma shielding is prominent in the case of air. The intensity of the probe laser has been observed to reduce at high intensities in case of air ambience.

The absorption is due to the inverse bremsstrahlung (IB) effect [10]. The inverse bremsstrahlung (α_{IB}) coefficient depends on the number density and the temperature of the plasma. In the case of vacuum as shown in Figure 3 the probe intensity is observed to reduce slightly indicating negligible effect of the plasma. The expansion of plasma is large in the case of vacuum [11], which results in the reduction in the number density of the plasma. The reduction in the depth for higher intensity in air was due to plasma shielding of the incident laser beam as seen in figure 4. At high energy the laser induced plasma above the work piece surface absorbs the incident laser beam and obstructs the incident laser beam from reaching the work piece hence reducing the micro channel depth. These observations related to plasma shielding effect on material removal are helpful in order to estimate the laser fluence window for laser scribing.

5 CONCLUSION

Influence of ambient medium on the plasma shielding effect is studied in air and vacuum using a nanosecond pulsed Nd^{3+}:YAG laser for laser with a wavelength of 355 nm while micro-scribing of Cu thin film. It is observed that in air, the depth of material removal increases with increase in the laser energy up to 30 mJ. However the depth attained is limited to ≈12 µm when the laser energy exceeded 30 mJ. Alternatively, in vacuum, the depth of material removed increased with the laser energy and it was limited by the Cu film thickness. In the case of vacuum the expansion of plasma resulted in less shielding of the incident laser beam.

References

[1] Singh RK and Narayan J, Pulsed-laser evaporation technique for deposition of thin films: Physics and theoretical model Physical Review B. **41** (1990) 8843

[2] Schittenhelm H, Callies G, Berger P and Hügel H, Investigations of extinction coefficients during excimer laser ablation and their interpretation in terms of Rayleigh scattering Journal of Physics D: Applied Physics. **26 (**1996) 1564

[3] Barthélemy O, Margot J, Chaker M, Sabsabi M, Vidal F, Johnston TW, Laville S and Le Drogoff B, Influence of the laser parameters on the space and time characteristics of an aluminum laser-induced plasma Spectrochimica Acta Part B: Atomic Spectroscopy. **60** (2005) 905-14

[4] Geohegan DB and Puretzky AA, Laser ablation plume thermalization dynamics in background gases: combined imaging, optical absorption and emission spectroscopy, and ion probe measurements Applied Surface Science. **96** (1996) 131-8

[5] Amorim J, Baravian G and Jolly J, Laser-induced resonance fluorescence as a diagnostic technique in non-thermal equilibrium plasmas Journal of Physics D: Applied Physics. **33** (2000)

[6] Dutouquet C and Hermann J, Laser-induced fluorescence probing during pulsed-laser ablation for three-dimensional number density mapping of plasma species Journal of Physics D: Applied Physics. **34** (2001) 3356

[7] Fujimoto JG, Lin WZ, Ippen EP, Puliafito CA and Steinert RF, Time-resolved studies of Nd:YAG laser-induced breakdown Plasma formation, acoustic wave generation, and cavitation. Investigative Ophthalmology & Visual Science. **26** (1985) 1771-7

[8] Tanabe R, Nguyen TT and Ito Y, Dynamical Studies on Laser Processes Induced by Short Pulse Lasers: From Nanoseconds to Milliseconds Physics Procedia. **31** (2016) 83-92

[9] Nammi S, Vas, N. J, Gurusamy B and Mathur A. C, Single laser based pump-probe technique to study plasma shielding during nanosecond laser ablation of copper thin films. Journal of Physics D: Applied Physics, **50** (2017) 355204.

[10] Amoruso S, Modeling of UV pulsed-laser ablation of metallic targets Applied Physics A: Materials Science & Processing. **69** (1999 69 (3) 323-32

[11] Ojeda-GP and Alejandro, Plasma plume dynamics, rebound, and recoating of the ablation target in pulsed laser deposition. Journal of Applied Physics **121** (2017) 135306.