ELSEVIER

Diamond and Related Materials 9 (2000) 1154–1158

DIAMOND AND RELATED MATERIALS

www.elsevier.com/locate/diamond

Precision micromachining of CVD diamond films

J.K. Park [a,*], V.M. Ayres [b], J. Asmussen [b], K. Mukherjee [a]

[a] *High Energy Laser Processing Laboratory, Department Materials Science and Mechanics, Michigan State University, East Lansing, MI 48824, USA*
[b] *Electronic and Surface Properties of Materials Center, Department Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824, USA*

Abstract

The laser ablation technique has been extensively recognized to be a unique method for the micromachining and designing of micro components. Chemical vapor deposited (CVD) diamond films have been processed by various types of pulsed lasers for this purpose. Nanosecond pulsed excimer lasers, and recently femtosecond pulsed lasers have been used for the micromachining of diamond films. Even though the interaction between the laser and the material is limited to the nanosecond to femtosecond range, plasma, induced by ablative material ejection, extends to tens of microseconds. Formation and expansion of the plasma give rise to thermal damage, material ejection and re-deposition, resulting in spoiled interfaces, recast layers, and rippled surfaces. The plasma generated thermal damage has been a major obstruction to micron and submicron micromachining of diamond films. To implement the laser ablation technique to the level of precision, a systematic investigation is required on the plasma interaction. This investigation is mainly focused on a novel approach to compensate for the deleterious plasma–diamond interaction. CVD diamond films were subject to various processing environments, such as atmospheric condition, vacuum condition and gas stream condition. Observed damage depends on behavior of the plasma in the different processing environments. In the gas stream condition, it has been clearly shown that proper dissipation of the high-temperature plasma leads to precisely irradiated surfaces, which are almost free from thermal damage. An emphasis of this research is to achieve maximum dissipation of the high-temperature plasma and proper quenching of the target surface. Based on a nanosecond pulsed excimer laser, technical and fundamental investigations for the precision micromachining are performed. Further investigations of the properties of the laser-irradiated films are also currently in progress, including investigations of laser-induced stress, surface morphologies, surface free energy and electronic properties.

Keywords: Diamond films; Laser; Micromachining; Plasma

1. Introduction

The excellence in mechanical and electrical properties makes diamond films uniquely qualified for applications to microelectromechanical system (MEMS), optics, electronic packaging and other micro components. To fully utilize diamond's excellent properties in the applications, micron or submicron micromachining of diamond films is required. The laser ablation technique has been extensively recognized to be a unique method for micromachining and designing of micro components [1]. CVD diamond films have been processed by various types of pulsed lasers for this purpose [2–12]. Nanosecond pulsed, excimer lasers have been applied for surface modifications of CVD diamond films [2–8]. In these investigations, the excimer lasers have shown their capabilities in polishing, etching, and patterning of the diamond films. Reduced surface roughness, improved optical transmittance, and patterned structures were reported from the applications. However, the processes have also exhibited some damage, such as transformed surface layers, and spoiled spot edges. These drawbacks have been obstacles to the application of the nanosecond pulsed excimer lasers to high resolution micromachining of CVD diamond. Recently, femtosecond pulsed UV lasers have been introduced to overcome the drawbacks of nanosecond pulsed lasers [9–12]. By utilizing the ultrashort pulsed irradiation on the CVD diamond films,

* Corresponding author. Fax: +1-517-353-9842.
E-mail address: parkjon@msu.edu (J.K. Park)

0925-9635/00/$ - see front matter
PII: S0925-9635(00)00222-3

the process showed some improvements, as compared to the nanosecond pulsed laser process. Even though the ultrashort laser ablation showed improvements on surface finish and purity of the irradiated diamond films, it was not successful in completely removing the imperfections, such as rippled surfaces, and blurred interfaces.

In the ablation processes by the lasers, plasma formation is inevitable due to the characteristics of short or ultrashort pulsed laser irradiation. Even though the laser–material interaction is limited to the nanosecond–femtosecond range, the plasma extends far longer than the laser pulse duration. In studies of ultrafast imaging of nanosecond pulsed laser ablation [13–16], it was visualized that the formation and expansion of plasma, induced by ablative material ejection, extended up to tens of microseconds. The propagation of shock waves was also observed due to the expansion of the high-temperature plasma. In this respect, the formation and expansion of the plasma give rise to almost all of the damage, such as surface phase transformation, plasma material ejection and re-deposition, and spoiled interfaces. The plasma generated thermal damage especially has been a major obstruction to micromachining of the diamond films in micron and submicron scale. To implement the laser ablation technique to the precision micromachining of diamond films, technical and fundamental approaches are required to circumvent the deleterious plasma effects. The aim of this investigation is to develop experimental techniques that compensate for the deleterious plasma–material interactions. Emphases of this research are to achieve maximum dissipation of the high-temperature plasma and proper quenching of the target surface.

2. Excimer laser micromachining of diamond films

A CVD diamond film was subjected to this preliminary investigation. The polycrystalline diamond film has an average grain size and thickness of 2 μm and 7 μm, respectively. The diamond film was subjected to three different processing environments, such as atmospheric condition, vacuum condition and gas-stream condition. The interaction, between the CVD diamonds and excimer laser pulses, showed drastic changes among the different processing environments. Other than the different gas processing environments, the same experimental conditions were applied to the diamond film. The energy fluence, repetition rate and number of pulses were fixed at 10 J/cm^2, 1 Hz, and 20 times, respectively. A circular beam spot (145 μm diameter) was illuminated on the film surface by a pin-hole (1 mm diameter) mask in the excimer laser imaging system. The temperature, around the irradiated spot, is assumed to have an exponential decay type of radial distribution, dispersed due to the formation of the plasma [17]. During the short dwelling (25 ns) of the excimer laser pulse on the film surface, atomic or molecular bonds of the material are disintegrated due to the transmission of high-energy fluence from the laser pulse. After the short interaction, disintegrated atoms and molecules are released from the surface, forming plasma due to their high-energy states [13–15]. The surface of the irradiated spot is heated by the high-temperature plasma, which results in thermal reactions, and possibly oxidation. The thermal expansion of the high-temperature plasma induces propagation of stress waves, resulting the ejection of materials and deposition of debris around the irradiated spot [17].

2.1. Atmospheric condition

SEM micrographs in Fig. 1 are taken from the irradiation under stationary air in ambient atmosphere. In Fig. 1a, the surrounding of the irradiated spot shows a distinctive plasma affected zone (PAZ), which has

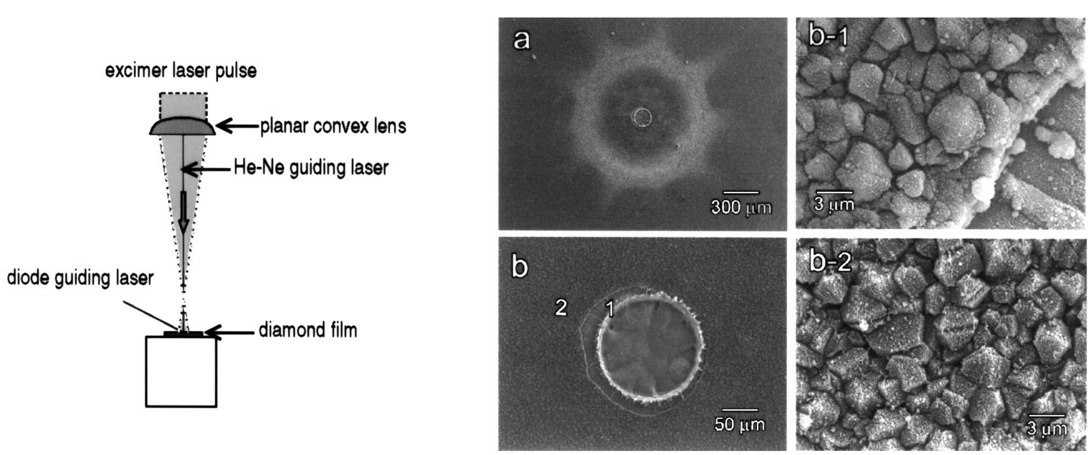

Fig. 1. Experimental setup and SEM micrographs for the excimer laser irradiation in atmospheric condition: (a) the irradiated spot and surroundings; (b) the irradiated spot; (b1) magnified view of area 1 from (b); and (b2) magnified view of area 2 from (b).

somewhat symmetrical, ring-shaped patterns with spikes. The areas of PAZ indicated by 1 and 2 in Fig. 1b are magnified in Fig. 1b1 and 1b2, respectively. In Fig. 1b1, the area near the edge of the spot has suffered from heavy deposition of debris and partial damage of diamond crystals. Energy dispersive X-ray (EDX) analysis indicated that the pulsed irradiation eradicated the diamond film, and revealed the silicon substrate, which created the ruffled crater. When the distance increases from the irradiation spot, the deposition is gradually reduced, as shown in Fig. 1b2. The debris and deposition of the ejected materials are observed at distances up to 10 times of the spot diameter. The PAZ is caused by combination of deposition of ablated debris and damage upon the thermal expansion of high-temperature plasma.

2.2. *Vacuum condition*

A vacuum chamber was constructed to examine the interaction in an airless condition. Using a rotary-vane vacuum pump, a low-vacuum condition (10 KPa) was gained in the chamber. In Fig. 2a, the PAZ, around the circular spot at the center, was considerably reduced as compared to that in Fig. 1a, in atmospheric environment. However, in Fig. 2b, the area surrounding the irradiated spot still shows an oval-patterned PAZ. Even though the heavy deposition of ablation debris is not observed in this condition, the edges of the spot are blurred and spoiled by the plasma. The areas in the PAZ, indicated by 1 and 2, are magnified in Fig. 2b1 and 2b2, respectively. In Fig. 2b1, the edge of the spot shows no deposition of debris; however, droplet-like precipitates are observed around the near-edge area. The damage on the diamond film appears somewhat different from the inside to the outside of the oval pattern. In Fig. 2b2, the area, outside of the oval pattern, show that layers of the diamond crystals are damaged by the expansion of the high-temperature plasma. The dispersion of the plasma is faster in the low-pressurized medium [13,16]. Even though damage is found in the wake of expanding plasma, the irradiated spot shows uniform reduction of surface roughness.

2.3. *Gas-stream condition*

In the gas-stream condition, a nozzle was installed to blow a 99.9% argon gas over the surface of the diamond thin film, upon the laser pulse irradiation. The nozzle was positioned approximately 3 cm from the irradiated spot and 30° to the film surface. Diameter of the nozzle was 2 mm and the argon gas flow rate was 4.72×10^{-4} m^3/s. In Fig. 3a, no PAZ was observed around circular spot at the center, in contrast to atmospheric and vacuum conditions. In Fig. 3b, areas near the irradiated spot show no visible damage. The arrows indicate the direction of the argon gas stream, which gives rise to slight imperfections along the streaming direction. The areas indicated by 1 and 2 are magnified in Fig. 3b1 and 3b2, respectively. Since the argon gas stream passed from area 1 to area 2, the area 1 in Fig. 3b1 shows intact diamond crystals. The damage is caused by the bent plasma, which was blown by the gas stream. Fig. 3b2 shows light damage on the crystal surface. Even though slight imperfections were found in some portions of the near-edge areas, overall feasibility of the gas-stream condition is exceptional for the micromachining of diamond films. The gas-

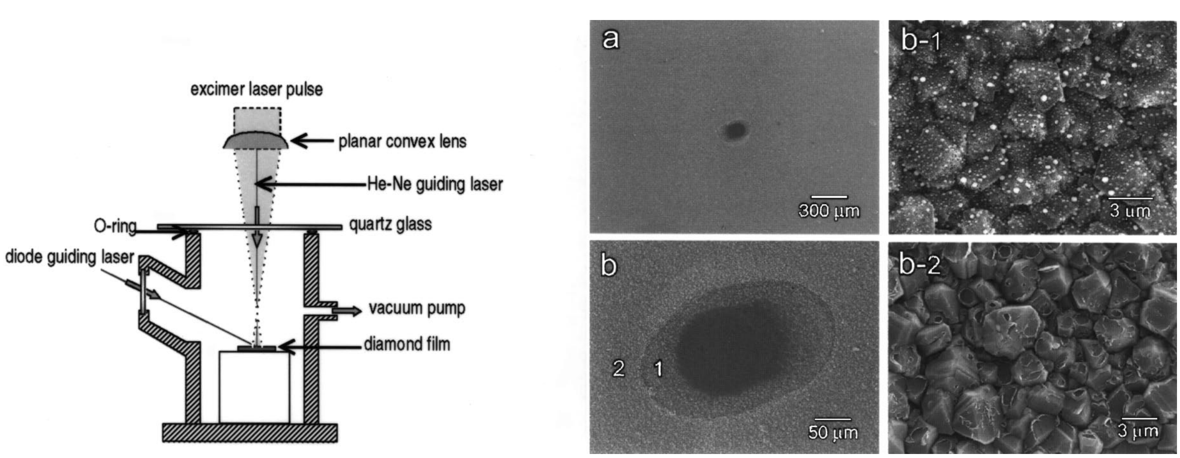

Fig. 2. Experimental setup and SEM micrographs for the excimer laser irradiation in vacuum condition: (a) the irradiated spot and surroundings; (b) the irradiated spot; (b1) magnified view of area 1 from (b); and (b2) magnified view of area 2 from (b).

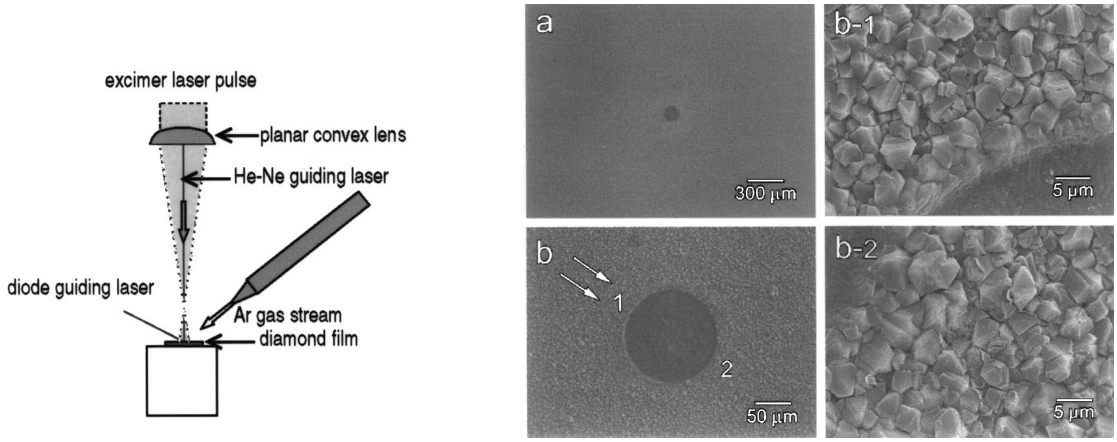

Fig. 3. Experimental setup and SEM micrographs for the excimer laser irradiation in gas-stream condition: (a) the irradiated spot and surroundings; (b) the irradiated spot; (b1) magnified view of area 1 from (b); and (b2) magnified view of area 2 from (b).

stream not only remove the ablated particles, but also quenches the surroundings.

3. Conclusions

To achieve maximum accuracy in laser micromachining of diamond films, a systematic and intensive investigation is required on the plasma interaction. This investigation is mainly focused on a novel approach to compensate for the deleterious plasma–material interaction. In our preliminary investigation, a CVD diamond film was subject to various processing environments, such as atmospheric condition, vacuum condition and gas stream condition. Observed thermal damage was dependent on the behavior of the plasma in the various processing environments. In the gas stream condition, it has been clearly shown that proper dissipation of the high-temperature plasma leads to a precisely irradiated surface, which is almost free from plasma damage.

References

[1] U. Brinkmann, S. Ishizaka, Laser LIGA-excimer laser microstructuring and replication, Lambda Phys. Highlights 45 (1994) 1–3.

[2] V.N. Tokarev, J.I.B. Wilson, M.G. Jubber, P. John, D.K. Milne, Modeling of self-limiting laser ablation of rough surfaces: application to the polishing of diamond films, Diamond Relat. Mater. 4 (1995) 169–176.

[3] A. Boudina, E. Fitzer, G. Wahl, H. Esrom, Improvement in IR properties of chemically vapour-deposited diamond films by smoothing with KrF excimer radiation, Diamond Relat. Mater. 2 (1993) 678–682.

[4] C. Johnston, P.R. Chalker, I.M. Buckley-Golder, P.J. Marsden, S.W. Williams, Diamond device delineation via excimer laser patterning, Diamond Relat. Mater. 2 (1993) 829–834.

[5] S.M. Pimenov, A.A. Smolin, V.G. Ralchenko et al., UV laser processing of diamond films: effects of irradiation conditions on the properties of laser-treated diamond film surfaces, Diamond Relat. Mater. 2 (1993) 291–297.

[6] V.G. Ralchenko, S.M. Pimenov, T.V. Kononenko et al., Processing of CVD diamond with UV and green lasers, in: A. Feldman, Y. Tzeng, W.A. Yarbrough, M. Yoshikawa, M. Murakawa (Eds.), Application of Diamond Films and Related Materials: Third International Conference, National Institute of Standard and Technology, Gaithersburg, MD, 1995, pp. 225–232.

[7] T. Chein, C. Cutshaw, C. Tanger, Y. Tzeng, Polishing of thick CVD diamond by an excimer laser and a cast iron wheel, in: A. Feldman, Y. Tzeng, W.A. Yarbrough, M. Yoshikawa, M. Murakawa (Eds.), Application of Diamond Films and Related Materials: Third International Conference, National Institute of Standard and Technology, Gaithersburg, MD, 1995, pp. 257–260.

[8] P. Tosin, W. Lüthy, H.P. Weber, Laser polishing of diamond films, in: A. Feldman, Y. Tzeng, W.A. Yarbrough, M. Yoshikawa, M. Murakawa (Eds.), Application of Diamond Films and Related Materials: Third International Conference, National Institute of Standard and Technology, Gaithersburg, MD, 1995, pp. 271–274.

[9] M.D. Shirk, P.A. Molian, A.P. Malshe, Ultrashort pulsed laser ablation of diamond, J. Laser Appl. 10 (2) (1998) 64–70.

[10] A.P. Malshe, T.A. Railkar, A.M. Ozkan, P.A. Molian, A. Muyshondt, W.D. Brown, Femtosecond lasers: a next generation tool for processing of semiconductors and metals, in: M.A. Imam, R. DeNale, S. Hanada, Z. Zhong, D.N. Lee (Eds.), The Third Pacific Rim International Conference on Advanced Materials and Processing, The Minerals, Metals & Materials Society, Honolulu, HA, 1998, pp. 2195–2201.

[11] P.A. Molian, R. Windholz, A.P. Malshe, S. Jamil, W.D. Brown, Femtosecond laser–diamond interactions for laser machining applications, in: J. Singh, S.M. Copley, J. Mazumder (Eds.), Proceedings of the Second International Conference on Beam Processing of Advanced Materials, ASM International, Cleveland, OH, 1995, pp. 199–206.

[12] M.A. Molian, R. Windholz, A.P. Malshe et al., Femtosecond laser processing of CVD–diamond, in: J. Singh, S.M. Copley, J. Mazumder (Eds.), Proceedings of the Second International

Conference on Beam Processing of Advanced Materials, ASM International, Cleveland, OH, 1995, pp. 275–278.
[13] R. Srinivasan, B. Braren, K.G. Casey, M. Yeh, Ultrafast imaging of ultraviolet laser ablation and etching of polymethylmethacrylate, Appl. Phys. Lett. 26 (1989) 2790–2791.
[14] P.E. Dyer, R. Srinivasan, Nanosecond photoacoustic studies on ultraviolet laser ablation of organic polymers, Appl. Phys. Lett. 48 (1986) 445–447.
[15] R. Srinivasan, K.G. Casey, B. Braren, M. Yeh, The significance of a fluence threshold for ultraviolet laser ablation and etching of polymers, J. Appl. Phys. 67 (1990) 1604–1606.
[16] U. Brinkmann, Ultrafast imaging of UV-photon ablation, Lambda Phys. Highlights 21 (1994) 1–4.
[17] K. Mukherjee, T.H. Kim, W.T. Walter, Shock deformation and microstructural effects associated with pulse laser-induced damage in metals, in: K. Mukherjee, J. Mazumder (Eds.), Lasers in Metallurgy, The Metallurgical Society of AIME, Chicago, IL, 1981, pp. 137–150.