Deposition of Interwoven Fibrous Nanostructure using Ultrafast Laser Ablation at Ambient Condition

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ABSTRACT

A new technique for site-specific deposition of fibrous nanostructure is demonstrated using Laser Induced Reverse Transfer (LIRT). Generation and deposition of fibrous nanostructures on transparent substrates for a wide range of materials would be possible by using the LIRT technique. The experiments were conducted using laser ablation of Silicon and Aluminum donors placed at the back of a transparent acceptor. The femtosecond laser beam transmits through the transparent acceptor and hits the donor target. Accordingly, a large amount of ejected species from the donor agglomerate into nanoparticles forming interwoven nanofibers. Further experiments show that the space between the donors and the acceptor is critical in the formation of nanofibers and the porosity of the formed nanostructure.

Keywords: Ultrafast Laser, Fibrous Nanostructure, Deposition, Laser Induced Reverse Transfer (LIRT)

1 INTRODUCTION

The development of metallic and semiconductor films on economical substrates like glass has been intensively studied because of their high performance, low cost, abundant raw materials, and the possibility of being deposited on large areas [1, 2]. Recently, tremendous advances have been made in the synthesis of nanoparticles, owing to the distinctive physical and chemical properties exhibited when the size of particles are in the order of sub 100 nanometers. Synthesized nanoparticles have many applications in the fabrication of nano-devices in microelectronics, photonics, filtration and tissue engineering.

Thus far several techniques have been suggested for the generation of nanoparticles. Among these techniques, laser ablation technique is preferred for its simplicity in equipment configuration and low investment. Laser-induced forward transfer (LIFT) has been widely studied as a technique for depositing and micro-patterning [3-6]. In the LIFT, the thin film which has already been deposited on a transparent donor substrate using PVD, CVD, etc. is ablated by a laser beam and removed from the donor target. Afterwards, the removed thin film is transferred to an acceptor substrate placed in close vicinity to the donor substrate. The thin film is then collided on the acceptor substrate, and deposited there [6].

Alternatively, Laser induced reverse transfer LIRT (backward-LIFT) can be used, where the donor substrate is placed after the acceptor substrate along the laser propagation direction. The LIRT has some distinct advantages compared to current patterning methods: unlike other techniques (e.g. LCVD), LIRT process can be performed in air and at room temperature without generating poisonous gases. Also, unlike the forward LIFT, in which the thin film should be deposited on donor substrate first, the LIRT can be applied directly to bulk material; therefore, the film deposition step is eliminated [7]. The LIFT technique usually allows the formation and fabrication of structures in the order of the laser beam focus and can be reduced to micrometer range [8, 9], while in the LIRT high pulse repetition ultrafast laser makes it possible to form and deposit nanofibrous structure in a single step. These advantages made the LIRT method fast and easy to implement.

In this research, we demonstrate that LIRT can be utilized to generate and deposit metallic and semiconductor nanofibrous structures on a transparent acceptor at ambient conditions. It is found that the distance between the donor and the acceptor has significant influence on the density of fibrous nanostructure.

2 EXPERIMENTAL DETAILS

Experiments were performed using a 515 nm wavelength direct-diode-pumped Yb-doped fiber amplified ultrafast laser system. The laser gives a maximum output power of 16 W with pulse repetition ranging from 200 kHz to 26 MHz. Laser parameters such as pulse width, repetition rate and total beam power, are computer monitored, which allows a simple interface with the performed experiments. The pulse width that the laser can produce ranges between 250 fs and 10 ps. The targets are an aluminum sheet and a polished blank silicon wafer with <100> crystal orientation. They are held stationary and close to a glass acceptor with various spacing in between. The experimental setup has been described in detail in reference [10].

The general laser-induced reverse transfer process is depicted in Fig.1.

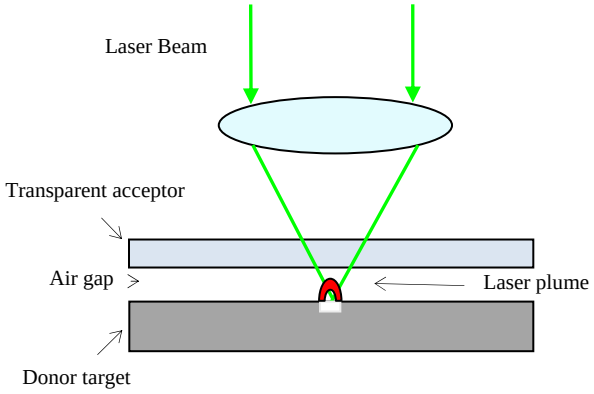

Figure 1: Diagram of Laser-Induced Reverse transfer process

The femtosecond laser beam passes through the transparent acceptor and irradiates the donor substrate. The plume generated from the donor surface scatters backward to the transparent acceptor and ejected species agglomerate into nanoparticles which form nanofibrous structure by more collision.

3 RESULTS

In laser ablation processes, when the laser intensity exceeds the ablation threshold of a target, it generates a heated region that causes evaporation leading to plasma that consists of various species with different velocities.

In LIRT, when a laser pulse is irradiated to the donor target, the plasma created on its surface propagates reversely to the transparent acceptor located adjacent to it. Consequently, depending on the distance between the acceptor and the donor target, emission and generation of various particle sizes on the acceptor may happen.

We start out experiments with a silicon donor and a glass acceptor in near contact. As shown in Figure 2, no fibrous nanostructures are generated, instead droplets in sub-micron size are observed. The short gap between the acceptor and the donor limits the plume expansion and condensation process, which results in reduction of the nuclei formation onset, and consequently leads to formation of large particles [11 and 12]. On the other side, because of very small spacing, molten liquid droplets are able to reach the acceptor surface and deposit.

The role of substrate distance has been discussed in detail for the LIFT technique [13 and 14]. We take advantage of this knowledge to estimate the suitable separation which results in nanofiber deposition, taking into consideration the laser fluence and the target material. The gap estimate to be 60 µm. The gap allows more space for plume expansion which results in a longer plume length. A longer plume length causes a lower concentration of ablated species in the plume resulting in smaller clusters [11 and 12]. Fig.3 presents the fibrous nanostructures obtained with the 60-µm gap [15]. However, a small amount of large droplets still can be seen from a close-up of the nanostructure. This implies that more spacing is needed to completely avoid molten liquid droplet deposition. Direct emission of liquid phase fragments from the donor surface might take place on a smaller scale due to the insufficient gap.

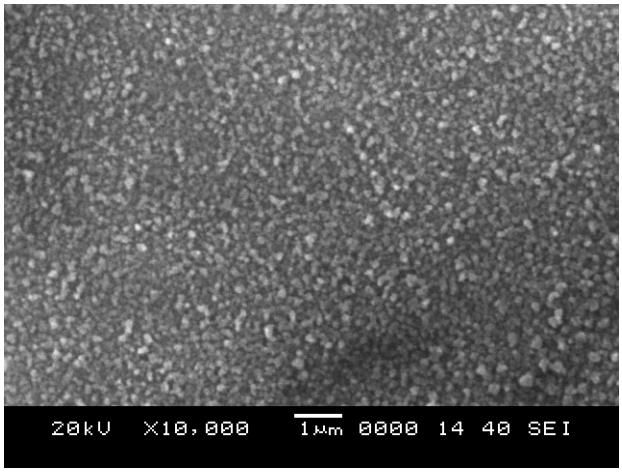

Figure 2: SEM image of Aluminum deposition on the glass acceptor in near contact with the donor, using 515 nm-wavelength laser beam, at laser repetition of 13 MHz and scanning velocity of 1000 µm/s.

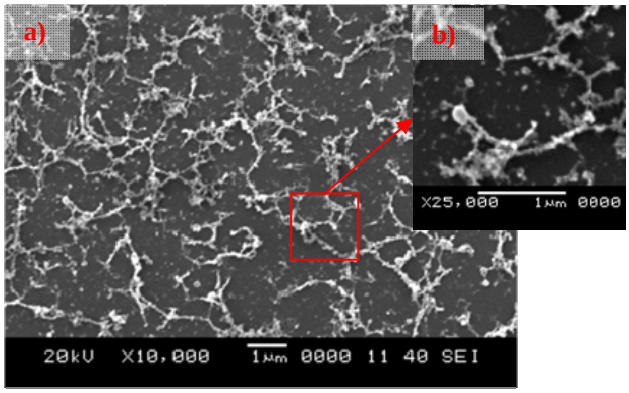

Figure 3: SEM image of silicon nanofibers deposited on the glass acceptor at 60 µm gap with the donor, using 515nm-wavelength laser beam, at laser repetition of 13 MHz and scanning velocity of 1000 µm/s.

We continue the experiments with wider gaps at 120, 180 and 240 µm to investigate the influence of the donor and acceptor distance on the nanofibrous structure. As depicted in Fig.4, the density and length of nanofibers

obtained at the 120µm gap are more than those with the 60µm gap. The average length of nanofibers generated at the 60µm gap was in the range of 0.55 µm to 0.70 µm whereas, it was about 1.06 µm to 1.18 µm for those obtained at the 120µm gap. It is found that the large droplets decreased in size and amount. Moreover, deposited nanofibers become thinner, as the gap between the donor and the acceptor increased.

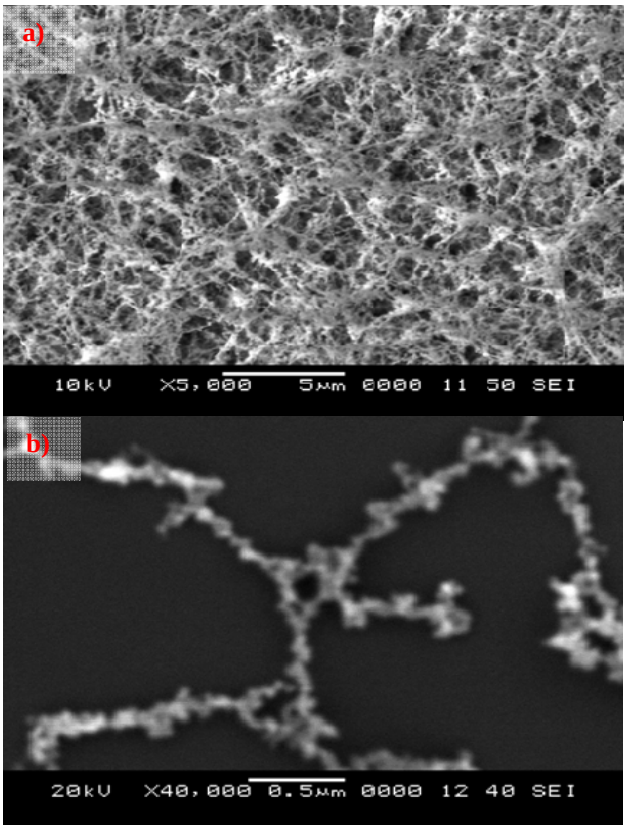

Figure 4: SEM image of silicon nanofibers deposited on the glass acceptor at 120µm gap with the donor, using 515nm-wavelength laser beam, at laser repetition of 13 MHz and scanning velocity of 1000 µm/s.

This experiment is conducted with several materials such as aluminum, silicon and carbon. It is found that the nanofibrous structures can be formed with all metals, semiconductors and alloys composed of these elements.

4 CONCLUSION

In this report, the potential of depositing metallic and semiconductor fibrous nanostructures on transparent substrates using femtosecond laser-induced reverse transfer has been studied. Deposition of nanofibrous structure was done in a single step at ambient condition. Our experiments demonstrated that the space between the donor and transparent acceptor plays a crucial role in the formation and density of formed nanostructures. Experimental results also confirmed that size, length, and porosity of aggregates can be controlled by laser parameters. Perfect controllability of nanofibrous structure deposition could extend the application of this technique. This technique may find wide application in synthesizing nano-composite, fabricating porous filters and tissue engineering, just to name a few.

REFERENCES

[1] H. Fujiwara, M. Kondo, A. Mastuda, J. Appl. Phys. 93, 2400, 2003.

[2] S.C. Saha, J.K. Rath, S.T. Kshirsagar, S. Ray, J. Phys. D 30, 2686, 1997.

[3] I. Zergioti, "Femtosecond laser microprinting of biomaterials," Appl. Phys. Lett. 86, 163902, 2005.

[4] M. R. Papantonakis and R. F. Haglund, Jr.Appl. Phys. A 79, 1687–1694, 2004.

[5] B. Tan, K. Venkatakrishnan, and K. G. Tok, Appl. Surf. Sci. 207, 365–371, 2003.

[6] H. Yamada, T. Sano, T. Nakayama and I. Miyamoto, Appl. Surf. Sci., 411, 197-198, 2002.

[7] V.P. Veiko, E.A. Shakhno, V.N. Smirnov, A.M. Miaskovski and G.D. Nikishin, Laser Part. Beams, 2006, 24, 203-209

[8] A.I kuznetsov, J. Koch and b.N. Chichkov, Opt. Express, 2009, 17, 18820-18825.

[9] M.L.A. Rigout, H. Niu, C. Qin, L. Zhang, C. Li, X. Bai and N. Fan, Nanotechnology, 19, 245303, 2008.

[10] B. Tan, A. Dalili and K. Venkatakrishnan, J. Appl. Phys.A, 95, 537-545, 2009.

[11] Y. khang and J. Lee, J. Nanopart. Res., DOI 10.1007/s11051-009-9669-z, 2009.

[12] S. R. Franklin and R. K. Thareja, Appl. Phys., 97, 123303-123308, 2005.

[13] V.P. Veiko, and S.M. Metev, Heidelberg: Springer Verlag, 1995.

[14] Sudipta Bera, A. J. Sabbah, J. M. Yarbrough, C. G. Allen, Beau Winters, Charles G. Durfee, and Jeff A. Squier, App. Optics, 46, 21-20, 2007.

[15] A.Tavangar, B. Tan, K. Venkatakrishnan, J. Micromech. Microeng. 20, 055002, 2010.