Aluminum film microdeposition at 775 nm by femtosecond laser-induced forward transfer

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Micro-deposition of an aluminum film of 500-nm thickness on a quartz substrate was demonstrated by laser-induced forward transfer (LIFT) using a femtosecond laser pulse. With the help of atomic force microscopy (AFM) and scanning electron microscopy (SEM), the dependence of the morphology of deposited aluminum film on the irradiated laser pulse energy was investigated. As the laser fluence was slightly above the threshold fluence, the higher pressure of plasma for the thicker film made the free surface of solid phase burst out, which resulted in that not only the solid material was sputtered but also the deposited film in the liquid state was made irregularly.

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The laser-induced forward transfer (LIFT) process uses a laser pulse to selectively remove thin film material from a donor substrate and transfer it in the form of micron-sized dots onto an acceptor substrate nearby. The advantages of LIFT process include simplicity and cleanness, high deposition rate, and localized material deposition. The ability to deposit micron-sized dots, lines, and patterns can be applied in the microelectronics and optoelectronics fabrication industries[1,2]. LIFT has been studied extensively during the last decade. Various kinds of thin film materials can be transferred by LIFT using short pulse lasers. Recent work has demonstrated the ability to deposit sub-micron scale features using ultrashort laser pulses[3−6]. In this paper, we report microdeposition of aluminum film by LIFT using a femtosecond laser pulse. With the help of atomic force microscopy (AFM) and scanning electron microscopy (SEM), the dependence of the morphology of the deposited aluminum film on the irradiated laser pulse energy was investigated.

The experimental setup is shown in Fig. 1. A commercial femtosecond laser workstation (UMW-2110i, Clark-MXR Inc.) operating at the center wavelength of 775 nm was used. Pulse trains with 148-fs duration were produced in the system. An aluminum film of ∼ 500-nm thickness was deposited on a 3-mm-thick quartz substrate. Another quartz substrate with the same specifications and thickness served as an acceptor. Experiments were performed in contact ($\Delta z = 0$) mode with single laser pulses in atmosphere at room temperature. Samples were mounted on a motorized x-y precision stage, whose resolution was 10 nm. A 5× objective lens was mounted on the z stage during the experiment. The laser beam was focused on the aluminum film through supporting quartz substrate. The laser pulse energy varied over a wide range of values in order to investigate the effect on material transfer. All the processes were controlled by a computer.

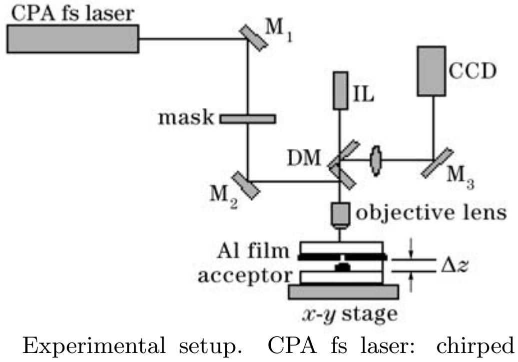

Fig. 1. Experimental setup. CPA fs laser: chirped pulse amplification femtosecond laser; M_1—M_3: reflecting mirrors; DM: dichroic mirror; IL: illuminating laser.

For the laser fluence below 5.6 J/cm^2, no transfer of dots was observed. The lowest laser fluence at which transfer was observed was 6.4 J/cm^2, i.e., the threshold fluence (E_{th}) for transfer was 6.4 J/cm^2 for an aluminum film of ∼ 500-nm thickness, which transferred a small spot of about 5 μm in diameter (which is only faintly visible in photo) in contact ($\Delta z = 0$) mode, as shown in Fig. 2. Figure 3 corresponds to the SEM image at the threshold fluence for transfer.

From Figs. 2 and 3, we can find that the deposited dots

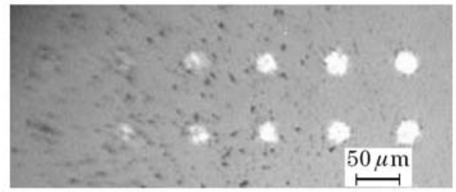

Fig. 2. Hirox microscope images of Al dots deposited on quartz substrate in contact ($\Delta z = 0$) mode. The laser pulse fluences were 6.4, 7.2, 8, 8.7, 9.2, and 9.7 J/cm^2, respectively, from left to right.

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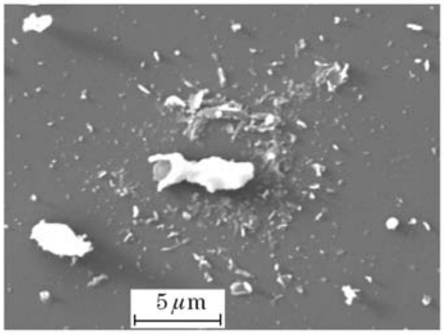

Fig. 3. SEM image of Al dot deposited on quartz substrate in contact ($\Delta z = 0$) mode at laser fluence of 6.4 J/cm^2.

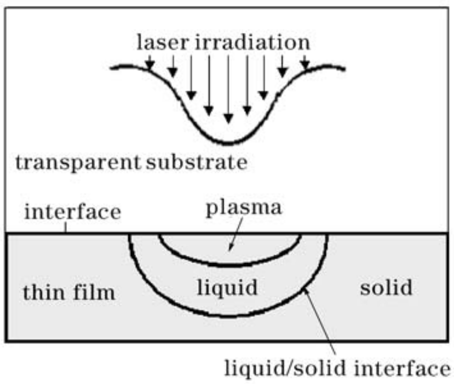

Fig. 4. Schematic diagram of heating of the donor film by femtosecond laser pulse.

were not only irregular but also nonuniform as the laser fluence was slightly above the threshold fluence E_{th}. An irregular droplet in shape was in the middle of the deposited dot and a lot of material particles were sputtered around the droplet. In respect that the thin film is heated by femtosecond laser at a constrained interface rather than the free surface and the threshold fluence of 6.4 J/cm^2 is greater than the threshold fluence for femtosecond laser produced plasma in aluminum[7,8], such deposits can attribute to phase explosion occurring in the interface (between the donor film and substrate) of the source film[9−11]. Because the threshold fluence E_{th} for the thicker film was larger, the pressure of plasma, which resulted from phase explosion inside the interface between the film and the support substrate, was relatively larger. At the same time, the free surface of the film was possibly remained in the solid phase, as shown in Fig. 4. The larger pressure of plasma made the free surface of solid phase burst out, which resulted in that not only the solid material was sputtered but also the deposited film of liquid state was made irregularly.

From Fig. 2, we can see that at the threshold fluence, the pulse-to-pulse energy variations resulted in deposits of various dimensions of approximately 5—6 μm. With the increase of energy, the diameter of the deposited spots increased gradually and the deposited dots became island-like, as shown in Fig. 5. It is observed that the center part of the dots is thinned down. This may be explained as follows. With increasing the energy, the thickness and pressure of the plasma in the inside surface of the film were increased. At the same time, liquid/solid

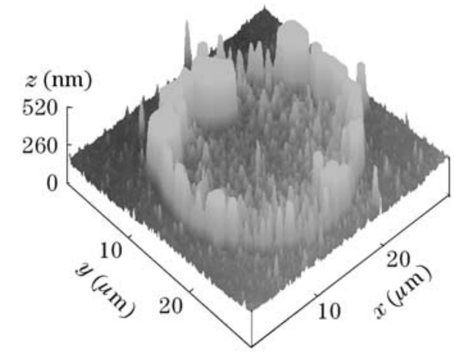

Fig. 5. AFM image of Al dot deposited on quartz substrate in contact ($\Delta z = 0$) mode at laser fluence of 9.2 J/cm^2.

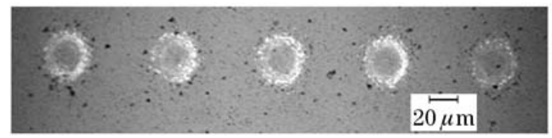

Fig. 6. Hirox microscope images of Al dots deposited on quartz substrate in contact ($\Delta z = 0$) mode. The laser pulse fluence was 12.5 J/cm^2.

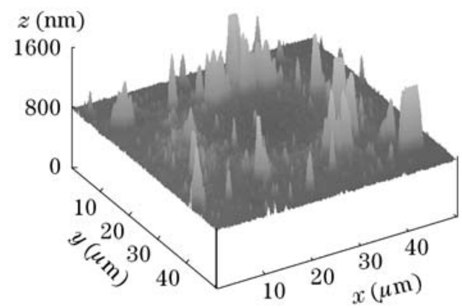

Fig. 7. AFM image of Al dot deposited on quartz substrate in contact ($\Delta z = 0$) mode. The laser pulse fluence was 12.5 J/cm^2.

interface was moved toward free surface so that the liquid/solid interface was close to free surface of the film. Therefore the material was mainly transferred in the mixture of liquid and gas phases. The very high energy explosive strike gave the transferred material with very high kinetic energy, which made the surface of the acceptor super hot to reduce the sticking coefficient in the process of deposition. Because of the inhomogeneous intensity distribution of the Gaussian beam, the sticking coefficients became minimal at the center of the irradiation. Therefore, a crater-like morphology was formed at the center of the deposited dot[12].

For higher energies, the transferred dots show ring-like morphology as shown in Figs. 6 and 7. The very big shock caused a wide spread of the deposited material when the collision happened between the transferred particles and the acceptor substrate, and the acceptor substrate may be damaged by striking at the center of the ring.

In conclusion, we have reported microdeposition of the aluminum film of ∼ 500-nm thickness by femtosecond LIFT on a quartz substrate. Three kinds of feature spots were deposited in contact ($\Delta z = 0$) mode, which are obtained over a relatively wider fluence range. We found that, for the thick film and the laser fluence slightly above the threshold fluence E_{th}, the larger pressure of plasma made the free surface of solid phase burst out, which resulted in that not only the solid material was sputtered but also the morphology of deposited film of liquid state was made irregularly. With the increase of energy, the diameter of the deposited spots increased gradually and the morphology of the deposited dots became island-like and circular. Whereas for higher energies, the transferred dots show ring-like morphology.

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