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Microdroplet deposition by laser-induced forward transfer

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Laser-induced forward transfer was used to deposit aluminum and nickel microdroplets onto a substrate using a *Q*-switched neodymium:Yttrium-aluminum-garnet laser. The droplets have diameters of a few microns, much smaller than the laser spot diameter, and are transferred at fluences slightly above the melting threshold. Scanning electron microscopy shows that the original donor film is deformed after laser irradiation, such that the film protrudes outward from the center of the laser spot. The film expands during laser heating, but is constrained until the melt interface reaches the free surface. When this occurs, the film is no longer constrained, allowing the melt to rapidly expand, forming the protrusions from which droplets are ejected. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1944895]

Laser-induced forward transfer (LIFT) has been studied extensively in recent years as a method of additive micropatterning.[1] Recent work has demonstrated the ability to deposit nanoscale features using femtosecond and picosecond laser pulses,[2–4] while features transferred by nanosecond laser pulses are typically limited to the laser focal spot size.[5,6] In this letter, we report microdroplet deposition by the LIFT technique using single nanosecond laser pulses. The process represents a precise method of material transfer that is interesting not only for microdeposition, but also for understanding laser-induced thermal phenomena on the microscale.

A *Q*-switched Nd:YAG laser [1.064 μm, 7 ns full width at half maximum (FWHM)] was focused to the interface between a film and transparent donor substrate as shown in Fig. 1. The laser spot diameter in the study was estimated to be approximately 25 μm. Samples of aluminum and nickel films were dc magnetron sputter coated onto glass microscope slides to a thickness of 1 μm. Experiments were performed in contact ($\Delta z=0$) and noncontact mode ($\Delta z=25\ \mu m$) with single laser pulses. Noncontact mode was achieved by placing a spacer of known thickness between donor and acceptor substrates. Samples were mounted on *x*-*y* motion stages and moved between each pulse such that only single-laser pulses were incident at a given location. Laser fluence was varied by a cross polarizer in the path of the laser beam while the laser diameter was held constant.

Laser fluence was varied over a wide range of values in order to investigate the effect on material transfer. At high fluences, the results were similar to that observed in other studies using nanosecond laser pulses: Material was transferred in an area of approximately the same size as the laser spot or larger, with an increasing amount of spatter at high laser fluences. The transfer mechanisms were of a different nature at high fluences and are discussed in another publication.[7] When the laser fluence was decreased to levels slightly above the melting threshold however, small individual droplets were transferred.

Aluminum microdroplets transferred to the acceptor substrate are shown in the scanning electron microscopy (SEM) photos in Fig. 2 for both contact and noncontact mode. Similar results were observed in both cases, although noncontact mode resulted in some debris formation. Droplet sizes were approximately 3 μm, much smaller than the laser spot size of approximately 25 μm. The size of the droplets was repeatable, although some size variation resulted from the laser pulse-to-pulse energy fluctuations.

The incident fluence used to obtain the droplets in Fig. 2 was approximately $6.06\ \mathrm{J/cm^2}$. SEM imaging of the donor film revealed interesting structures in the irradiated region, shown in Fig. 3. A protruding "bump" in the center of the region is surrounded by a depression and a raised circular rim. The rim appears to be a ridge of resolidified melt displaced by surface tension gradients, a common feature in thin-film micromachining.[8] Further inspection of the donor film revealed that the central protruding bump existed at fluences below the threshold for material transfer. Figure 4 demonstrates a series of bumps on the donor film, formed below the transfer threshold fluence, which appear as large droplets protruding from the surface. Figure 4(b) is a close-up view of the protrusion from the upper right side of Fig. 4(a). The protrusion is aluminum that was being expelled from the donor film at the center of the laser spot, but solidified before a droplet separated. Experiments were also performed with nickel films, and the results are shown in Figs. 5 and 6. Similar results were observed, with protruding

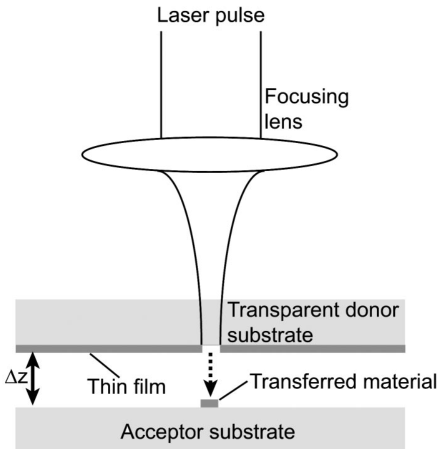

FIG. 1. LIFT.

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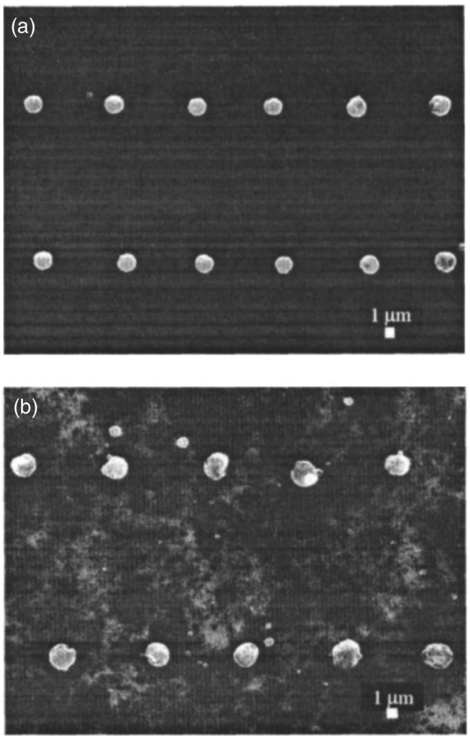

FIG. 2. SEM images of aluminum droplets deposited by laser-induced forward transfer in (a) contact mode and (b) noncontact mode.

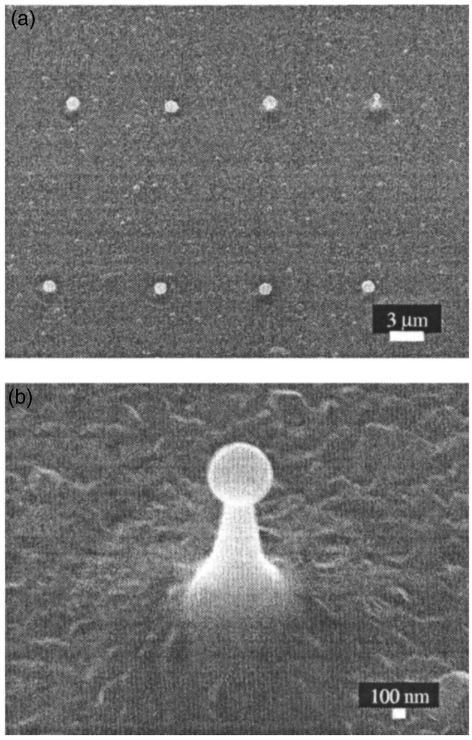

FIG. 4. SEM images of aluminum donor film below droplet transfer threshold in noncontact mode.

bumps on the donor film above and below the transfer threshold.

The protrusion on the donor film in Figs. 4 and 6 are the source of the droplets that are expelled and transferred to the acceptor substrate. Based on the experimental observations, we believe that the physical mechanism responsible for the protrusions from which droplets form is as follows: The liquid phase has a lower density (higher specific volume) than the solid phase, thus the film will normally expand as it melts. During the solid-liquid phase transition, the density decreases by 11.7% for aluminum and 11.2% for nickel.[9] In laser-induced forward transfer, the thin film is heated at a constrained interface (between the donor film and substrate) rather than the free surface, thus the film expansion is constrained until the melt interface reaches the free surface. The laser beam has a Gaussian irradiance distribution, thus at fluences slightly above the melting threshold only a small central portion of the melt interface will reach the free surface, as shown in Fig. 7. When this happens, the melt is no longer constrained, allowing expansion through a small region in the free surface, forming the protrusions from which droplets form. At higher fluences, the droplet expulsion is not observed since other phenomena become dominant, such as melt motion due to surface tension gradients, vaporization, and boiling of the film.[7] Although droplet formation is a common phenomena in thin-film laser micromachining, outward protrusions at the center of the laser spot were not observed near the melting threshold in other micromachining studies.[8] This can be explained because during normal laser micromachining the film is heated at the free surface, allowing the film to expand gradually during the heating phase, rather than a sudden release as observed in the present work. Droplets in other studies were a result of a high acceleration in the radial direction due to surface tension gradients.[8]

In conclusion, we have reported microdroplet transfer and deposition by LIFT at laser fluences slightly above the

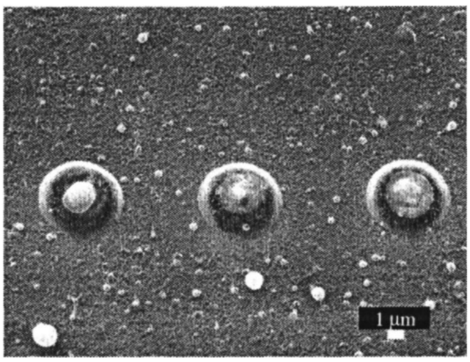

FIG. 3. SEM images of aluminum donor film above droplet transfer threshold in contact mode.

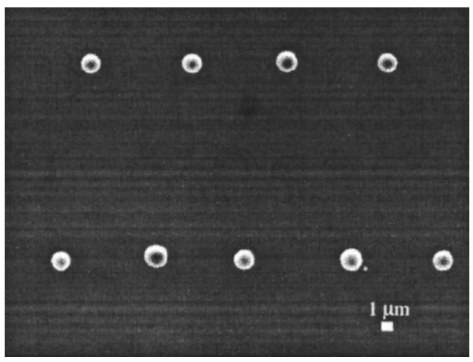

FIG. 5. SEM images of nickel droplets deposited by laser-induced forward transfer in contact mode.

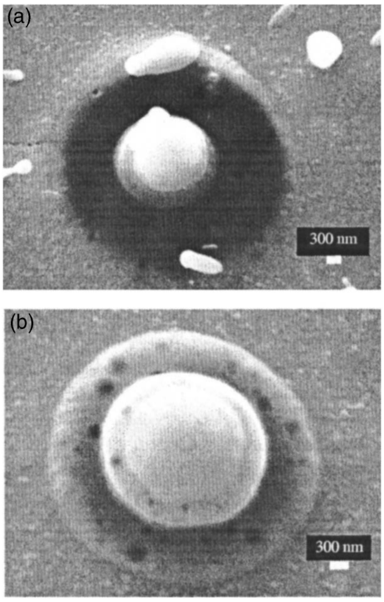

FIG. 6. SEM images of nickel donor films in non-contact mode (a) above droplet transfer threshold and (b) below droplet transfer threshold.

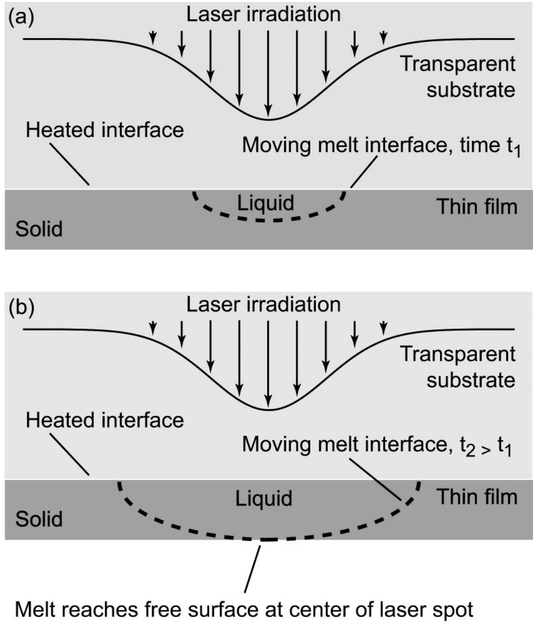

FIG. 7. Schematic diagram of laser heating of the donor film, (a) at a time early in the laser pulse, (b) at the moment the melt interface reaches the free surface, the expanding melt is no longer constrained.

melting threshold. The droplet formation is a result of expansion of molten film from the center of the laser spot when the melt front reaches the free surface. The authors are developing numerical models of the laser-induced thermal-fluid processes in order to develop a better understanding of the droplet formation, including the competition between volumetric expansion and surface-tension effects. Such a model is interesting not only for understanding LIFT, but is of general interest to the laser processing community.

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