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Multi-jets formation using laser forward transfer

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ABSTRACT

The dynamics of multi-jets formation in liquid films has been investigated using the laser-induced forward transfer (LIFT) technique. This technique allows the deposition of micrometer-sized droplets with a high spatial resolution from a donor substrate to a receiver substrate. The donor was a silver nanoparticles ink-coated substrate. The interaction of the laser pulse with the donor ink layer generates an expanding bubble in the liquid which propels a jet towards the receiver. Silver lines have already been printed by depositing overlapping droplets in a “low speed” process. In order to increase the throughput, it is necessary to decrease the time between the depositions of two droplets. By scanning the beam of a high repetition rate UV picosecond laser (343 nm; 30 ps; 500 kHz) with a galvanometric mirror, successive pulses are focused on the silver nanoparticles ink-coated donor substrate. The shape and dynamics of single jets and adjacent jets have been investigated by means of a time-resolved imaging technique. By varying the distance between the laser spots, different behaviours were observed and compared to the printed droplets. A spacing of 25 μm between laser spots was found to generate both stable jets and well-controlled, reproducible droplets at high speed.

1. Introduction

With the development of nomadic devices and cheap flexible microelectronics, there is a growing need for printing electrical connections at high speed. Non-lithographic and digital printing techniques are more and more attractive because they can transfer small amounts of materials at reasonable speed and with great precision. A promising solution for rapid-prototyping is the laser-induced forward transfer (LIFT) process because of its high versatility, especially concerning the computer controlled designs and the large set of transferable materials. The LIFT process consists in transferring a small amount of a material previously deposited on a transparent donor substrate, as a thin film, to a receiver substrate placed nearby. The LIFT technique has been studied and used for over two decades [1] and has proven to be efficient to transfer a wide range of materials: metals [2–5], polymers [6–10], but also liquid or viscous materials like metal nanoparticle inks [11–13] and pastes [14], immunoglobulin [15] or water [16]. It is a promising technique in the field of biotechnology thanks to its ability to transfer biological sensitive materials without altering their properties [17,18]. Its main field of application is plastic electronics, where it can be used to transfer conductive lines [2], free-standing structures for microelectromechanical systems (MEMS) fabrication [19], or complete stacks of materials to make OLEDs [20–22], OTFTs [23,24] or MEMS [25,26].

This technique can be of particular interest to print custom patterns of metallic interconnections for microelectronic devices. It can be used with solid metals or metal nanoparticle inks. When using inks, the samples are cured at medium temperature (below 250 °C) after the transfer to allow the nanoparticles to coalesce. The LIFT of liquids has been well studied over the last decade. The laser pulse absorbed by the ink generates a cavitation bubble which expands away from the surface and propels the ink, forming a jet [27,28]. This jet is collected on a receiver substrate, forming a droplet. Printing overlapping droplets results in continuous lines. The dimensions and quality of the lines are impacted by the thickness and viscosity of the ink film on the donor, the laser fluence, the distance between the donor and receiver substrates [12,16,29] and the presence or the absence of a dynamic release layer [30–32].

Previous studies have focused on single pulses forming single jets. In order to increase the speed at which a line is printed, it is of interest to generate jets close to each other in a short amount of time. This paper expands the current understanding of the LIFT process to multi-jet transfer. Combining a very high repetition rate pulsed laser with a galvanometric mirrors scanner system which can scan the beam over a large surface, we can focus several successive laser pulses on the donor substrate at high speed and with controlled spacing. The behaviour of several jets close to each other is investigated through shadowgraphy for several spacings between the laser pulses and the results are compared with the printed droplets.

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2. Experimental setup

The laser system used for the study was a frequency-tripled fiber laser (Hegoa, EOLITE Systems) with a wavelength of 343 nm and a pulse duration around 30 ps. Its repetition rate can vary from 0.2 to 2 MHz and has been set to 500 kHz. The number of pulses was computer-controlled by software. The beam energy was controlled by a rotative wave plate and a polarizing beam-splitter cube. The beam was moved in two directions (x and y) by a scanner system with galvanometric mirrors and focused by an F-theta telecentric objective (focal length = 160 mm). This objective was used in order to keep a planar focal plan in spite of the deflection of the beam by the galvanometric mirrors. The illumination of the shadowgraphy system consisted in a NANOLITE KL-M flash lamp (High-Speed Photo-Systeme) delivering sparks of 16 ns. Two quartz lenses collected and focused the light below the donor on the trajectory of the laser beam, and images were taken by a fast QICAM 12-bits camera equipped with a 12X zoom lens system. A digital delay generator (DG535, Stanford Research Systems) was used to tune the delay between the emission of the laser pulses and the triggering of the flash lamp.

The conductive ink used for the study was purchased from SunChemical. It contained 20% of silver nanoparticles (size: 80–100 nm), had a density of 1.22 g/mL and a viscosity of 10–13 mPa s. The main solvents were ethanediol, ethanol, glycerine, 2-isopropoxyethanol. The ink was spin-coated for 30 s at 2900 rpm (acceleration 1660 rpm/s) on donor substrates, which consisted in $2 \times 2\,cm^2$ quartz Suprasil® substrates (transparent at the laser wavelength). The average weight of the ink layer was 1.87 mg and its average thickness was 3.8 μm. All ejection experiments were done at room temperature and pressure between 1 and 3 h after donor preparation, which ensured stable ink conditions. Receiver substrates were silicon wafers. Samples with ink deposits were analyzed with a Leica DMC 3D confocal microscope. They were cured in an oven at 150 °C for 30 min to evaporate the solvents and bond the nanoparticles together.

3. Results and discussion

3.1. Dynamic of a single jet formation

A microarray of droplets printed at different fluences is presented in Fig. 1. The separation between the donor and receiver was 100 μm. The threshold fluency of deposition F_{min} is approximately 25 mJ/cm^2 and no droplets are observed at lower fluences. The smallest droplets obtained had a diameter of 16 μm. At 30 mJ/cm^2, droplets are circular and have a diameter of around 20 μm, with no splashes, debris or satellites observed. Their height is 2 μm, their volume 260 μm^3 and their surface 300 μm^2. After the annealing process, the volume was reduced of 75% to 70 μm^3. The height was reduced to 300 nm but the diameter increased slightly to 20.5 μm. Increasing the fluence to 50 mJ/cm^2 increased the size of the deposited droplets. The round-shaped form is preserved on some of them and satellite droplets can be observed. From 60 mJ/cm^2, the droplets have irregular shapes, with a lot of satellites and splashes around them. Among the explored conditions, it can be concluded that the optimum laser condition to obtain arrays with the best uniformity is at and slightly above F_{min}, as it has been already observed for the deposition of liquids [16,33].

A series of shadowgraphy images of the transfer process is presented in Fig. 2. It corresponds to a sequence of a single droplet printing and illustrates how the process takes place. The laser fluence has been set to 30 mJ/cm^2 in order to obtain droplets similar to those obtained in Fig. 1. Due the high reflectivity of the ink film, two liquid expansion fronts seem to evolve in opposite directions. The upward front corresponds to the reflected image, only the downward one must be considered. The receiver substrate has been removed.

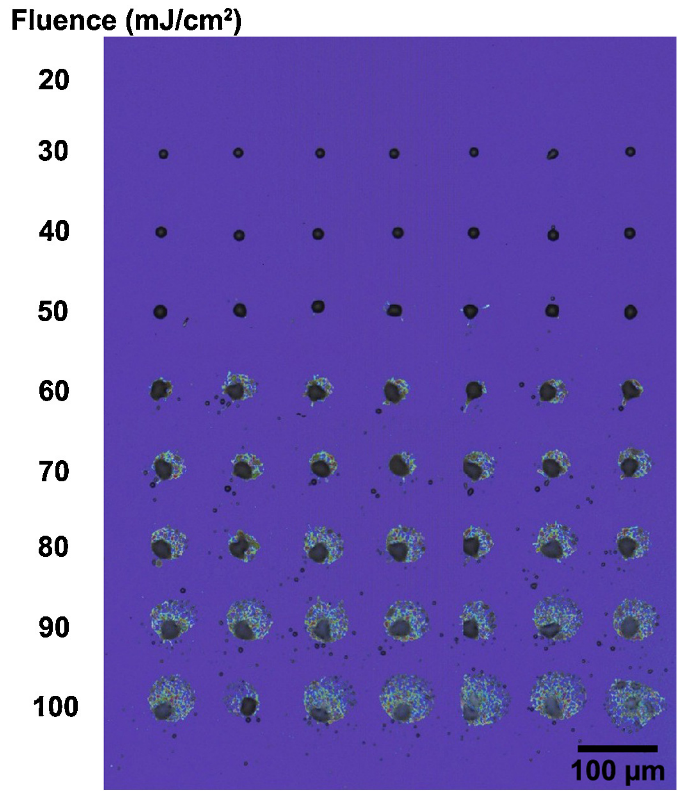

Fig. 1. Optical microscopy image of the droplets obtained immediately after LIFT transfer of the silver nanoparticles at different laser pulse fluences.

The process of jet formation in liquid has been many times investigated [27,32] and treated in a number of theoretical works [34]. To summarize, the laser pulse interacts with the thin ink layer (3.8 μm thick) and creates an expanding and highly confined plasma, which leads to the generation of a hemispherical cavitation bubble in the ink layer (~25 μm long at t = 250 ns). Its expansion propels the adjacent liquid away from the substrate. The bubble elongates and expands into a triangular shape, then forms a thin and stable jet at 700 ns. The jet has a diameter of ~4 μm and continues its propagation until ~7 μs, then starts to fragment. If a receiver substrate is placed in proximity of the donor substrate (50 μm to 150 μm), a well-defined round-shaped sessile droplet can be collected. When the gap between donor and receiver substrates is increased, satellite droplets start to appear. Droplets were collected on the receiver substrate at more than 1 mm as observed in other experiments with liquids [35].

Fig. 3a represents the evolution of the size of the jet as a function of the time delay for two fluences. Each data point is the result of an average taken from several measurements. As expected, increasing the fluence increases the speed of the jet front, as more energy is transferred to the ink. The initial speed is constant (~60 m/s for 30 mJ/cm^2 and ~100 m/s for 40 mJ/cm^2) and then starts to decrease as the jet becomes longer than 400 μm (see Ref. [27]). Fig. 3b represents the evolution of the width of the cavitation bubble as a function of the time delay. At early times, the width of the cavitation bubble immediately following its formation is ~22 μm. The movement of the fluid and the collapse of the bubble are accompanied by a decrease in the bubble diameter. At 700 ns, the bubble is not visible anymore and only the jet can be seen. The bubble then appears again but with a smaller maximum diameter as energy is lost during the rebound (classical rebound of a cavitation bubble