Process optimization of LIFT through visualization: towards high resolution metal circuit printing

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ABSTRACT

Laser induced forward transfer (LIFT) is a freeform, additive patterning technique capable of depositing high resolution metal structures. A laser pulse is used to generate small droplets from the donor material, defined by the spot size and energy of the pulse. Metallic as well as non-metallic materials can be patterned using this method. Being a contactless, additive and high resolution patterning technique, this method enables fabrication of multi-layer circuits, enabling bridge printing, thereby decreasing component spacing. Here we demonstrate copper droplet formation from a thin film donor. The investigation of the LIFT process is done via shadowgraphy and provides detailed insight on the droplet formation. Of particular importance is the interplay of the droplet jetting mechanism and the spacing between donor and receiving substrate on a stable printing process. Parameters such as the influence of laser fluence and donor thickness on the formation of droplets are discussed. An angle deviation analysis of the copper droplets during flight is carried out to estimate the pointing accuracy of the transfer. The possibility of understanding the droplet formation, could allow for stable droplets transferred with large gaps, simplifying the process for patterning continuous high-resolution conductive lines.

Keywords: Laser Induced Forward Transfer, high resolution metal printing, laser, additive, non-contact, shadowgraphy, metal droplets, conductive tracks

INTRODUCTION

Laser induced forward transfer (LIFT) is a direct deposition technique that uses a laser pulse to transfer materials from a transparent support onto a receiving substrate (see Figure 1). LIFT was first shown for direct deposition of materials from a thin film by Bohandy et al.[1],[2]. Since then, the LIFT process has been used to transfer metals [3]–[6], inks [7]–[9] and even interconnect materials [10]–[11]. Direct LIFT of metals is relevant, because it combines deposition as well as patterning of metallic structures in a single step. Compared to other metal deposition processes such as photolithography in combination with etching or metal ink printing, it could lead to simplified tooling, reduced material costs and fewer process steps. The LIFT of copper is particularly interesting because it allows for additive printing of a low cost metal, exhibiting good conductivity which is used in a wide range of applications[12]. Contamination free depositions of copper via LIFT have been shown[11]. These results were however obtained for relatively small spacing (25µm) between the donor and receiver substrate. For industrial printing applications, it is preferable to have a larger distance between donor layer and acceptor substrate. To assess the stability and process window of the copper LIFT process for large donor acceptor spacing, the droplet formation at the donor interface was in-situ visualized using a high speed shadowgraphy imaging setup. The role of droplet formation and stability as a function of laser fluence and donor substrate thickness was investigated.

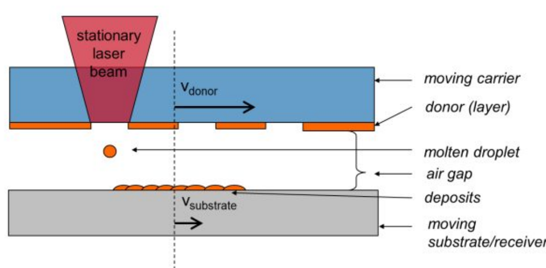

Figure 1: Schematic overview of a typical LIFT setup. The donor layer (pure copper) is coated onto a transparent carrier, which is moved with respect to a stationary laser beam, thus supplying fresh donor material. To make continuous patterns from the droplet

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deposits onto the substrate, the receiver substrate is also moved with respect to the laser beam. The light of the laser pulse is absorbed at the carrier-donor interface, where it generates metal droplets which are propelled across the air gap.

EXPERIMENTAL SETUP

A visualization setup was built to observe the LIFT transfer process of the copper the droplets. The donor substrates consisted of standard glass microscope slides which were cleaned using scrubbing with soap (Teepol), ultrasonic cleaning and cascade baths. Thin layers of copper ranging from 100 nm up to 5 um were sputtered onto the microscope slide. A Coherent AVIA 4500-355 laser, with a 15 ns pulse width at 355 nm wavelength focused into a 16 µm spot ($1/e^2$ spot diameter) was used for the LIFT process. To visualize the ejected copper droplet a visualization flash was used.

Visualizing the small droplets (approximately 3 µm), was done with a high resolution camera in combination with a magnifying objective. The resulting field of view of the imaging system was 330 µm in the vertical direction. Because of the high droplet speed (estimated at 40-100 m/s depending on laser fluence) and the small field of view of the camera, the visualization flash needed to be both short and accurately timed (typically in the orders of a few nanoseconds). Therefore a pulsed laser (pulse width of 500 ps, 532 nm wavelength) was used as visualization flash. The accurate timing of the visualization laser pulse with respect to the process laser pulse was handled by a programmable delay unit as shown in Figure 2. The resulting jitter of the total system was less than 5ns.

While a laser light source brings many benefits in terms of pulse length, in the case of imaging it caused unwanted diffraction patterns in the recorded image, making accurate droplet visualization difficult. As the diffraction patterns arise from the coherent nature of the laser light, using an organic fluorescent dye to convert the laser light into a non-coherent light source effectively solved the issue. We note that the fluorescent dye causes a redshift in wavelength of the light as well as slightly increasing the pulse duration (<5 ns) due to the fluorescence lifetime of the dye. The flash pulse was still sufficiently short to get 3 µm diameter droplets travelling at speeds of <100 m/s properly imaged. Shadowgraphic measurements of the LIFT process could be performed to determine the shape of the transfers. In addition the velocity of the transfers was measured using a double pulse with a 100 ns delay between the pulses. The double pulse was generated by splitting the initial laser pulse into two fibers, one connected to a fiber optic delay line and then joining the two fibers again. This resulted in a delayed double pulse with a well-defined time interval.

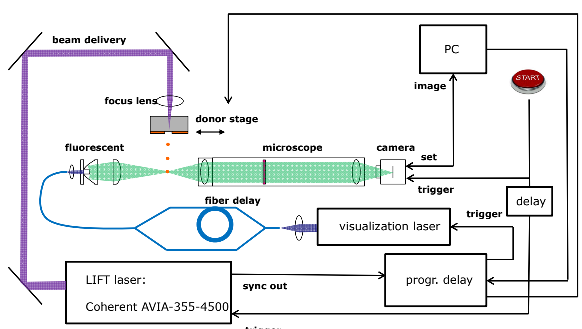

Figure 2: Schematic representation of LIFT visualization set-up. The system comprises of a laser (AVIA-355) with its beam directed and focused on the back of the donor layer. A second visualization laser is directed to the system and is used for providing a short light pulse during the LIFT process for visualization. The light provided by the visualization laser is passed through a fluorescent medium to remove the coherence and then focused onto the droplet. The image is recorded using a standard high resolution camera. The timing of the system is controlled through a trigger. The trigger is used to start the camera recording the image. The signal is then passed with a short delay to the LIFT laser to start a transfer. Using an accurate programmable delay to trigger the visualization laser was initiated at a defined interval after the LIFT process was started. After the LIFT process was performed the donor stage is automatically moved to a new position and a new capture could be performed.

EXPERIMENTAL RESULTS

Previous experiments reported elsewhere [11] indicated that donor layer thicknesses of 600-800 nm of Cu were found to yield uniform deposits with low amounts of debris for this specific laser system and spot size. While excellent results were obtained for relatively small gaps of 25 µm. Typically the copper LIFT process exhibited a strong dependence of the gap spacing on the stability of the droplets. As an example, the LIFT of copper droplets from an 800 nm donor substrate is shown in Figure 3 for 25 µm spacing (a) as well as for 100 µm spacing (b). While consistent clean transfers are observed for gap spacings of around 25 µm, at only 100 µm's the droplets exhibit satellite formation and breakup. To understand the nature of this apparent instability, shadowgraphy was performed to visualize the droplet stability in time and distance from the donor substrate.

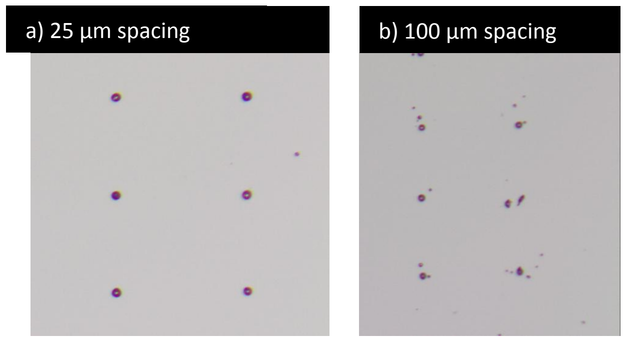

Figure 3: Copper droplet a glass acceptor deposited by LIFT as a function of droplet height for a 800 nm Cu donor layer with typical settings. While clean round droplets are observed for 25 um gap (a) spacing, at a gap of 100 um (b) the droplets either broke up or were surrounded by satellites.

Typical images of the detachment of a copper droplet during the LIFT process are given in Figure 4. The images were recorded at 275, 455, 875 ns after the laser pulse was fired onto the donor substrate. Figure 4a. shows that initially a jet is formed similarly to that commonly observed in other jetting systems such as inkjet printers [13]. During the initial jetting process a droplet at the end of the jet can be discerned. After only 455 ns, while the jet is still present, the droplet detaches from the jet and finally after 875 ns the jet retracts to the donor substrate while the droplet continues its trajectory. The behavior of the copper droplet is similar in nature to the jetting and detachment of a liquid droplet. The round shape and fluid behavior makes it reasonable to conclude that the copper is in a liquid state during the droplet formation and detachment. This is further confirmed by Figure 5, where a higher fluence lead to a larger single jet after 520 ns, which broke up into multiple droplets. Similar jetting and necking processes are a common behavior of liquids. Finally, in Figure 6 the effect of excessive laser energy of the copper donor can be observed. The experiment, was conducted at a significantly higher fluence than required and, resulted in the uncontrolled explosion of the copper droplet due to an excess in thermal energy. While the copper is still transferred, it is deposited as a spray of copper onto the receiving substrate.

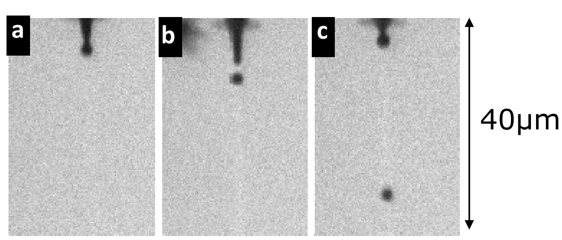

Figure 4: Single droplet regime shown by shadowgraphy of the LIFT process for a 600 nm copper donor a) 275 , b) 455, c) 875 ns after the laser pulse with 2.24 J/cm^2. In image a) a liquid copper droplet connected by a liquid copper tail to the donor can be discerned. b) then droplet is detached from the tail c) finally the tail retracts to the donor substrate and a single droplet is propelled to the acceptor substrate.

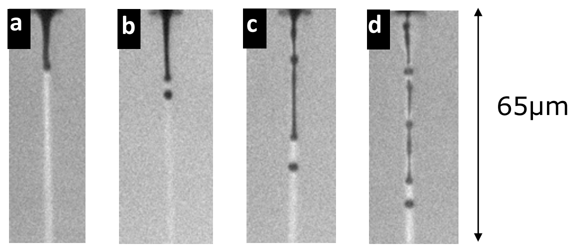

Figure 5: Multiple droplet regime shown by shadowgraphy of the LIFT process for a 800 nm copper donor a) 275, b) 450, c) 520, d) 670 ns after the laser pulse with 3.16 J/cm^2. The images show the LIFT process in the jet break-up regime where multiple droplets are generated during a single shot.

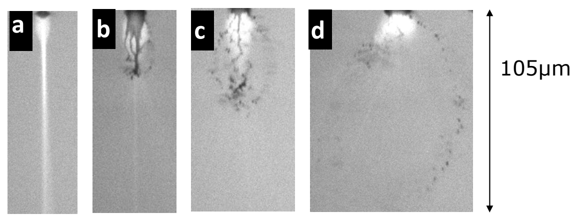

Figure 6: Spray regime shown by shadowgraphy of the LIFT process for a 600 nm copper donor a) 35, b) 250, c) 320, d) 450 ns after the laser pulse with 3.16 J/cm^2. The images show the LIFT process in the spray regime where the droplet violently exploded.

An important parameter for the shape and stability of the droplets is the velocity of the exiting droplets. The velocity of the droplet could accurately be measured using a double exposure of the illumination laser. The results are shown in Figure 7. To account for possible variations, all measurements were carried out multiple times for each laser fluence, providing an average velocity and standard deviation. A drastic increase in droplet velocity from around 20 m/s increasing the laser fluence to 80 m/s could be inferred. As well, an optimum window with high reproducibility of the droplet velocity was present for low fluences at around 1.47 J/cm^2. This indicates that at a stable process window could be found at relatively low fluences. Further lowering the fluence, too close to the droplet formation threshold resulted in a decrease in stability of the process.

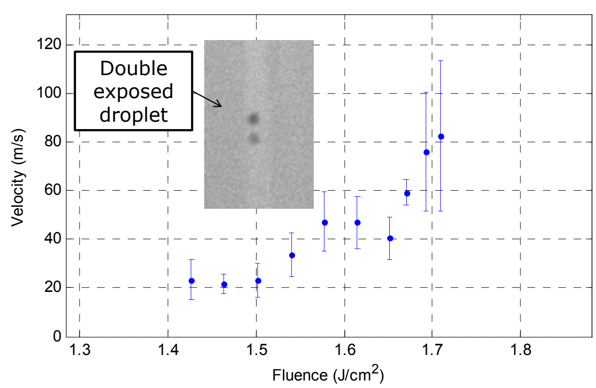

Figure 7: Droplet velocity, measured as a function of laser fluence for a 600 nm Cu donor layer. The velocity was defined using a double pulse with a 100 ns interval.

With the jetting regime strongly depending on the laser fluence, the process stability for generating stable single droplets was investigated. While an excess of laser fluence resulted in a continuous molten metal jet break-up into multiple droplets, (Figure 5), and in a fragmented deposition at larger gaps (Figure 3). Stable single droplet (Figure 4) that will not break up even for donor acceptor gaps of 100 um's , enabling a larger distance between donor and acceptor substrate are possible. The stability of the jetting process was investigated by performing a large number of transfers. The average amount of droplets ejected per LIFT laser pulse as a function of laser fluence was extracted using image processing software. Figure 8 shows the average number of ejected droplets and the standard deviation as a function of laser fluence. An increasing number of ejected droplets with increasing fluence was observed. At higher and at lower fluences, the amount of ejected droplets became increasingly unreproducible. At lower fluence values the energy was sometimes not high enough to liberate a droplet, which makes the process sensitive to laser power and donor thickness fluctuations. At higher fluences, the material was ejected as a long jet of molten material. The jet however necks and breaks up, forming series separate droplets of various sizes (Figure 5). The process of jet breakup is dependent on the surface tension of the liquid copper melt and the length of the jet, and the jet's velocity. Since at higher fluences, a large variation in velocity is observed (see Figure **7**), the length of the jet exhibited a large variation. This can in part clarify the large variation on the number of droplets in that region. An optimum fluence, resulting in reliable single droplets with a small variation at a laser fluence of 1.77J/cm^2 could be defined.

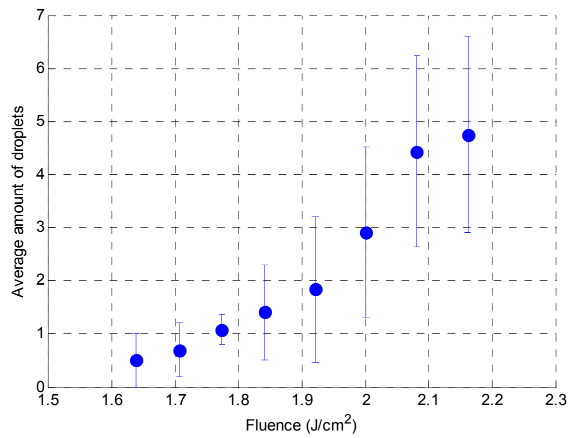

Figure 8: Average number of droplets ejected per LIFT laser pulse as a function of laser fluence for a 600nm Cu donor layer. A steady increase in number of droplets from approx. 1 drop for 1.7 J/cm^2 to approx. 5 drops for 2.2 J/cm^2

For printing type of processes where a large gap between the droplet origin and the substrate surface is favorable, the reproducibility of the angle of deflection of the droplets is a critical parameter. Potential variation in droplet exiting direction will directly influence the pointing accuracy of the patterning process especially at larger distances of the donor film from the substrate. The average angle of deflection for each pulse energy was extracted by analyzing the images with an image processing tool (see Figure 9).

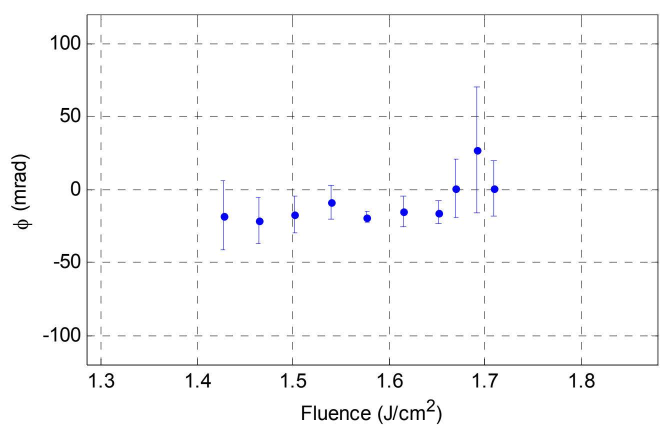

Figure 9: Angle of deflection of droplets as function of laser fluence for a 600 nm Cu donor layer. Small angular deviations of below 25 mrad were typically obtained for optimal settings in the lower fluence regime. Under high fluences large angular deviations as well as droplet instabilities were observed.

From the images small angular variations of around 25 mrad (approx. 1 deg) were observed. At a laser fluence of 1.58 J/cm^2, an optimum setting was obtained exhibiting the smallest standard deviation for the angle of deflection of the droplets. At lower and higher fluences, the angular deflection of the droplet became increasingly irreproducible. At higher fluences this was caused by the uncontrolled expansion and consequently jetting of the donor material. At lower fluences, the energy was very close to the threshold of droplet generation. Consequently the process became very sensitive to imperfections in the donor layer and laser spot. Potentially around threshold the melting and ablation of the donor layer could be inhomogeneous, causing the larger spread on the angle of deflection of the droplets.

CONCLUSION

In conclusion we demonstrate the existence of different transfer regimes for the LIFT of copper, namely a single droplet, a jetting regime and an spraying regime. In all regimes the copper behaved as a liquid indicative of transfer occurring through melt. While previous results reported on the LIFT process with a relatively small donor acceptor gap were not very sensitive on jetting regime. We demonstrated through shadowgraphy measurements that for larger gaps a single droplet regime is beneficial. In the case of 600 nm thick copper films an optimum fluence could be found combining low angle deviation, with on average only one droplets per pulse, and a low and reproducible velocity. Within this optimum regime a stable process could be defined for printing copper circuitry by LIFT with a relatively large gap.

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