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Towards 3D digital printing of micro-electromechanical systems

Ofer Fogel[1,2], Zvi Kotler[2] and Zeev Zalevsky[1]
[1]*Faculty of Engineering and the Nanotechnology center, Bar-Ilan University, Ramat-Gan 5290002, Israel*
[2]*Additive Manufacturing Lab, Orbotech Ltd. P.O. Box 215, Yavne 81101, Israel*

Abstract

Additive manufacturing offers several advantages over conventional methods of production, such as flexibility in design and reduction of required steps during fabrication, leading to faster production times. One promising method for manufacturing complicated 3D devices is based on laser induced forward transfer (LIFT); LIFT is a printing method which allows solid bulk materials to be printed directly. The backside of the supplier material, which is a transparent substrate coated with a thin layer of material, is heated with a pulsed laser and jets a micro-droplet (6-8 um) of the coated material. The ability to print almost any material and the high accuracy and resolution of the droplet deposition gives LIFT a strong potential to be used in printed functional devices. Moreover, in the field of 3D structures this method can contribute to designing novel structures such as multilateral structures and complicated geometries (e.g. hollow cubes). Such structures are very hard to create using conventional methods and can be used for various implementations such as MEMS and micro-batteries. In this paper, we present initial steps towards additive manufacturing of 3D functional devices, by showing 3D metallic micro-structures printed using the LIFT method. In order to print complex 3D structures (e.g. bridges), a sacrificial layer technique was used. Sacrificial layers were printed for support of the desired design and are later removed using a selective etching process, leaving only the required 3D structure.

Introduction

LIFT is a printing method suitable for additive manufacturing and which allows solid bulk materials to be printed directly. The backside of the supplier material, which is a transparent substrate coated with a thin layer of material, is heated with a pulsed laser and jets a micro-droplet (6-8 um) of the coated material [1,2]. Figure 1 described the LIFT process

The ability to print almost any material and the high accuracy and resolution of the droplet deposition gives LIFT a strong potential to be used in printed functional devices. Fundamental studies have been carried out to understand the LIFT mechanism such as investigations of printing accuracy, droplet deformation, droplet velocity, effects of the printing conditions and contaminations of given structures [3].

More recently, there has been a shift in LIFT-based research from the mechanism of the process to functional oriented studies of LIFT [4]. Several studies were performed and demonstrated the ability of printing high aspect ratio pillars and other mechanically complicated structures. In addental, a thermocouple based on such pillars was presented as the first LIFT printed functional device [5]. The ability of printing 3D structures via LIFT were demonstrated and experimentally validated [6].

In this study, we will provide an overview of the LIFT mechanism and the optical/mechanical setup used for LIFT; The printing algorithm which supports the printing process will be presented.

A particular focus is made on the printing process and the sacrificial layer technique which allows printing complex 3D structures; by digital deposition of both the structural and the support (sacrificial) metals. By controlling the laser-based printing parameters both metals can be printed with the same setup arrangement. The final free-standing structure is released by selective chemical wet etching of the support material. In addition, demonstrator of 3D complex structures (e.g. bridges and cantilever beams) will be presented and a printed thermal actuator will be demonstrated as the first micro-electromechanical system being printed by LIFT (see Fig. 1).

Setup and methods

In this study, we used a standard LIFT setup. Fig. 1 shows the LIFT setup used for printing metallic test structures. A laser with a pulse duration of 0.8 ns and a wavelength of 532 nm (Picospark, Teem Photonics) is used for the LIFT process with a fixed spot of 28 ± 0.5 µm (4-sigma) at the donor interface. To allow patterns to be printed, an acoustic-optical deflector (AOD) and a scanning mirror control the spot position and an F-theta lens focuses the beam onto the donor. As a result, each laser pulse causes the ejection of a single droplet of metal at a specific location. The donor and the acceptor are each positioned on separate xyz translation stages and are held in place by vacuum holders, where the donor holder can simultaneously support two

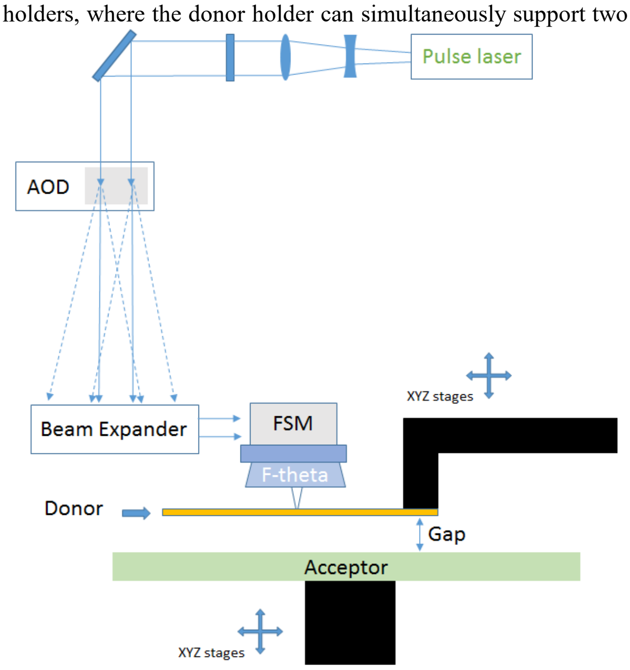

Figure 1. LIFT printing

different donors, allowing for printing of multi-material structures. The donors' materials which used for the printing were made by deposited 500 nm of the metal on slide of glass, this done via PVD or sputter. In short, the 3D structure obtained by printing 2D layers until the desired thickness achieved. Since the distance between two adjacent droplet ejections is larger than the spot size, each layer consists of N droplet matrices when the distance between two adjacent droplet ejections within a single matrix is larger than the heat affected zone of a single jetting spot on the donor. After printing any matrix the donor being moved to a new clean area. In this study, the distance between two adjacent ejections was 35 um and each layer consisted of 64 matrices. In some cases, for high structures it is necessary to move down the acceptor due to the printing process in order to keep the gap between the acceptor and the donor close to its initial value usually 300 um.

Experimental results

In order to demonstrate the potential of LIFT as 3D metallic printing methods we focused on accuracy, 3D complex structures and functional device. One of the main advantages of the LIFT process is the high accuracy of the droplet deposition, to show the accuracy of this method a high aspect ratio single droplet width pillars were printed. These pillars were printed by deposition while more than 1000 droplets were printed one by one.

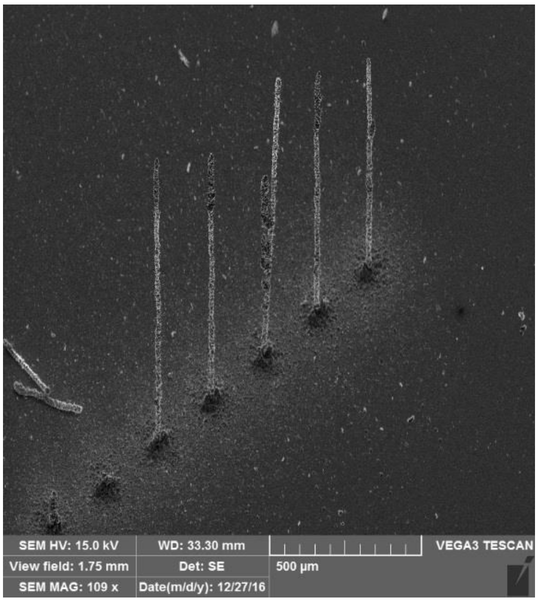

Figure 2. SEM image of high aspect ratio copper pillars. The height of those pillars is more than 1mm and width of ~15 um

The gap between the donor and the printed structure was kept 300 ± 50 um by moving down the acceptor when the gap between the donor and the build up pillar was reduced. Figure 2 shows Cu printed pillars with aspect ratio larger than 75. The width of these pillars was 13 um and they had more than 1mm height.

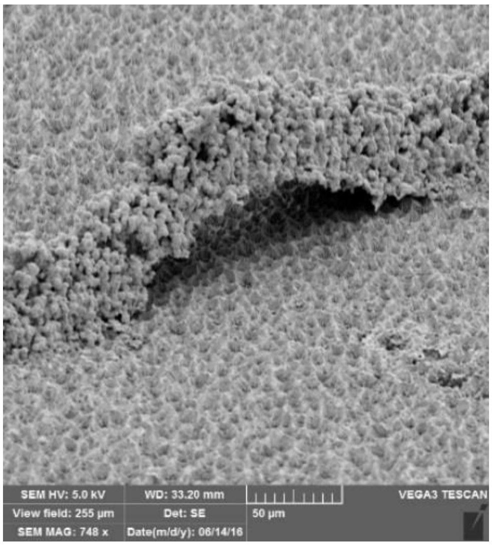

Figure 3. SEM image of printed Au bridge. The space between the bridge and the substrate is 60 um.

Printing 2D structures (or even 2.5D structures) is straightforward and required only an image of the required structure and the appropriate laser parameters. However, in order to print 3D "open" structures and structures that require support layers, need another technique. This can be done by combining printing of a sacrificial metal along with a structural meta. Both metal types are printed using the same laser setup and under similar printing conditions with only changed laser parameters (e.g. pulse energy). After printing, a proper chemical etch process removes selectively the sacrificial material. Figures 3 and 4 present two examples of 3D Au structures printed on standard laminate. In these structures printing process copper was used as a sacrificial layer were both material Au and Cu were printing in the same setup with the same laser parameters except the energy when the pulse energy for Cu was 5.5 uJ and for Au 4.2 uJ.

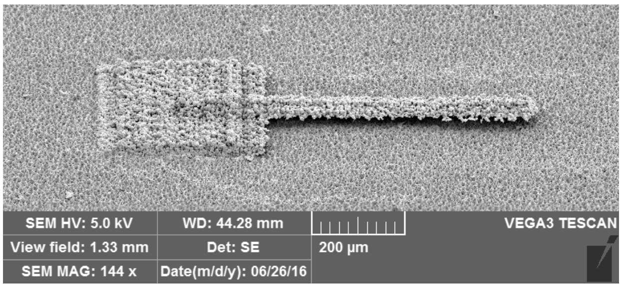

Figure 4. SEM image of cantilever Au beam; beam length ~500 um , width ~50 um .

Figure 5 shows a double bridges structure made of copper, when the space between the bridges was ~10um and the total length of the bridges was more than 450 um. The way build 3D Cu structures was by using aluminium as a sacrificial layer. The pulse energy which required for printing Al was 5 uJ.

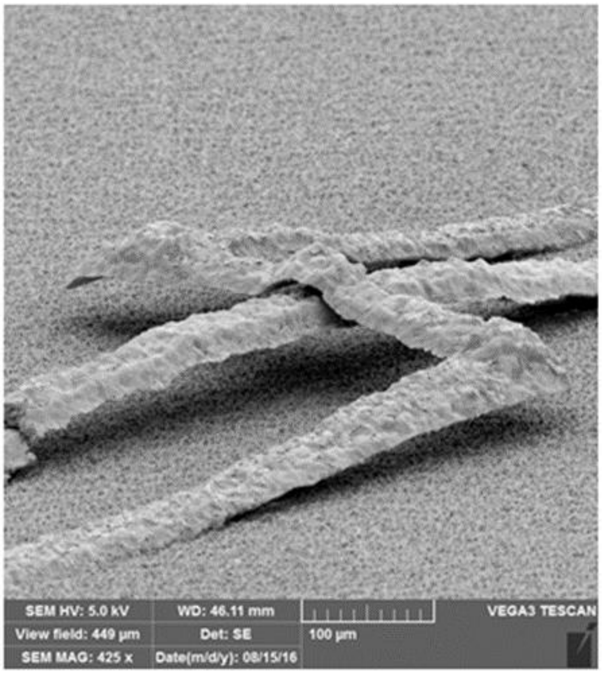

Figure 5. SEM image of Cu double bridges.

The last part is demonstrating the potential of LIFT for printing 3D functional metallic devices. Figures 6 and 7 show a printed v-shape thermal actuator, before the selective etch and after when the released structure is generated and the movement is possible. The thermal actuator was made of gold and a printed copper was used as a sacrificial layer. The space between the actuator and the substrate is ~100um and the total length is more than 3 mm. The thermal actuator characterization showed a good fit to the theory when the thermal conductivity was 8 times lower than bulk.

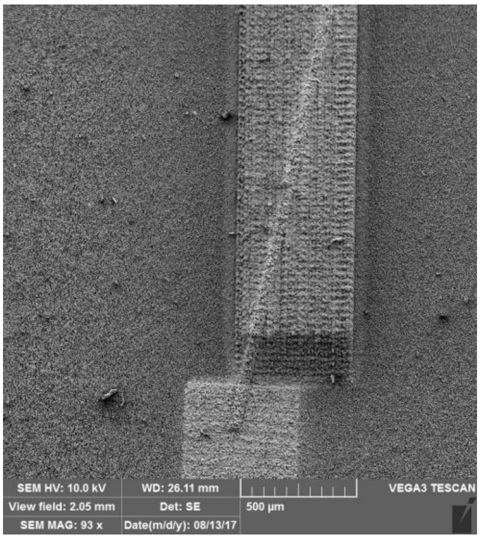

Figure 6. SEM image of high aspect ratio copper pillars. The height of this pillars is more than 1mm and the width is of ~15 um

Conclusions

In summary, we have demonstrated the potential of using LIFT to print 3D metallic micro-structures with focus on

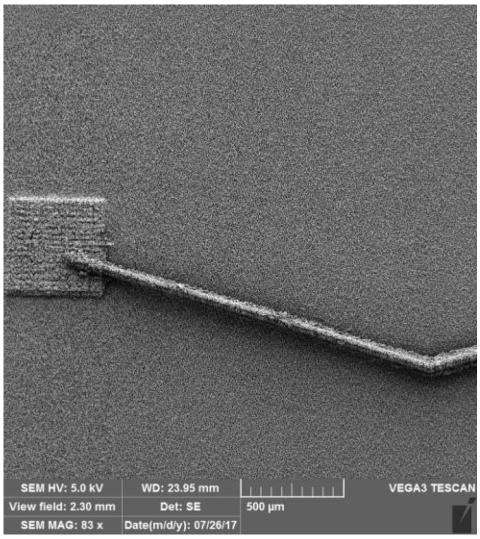

Figure 7. SEM image of high aspect ratio copper pillars. The height of this pillars is more than 1mm and the width is of ~15 um

functional devices. The methods used to support the layers was presented for Au and Cu structures. However, the electrical, thermal and mechanical properties of the LIFT printed metal were not mentioned in this review. Several studies showed that the values of the electrical and thermal properties are 4 – 10 times lower compared to bulk. Electrical properties can be controlled in some cases by modifying the parameters of the printing process. Recent work has shown that the properties of the printed structures are influenced by several parameters such as porosity (which is less than 10%), grain size and droplet boundaries. These effects appear due to the fast cooling of the tiny ejected metallic droplet.

As there is already quite a large variety of metals which can be LIFT printed, the approach described here may enable the digital additive manufacturing of new functional micro devices. It can offer a new and simple way to fabricate a multi-metal functional devices.

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