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Direct fabrication of electrically functional microstructures by fully voltage-controlled electrohydrodynamic jet printing of silver nano-ink

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Abstract We report electrohydrodynamic jet (E-jet) printing of a commercialised silver nano-ink in fully voltage-controlled fashion. Metallic pads and conducting tracks with hundred-micron feature size were drop-on-demands produced on Si substrates. Layer-by-layer printing was further performed, demonstrating a capability in creating 3D multi-structures. Planar pattern with a large inductance of 2.5 μH and an excellent resistivity of 4.2×10^{-8} Ω m was fabricated, showing a true inductive device. Our result demonstrates a feasibility of E-jet printing in the application of smart electronic devices fabrication.

1 Introduction

Recently, jet-based printing technology has been used in direct deposition as a rapid prototyping of microstructures or patterns [1, 2]. This solid freeform fabrication (SFF) approach is rapidly developed as a low cost mask-free technology to create and form metallic conducting tracks or ceramic materials on a range of substrates [3–6]. Among them, jet-printing based on electrohydrodynamic atomisation (EHDA) has recently received special attention for its wide applications in electronics, biomedical and nanoscience [2, 7, 8]. In EHDA free charges on the liquid surface are induced by the electrical field and rich set of associated phenomena including jets formation, Coulomb fission and ion-field evaporation etc. can occur, which makes it essentially different from other jet-based printing technologies [9].

In the electrohydrodynamic printing, an electrified jet emanates from the tip of the nozzle once the electrical field overcomes the surface tension of the liquid and fluid flow occurs [10]. Accordingly, tiny materials (typically ∼pL volume) can be locally delivered and freeformed on the desired position in drop-on-demands (DOD) fashion. In contrast with a commercialised ink-jet printing, solutions with a wide range of viscosity are allowed in the E-jet printing [11]. Also, it can be operated simply in a full voltage-controlled form, i.e. without an auxiliary assistance of pump or gas pressure [12, 13]. This unforced configuration makes the printing system very compact, where both flow rate and electrical field strength are uniquely controlled by the applied voltage. Compared with the pressure-assisted counterpart, pronounced different characteristic in this unforced EHDA was observed experimentally [12, 13]. Although the physical mechanism has not been fully understood yet, an analysis method based upon equivalent circuit is recently developed by the QMUL electrospray group [14]. It can well capture I–V behaviour exclusively observed in fully voltage-controlled atomisation. This method provides useful information and technical apprehension in the designing and evaluation of this compact E-printing technology. By this E-jetting technology performed with a reduced printing distance, micro-tracks with a feature size down to 35 μm with excellent conductivity were achieved on Si substrate [15].

In this letter, we report on a further application of a compact E-jetting rig to print electrically functional microstructures on Si substrates. Besides basic structures of pads and tracks, planar electronic devices were successfully fabricated. These show a strong capability of the pulsed-voltage controlled E-jet printing approach in flexible low-cost applications for the electronic manufacturing industry.

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2 Experimental details

Figure 1 is a schematic diagram of a fully voltage-controlled E-jet printing rig, which was set in point-plane geometry as described in our previous work [15–17]. The power supply was a 2 kV high-voltage source (F.u.G. Electronik). A negative pulsed voltage was applied to an aluminum plate electrode via a fast voltage switch (PVX4130, DEI). A 4-µm nozzle (PicoTip), which was perpendicular to the Al planar plate, was used as grounding. A Si substrate for the deposition was placed on top of the Al electrode, which was fixed to a movable computer-controlled translation stage. The printing distance between the nozzle and the substrate can be flexibly adjusted. Additionally, a high-resolution CCD video microscope (UI-2230-C, UEye) was used to monitor the jetting under an illumination of a cold-light source.

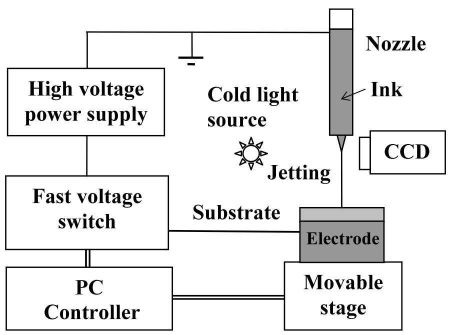

Fig. 1 Schematic configuration of an E-jet printing system in a fully pulsed voltage-controlled form

For the deposition a commercial metallo-organic, silver ink (TEC-IJ-020, InkTec Elec.) was used, which was filled into the nozzle by a fine pipette. The surface tension and viscosity of the ink were specified to be in the range of 0.03–0.032 N/m and 9–15 mPa s, respectively. The density of the silver ink is 1.07 g/cm^3 at room temperature. After the deposition, the samples were subsequently cured at 250°C for 10 minutes to complete thermal decomposition. The morphology and chemical composition of the relics were investigated by a scanning electron microscope (SEM, Inspect F, FEI) and an energy-dispersive X-ray spectrometer (EDX, INCA x-act, Oxford), respectively. The topography of the relics was measured by an atomic force microscope (AFM, NT-MDT, NTEGRA). The electrical properties were characterised by a home-made two-point probe measurement and an RLC meter (B131, MEGGER).

3 Results and discussion

Figure 2a shows an array of silver pads created by e-jet printing at pulsed voltages ranged from 500 to 800 V with a fixed 200-ms duration. After curing at 250°C, metallic silver was fully developed in the patterns, which was confirmed by EDX analysis [17]. In each column two depositions were repeatedly performed at the same voltage with a 200-µm separation. With 125-µm printing distance and voltages applied from 500–800 V, the diameters of the pads were created in the range of 120–185 µm. It shows an obvious increase in size of relics with the applied voltage. Figure 2b

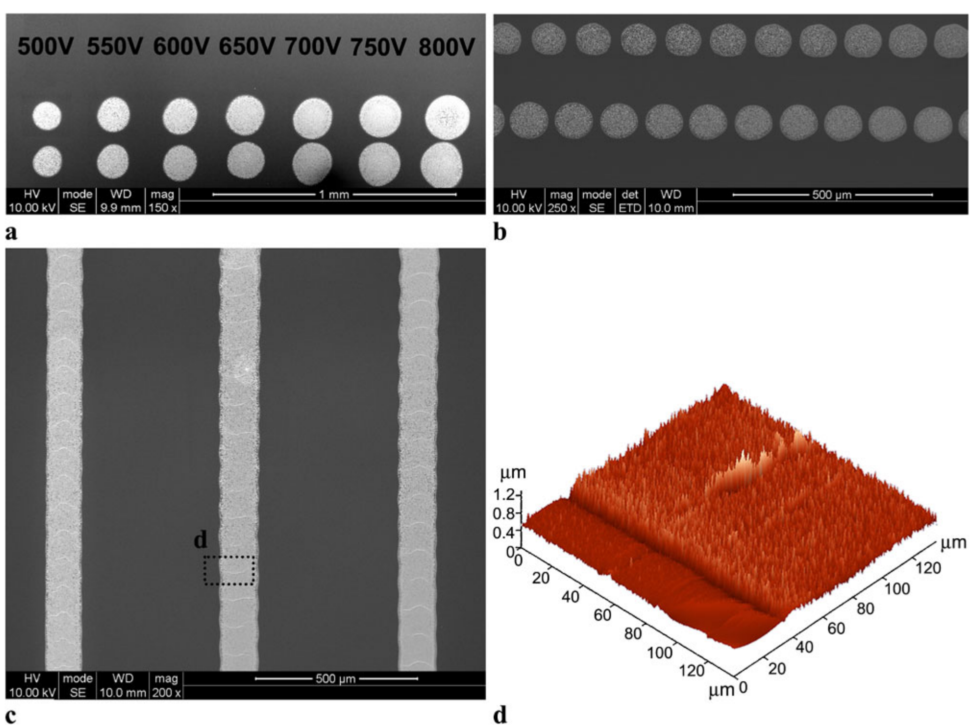

Fig. 2 (**a**) and (**b**) silver pads created on Si substrate by different voltage pulses, (**c**) SEM of continuous silver tracks formed by overlapping discrete drops and (**d**) an AFM image of 3D topology

shows two rows of silver pads created by a fixed voltage pulse of 550 V and 50-ms duration. 88-µm sized pads were produced with a printing distance of 95 µm. The volume ejected during a pulse can be roughly estimated using the volume of the deposited silver materials by assuming an idea cylinder shape of the pad [15]. The volume of silver materials remains on the substrate per drop is derived to be $V_{Ag} = 0.91 \times 10^{-15}$ m^3 by using a pad diameter of 88 µm and a thickness of 150 nm, which determined from AFM. Considering the density of the ink and the silver and the 20% weight contents of silver in the ink, the total volume of the ink ejected by one pulse is estimated to be 4.46×10^{-14} m^3 (i.e. 44.6 pL).

Continuous silver tracks, shown in Fig. 2c, were formed during the printing on continuously moving substrate [15]. Pulsed voltage of 550 V with duration of 100 ms at a frequency of 1 Hz was applied. Single drop size of 110 µm in diameter was created with 125-µm printing distance. The moving speed of the substrate was set at ~80 µm/s, and uniformed tracks were formed from discrete drops. Figure 2d shows an AFM image of a 3D topographic part of the track. Bump in the center was observed, which is arising from the overlapping of the drops. Apart from that, a feature of the ridge at the track edge was noticeable due to Marangoni convection [18], which was commonly observed in the dried printing patterns [17]. The mean thickness of the track was determined to be ~200 nm.

In order to investigate a capability in creating 3D structures, multilayered printing was attempted by direct placing the deposition on top of each other. Figure 3a shows a pattern of 5 strips created on Si substrate. Each stripe was formed by 5 overlapping drops of 88-µm size, which was individually created by fixed voltage pulse of 560 V and 50-ms duration. A printing distance of 95 µm was set. Figure 3b shows three-layered printing of the same structure, and the deposition was repeatedly produced on the top of the previous patterns. Only slight increase in the line width was noticeable, implying the material mainly accumulated vertically rather than spreading laterally. Compared with the porous structures created by single-layered printing, dense close-packed morphology was obtained after three-layered printing, shown in the insets at 10k× magnification. It indicates that not only 3D structures can be achieved, but surface quality of the patterns can be greatly improved by the layer-by-layer printing.

In Fig. 4a a simple planar pattern was printed by using program-controlled 2D movement with a 95-µm printing distance. The applied voltage was 550 V with 200-ms dura-

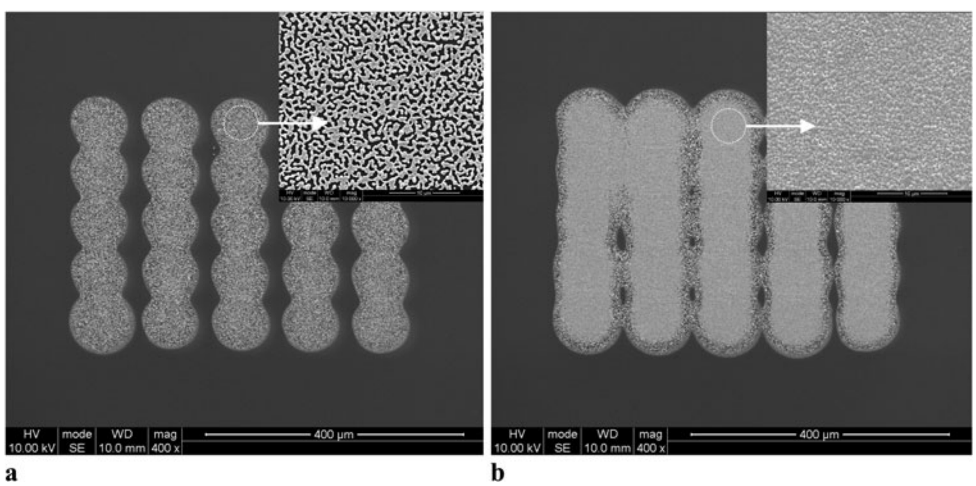

Fig. 3 SEM image of (**a**) a pattern consisting of five stripes created by single-layered printing and (**b**) created by three-layered printing. *Insets* show microstructures at a high magnification of 10k×

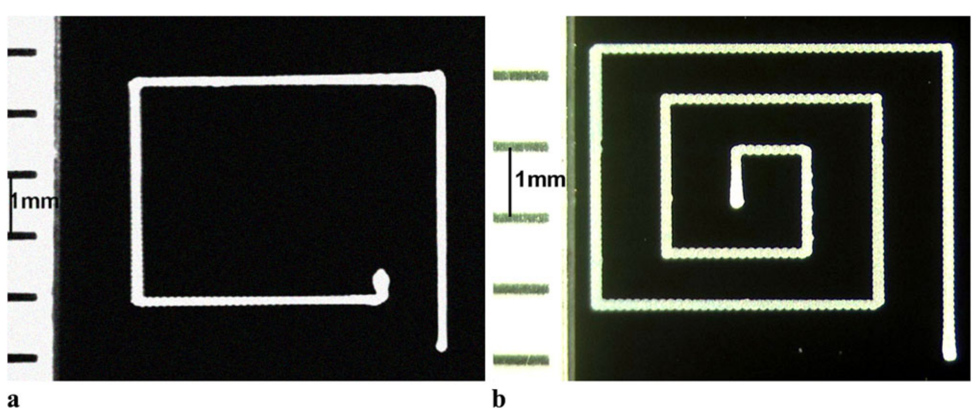

Fig. 4 Optical micrograph of (**a**) rectangular pattern and (**b**) spiral-liked pattern created on Si substrates

tion. The moving speed of the substrate was set at ∼75 µm/s. This pattern has a total length of 17.5 mm and an area of ∼18 mm^2. An electrical resistance value of 30.6 Ω was measured. The linewidth and the average thickness of the tracks were determined to be around $w = 150$ µm and $t = 150$ nm, respectively, by SEM and AFM. From this derived cross-sectional area for the tracks the electrical resistivity is obtained approximately to be 3.9×10^{-8} Ω m. This value corresponds to 2.5 times of the theoretical value of bulk silver (1.6×10^{-8} Ω m), showing a good conductivity. Meanwhile, an inductance of 1.7 µH at 1 kHz was measured for this one-turn structure, showing an inductive device.

Figure 4b shows a rectangular spiral-liked structure, which was created to increase the inductance. It possesses $2\frac{3}{4}$ turns, total length of 27.2 mm and line space of 0.75 mm. A large inductance of 2.5 µH at 1 kHz was determined, which confirms it is a real inductor. An electrical resistance value of 50.5 Ω was measured for this printed track. An electrical resistivity of 4.2×10^{-8} Ω m was calculated, corresponding to 2.6 times of the theoretical value of bulk silver.

4 Conclusions

In summary, deposition of a silver nano-ink was demonstrated by pulsed E-jetting in unforced form. Basic metallic structures like pads and micro-tracks were created drop-on-demands on Si substrates. Planar device with a sufficient inductance and an excellent conductivity was fabricated. A capability to create 3D structures was also demonstrated. Our results show a feasibility of E-jet printing technology in the application of smart electronic devices fabrication.

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