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Digital Printing of the Thin Film Sensor with Sharp Edge Based on Electrodynamics 3DP

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Abstract: We present a digital voltage printing regime for high-speed and high-precision Micro-jet printing. The voltage pulse peak induces a very fast Micro-jetting mode from the nozzle for a short duration, while a low voltage is picked to ensure the sharp edge, and the high voltage is picked to ensure the printing speed. The conducting films were assembled on electrode arrays of substrate and characterized with respect to their layer thickness and thermal properties. Through an optimal choice of the digital frequency dynamically, a jet-printing regime with a specified droplet size and droplet spacing can be created in different steps. High spatial resolution can also be achieved by properly coordinating the pulsing with large and small current. The edge burr problem was solved by using the dynamic control of the droplets sizes and jetting rapid through the pulse signal. The sensor was printed using heterogeneous material model. Sensor recovery time, response linearity and sensitivity were all significantly improved using the digital pulse regime fabrication.

Keywords: 3DP (Three Dimension Printing), Micro-jet, Digital Manufacturing, Printed Sensor.

1. INTRODUCTION

Micro-jet at the nano and micro-scales has became a research hotspot because the potential manufacturing ability of the 3DP. Micro-jet print can generate very small scale droplets, superior resolution, printing of micro and submicron scale droplets using a wide variety of inks. However, the speed of the process and the edge burr has been seen as the important questions to be solved.

Micro-jet printing has shown many good performances in applications such as printing metallic (Ag) interconnects for printed electronics, bio-sensors, etc. The ability of precisely control of sizes should be developed and the edge burr problem should be solved to fabricate the MEMS device. Then the digital model of heterogeneous materials should be constructed for device. Therefore, to fully realize the capability of the Micro-jet printing, this work researches on how to modulate input voltage to enhance droplet deposition performance, obtain accurate spatial placement of droplets and sharp edge.

Micro-jet 3DP uses electric-field induced fluid flows through capillary nozzles to create devices in the micro- and nano-scale range [1]. The electric fields are created by establishing a constant voltage difference between the nozzle carrying the ink (the print head) and the print substrate. The electric field attracts metal parcels in the fluid toward the substrate, deforming the meniscus to a conical shape and eventually leading to instability which results in droplet release from the apex of the cone [1, 6]. Electro hydrodynamic discharge from the nozzle causes a pulsed current. Some people researched that this pulsing persists in the spray regime reporting both low frequency 15 Hz and high-frequency 1 kHz pulsations in a electro hydrodynamic spray [7]. Scaling laws have developed for characterizing micro-jet [6, 5]. Pulsing of ac has been demonstrated for Micro-jet by Nyugen [8]. Modulation of ac showed advantages over dc voltage in terms of fabrication of nozzles, droplet repulsion and drop-on-demand capabilities based on the frequency of sinusoidal voltage applied. Kim [9] used a digital dc for micro-jet printing and used the value of the voltage to control the droplet size. A single-event pulsed droplet generation for micro-jet was demonstrated in reference [10], as well as a study of relaxation times for drop-on-demand electro spraying [11].

To the best of our knowledge, no systematically controlled high-speed printing regimes have been developed for delivering precise droplet volumes with high fidelity spatial and sharp edge performance. This paper presents a manufacturing oriented approach to dynamic input voltage Micro-jet printing including (1) sharp edge printing, (2) heterogeneous material printing.

In this paper, we present a Micro-jet printing mode capable of heterogeneous material. Specifically, this mode demonstrates capability for printing three different materials, while producing consistent and controllable droplet sizes of 1–3 μm. This mode uses a dc voltage signal to generate electro hydrodynamic flow from the nozzle. The pulse peak is chosen so as to induce a sharp edge. Micro-jetting mode from the nozzle, while the baseline voltage is picked to ensure that a near conical shaped meniscus is always present,

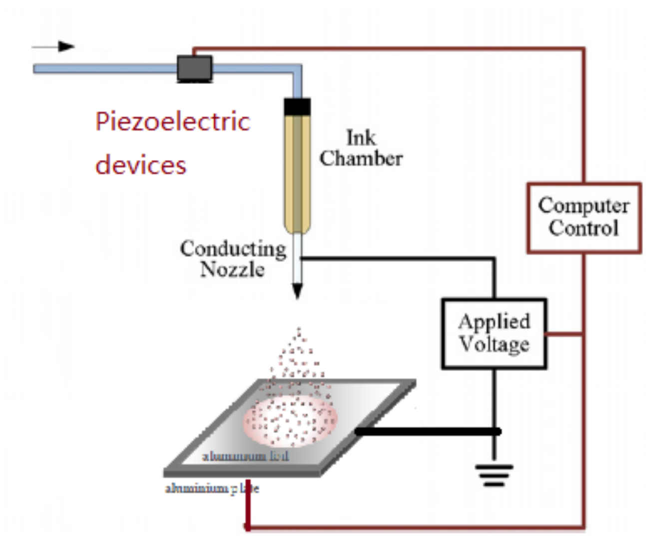


Fig. (1). Micro-jet Printing Set-up.

but not discharging any fluid. The duration of the pulse determines the volume of the droplet and therefore the edge of the component on the substrate. On the other hand, the droplet deposition rate is controlled by varying the time duty ratio between two successive pulses.

Through suitable choice of the duty ratio and frequency dynamically, a jet-printing regime with specified feature size and deposition rate can be created.

2. ELECTOHYDRODYNAMIC JET 3DP

Fig. (**1**) presents a schematic of the Micro-jet printing process. As can be seen from Fig. (**1**), the main elements for Micro-jet printing include a syringe, stainless steel capillary, aluminum substrate and positioning system. The controllable printing process parameters are the back pressure is piezoelectricity that applied to the ink chamber, the offset height between the nozzle and substrate and the applied voltage potential between a conducting nozzle tip and substrate. Note that the nozzle tip and substrate are generally coated with metal to ensure conductivity. Pet solutions were extruded through the nozzle at a constant rate of either 0.2 or 0.5 mL/h using a syringe pump (WPI, USA). The tip-to-collector (TTC) distance was set to 15, 20 or 25 cm respectively. High-voltage was applied between the needle and collector ranging from 10 to 18 kV.

A voltage applied to the nozzle tip causes mobile ions in the ink to accumulate near the surface at the tip of the nozzle. The mutual Coulomb repulsion between the ions introduces a tangential stress on the liquid surface, thereby deforming the meniscus into a conical shape [1]. The change in the ink meniscus due to an increase in voltage is based on the fluid properties; the applied field can control the discharge as a pulsed or intermittent jet. Piezoelectricity is transitioning into a stable single jet, multiple unstable jets and finally becoming a spray for very large electric field strengths. Pulsating jetting modes can be used to achieve various printing/spraying applications. Pulsating modes are used here for printing because of better controllability at dynamic control the edge to form the sharp edge. Changes in back pressure, stand-off height and applied voltage affect the size and frequency of the droplets. The voltage pulse of the process output to variations under the printing conditions requires high-resolution movement and control in order to achieve predictable printing droplets.

3. THE CONTROL MODEL OF VOLTAGE FOR MICRO-JET PRINTING

The jet frequency and droplet diameter could be controlled by changing the applied voltage difference between the nozzle and the substrate. Scaling laws from Choi [5] capture this dependence with the following equations:

$$f = \frac{E^2}{d_N},\ d = \frac{\sqrt{E}}{d_N},\ D = dF(\theta) \quad (1)$$

where d_N is the anchoring radius of the meniscus, d is the droplet diameter of the ejected droplet, E is the electric field because of the applied potential and θ is the contact angle at the surface; $F(\theta)$ is a function of the contact angle θ. First, for a given nozzle diameter, printing ink and stand-off height (distance of the nozzle tip from the substrate), the droplet diameter on the surface (D) and jetting frequency are coupled, which is disadvantage from the process development point view. A desired droplet diameter can be got by setting voltage level, or a printing speed (droplets/sec) can be set. The problem associated with printing by setting a constant voltage different between the tip and substrate accrues from the fact that minute changes in the stand-off height can cause significant changes in the jetting frequency and droplet

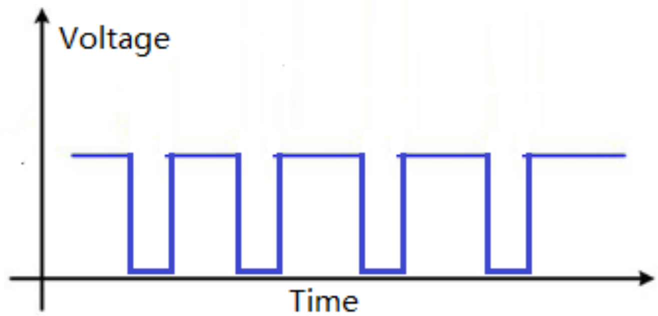


Fig. (2). Signal Pulse For Droplets Control.

diameters. The dynamic control method is used to get sharp edge. The fast jetting frequencies of several kHz can be achieved using a sufficiently high potential difference. However, at the resulting strong electric field, the system becomes more sensitive to ariations under operating conditions such as space height, meniscus wetting properties, etc and the jetting frequency may vary substantially during printing, leading to inconsistent droplet spacing. Therefore, constant high-voltage E-jetting is unsuitable for printing large droplet arrays with regular droplet diameters and consistent droplet spacing. Low-voltage Micro-jetting used to fabricate the middle component and high-voltage Micro-jetting used to fabricate the edge component.

We propose a long-time low-voltage pulse superimposed over a baseline constant voltage. The short low-voltage pulse releases a droplet (or a finite number of droplets) from the nozzle, while the lower constant voltage holds the charge in the meniscus. In different edge it can have different low voltages. Viscosity of the ink affects the edge, but sharp edge can get with the control of different voltage pulse. Fig. (**2**) shows the time plot of a typical pulse. The digital pulse controls the number of droplets released. These droplets form a larger droplet on the substrate surface. Hence the volume of fluid deposited on the substrate is controlled by the number of droplets released per high-voltage pulse and consequently, the duration of this pulse. It is related with the viscosity of the ink. The time between two pulses determines is changed dynamically to get sharp edge.

3.1. Low Spacing T_d of Pulse

The low spacing Td is determined the droplet spacing onto the substrate. This is because the distance between droplets can be changed by adjusting the time between successive pulses and the speed of movement (w_{st}) of the substrate with respect to the nozzle tip. The droplet spacing is given by

$$s_d = \omega_{st} T_d \tag{2}$$

The produce of electro sprayed particles is widely accepted to be controlled by two main mechanisms: solvent evaporation from droplets *en route* from the tip to the collector, and contemporaneous polymer diffusion during evaporation. Rapid polymer diffusion does not necessarily lead to spherical particles but will ensure solid, dense particles. Both these mechanisms are dictated by the characteristics of the electro sprayed polymer solution itself, dependent on molecular weight and polymer solution.

3.2. Duty Ration T_p

Given a microspheres or flattened particles droplet of *D* on the surface of the substrate, we have (for $f_h T_p > 1$) where V_h is the volume of a single droplet released from the nozzle and T_p is the pulse width. Given a specific V_h (pulse peak), f_h and V_h are constant. Therefore we can control the edge of the deposited droplets by changing the pulse width T_p. For a narrow pulse width, there may be no droplet released from the tip because of the time delay in formation of the micro spheres or flattened particles and ejection of the droplet. This minimum possible *Tp* is dependent on the choice of Vh. Fig. (**3**) shows a plot of this relationship for a photo curable polyurethane polymer. Therefore we can fix the desired droplet diameter and spacing *independently* by adjusting T_p and T_d.

4. DIGITAL FABRICATION FOR HETERO- GENEOUS MATERIALS

To fabricate a prototype, it must first be represented in a CAD platform. If the concentration of each primary color binder is diluted in different degrees, when a color prototype is fabricated, a non-homogeneous or functionally graded one can be obtained. In general, a wider spectrum of binder concentration of a pixel can be achieved by printing two binders with different concentrations in the appropriate proportion. To apply this concept for fabricating an FGM prototype, the proportion of the primary binders printed on different pixels of the object must be modeled so that varying binder concentration information can be obtained.

In the case of 3DP, only four primary binders are available (i.e, n= 4) and a tetrahedral binder concentration simplex is shown in Fig. (**10a**). The colors of these primary binders are blue (B), red (R), yellow (Y), and clear (W) and their proportion vectors in the binder concentration simplex are denoted as $\mathbf{p}_1$,$\mathbf{p}_2$, $\mathbf{p}_3$, and $\mathbf{p}_4$ (corresponding to, $\mathbf{p}_C$, $\mathbf{p}_M$, $\mathbf{p}_Y$,and $\mathbf{p}_W$) respectively.

The corresponding sub-hyper-volume corresponding to pm can be calculated as:

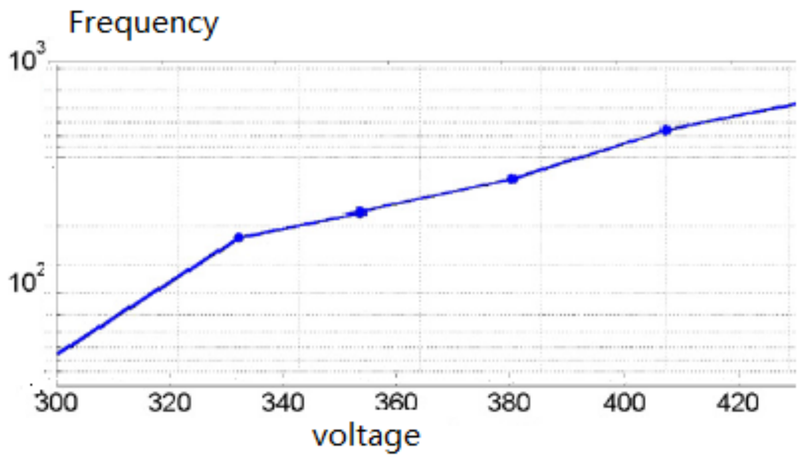


Fig. (3). Relationship of Field Voltage and Droplets Jetting Frequency.

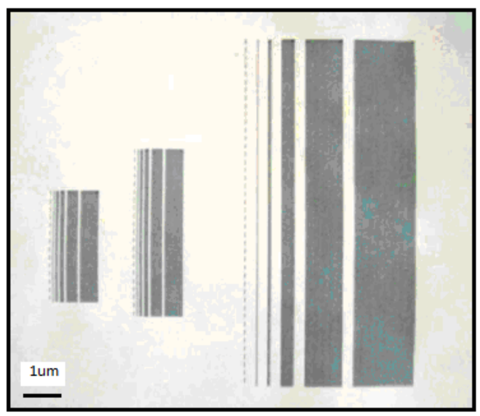


Fig. (4). Sharp Edges with Dynamic Control.

$$M_{m1} = \begin{pmatrix} p_m \\ p_2 \\ p_3 \end{pmatrix}, M_{m2} = \begin{pmatrix} p_m \\ p_1 \\ p_3 \end{pmatrix}, M_{m3} = \begin{pmatrix} p_m \\ p_1 \\ p_2 \end{pmatrix} \quad (3)$$

In general, the individual component (p_{mk}) of any point p_m is equal to the corresponding α_{mk} if the vertices of the binder concentration simplex (p_i) are unit vectors and mutually orthogonal to each other, i.e.

$p_i = [\ p_{i1} \quad p_{i2} \quad \dots \quad p_{im-1} \quad p_{im} \ ]$, and

$$p_{ij} = \begin{cases} 0 & if\ i \neq j \\ 1 & if\ i = j \end{cases} \quad (4)$$

Three-dimensional printing is one of the DDM technologies that can be used for fabricating prototypes directly from CAD models in a layer-by-layer manner [3]. There was a large variety of 3DP processes introduced in the past decade. In 3DP, successive layers of prototype are printed until the whole prototype is fabricated. Post-treatment of the prototype (such as infiltrating the part with other materials for strengthening or producing the part with the specified infiltrated material) will also be performed. There are numerous applications of 3DP, including model verification, functional testing, form and fit checking, etc.

The input parameters specifically the pulse modulation parameters Vh, Vl, Tp and Td are choused based on output requirements of the printing process, such as droplet spacing and droplet (feature) size.

5. SHARP EDGE PRINTING RESULTS

The pulsed Micro-jet printing can significantly enhance edge performance through changing the voltage of the working space dynamically. Typically in constant jet mode printing applications, jetting frequencies are around 1–3 droplets per second. A thin film was used as a basis for comparison of printing speeds for constant voltage and pulsed voltage Micro-jet printing. The constant voltage printing was executed at 2 droplets per second jetting frequency, using pulsed jetting at 60 droplets per second.

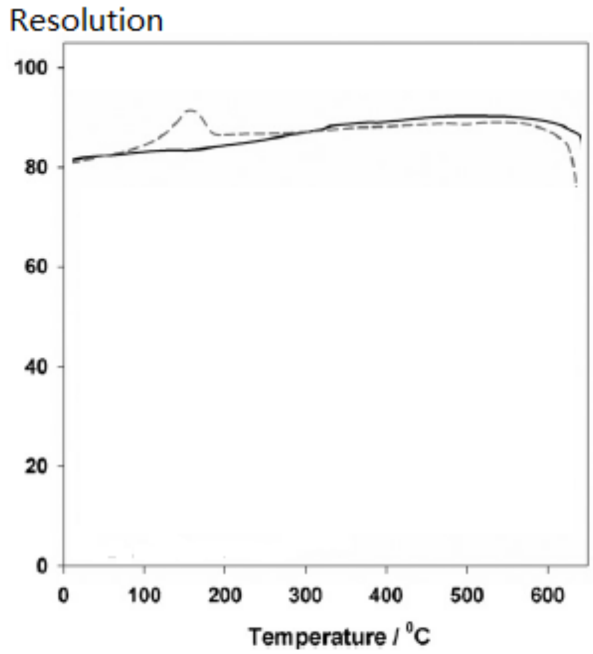


Fig. (5). Resolution and Temperature.

5.1. Effect of Operating Temperature on Sensor Behavior

The impact of elevated temperature on the sensor performance was investigated with the assumption that an increase in temperature would have an impact on the reaction of formation process. To this end and for its potential application across a range of environmental conditions, it was vital to understand the effects of heat on the behavior of the sensor; specifically the effect on sensor conductivity and lifetime. Numerous models have been proposed to explain conduction mechanisms within polyaniline and the variations in conductivity observed at different temperatures. The effect of temperature on the sensor background current is given in Fig. (**5**). In Fig. (**5**), a printed sensor was progressively heated from room temperature to 140 ◦C. Initially, only a slight increase in current was observed, though at temperatures above 40 ◦C, this increase was much more pronounced. At temperatures between 100 and 140 ◦C, the rate of increase began to slow before a rapid, irreversible degradation was observed above 120 ◦C, at which point a permanent drop in measured current occurred. This rapid degradation correlates with the onset of thermal degradation implied by the accelerated rate of weight loss above these temperatures in Fig. (**5**).

5.2. The Relationship Between the Edge and the Current

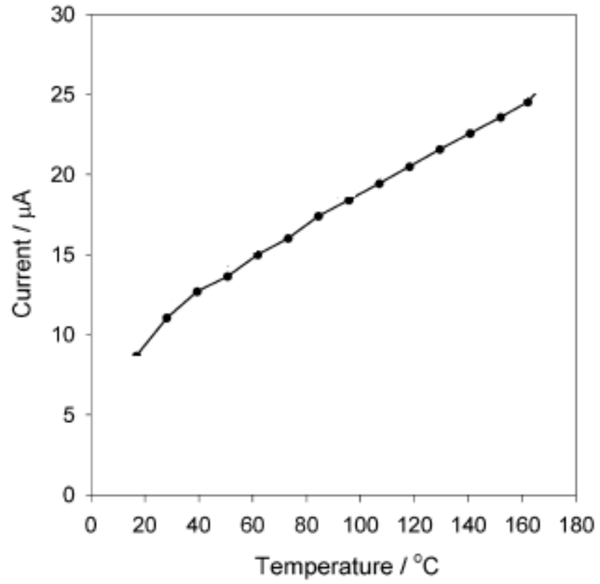
Monitoring the Micro-jet process optically becomes very challenging especially with printing at single micron resolutions and speeds approaching

According to 1000 droplets per second, a scheme based on current monitoring is developed for the process. In the middle of the device the large current was used to get high speed fabrication, and the small current was used to get sharp edge. The Micro-jet process involves combined mass and charge transfer between the nozzle and substrate, i.e. each droplet released from the nozzle carries a net positive or negative charge [2], depending on the direction the substrate-ground connection. This measurement scheme is termed substrate-side measurement. Fig. (**6**) shows a schematic of substrate-side current measurement set-up. The high-voltage source is connected to the nozzle side, while a current sensor is connected to the substrate side. The free end of the current sensor drains to ground. While both schemes work well for process monitoring, we will use the substrate side configuration.

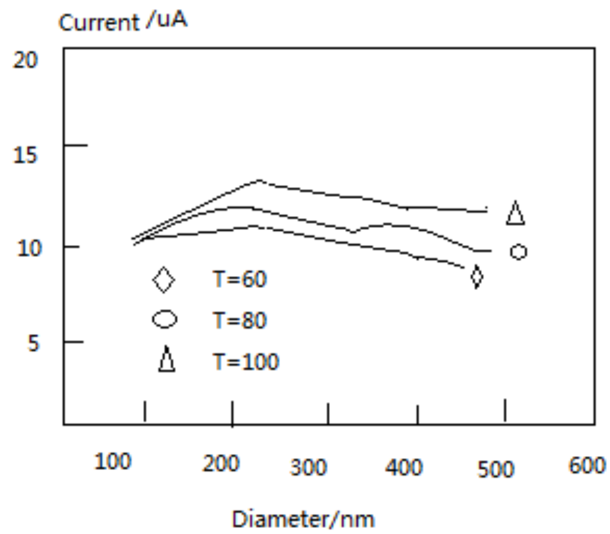
The frequency of jetting was determined by measuring the time elapsed between two successive jets. Each peak in the current signal corresponds to a single jet. The relationship of current and droplets was illustrated in Fig. (**6**). In the middle edge larger droplets were used to improve the rapid, and the small droplets were generated through small current to form the sharp edge of the device. For the resolution range (<0.7 μ m) in which we operate, the measured current associated with each droplet is found to be in the range of 5 to 15 μ A. This information can then be used for establishing voltage pulse modulation parameters.

CONCLUSION

Micro-jet printing technology has shown tremendous potential for applications in printed electronics, biotechnology and micro- electromechanical devices. Printing speed and droplet size control present the biggest challenge for jet-printing techniques. In order to address these issues simultaneously, a high-speed high-precision Micro-jet printing technique was investigated. By using a pulsed dc voltage signal to produce Micro-jetting, precise droplet placement



(**a**) Thermal performance



(**b**) Performance in different diameter of droplets

Fig. (6). Electrical performance of printed film.

and droplet spacing was obtained at very fast printing speeds. The printing times were cut down by three orders of magnitude, while delivering specified droplet deposition rates and feature sizes. Further, the proposed method also demonstrated drop-on-demand capability, as well as on-the-fly droplet feature size and droplet volume control.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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