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(ICMA) Fabrication of Electronics Devices with Multi-Material Drop-On-Demand Dispensing System

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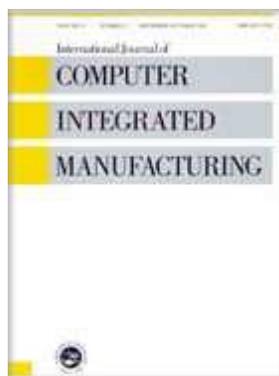
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(ICMA) Fabrication of Electronics Devices with Multi-Material Drop-On-Demand Dispensing System

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Response to reviewer's comments:

The authors wish to take this opportunity to appreciate reviewers' valuable comments.

In this response, *the italic sections* have incorporated into the revised paper.

Reviewer: 1

1. typos: p4, paragraph 1, the second line from last, 'broke'->'broken'; p5, line before 'Figure. 1 ...', 'x-axis'->'X-axis'; p6, paragraph 2, line 4, 'pressure the piezoelectric actuate'->'pressure to the piezoelectric actuated'; p10, paragraph below eq. (2), line 3, 'is keep on'->'keeps on'; p14, line 2/3 from last, 'impence'->'impedance'; p15, paragraph 3 under 'conclusion', line 3, 'it is found'->'it was found'; whole paper, 'IV'->'I-V'; use 'printhead' systematically throughout the paper.

[Response]: As advised, the above mentioned typos are corrected in the revised paper.

2. The authors should label the XYZ axes in Fig.1. Also, the model and make of the motion stage should be given.

[Response]: As advised, the XYZ axes are labeled in the Fig.1 as below.

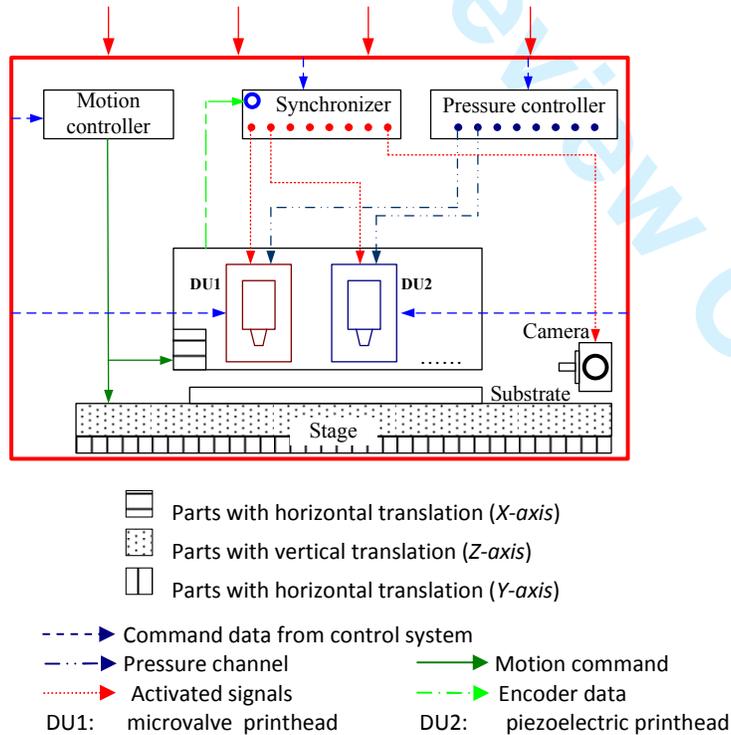


Figure. 1 Multiple nozzle DOD system

The model and make of the motion stage are given in the revised version.

The resolution of the motorized stage is 12um in the X and Y axis, and 24um in Z direction, and all the three axes are linear precision stages (IDC RC6 precision table). Each stage consists of servo motor, 2000 lines linear encoder and controller.

3. Give reference for Equations (4) and (5).

[Response]: A new reference as below is added in the revised version.

Capacitors and ESR, Available from:

http://wiki.xtronics.com/index.php/Capacitors_and_ESR

4. There is wrongly a break between one paragraph, the last paragraph on p14.

[Response]: As advised, the break between two last paragraphs has been deleted.

5. p3, paragraph 2, the authors state that 'multiple printheads on micro level fabrication are preferred in multi-material dispensing task.' It will be more convincing if the authors can name some of these tasks.

[Response]: As advised, the above sentences have been revised as below.

However, multiple printheads on micro level fabrication are preferred in multi-material dispensing task, such as biomimic scaffold fabrication, bioactive coating.

6. p4, paragraph 1, the author cites Li et al. 2008 work. The transition from previous literature review to this particular work is not natural or logic.

[Response]: As advised, the sentence with the above citation has been revised as below.

Li et al. (2008) investigated other printing parameter effects, such as printing frequency, and reported that distorted meniscus and liquid thread were broken into several satellites at higher frequency.

7. When the resistor was fabricated, from the paper, the authors printed it using only the piezoelectric printhead. This case was not as strong as the capacitor's fabrication, which involves both the printheads. The authors need to clarify in the paper how this resistor fabrication benefits from the multi-material DoD dispensing system.

[Response]: As advised, the following description has been added in the 1st paragraph of Section 3.

Resistor fabrication is a single material printing process with PEDOT: PSS, while this material is widely used in multi-material electronics device fabrication tasks such as capacitor, inductor fabrication. A proper way for PEDOT: PSS dispensing would benefit electronics device fabrication. Therefore, our study starts from investigation of resistor printing.

Reviewer: 2

(1) Figure 4 is hard to see and understand. Higher image quality and some notations need to be considered.

[Response]: As advised, some notations have been added in this figure in the revised version as shown in Figure 5.

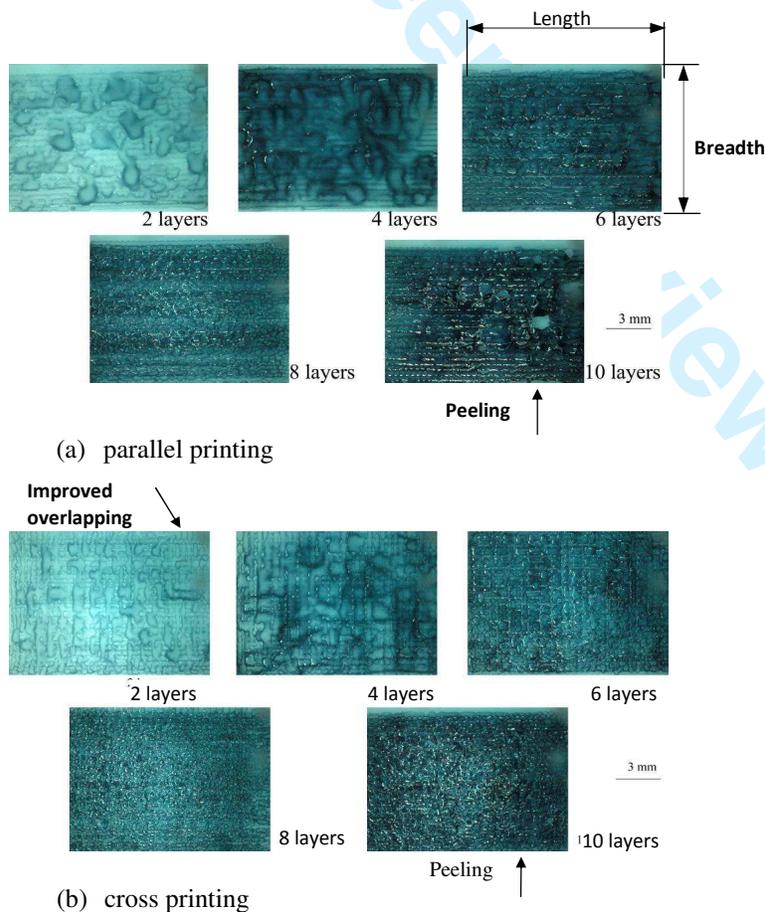


Figure 5 Photos of printed resistor

(pitch=0.4mm, printing speed=9mm/s, $p_a=90V$, $p_w=475\mu s$, $\eta=9cps$, $N_z=180\mu m$)

(2) In Page 8, two printing methods, parallel and cross printing, were studied and related results were given. However, it is not clear to the reviewer what they exactly are. They need to be better explained or by adding a schematic figure to illustrate.

[Response]: As advised, the following schematic figure has been added in the revised version.

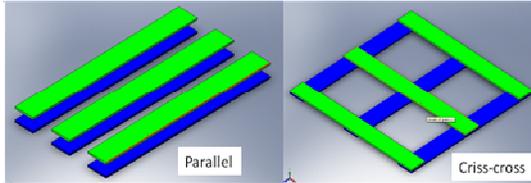


Figure 4 Parallel and Criss-cross printing

(3) In Page 9, experimental results were given long the breadth and length directions. Again it is not clear to the reviewer what they exactly are. The authors may consider adding a schematic figure to illustrate them.

[Response]: As advised, the descriptions of breadth and length directions are given in Figure 5.

(4) In Figure 6, it is noticed R is bigger at 8 layers than both those at 6 and 10 layers. Is it due to the fabrication or measurement errors or other justifications?

[Response]: As advised, the below has been added in the revised version.

It is noticed that the resistance is slightly bigger at 8 layers than both those at 6 and 10 layers. Two possible reasons can contribute to this phenomenon: fabrication error or measurement error, and we are not clear the exact source at this moment.

(5) In Page 14, “.. with increasing frequency from 20KHz to 10KHz.” It seems a typo (from 2KHz to 10KHz?)

[Response]: As advised, the typo has been corrected in the revised version.

Fabrication of Electronics Devices with Multi-Material Drop-On-Demand Dispensing System

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Abstract - One of the key engineering applications of drop-on-demand (DoD) micro-dispensing system is to fabricate functional devices. Diverse materials with wider range of properties are needed in this process. To satisfy this requirement, multiple printheads on micro level fabrication are preferred to perform multi-material dispensing task. This paper proposes a micro dispensing system with two printheads (microvalve printhead and piezoelectric printhead), which overcomes the limitations from single type printhead system in various specific fabrications.

This proposed system has demonstrated its capability for printing resistor and capacitor. The functionalities of these components are tested such as I-V characterization for resistor, and frequency characteristics for printed capacitor, followed by a detailed discussion and in-depth analysis. Our experimental results have approved that micro DoD dispensing is a feasible way to fabricate passive electronic devices.

Keywords - drop-on-demand(DoD); micro-dispensing, multiple nozzle; multi-material dispensing, piezoelectric printhead; distribution functions

1. Introduction

In recent years, one of the key engineering applications of drop-on-demand (DoD) micro-dispensing system is to fabricate polymer devices, particularly electronic devices due to the simplicity of fabrication, low cost and compatibility with a larger range of substrates (Gans et al. 2004). It has been shown to successfully fabricate all-polymer transistor (Kawas et al 2000, Sirringhaus et al. 2000, Kawase et al. 2001), polymer light emitted diode (PLED) (Yang et al. 2000) and other MEMS devices.

Chen et al. (2003) fabricated all-polymer RC filter circuits by all-inkjet printing technology using polyaniline and poly(3, 4-ethylenedioxythiophene). He

demonstrated the characteristics of the printed capacitor and RC filter and compared the measurement results with that of simulation. Liu et al. (2006) fabricated an all-polymer field-effect transistor using a piezoelectric inkjet printing, where Poly(3,4-ethylenedioxythiophene) was used as source/drain/gate electrode material, Polypyrrole as semiconducting layer, and Poly(vinyl pyrrolidone) K60 as dielectric layer. Mei et al. (2005) printed 3-D electric circuits using two particle-free conductive solutions: a novel aqueous solution consisting of silver nitrate and additives, and metallo-organic decomposition ink. He found that the latter exhibited excellent wear, fracture resistance and good electrical properties. Rothe et al. (2005) printed colloidal silver ink with a piezo-driven DoD micro feeding system. In order to achieve homogeneous distribution of the particles, the printed surface was characterized by nanometre coordinate measuring machine in his work. Veronica et al. (2008) described the inkjet printing of both a commercial silver nanoparticle metal and a thermally cured epoxy insulator, SU8, and discussed the role of print strategy and surface treatment on retaining functionality. Cao et al. (2009) fabricated a micro air-bridge array with microPen direct-write deposition technique using commercial gold paste (Au) as the structural layer material and polyimide as the sacrificial layer. Ebrahim et al. (2009) utilized micronozzle for microchannels, microvalves fabrication as well as microfluidic packaging of CMOS chips. He fabricated a thermally-actuated microvalve incorporated with a capacitive sensor for demonstration.

In addition, various printing materials are used for polymer electronic devices such as polyimide (PI), poly(3,4-ethylenedioxythiophene (PEDOT) and poly(4-vinylphenol) (PVP). Some are conductive while others are isolative or dielectric. Due to varied material properties on chemistry, conductivity, surface tension and viscosity, different DoD printing system design are used. For example, MicroFab Technologies

produced a four-channel piezoelectric nozzle set with the controller MicroJet III (Microfab Technote 99-03). Ibranium et al. (2006) modified a commercial printer to simultaneously deposit materials through a number of nozzles to fabricate a layer by layer 3D multi-material pattern. Liu et al. (2003) successfully printed an all polymer capacitor that consisted of conductive and insulative layers using a commercial inkjet printer, however, the capacitor was not printed in a single process but in intervals of about 2 minutes between layers of different materials.

Generally, most available multiple nozzle DoD systems in the market consist of multiple nozzles with the same mode of actuation. It is quite rare, to the knowledge of the author, to see a multiple nozzle system with multi-actuation methods. However, multiple printheads on micro level fabrication are preferred in multi-material dispensing task, such as biomimic scaffold fabrication, bioactive coating. To meet the growing requirement of fabrication electronic devices, this work is to develop a multi-nozzle DoD inkjet machine which is capable to print diverse materials with wider range of properties.

Each printhead is unique in the sense of its operation method and operating parameters, which gives each printhead its advantages and limitations over the others in a specific fabrication. In our DoD system, two kinds of dispensers are used: piezoelectric printhead and solenoid micro-valve. With the common ability to exert droplet production control over a range of frequencies, the two DoD printheads achieve this objective differently.

The advantage of piezoelectric actuation is that the pressure, pulse rise and fall time can be tailored to optimize monodisperse satellite free droplet production and dynamically alter the diameter of the ejected drops (Sun et al. 2009). Microfab Company (Microfab Technote 99-03) examined the effects of pulse amplitude and

pulse width on droplet velocity and volume. With single waveform, droplet velocity and volume increased with pulse amplitude. Also, the optimum pulse width was found associated with printhead length, the acoustic wave propagation speed, and the nozzle geometry. Reis et al. (2005) investigated the influence of pulse width and amplitude on printing alumina powder suspension, and gained similar experimental results. By changing the waveform of driving voltage signal, Chen et al. (2007) managed to obtain drops smaller than nozzle size. But this method was only limited to low viscosity fluid. Li et al. (2008) investigated other printing parameter effects, such as printing frequency, and reported that distorted meniscus and liquid thread were broken into several satellites at higher frequency.

Micro-valve nozzle is also widely used in micro-dispensing applications. To build tissue scaffold, Khalil et al. (2005) and Lee et al. (2003) proposed a multi-material deposition system with different types of nozzles, among which micro-valve was applied. Kwang (2006) gave a brief overview of micro-valves, based on the actuation mechanisms and their applications. He believed that reliability was the key for successful miniaturization and commercialization of fully integrated microfluidic systems, and there was plenty of room for further improving the performance of existing micro-valves.

The rest of the paper is organized as follow. Section 2 discusses the set up of multiple nozzle DoD system for micro-fabrication. Section 3 describes the fabrication process of resistor, followed by detailed discussion for further understanding these results. Section 4 describes the fabrication of functional capacitor and its characterization results. Finally remarks and conclusion are given in section 5.

2. Set up of the multiple nozzle DoD sytem

Similar to a single nozzle DOD system, our multiple printhead DoD dispensing system consists of three key components: motion stage, dispensing units, and visualization system as shown in Figure 1.

2.1 Motion stage

The motion stage controls the movement of the printheads and the substrate so that the droplets are deposited at the desired position commanded by the user, through the user interface. It includes a Galil motion controller embedded in the PC and a motorized stage with X, Y, and Z axis movement. The resolution of the motorized stage is 12 μ m in the X and Y axis, and 24 μ m in Z direction, and all the three axes are linear precision stages (IDC RC6 precision table). Each stage consists of servo motor, 2000 lines linear encoder and controller. The dispensing unit is attached on the X-axis track by a mechanical mounting while the substrate plate is mounted on the Z-axis track and is designed to ride on the Y-axis track. Therefore the substrate is able to move along both Y- and Z-axis directions while the printheads move along the X-axis direction.

Figure. 1 Multiple nozzle DOD system

The user interface is to input necessary printing parameters such as printing pitch between dispensed droplets, gap between printed lines, and pathway of the dispensers regarding the starting position of a specific printhead in diverse tasks from printing single line to fabrication multiple layers.

2.2 Dispensing units

The printheads used for dispensing consist of 1) piezoelectric actuated dispenser and 2) micro valve dispenser (Sun et al. 2009). A synchronizer is designed to synchronize the printing tasks among the two dispensing units and motion stage.

2.2.1 Piezoelectric actuated dispenser

The print-head for the piezoelectric actuate dispenser is self-developed and house made (Figure 2), which is composed of a printhead chamber and an interchangeable glass nozzle connected by thread. The piezoelectric crystal PZT-5H radial cylinder of 0.635cm OD, 0.05cm thickness and 2.54cm long is from Boston Piezo-Optics Inc. The PZT-5H cylinder surrounding a 5cm long PET plastic tube is placed at middle of the tube. The PZT-5H tube is super glued to the PET plastic tube using conductive epoxy (VHS Micro Dispensing Starter Kit). Two wires are attached to the inner and outer surfaces of the PZT-5H using epoxy, as positive and negative electrodes.

Negative pressure is to hold the bulk of the printing material within the printhead, from the reservoir to the nozzle tip. The Automatic micro-dispenser (AD3000C controller), a commercial vacuum generator from Iwashita Instruments Pte Ltd provides negative pressure to the piezoelectric actuated printhead. The pressure regulator is adjusted such that the negative pressure is enough to maintain a flat meniscus at the nozzle tip. A stable negative pressure of -0.2 to -0.4 psi is applied during our experiments.

Figure. 2 Piezoelectric Printhead dispenser

2.2.2 Micro valve dispenser

As shown in Figure 3, the micro valve dispenser is from the Lee Company (VHS Starter Kit P/N IKTX0322000A), which operates through a solenoid system to open or close. An induced magnetic field forces an internal piston to open the valve; otherwise, a spring forces the piston onto the valve seat to close the valve. Under external trigger TTL signal between 60 Hz and 1 KHz, the valve driver outputs 24V

spike voltage to activate the valve and 3.5V to hold the open status for a period. The total time period including spike and hold status is defined as operational on time (OOT, VHS Micro Dispensing Starter Kit). The pneumatic system for the micro valve dispenser consists of 2 outlets: one is to dispense positive pressure during normal printing (the default outlet), and the other is to purge clogged nozzle for cleaning. A 3/2 way solenoid valve allows the user to toggle between the 2 outlets.

Figure. 3 Print heads and their driving voltage waveform

2.2.3 Synchronizer

The synchronizer with a total of 8 TTL signal outputs synchronizes tasks among the multiple dispensing units and other supplementary components. When the printhead has arrived at a specific location on the substrate on the motion stage, the TTL signal output from the synchronizer to printhead drivers activates individual printhead for dispensing.

2.3 Droplet vision system

The visual system consists of a CCD camera, LED array, LED driver, and computer monitor. The CCD camera, FireFly MV with 29 zoom is from Point Grey Research Inc. It captures the droplet generation image and displays it on the monitor. This camera is mounted on a metric stage and positioned between the camera lens and the LED array.

A high luminance LED array is utilized as stroboscopic light which is controlled by the PP610 LED driver from Gardasoft Vision. The stroboscopic light is synchronized with the printhead operation with the same trigger pulse. Thus, a stationary droplet appears on the monitor under stable ejection condition. Hence, the

presence and consistency of droplets are easily verified by this visual inspection. The different states of droplet formation process can be observed by varying the time delay in the LED driver. According to our experimental results, the distance between the substrate and the nozzle tip in the system characterization experiment, should be between 1.0 mm and 3.0 mm. To avoid other possible factors that can affect droplets like wind, a distance of 1-2 mm would be ideal.

3. Fabrication of Functional Resistor

Resistor fabrication is a single material printing process with PEDOT: PSS, while this material is widely used in multi-material electronics device fabrication tasks such as capacitor, inductor fabrication. A proper way for PEDOT: PSS dispensing would benefit electronics device fabrication. Therefore, our study starts from investigation of resistor printing.

3.1 Fabrication

In this section, a resistor is printed on glass substrate and tested in terms of printing methods and layers. Since the rubber inside the micro-valve swells with conductivity material PEDOT: PSS and results in clogging, piezoelectric printhead is chosen for this fabrication. Before fabrication, the glass substrate is swiped using alcohol to erase impurities, and put on a heating pad for curing purpose.

In order to investigate the influence of printing methods, both parallel and cross printing are conducted as shown in Figure 4. The former is to print lines parallel with each other, and the latter is to print lines perpendicular with each other. The PEDOT:PSS is dispensed at a square area with the length of 15mm and width of 9mm for demonstration purpose. The microscope photos of printed resistors from parallel and cross printing are provided in Figure 5(a) and 5(b) separately.

Figure 4 Parallel and cross printing

Figure 5 Photos of printed resistor

As shown in the first photo in Figure 5(a) and 5(b), the material distribution of 2 layers cross is more even than that of parallel. While this phenomenon become less significant for 6 layers and above. As more layers are dispensed, the overlapping among droplets has been improved. Thus, the dispensed material is more evenly distributed within the printing area. Peeling of printed samples is observed at 10 layers printing. With more layers, the glass slide has to be placed on the heating pad for longer time, which results in overheating and peeling.

3.2 I-V characterization

I-V characterization of the printed resistor is measured by Hioki LCR Hi tester 3520 system in an air environment at room temperature. The measurement with 400 readings is taken to describe this device's behavior for the voltage range [-10V, 10V]. The results from the length and breadth directions are recorded and plotted in Figure 5, to compare the fabrication performance of two printing methods (cross and parallel).

3.3 Result analysis

As shown in Figure 6, I-V curve is almost a straight line for the range [2.5V, 10V] and [-10V, -2.5V] which is the same as that of a typical resistor. The resistance is a bit different for 4 layers cross and parallel, and nearly the same for 6 layers cross and parallel. For 4 layers printing along the breadth direction, the current reaches 260 μ A in cross and 180 μ A in parallel, when the testing voltage increases to 10V. This is because the overlapping between lines and rows of 4 layers cross is better than that of 4 layers parallel. Hence, it has better conductivity and lower resistance. With the

increasing number of layers, the overlapping has been enhanced in parallel printing. Thus, no much difference is observed for 6 layers printing using the two methods. It is also found that the resistance for 6 layers is higher than that of 4 layers. This is as expected since resistance increases with film thickness.

Figure 6 I-V curve of multilayer cross and parallel printing

For the region $[-2.5V, 2.5V]$, almost no current passes through. It is believed that donor-like trap states in the PEDOT:PSS films may be responsible for this behaviour. The contribution of capacitance variation $V(\frac{dC}{dt})$ on I_d is much stronger than that of voltage variation $C(\frac{dV}{dt})$. Thus the displacement current I_d can be approximated by equation (1) (Liu, 2003).

$$I_d = \frac{d(CV)}{dt} = V \frac{dC}{dt} + C \frac{dV}{dt} \approx V \frac{dC}{dt} \quad (1)$$

The total current I can be approximated by

$$I = I_r + I_d \approx I_r + V \frac{dC}{dt} \quad (2)$$

Where I_r is from the resistive part. In Figure 5, the current is very small (nearly zero) under $[-2.5V, 2.5V]$, which indicates that the direction of I_d is opposite to I_r at this range, i.e. the charge state of the traps keeps on changing according to the direction of I_d . This results in that the device characteristics are influenced by charges de-trapped/trapped within the printed layers. Due to $\frac{dC}{dt} < 0$, the trap states would tend to give up its trapped hole or trapped electron and become neutrally charged, resulting in the formation of displacement current. The de-trapping of electrons can be neglected in the PEDOT:PSS films, because its concentration is small compared with that of the

majority carriers (holes)(Majumdar et al. 2002). Also, the displacement current is roughly the same as that of resistive current for [-2.5V, 2.5V], but in opposite direction. With the increasing voltage, the contribution of the 2nd term in equation (2) becomes less significant. Therefore, a linear relationship between current and voltage range is observed under [2.5V, 10V] and [-10V, -2.5V], i.e. resistor characteristics.

Table 1 lists the current value at V=0 in I-V curve. With the increases of the depth of PEDOT:PSS film from 4 to 6 layers, the current at V=0 decreases from 6.74 μ A to 5.76 μ A in breadth, 6.01 μ A to 5.06 μ A in length respectively. The same phenomenon is also observed for parallel printing.

Table 1
List of current at V=0 in I-V curve

| Current(μ A) | 4 layer (Cross) | 4 layer (Parallel) | 6 layer (Cross) | 6 layer (Parallel) |
|-------------------|-----------------|--------------------|-----------------|--------------------|
| Breadth | 6.74 | 5.22 | 5.76 | 4.18 |
| Length | 6.01 | 1.51 | 5.06 | 1.21 |

The capacitance variation related to I-V characteristics for PEDOT:PSS/glass devices is believed greatly contribute to this phenomenon. In analogy with the parallel plate capacitor, the depth d of the PEDOT:PSS layer corresponds to the plate separation of the convention capacitor. The capacitance is represented by:

$$C = \frac{\epsilon_0 \epsilon_r S}{d} \quad (3)$$

where ϵ_0 is the permittivity in vacuum, ϵ_r is the dielectric constant of PEDOT:PSS, and S is the cross-sectional area of the parallel plate capacitor. As expected, an increase in d could lead to the decrease in C and the corresponding displacement current. Besides, the space charges accumulated at the interface or in the bulk can limit charge injection in the polymer layer, and result in the variation of dielectric constant and the capacitance of the corresponding device.

Figure 7 shows the relationship between the value of resistor and printing layers. The obvious difference can be observed for 2 layers between cross printing and parallel printing, while there are almost the same for 4 to 10 layers. This is probably because the overlapping from 2 layers printing is not so good, and has been improved for 4 layers and above. Therefore, no much difference can be found between cross and parallel printing for 4 layers and above. Since the overlapping for 2 layers cross printing is better than that of parallel, the resistor of the latter is always higher than that of the former. It is noticed that the resistance is slightly bigger at 8 layers than both those at 6 and 10 layers. Two possible reasons can contribute to this phenomenon: fabrication error or measurement error, and we are not clear the exact source at this moment.

Figure 7 Relationship between resistor and printing layers

4. Fabrication of Multiple Material Capacitor

In order to verify the functionality of the developed multiple nozzle DoD system, a capacitor with multi-material multi-layer is fabricated using our developed DoD system.

4.1 Printing materials

PEDOT:PSS is used for the top and bottom electrode, which comes in the form of an aqueous dispersion with a solids content of approximately 2.5% by weight. The material used for the insulative part is Polyvinylpyrrolidone (PVP). The PVP solution is prepared by mixing 0.4g of PVP powder to 20ml of DI water in a small conical flask, followed by stirring the mixture for 2 hours until the powder is fully dissolved. In this fabrication, PEDOT: PSS is dispensed by the piezoelectric printhead, and PVP solution is dispensed by the micro valve printhead since it can easily clog the small

nozzle of piezoelectric printhead. Our capacitor is printed on photo paper, which can avoid excessive merging of adjacent droplets for better surface finish. The photo paper is placed on a heating mat, and the curing temperature is fixed at 50°C throughout the whole fabrication.

4.2 Fabrication of multiple material capacitor

As shown in Figure 8, 2 layers PEDOT: PSS film is firstly printed onto the photo paper as the bottom electrode, followed by 2 layers PVP film between, and then the other 2 layers PEDOT: PSS film on the top. Thus, this capacitor is made of two types of material and three regions (the bottom electrode, the insulative layer and the top electrode). The effective capacitance is the overlapping area, which is measured to be at 80mm², with a length of 10mm and breadth of 8mm.

Figure. 8 Schematic of multiple material capacitor

4.3 Measurements of printed capacitor

As shown in Figure 8, one terminal of the probe is attached to the portion of the bottom electrode while the other is to the shaded area. The printed multi-material capacitor is tested under varied frequencies from 10 Hz to 10kHz. The results from the parallel configuration and series configuration, which assume the capacitance is parallel/serial to the equivalent series resistance (ESR) and the probe, are recorded.

The relationship between the capacitance and frequencies is illustrated in Figure 9(a). The measured capacitance under the above two configurations starts out high at low frequency 10 Hz, and then decreases sharply between 10Hz and 2kHz, and approaches a stable but much lower value at high frequency (3kHz to 10kHz). The experimental results are in agreement with the expectation. At low frequency, the larger period gives more time for charges to be fully built up in the printed capacitor

and dissipation, giving a larger capacitance value. At higher frequencies, the switching of the AC current is so fast and the capacitance approaches near zero.

For the measurement method with parallel configuration and series configuration, there is an obvious difference for the frequency below 3KHz, and no much difference can be observed above 3kHz. The reason lies in that the ESR value decreases with testing frequency, and the smaller resistance will result in the less difference on the measured capacitance values for the two configurations. In general, parallel configuration is recommended to measure this film capacitor due to the relatively low capacitance and high impedance, since parallel resistance can cause great loss in this case.

From the above results, it can be concluded that the printed multiple material capacitor is functional in terms of frequency response.

As in Figure 9(b), the ESR and the impedance of the capacitor tend to decrease non-linearly with increasing frequency from 2kHz to 10kHz. The LCR Hi tester only registers a value when the frequency is around 2kHz for both impedance and ESR. At frequency lower than this, the measurement is out of range. The ESR is essentially from the connecting materials, i.e. the conducting PEDOT: PSS films and the dielectric PVP film. It is a parasitic component that tends to lower the capacitor's performance or even cause breakdown due to the heat generated from the power loss. The ESR (Capacitors and ESR, 2011) varies inversely to frequency according to Equation (4):

$$ESR = \frac{DF}{2\pi fC} \quad (4)$$

where DF is the dissipation factor of the capacitor, f is a particular frequency and C is the capacitance. For a constant capacitance, the ESR decreases with the

increasing frequency. Impedance Z can be presented by Equation (5) (Capacitors and ESR, 2011).

From Figure 9(a), it can be seen that the capacitance value is nearly constant for the frequency above 4kHz. This results in both the real component (ESR) and imaginary component of impedance decrease between 4kHz and 10kHz, according to Equation (5) (Capacitors and ESR, 2011). Hence, the impedance $|Z|$ decreases more than that of the ESR as shown in Figure 9(b). From 2kHz to 4kHz, the capacitance decreases as shown in Figure 8(a), which may contribute to the increase of ESR and impedance. While, the ESR and impedance as shown in Figure 8(b) keep on decreasing, due to the contribution of increasing frequency.

$$Z = ESR + \frac{1}{j2\pi fC} \quad (5)$$

Figure. 9 Characteristics of the printed capacitor

5. CONCLUSION

This paper presents the development of a multi-nozzle multi-material DOD micro-dispensing system and its application on fabricating resistance and capacitor.

The developed dispensing system integrates motion stage, dispensing units (micro valve printhead and piezoelectric printhead), and visualization system, so that it can fabricate functional electronic devices with multi-material in a single process. Both resistor and capacitor have been fabricated with this system, and their functionality is verified. For resistors, the I-V curves are measured in both length and breadth direction. According to the results, it was found that cross printing is more reliable for 2-layer film resistor fabrication, while both cross and parallel printing achieve nearly the same performance for 4-layer film resistor or above. The fabricated

capacitor has also been proved to function similarly as a traditional parallel plate capacitor. Although further improvements are needed for this study, the developed system paves the way for low-cost fabrication of passive electrical components.

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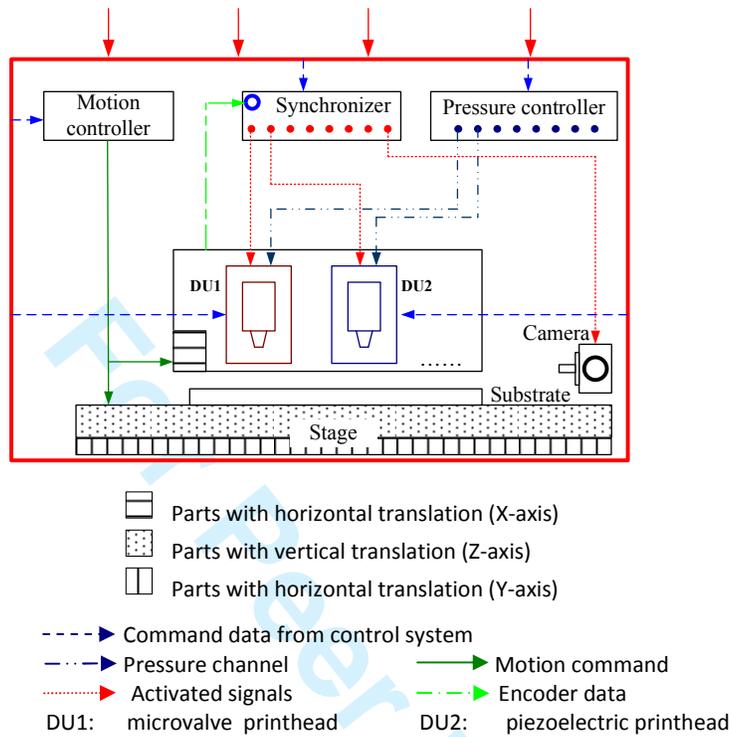
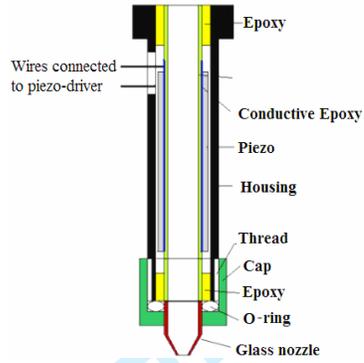
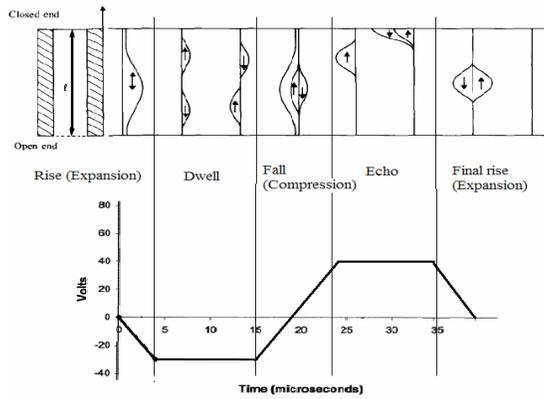


Figure. 1 Multiple nozzle DOD system

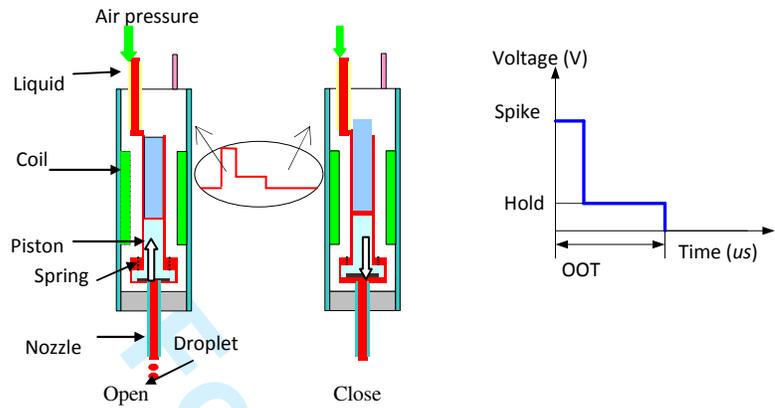


(a) Piezoelectric actuate dispenser



(b) Driving voltage waveform

Figure. 2 Piezoelectric Printhead dispenser



(a) Solenoid actuated micro-valve mode (b) Driving voltage waveform

Figure 3 Micro valve dispenser

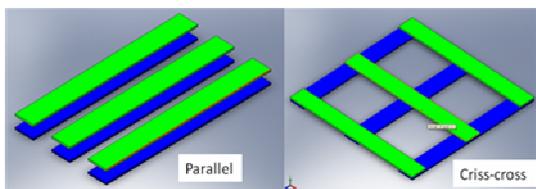
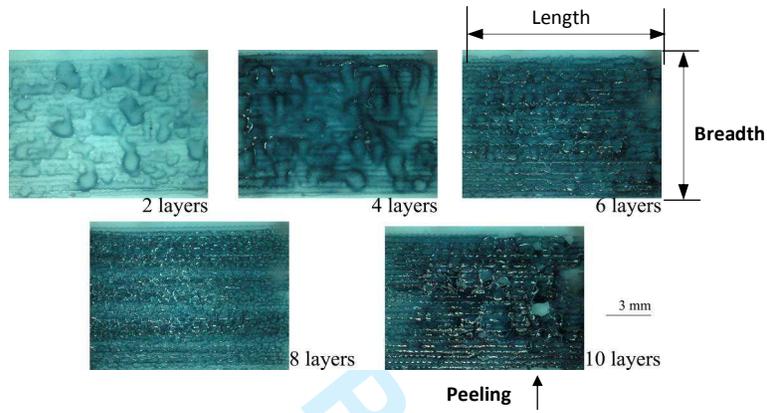
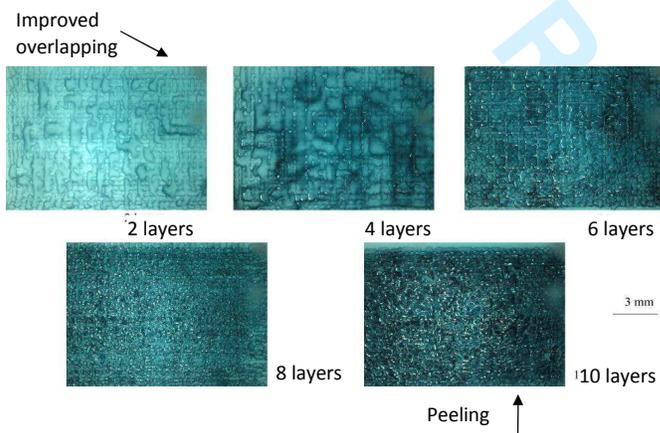


Figure 4 Parallel and Criss-cross printing

For Peer Review Only



(a) parallel printing



(b) cross printing

Figure 5 Photos of printed resistor

(pitch=0.4mm, printing speed=9mm/s, $p_a=90V$, $p_w=475\mu s$, $\eta=9cps$, $N_z=180\mu m$)

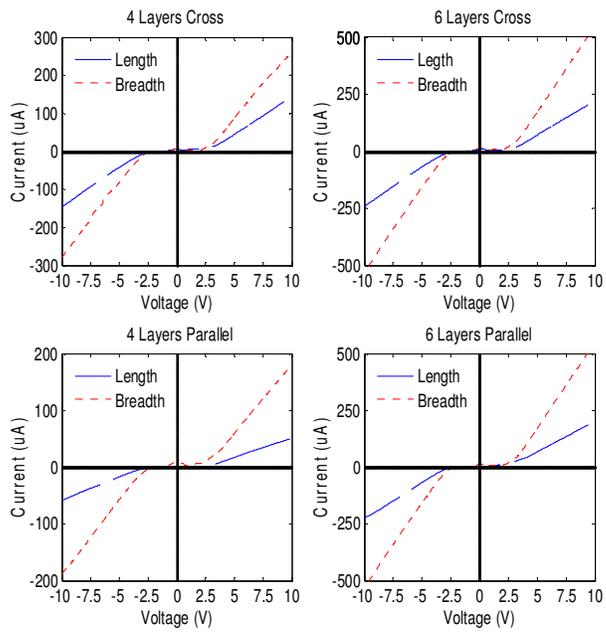
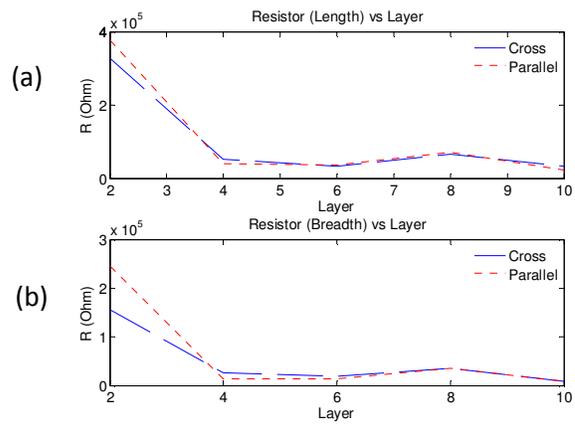


Figure 6 I-V curve of multilayer cross and parallel printing

Review Only



(a) Relationship between resistor (length) and layer

(b) Relationship between resistor (breadth) and layer

Figure 7 Relationship between resistor and printing layers

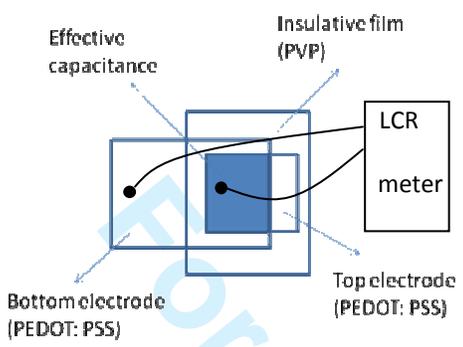
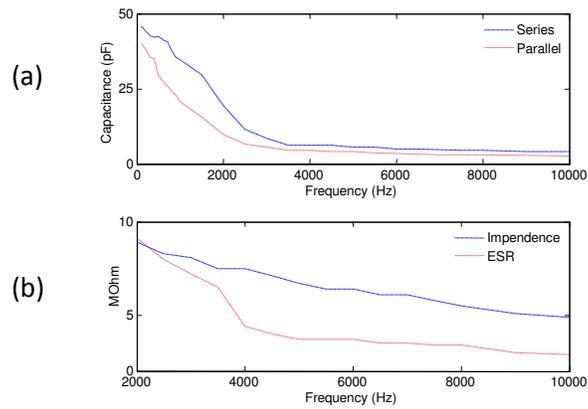


Figure 8 Schematic of multiple material capacitor



(a) Relationship between capacitance and frequency
(b) Relationship between resistance/impedance and frequency
Figure. 9 Characteristics of the printed capacitor