Drop on Demand Non-contact Hydrophilic Electrostatic Deposition Head


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Abstract- There have been growing interests in direct patterning of metallic contents on the surface of the substrate without including complex steps of the micro fabrication lithography process. The direct fabrication process using ink-jet printing can be expected to be a powerful tool for both nanotechnology research and applications such as micro electronics. Inkjet printers operate by propelling various size droplets of conductive ink onto the substrate. The electrostatic inkjet system is one of the important candidates, in terms of cost and time effected manufacturing of printed electronics like RFID, electronic devices and flexible display, solar cell, sensors etc.

Paper experimentally studies and analyze hydrophilic electrostatic head design having nozzle with micron orifice for the contactless deposition of metallic contents. The lab fabricated electrostatically -micro machined actuated inkjet head, tested for low power and high resolution with nano-particle ink containing metallic particle as pigment. The issues like the drop on demand using metallic ink and ejection at low voltage with stability problems are also addressed. The meniscus formation on the nozzle orifice with the relation to hydrophilic properties is also analyzed experimentally and optimize model for metallization is proposed. The electrostatic forces enable the system to overcome the mechanical actuation which is often require high fabrication cost, actuation limitation and integration problems to produce printed electronics and electrical patterns at higher frequencies rate.

Index term-- Drop on demand, electrostatic inkjet head, hydrophilic head, and meniscus control

I. INTRODUCTION

Contact-less drop on demand deposition method is very appealing technique to fabricate different electronics and electrical patterns as this technique has advantages over conventional photolithography technique in source dissipation and energy level [1, 2]. The industrial trend is to achieve fine metalized line with high aspect ratio with maximizing the current and by reducing the shadowing effect and contact resistivity. All these contact requirements can be realized in a photolithography defined, evaporated and plated front contact structure. However, this process includes too many production steps which are too time consuming and not economical for an industrial production [3]. Electrostatic inkjet technology seems to be a promising technology as electrostatic inkjet printing system has advantages over other types of the inkjet (piezo, thermal) printing techniques in size of fabricated...
device and precision in extraction [4]. Electrostatic head printers are faster than piezo and thermal inkjet technologies and capable of variable printing. It offers the best transfer of chemistry to the media because toner consists of metallic particles that become physically fused to the substrate surface. Electrostatic printing prevents the absorption, density loss, and colorant related stability problems found in other inkjet types [5]. As the name implies, electrostatic printers use electrostatic attraction of particles to create an image. Material handling through electrostatic droplet manipulation technique, with high precision, is of paramount importance and is powerful technique that has received interests in the recent years in fields; like protein crystallization, drug discovery, printed electronics, solar cell etc [6].

In this paper, experimental results with thorough study with emphasis on the formation of a charged droplet for printing electronics, through different designed based electrostatically driven hydrophilic heads are studied. The behavior of the head is also analyzed by designing the equivalent model. And in the end, a fully micro machined, low power and high resolution electrostatic head is proposed. The high resolution nozzle head, consisting of nozzle orifice, ink reservoir, ink supply connection and electrode connected with high voltage source for maintaining the polarity in the ink, fabricated by using micro machining process is suggested. And lastly, nano particle printing ability of the best optimal head is studied to determine the better nozzle head on the substrate, by reducing droplet size, improving droplet consistency, and eliminating satellite droplets.

II. GOVERNING METHODOLOGY

The drop generation mechanism in the electrostatic system is different as compared to the piezo and the thermal based inkjet system. In piezo or the thermal based system, a complete drop from the orifice of the nozzle emerges due to applied force. Whereas, in electrostatic case, firstly the meniscus is generated, then the field is applied on the meniscus. The drop comes from the surface of the meniscus and the droplet is much smaller as compared to the diameter of the orifice. The drop size depends on the applied field on the surface of the meniscus. Therefore, it’s important that the meniscus is charged adequately to produce the droplet. When the surface of a meniscus is subjected to an electric field, the field causes a deformation of the meniscus and eventually a stable drop is formed.

In general terms, for the stable meniscus and stable drop-on-demand generation, molecule forces (inter and intra) should be equal to forces of the system values. In this scenario, it can be divided into two cases, namely stable meniscus and stable drop generation behavior. For obtaining the stable meniscus shape, the main parameters include surface tension of fluid which is countering the effect of the pressure applied by the flow of the ink and gravity. Whereas, the stable on-demand behavior need the study of the electrical forces and can be given as:

\[ F_{st} - F_{gr} + F_e = 0 \]  

(1)

Where \( F_{st} \) is surface tension, \( F_{gr} \) is the force due to gravity and \( F_e \) is electrostatic force applied to the meniscus.

But above mentioned case is applicable when the electric field and gravity is the only force on the nozzle orifice. If the flow rate is also applied on the nozzle then the above equation can be modified as:

\[ F_{gr} - F_{st} + F_e + F_q = 0 \]  

(2)

Where \( F_q \) is the applied flow rate. The effect of the gravity is negligible, as the other forces on the meniscus (like surface tension, electrical stress, viscosity, pressure and electric field) are much more in magnitude than gravity as shown in the fig. 1. Thus above equation can be reduced to:

\[ F_{st} = F_e + F_q \]  

(3)

In this paper, the effect of the \( F_e \) will be studied and discussed keeping all other parameters of the system constant. But to predict the meniscus shapes both theoretically and experimentally under the influence of given electric pressure and hydrostatic pressure, the electrostatic and hydrostatic equations should be solved simultaneously [3]. The maximum meniscus extension is presented as a function of voltage, surface tension, hydrostatic pressure, orifice diameter, material and electrode spacing for tube-plane geometry, surface of nozzle and its relation to fluid properties. Cone jet shape can be obtained from the meniscus of nozzle head after the applied voltage. The jet shape depends upon the rate at which the forces are acting on it. The developed shape has number of active forces acting on it as shown in the fig. 1. When the surface of a meniscus is subjected to an electric field, the field causes a deformation of the meniscus and eventually a stable liquid meniscus is formed again as shown in fig. 1(a). The surface of the liquid meniscus is subjected to surface tension \( \sigma_s \), hydrostatic pressure \( \sigma_h \) and electrostatic pressure \( \sigma_e \) is valid at each point on the liquid surface [3], given as:

\[ \sigma_h + \sigma_e + \sigma_s = 0 \]  

(4)

\[ \sigma_h = \rho g \Delta h \]  

(5)

\[ \sigma_e = \frac{E_e^2}{2\varepsilon} \]  

(6)

Where \( \rho \) is the density of liquid, \( g \) the acceleration due to gravity, \( \Delta h \) is the liquid level difference between the container and the free end of the nozzle, \( \varepsilon \) is the relative permittivity of the liquid to vacuum permittivity, and \( E_e \) the electric field strength normal to the liquid surface. Li et al has explained this behavior, that in the electro-hydro dynamics spraying process, the normal electric stress is likely to produce a dripping mode while the tangential electric stress will move liquid from the meniscus.
surface to the apex of the meniscus to form a jet \[3\]. When the tangential stress is intensive enough, a cone-jet is formed. For this reason, both the normal electrical stress and tangential electrical stress are important in the drop generation mechanism and this behavior has been analyzed using two different nozzle heads. If the tangential electric stress is great enough to move the surface layer of the meniscus to form a jet, a portion of the liquid in the meniscus has to backflow into the meniscus because of the electric stress \[4\]. And thus flow rate is required to compensate fluid in the meniscus which is directly proportional to the backflow of fluid due to the electrical stress. Thus, the governing force for the ejection of the droplet is electrostatic force since the flow rate is provided to maintain the steady level of ink at the orifice outlet. Whereas the gravitational force has little contribution due to the high fluidic resistance in the micro channel.

III. EXPERIMENTAL SETUP AND PROCEDURE

The experiment setup and print head driven by on demand electrostatic forces specifically designed for this study, is shown in the fig. 5. The apparatus consists of X-Y stage, electrodes, a high voltage source, an observation system, ink supply system, and nozzle holder with z-axis control. The two types of electrodes were used for the ejection of droplets are: the actuating electrode and ground electrode. The physical experiment setup is based on pin to pin configuration \[8\]. The ground electrode is connected to the negative potential of the high voltage source and the other potential in the nozzle head for activating the ink and providing the necessary potential to the ink in the nozzle head for the drop extraction. To control droplet ejection, the square wave form is applied between the nozzle head and the ground electrode to develop extraction potential. The duty cycle maintained 50% at all frequencies. For experiment purpose, a commercial available solvent based ink containing 20% silver pigments is used.

![Fig. 2](image1.png)

Fig. 2. (a) shows schematic diagram of the electrostatic contactless printing system and (b) shows the physical setup of the systems.

![Fig. 3](image2.png)

Fig. 3. Schematic diagrams of micron-level electrostatic head designs for the contact-less fabrication of printed electronics

The other properties of the ink such as density, viscosity, surface tension and metallic pigments were found to be: 1070 kg/m\(^3\), 10cps, 30–32 dynes/cm with silver (Ag) particles respectively. The liquid pressure is controlled by using the pressure injection pump. The inlet flow rate is an important parameter to maintain the uniform static pressure in the ink chamber when the reservoir head is changing due to the ejection of ink during the printing process. After developing the meniscus, the result is analyzed to find the optimal values for the given nozzle. This is done by applying different voltages and different frequencies until optimal position of the jetting voltage point is determine. For observation purpose, ITI drop watcher® with modified structure is used. The zooming magnification of lens is 0.75X to 4X with high-magnification option 2.5X to 10X with frame rate of 30 frames per second.

IV. RESULTS AND ANALYSIS

In this study, high precision structures such as nozzles, walls and electrodes, were designed. The head fabrication demands several new micromachining process and technology. Below is mentioned the step by step progress to optimal results using the hydrophilic head. The general micromachining process of each nozzle head is given below:

For the metallic composition of the hydrophilic thin metallic layer of metallic layer of copper (Cu) is less than 70 µm is taken and baked with the insulator sheet having teflon layer sheet between it for 150° C for 10 minutes. After the
connection between the insulating and metallic layer a drill has been done to generate ink channel and nozzle orifice. After drilling the hole in the insulated layer, the Electrical Discharge Machine (EDM) is used to drill the hole in the metallic layer for the fabrication of specified nozzle hole as shown in the fig. 4(b). By using EDM less than 100μm outer diameter was manufactured. For holding and ink supply system in nozzle holder the alkenes material is used. The metallic orifice bottom layer has two fold advantages: firstly, the layer provides the charging to ink and 2ndly the EDM machining is possible. The holding and ink supply is glued with the ink orifice based in head structure. And for high power supply, the power transfer connection is also provided to the nozzle head. For charging the ink the connection is given to the outer layer of the orifice. In first three cases, there is not electrode inside the ink bank to charge the ink. But in fourth case, the electrode tip of 50μm is used to charge ink. After the fabrication of the head, the head is installed in the system and tested for the performance using the high speed camera. The results of the orifice and the meniscus are shown the fig. 6. The meniscus formation instead of drop down shape, expanded on the surface of the nozzle head even at a constant flow rate is maintained. And after the application of high voltage, the meniscus starts expanding on the surface of the nozzle head. And even after the application of very high voltage around 7kV the drop on demand generation process was not observed.

Fig. 6. (a) high resolution image of the NPH nozzle orifice and (b) the initial meniscus (c) meniscus after applying electrostatic potential

b. Prominences Hydrophilic Nozzle Head

From NPH head, it was analyzed that as the voltage is increase the meniscus also expands on the surface. Thus another head was fabricated to remove the above mention instabilities. In this case a prominent head was introduced, in such a way that its acts like a converging nozzle head. The model and the fabricated structure of the prominences hydrophilic (PH) nozzle are shown in the fig. 7. The idea is to minimize the contact interaction area between the meniscus and the nozzle orifice. Firstly, the ink reservoir was developed and before using EDM the angle of the nozzle is developed using the pushing mechanism. When the electrostatic force is applied on the surface of the nozzle head, the voltage shapes in cone jet mode but the results are still not synchronized and the expanding behavior and hydrophilic behavior of the head makes it highly unstable.

Fig. 7. (a) the fabricated model head (b) bottom view of the fabricated orifice (bottom view).

Fig. 8. Effect of difference voltages on NPH meniscus.

c. Modified Prominences Hydrophilic Nozzle Head

The jetting process in PH is highly unpredictable, unreliable and as drop generation is not synchronized with the applied voltage even at very high voltage and low frequency. So modified prominences hydrophilic (MPH) head is fabricated.
The model diagram is shown fig. 9. In this head, boarder is introduced around the nozzle orifice to control the meniscus inside the orifice. For controlling the meniscus, the silver based ring around the meniscus is used. This ring provided the sufficient height to control the meniscus around the head. The design heads then tested for the patterning to find the optimal results and driving ejection. The deviation of the droplets is also tested on the substrate. For jetting behavior different potentials are applied to the nozzle head. From 1 kV to 4 kV potential, different dripping modes were observed but jetting mode was observed only after 5 kV as shown in the fig. 10.

![Fig. 9. (a) The MPH fabricated model head (b) the fabricated orifice bottom view](image)

Fig. 9. (a) The MPH fabricated model head (b) the fabricated orifice bottom view

d. *Modified Prominences Hydrophilic Nozzle Head with electrode (MPHE)*

![Fig. 10. Effect of difference voltages on MPH meniscus (a) the overall jetting behavior and meniscus shape after the ringing the orifice (b) jetting at 5 kV (c) jetting at 6 kV (d) jetting at 7 kV](image)

Fig. 10. Effect of difference voltages on MPH meniscus (a) the overall jetting behavior and meniscus shape after the ringing the orifice (b) jetting at 5 kV (c) jetting at 6 kV (d) jetting at 7 kV

e. **Comparison**

Firstly comparison of controlled meniscus and uncontrolled meniscus is studied. The study of angle between the cone surface and the axis of the nozzle heads at the point of the orifice is undertaken. For comparison and evaluation purpose of each controlled meniscus head, different electric potential wave form is being applied to compare and observe different dripping modes. The detail is summarized in Table I. From the table I, it can be seen that the MPH nozzle head has the ability to sustain the wide range of voltage than the hydrophilic head but the jet formation is more easily can be obtain than the MPHE head and MPHE head need less voltage for the transition from meniscus to jet to spay. Table I summarizes the different dripping behavior of the heads. The other value of the parameters like duty cycle, flow rate and substrate speed kept constant with 50%, 10µl/hr and 5mm/sec respectively. Where legends of table are: NA, D, MD, S, MS, RM, CJ, OJ, P, MJ and RJ can be interpreted as not applicable, dripping mode, micro-dripping, spindle, multi-spindle, ramified-meniscus, cone-jet, oscillating-jet, precession, multi-jet and ramified-jet mode respectively. To compare the droplet ejection and transition behavior of the both optimize type of inkjet nozzle heads to formulate the behavior. Table II shows each lab fabricated head. The table II also shows and compares different specification of each head type. From the table, the initial meniscus design and the jetting behavior can also be seen.
TABLE I
DRIPPING MODES

<table>
<thead>
<tr>
<th>Pulsed voltage</th>
<th>Pulsation time period</th>
<th>Mode Observed</th>
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<tr>
<td>(kV)</td>
<td>(Sec)</td>
<td>MPH</td>
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<td>0.01</td>
<td>NA</td>
</tr>
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<td>0.01</td>
<td>NA</td>
</tr>
<tr>
<td>3</td>
<td>0.01</td>
<td>NA</td>
</tr>
<tr>
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<td>D</td>
</tr>
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</tr>
<tr>
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</tr>
<tr>
<td>8</td>
<td>0.01</td>
<td>P</td>
</tr>
<tr>
<td>9</td>
<td>0.01</td>
<td>MJ/RJ</td>
</tr>
</tbody>
</table>

TABLE II
COMPARISON OF DIFFERENT HYDROPHILIC HEADS

Fig. 13. (a) Results of controlled hydrophilic nozzle head on PET substrate, (b) shows the graphical variation of line width on the substrate.

To analyze the results of MPHE experiment were also done on the moving substrate with 5mm/sec and results obtain is shown in the fig. 13. Different experiments were conducted to see the resemblance between the results. As the meniscus is more stable due to which the line due to drop extraction is more stable as shown in fig. 13. The line resolution is more stable and focus and less oblique. And controlled line width is also observed as shown in the graph.

V. CONCLUSION

Newly developed micromachining technologies enable the production of high resolution, electrostatically driven head. In this research, the focus of the analysis and investigation was to study the behavior of droplet ejection from hydrophilic for electrostatic system. Different hydrophilic type inkjet nozzle heads were compared and the behavior of the meniscus and the required extraction force being analyzed. Jetting and drop on demand behavior is also investigated. It was also found that the later could eject drop more precisely and synchrony with the pulsation and verified by printing conductive lines on PET substrate.

It was analyzed that when the pulsed voltage magnitude and width are further increased on heads, the induced electric stress becomes great enough to produce a cone-jet. As a result, the liquid at the tip of meniscus,
subjected to the most intensive normal electric stress, can be ejected directly out from the apex, thus causing a dripping mode. If the electric stress is small, some liquid on the meniscus surface will still be removed to the apex of the meniscus by the tangential electric stress, but no jet is created due to the lack of sufficient electric stress. Thus, a voltage pulse of greater amplitude can move the liquid on the surface of the meniscus and force it to form a much finer jet. From these results, the hydrophilic needle type inkjet nozzle permits us to eject precisely controlled very fine droplets and to print very fine linewidth at 6kV. This has advantages of small size, low power consumption, long life time and precise dropping of drop with high printing speed. This study will help to liquid ejection technique to facilitate the application of the inkjet printing technology for electronics devices.

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REFERENCES