A review on multi nozzle electrohydrodynamic inkjet printing system for MEMS applications

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Abstract. New microproducts require to utilize the variety of materials. Their complex three-dimensional microstructures have big aspect ratios. This ability to fabricate geometrically complicated 3D microstructures provides some additional profits to the additive manufacturing systems over traditional methods. Among the enormous variety of micro-products, depending on the mixtures of usefulness of the product and fundamentals of operation, the foremost types are micro-opto-electro-mechanical systems, micro electromechanical systems, micro-optical electronics systems and microelectronic products. Electrohydrodynamic inkjet printing is an innovative high-resolution technology of inkjet printing which has the benefits of being a non-contact, maskless, additive and direct-write methods. The resolution of printing of EHD surpasses by approx. two orders of magnitude compared to the general inkjet printing methods. It has been used mostly in cases of nano or micro manufacturing of very small objects for modelling of a big range of constituents on different substrates having the alternatives of either Drop-On-Demand mode or continuous mode. It is considered to be a capable substitute to thermal and piezoelectric based inkjet printing methods since it has a unique quality of producing small jet or droplets in comparison to the nozzle orifice. Several advantages in fine patterning are presented by EHD inkjet printing processes, but the little manufacturing speed of EHD inkjet printing is an unadorned disadvantage that has been hindering its probable extensive uses in the industry of electronics. To overcome this restriction, the direct printing of colloidal solutions with the help of multiple nozzle EHD inkjet printing method is used. This review offers a short account of multiple-nozzle electrohydrodynamic inkjet printing of colloidal solutions for its application in MEMS.

Keywords: Electrohydrodynamic inkjet. MEMS, multi-nozzle

1. Introduction

Patterning means deposition of selective functional ingredients on chosen substrates. It is an elementary prerequisite in several micro/nano manufacturing operations which are based on printing; like the investigation areas such as pharmacological industries in cases of discovering drugs, the production of microelectronic devices and in genetic engineering to produce microarrays of DNA. Several inkjet printers based on various actuation procedures such as aerosol, thermal and piezoelectric are broadly required in the industry. [1] Multiple-nozzle piezoelectric inkjet printing heads chiefly consists of thousands of different nozzles which were invented and successfully used for microelectronic devices. The piezoelectric elements used in these thick arrays of inkjet were reduced by the bulk piezoelectric materials. They covered big areas and achieved sufficient actuating strength for uniform drop generation. A multiple needle inkjet print head (thermal) by the technology of silicon
micromachining was fabricated by Wang and Bokor which used an array of thick bubble of thermal inkjet objects created over a single wafer of silicon [2]. To encounter the requirements of photovoltaic manufacturers, a commercially obtainable multiple nozzle aerosol inkjet printing head was established by Optomec Inc. One crucial resource in microelectronics is Silver due to its resistance to surface oxidation, High conductivity and chemical stability [3]. Here, to avoid the restriction of small throughput of the EHD inkjet method, a multiple nozzle of the same containing 3 nozzles is created.

2. Fundamentals of EHD Inkjet printing processes
Electrohydrodynamic (EHD) inkjet printing draw the fluid rather than pushing them just like usual inkjet printing methods; therefore, it produces very small droplets in comparison to the nozzle orifice and offers some exclusive features, like permitting very resolution of micro/nano objects and affluent dispensation of particulate solutions preventing any kind of nozzle obstructions. Here, the printing quality is never obstructed by the diameter of nozzle and the droplets size can be in the range of sub-micrometre.

2.1. Working Principle
Electrohydrodynamic inkjet printing uses electric fields for liquid flow generation. When an ink is provided to a nozzle without providing electrical potential, a meniscus in the shape of a hemisphere pendent at the nozzle tip is shaped by the surface tension at the liquid-air interface, because droplet remains hemispherical since the surface tension has a tendency to lessen the interfacial energy. This hemispherical meniscus is distorted into a cone with the help of electric field and a certain amount of electric potential is required [2]. As the potential difference is applied between the ground electrode and the nozzle, electric charges having the same polarities gather at the liquid meniscus surface due to Maxwell electrical stress; this ultimately affects the hemispherical meniscus and it distorts to produce a liquid cone which is known as the Taylor cone. As the electric field strength increases, the pinnacle of Taylor cone ejects a small liquid droplet, depending on the type of the applied electric potential. This discharge of a minute droplet in comparison to the needle opening has been the chief benefit of electrohydrodynamic method. Therefore, it enables printing at much finer resolution without reducing the size of the printing nozzle, which is particularly useful in printing highly viscous colloidal solutions or viscous polymeric fluids.

![Methodology of electrohydrodynamic printing method](image)

**Figure 1**: Methodology of electrohydrodynamic printing method (a)Schematic illustration of
electrohydrodynamic printing technique (b) When no electric potential is applied i.e. liquid is driven by pressure forces only (c) Schematic diagram of a Taylor cone with a continuous thin jet being emitted from its tip (d) Taylor cone with a small droplet ejecting from its tip.

2.2. Forces acting on liquid meniscus
On the application of electric potential, the liquid meniscus surface (Figure 2) is exposed to forces like surface tension ($\sigma_s$), hydrostatic pressure ($\sigma_h$) and electrostatic pressure ($\sigma_e$). The liquid surface and the electric field will be perpendicular to each other in case of the liquid being a pure conductor and the liquid surface will not be acted upon by any tangential stress component. This liquid bulk will be neutral in nature and the charges which are free will be restricted within a narrow layer [2]. This is not a flawless ink conductor, so the resultant stress of electric polarization acting on the surface of liquid has two separate components -the tangential component and the normal stress component. The stress components acting on the liquid surface in their respective directions has been shown below in Figure 2. The normal component of electric stress disrupts the liquid cone-jet where as the liquid will be moved from the surface of the meniscus to its apex with the help of the tangential electric stress to produce a jet. A stable cone-jet is created when the stress acting tangentially is adequately strong [2].

![Figure 2. Stresses developed in a liquid meniscus under the influence of external electric field](image)

2.3. Major Modes of EHD Inkjet Printing
In the following subsections, two major modes of printing is discussed- the Continuous Inkjet mode where jet comes out of the nozzle followed by breaking into a course of droplets and the D-O-D mode where the droplets are discharged from the nozzle opening whenever needed. Continuous EHD inkjet method of printing is the most appropriate direct writing approach of colloidal solutions for low resolution patterning [3]. The main advantages of continuous inkjet are its speed and the high speed of the liquid that allows it to travel a larger distance to the substrate. The fact that there is a continuous flow of ink through the nozzles minimizes the risk of clogging them. Another advantage of continuous EHD inkjet printing is that the scattering masses is significantly less for the submicron resolution printing in continuous mode than that of drop-on-demand mode. Also, since continuous mode is able
to form only continuous lines instead of a sequence of dots, therefore the use of continuous mode eliminates the requirement of overlapping of successive ink droplets to produce a continuous line. In EHD D-O-D printing method (Figure 1d), a pulsed voltage has been given to a vessel for charging liquid in place of constant dc voltage that distorts the meniscus to form a cone and hence create a droplet instead of a continuous jet [4,5]. The motive for this approach is that the normal electric stress (Figure 2) is probable to generate a D-O-D printing which is also called the mode of dripping whereas the tangential component of electric stress will transfer the ink to its apex from the liquid surface meniscus to produce a minute liquid jet. Once this tangential component of electrical stress is sufficiently strong, a jet is formed which is called continuous mode. Hence to evade the rigorous tangential stress in case of continuous printing mode, rather than simple dc voltage, a pulse voltage is superimposed over dc voltage in case of DOD printing.

2.4. EHD Inkjet Printing Jetting Modes

Maximum methods are categorized depending on these features. For any specific size of nozzle, ink and value of stand-off height, every mode begins at definite flow rate and voltage value, and it is continued inside a definite range of values [6]. Outside the given range, the jetting approach varies. Thus, every jetting approach has a definite range of rate of flow as well as voltage standards inside which it takes place. Jetting modes are split into 2 groups (Table 1). One group comprises of the methods where only bits of ink are emitted from the nozzle directly. It consists of modes such as: spindle, multi-spindle, dripping, micro-dripping and the ramified-meniscus mode. Another group contains the methods where the ink is issued in a vessel in a lengthy continuous jet breaking into minute droplets within a short space from needle mouth. The above group contains precession, cone-jet, multi-jet, oscillating-jet and ramified-jet method. Maximum scholars use micro-dripping or steady cone-jet method for printing. [7]

| Pieces of liquid           | Liquid Jets           |
|---------------------------|-----------------------|
| Dripping Mode             | Cone-jet Mode         |
| Micro-dripping Mode       | Oscillating-jet Mode  |
| Spindle Mode              | Precision Mode        |
| Micro-spindle mode        | Multi-jet Mode        |
| Ramified-meniscus mode    | Ramified-Jet Mode     |

3. Multiple Nozzle Electrohydrodynamic Printing

3.1. Multiple needle Multi material electrohydrodynamic deposition systems

A significant zone of sustained attention in the EHD-inkjet method is the enhancement of process throughput. Improved throughput is crucial to facilitate EHD-inkjet a feasible profitable manufacturing method. The two important methods for improving the process throughput are: rising the process speed which is also known as frequency of printing and by rising the amount of nozzles needed for any specified printing head. It was determined that using 3 nozzle printing head caused a 3
times reduction accordingly in the time taken for printing in comparison to a single nozzle printing head to print one device without any part fidelity loss. Hence, for huge areas of printing, it is essential to use multiple nozzle printing system. Again, heterogeneously combined practical automated systems frequently need various materials to be collocated on the same substrate. Hence, the requirement of highly complicated multiple material functionality results in the requirement for an EHD inkjet tool which is efficient of depositing multiple material liquid with pace and quality equal to that of a single material single nozzle system. Currently, multi-nozzle printing systems permit up to four kinds of materials to be patterned on a single substrate, quickly and with brilliant management of spatial measurements. A multiple nozzle multiple material deposition system was testified for heterogeneous addition of various characteristics over one substrate. The progress and assessment of an EHD inkjet method was also reported. The foremost problem with the progress of a multiple nozzle printing head is the communication of electric fields among all the nozzles that disturbs the print resolution. The preliminary characterization of electrostatic intervention presented in the scheme of multiple nozzle was carried out.

3.2. Cross-Talk or Interaction among multiple needles of Multi-nozzle electrohydrodynamic Printing
Electrohydrodynamic printing method offers various advantages in production of microelectronic devices by direct deposition of printed metal of high resolution with interconnected electrodes [8], the collectors for printed solar cells [9] and thin film transistors electrodes [10,11], yet the slow speed of production electrohydrodynamic printing has been a grave disadvantage that has been hindering its possible extensive uses in the industry on a large scale. To overcome this problem and achieve high manufacturing efficiency electrohydrodynamic printing process for large scale fabrication of printed circuit boards (PCB), displays, solar cells and printed thin film transistors (TFT), a multiple needle electrohydrodynamic printing method is still being principally examined by scholars. Mostly, articles concentrated on creating stable cone-jet and lowering the fault in the placement of the emitted jet. On the other hand, due to the interaction among the neighbouring jets which are charged electrically, a well-controlled multiple needle electrohydrodynamic printing method for simultaneous printing is very hard to achieve. It is due to the interaction for which the uneven distribution of electric field around the meniscus of all the needles, ultimately weakening the resulting liquid jets.

3.3. Development of Multiple Needle Electrohydrodynamic Print Head
This present article describes three types of multiple needle electrohydrodynamic print heads were used for utilized to print colloidal solutions. First, a prototype multiple needle electrohydrodynamic inkjet print head containing three needles and having discrete counter electrode were fabricated and successfully tested for deposition of silver colloidal solution. Then, this prototype head has been enhanced to a multiple needle electrohydrodynamic print head containing five needles and having discrete counter electrode were developed and successfully tested for printing of copper colloidal solution. Finally, the prototype multi-nozzle head been improved to a multi-nozzle EHD inkjet printing head consisting of five nozzles and having integrated counter electrode. In this article for simplicity, from now on the term “3ND multiple needle electrohydrodynamic print head” is being used for multiple needle electrohydrodynamic print head containing three needles and having discrete counter electrode. Similarly, the name “5ND multiple needle electrohydrodynamic print head” is being used for multiple needle electrohydrodynamic print head containing five needles and having discrete counter electrode and “5NI multiple needle electrohydrodynamic print head” has been used for multiple needle electrohydrodynamic print head containing five needles which are having integrated counter electrode.

3.4. Inks used
For printing metallic patterns, two kinds of conducting inks where the inks which are built on the suspension of metallic nanoparticle known as colloidal solution and the organo-metallic compounds are commonly used in printed electronics. Here both types of inks i.e. colloidal solutions containing
silver nanoparticles and copper nanoparticles and organo-metallic compound like organo-silver are printed. [5]

3.5. Manufacturing of a multiple needle electrohydrodynamic print head

The head of multiple needle electrohydrodynamic inkjet comprises of three parts: a polydimethylsiloxane holder, copper electrodes and glass capillaries. The PDMS holder is made-up with soft lithography method. The capillary holder is usually chosen due to its low price, hydrophobic nature, dielectric deposition, low thermal expansion constant and necessary optical characteristics. Here, six circular rods, three 4-mm-long and three 3-mm-long respectively has been used which are made of stainless steel both having outer diameters as 1.5mm. They are partially implanted respectively into two different rectangular poly-methyl meth-acrylate (PMMA) plates through small drilled holes. The dimensions of each of the plates 15.5 mm × 6.5 mm and 14.5 mm × 5.5 mm, respectively and an open shaped mould was made after gathering the plates. The mixture of PDMS comprises of a curing agent (Dow Corning, Midland) Sylgard 184 silicone elastomer base and a that are added in a ratio of 10:1 by mass with ten parts of base to one part of curing agent. The prepolymer combination is poured on the mould, then degassed at a pressure of around 5–10 Pa inside a desiccator by a mechanical vacuum pump for 1 hour to eliminate any air bubbles in the mixture and to ensure complete mixing of the two parts. The PDMS prepolymers is then treated for 1 hour at a 100°C temperature over a hot plate. After that, PDMS imitations were unpeeled from the mould keeping three L-shaped flow-ready channels. Subsequently the rods made of stainless steel which are required to mould the channels are even, since the process of eliminating them from the treated PDMS did not allow imperfections from rubbing or tearing. 3 glass vessel tubes of 0.75-mm inner diameter and 1.5-mm outer diameter and were pulled; then microscopic needles were shaped having a sharp tip approximately equal to 140–170 μm outer diameter and 100-μm inner diameter by means of a micropipette puller. Then 3 glass tubes were injected in the outlet channels of PDMS holder. Ultimately, from the top of the PDMS holder, 3 electrodes of copper which have the outer diameters as 500 μm were implanted[12,13].

![Figure 3](image-url)

**Figure 3.** Simplified representation of a multiple needle electrohydrodynamic print head manufacturing process: (a) Schematic manufacturing steps of preparation of mould, (b) resulting PDMS container with L-shaped channels for supplying ink, (c) complete electrohydrodynamic print head.
3.6. MEMS Fabrication using Inkjet

The first endeavour to fabricate printed MEMS devices was made by Fuller in 2002 [4]. They inkjet-printed metallic inks formed from gold nano particles at ~300°C platen temperature to make an additively built three dimensional structures without employing any sacrificial layer; and demonstrated vertical electrothermal actuators, resonant inductive coil and linear as well as rotary electrostatic-drive motors. They also realized the necessity of using a sacrificial layer for the fabrication of planer vertical electrothermal actuators. Poly(methyl methacrylate)(PMMA), patterned using a draw-down bar, was used as the sacrificial layer. Wilhelm et al. demonstrated actuators to modulate light employing an offset liquid embossing technique [4,5]. Solution-processed nanoparticles were used as the structural material. Polyimide was used as the sacrificial material and etched using oxygen plasma. Nakano et al. employed inkjet-printing and a NC cutting machine to fabricate MEM switches with an operating voltage of ~70 V [14,15]. They inkjet-printed silver nanoparticles as control electrodes on two polyimide substrates. A NC cutter processed adhesive film was sandwiched between the two polyimide films containing the control electrodes. Parylene was coated on one control electrode to avoid any short from one to another control electrode. Holes were formed by a punching machine and signal electrodes were inkjet-printed with silver nanoparticles ink. A similar fabrication approach was employed to fabricate a complementary MEM switches from the same research group, where a cantilever-type polyimide beam was placed in between two actuating electrodes [16,17]. The demonstrated MEM switch showed an operating voltage of ~60 V with switching delays in the range of few milliseconds. Although these works successfully demonstrated printed MEM switches, a great deal of manual assembling was involved in the process which may limit the process ability. Lam et al. demonstrated an inkjet-printed cantilever as a structural material [17]. PMMA was inkjet-printed and smoothed with solvent vapor annealing. A PMMA barrier was created on two sides of the sacrificial layer to form a mold-like structure. Silver nano particles ink was inkjet printed inside the mold and any undesired rims were trimmed using a laser trimmer. They also implemented an accelerometer structure using this technique. This work showed a repeatable inkjet-printed process flow excluding any manual processing and provided a very important improvement in printed MEMS.
Figure 4. Inkjet-printed MEM relays. (a) Three terminal and (b) four terminal relays. Structures were inkjet-printed using silver nano particles ink. Poly(methyl methacrylate) (PMMA) sacrificial layers were spin coated.

4. Conclusion

EHD-inkjet printing is an influential method for modelling of the functional constituents directly over different substrates. The capability of it to do modelling along with thin layer deposition helps in production of some electronic devices such as OLED/ Solar Cells, TFT and so on with the help of a single technology. Multi-nozzle multi-material deposition EHD-inkjet methods serve the purpose of process throughput improvements [8]. Here, to curtail the interaction among the neighbouring jets, the space from one nozzle to another was adjusted mathematically by inspecting the proportion of the electric field strength around the needle apexes. The effects of substrates on printing parameters are removed by assimilating the ring-shaped ground electrodes with each nozzle of the printing head in this multiple needle electrohydrodynamic print head. The printed results of 3ND, 5ND, and 5NI multi-nozzle EHD inkjet printing heads are examined both physically and electrically by using various characterization tools like scanning electron microscopy, optical microscopy, optical microscopy, X-ray diffraction, atomic force microscopy and four-point probe [13]. The practicability of multiple nozzle EHD inkjet printing process in industrial manufacture of microelectromechanical structures are established by such electrically conductive micro-tracks.

References
[1] Muhammed AK 2016 Inkjet-Printed Microelectromechanical Systems: Materials, Process and Devices, *University of California, Berkely* 12-37
[2] Arshad K, Khalid R, Dong SK, Kyung HC 2012 Direct printing of copper conductive micro-tracksby multi-nozzle electrohydrodynamic inkjet printing process, *Journal of Materials Processing Technology*, 27-60
[3] Arshad K, Khalid R, Myung TH, Dong SK and Kyung HC 2011 Multi-nozzle electrohydrodynamic inkjet printing of silvercolloidal solution for the fabrication of electrically functional microstructures, *Applied Physics A*, 4-9
[4] Nathan J, Robert W, and Russell A. 2020. Electrohydrodynamic and Aerosol Jet Printing for the Copatterning of Polydimethylsiloxan and Graphene Platelet Inks. *Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim* 1-3.

[5] Kyung HC. 2009. Development and ejection behavior of different material-based electrostatic inkjet heads, *International Journal of Advanced Manufacturing Technology*, 1-31.

[6] Zhang H, Wang C, Wang F, Wang Y, Wang Z, Chen X, Gui J. 2019. Studies on Ejection on of Cell Culture Medium by Electrohydrodynamic Method, *E3S Web of Conferences*, 3-8.

[7] K. Vikramaraj R and Naresh M. 2014. A Review on Electrohydrodynamic-Inkjet Printing Technology, *International Journal of Emerging Technology and Advanced Engineering*, 1, 1-4.

[8] H. F. Poon. 2002. Electrohydrodynamic Printing. PhD Thesis, *Princeton University*.

[9] Kyung HC, Arshad K, Khalid R, Doh YH, Kim DS and Kwan KR. 2011. Effects of Nozzles array configuration on cross-talk in multi-nozzle electrohydrodynamic inkjet printing head, *Journal of Electrostatics*, 3-8.

[10] Abdolkarim, Reza E, Mortezar, and Ahmad N. 2013. Numerical Simulation of electrohydrodynamic (EHD) Atomization in the Cone-Jet Mode, *Applied Mechanics and Materials*, 1-2.

[11] Khalid R, Arshad K, Nam NM, Kyung HC, and Kim DS. 2011. Study of electrohydrodynamic drop-on-demand printing through multi-step pulse voltage, *International Journal of Precision Engineering and Manufacturing*, 12.

[12] Arshad K, Khalid R, Kim HC, Kyung HC and Kim DS. 2010. Effects of process parameters on cross-talk in triangular array multi-nozzle EHD inkjet printing head, *Proc. of IEEE-ICIET*, 8-13.

[13] Lee HH, Chou KS, Huang KC. 2005. Nanotechnology, 16. 2436.

[14] Bali C, Brandlmair A, Ganster A, Raab O, Zapf J, Hübler A. 2016. Fully Inkjet-Printed Flexible Temperature Sensors Based on Carbon and PEDOT:PSS, 12th International Conference on Nanosciences & Nanotechnologies & 8th International Symposium on Flexible Organic Electronics, 6-7.

[15] Hadi Y, Vu-Dat N, Prashanta D, and Doyoung B. 2010. Flight behavior of charged droplets in electrohydrodynamic inkjet printing, *Applied physics letters*, 96, 1-3.

[16] King BH, O’Reilly MJ, Barnes SM. 2009. Charactersing aerosol jet multi-nozzle process parameters for noncontact front side metallization of silicon solar cells, *34th IEEE Photovoltic Specialists Conference*, 1107-1111.

[17] Umezu S, Nakazawa R, Kawam O. 2008. Cross-talk of multi-nozzle in electrostatic inkjet system, *International Conference Digital Printing Technologies*, 66-68.