A Review on Electrohydrodynamic-inkjet Printing Technology

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Abstract—Electrohydrodynamic (EHD)-inkjet printing is a novel high resolution inkjet printing technology with the advantages of being a maskless, non-contact, direct-write and additive process. Its printing resolution exceeds by about two orders of magnitude in comparison to the conventional inkjet printing systems. It is used in the field of micro/nano manufacturing for patterning of large class of materials on a variety of substrates with the options to use either Drop-On-Demand (D-O-D) or continuous mode. Printable electronics especially flexible electronics is one of the many fields where this technology has a lot to offer as the same EHD-inkjet setup can be used for electrospinning for thin film layer deposition, electrospinning for interconnection and EHD jetting for making electrodes. A lot of research has been carried out in the recent past to make its transition from a research tool to a commercial manufacturing process. Many challenges such as increasing the process throughput (i.e. the printing speeds) have to be overcome before the commercialization of this technology. Another major challenge is to develop a compact, affordable and user friendly test platform to further develop the process and associated applications. This review gives a brief account of the EHD-inkjet technology; the research activities carried out in recent years and the wide areas of applications of this technology. The working of the EHD-inkjet system along with the physics of the process has also been discussed in brief.

Keywords—Drop-on-Demand (D-O-D), Electrohydrodynamic (EHD)-inkjet printing, Electrospinning, Flexible electronics, Inkjet printing systems

I. INTRODUCTION TO THE INKJET BASED MICRO/NANO PATTERNING TECHNOLOGY

Patterning, i.e. selective deposition, of functional materials on desired substrates is a basic requirement in many of the printing based micro/nano manufacturing operations like the fabrication of microelectronic devices, research fields like pharmaceutical industries for drug discovery purposes and in biotechnology to make DNA microarrays. Controlled generation and deposition of micro/nano drops at higher and higher resolutions without adversely affecting the chemical properties of the deposited materials is the major challenge in micro/nano fabrication.

Traditionally, lithographic processes like nanolithography or photolithography etc. are used for achieving micro/nano patterning but these are too time consuming and expensive [1,2]. As an alternative to the lithographic processes, non-lithographic direct fabrication methods like inkjet and roll-to-roll printing are used because of their reasonable resolutions and higher throughputs. These direct fabrication methods can be classified as contact methods i.e. gravure, offset, flexographic etc. and non-contact methods i.e. inkjet technology. Because of the inkjet technology’s simple setup, cost effectiveness, additive process which reduces material loss and non-contact nature which nullifies any adverse effects to the substrate making it suitable for flexible electronics, it became one of the best choices for micro/nano fabrication.

Originally invented for printing computer graphic outputs, from the last few decades inkjet printing technology is widely used for patterning in the micro/nano manufacturing industries. It encompasses a wide variety of different techniques by which micro/nano droplets are generated and controllably deposited. It has forced its way from being just a graphic arts printing tool to the paradigm of micro/nano manufacturing. It has also been successfully used for the direct 3-D fabrication of micro/nano structures. Its areas of application includes micro-electronics, drug discovery, tissue engineering and biomaterials development, materials science and device preparation, MEMS, solar cells, mass-spectrometry, sensors and the list goes on.

Ink-jet printing systems also find its applications in the rapidly emerging field of flexible electronics. As ink-jet printers are contact-free (print heads are not in a direct contact with the substrates), printing can be done on very flexible and delicate substrates with remarkable precision and accuracy at higher speeds with minimum feature size in the sub-micron range.

Inkjet is not a single process but a diverse, versatile and multi-length scale group of process technologies, and a variety of mechanisms and energy modes are used to create material transfer to produce features from nanometer to micrometer range.
It exploits the **Plateau-Rayleigh instability** (often called only as the Rayleigh instability), named after Joseph Plateau and Lord Rayleigh, which explains the disintegration mechanism of the liquid jet into droplets [3]. Elmqvist of Siemens, in 1951, patented the first ink-jet device based on this instability [4]. Since then, the ink-jet technology saw many inventions like Dr. Sweet’s Continuous Inkjet (CIJ) printing system [5,6] in the early 1960’s and Zoltan (1972), Kyser and Sears’s (1976) Drop-On-Demand (D-O-D) inkjet printing system [7,8].

Commercially available inkjet printing systems can be divided into two modes based on the ejection of the inks: Continuous inkjet (CIJ), where jet emerges from the nozzle which breaks in stream of droplets and Drop-On-Demand (D-O-D) wherein the droplets are ejected from the nozzle orifice as and when required. Many researchers have reported problems of ink wastage in the start and end of the printing in continuous mode. This problem of ink wastage has been addressed by the introduction of D-O-D inkjet printing. Thermal Inkjet (TIJ) and Piezoelectric Inkjet (PIJ) printing systems are the predominant players in the area of inkjet technology (Fig.1).

PIJ printing systems are the piezoelectrically driven drop-on-demand devices which rely on the mechanical action of a piezoelectric membrane to generate a pulse which squeezes the nozzle to eject drops. Epson printers use this technology.

TIJ , sometimes referred to as bubble jet, is a drop-on-demand technology wherein a thin layer of liquid is heated locally by a thin film heater in a few microseconds to form a rapidly expanding vapour bubble that ejects an ink droplet. Hewlett Packard and Canon have manufactured highly successful lines of inkjet printers that have used this technology for over two decades [53].

However, PIJ and TIJ D-O-D systems are not able to produce droplets with a broad range of size distributions from the same nozzle. There resolution is limited to feature sizes of 20-30 µm [10]. For getting higher and higher resolutions in terms of the feature size, inkjet systems requires the use of smaller sized nozzles which faces the difficulty of manufacturing and also the problem of nozzle clogging. Also, the droplet placement accuracy for these processes is not high enough. So, the quest for getting higher and higher resolutions at higher and higher printing speeds with more precision and accuracy led to the development of various novel non-conventional ink-jet printing methods. One such technology for getting higher resolutions and better droplet placement accuracy utilizes externally applied electric fields.

This elegant way of manipulating droplet sizes, their ejection frequencies and placement on the substrate using externally applied electric fields is called as the Electrohydrodynamic inkjet (EHD inkjet) printing technology.

II. **EHD-INKJET PRINTING TECHNOLOGY: WHAT IT IS AND WHAT IT CAN DO?**

The great experimentalists like Robert Millikan, Lord Rayleigh and G. I. Taylor [11] have earlier tested the behavior of liquid jets and liquid drops in electric fields. Since then many researchers have tried to adapt the technique of controlling and manipulating the drop formation process by applying electric fields and EHD inkjet system has evolved as a prospective technology for micro/nano patterning.

EHD-inkjet printing technology has been a target of much research because of its ability to generate drops of very small size as compared to the other inkjet techniques like TIJ and PIJ for the same nozzle sizes.
Unlike the conventional inkjet methods, it pulls the liquid inks out of the nozzle rather than pushing it. As a result, it is able to produce ink-drops or ink-jets of size 2 to 5 orders of magnitude smaller than the nozzle size [12] which is not possible in case of the conventional ink-jet printing systems. The main components of a EHD inkjet printer can be classified into four sub-systems.

1) **Liquid supply system** which consists of a device to deliver the ink at desired flow rates to the tip of the conducting needle. The liquid can be supplied by using a syringe pump or a vacuum pump and the tubings.

2) **Positioning system** which consists of a motorized stage on which the substrate is mounted to position it as desired with respect to the tip of the needle for patterning. The needle can be mounted on either a manual or motorized stage to control its distance from the substrate (called as the stand-off height).

3) **Electrical system** which consists of a high voltage DC amplifier for applying voltages across the needle and the substrate. A function generator is also required to supply pulsed width modulated (PWM) signals which is the requirement in case of the D-O-D mode.

4) **Visualization system** is required to monitor and study the process of drop formation for various values of the process parameters. This is helpful in improving the process. The visualization system consists of a high speed camera, a microscopic zoom lens system and an illumination source.

Fig. 2. shows the schematic of an EHD inkjet printing system.

A wide range of functional organic and inorganic inks, including suspensions of solid objects can be printed using this technique with resolutions extending to the submicron range. The applications in printable electronics require higher print rates, better resolution and higher reliability while printing more complex Non-Newtonian and heavily solid loaded liquids. So, printed electronics represents an important application area that can take advantage of both the extremely high-resolution capabilities of EHD-inkjet printing as well as its compatibility with a range of functional inks.

Fig. 2. Schematic of the EHD inkjet printing system

Also, different devices require different fabrication processes for eg. Solar cell needs uniform thin film, TFT needs high resolution line width and uniform structure, sensors and MEMS need more complex patterns. EHD inkjet printer uses a fine jet generated at the apex of a liquid cone in the cone jet mode to create spray by electrospraying, fibre by electrospinning or inkjet and droplets by EHD jetting. These three types of EHD printing hold the same mechanism of EHD and the homologous experiment setups. Thus, it is promising for all the three methods used in printed electronics, such as electrospray for thin film layer, electrospinning for interconnection and EHD inkjet for making electrodes. Also different types of materials are required for the fabrication of a single component. All these requirements can be fulfilled by the same EHD inkjet printing set-up. Thus, EHD-inkjet printing has great potential to offer complex and high resolution printing and is opening new routes to nanotechnology. Many researchers have shown the capabilities of EHD-jet printing applied to different applications from biotechnology to microelectronics.

As with any manufacturing process, throughput rates (in this case printing speeds) and process robustness are key decision parameters for the commercialization of this process. EHD-inkjet printing system has seen recent advancements in the printing speed and reliability [10, 12]. EHD inkjet printing has emerged from the realm of pure research into the very early development stages of a potential commercially viable technology for micro/nano patterning.
Fig. 3. shows some of the application areas of the EHD-inkjet printing technology.

III. WORKING OF THE EHD-INKJET SYSTEM AND PHYSICS OF THE ELECTRIC FIELD DRIVEN JETTING BEHAVIOR

The electrohydrodynamic jetting was first reported by Bose in 1745 [13]. Many years later, in 1882, Rayleigh [14] did a theoretical analysis of the break-up of liquid under electrical stress and derived instability condition for the electrically charged droplets. Zeleny in 1917 [15] determined the criterion for the disruption of the jet issuing from the capillary maintained at high potential. In 1952, Vonnegut and Neubauer applied the principle of minimum energy to determine the most probable specific charge of the droplets. In 1964 and 1969, Taylor showed that the semi-vertical angle of the cone at the outlet of the capillary assumes the value of 49.3°.

Rayleigh’s theory is based on the balance between the repulsive electrostatic force and the surface tension of the liquid restoring forces. Rayleigh limit for the instability of charged droplet is given by

$$Q = \left(8\pi^2 \varepsilon_0 \gamma d^3\right)^{1/2}$$

Where \(Q\) is the charge on the droplet, \(\varepsilon_0\) the permittivity of the surrounding gas, \(\gamma\) is the surface tension of the liquid and \(d\) is the diameter of droplet. When the electrostatic force overcomes the surface tension of the liquid, electrically charged fine droplets are ejected from cone [16]. It is also referred to as Coulomb fission [17].

This relationship has been evaluated by a number of charge-to-mass ratio measurements [18-20] and size distribution [20-22]. However, Michelson indicated that the Rayleigh’s analysis considering only the electrical stress and surface tension is oversimplified [23]. The real process is greatly influenced by many parameters and these two forces cannot explain all the phenomena encountered in the electrospraying.

The control of the droplet size and modes of the electrospraying offer a wide spectrum of practical applications. EHD-inkjet printers eject liquid jets due to the Electrohydrodynamic instability. The main components of a EHD inkjet printer consists of a liquid supply system to supply liquids at desired flow rates to the tip of a conducting nozzle and a DC power source to apply voltages across the conducting nozzle and the substrates.

Before applying the electric field, the liquid is supplied to the tip of the nozzle until a hemispherical meniscus is formed there due to the surface tension between the liquid-air interface. After the hemispherical meniscus is formed, electric field is applied. The liquid contains equal number of positive and negative ions which are its conducting species. As the voltage is increased, depending on the polarity of the applied voltage, either the positive or the negative ions will start moving towards the liquid surface at the tip of the nozzle. With increase in the voltage, more and more ions will start accumulating near the liquid surface and due to the mutual columbia repulsion between them, the liquid surface starts experiencing a tangential electric stress.

![Stresses developed in a liquid meniscus under the influence of external E-field](Kim et al. 2011)
The magnitude of this tangential electric stress goes on increasing with the increase in voltage. At some voltage value, the tangential stress on the liquid surface along with the electrostatic attraction to the substrate deforms the hemispherical meniscus at the nozzle tip into a cone shaped pendant called as the famous Taylor’s cone having a semi-vertical angle of 49.3°. This is the boundary between stability and instability. A slight increase in the voltage beyond this value causes the electrostatic stress to overpower the surface tension resulting in the jet ejection from the Taylor’s cone. Different jetting modes like dripping mode, micro-dripping mode, spindle mode, cone-jet mode etc. are obtained as the voltage is kept on increasing.

Now depending upon the type of the applied voltage, we can have either Continuous Inkjet (CIJ) mode or Drop-on-Demand (D-O-D) mode.

CIJ mode is obtained if the voltage applied between the conducting nozzle and the substrate is a constant DC one whereas for the D-O-D mode, pulsed DC voltage is required. In the CIJ mode, stabilization of the micron size jet is very difficult. Also, problems in the placement of the liquid drops at start point and end point of the pattern are encountered.

The D-O-D mode has the biggest advantage that the jet emission is controlled, i.e., the jet is ejected from the Taylor’s cone as and when required. So, the placement accuracy of the drops on the substrate is high as compared to the CIJ mode.

**IV. VARIOUS JETTING MODES**

The application of potential difference between a conducting needle and a grounded electrode placed centrally below it with the flow of liquid ink in the region between gives rise to a phenomenon referred to as electrohydrodynamic jetting also known as electrospraying. The liquid ink travelling through the needle acquires a charge and after exiting the needle, it enters a high intensity electric field. At the needle’s tip, it can form different geometries like Taylor’s cone from which a jet or jets or even monodisperse droplets can evolve. The disruption of the evolved jets into droplets also depends on the applied electric field. Choi et al. [24] presented simple scaling laws that describe the intrinsic pulsation of a liquid jet that forms at the tips of fine nozzles under electrohydrodynamically induced flows. They also found that the force of gravity is negligible compared to the other forces, i.e., electrical and surface tension in both horizontal and vertical nozzle orientations. The break-up of the jets into different droplet sizes can be controlled through the applied potential difference, the flow rate of the liquid ink to the needle, the size of the needle and its configuration, i.e., its distance from the substrate and the ink’s mechanical and electrical properties; which are called as the process parameters.

The geometrical forms of the jet and the ways in which it disrupts into droplets have been classified into modes of spraying. There are various modes of spraying with various jet structures and break-up mechanisms, depending on the different values of the process parameters.
Classification of jetting modes has been the subject of intensive work, which can provide insight into the electrospray [25-27]. The size of liquid droplets ejected varies from the millimeter to the submicron range.

Several attempts, based on different criteria, have been undertaken to classify the modes of EHD spraying. [28] studied the various jetting modes of deionized water using a high speed camera. [29] studied the various ejection modes for pulsed-DC EHD inkjet printing using diethylene glycol (DEG).

[30] proposed a definition of the jetting modes of the electrohydrodynamic-jet as the way the liquid is dispersed into droplets, and characterized it by two criteria:

1. The geometrical form of the liquid at the outlet of the capillary (drop, spindle, jet), and
2. The mechanism of the disintegration of the jet into droplets (type of instability).

### TABLE I

**EHD-INKJET PRINTING JETTING MODES [30]**

<table>
<thead>
<tr>
<th>Pieces of liquid</th>
<th>Liquid jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dripping mode</td>
<td>Cone-jet mode</td>
</tr>
<tr>
<td>Microdripping mode</td>
<td>Oscillating-jet mode</td>
</tr>
<tr>
<td>Spindle mode</td>
<td>Precession mode</td>
</tr>
<tr>
<td>Multispindle mode</td>
<td>Multijet mode</td>
</tr>
<tr>
<td>Ramified-meniscus mode</td>
<td>Ramified-jet mode</td>
</tr>
</tbody>
</table>

Most of the jetting modes are classified according to these criteria. For a particular ink, nozzle size and stand-off height value, each mode commences at certain voltage value and flow rate, and is sustained within a certain interval of their values. Outside that interval, the jetting mode changes into another. Thus, each jetting mode has certain intervals of voltage and flow rate values within which it occurs. [30] divided the jetting modes into two groups. The first group consists of the modes in which only fragments of liquid are ejected from the nozzle directly. This group comprises: the dripping mode, microdripping mode, spindle mode, multi-spindle mode, and ramified-meniscus mode.

The second group includes the modes in which the liquid issues a capillary in the form of a long continuous jet which disintegrates into droplets only in some distance from the outlet of the nozzle. This group includes cone-jet mode, precession mode, oscillating-jet mode, multijet mode and ramified-jet mode. Majority of the researchers use stable cone-jet mode or micro-dripping mode for printing purposes.

V. DROP-ON-DEMAND (D-O-D) MODE

To generate uniform micro-drops for high-resolution printing, the pulsed-DC voltage method is superior to continuous-DC voltage methods because of its controllability. Printing time is cut down by a factor of 30 using the pulsed mode operation as compared to a constant voltage jet printing mode [12]. Also D-O-D EHD-inkjet enables on the fly diameter change, i.e., the droplet diameter is varied while printing the same pattern without changing the nozzle tips. Using D-O-D mode, Park et al [31] realized printed dots under 1 µm at 300 Hz, Paine et al [32] printed 2.886 µm dots at 1 Hz, Wang et al [33] printed 120 µm dots at 1 Hz, and Nguyen et al [34] printed 15 µm dots at 10 Hz. Young et al [35] investigated electrohydrodynamic jetting in order to print ultra-fine dots and lines in drop-on-demand (DOD) mode, using a hybrid micro-electromechanical system-based printhead with a piezoelectric actuator. Such hybrid system enabled jetting without applying an extremely high-voltage pulse.

Scaling laws describing the jet diameter and frequency have been described by Choi et al [24] through experimentation and literature results. They propose the following relationship between the frequency of jetting, f, the voltage potential, V, and stand-off height, h:

\[
g = \frac{V \sqrt{V}}{h}
\]

Where k is a scaling factor constant dependent on the viscosity of the ink, the nozzle diameter, fluid flow rate, and permittivity of free space.

Due to the relationship between frequency and droplet diameter according to Equation (1), a method for controlling them independently was developed in [12]. A DC voltage is applied to the nozzle which forms the Taylor cone but does not allow jetting of the ink. When a droplet is required, the voltage is then pulsed to a much higher value that guarantees a jet to be formed. A pulse width modulated (PWM) DC voltage signal which is fed to the nozzle has the following characteristics:
D-O-D: Pulsed voltage characteristics

- Voltage pulse peak ($V_p$) induces a fast EHD-jetting mode for a short duration while a baseline dc voltage ($V_d$) is picked to ensure that the meniscus is always deformed to nearly a conical shape but not in a jetting mode.
- Duration of pulse ($T_p$) determines the volume of the droplet, i.e., feature size on the substrate.
- Droplet frequency is controlled by the time interval between two successive pulses ($T_d$).
- A jet printing regime with a specified droplet size and droplet spacing can be created through a suitable choice of the pulse width and frequency.

Thus, there is a nonlinear relationship between the applied voltage frequency and droplet deposition frequency under pulse voltage at voltage frequency values greater than the plateau frequency. So, for getting hindrance-free on-demand printing even in the case of pulsed DC voltage, the frequency of the input signal needs to be set below the plateau frequency.

The diameter of an ejected drop $D_{drop}$ from the nozzle tip can be calculated by using the following relation:

$$ V_{drop} = \frac{Q}{f_{input}} = \pi \left( \frac{D_{drop}^2 h_{drop}}{8} + \frac{h_{drop}^3}{6} \right) $$

Where $V_{drop}$ is the volume of one drop, $Q$ is the flow rate, $f_{input}$ is the frequency of the pulsed voltage and $h_{drop}$ is the height of a drop.

VI. MULTI-NOZZLE MULTI-MATERIAL EHD-INKJET DEPOSITION SYSTEMS

A critical area of continued focus in the EHD-inkjet technology is the improvement of the process throughput. Increased throughput is a key for enabling EHD-inkjet as a viable commercial manufacturing process. There are two main approaches for increasing the process throughput: improving the speed of the process also defined as printing frequency, and increasing the number of nozzles for a given printhead. As the number of nozzles increases, the printing time will go down to $\Delta t / n$, where $\Delta t$ is the printing duration of a single nozzle and $n$ is the number of nozzles. [37] concluded that the use of a 3 nozzle printhead resulted in a corresponding 3 times reduction in printing time as compared to a single nozzle printhead for printing a single device without the loss of part fidelity. So, for large area printing, multi-nozzle printing system is the need. Also, heterogeneously integrated functional electronic systems often require multiple materials (polymers, metals, biological materials) to be present and collocated on the same substrate. Thus, it is also this demand for more complex, multimaterial functionality that leads to the need for an EHD inkjet printing tool capable of depositing multiple material inks with same speed and resolution as with the case of a single nozzle single material deposition system. Presently, multinozzle printing systems enable upto 4 different types of materials to be patterned on a single substrate, in rapid fashion and with excellent control over spatial dimensions and registration. [38] reported a multi-nozzle multi-material deposition system for heterogeneous integration of different functionalities on a single substrate.
[39] reported the development and evaluation of a EHD jet printing that uses an addressable multinozzle. The main issue with the development of a multi-nozzle printhead is the interaction of electric fields between the multiple nozzles which affects the print quality. [37] performed the initial characterization of the electrostatic interference introduced in the multi-nozzle design.

VII. DEVELOPMENTS IN THE EHD-INKJET TECHNOLOGY

D.H. Choi and I.R. Smith (1998) from the Natural Imaging Corporation claimed the first patent for EHD inkjet printing under the US patent 5838349. The process was not used for high-resolution printing until the University of Illinois developed a manufacturing system specifically for that purpose. In January 2009, the University of Illinois was granted a patent (WO2009/011709) for high resolution EHD-inkjet printing for manufacturing systems.

Majority of the research activities for the development of a commercial EHD inkjet printing system are taking place in the University of Illinois at the Urbana Champaign. Park et al. [31] demonstrated high resolution EHD-inkjet printing using expensive custom built equipments. Barton et al. [10] developed a desktop system for EHD-inkjet printing designed from the commercial off-the-shelf technology (COTS) components. They were able to generate average droplet size of 2.8 microns from a nozzle size of 5 microns, i.e., droplets nearly half the size of the nozzle size. [40] deposited 20 micron circularly shaped polymeric droplets from 100 micron size nozzle at voltage frequencies less than 100 Hz, i.e., droplets 5 times less than the nozzle size. Graf et al [41] developed a second generation EHD inkjet printing system with a budget less than USD 50,000 having multi-material capabilities with a dual print head, interpolation and NC programming for line writing capabilities in addition to raster-scan printing, and automated image analysis-based overlay registration capabilities for quick set-up.

[42] described the application of EHD inkjet in wide-ranging areas of biotechnology. [43] patterned DNA without adversely affecting its properties in arrays and other various complex patterns with printing resolutions approaching 100 nm. [42] reported the use of EHD inkjet printing for creating micro and nanoscale patterns of proteins on various surfaces ranging from flat silica substrates to structured plasmonic crystals, suitable for micro/nano array analysis and other applications in both fluorescent and plasmonic detection modes.

The approaches function well with diverse classes of proteins, including streptavidin, IgG, fibrinogen and gamma-globulin without adversely altering the protein structure or function. [44] showed that EHD inkjet printing can be used to process and deposit living cells (Jurkat cells) in suspensions onto surfaces without having adverse effects on living cells. Kim et al [45] patterned and then grew viable Escherichia coli cells. Jayasinghe et al [44] used a pipette to electrospray cell samples onto a substrate.

[46] reported the applications of inkjet printing in microelectronics. [2] concluded that EHD inkjet printing can be used for printing of conductive lines for metallization in printed circuit boards and backplanes of printable transistors. [47] showed applications in fabricating conductive microtracks and microconnects and printed silver tracks with feature size down to 35 microns. Wang and Stark [33] demonstrated 3D silver microstructures with 100 μm resolution. Youn et al [48] showed 6 micron silver lines using a tilted nozzle. [49] printed a set of silver lines with a few hundred nanometers in thickness and with a few hundred micrometres in width with EHD inkjet printing. [50] used EHD-inkjet printing for producing arrays of colloidal suspensions of colloidal crystalline stripes on surfaces. [1] generated discrete droplets with 45-55 microns in diameter and continuous tracks with 60 microns in width by using a 110 micron nozzle. They also fabricated basic electronic components such as coated resistors, inter-digitated capacitors and spiral inductors by printing continuous silver tracks as the conducting leads using EHD-inkjet. [31] demonstrated the high resolution EHD-inkjet printing with print feature sizes in the range from nearly 240 nm to 5 nm. [51] characterized the jetting rule of polymer solution experimentally under low frequency pulsation. [12] demonstrated the capability for printing speeds of 1000 droplets per second, while producing consistent and controllable droplet sizes of 3-6 microns. [29] Created a map of different ejection modes with droplet ejection frequencies of 1 Hz, Q= 0.2 ml/h using a nozzle diameter of d_n=1.27mm with DEG as the working fluid. Muhammad et al 2010 performed thin film deposition of CIS (Copper-Indium di-Selenide) through electrospray deposition by using 430 micron ID metallic nozzle. [52] reported a hybrid EHD inkjet system where piezoelectric actuator is used to supply a fixed volume of ink to the nozzle’s exit and electrohydrodynamic technique is used to form ink droplets.

Thus, lot of research activities have been carried out which shows the high resolution printing abilities of the EHD-inkjet with wide range of functional inks.
However, a database of printing conditions for different commercially available functional inks should be built which will serve as a recipe to the subsequent EHD-inkjet users. Also, throughput improvement is critical to fully realize the potential of this emerging manufacturing process.

VIII. CONCLUDING REMARKS

EHD-inkjet printing is a very powerful tool and process for the direct patterning of the functional materials on a large variety of substrates. Its ability to do patterning as well as thin film deposition can help in fabrication of the electronic devices such as TFT, OLED or Solar Cells etc. through a single technology. Its flexibility in terms of selection of the wide range of ink materials and substrates together with its high resolution capability and high droplet registration accuracy makes it a forefront runner for micro/nano fabrication. However, process throughput improvements remains to be a major challenge before its complete transition into a commercial technology. Multi-nozzle multi-material deposition EHD-inkjet systems can serve this purpose. Developing this technology will allow exploring the potential of EHD-inkjet printing in high resolution fabrication of micro-electronic devices which appears to be the promising direction for the future.

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