碩士學位論文

Study of Electrostatic Inkjet Printing Head Performance with Electrode Configurations

濟州大學校大學院

기계 工學科

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Study of Electrostatic Inkjet Head Performance with Electrode Configurations

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And Co-supervised by Professor Jung Dong Won,

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The thesis has been examined and approved.

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Department of Mechanical Engineering

GRADUATE SCHOOL

JEJU NATIONAL UNIVERSITY

DEDICATED TO

MY PARENTS, MY FAMILY AND TEACHERS

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In the end I would like to honor the lovable and respectful Korean people who supported me when I was in trouble despite of language barrier. They are the wonderful nation and deserve more than mentioned here. I thank them all.

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ABSTRACT

전자 회로와 flexible substrates 위로의 전도성 패턴 개발은 저렴한 비용과 전자 제품조립의 용이함을 위한 방법으로서 관심을 받고 있다.

인쇄 전자에는 스크린 인쇄, flexography, 그라비아, 리소그래피 및 잉크젯 오프셋 등 다양한 기술이 있다.

이러한 여러 가지 기술 중 inkjet printing techniques 은 전자공학의 여러 분야로의 적용, 유연 기판, 저온 처리 능력과 낮은 에너지 비용 등의 큰 이점을 가지고 있기 때문에 가장 유망한 기술로서 많은 연구가 이루어지고 있다.

잉크젯 인쇄의 운전 방법은 세 가지 방법(electrostatic, piezoelectric and thermal methods)으로 나뉠 수 있다

잉크젯 프린터는 기판위로 패터닝 하기 위해 다양한 사이즈의 droplets 또는 용액을 jetting 한다.

그러나 Piezo and thermal inkjet printers 타입에는 몇 가지 제한 사항들이 있다.

Piezo inkjet printing head 의 경우, droplet 은 노즐사이즈 보다 작을 수 없고 thermal inkjet printing head 인 경우 잉크 특성의 유지가능성이 문제가 된다.

반면에 electrostatic inkjet printing head 의 경우, jet 을 발생시키는데 특정 조건을 부가하여 주면 노즐 사이즈 보다 70%정도 작은 사이즈의 jet 을 얻을 수 있고 잉크의 특성 또한 유지 할 수 있다.

따라서 잉크의 정전기 증착은 이 연구 분야에 있어서 여러 가지 이점을 가지고 있고 나아가 다른 종류의 기판에 적용에도 많은 향상을 가지고 올 것이다.

Inkjet printing 은 organic light-emitting diode displays, field–emission displays 와 printed–circuit–board wiring 등과 같은 인쇄 패턴분야에 있어서 유용하고 유리한 기술이다.

Electrostatic inkjet printing 은 헤드 제작비용을 절감 할 수 있도록 시스템이 기계적 작동을 극복할 수 있게 한다.

통상 metallic capillary 는 정전기적 잉크젯 인쇄 헤드에 사용된다.

정전기 잉크젯 인쇄는 기계적인 노력을 줄일 수 있고 시스템을 더 높은 주파수 영역에서도 더 정확하게 할 수 있다. 하지만 multi-nozzle electrostatic inkjet printing head 개발에 있어서는 cross talk 를 최소화 하기위해 metallic capillary 대신 conductive metallic electrode 를 헤드에 삽입하여 사용한다.

하지만 수직으로 삽입된 electrode head 는 몇 가지 문제점들을 가지고 있다. 일반적인 대안으로는 하나의 전극을 수직으로 정전기 잉크젯 인쇄 헤드에 삽입하는 방법이 있다.

헤드 안의 전극의 배치는 안정된 meniscus, droplet extraction 과 jetting 을 얻기 위한 요구전압이 매우 높다.

또한 head 에 수직으로 삽입된 단일 전극으로 부터 균일한 패턴을 얻는 것은 쉽지 않다.

여러 가지 원인들이 있지만 conventional electrostatic inkjet printing head 에 수직으로 전극을 삽입하는 것이 주요 원인이다.

이 실험 장치에서 얻어진 Jet 은 불안정한 meniscus 에서 얻어지기 때문에 안정하지 않다.

따라서 균일한 패턴을 얻기 위해선 안정적인 jet 이 필요하고 안정적인 jet 을 위해선 안정적인 meniscus 의 개발이 필요하다.

안정적인 meniscus 는 안정적인 cone 을 만들고 그것은 안정적인 jet 을 만들기 때문에 Head assembly 는 안정적인 meniscus 를 얻는데 매우 중요한 요인이 된다.

Head 에서 안정적인 meniscus 와 droplet extraction potential 의 최소화를 얻어내기 위해선 잉크 특성과 노즐입구의 사이즈, actuator 와 접지사이의 거리를 적절히 조절해야한다.

안정적인 meniscus 를 얻기 위하여 printing head 에서의 electrode 장치의 새로운 접근법이 고려되었다.

electrode 를 서로 다른 위치에 적절하게 노출된 채로 삽입시켰다.

안정적인 meniscus 와 jet 은 50°~60°의 각도로 삽입된 두 개의 전극(DSIAEs: double side inserted angular electrodes)으로부터 얻을 수 있었고 실험을 통하여 균일한 patterns 을 얻을 수 있었다. electro static inkjet polymericglass capillary printing head(PGH)는 평행하게 power supply 에 연결하였다.

새로운 head 개발 방식(DSIAEs Head)으로 얻어진 pattern 들과 conventional head assembly 방식에서 얻어진 pattern 을 비교하고 분석하였고 각 방식에서 얻어낸 Pattern 결과로부터 두 가지 방법모두 거의 동일한 resolution 을 갖는 것을 알 수 있었다.

하지만 인쇄된 pattern 들의 균일성면에서는 DSIAEs head 에서 더 높은 결과를 얻었다.

또한 high RMS values 기판으로의 patterns 이 더 높은 고착력을 보였다.

Patterns 의 기판 위 고착을 위하여 ASTM D3359 B 방식을 사용하였다.

ABSTRACT

Development of electronic circuitry and conductive patterns on flexible substrates has attracted significance interest as a pathway for easy fabrication of low-cost and large area electronics. There are various printed electronics technologies such as screen printing, flexography, gravure, offset lithography and inkjet. But in all of these technologies inkjet printing techniques are the most promising. Because it has a great advantage over other owing to its applicability to electronics large–area, flexible substrates, low temperature process ability and low energy cost. The driving methods of inkjet printing can be divided into three types: electrostatic, piezoelectric and thermal methods. Inkjet printers operate by propelling various size (mostly tiny) droplets or jet of fluid depends on application, onto substrate to print patterns. There are some constraints in Piezo and thermal inkjet printers. In case of Piezo inkjet printing head it is not possible to get droplet less than nozzle orifice size and in thermal inkjet printing head sustainability of ink properties is a big issue. While in case of electrostatic inkjet printing head a jet can be achieved which is It gives the provision to produce jet which is almost 70% smaller in diameter from nozzle diameter and also ink properties remain the same as it is. Therefore, electrostatic deposition of ink is taking boost in research and will be helpful in future for printing patterns on different substrates. Inkjet printing is a smart technology for printing patterns i.e. organic light-emitting diode displays, field–emission displays and printed–circuit–board wiring etc. Electrostatic inkjet printing enables the system to overcome the mechanical actuation which helps in reducing head fabrication cost.

Conventionally a metallic capillary is used for electrostatic inkjet printing head. Electrostatic Inkjet printing reduces mechanical effort, make system more precise even at higher frequencies. But in view of developing multi-nozzle electrostatic inkjet printing head, a conductive metallic electrode is inserted in head for electrification of ink, instead of using metallic capillary to minimize crosstalk. But, still there some issues are related to vertically inserted electrode head. Usual practice is that a single electrode is inserted vertically in electrostatic inkjet printing head. With this configuration of electrode in head it is observed that voltage requirement for getting stable meniscus, droplet extraction and jetting is very high. Also obtaining uniform patterns with vertically inserted single electrode head is not easy to obtain. There are so many reasons for it. One of the reasons is vertical insertion of electrode in conventional electrostatic inkjet printing head. Jet obtained with this configuration is not stable because it is obtained from less stable meniscus. Reason for less stable meniscus is vertical inserted electrode vibration when voltage is applied to it. Therefore, to get uniform patterns, a stable jet is required for it and for a stable

jet attainment a very stable meniscus is needed to develop. Because a stable meniscus gives a stable cone and a stable cone in turn gives a stable jet.

To get a stable meniscus, head assembly is very important. For obtaining stable meniscus and minimizing droplet extraction potential, electrode configuration in head, ink properties, nozzle orifice size and distance between actuator and ground electrode can be manipulated.

For getting stable meniscus a new approach of electrode configuration in printing head is taken on. Electrode is inserted at different positions with suitable exposure and its performance is noticed. It is observed that stable meniscus and jet are obtained with configuration of two electrodes inserted with suitable exposure at an angle of (50^0~60^0) from opposite sides i.e. double side inserted angular electrodes (DSIAEs) inside electrostatic inkjet polymeric glass capillary printing head (PGH), connected in parallel to power supply. Also in turn uniform patterns are obtained with it.

Printed patterns obtained with new developed head (DSIAEs Head) assembly and conventional head assembly are compared and analyzed. It is observed that printed patterns obtained in each case turns out of almost the same resolution. But uniformity of printed patterns has been increased more with DSIAEs head. For adhesion of printed patterns with substrates ASTM D3359 B is followed. It is observed that patterns have shown better adhesion with high RMS values substrates.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

In the last decade there has been tremendous focus on producing cheaper technology which can replace micron level low throughput MEMs manufacturing with the focus of printing on the flexible substrate. Thermal or piezo driven inkjet technology is widely in use for physical document archiving and fabrication of printed electronic devices. Both of these technologies have been matured and are being in use for the last three or four decades (Elmqvist 1951, Sweet 1965 & 1971, Buehner et al., 1968-1977). Although the drop-on-demand droplet can be achieved through these technologies but these are also confronted by the challenges in the printed electronic industry.

For instance thermal inkjet which works on the principle of forming a minute bubble in the ink chamber by heating element and displacing enough volume in the ink chamber so that the droplet can be ejected through the nozzle outlet has two major drawbacks. First, the thermal sensitive liquid in the ink chamber cannot be used as a working fluid and secondly it is difficult to achieve smaller droplet size than the nozzle outlet diameter. These drawbacks put the limitation on the usage of thermal inkjet print head to be utilized for fabricating electronic devices since the ink characteristics changes due to heating especially in case of biomedical devices.

Whereas in case of piezoelectric inkjet print head some of the issues pertaining to thermal inkjet such as the use of thermal sensitive ink and higher print frequencies can be addressed but generation of droplet size smaller than the diameter of nozzle remains in question. Moreover, the high fluidic channel resistance offers physical challenges in overcoming the ink chamber pressure and generating the necessary pressure for droplet size smaller diameter through piezoelectric print heads.

Improvement in the produced image quality, printing speed, printing resolution and accuracy is under constant demand. In order to confront these challenges electrostatic inkjet printing seems to be the promising technology in addressing the tailbacks in the printed electronic industry for fabricating devices at higher throughput and resolution.

Even though the thermal and piezo driven inkjet technology offers one of the solution to produce cheaper fabrication process for producing high throughput printing of micro droplets with appreciable control over the placement of drop but the drop size has the limitations. Firstly the drop size smaller than the nozzle orifice size is difficult to achieve and secondly droplet generation through outlet orifice smaller than 30μm is difficult to achieve.

Moreover incase of thermal inkjet process the thermal dissipation of electric heater in the ink chamber to form the bubble responsible for droplet ejection put limitation on the usage of ink. For the same reason in many bio applications thermal inkjet printing doesn't seems to be applicable.

To overcome the above mentioned issues Electrostatic Inkjet printing technique of printing electronics is introduced. Nowadays electrostatic deposition of ink is taking boost in research and will be helpful in future for printing patterns on different substrates [1]. Main advantage of this technique is that it can produce jet which is almost 70% smaller in diameter from nozzle diameter [2]. It reduces mechanical effort, make system more precise even at higher frequencies. Electrostatic inkjet system increases robustness of system. Initially in conventional electrostatic inkjet printing head a metallic capillary is being used. But when it comes to developing multi-nozzle electrostatic inkjet printing head, a conductive metallic electrode is inserted for electrification of ink. In electrostatic inkjet printing head a single electrode is inserted vertically. But with this configuration the issues of voltage requirement for getting stable meniscus, droplet extraction and jetting is very high [3]. Also obtaining uniform patterns with this head assembly is not an easy job. To obtain uniform patterns, getting a very stable jet is required and it can only be obtained from a very stable meniscus. So to get a stable meniscus, head assembly can be manipulated.

This thesis is a trying effort in addressing some of the issues related to electrostatic inkjet printing technology and trying to introduce new head assembly for overcoming deficiencies related to current conventionally used one.

Along with this, printed patterns adhesion with substrate is studied and analyzed obtained with conventional head and new developed head, while keeping in view, ink and substrate properties and co-related properties of them.

1.2 MOTIVATION

The Electrostatic inkjet provides the solution to the aforementioned challenges but the device itself is difficult to fabricate and offers research challenges. Due to its complex integration in the existing printing technology and drive for achieving smaller droplet size; this field offers exciting opportunity. Stable head assembly ensures stable meniscus generation and stable jetting. In turn uniform printing of printed electronics is assured. Also the driving energy for the droplet generation can be reduced by suitable exposure of electrode in electrostatic inkjet head. The proposed work in this thesis explores the possible solution by proposing a suitable electrode configuration of head assembly, from which a stable meniscus can be obtained. Consequently from stable meniscus a stable jet can be obtained by utilizing the electrostatic potential in a pragmatic manner.

1.3 THESIS OVERVIEW

In this dissertation two issues pertaining to printed electronics are discussed. First Electrostatic Inkjet Printing Head Development has been discussed for achieving uniform patterns by minimizing extraction voltage. For this purpose different head with different electrode configurations in inkjet head are developed and their performance are studied i.e. single side inserted angular electrode head (SSIAE),double side inserted angular electrodes head (DSIAEs Head), double side inserted electrodes head (DSIEs Head) and ring shaped electrode head. In this approach inserted electrode electrifies ink with minimum exposure inside the head.

It was found that it is possible to achieve stable jetting through a stable head assembly main but to modify and convert it to a multi nozzle head is difficult to achieve. For the same reason the vertically inserted electrode or metallic capillary for designing an existing electrostatic inkjet head needed to modify. Such a modified configuration of head assemble is needed to develop which is compatible for designing multi nozzle head and to minimize or fully avoid cross-talk in it. It is also shown in the work presented in this thesis that for a conductive liquid it is possible to achieve the stable meniscus and stable jet with 40% to 50% less potential for double side inserted angular electrodes head as compared to vertically inserted electrode head.

The second section of the thesis presents the interface attachibility analysis and adhesion of printed patterns to different substrates. For this purpose two types of substrates has been used i.e. hydrophilic and hydrophobic substrates. For checking hydrophilicity and hydrophobicity, AFM and contact angle analyzer are use for surface topography and measuring contact angle respectively. For attachibility between ink particle and substrate, adhesion of printed patterns is checked by standard test of ASTM D 3359 B using 3M 610 pressure sensitive tape. It has been observed that printed patterns have better adhesion with high surface roughness substrates and vice versa.

Furthermore the thesis provides the overview of printed electronics with reference to flexible printing and its importance by keeping in view the market investment for producing printed electronic devices. The role of electrostatic printing is also highlighted for potential benefit that can be achieved through electrostatic inkjet printing.

The forth coming compilation of the dissertation is as follows

Chapter 2 provides the overview of the emerging printing electronics market with the share of the inkjet printing technology in that market and details the existing printing technology. Furthermore, it outlines the role of inkjet printing in printed electronics.

Chapter 3 provides the literature survey regarding ink, substrate, sintering, adhesion and interface analysis of printed patterns.

Chapter 4 outlines the conventional head assembly and developed head assembly. Electric field strength simulation inside and at the tip of conventional and developed head have been done.

Chapter 5 discusses the experiments done with each fabricated head, results obtained through and highlights the benefits of the developed head for obtaining stable meniscus and stable jet and its efficacy in obtaining the the uniform printed patterns through electrostatic inkjet printing. Also adhesion and interface analysis have been discussed.

Chapter 6 presents the summary of the dissertation, draws conclusion to the research and sheds light on possible enhancements in the proposed work.

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[3] Droplet Ejection Behavior in Electrostatic Inkjet DrivingYuji Ishida, Keigo Sogabe, Shintaro Kai, and Tanemasa Asano Graduate School of Information Science and Electrical Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

CHAPTER 2

PRINTED ELECTRONICS

2.1 INTRODUCTION

Printed electronics is a set of printing methods used to make electrically functional devices. Paper has been often proposed to be used as substrate but due to very rough surface texture and high humidity absorption other materials such as plastic, ceramics and silicon has been applied more widely. Several printing processes have been piloted and printing preferably utilizes common printing equipment in the graphics arts industry, such as screen printing, flexography, gravure, offset lithography and inkjet. Instead of printing graphic arts inks, families of electrically functional electronic or optical inks are used to print active or passive devices, such as thin film transistors or resistors. Printed electronics is expected to facilitate widespread and very low-cost, low-performance electronics useful for applications not typically associated with conventional high performance (i.e., silicon-based) electronics, such as flexible displays, smart labels, decorative and animated posters, and active clothing[1].

The term printed electronics is often used in association with organic electronics or plastic electronics, where one or more functional inks are composed of carbon-based compounds. While these other terms refer to the material system, the process used to deposit them can be either solution-based, vacuum-based, or some other method. Printed electronics, in contrast, specifies the process, and can utilize any solution-based material, including organic semiconductors, inorganic semiconductors, metallic conductors, nano-particles, nano-tubes, etc. Electronic applications with high switching frequencies and high integration density (so-called "high-end electronics") will be dominated for a foreseeable future by conventional electronics, [2] which in turn needs high investment and fabrication costs. In contrast, printed electronics as a complementary technology targets at the establishment of a "low-cost electronics" for application fields, where the high performance of conventional electronics is not necessary as shown in figure2.1.

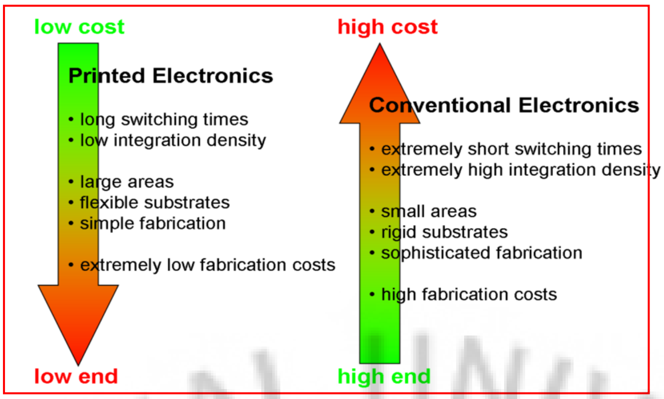


Figure2.1. Printed Electronics Vs Conventional Electronics

Inkjet printing is one of the methods of generating micro drop as a substitute process for conventional manufacturing of electronic integrated chip as shown in figure2.2. There are numerous applications of such a micro drop generated through inkjet process and more specifically drop-on-demand inkjet process. It will be of foremost importance that the drop-on-demand inkjet printer provides high printing speed with higher printing resolution. Since electrostatic printing can address both the in-demand issues for the printing therefore it has numerous applications in printed electronic devices such as RFID, flexible display, solar cell, sensors, batteries etc (Ishida et al., 2008). Moreover contact-less drop on demand printing scheme 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 (Heinz and Hertz 1985, Le 1998).

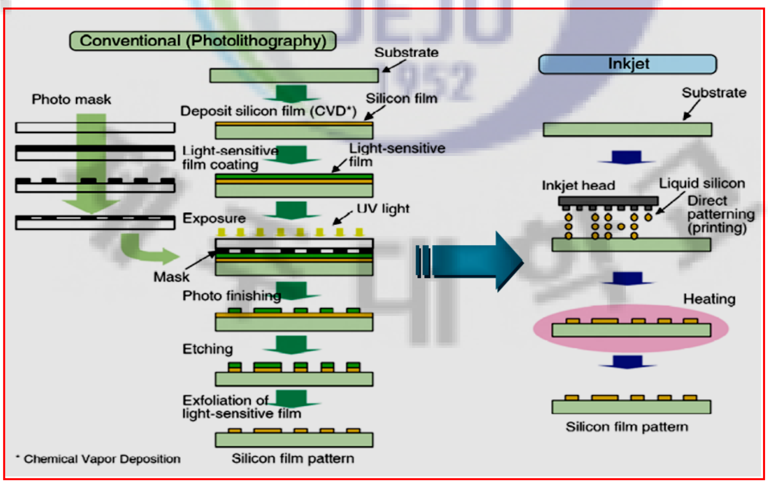


Figure2.2. Conventional Integrated Chip Manufacturing Process Vs Inkjet Process

2.2 Future Trend and Forecast

The present technology trend is gathering momentum towards the application of the flexible devices since these devices can easily adhere the shape of the surface they are being deployed. This single advantage is so enthralling since, the application of the new technology can be seamlessly employed without the significant changes in the existing infrastructure which is the most significant factor in adapting the new technology and its economic viability in terms of return/earning on investments. For the same reason the continuously evolving and maturing flexible printed electronic industry shows a steep increase in the forecasted printed electronic industry share as being depicted in the figure2.3.

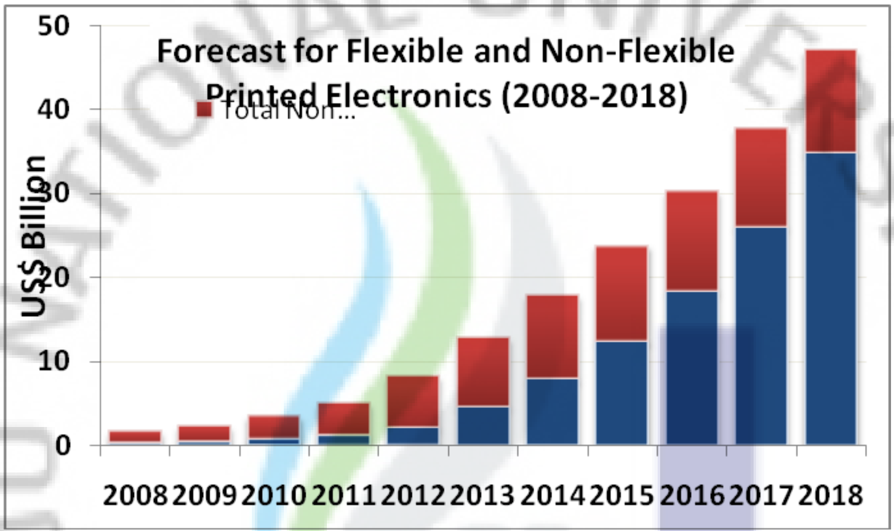
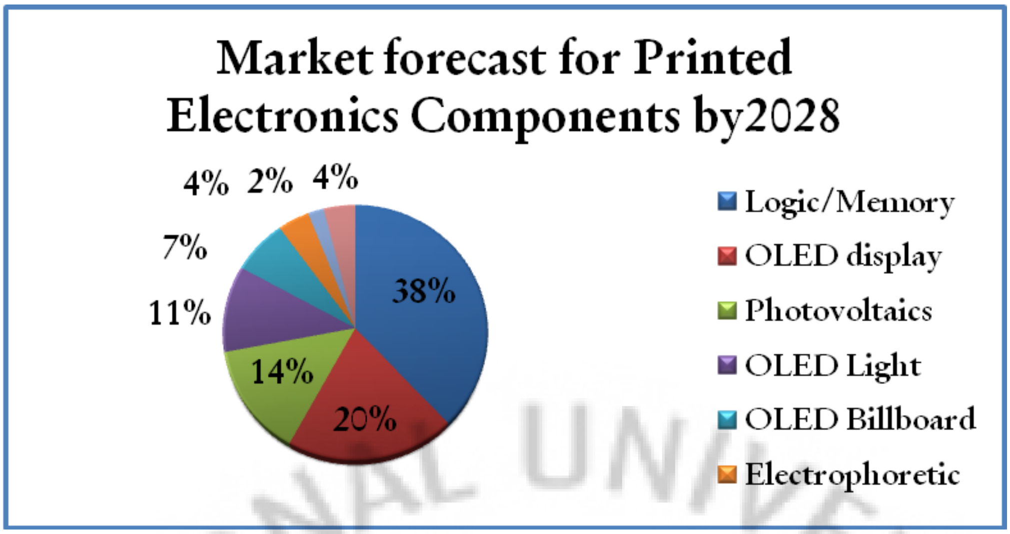


Figure2.3. Forecasted market for flexible and non-flexible printed electronics (Source: IDtechEx)

Consumer market will be one of the main markets for printed electronic applications. OLED displays, OLED lighting, Photovoltaic and logic memory will be rapidly increasing market for the printed electronic industry. Figure2.4 shows the forecasted component wise distribution for printed electronics.



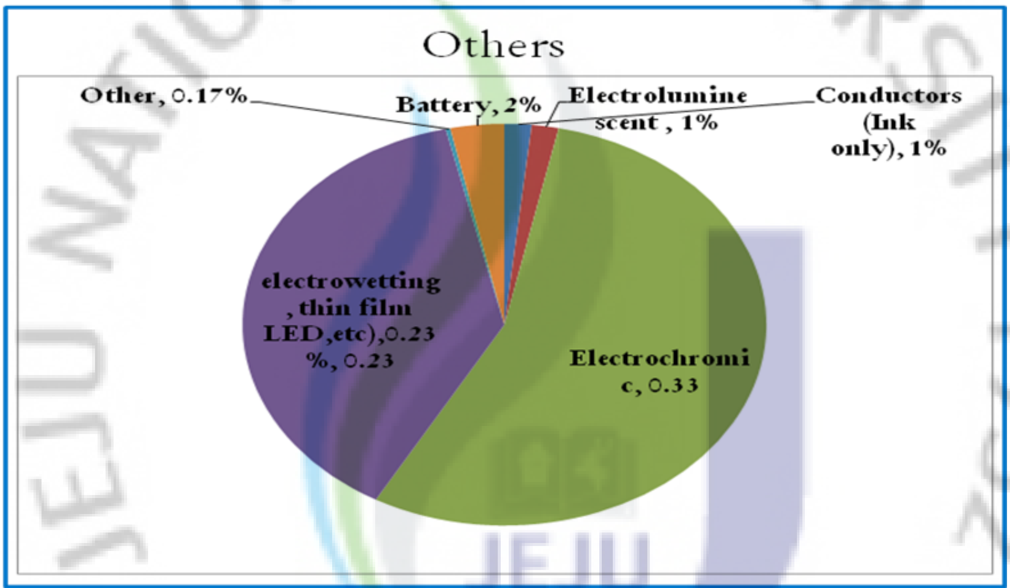
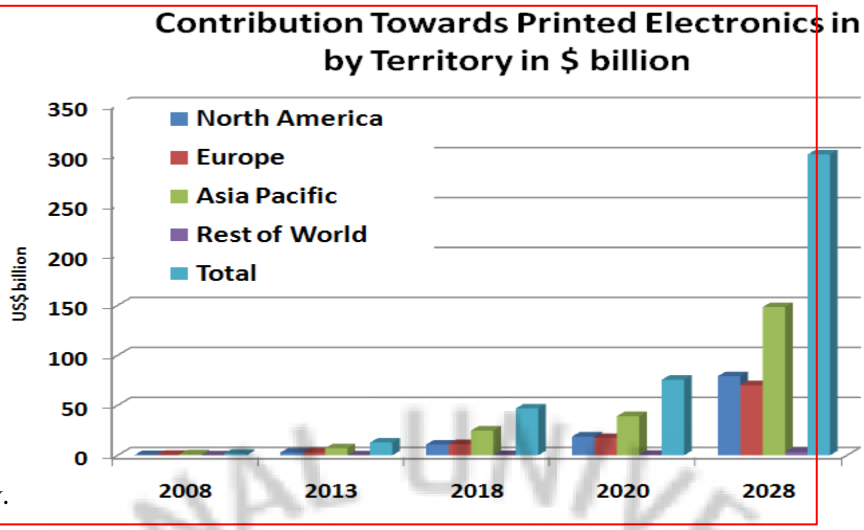


Figure2.4. Forecasted market by components for printed electronics (Source: IDtechEx)

Inkjet printing proves to be a promising technology for fabricating technology for printed electronics devices. Issues pertaining to the printing resolution and replacing the expensive Micro-Electro-Mechanical (MEMs) lithography fabrication techniques cannot be justified for some of the present electronic devices to be scaled for the consumer markets. It is daunting task for the inkjet technology to replace the traditional MEMs process for the fabrication of cheap electronic devices by improving the print resolution. United States followed by Asia Pacific and Europe respectively, will be the most contributing nations to the printed electronic industry. It is also envisaged that the future fabrication trend of printed electronics will lean towards the technology which can produce the cheaper printing technology. Figure2.5 shows the forecasted contribution towards the printed electronic by



Territory.

Figure2.5. Contribution towards Printed Electronics by Territory (Source: IDtechEx)

South Korea will be the major contributor in Asia for the printed industry due to its huge market share in the display and consumer market. This also provides the importance of printed electronics in this region and regions which invest heavily in the emerging printed electronic industry will rule this industry. Figure2.6 shows the expected market share of East Asia by region.

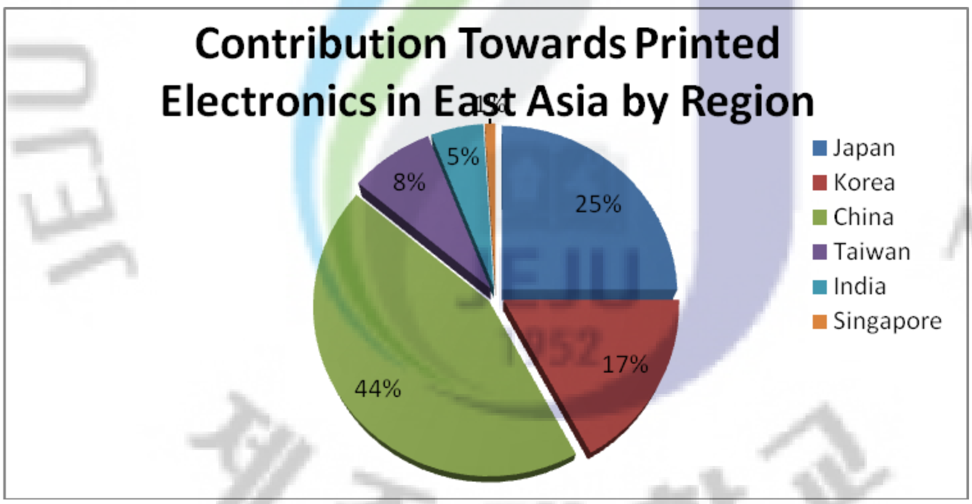


Figure2.6. Contribution towards printed electronics in East Asia by Region (Source: IDtechEx)

2.3 Key Printed Technologies

Primarily the key printed technologies can be divided into contact printing and non-contact printing method. Non-contactless printing method mainly comes in the inkjet technology. Contact printing is widely in use in paper industry and print media. Table 2.1 below shows the key printing technologies under the contact and contact less printing.

Table 2.1. Key Contact and Contact Less Printing Technologies

Contact Printing Technologies	Non-Contact Technologies
Screen Printing	Aerosol Inkjet Printing
Offset Printing	Thermal Inkjet Printing
Flexography Printing	Piezoelectric Inkjet Printing
Gravure Printing	Electrostatic Inkjet Printing
Pad Printing	Acoustic Inkjet Printing

Advantages of these printing methods are the high throughput with accuracies up to 50µm (Hughes and Ernster 2003) in case of screen printing is being reported. With gravure printing process, higher resolution and higher aspect ratio can be obtained. Almost all of contact printing method utilizes the roll-to-roll technology to transfer the base pattern on the substrate. Whereas the registration control in case of tight tolerances can be of challenge since the printing pressure is high with high web velocity and elastic nature of the flexible substrate makes it even more difficult. However the resulting product is cheaper than non-contact printing method due to the high printing speed.

Inkjet printing has certain advantage in printed electronic applications. Not only it is a non-contact printing method but also a additive fabrication process which involves the pattern printing to be in a discrete or continuous manner depending upon the selection of the inkjet process. Moreover the emerging electrostatic printing can yield to high resolution of printer than the former processes.

2.4 Inkjet Printing System

In Inkjet Printing System ink must wet the media but not run off before drying. Also Surface and physical characteristics of the substrate must allow it to reproducibly transport in the printer. Finally, the ink must be compatible with the whole delivery system in the printer.

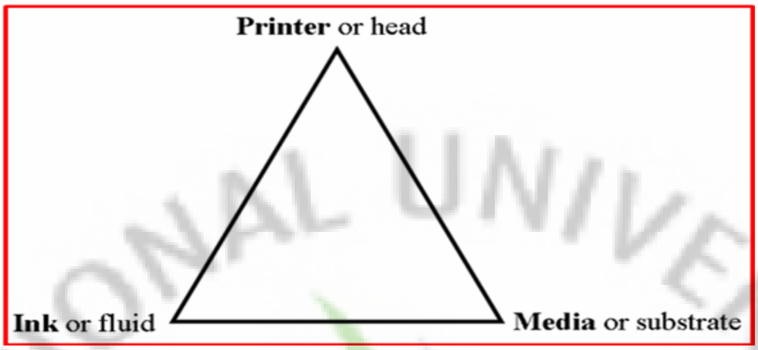


Figure2.7: Main requirements Inkjet Printing System

Non-Contact inkjet printing is classified into two categories;

1) Continuous and

Continuous inkjet printing [3] is suitable for similar material deposition on the substrate and relatively low resolution printing since the deposition force is relatively higher and yield higher deposition velocity which is prone to offer more spreading on the substrate. Whereas the printing speed is fast as compared to the drop-on-demand process and is suitable for high printing throughput. However the equipment cost is high as compared with the on-demand inkjet printing setup.

2) Drop-on-demand

Drop-on-demand inkjet printing provides more flexibility in terms of the ink deposition on the substrate and provides higher accuracy than the continuous printing. Various printing technologies under the Inkjet Technology are:

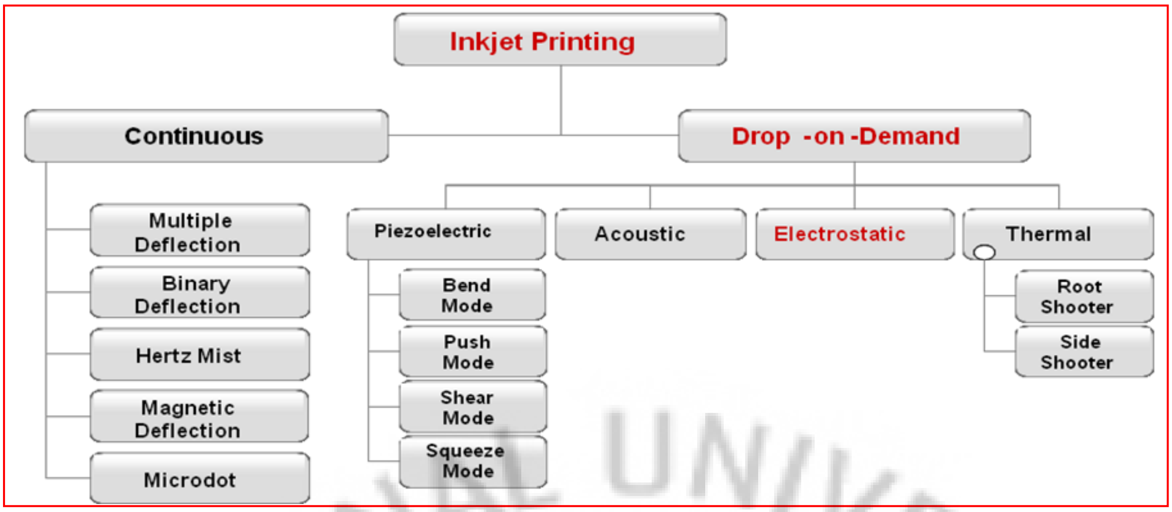


Figure2.8. Classification of Inkjet Technology

As shown in the figure2.8 the drop-on-demand printer can be classified into three main categories namely Thermal inkjet (TIJ), piezoelectric inkjet (PIJ) and Electrostatic Inkjet (EIJ). In the discussion to be followed TIJ, PIJ and EIJ will be discussed briefly.

2.4.1 Thermal Inkjet

A thermal ink-jet consists of an ink chamber having a heater with a nozzle nearby [4, 5].With a current pulse of less than a few microseconds through the heater, heat is transferred from the surface of the heater to the ink. The ink becomes superheated to the critical temperature for bubble nucleation, for water-based ink, this temperature is around 300°C. When the nucleation occurs, a water vapor bubble instantaneously expands to force the ink out of the nozzle. Once all the heat stored in the ink is used, the bubble begins to collapse on the surface of the heater. Concurrently with the bubble collapse, the ink droplet breaks off and excels toward the substrate. Then the ink refills back into the chamber and the process repeats again.

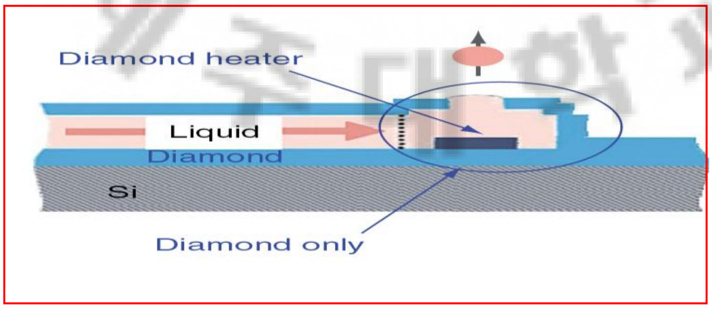


Figure2.9. Thermal Inkjet: Principle of Operation (Source: Mueller et al. 2005)

2.4.2 Piezoelectric Inkjet

Most commercial and industrial ink jet printers use a piezoelectric material in an ink-filled chamber behind each nozzle instead of a heating element Yong Zhou, 'Measurement of the Displacement of a Shear Mode Piezoelectric Transducer using [6,7].

When a voltage is applied, the piezoelectric material changes shape or size, which generates a pressure pulse in the fluid forcing a droplet of ink from the nozzle. This is essentially the same mechanism as the thermal inkjet but generates the pressure pulse using a different physical principle. Piezoelectric (also called Piezo) ink jet allows a wider variety of inks than thermal or continuous ink jet but the print heads are more expensive. Piezo inkjet technology is often used on production lines to mark products - for instance the use-before date is often applied to products with this technique; in this application the head is stationary and the product moves past. Requirements of this application are a long service life, a relatively large gap between the print head and the substrate, and low operating costs.

2.4.2.1 Squeeze Mode PIJ

A squeeze-mode ink-jet can be designed with a thin tube of Piezo-ceramic surrounding a glass nozzle or with a Piezo-ceramic tube cast in plastic that encloses the ink channel. When a voltage is applied on the piezoelectric material, the ink chamber is squeezed and a drop is forced out of a nozzle.

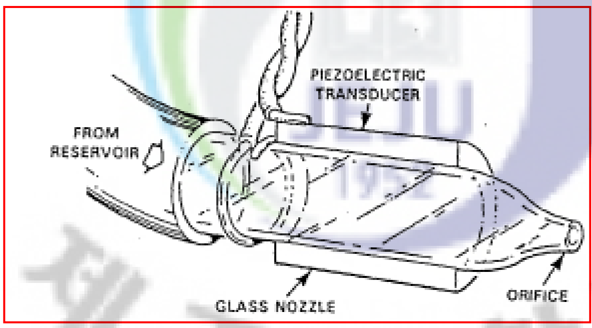


Figure2.10. Squeeze Mode: Principle of Operation

2.4.2.2 Bend Mode PIJ

In a typical bend-mode design (Figure2.11), the Piezo-ceramic plates are bonded to the diaphragm forming an array of bi-laminar electromechanical transducers used to eject the ink droplets. The electric field generated between the electrodes is in parallel with the polarization of the Piezo-material.

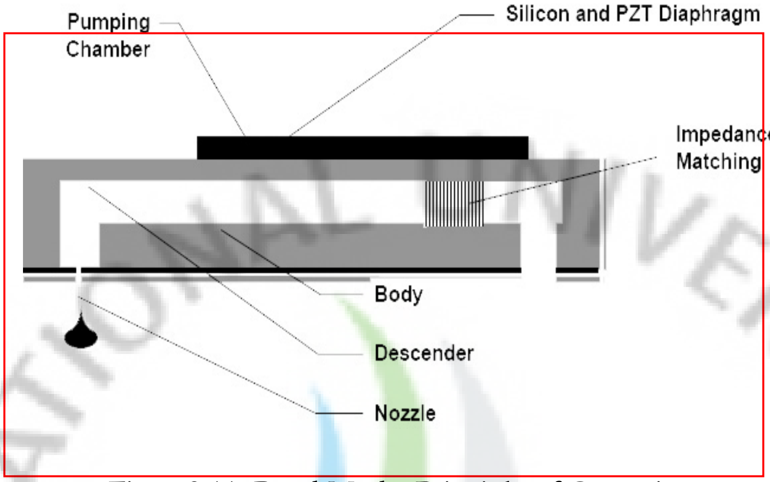


Figure2.11. Bend Mode: Principle of Operation

2.4.2.3 Push Mode PIJ

In Push-mode design the piezoelectric material is stacked as a rod. As the piezoceramic rods expand, they push against ink to eject the droplets. The electric field generated between the electrodes is in parallel with the polarization of the piezomaterial and since the piezo-ceramic rod is just placed over the ink chamber it provides the necessary ejection force to generate droplet.

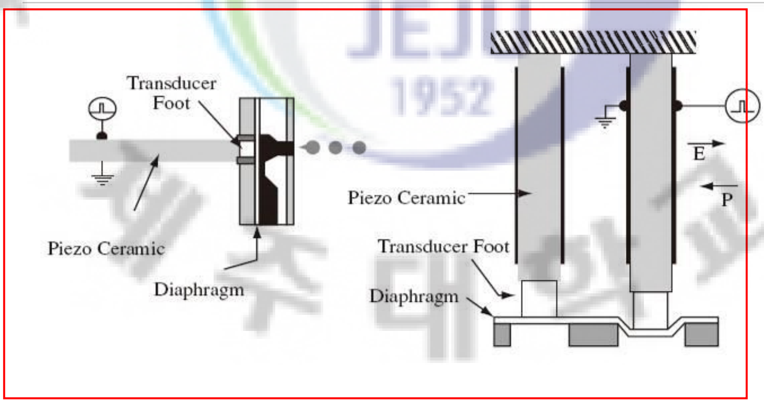


Figure2.12. Push Mode Inkjet: Principle of Operation

2.4.2.4 Shear mode actuator

The basic operation of a shear mode type inkjet head utilizes the shear mode deformation force of piezoelectric elements. Figure2.13 shows the working principle of the shear mode piezoelectric actuator. Voltage is applied to the piezoelectric walls on both sides of the ink pressure chamber due to this deformation occurs to both sides of the ink pressure chamber. When the reverse polarity voltage is applied to the piezo walls they more aparts and ink flows inside the chamber due to the displace volume. A reverse electric field is generated, which makes the nozzle walls curve in the closing direction, delivering ink drops and finally the nozzle walls are returned to initial position.

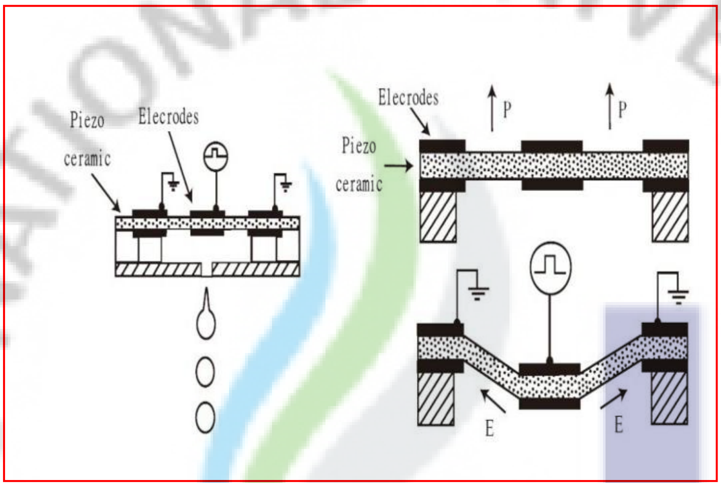


Figure2.13. Shear Mode Inkjet: Principle of Operation

2.4.3 Electrostatic Inkjet (EIJ)

In electrostatic inkjet operation the driving force for ejecting the droplet is governed by electrostatic potential. Ink chamber is charged with the electrode by applying a positive or negative potential. The counter electrode is placed just below the nozzle either integrated in the nozzle by means of insulation layer or orthogonal to the nozzle below the printing substrate in a discrete manner. Classification of EIJ is given as in figure2.14.

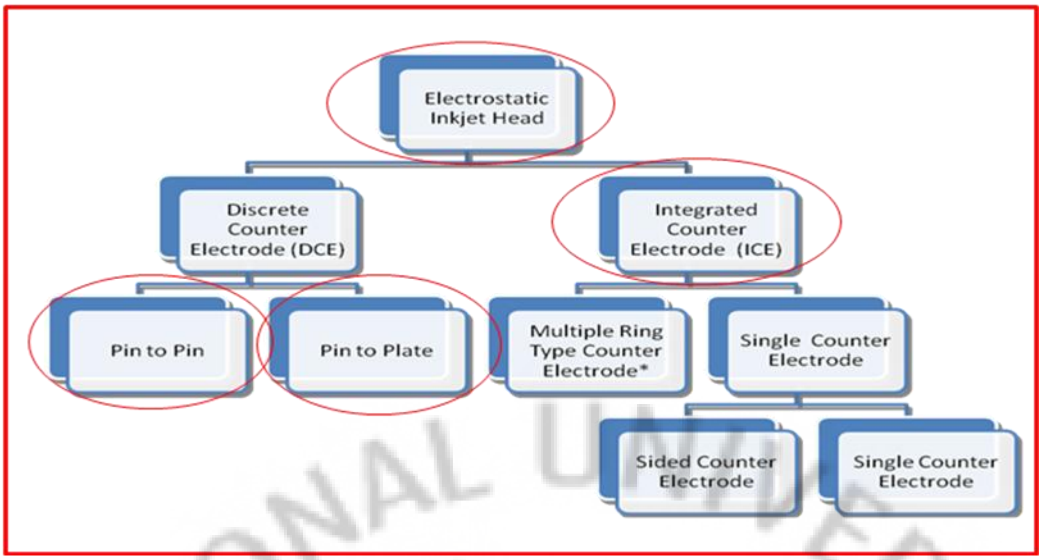
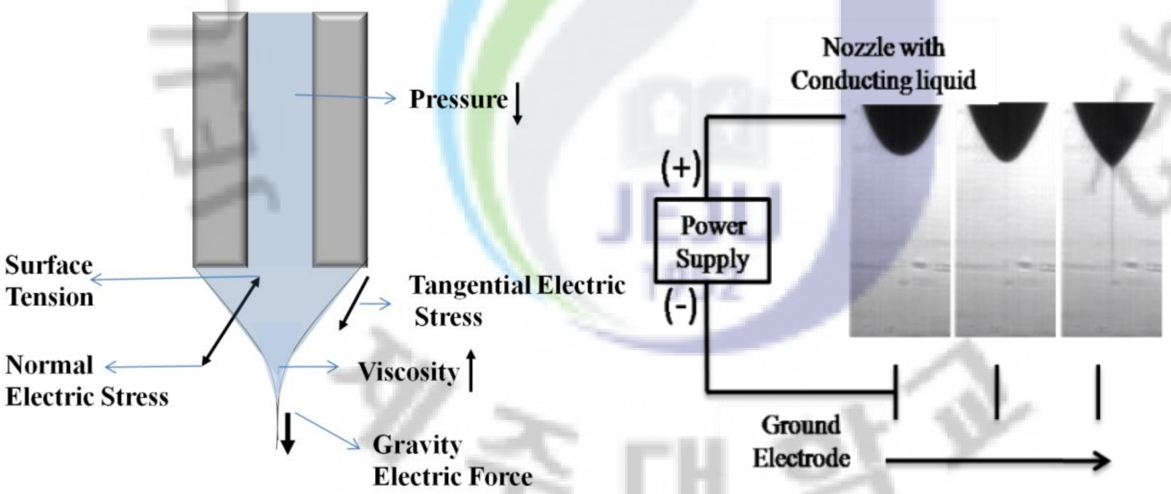


Figure2.14. Classification of EIJ

Due to the reverse polarity or grounding effect of the counter electrode ink/liquid in consideration experiences the shear force and forms the cone jet shape which is referred as Taylor cone (Taylor 1969) in literature. Schematic of electrostatic inkjet is shown in figure 2.15, which describe the cone shape being attained by the liquid and other forces which act on the liquid.



(a) (b)

Figure2.15. (a) Schematic of the nozzle orifice and Effective forces (b) Jetting Principle of Electrohydrodynamic Printing

Cone jet shape is attained since the electrostatic potential gradient is orthogonal to the center of the nozzle. Also the electrostatic force increases with cubic of the distance between charge liquid at the interface of the nozzle and the counter electrode.

The main advantage being offered by the electrostatic inkjet printing is the reduced droplet size when compared to the size of the ejection nozzle due to the formation of cone jet during the droplet generation process.

2.4.3.1 Working Principle:

Figure 2.15 (a&b) shows the effective forces and behavior of the liquid meniscus before and after applying voltage. The effective forces acting at the meniscus consist of gravitational force, surface tension, viscous, electric and the flow rate pressure. As soon as the electric forces accompanied by flow pressure exceed the surface tension forces, ejection of droplets begin. For ejection, the liquid meniscus is affected mainly by two forces: an electric field force and the surface tension force [8].

To fully describe the electro hydrodynamic phenomenon of cone-jet it is necessary to indicate the forces acting on the fluid-air interface, stresses being imparted by electrical forces, channel forces and gravitational forces acting on the system in consideration. It is also pertinent to mention here that the electrical properties of the fluid also affect the shearing forces being generated on the charged liquid under the influence of electric field directed towards the exit of the orifice. For instance with perfect conductors or dielectrics, the electrical stresses are perpendicular to the interface and alteration of interface shape in the presence of surface tension balances the counter electrical stresses. However, leaky dielectric (which is neither a perfect conductor nor dielectric) behaves differently due to the presence of free charges which accumulates at the interface of the two-phase liquid (ink and air in this case) alters the electric field. Whereas the viscous effect of the liquid balances the tangential component of the electric field acting on the charged interface. It is also envisaged that the system in consideration is under the static influence of electric field hence the magnetic phenomenon can be ignored under such conditions, Feynman et al 1964[9].

Furthermore influence of electrostatic force is higher than the magnetic force to generate the Taylor Cone, therefore electrostatic phenomenon can represent the major of the shearing force. Figure2.14 (a) highlights the aforementioned forces acting on the leaky dielectric media under the influence of electrostatic forces.

Maxwell's equations, simplified for electrostatics are given as

$$\boldsymbol{\varepsilon_0 \nabla . E = \rho^{(e)}} \qquad \mathbf{(1)}$$

And

$$\nabla \times E = 0 \qquad (2)$$

Where

E = electric field (The force per unit charge)

ρ^{ε} = total electric charge per unit volume

ε_0 = permittivity of the vacuum

By combining equations (1) and (2) and applying divergence theorem for formulating electric field on a closed surface 'S', to the charge 'Q' enclosed in the volume 'V',

$$\int E.ndS = \frac{1}{\varepsilon_0}\int_v^0 \rho^{(e)}\, dV = \frac{Q}{\varepsilon_0} \qquad (3)$$

where n is the outer unit normal.

As electric field is defined as the force per unit charge, therefore the force exerted according to the coulomb law is

$$F = E\,\rho^{(e)} \qquad (4)$$

From Eq. (2) the electric field is conservative that is the line integral of $E.t$ (where t is tangent to a closed curve) is zero. Thus, there exists a potential function such that

$$E = -\nabla\phi \qquad (5)$$

By combining Eq. (1) and Eq. (5)

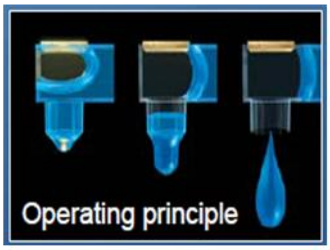
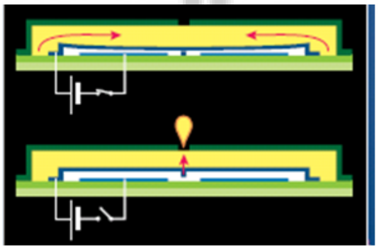
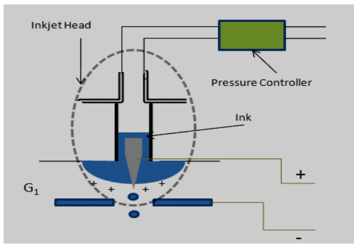
$$\varepsilon_0 \nabla^2 \phi = \rho^{(e)} \qquad (6)$$

If the vacuum is replaced by a dielectric medium, the capacity of the charged particles increases because of polarization of dielectric.

2.4.4 Comparison of Drop-on-Demand and Continuous Inkjet Printing Technologies

Inkjet printing methods are roughly divided into the piezoelectric type, thermal type and the emerging electrostatic printing. Table 2.2 summarizes the advantages and disadvantages of piezoelectric, thermal and electrostatic type print heads for inkjet printing. Electrostatic printing is still in the development phase therefore comparison of different parameter is difficult to find in literature.

Table2.2. Comparison of Piezo, Thermal and Electrostatic Inkjet Printing

	Thermal Inkjet	**Piezoelectric Inkjet**	**Electrostatic**
Principle	Drop on demand: Drops generated only when needed. Heater generates a bubble that forces an ink drop out of the nozzle orifice.	Drop on demand: Piezoelectric crystal generates a pressure pulse that forces an ink drop out of the nozzle orifice.	Drop on demand and continuous drop formation. Electrodes guide image forming drops to substrate and other drops for recirculation
Benefits		Only acoustic pressure affecting ink during drop formation. Durable Print heads.	High speed Different pattern Sub-micron feature accuracy High volume manufacturing Increase speed, jetting reliability and accuracy Decrease drop size
Drawbacks	Ink sedimentation. Low speed. Short print-head lifetime. Ink exposed to high temperature (even 300°C) during drop formation.	Nozzle drying. Drop on Demand Not feasible for versatile inks	
Schematic Diagram			

2.5 APPLICATIONS

Applications of drop-on-demand inkjet ejectors is unlimited and in various field they are mentioned as below (Lee 2003)

Applications in Applied Science

- Combinatorial Chemistry
- Micro-mixing
- Automated Micro-titration
- Matrix Assisted Laser Desorption Ionization Time Of Flight (MALDI TOF) Spectroscopy Sample Loading
- Loading and Dispensing Reagents from Micro-reactors
- Gas Flow Visualization

Applications in Biotechnology

- Cell Sorting
- DNA Microarrays
- DNA Synthesis
- Drug Discovery
- Medical Therapeutics

Applications in Manufacturing & Engineering

- Optics
- Droplet-Based Manufacturing
- Inkjet Soldering
- Precision Fluid Deposition
- Displays
- Thin Film Coating
- Heat Radiators
- Mono-disperse Aerosolizing for Combustion
- Mono-disperse Aerosolizing for Dispersing Pesticides
- Document Security

- Integrated Circuit (IC) Manufacturing
- IC Manufacturing — Photo resist Deposition
- IC Manufacturing — Conductor and Insulating Dielectric Deposition
- Manufacturing — Depositing Sensing and Actuating Compounds

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CHAPTER 3

INK, SINTERING AND ADHESION OF PRINTED PATTERNS

3.1. Functional Ink for Printed Electronics

Printed electronics require a variety of functional inks including conductive inks. Conductive inks are made of silver (Ag) or carbon (C). Every print method has a unique set of requirements for ink properties such as viscosity, surface tension, particle size, and solids content. Ink designers must find a way to meet all the performance properties for successful printing without sacrificing the conductivity needed by the application.

Inherently conducting polymers (ICPs) such as polyaniline (PANI) and polyethylene dioxythiophene (PEDOT) are recent alternatives. Unlike conductive pastes, they are compatible with high-speed printing methods. The low conductivity of ICPs, however, limits their use and attractiveness for printed electronics. Carbon nano-tubes (CNTs) are highly conductive and can be formulated into inks, but the cost and availability of CNTs are major drawbacks.

Nanotechnology has enabled a new generation of cost-effective, highly conductive inks that are compatible with high-speed printing methods. Several nano-silver-based inks are available for various printing methods. Silver (Ag) is the dominant metal used due to the relative ease with which Ag can be sintered. Typical curing temperatures range from 130°C to 150°C.

Nano-copper inks are also in development as a low-cost alternative to Ag. Copper (Cu) oxidization makes sintering more difficult to accomplish. There are approaches to solving this problem, but so far, Ag is the best overall solution for printed electronics.

Industries are developing conductive nanoparticle-based inks for the printed electronics industry along with a new curing method called photonic curing, which relies on pulsed light rather than heat to sinter conductive inks.

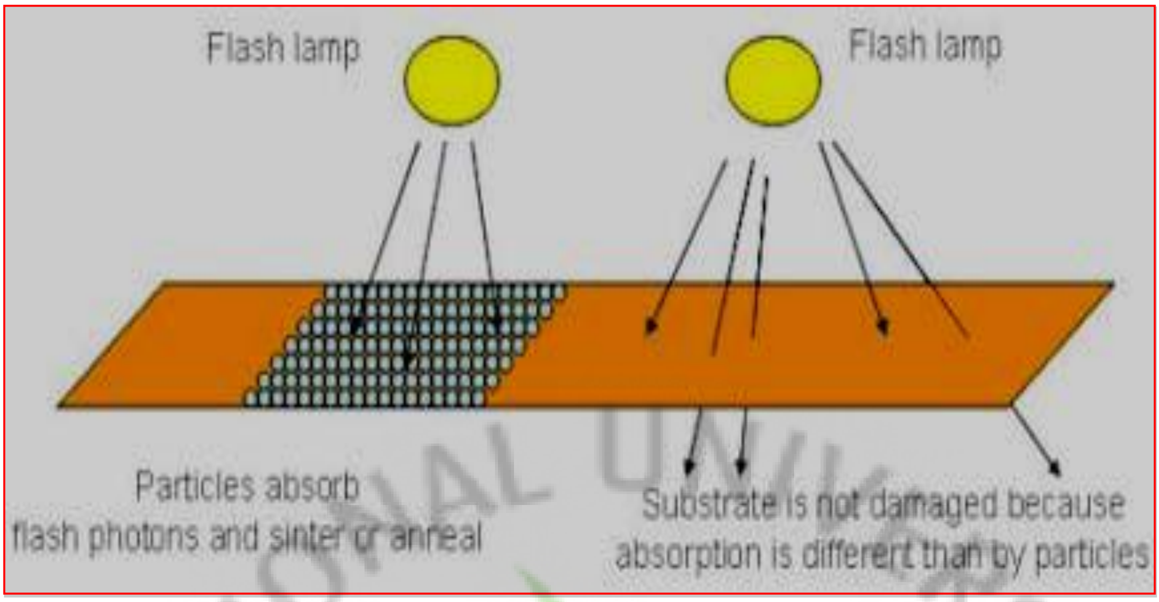


Figure3.1. Pulse Forge Method of Curing patterns without affecting substrate materials

Metalon JS-011 is an ink-jettable nano-silver ink that is conductive almost immediately after printing without any curing. With thermal or photonic curing resistivities below 10^0 C, bulk Ag is achievable on paper substrates. The formulation was developed for drop-on-demand inkjet (DOD) and is now being modified for continuous inkjet (CIJ) systems.

Some advantages of the photonic curing process are:

- Substrate is not heated and the curing time is less than a millisecond
- Cu inks can be cured in air without using inert gases to prevent oxidation which is not possible with thermal curing

Nano materials may have a significantly lower melting point or phase transition temperature and appreciably reduced lattice constants, due to huge fraction of surface atoms in the total amount of atoms.

Nano particles are employed because of their remarkably lower melting temperature compared to bulk materials. This low melting temperature of nano particles is due to the large ratio of surface atoms to inner atoms. For example, a gold particle of 4 nm diameter has 25% of the atoms on the surface. This high portion of surface atoms drastically decreases the melting temperature, since smaller particles exhibit reduced interaction between the surface and the inner atoms; i.e., the surface energy of the surface atoms is reduced. To exemplify, the melting point for gold nano particles in the range of a few nanometers lies approximately between 300– 400 °C versus 1064 °C for bulk gold. The following graph in figure3.2 shows the melting temperature depression with particle size reduction.

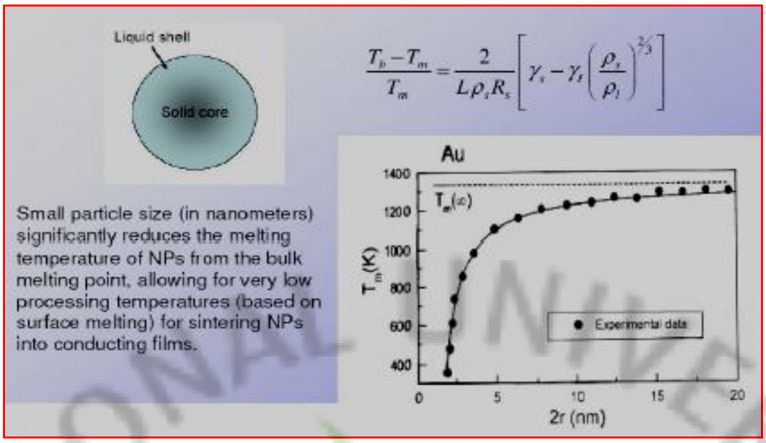


Figure3.2. Size- Dependent Melting Point of Nanoparticles

3.2 Types of Ink Used for Printing Electronics Patterns

1) Non-conductive Ink
2) Semi conductive Ink
3) Conductive Ink

Table3.1. Printed Electronics require variety of Conductive Inks

Summary of Conductive Ink Types		
Conductive Ink Technology	Conductivity (S/cm)	Compatibility with high-speed printing
ICPs	10^{-2}	Yes-Gravure, Flexography, Inkjet
Conductive Pastes- carbon	10^{0}	No- Screen Printing
Conductive Paste- Silver	10^{4}	No- Screen Printing
Nano-metal Conductive Inks	10^{4}	Yes- Gravure, Flexography, Inkjet
Etched Metal	10^{5}	No- Subtractive Processing

3.2.1. Other classification of Ink for Inkjet Printing:

There are three major groups of inkjet ink: aqueous, non-aqueous, and hot melt

3.2.1.1 Aqueous and Solvent-Based Inks

Aqueous and solvent-based ink formulation consists mainly of a carrier fluid that keeps the ink in a liquid state, acting as a "carrier" for the colourant. A co-carrier - usually glycol or glycerine - is often used to control the ink's drying time, as well as its viscosity during manufacturing. Small amounts of other additives are also present in most inks. These additives help control such factors as: dot gain, drop formation, print head corrosion, pH level, fade resistance, and colour brilliance [1].

3.2.1.2 Aqueous-Based Inks

Aqueous-based inks the first to be used in inkjet printing, and are still common today. They have no volatile organic compounds, and have low toxicity. Aqueous-based inks have a relatively slow drying rate (on uncoated media) and the prints have a low water fastness.

3.2.1.3 Solvent-Based Inks

The term "solvent" is often described as "a substance having the power of dissolving other substances". This could describe most liquids, including water. **However, in the inkjet industry, "solvent" is used generically to describe any ink with a carrier fluid that is not water-based.** Solvent-based inks are largely made up of: a solvent (often containing glycol ester or glycol ether ester), a pigmented colourant, a resin, and a "glossing" agent [1]. When the solvent evaporates, the pigmented particles are "glued" to the media by the resin. Solvent-based inks are usually used for commercial printing, such as the coding and marking on cans and bottles. These inks dry faster that aqueous based inks, but emit volatile organic compounds.

3.2.1.4 Oil-Based Inks

Oil-based inks use a very slow drying carrier fluid (such as Isopar) that is usually derived from a mineral oil source, hence, the term "oil-based." The benefit of this approach is that the printer is very easy to use and maintain as the print head jets are unlikely to clog with dried ink. Oil-based inks are used for card printing, packaging, labels, and boxes where ink is fully absorbed. As the droplets can be formed with very small quantities, they can be used for high-resolution printing [1].

3.2.1.5 Hot Melt Inks/Phase Change Inks

Hot melt inks are gel-like at room temperature. When heated, they melt; in the melted condition, they are jetted to the substrate where they immediately cool down again. Due to the change in state of the ink (solid - liquid - solid), these inks are also called phase-change inks. In phase change inks, low viscosity waxes are the vehicle for the colourants; the inks have polymer-like properties in the solid phase while maintaining a very low viscosity in the melt. One of the main advantages of these inks is that final print quality is relatively independent of substrate type or quality. The hot melt inks give a distinct topography that may be subject to wear and abrasion, or cracking with flexible substrates [2]. The inks are predominantly used in industrial marking and in labeling [3].

3.2.1.6 UV-Curable Ink

UV inkjet inks are inks that are cured with the use of an ultraviolet light. UV inks have mainly been used in wide-format printing of rigid substrates: corrugated plastics, glass, metal, and ceramic tile are a few examples. UV inks have the main advantage of instant drying that leaves the print completely cured; as a result, no solvents penetrate the substrate once it comes of the printer. Due to the rapid drying, there is less substrate dependence, and there is a diminishing need post-print processes. Recently, opaque white ink has been introduced in UV-printing. These inks can be used as an undercoat, allowing colour-correct printing on non-white or transparent substrates. It can also be used to create additional highlights to printed images [3]. The drawbacks of UV inks are the relatively high cost and health and safety-related issues. The high cost is due to the specialty raw materials used in the formulations. UV inks can be up to two to three times more expensive than conventional inks [2]. The exposure to UV materials can result in chronic health effects on the skin, eye, and immune system. The UV-lamps generate ozone, and that must be vented or neutralized. The printers also generate a small amount of mist that has to be removed from the printer enclosure.

3.3 Substrate for Printed Electronics

To Control the morphology of the printed dots or elements is key to making paper substrates work for printed electronics. Amorphous or irregular structures such as those exhibited by plain and cast coated papers are unlikely to be of use in anything other than the most coarsely printed electronic component. However, dot shapes such as that exhibited by the polymer coated product are likely to be much more acceptable.

Substrates use for Printing Electronics can be of two types:

1) Hydrophilic Substrates (Contact Angle < 90^0)
2) Hydrophobic Substrates (Contact Angle > 90^0)

Table3.2 Measuring Instruments for Substrate Properties

Measure Property	**Method**	**Instrument**
Porosity	Air Leak Method	Parker Print Surf
Dynamic Contact Angle	Sessile Drop Method	Contact Angle Analyzer
Surface Energy	Owens-Wendt Method	Contact Angle Analyzer
Dynamic Liquid Penetration	Ultra sonic Transmission Measurement	Emco Dynamic Penetration Tester DMP30
Topography	Attractive/Repulsive Atomic Forces	Atomic Force Microscopy

Surface roughness plays an important role in the adhesion of small particles. The strength of the adhesion of small particles on rough surfaces is mainly determined by the geometrical effects of the surface–particle system. The adhesion of particles smaller or similar in size than the dominant surface features is only weakly dependent on the particle size. The interaction is limited to one contact between the particle and a single asperity and the strength of the adhesion is determined by this contact alone. Particles much larger than the surfaces features have several contacts with the surface leading to interaction where, in addition to the asperity geometry, the size of the particle has a major influence on the adhesion. Relative size of the adhering particle and the surface features play the most important role in the interaction.

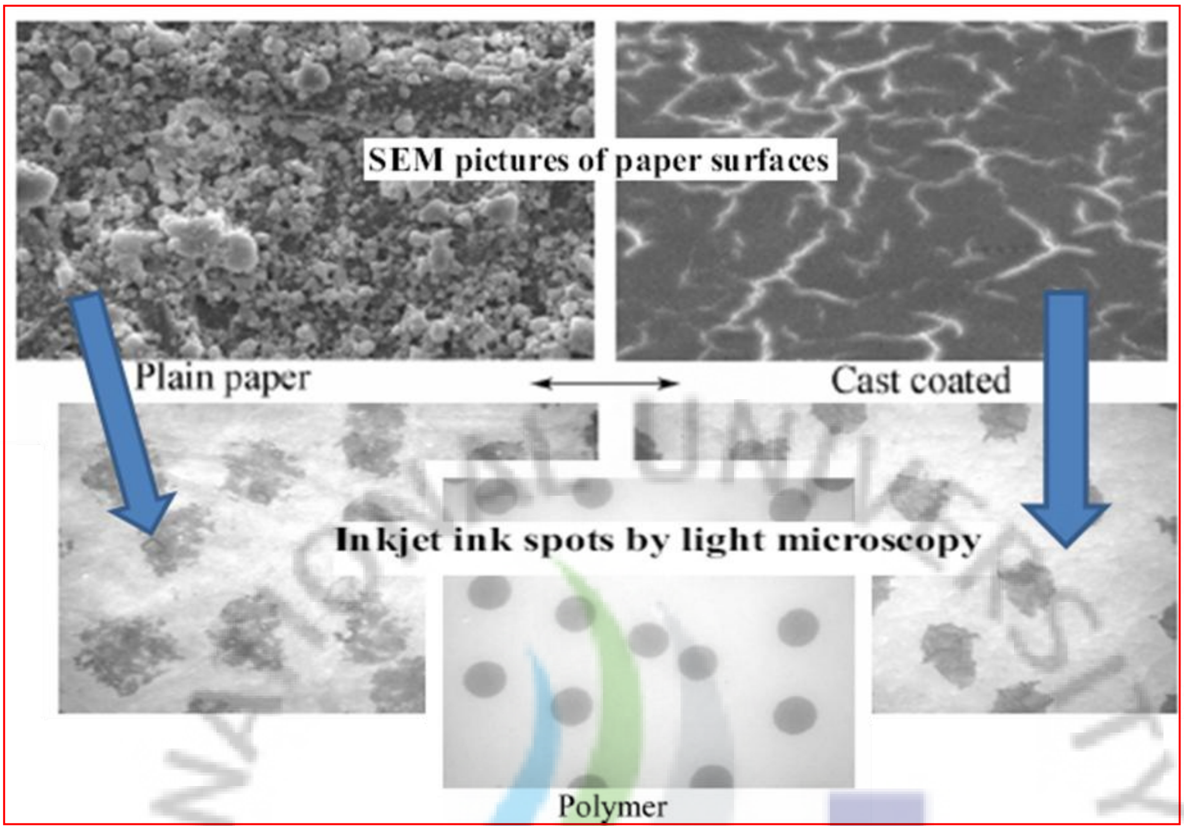


Figure3.3. Substrate surface texture effect on Printed Pattern uniformity

Table3.3. Some commonly used substrates for printed electronics are:

Glass	Silicon
PET (ITO Coated)	Glass (ITO Coated)
PET (Polyethylene Terepthalate)	PEN (Polyethylene Naphthalate)
PBT (Polybutylene Terephthalate)	PTFE (Polytetrafluoroethylene)
PI (Polyimide)	PEEK (Polyetheretherketone)

For testing hydrophobicity and hydrophilicity of a substrate surface, fluid single droplet behavior on substrate is analyzed. This analysis of droplet behavior on substrate can be related to printed patterns on different substrates. For measuring contact angle, a drop of ink is impacted on substrate. The angle formed between the solid/liquid interface and the liquid/vapor interface and which has a vertex where the three interfaces meet is referred to as the contact angle. The Young relationship involves the contact angle θ, defined as the angle between the tangent to the liquid–gas interface and the tangent to the solid interface at the contact line between the three phases; it also involves the values of liquid–vapor surface tension, γ^{LV}, solid–liquid surface tension, γ^{SL}, and solid–vapor surface tension, γ^{SV} [4].

$$\gamma^{LV}\cos\theta = \gamma^{SV} - \gamma^{SL} \qquad (1)$$

$$\theta = \cos^{-1}(\gamma^{SV} - \gamma^{SL})/\gamma^{LV} \qquad (2)$$

Ink–substrate interaction usually takes place in three steps, Inertial Spreading (Droplet spreads due to its own inertia to an extent that is mainly governed by Kinetic Energy, Viscosity and Surface Tension (Final dot Product)), Adsorption (Smooth and Isotropic medium is required for circular horizontal drop profile) and Evaporation (When printing onto a non absorbing medium such as glass or metal the process is dominated by evaporation).When a liquid drop strikes a substrate before final spreading droplet passes through these stages splashing, rebound, recoil, wetting, maximum spread and final spread. Adhesion of ink also depends on nano particle shape, momentum droplet transferred to substrate and surface energy of the substrate [5].

3.4 Sintering

It is a method for making objects from powder; by heating the material in a sintering furnace [1] below its melting point (solid state sintering) until its particles adhere to each other.

3.4.1 Sintering Mechanisms

Sintering occurs by diffusion of atoms through the microstructure. This diffusion is caused by a gradient of chemical potential – atoms move from an area of higher chemical potential to an area of lower chemical potential. The different paths the atoms take to get from one spot to another are the sintering mechanisms. The six common mechanisms are:

1) Surface diffusion - Diffusion of atoms along the surface of a particle
2) Vapor transport – Evaporation of atoms which condense on a different surface
3) Lattice diffusion from surface – atoms from surface diffuse through lattice
4) Lattice diffusion from grain boundary – atom from grain boundary diffuses through lattice
5) Grain boundary diffusion – atoms diffuse along ground boundary
6) Plastic deformation – dislocation motion causes flow of matter

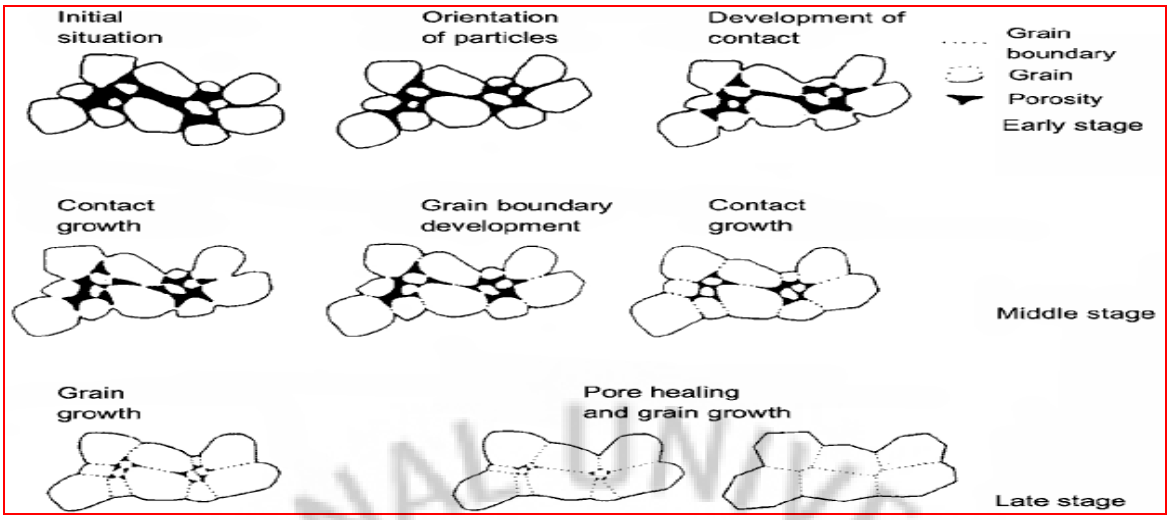


Figure3.4. Sintering Mechanism Steps

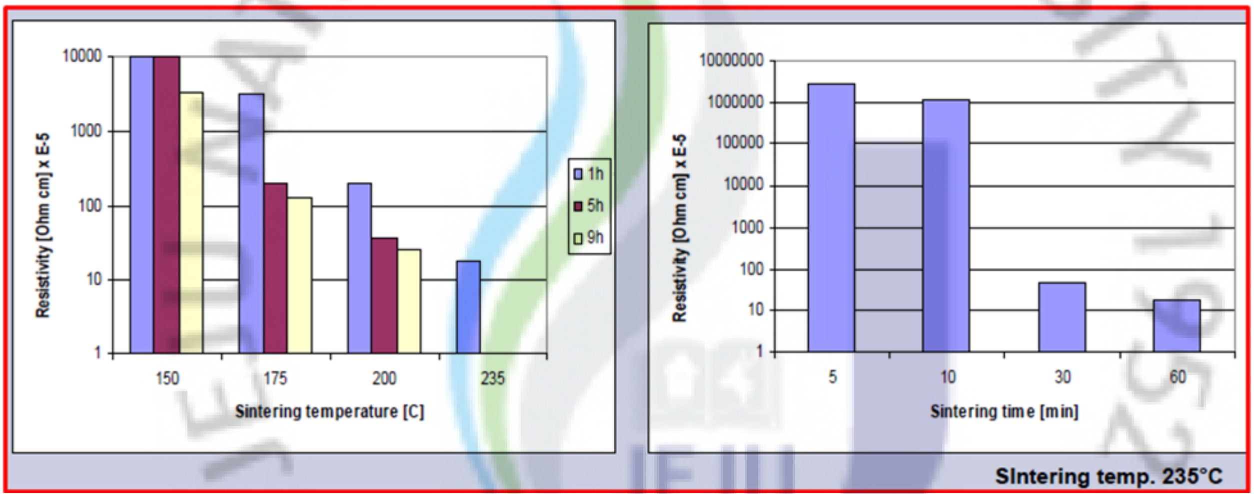


Figure3.5.Obtaining conductivity as a sintering temperature and sintering time

3.5 Adhesion

Durability of printed patterns of electronic circuitry is important for proper functioning. Therefore its adhesion with the substrate is of prime importance. Adhesion is the tendency of certain dissimilar molecules to cling together due to attractive forces. To know about adhesion behavior between two different surfaces, interface study is very important because only this region can give enough information about its life and durability.

Factors Affecting Adhesion

- Surface roughness of the substrate(Mechanical interlocking are formed easier on the rough surface than on the smooth surface)
- Surface energy of substrate
- Polarities of the joined surfaces

- Solvent residues in the ink
- Absorption of solvent into the substrate surface
- Weak adhesion of ink also happens, because of higher nano content of ink
- Closed steric match between binder and substrate increases adhesion
- Curing temperature

One of the most important properties of substrate during curing of printed patterns on it is the curing temperature sustainability. Each substrate has certain limit of sustainable temperature till which it can retain its properties and beyond that point its properties start changing. Most of the flexible polymeric substrates have glass transition temperature (Tg) around in the range 50^0C~300^0C. By heating substrates beyond Tg value and subsequently cooling it induces residual stresses that have a negative effect on

- ➢ Printed patterns
- ➢ Interface between the patterns and substrate

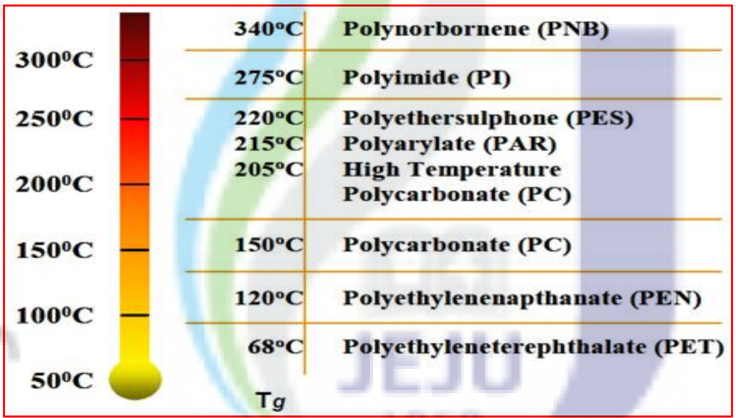


Figure3.6. Substrate Sustainable Temperature

So to solve this problem, ink with a lower sintering Temperature (150^{0}C or below) and alternate sintering methods like microwave sintering as well as other fast and select sintering methods would go long way in solving the adhesion problem.

Improving adhesion strength of nano particles with flexible substrate is a key issue for reliable printed electronic devices. Quantitative as well as qualitative measurement of the adhesion strength of nano particles is necessary to investigate the adhesion improvements of nano particles.
Adhesion between two different materials is a complicated phenomenon and is comprised of

1) Physical
2) Mechanical
3) Electrostatic
4) Diffusion
5) Chemical

3.5.1 Physical Adsorption

The well known wetting phenomenon is closely related to physical adsorption, in which surface forces are due to molecular contact within 5Å between two materials. In addition, physical adsorption is mostly due to Van der Waals forces. Good [3] found that wetting, thus Van der Waals force, can be determined by contact angle measurements. Young and Dupre's equation [4] describes the relationship between contact angle and thermodynamic interfacial fracture energy. Therefore, the contribution of physical adsorption to the interfacial fracture energy could be determined by measuring contact angles and using Young and Dupre's equation.

3.5.2 Mechanical Interlocking

Adhesive penetrates into any irregularities such as pores, holes, and crevices and locks mechanically to the adhered surface. This adhesion mechanism, which is called mechanical interlocking, has been studied by many researchers from the perspective of surface roughness effects. Gent and Lin [5] developed a mechanical interlocking model to predict the interfacial fracture energy between adhesives and substrates with cylindrical pores. Yao [7] suggested another mechanical interlocking model to estimate the contribution of surface roughness to the interfacial fracture energy.

3.5.3 Chemical Bonding

Chemical bonding is achieved by various mechanisms such as ionic bonds between positive and negative ions, covalent bonds, metallic bonds, coordinate bonds, and hydrogen bonds. Chemical bonds have large energies of an order of 100 times of physical forces [8] found that the epoxy to aluminum bond was due to hydrogen bonding. Parent [9] investigated the intermetallic formation between lead or lead-free solders and copper. Park [10] examined the covalent bonding effect obtained by adding silane coupling agent on the glass-fiber composite. It has been known, however, that identifying each chemical bond across the interface is almost impossible because the interface layer is extremely thin and chemical bonding is very complex.

3.5.4 Electrostatic Force

The forces between atoms or molecules which bear a charge are called electrostatic forces. Possart [11] identified the electrical double layer that is closely related to electrostatic force by using potential contrast SEM. Horn and Smith [12] verified charge transfer between glass and mica. Dickinson [13] found that discharge occurred when adhesive was peeled from substrates.

3.5.5 Diffusion

Polymer to polymer adhesion generally occurs through the inter-diffusion of molecules in the adhesive and the adherend. The adhesive and adherend must be chemically compatible in terms of diffusion and miscibility for this inter-diffusion to take place [14]. De described the diffusion of a mobile polymer chain through a net of impenetrable and immobile obstacles using the Reptation model, which is a widely used concept of polymer motion. However, diffusion theory addresses polymer to polymer adhesion, and there is insufficient evidence for polymer-metal diffusion. Although Wu [15] examined the migration of sputtered gold particles toward the fastest-diffusion phase, it is not clear that the migrated gold particles contributed to the improvement of adhesion strength. Thus, diffusion mechanism in NPS adhesion to polymer substrates can be neglected.

3.6 Adhesion Models

1) The Hertz model of solids adhesion

2) The DMT model of solids adhesion

3) The JKR model of solids adhesion

4) The Maugis model of solids adhesion

Table3.4. Comparison of quantitative adhesion models [16]

Theory	Assumptions	Limitations
Hertz	No surface forces	Not appropriate for low loads if surface forces presents.
JRK	Short-ranged surface forces act only inside contact area. Contact geometry allows to deform.	May underestimate loading due to surface forces. Apply to high λ systems only.
DMT	Long-ranged surface forces act only outside contact area. Geometry constrained to be Hertz.	May underestimate contact area due to restricted geometry. Applies to low λ systems only.

3.7 Adhesion Testing Methods

For coatings to perform satisfactorily, they must adhere to the substrates on which they are applied. A variety of recognized methods can be used to determine how well a coating is bonded to the substrate. Commonly used measuring techniques are performed with a knife or with a pull-off adhesion tester. After any test it is important to record if the bond failure was adhesive (failure at the coating / substrate interface) or cohesive (failure within the coating film or the substrate).

3.7.1 Knife Test

A standard method for the application and performance of this test is available in ASTM D6677.

3.7.2 Tape Test

On metal substrates, a more formal version of the knife test is the tape test. Pressure sensitive tape 3M 610 is applied and removed over cuts made in the coating. It is standardize for adhesion testing because it has many features like temperature resistant, good initial bond, dimensionally stable on the application up to 422.15 K (149 ^{0}C) and immediate adhesion to a variety of substrates. There are two variants of this test;

1) X-cut tape test

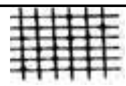
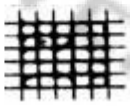
The X-cut tape test is primarily intended for use at job sites. Using a sharp razor blade, scalpel, knife or other cutting device, two cuts are made into the coating with a 30 – 45 degree angle between legs and down to the substrate which intersects to form an "X". A steel or other hard metal straightedge is used to ensure straight cuts. Tape is placed on the center of the intersection of the cuts and then removed rapidly. The X-cut area is then inspected for removal of coating from the substrate or previous coating and rated.

2) Cross hatch tape test

The cross hatch tape test is primarily intended for use in the laboratory on coatings less than 5 mils (125 microns) thick. It uses a cross-hatch pattern rather than the X pattern. A cutting guide or a special cross-hatch cutter with multiple preset blades is needed to make sure the incisions are properly spaced and parallel. After the tape has been applied and pulled off, the cut area is then inspected and rated.

A standard method for the application and performance of these tests is available in ASTM D3359.

Table 3.5 Adhesion Test ASTM D3359 Scaling

Description	Surface	IS0/ BS/DIN	ASTM
The edges of the cuts are completely smooth, none of the squares of the lattice are detached	None	0.5	5B
Detachment of small flakes of the coating at the intersections of the cuts, A cross cut area not significantly greater than 5%, is affected		1	4B
The coating has flaked along the edges and/or at the intersections of the cuts. A cross cut area significantly greater than 5%, but not significantly greater than 15%, is affected		2	3B
The coating has flaked along the edges of the cuts partly or wholly in large ribbons, and / or it has flaked partly or wholly on different parts of the squares. A cross cut area significantly greater than 15%, but not significantly greater than 35%, is affected		3	2B
The coating has flaked along the edges of the cuts in large ribbons and/or some squares have detached partly or wholly. Across cut area significantly greater than 35% but not significantly greater than 35% is affected		4	1B
Any degree of flaking that cannot even be classified by classification 4/1B		5	0B

3.7.3 Pull-Off Tests

A standard method for the application and performance of this test is available in ASTM D4541 and ISO 4624.

3.7.4 Scrape Tests

A standard method for the application and performance of this test is available in ASTM D2197.

3.7.5 Nano Scratch/Adhesion Testing

Nano Scratch/Adhesion Testing exploits a normal force range to 400mN to 1600mN which is highly recommended for adhesion failure studies of thin films.

Test Method: During Nano Scratch/Adhesion Testing, a sharp metal tip or a Rockwell C diamond is drawn across the coated surface with an increasing load, resulting in various types of failure at specific critical loads. Nano Scratch/Adhesion Testing identifies critical loads optically using a built-in video microscope. Once known, these critical loads are used to quantify the adhesive and cohesive properties of different film/substrate combinations. Additionally, failure points can be determined by using frictional force, optional acoustic emission and depth measurement. These parameters constitute a unique signature of the coating/substrate system.

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CHAPTER 4

ELECTROSTATIC INKJET PRINTING HEAD

Printing head assembly is consisted of ink source, metallic electrode and capillary. For obtaining uniform patterns, first condition is to get a very stable jet and it can only be obtained from a very stable meniscus. So to get a stable meniscus, head design is very important. Due to these requirements, in printing different types of materials, mechanisms, arrangements and strategies are needed to evaluate its performance and to make electrostatic system more useful and attractive [1].

For obtaining stable meniscus and minimizing droplet extraction potential from it, electrode configuration in head, ink properties, nozzle orifice size and distance between actuator and ground electrode can be manipulated.

To get a stable meniscus, a new approach of electrode configuration in printing head has taken on and its performance has undertaken for various arrangements in Electrostatic Inkjet Head.

4.1 Vertically Inserted Single Electrode Head (VISE Head)

In conventional electrostatic inkjet printing head a metallic capillary is being used. But in view of developing multi-nozzle electrostatic inkjet printing head, a conductive metallic electrode is inserted for electrification of ink. Usually in conventional electrostatic inkjet printing head a single electrode is inserted vertically. In VISE head, almost 20 mm long electrode with diameter 0.20 mm tungsten electrode is inserted, figure 4.1. So, exposed surface area of inserted electrode to ink is 12.56 mm^2. But with this configuration voltage requirement for getting stable meniscus, droplet extraction and jetting is very high [2].

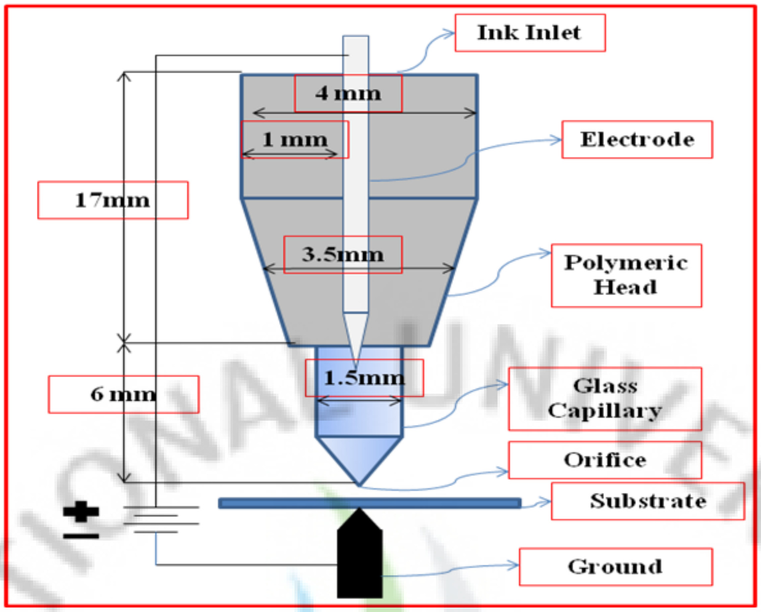

Figure 4.1. Schematic description of discrete pin to pin VISE (Vertically Inserted Single Electrode) Head set up for Electrostatic Inkjet Printing

Some of the issues with VISE Head:

1. Electrode Inserted from top through Ink source
2. Large Area of Electrode Exposed to Ink
3. Affecting Ink Properties
4. Electrode Tip Vibration at high voltage

4.2 Double Sided Inserted Angular Electrodes Head (DSIAEs Head)

Obtaining uniform patterns with VISE head is not an easy job. Therefore a new head is developed with a different approach of electrode configuration. Two electrodes are inserted with suitable exposure at an angle of (45^0~60^0) from opposite sides i.e. DSIAEs (double side inserted angular electrodes) inside electrostatic inkjet printing polymeric head, connected in parallel to power supply and a glass capillary is fixed at the bottom end of polymeric head figure 4.2.

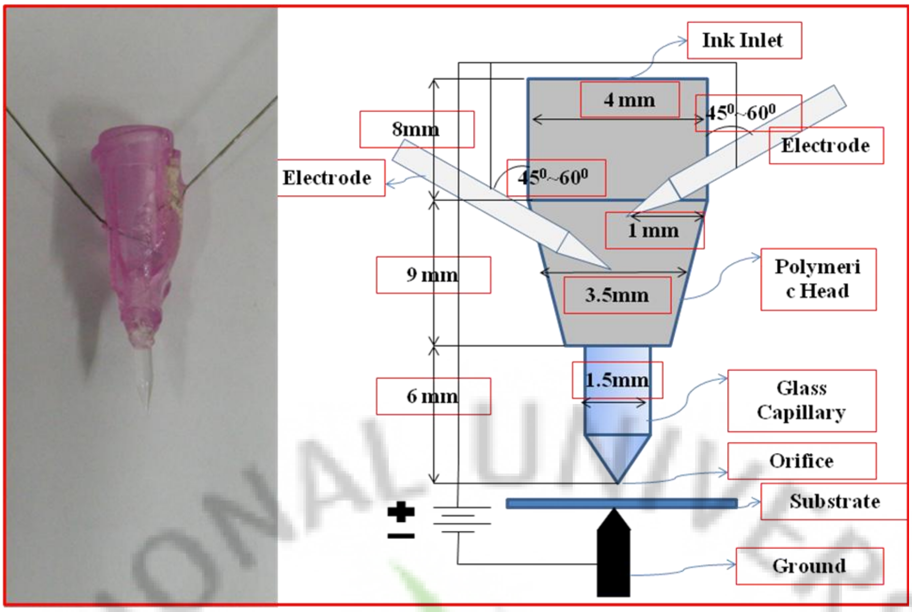

Figure 4.2. Schematic description of new developed DSIAE (Double Side Inserted Angular Electrode) Head set up for Electrostatic Inkjet Printing

In DSIAEs each tungsten electrode is inserted 1.5 mm from opposite sides in head. So, exposed surface area of inserted electrodes to ink is (1.884 mm^2) which is very small as it is in case of VISE head i.e. 12.56 mm^2.

4.3 Simulation for Electric Field Strength

For supporting purposes of electrode configuration in electrostatic inkjet printing head simulation is done by using "Comsol Multiphysics 3.5a" software. Simulation model of "Two Phase Flow Laminar Level Set using MEMS Module" is used for checking electric field at various positions in electrostatic inkjet printing heads. Water has taken as fluid for simulation.

4.3.1 Simulation for Electric Field Strength of VISE Head and DSIAEs Head

Obtained electric field simulation results for VISE Head is given in figure 4.3. Simulation results show that electric field at VISE tip is 33 times stronger as compared to upper electrode tip and 3.3 times stronger as compared to lower electrode tip of DSIAEs, respectively [3].

Also electric field strength along both sides of VISE and in DSIAEs head along lower electrode is simulated figure4.5 and figure4.8. It is analyzed from simulation that electric field changes uniformly along VISE and almost $2.4*10^6$ times lesser as compared to electric field strength at lower side of lower electrode in DSIAEs head.

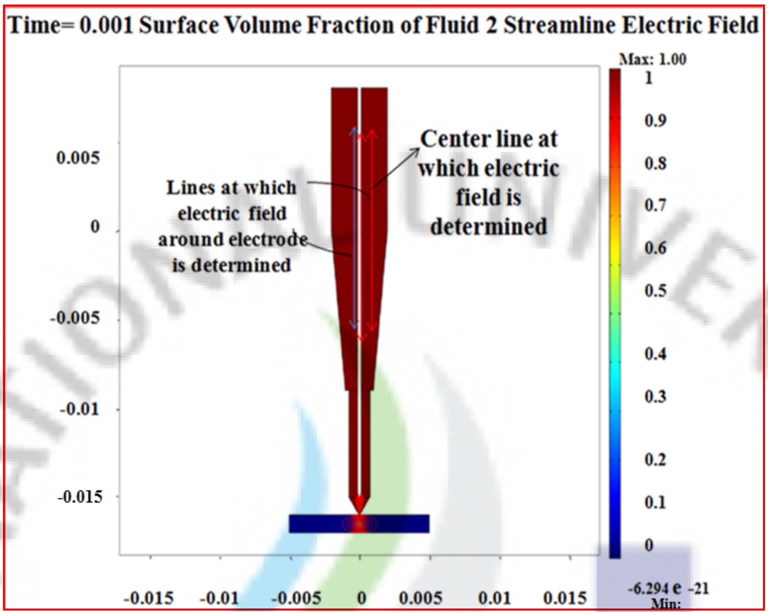

Figure 4.3. Electric field simulation results for VISE Head

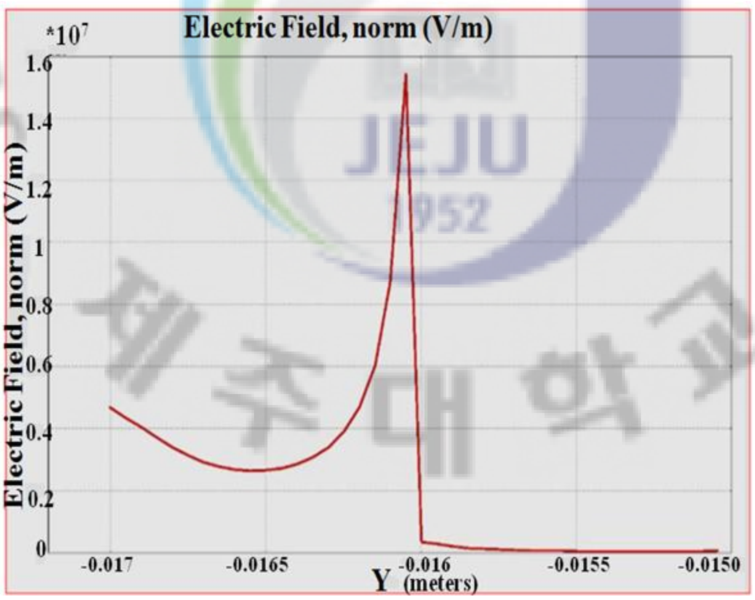

Figure 4.4. Electric Field along the center line in VISE Head

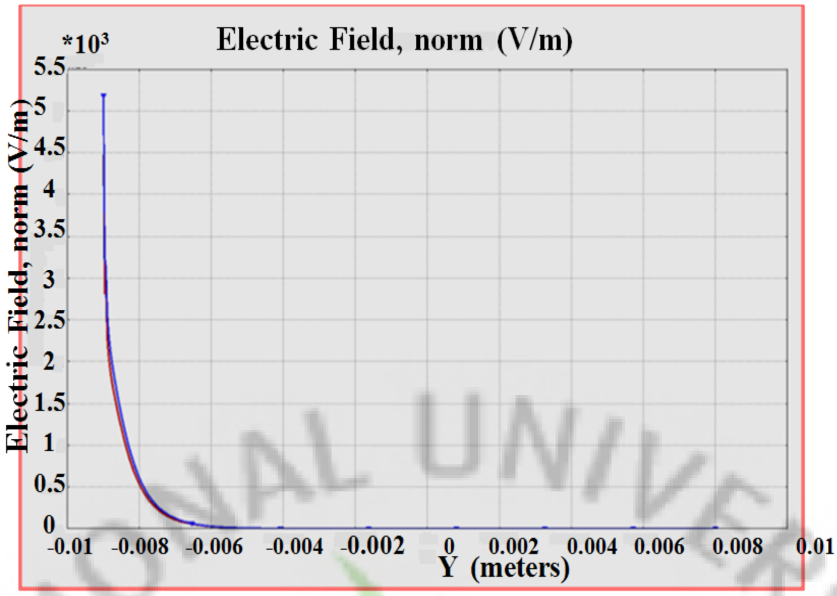

Figure 4.5. Electric Field around VISE Head

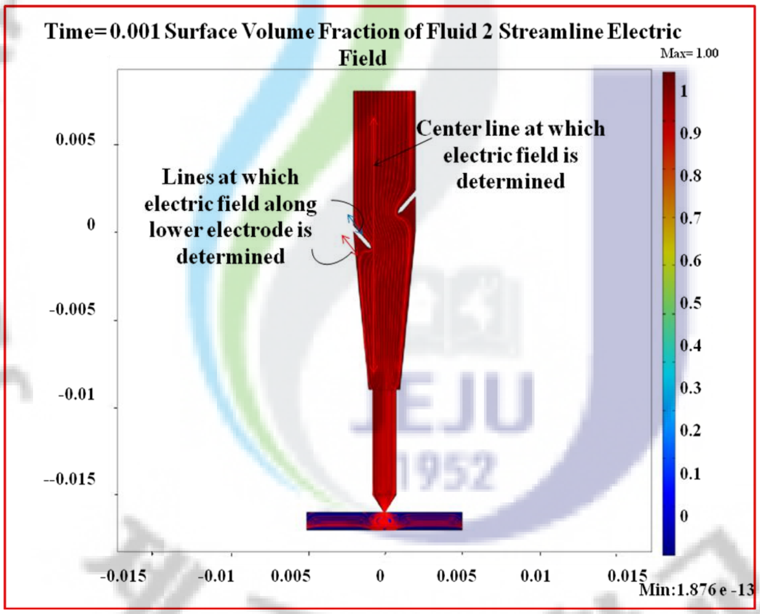

Figure 4.6. Electric field simulation results for DSIAEs electrode head

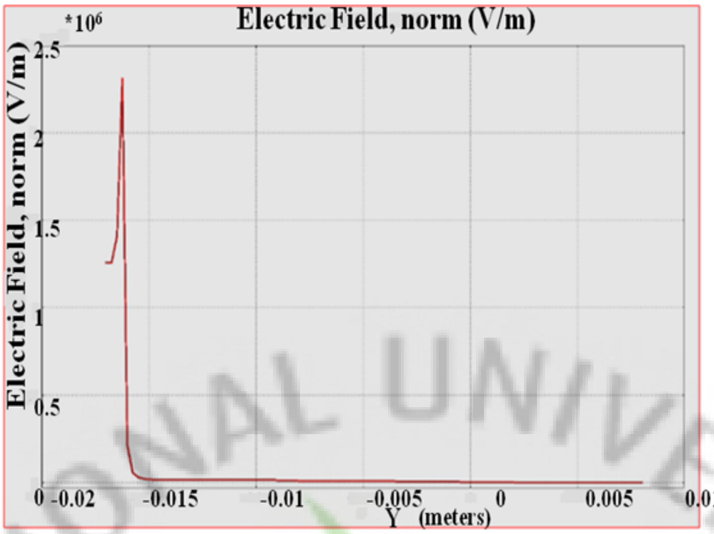

Figure 4.7. Electric Field along the center line in DSIAEs Head

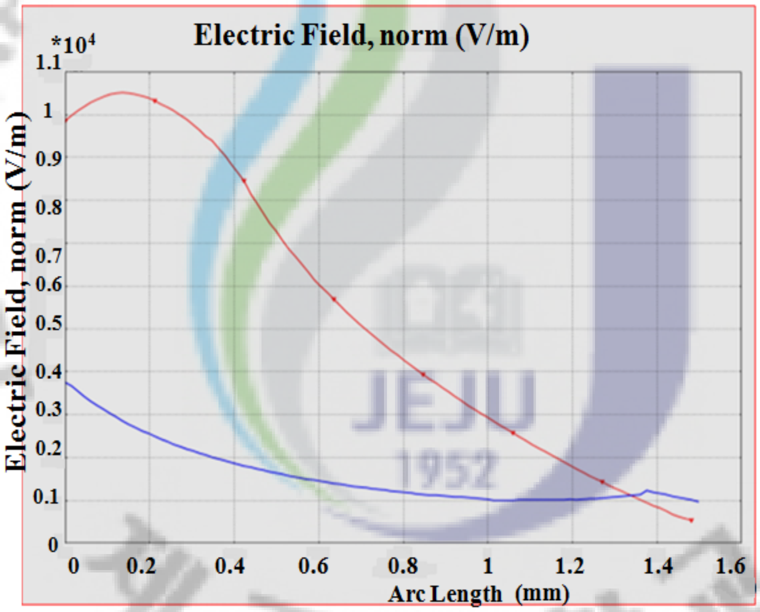

Figure 4.8. Electric Field along Lower Electrode (red line indicates lower side of electrode and blue line indicates upper side) in DSIAEs Head

4.3.2 ELECTRIC FIELD STRENGTH SIMULATION RESULTS COMPARISON OF DSIAEs HEAD and VISE HEAD

From simulation results it is analyzed that in DSIAEs head, upper electrode enhances electric field strength at lower electrode. Therefore, electric field at lower electrode tip is larger than upper electrode tip. Electric field at lower electrode tip is almost 2 times greater than upper electrode tip. Also electric field strength is 3 times lower at DSIAEs lower electrode tip as compared to VISE head electrode tip.

Simulation supports that electric field intensity on electrode is more in VISE (i.e. center line) and away from center line its intensity decreases. But in case of DSIAEs head at lower electrode, electric field strength comparatively stronger away from it. This simulation analysis supports that bulk of fluid ionizes more in DSIAEs head as compared to VISE head. This supports that electrification intensity increases in DSIAEs head.

Also electric field simulation comparison along the sides of VISE and lower electrode in DSIAEs head are compared which shows that electrical field near lower electrode is stronger in DSIAEs head as compared to VISE head. It means that in VISE head only at tip of electrode and at center line of electrode electric field strength is high. But in case of DSIAEs head, electric field strength away from electrodes is also effective. These simulation results support that electrification intensity inside head increases in case of DSIAEs.

4.4 Single Side Inserted Angular Electrode Head (SSIAE Head)

A single electrode of tungsten is inserted at lower point with same suitable exposure at an angle of (50^0~60^0) as in DSIAEs head inside electrostatic inkjet printing polymeric head, and a glass capillary is fixed at the bottom end of polymeric head figure 9.

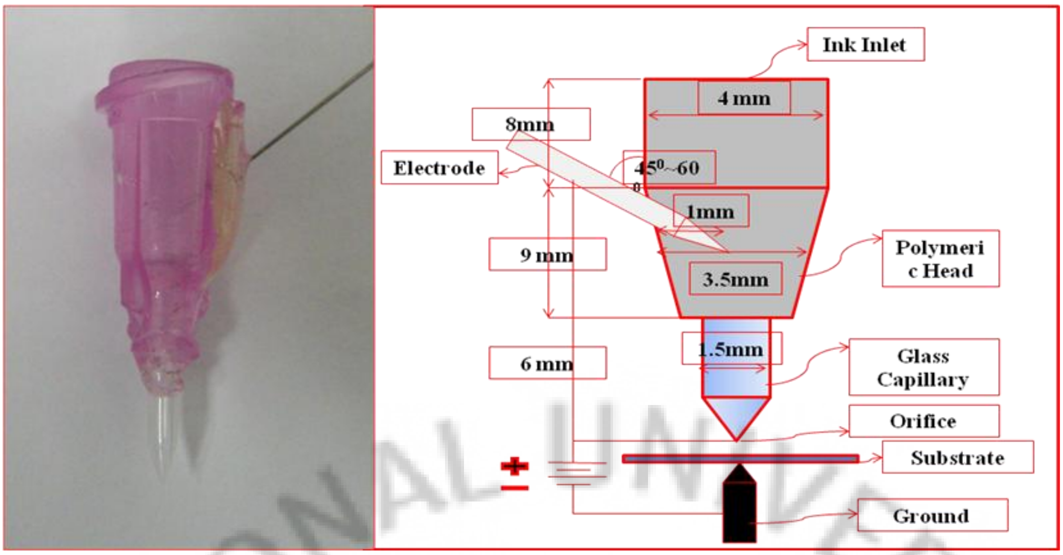

Figure4.9. Schematic description of new developed SSIAE (Single Side Inserted Angular Electrode) Head set up for Electrostatic Inkjet Printing

In SSIAEs tungsten electrode is inserted 1.5 mm in polymeric head. So, exposed surface area of inserted electrode to ink is (0.942 mm^2) which is very small as compare to VISE head and half to DSIAEs head.

4.4.1 Simulation of SSIAE Head

Obtained electric field simulation results for SSAIE Head is given in figure10. Electric field strength at center line is simulated it is observed that electric field strength at center line is 1.65×10^7 V/m which is almost the same as in case of VISE head, figure4.11. But it is notice worthy point that in VISE head at center line there is electrode but in SSIAE head at center line bulk of fluid.

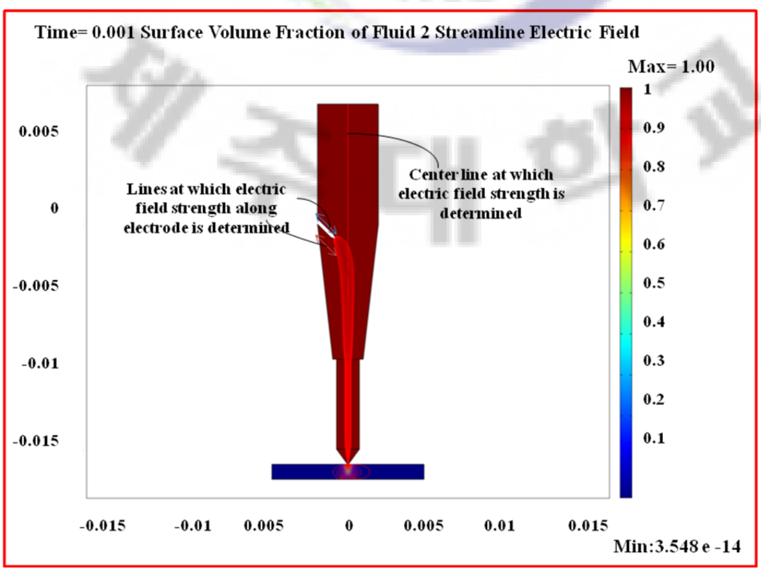

Figure 4.10. Electric field simulation results for DSIAEs electrode head

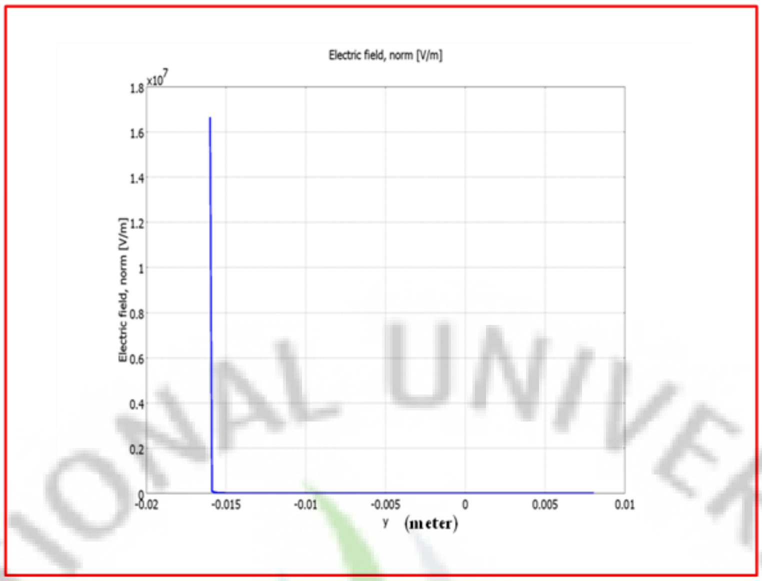

Figure 4.11. Electric Field along the center line in SSIAEs Head

Besides this electric field strength along both sides of SSIAE is simulated, figure12. It is analyzed from simulation that electric field is not changing uniformly along SSIAE. Electric field strength is stronger along lower side as compared to upper side of SSIAE inside head. By comparing electric field strength at lower side of SSIAE to VISE head, it is noticed that electric field strength is 2 times stronger.

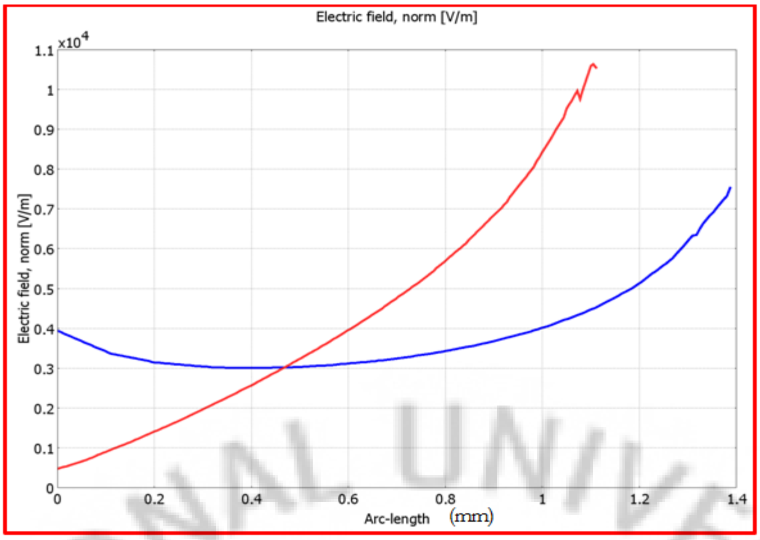

Figure 4.12. Electric Field strength along Lower side (red) and Upper side (blue) of Electrode in SSIAEs Head

4.5 Double Sided Inserted Electrodes Head (DSIEs Head)

Electrode configuration for Electrostatic Inkjet head with two electrodes inserted horizontally to one another is also checked. Two tungsten electrodes are inserted horizontally from opposite sides with same suitable exposure as in DSIAEs head inside electrostatic inkjet printing polymeric head, and a glass capillary is fixed at the bottom end of polymeric head figure4.13.

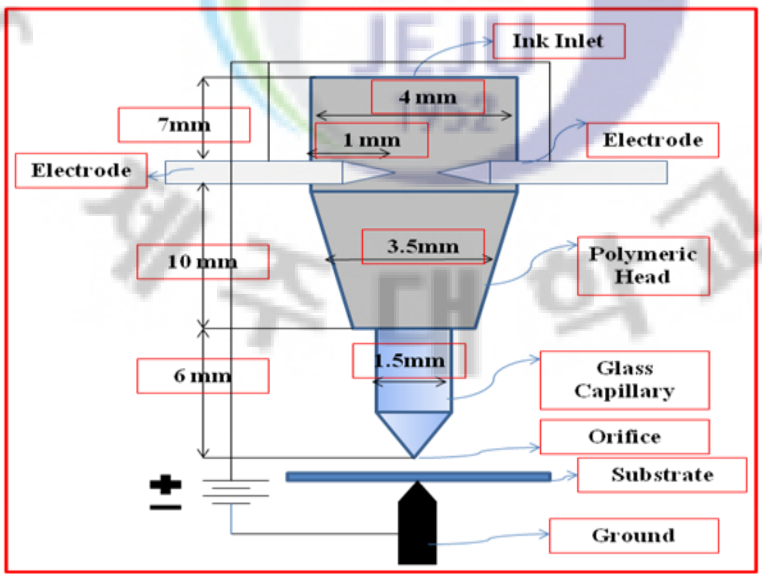

Figure 4.13. Schematic description of new developed DSIE (Double Sided Inserted Electrodes) Head set up for Electrostatic Inkjet Printing

4.5.1 Simulation of DSIEs Head

Simulation is done for Electric field strength of EIJ developed head (DSIE), figure 4.14. Electric field strength at the center line is simulated. It is noticed that electric field in DSIEs head at center line is almost the same as compared to VISE head as shown in figure 15.

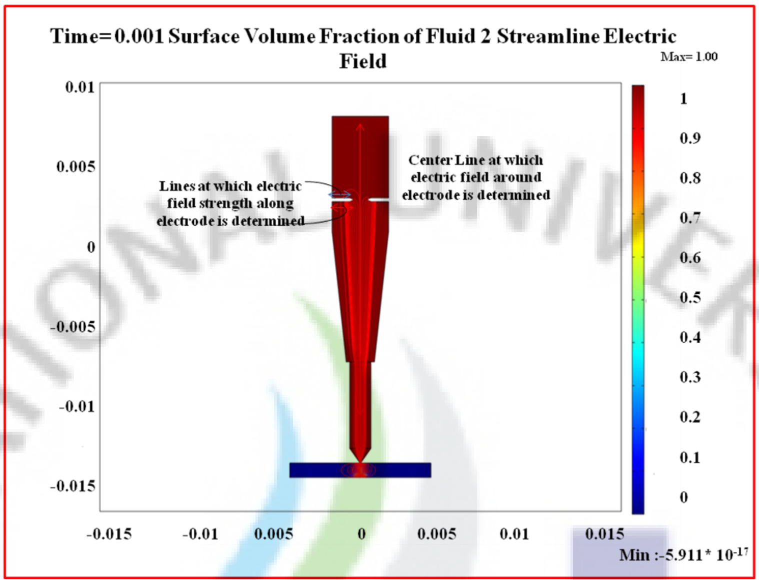

Figure 4.14. Electric field simulation results for DSIE Head

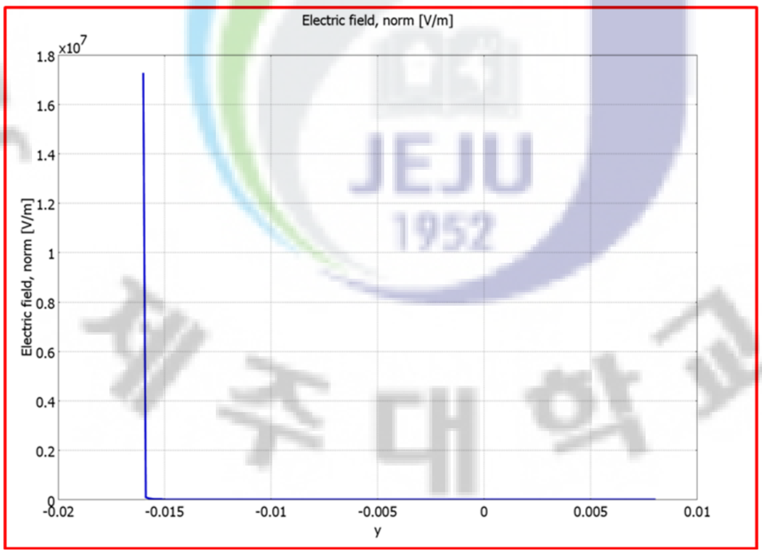

Figure 4.15. Electric Field along the center line in DSIEs Head

Similarly, electric field strength along both sides of DSIEs is simulated, figure4.16. It is noticed that electric field strength is almost 10 times stronger along lower side as compared to upper side of DSIEs. Also this is very weak as compared lower electrode in DSIAES.

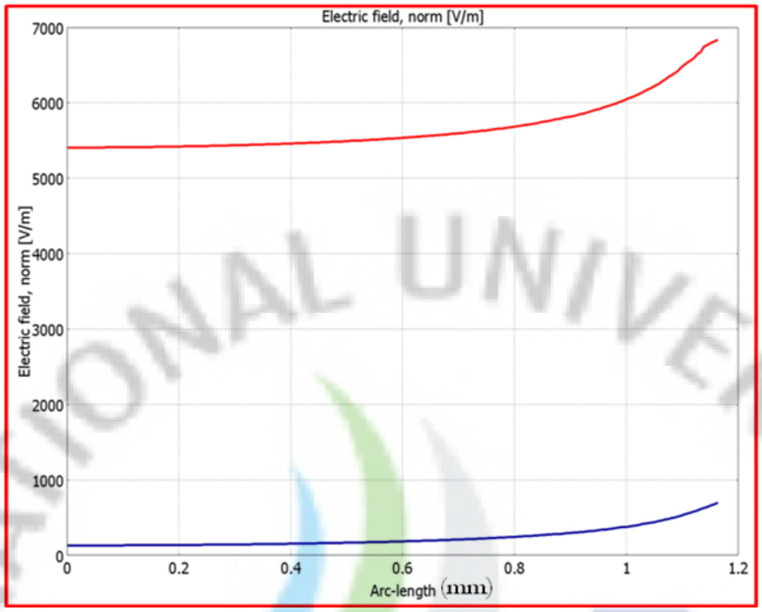

Figure 4.16. Electric Field strength along Upper side (blue) and Lower side (red) of Electrode in DSIEs Head

References:

[1]. GENT, A.N. LIN, C. W: J. ADHESION AND TECHNOLOGY. VOLUME 32, (1990) 113.

[2]. Droplet Ejection Behavior in Electrostatic Inkjet DrivingYuji Ishida, Keigo Sogabe, Shintaro Kai, and Tanemasa Asano Graduate School of Information Science and Electrical Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

[3]. Electrode Configuration Effects on Electrification and Voltage Variation in Electrostatic Inkjet Printing Head

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CHAPTER 5

EXPERIMENT AND RESULTS ANALYSIS

5.1 Experiments

The experimental setup designed for electrostatic inkjet print head driven by electrostatic forces is shown in the figure5.1.

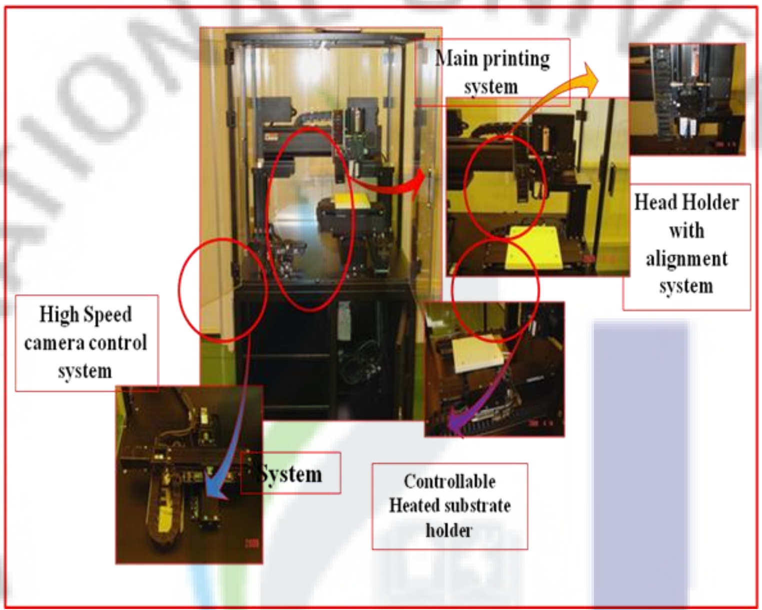


Figure5.1. Experimental set up for Printing Printed Patterns

The apparatus consists of X-Y stage, electrode, a high voltage source, high speed camera, ink supply system, and a holder with z- axis control. Discrete Pin-to-pin [1] set-up is used for experiment. The ground electrode is connected to negative potential of voltage source and the positive potential to electrode in the nozzle head for electrification of ink and providing the necessary potential for droplet extraction from meniscus. A commercially available, solvent based ink (TEC-IJ-040) containing 20 % silver pigments is used. Other properties of the ink such as density, viscosity, surface tension, metallic pigments and conductivity are: 1.07 g /cm^3, 15 cps, 32 dynes/cm with silver (Ag) particles and 2.06 mS/cm respectively. The liquid pressure is controlled by using pressure injection pump. After developing the meniscus, result is analyzed to find the optimal values for the given nozzle. This is done by applying different voltages until optimal values of stable meniscus and jetting voltages are determined[2]. For observation purpose, high speed camera is used. The magnification of lens is 11X with frame rate of 600 frames per second.

In first conducted experiment, a single electrode is inserted 20 mm vertically (VISE) from top in polymeric head with glass capillary with 60μm orifice at the bottom, as shown in figure1 **(Electrostatic Inkjet Printing Head)**. Conventionally electrode tip is close to glass capillary inside head.

In VISE head, it has been observed that when voltage is applied to meniscus, it has taken 2.6 kV to get stable meniscus, and for converting into jet it has taken more 2.4 kV i.e. it has started jetting at 5 kV, given in table 5.1. Meniscus is not that stable i.e. its shape is varied with increase in applied voltage as shown in figure5.2. It happens because of electrode tip vibration at applied high voltage. Similarly jet obtained from unstable meniscus is also not stable and changes its orientation.

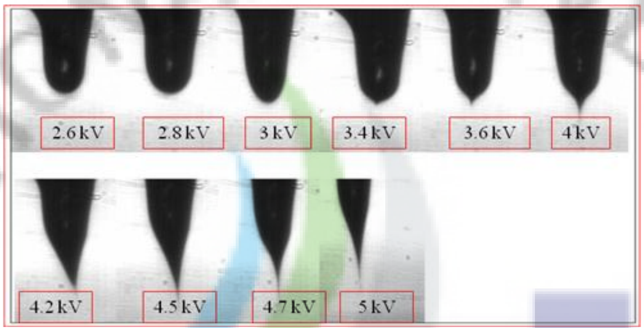
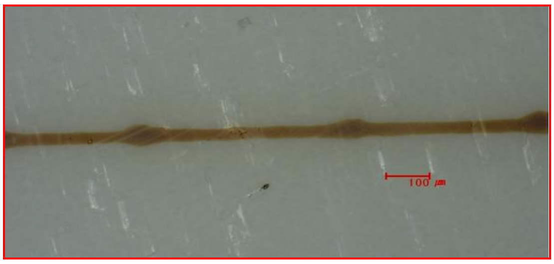


Figure5.2. Meniscus to jet transition with increase in voltage for VISE (vertically inserted electrode) head

Printed patterns on substrate, obtained from jet developed in VISE head are given below in figure5.3. It is obvious that printed patterns are not very uniform due to unstable meniscus. Bumps in pattern are obvious which indicates hindrance to ink flow inside head.

(5.3a)



(5.3b)

Figure5.3. (a) & (b) Pattern Lines obtained with vertically inserted Single Electrode (VISE) head

Second experiment is conducted with double side inserted angular electrodes (DSIAEs) head. In this arrangement two electrodes connected in parallel to external power supply are angularly inserted from opposite sides in polymeric head. Each electrode is inserted 1.5 mm into polymeric head at an angle of (50^0~ 60^0) from opposite sides. It is clear from figure2**(Electrostatic Inkjet Printing Head)** that both electrodes are almost 9 mm above from glass capillary orifice, while distance between tip of lower actuator electrode and counter electrode tip is 10 mm.

In this experiment it is observed that when voltage is applied, it has taken 1.3 kV to get a stable meniscus. Distance between stable meniscus tip and counter electrode is 750 µm. To convert stable meniscus into jet it has taken more 1.42kV i.e. it has started jetting at 2.75 kV, table5.1. In DSIAEs case, meniscus remains very stable because both the electrodes are comparatively above from glass capillary orifice and have almost no effect on meniscus. Jet retains its shape because it is transformed from a stable meniscus. Meniscus and jet are shown in figure5.4.

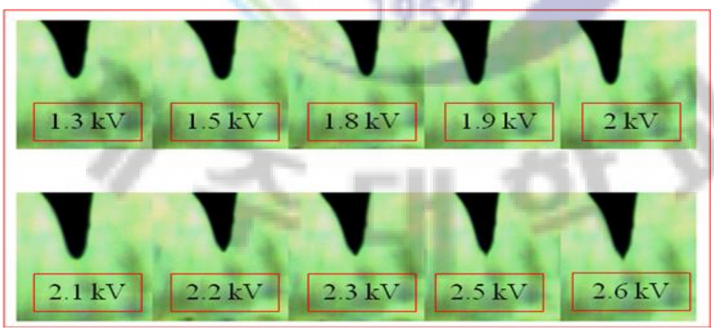
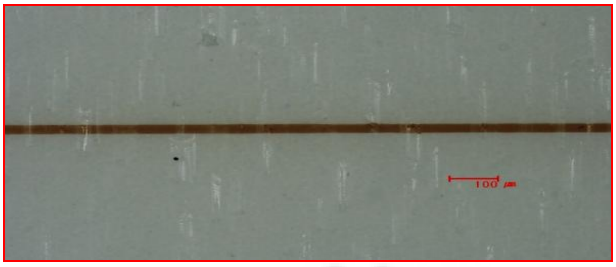
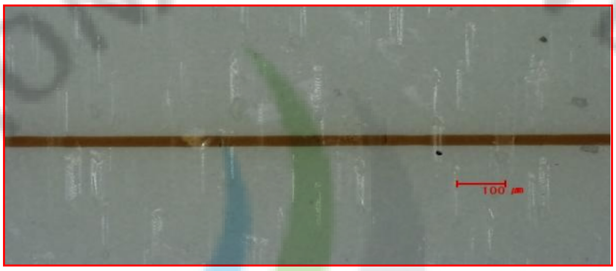


Figure5.4. Transition from meniscus to jet, with increase in voltage for DSIAE (double side inserted angular electrode), head

Printed patterns obtained with DSIAEs head on substrate are shown in figure5.4. It is obvious that printed patterns in this case are very much uniform and no bumps are observed, which indicates that ink flows smoothly inside head toward orifice. It supports the argument that jet obtain from a stable meniscus is also very stable.



(5.5a)

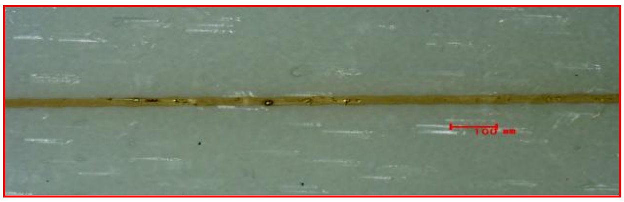


(5.5b)

Figure5.5. (a) & (b) Pattern lines obtained with DSIAE (double side inserted angular Electrodes) Head

For SSIAE head experiment has conducted. In this arrangement single electrode connected to external power supply. Electrode is inserted 1.5 mm into polymeric head at an angle of (50^0~ 60^0). Electrode is almost 9 mm above from glass capillary orifice, while distance between tip of lower actuator electrode and counter electrode tip is 10 mm.

It is observed that when voltage is applied, it has taken 3 kV to get a stable meniscus. Distance between stable meniscus tip and counter electrode is 750 μm. To convert stable meniscus into jet it has taken more 0.800kV i.e. it has started jetting at 3.8 kV, table5.1. In SSIAE case, meniscus remains stable because electrode is comparatively above from glass capillary orifice and has almost no effect on meniscus. Jet retains its shape because it is transformed from a stable meniscus. Pattern lines obtained with SSIAE head are given in figure5.6.



(5.6a)

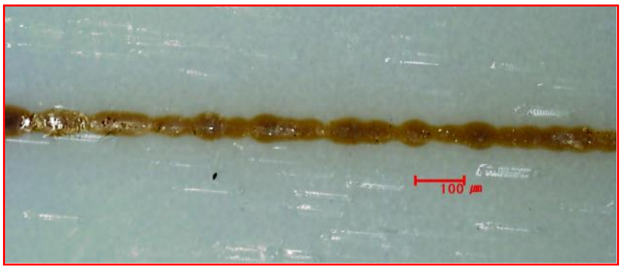
(5.6b)

Figure5.6. (a) & (b) Pattern Lines obtained with SSIAE (double side inserted angular Electrodes) Head

Experiment is conducted with DSIAEs head. In this configuration, two electrodes connected in parallel to external power supply are horizontally inserted from opposite sides in polymeric head. Each electrode is inserted 1mm into polymeric head. Both the electrode are well above the glass capillary orifice.

In this experiment it is observed that when voltage is applied, it has taken 2.7 kV to get a meniscus. Distance between meniscus tip and counter electrode is 750 µm. To convert meniscus into jet it has taken more 3kV i.e. it has started jetting at 5.7 kV, table5.1. In DSIEs case, meniscus remains very unstable because both the electrodes are horizontally inserted and perpendicular to ink supply channel. So because of this perpendicularity when ink passes through electrodes more vibrations produces which in turn disturbs electrification intensity and also increase power dissipation. Due to vibrations developed meniscus also becomes unstable. Jet obtained from unstable meniscus also remains unstable. It is clear that obtained patterns with DSIEs head are not uniform, figure 5.7.

(5.7a)



(5.7b)

Figure5.7. (a) & (b) Pattern Lines obtained with DSIEs (double side inserted angular Electrodes) Head

5.2 RESULT ANALYSIS

Experimental parameters for each head are given below in table1. It is palpable that in case of DSIAEs head, required applied voltage for achieving stable meniscus has decreased 50% and for transforming meniscus into a jet, it has decreased 45%, as compared to conventional VISE head, figure5.6. This decrease in applied potential has taken place because in DSIAEs head, meniscus gets charged more quickly and requires less applied potential for transforming to a jet as compared to VISE head. This phenomenon of increasing ink electrification intensity has happened because of two electrodes connected in parallel at suitable exposure to the ink.

Table 5.1. Stable meniscus and Jetting parameters for each Electrostatic Inkjet Head

	Electrode Configuration in Electrostatic Inkjet Printing Head	Nozzle to Substrate distance (µm)	Analysis			
			Applied Potential for getting Meniscus (kV)	Flow rate (µl/hr)	Applied Potential for Jetting (kV)	Line Width (µm)
Discrete Set Up	Vertically Inserted Single Electrode (VISE)	250	2.6	100	5	20 ~ 30
	Double Side Inserted Electrodes (DSIEs)	250	2.7	100	5.7	40~60
	Single Side Inserted Angular Electrode (SSIAE)	250	3	100	3.8	30~40
	Double Side Inserted Angular Electrodes(DSIAEs)	250	1.3	100	2.75	20 ~ 30

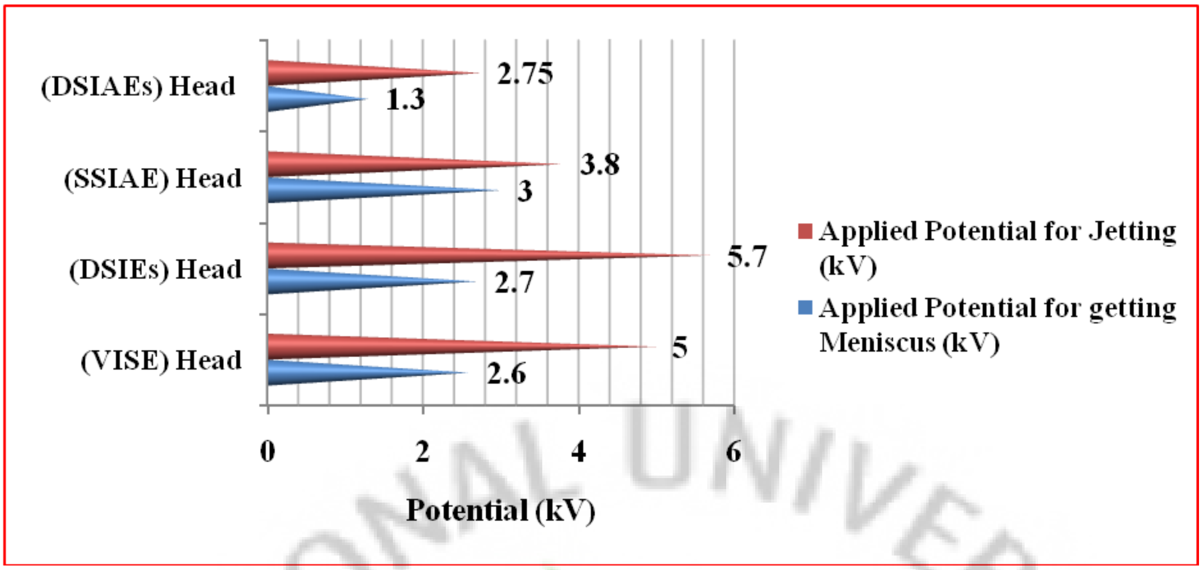


Figure5.8. Variation in Meniscus and Jet Voltages in VISE Head, SSIAEs Head, DSIEs Head and DSIAEs Head

It is observed that meniscus obtained from DSIAEs head remains very much stable as compared to meniscus obtain from VISE head. It is because that when voltage is applied to electrode in VISE head, its tip vibrates more which perturbs the developed meniscus, as shown in figure5.2. Therefore jet obtained from less stable meniscus, prints less uniform patterns, as shown in figure5.3.

But in DSIAEs head, tips of both electrodes are above from glass capillary orifice. So, when voltage is applied to electrodes in DSIAEs head connected in parallel, have almost no effect on the developed meniscus. Therefore, developed meniscus in DSIAEs head, remains very stable and similarly jet obtained from it also remains very stable, as shown in figure5.4. Therefore, printed patterns obtained with DSIAEs head are more uniform as compared to VISE head, as shown in figure5.5.

In case of SSIAE head stable meniscus is obtained very quickly but it is observed voltage required for jet from developed meniscus is less than VISE head but it is more than DSIAEs head. Also pattern obtained with this configuration are more uniform than VISE head and comparatively uniform as in case of DSIAEs head.

But in DSIEs configuration in head, developed meniscus remains very unstable. Also it takes more voltage as compared to VISE head and DSIAEs head while compared to SSIAEs head it takes less voltage. In VISE head more surface area of electrode is exposed to ink while in DSIAEs head both electrodes are connected in parallel to power supply so therefore, adequate electrification takes place. But in case of SSIAE head very less surface area of electrode is exposed to ink so initially it requires more power for electrification of ink.

5.3 Adhesion Analysis of printed patterns with VISE head on ITO Coated Substrates with different RMS values

Adhesion of electro-statically inkjet printed patterns is studied in relation to ink droplet behavior on substrate. For analyzing droplet behavior contact angle analyzer is used by utilizing Image Xp software. Droplet behavior on substrate is analyzed in terms of its contact angle, wetting, spreading and adhesion with substrate. Commercialized ink is used which has made different contact angles on different substrates. Contact angle on droplet on substrate depends on respective substrate RMS value. Keeping its Image Xp software data in view, it is subjected for printing patterns electrostatically. Conductive patterns have printed on ITO coated substrates (Glass (ITO Coated), PET 1 (ITO Coated), PET 2 (ITO Coated)) which are being used for printing electronics devices. It has been observed that substrate with higher RMS value on which ink makes high contact angle, showing good adhesion for electrostatically printed patterns as compared to other substrates with less RMS value on which ink has made lower contact angle. Also relationship of wetting energy, work of adhesion and spreading coefficient is studied with respect to droplet behavior on substrate.

5.4 Ink Analysis by Contact Angle Analyzer

First contact angle on each substrate is measured by using Contact Angle Analyzer (Phoenix 300).The experimental setup for analyzing single droplet behavior on substrate is given in figure5.9.

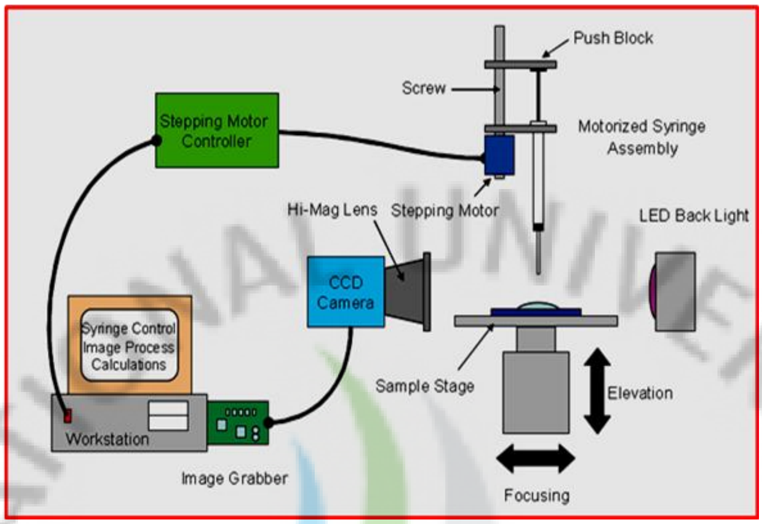


Figure5.9. Contact Angle Analyzer for measuring droplet behavior on Substrate

First of all, ink is loaded in syringe and then after putting the syringe in contact angle analyzer a drop is generated and allowed to strike the substrate and make a contact angle. The image of contact angle made by drop on substrate is captured and each image of contact angle till final spread is monitored and measured by Image- Xp Software. Image- Xp Software analyzes and calculates drop behavior on substrate, as given in figure 5.10[9].

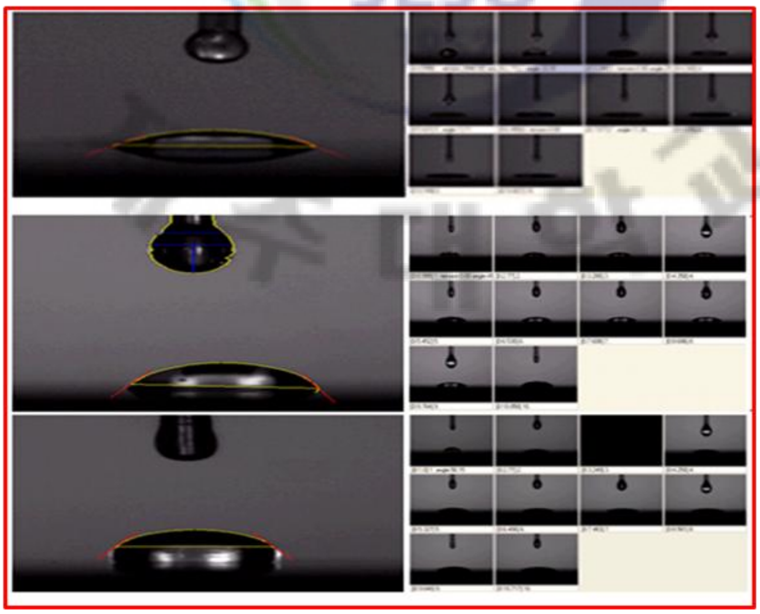
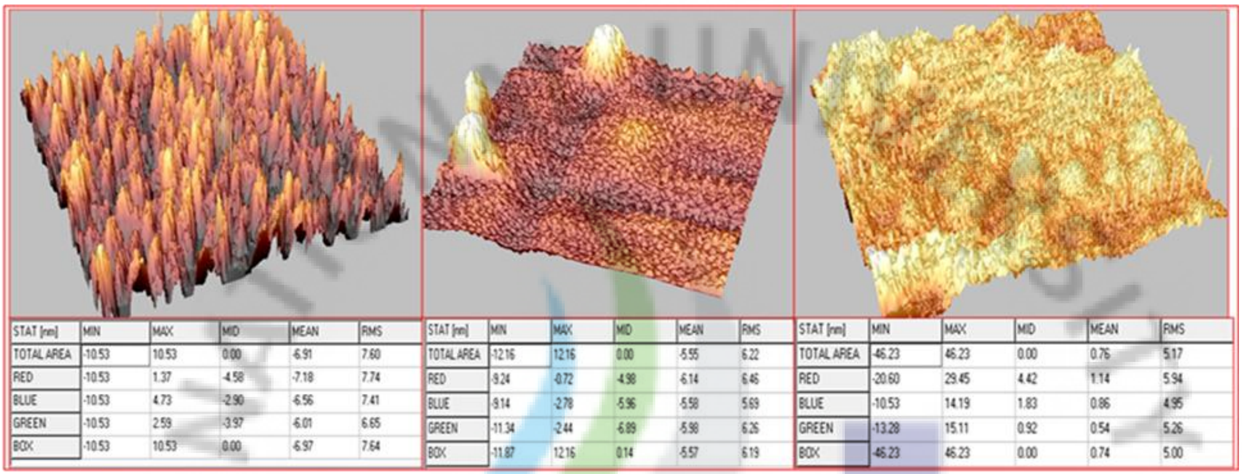


Figure5.10. Contact angle of 040 ink on substrates a) Glass (ITO Coated), PET1 (ITO Coated), PET2 (ITO Coated), respectively, b) Images of 040 ink on each substrate till final spread

Also for measuring surface roughness of substrate AFM non-contact mode is used. Surface morphology and statistical data obtained by AFM is given in figure5.11. RMS values for each substrate are obtained. In table 5.2, surface roughness of substrates by AFM and ink droplets data by contact angle analyzer on the substrate are given.



a) Glass (ITO Coated) b) PET Max Film (ITO Coated) c) PET Sigma Aldrich(ITO Coated)

Figure5.11. Surface Morphologies of substrates obtained by AFM

Table5.2. Surface Roughness by AFM and Ink Droplet Analytical Data by Contact Angle Analyzer

Properties / Substrate	Surface Roughness (RMS) [nm]	Contact Angle (Average) [degree]	Wetting Energy [mN/m]	Spreading Coefficient [mN/m]	Work of Adhesion [mN/m]	Pattern Width [μm]
Glass (ITO Coated)	7.6	63.698971	32.256771	40.54324	105.0568	20
PET (Max film) (ITO Coated)	6.37	61.427551	34.818039	37.98196	107.618	35
PET (Ald -sigma) (ITO Coated)	5.39	56.547839	37.371922	34.428082	110.1719	70

Printed patterns obtained on different substrates by Electrostatic Inkjet Printing system have been used for ASTM 3359D-B test i.e. (Glass (ITO Coated), PET 1 (ITO Coated), and PET 2 (ITO Coated), figure 5.12.

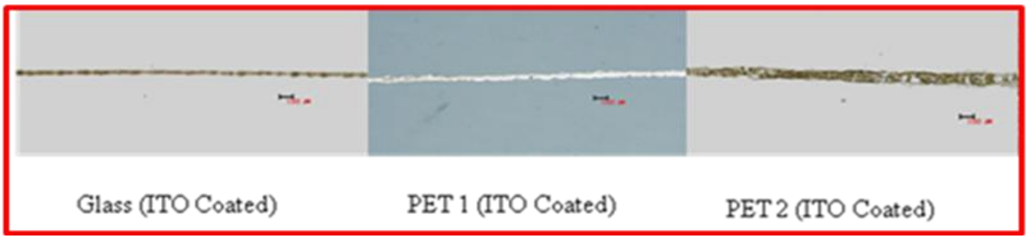


Figure5.12. Printed Patterns on different substrates

Experimental parameters for each substrate are given in table 4.3. To achieve conductive lines on each substrate, values of voltages and stand-off are varied. Due to different texture and thickness of each substrate, these parameters need to be changed.

Table5.3. Printing Parameters for each substrate are given after impacting on substrate

Substrate	**Voltage (kV)**	**Stand-off (μm)**
PET 1(ITO Coated)	5.3	<250
PET 2 (ITO Coated)	5.8	<250
Glass (ITO Coated)	6.5	<250

5.5 Results and Discussions

Data has obtained from droplet analyzes by Image Xp Software, for conductive ink on different substrates. Data has shown that there are some relationships exist among different properties of ink and substrate properties, when droplet strikes on substrate. Behavior of ink on each substrate, from initial impact to final spread is shown in figure 5.10 (a, b) which is according to surface properties of substrate. It is observed that droplet imparts its maximum energy in initial impact with substrate. Adhesion of droplet mostly depends on its first impact with substrate. In figure 5.13, relationship trends are given that contact angle of ink has direct proportionality with surface roughness (RMS value) of substrate. Further it shows that adhesion work and wetting energy of ink decreases with increase in substrate surface roughness (RMS). It is because for substrates with high surface roughness, less effort is required by the droplet to adhere more firmly with it. Similarly; it is palpable that spreading coefficient of ink on substrate increases with increase in surface roughness (RMS) of substrate. It is because substrate with high surface roughness (RMS) has less surface energy and it does not consume that much energy on droplet to spread.

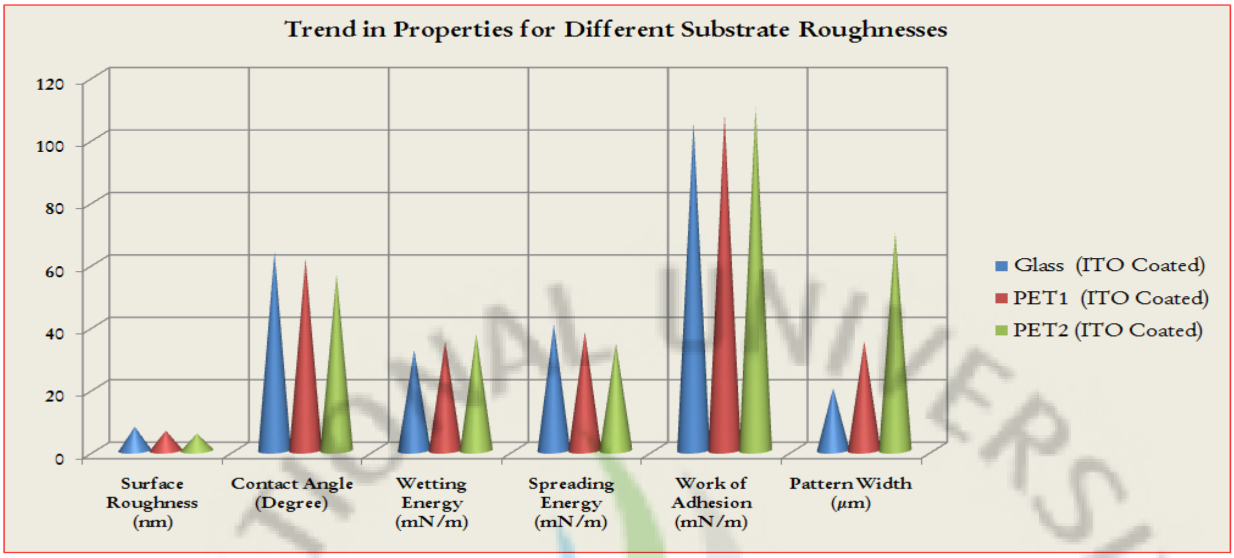


Figure5.13. Graph indicates trend of different properties with respect to Contact Angle

Keeping contact angle analyzer data, printed patterns are analyzed. It is observed that printed pattern width has decreased on substrates with which ink has made high contact angle i.e. pattern line width in case of glass (ITO Coated) is the smallest (20μm) and in case of polyimide it is (112 μm).

After curing of substrate, printed patterns adhesion with substrate is evaluated by ASTM D 3359 B standard procedures. For this purpose 3M 610 pressure sensitive tape is used. Comparing data, given in table5.2 obtained by contact angle analyzer and in table5.4 obtained by ASTM D 3359-B.

TABLE5.4. ADHESION TEST ASTM D 3359-B

ASTM D 3359-B / Substrate	5 B	4 B	3 B	2 B	1 B	0 B
PET 1(ITO Coated)	-	+	-	-	-	-
PET 2 (ITO Coated)	+	+	-	-	-	-
Glass (ITO Coated)	+	-	-	-	-	-

It is observed that the substrate (Glass (ITO coated)) on which ink has made high contact angle, printed pattern has higher adhesion on that substrate and vice versa.

It means that printed patterns have better adhesion with that substrate which has higher RMS value as compared to substrates having lower RMS values. Reason for this phenomenon is that nano particles make better interlocking on rough surfaces as compared to smooth surfaces. Because rough surface have many asperities as compared to smooth surface.

Reference:

[1]. "Study of Droplet Generation through Drop on Demand Electrostatic Inkjet for printed Electronics", A. Rahman ,J.B. Ko, K. Rehman, M. A. Ali Rehmani, Y.H. Doh, K.H. Choi at 1st International Conference on R2R PrintedElectronics Apr 30-May 2, 2008 in Konkuk University, SEOUL, KOREA

[2]. Ioan Marginean[a], Ryan T. Kelly[a], Ronald J. Moore[a], David C. Prior[a], Brian L. LaMarche[a], Keqi Tang[a] and Richard D.

CHAPTER 6

SUMMARY, CONCLUSION AND FUTURE WORK

6.1 Summary

Inkjet printing technique is the most promising in all printing techniques. Inkjet printing has a great advantage over other owing to its applicability to electronics large–area, flexible substrates, low temperature process ability and low energy cost. Inkjet printing can be divided into three types: electrostatic, piezoelectric and thermal methods. There are some constraints in Piezo and thermal inkjet printers. While in case of electrostatic inkjet printing head a jet can be achieved which is It gives the provision to produce jet which is almost 70% smaller in diameter from nozzle diameter and also ink properties remain the same as it is. Inkjet printing is a smart technology for printing patterns i.e. organic light-emitting diode displays, field–emission displays and printed–circuit–board wiring etc.

For developing multi-nozzle electrostatic inkjet printing head, a conductive metallic electrode is inserted in head for electrification of ink, instead of using metallic capillary to minimize crosstalk. But, still there some issues are related to vertically inserted electrode head. In usual practice VISE head is being used. But with this configuration of electrode in head it has been observed that voltage requirement for getting stable meniscus, droplet extraction and jetting is very high. Also obtaining uniform patterns with vertically inserted single electrode head is not easy to obtain. Jet obtained with this configuration is not stable because it is obtained from less stable meniscus. Reason for less stable meniscus is vertical inserted electrode vibration at applied high potential.

To get uniform patterns, a stable jet is required for it and for a stable jet attainment a very stable meniscus is needed to develop. For getting stable meniscus a new approach of electrode configuration in printing head is taken on i.e. DSIAEs head. It is observed that printed patterns obtained are turned out very uniform.

6.2 Conclusion

In this research a new electrostatic inkjet printing head i.e. DSIAEs (Double Side Inserted Angular Electrodes) has been developed and its behavior for meniscus and jet has been investigated. From observation of experiments with DSIAEs head and conventional VISE head it has concluded:

- In DSIAEs head, bulk of ink inside head charges more quickly because two electrodes connected in parallel at same applied potential
- In DSIAEs head electrification intensity of ink increases
- DSIAEs head gives more stable meniscus and jet as compared to conventional VISE head
- In DSIAEs head, applied potential for getting stable meniscus decreases 50 % and for converting meniscus to jet, applied potential decreases 45%, as compared to VISE head
- More uniform patterns are obtained with DSIAEs head

Besides this printed patterns obtained on ITO coated substrates are subjected for adhesion test using ASTM standard ASTM D 3359 B. Ink behavior on substrate is studied through contact angle analyzer. Also substrate surface texture is studied by using AFM 100. It is concluded that printed patterns have better adhesion with high surface roughness substrate.

It is concluded that by changing surface roughness of substrate and keeping all other parameters constant, printed pattern adhesion with substrate can be improved.

6.3 Future work

For future work related to this study, the developed head i.e. DSIAEs head can be used in integrated ink jet printing head. Suggested assembly of DSIAEs head for integrated inkjet printing head is given below in figure 6.1.

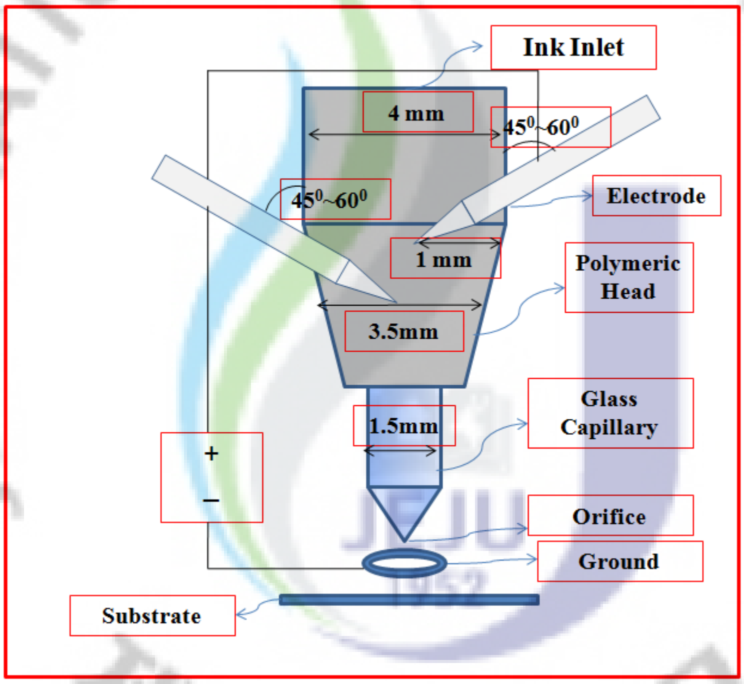


Figure 6.1. Integrated Head Assembly using DSIAEs head