修士論文

Assistant Tools and Techniques for Rapid Prototyping with Conductive Inkjet Printing

「導電性インク印刷技術を用いた
ラピッドプロトタイピング支援手法」

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Abstract

This master dissertation will focus on discussing tools and techniques which can be used to improve the functionality of conductive inkjet printing technology. Conductive inkjet printing, especially Instant Inkjet Circuits have brought a brand new approach to rapidly fabrication of conductive patterns. A novice user can use Instant Inkjet Circuits with almost any commodity inkjet printers to make flexible electronic circuit without hassle of setting or concerning about price too much.

Though enjoying great adoptions from a wide range of users, conductive inkjet printing and Instant Inkjet Circuits still have several weaknesses that leave room for improvement. Our first improvement will be tweaking an open-source printer driver to gain more control on the behavior of the printer. Thus, we can implement an auto-overprinting mechanism to reduce sheet resistance of the printed pattern for about 5 times. After this improvement of conductivity, we propose a simple, yet effective method to make interconnections for double sided layer conductive inkjet printed electronic circuit. The interconnections are made by making via-holes on surface of printing substrate. By selectively choosing hole openers, we show that felting needles (needles with barbs along its body) can make highly conductive via-hole (resistance is less than 1 ohm) for Instant Inkjet Circuits without any additional post-treatment.

With those improvement, we also show several extended applications of Instant Inkjet Circuits which are used to be ineffective or impossible.

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Abbreviations

$\Omega/\square$	ohm per square, page 7
BSD	Berkeley Software Distribution, page 19
CAD	Computer-Aided Design, page 59
CUPS	Common UNIX Printing System, page 19
GUI	Graphical User Interface, page 2
OS	Operating System, page 19
PET	PolyEthylene Terephthalate, page 7
RFID	Radio-frequency identification, page 11
VNA	Vector Network Analyzer, page 28
WPT	Wireless Power Transmission, page 54

Chapter 1

Introduction

1.1 Background

For recent years, rapid prototyping has received a lot of attentions from both maker and researcher. In the field of electronic circuit fabrication, there are several methods that have been widely used in both prototyping and mass production. These methods vary from solder-less breadboard to breakaway board, from lab scale milling machine to printed circuit board (PCB) production. However, they are either not reliable, effective or not flexible enough for rapid iteration of prototyping. To address this, Instant Inkjet Circuits [20] has been proposed as an electronic circuit rapid prototyping tool that is not only fast, neat, effective but also at low-cost and widely available with off-the-shelf tools like home grade inkjet printer and sintering-free silver nano-particle ink. Even so, such conductive inkjet printing technology is stilling facing several problems that restrict its application scenarios.

1.2 Purpose

This work aims at providing techniques and tools to improve performance of conductive inkjet printing technology, especially for Instant Inkjet Circuits.

In order to broaden the application range of conductive inkjet printing, we propose a simple method to reduce the sheet resistance of conductive printed pattern to the level that it is useful in applications that require highly conductive pattern such as RF circuitry or ultra low power devices. By tweaking an open-source printer driver (Gutenprint), we show that it is possible to gain more control of printer operation, and thus, change the way the printer prints conductive ink onto substrate. These tweaks include implementation of auto-overprinting, print density adjustment and an additional Graphical User Interface (GUI) component to control those parameters. Our experiments showed that with appropriate setting, conductivity of the printed pattern is significantly improved.

In the same attempt to enhance the functionality of conductive inkjet printing, we introduce and characterize double sided circuit as the first step to implementation of multi-layered circuit with Instant Inkjet Circuits. Multi-layered circuit boards have been used for a long time in fabricating electronic devices. The advantage of the multi-layered circuit is that it can reduce the complexity of the circuit routing. Additionally, in many circuit designs, it is impossible to wire without multi-layered circuit support. Multi-layered circuit is not simply stacking separated single circuits. It is necessary to have interconnections among these stacking circuits. In this work, we will discuss about the selection of tools to make small footprint interconnection with high conductivity and without involving in toxic materials or hazardous environment.

1.3 Applications

Our research on boosting functionality of conductive inkjet printing give user more control on fabrication with flexible conductive circuits. Along with retaining the advantages of Instant Inkjet Circuits (low-cost, off-the-shelf and fast), we propose a path to a new range of applications which are hard or even impossible with the old Instant Inkjet Circuits.

Improvement of conductivity helped us to make better antenna for energy harvesting, wireless power transmission or pressure sensors. This contribute to other researches as a effective support tool to rapidly fabricate and re-fabricate. This shortened iterative fabrication process can help to achieve better prototype in shorter time. Software approach in the attempt to implement overprinting also shows that it is possible to gain more control on the operation of commodity printer to improve conductive inkjet printing process. It is worthy to note that unlike hardware methods, our software approach help to eliminate the hassle of the deploying and reproducing. No hardware replacement is needed. All user need to do is to install a revised open-source printer driver.

In the case of double sided circuits, the possibility is increased even more. Applications which are difficult to make with single sided circuits such as LED matrix, tuneable RFID tag or tuneable wireless power transmission coil are now simply made with double sided circuits. This addition of another dimension has brought us more flexibility in designing of flexible electronic circuits. The arrival of double sided circuits also freed graphic designer, one of the main users of Instant Inkjet Circuits, from the struggle of balancing between art aesthetic and electronic functionality. Conductive ink has been used to design interactive arts like drawings, post-cards or advertisements. In single sided circuits, graphical design and electronic circuits are printed/drawn on the same side of the paper. These two components was mutually restricting each other. However, with double sided circuits, conductive pattern can be printed on one side of the paper, leaving the another side for artists to be creative with graphic design.

1.4 Thesis Organization

This thesis is organized as follows.

In chapter 2, basic principle of conductive ink is introduced. This chapter attempts to give a brief view on conductive inks and their pros/cons. A large part of this chapter will explain the principle of room temperature sintered conductive ink. This is a very important point that will give us better understanding of the reasoning in latter chapters.

Chapter 3 is the proposal of using open-source printer driver in enhancing the functionality of conductive inkjet printed pattern. This chapter shows the detail of modifications made in this open-source driver code base to implement auto-overprinting and printing density adjustment in a attempt of improving conductivity of conductive printed patterns. The effectiveness of those modification will be discussed through the evaluation of experimental result on resistance of the printed pattern.

Chapter 4 is the introduction of double sided circuits in Instant Inkjet Circuits. This chapter will describe the method of making interconnections for such double sided circuits. The selection of tools and post-processing will be discussed to figure out the best setting for making those interconnections. In the latter par of this chapter, we add a detail explanation of several exampled applications to illustrate the broadening of possibility with double sided circuit with Instant Inket Circuits.

Finally, chapter 5 concludes the thesis with contributions and future work.

CHAPTER 2

RESISTANCE IN INSTANT INKJET CIRCUITS

As our work is about the improvement of Instant Inkjet Circuits functionality, this whole chapter is dedicated to give a introduction to Instant Inkjet Circuits and its resistance characteristic. The first part briefly describes about conductive ink which is emerging increasingly as a great material for flexible electronic circuits. The second part focuses on introducing Instant Inkjet Circuits and sintering-free silver nano particle ink. In the last part, we will discuss about resistance in Instant Inkjet Circuits.

2.1 Conductive Ink

Emerging as a replacement for traditional wiring in electronic circuitry, conductive ink has been taking an important role in transforming how people make and enjoy the fun of electronic circuit making. Instead of using messy wiring jumper in breadboard, or long waiting for production of PCB, anyone can now use conductive ink to rapidly form the wiring in a electronic project, quickly fix an broken connection in the circuit, or even form a specially designed conductive pattern on flexible substrate (paper, for example) to make a new sensor. All of these are enabled by the present of the new generation of conductive ink – a new conductive material that can be flexibly deposited onto many commodity substrates by drawing, painting or printing.

2.1.1 Non-inkjetable Conductive Ink

In the early stage of conductive ink, micro-size conductive material particles are mixed with special binders to form a conductive material that can be used to draw or paint using a pen.

Among many non-inkjetable conductive inks, BarePaint [6] from BareConductive seems to get the most noticeable adoption from end users. The main conductive material in BarePaint is carbon or graphite

(a) BarePaint [6]

(b) CircuitScribe [10]

Fig. 2.1: Micro-size particle conductive ink

powder with particle size ranges from 40 μm to 150 μm [32]. After drawing, BarePaint takes about 10 to 20 minutes to be dried up. After this, the trace becomes conductive, with high resistance though. BarePaint can be deposited onto a variety of substrates such as paper, plastic, PolyEthylene Terephthalate (PET) film, wood, or even human skin, etc.

Another well known member of micro-size conductive material family is CircuitScribe [10] from Electroninks. CircuitScribe is a ball-point pen which is filled with 0.4μm silver particle paste. This silver paste can establish conductivity almost immediately after deposited onto substrate. The sheet resistance (measured in ohm per square – $\Omega/\square$) varies from 0.05 $\Omega/\square$ to 0.2 $\Omega/\square$. Similar to BarePaint, CircuitScribe can be drawn on a variety of substrates. This makes it very flexible to use in real life scenarios.

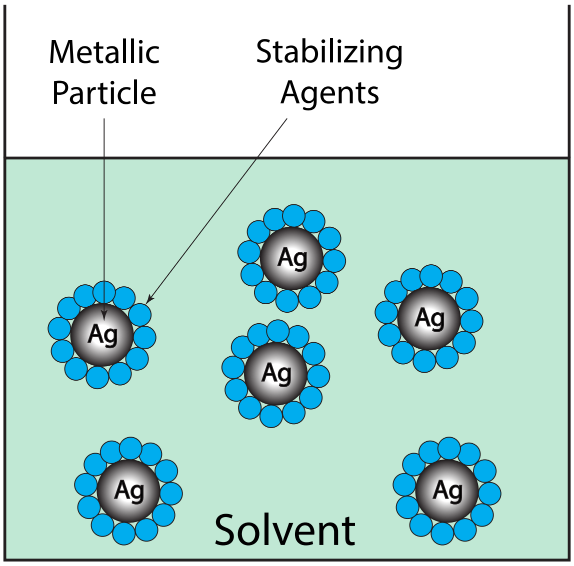
Targeting a different segment of users, BarePaint or CircuitScribe is not made for printing. Due to particle size, viscosity, and other characteristics, these conductive inks are only suitable for drawing pen, not for inkjet nozzle.

2.1.2 Inkjetable Conductive Ink

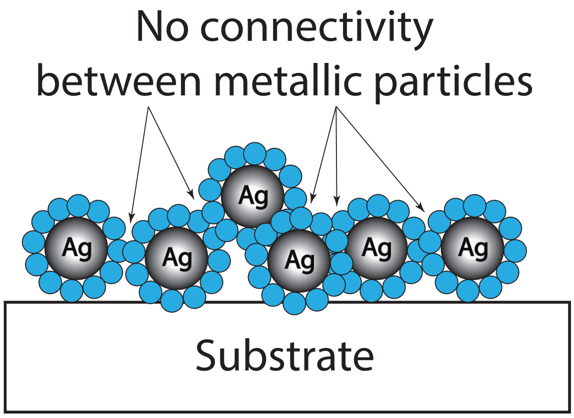
Printing technology has been developed for decades to increase resolution, speed, deposit precision. The development of printing technique along with a variety of color inks has enable us to print large area with high resolution in short time manner and acceptable price. Many types of printing technique had been applied in fabrication of electronic circuitry like lithography, rotary printing, rotogravure, screen printing or inkjet print. Among these, inkjet printing is steadily becoming a convenient way to quickly deposit electronic and non-electronic materials. Especially, nowadays, most of modern home commercialized inkjet printers are drop-on-demand printers with hundreds of nozzle. This is a strong preamble to make inkjet printer become a home-used/lab-used electronic circuit maker. With such technology, users are kept away from hassles of making electronic circuit so that they can invest more time on other important stage of designing job. In order to make this happen, conductive ink should be optimize to work with inkjet printer.

Composition of Inkjetable Conductive Ink

Certainly, inkjetable conductive ink needs to satisfy a set of requirments about viscosity, surface tension, wettability [19, 27] to be qualified as inkjet ink. Besides, in order to establish conductivity, nano-particles



(a) Dispersion of metal nano-particles is stabilized by stabilizing agents



(b) Conductive ink was printed on substrate but have not sintered yet

Fig. 2.2: Metal based inkjetable conductive nano-particle ink before and after printing

with highly conductive metals like Ag or Cu are usually employed as functional molecules in inkjetable conductive ink. In such inks, the metallic dispersion should be stabled to prevent aggregation and precipitation. Otherwise, the ink is not printable or will not establish conductivity after printing. This stabilization is attained by adding polymeric materials as stabilizing agents [19]. This leaves us with a general view of inkjetable conductive ink composition as Figure 2.2 (a).

Sintering

As mentioned above, stabilizing agent is necessary to keep dispersion of metal nano-particle from aggregation. However, the functionality of stabilizing agent has a bad side effect. This stabilizing agent, along with other components of the ink composition contribute to the prevention of bulk metal formation process after printing. These additional components form an insulating layer between the metal particles, and thus, reduce electrical conductivity of the printed pattern (as illustrated in Figure 2.2 (b)). For this reason, a post treatment is usually required to make the printed pattern conductive. This process is usually call sintering.

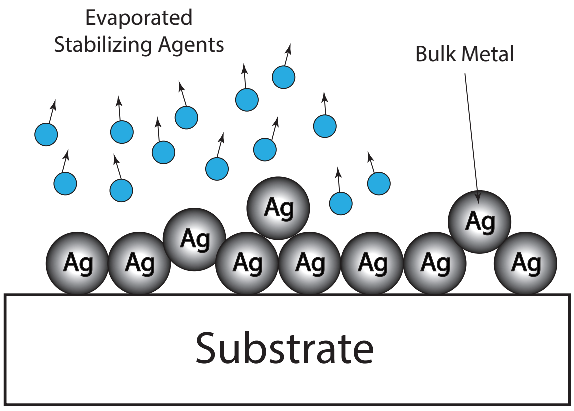


Fig. 2.3: Printed pattern after elimination of stabilizing agents by sintering

Sintering involves in elimination of stabilizing agents and other additional component by heating the printed pattern. The constrain of heating is to avoid destroying the printed substrate. The most simple sintering process is thermal sintering in which printed pattern is put into high temperature but not too to destruct the substrate. At suitable high temperature, additional component in the ink composition will be evaporated leaving us connected bulk metal trace. There are several forms of thermal sintering such as photonic sintering [22], microwave sintering [31], plasma sintering [34], electrical sintering [2]. The common mechanism of these methods is that they all use an external actor to heat the printed pattern, resulting in evaporation of additional components and develop bulk metal, thus establish conductivity. Figure 2.3 illustrated the printed pattern is developed into bulk metal state after sintering.

Though some of thermal sintering methods mentioned above can give good conductivity to the printed patter, most of them are difficult to implement without special and expensive tools. Many methods require long time of processing for several hour. Furthermore, some thermal sintering processes is only successful with some constrains in the design of the printed pattern. Like in microwave sintering method, the performance heavily depends on the dimension of the printed pattern. In addition, the fact that the printed pattern needs to be exposed to high temperature also limits the application of inkjet conductive ink to only some specific substrates that can stand the high temperature during sintering process.

2.2 Room Temperature Sintering Silver Nano-particle Ink – Instant Inkjet Circuits

2.2.1 Room Temperature Sintering

In order to workaround the limitation of high temperature sintering (processing time, high cost, printed pattern constrain, substrate destruction, etc.), a room temperature sintering method is desirable. According to researches reported in [28, 15], metal nano-particle based conductive ink is triggered into a coalescence process when they meet oppositely charged poly-electrolytes. This phenomenon enables the formation of bulk metal on the printed substrate at room temperature without destruction of the substrate. With the same mechanism, Mitsubishi Paper Mills has developed a room temperature sintering silver nano-particle ink [29] that will establish conductivity almost immediately right after coming into contact with photo paper. This special silver nano-particle ink will be discussed the following part about Instant Inkjet Circuits.

2.2.2 Instant Inkjet Circuits

Mitsubishi Paper Mills Limited Silver Nano-particle Ink

Mitsubishi Paper Mills Limited's silver nano-particle ink (Mitsubishi's silver ink) is a member of room temperature sintering conductive ink family. Instead of using heat to eliminate stabilizing agents and anneal silver nano-particles, Mitsubishi silver ink uses a specially coated porous layer on the substrate (Figure 2.4) to absorb stabilizing agents. All silver nano-particles will be left on top of the porous layer and developed to bulk silver as illustrated in Figure 2.5

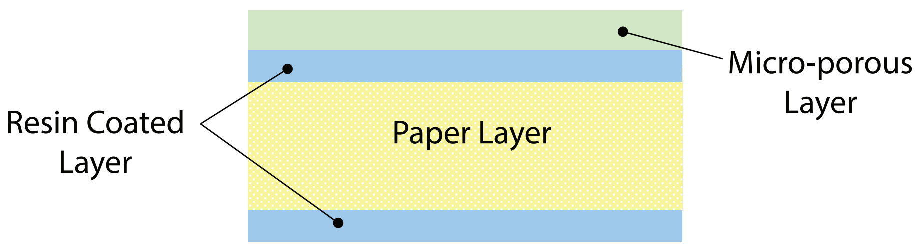


Fig. 2.4: Mitsubishi specially coated resin paper [38]

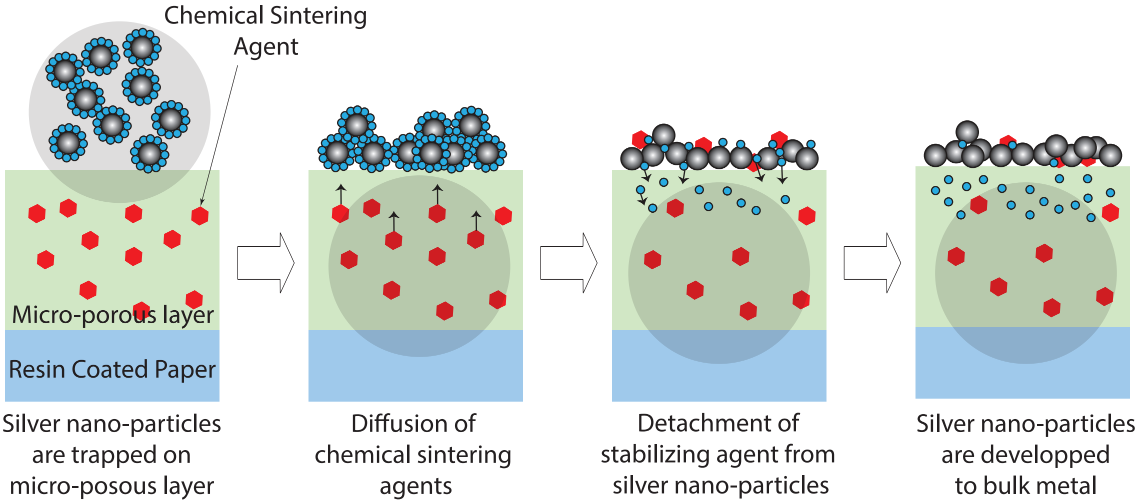


Fig. 2.5: Mitsubishi silver nano-particle ink is developed to bulk silver [38]

Instant Inkjet Circuits

Instant Inkjet Circuits [20] is an application of of Mitsubishi Paper Mills Limited's silver nano-particle ink. The main idea of Instant Inkjet Circuits is to use that room temperature sintering silver nano-particle ink to rapidly fabricate flexible electronic circuits. By loading silver nano-particle ink into home commodity inkjet printers (as illustrated in Figure 2.6), anyone can make a neat and stable electronic circuit without any hassles. Instant Inkjet Circuits stood out as great tool for rapid prototyping tool thank to its natures of low-cost, off-the-shelf and fast. One can use Instant Inkjet Circuits with less than a few hundred dollars of investment. Every components for Instant Inkjet Circuits are widely available in the market and electronic circuits fabrication takes only less than a few minutes.

With a little knowledge of electronic circuit design, one can easily make a variety of interesting project such as an RFID (Radio-frequency identification) tag, touch sensors, moisture sensors or capacitive sensors. It is even possible to download blueprint design for open hardware from the Internet and make an home-brew Arduino board on paper (with the support of via-hole mention in chapter 4). Figure 2.7 shows some applications of Instant Inkjet Circuits.

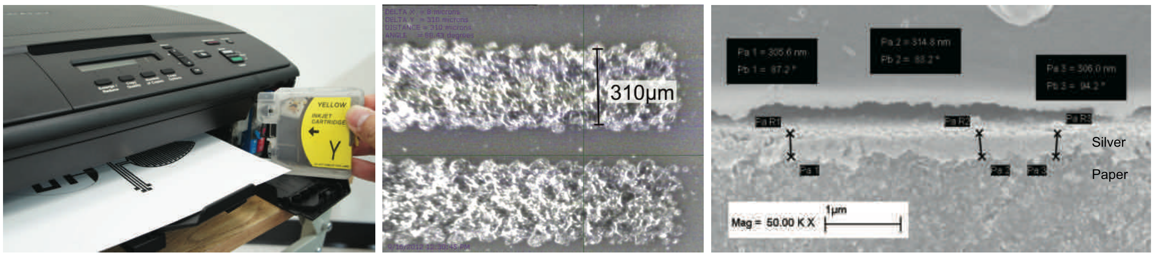
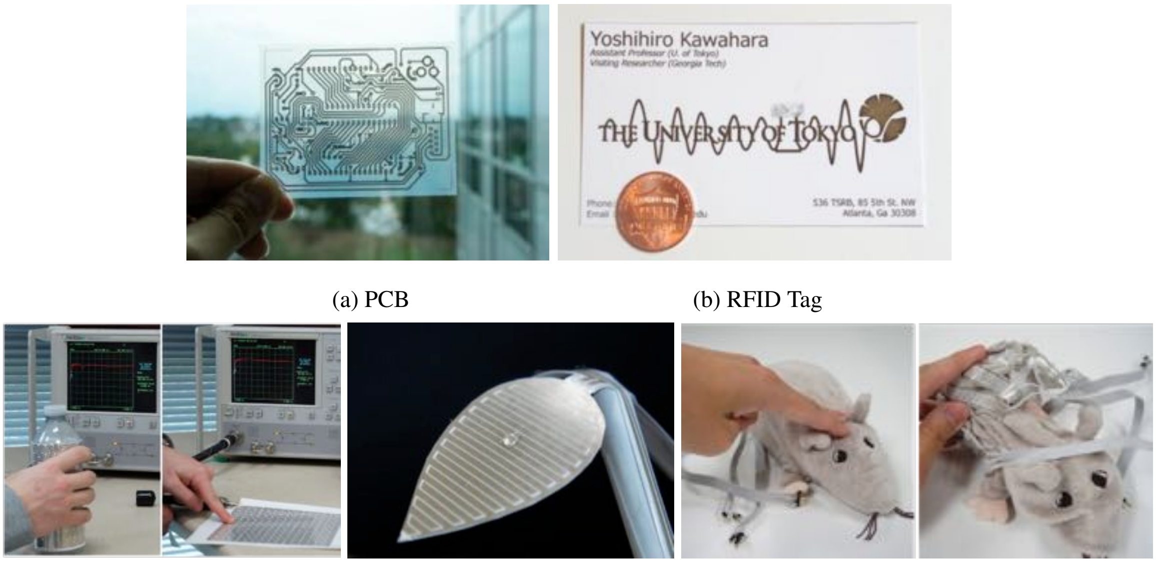


Fig. 2.6: Instant Inkjet Circuits [20]

2.3 Resistance in Instant Inkjet Circuits

Thank to the fast room temperature sintering process, Instant Inkjet Circuits printed pattern can establish conductivity almost immediately after printing. However, different from thermal sintering when one can control temperature and sintering time to increase annealing ratio, Instant Inkjet Circuits depends heavily on reaction between the ink composition and substrate surfaces. At the particle level, this reactions are chaos and generally not 100% completed. As a result, conductive patterns which are made by Instant Inkjet Circuits are usually not highly conductive. As reported in [20], the sheet resistance value immediately after printing on Mitsubishi paper mentioned at part 2.2.2 varied from 0.19Ω/□ to 0.25Ω/□. Although this resistance is acceptable for most applications, it still becomes an issue in the case of projects involving RF circuitry or ultra low power design.

Regarding of reducing resistance of Instant Inkjet Circuits printed pattern, a well-known technique is to accelerate the chemical sintering process by adding water [42]. It is partly explained in [3] that exposing silver nano-particle ink printed sample to humidity help to transport ions from the coated layer on the substrate onto the printed structure. These additional ions help to improve the conductivity of the printed pattern. As reported in [20], the resistance was decreased by 4.8% after being exposed to high humidity atmosphere. Though this improvement is still too small to be really useful in highly conductive required applications mentioned above, its effect is permanent. This technique will be used and discussed furthermore in the later part in chapter 3 about improving printed pattern's conductivity by overprinting.



(a) PCB (b) RFID Tag

(c) Touch sensor (d) Moisture sensor (e) Capacitive sensor

Fig. 2.7: Instant Inkjet Circuits Applications [20]

2.4 Conclusion

In this chapter, we have discussed about conductive ink from non-inkjetable to inkjetable nano-particle ink.

- Conductive ink is used to paint or print conductive pattern on a variety types of substrate such as wood, paper or plastic film. They are extremely useful in rapid prototyping of electronic circuit.
- In order to make conductive ink inkjetable, stabilizing agent and additional components are added into the ink composition. The side-effect of such additives is that the printed pattern does not establish good conductivity after printing. They need to be sinter to develop bulk metal inside printed structure.
- The most appealing sintering method is thermal sintering. There are several forms of thermal sintering vary from direct heating to using external actors such as light, electric, microwave or plasma. However, these processes are neither time-cost effective nor robust.
- Room temperature sintering was developed based on reactions between specially coated layer on the

substrate and additives consisted in the ink composition.

- Instant Inkjet Circuits is an example of using room temperature sintering silver nano-particle ink in rapid prototyping electronic circuits on flexible substrates.

In the following chapters, we will discuss about how to improve performance and broaden the application range of the room temperature sintering silver nano-particle ink inkjet printing.

Chapter 3

Improve Conductive Printing by Tweaking Printer Driver

This chapter will focus on discussing the potential of tweaking printer driver to get higher freedom on printing with conductive ink. By employing an open-source general printer driver name Gutenprint, we show that it is possible to gain control on the operation of inkjet printer. Backing by the strength of open-source software, a modification made in Gutenprint for an inkjet printer family can be seamlessly ported to hundreds of other printer families. Complying to this mindset, we have succeed in improving the conductivity of Instant Inkjet Circuits printed pattern by tweaking printer driver to implement an automatic overprinting mechanism along with adjusting of printing density. The lowest achieved sheet resistance was $0.043\Omega/\square$.

3.1 Related Works

Though conductive inkjet printing can rapidly fabricate electronic circuits or conductive patterns on several type of substrate, there are still many problem with these new technology. Questions on how to improve functionality of conductive inkjet printing, how to make it easier to approach for non-expert users have been appealed to many researchers from material science, electronic, or ubiquitous computing society. Following are 3 main approaches:

3.1.1 Conductive Ink

In conductive inkjet printing, it is obvious that conductive ink is one of the most important elements. It has the biggest impact on the characteristics of printed patterns. Therefore, improving conductive ink composition is very attractive. These improvements consist of both the formulation of conductive ink composition and sintering methods [26]. Although they are promising to give great boosts to the printed pattern, the development of a new type of ink is quite complicated and time consuming.

3.1.2 Hardware

Besides attempts to conductive inks with better properties, another approach came from hardware alterations. However, changing behaviour of inkjet printer is not a simple task and normally, this approach end ups with building a new printer. Argentum [8], formerly named as EX1, is one of the projects which tried to build a new printer for conductive printing. Building a new printer goes along with using different type of conductive ink. Though this approach brings more freedom in designing and adjusting characteristics of printed pattern, it is facing the problem of high cost and time consuming in fabricating of electronic circuits.

3.1.3 Software

Along with efforts to advance functionality of conductive ink printed patterns, the way that users design and interact with conductive ink is also getting much attention from researchers. In PaperPulse [33], authors proposed a software to support designing interactive applications with conductive inkjet printing. In another

Fig. 3.1: Argentum - a printer used to print conductive material for fabrication of circuit boards [8]

attempt to enhance the use of conductive ink, ConductAR [30] proposed a computer vision solution to quickly identifying resistance of a painted/printed conductive pattern, thus, help to suggest quick-fixes if needed.

3.2 Resistance Problem

As fore mentioned in chapter 2, part 2.3, although room temperature sintering silver nano-particle ink used in Instant Inkjet Circuits can get to good conductivity at a short time (less than a minute) and this conductivity is acceptable for most applications, there are still projects involving RF circuitry or ultra low power devices in which, electrical resistivity might be an issue. For instance, we have been using an conductive inkjet printed antenna in researching of Wireless Power Transmission and energy harvesting for a long time. However, the resistance of the printed antenna has decreased the transmission efficiency a lot. In order to increase the Q-factor of Wireless Power Transmission antenna, conductivity must be improved. In the work of Lee. et al. [24], the authors used silver nano-particle ink without any modification to print the UHF RFID antennas. The conductivity was better than micro-particle ink but still by far worse than copper. Another example to show the importance of the low resistance is the fabrication of silver ink printed capacitive pressure sensor. A highly conductive pattern will help to boost the sensitivity also the accuracy of such sensor [43].

3.3 Manual Overprinting for Conductivity Improvement

Beside improving conductivity by exposing silver nano-particle ink printed pattern to high humidity atmosphere as reported in chapter 2, part 2.3, overprinting also shows good result in reducing the final resistance of printed pattern. By manually re-feeding the printing paper, one can re-print the same pattern on the same paper for multiple times. By common sense, when the thickness of a conductive printed pattern is doubled, its resistance will be halved. However, due to the not-so-accurate tray-based paper feeding mechanism, which is very common on low cost desktop inkjet printer, manual overprinting results in about 0.5 mm misalignments between each printing times (Figure 3.2). Therefore, this technique is only practical for wider traces [20]. A solution to this misalignment problem is to implement overprinting without manual re-feeding of paper. This can be achieved by gaining control of the printer's operation.

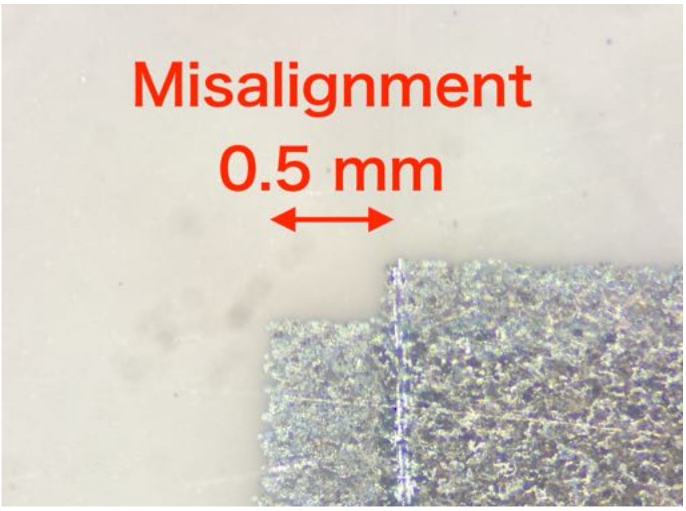


Fig. 3.2: Up to 0.5 mm misalignment between each printing times

3.4 Open-source Printer Driver Gutenprint

There are several ways to control the behaviour of a printer. The first one is trying to modify the hardware of the printer. This seems to be very hard and may end up with making a new printer. In this case, the development and testing will be troublesome and costly. A second idea might be some modifications of the printer's firmware. This sounds possible but we need to note that most of printer makers do not disclose the source code of their printer's firmware. Therefore, it is very difficult to access and modify the firmware. Not only that, these 2 approaches share a same big problem of inflexibility. Normally, neither hardware or firmware modification could be applied to a printer brand other than the targeted one. That means, a modification on a Canon printer, probably can not be applied to an Epson printer. In order to overcome these, an easier method is to modify the driver used to control printer on operating system (OS) level. Gutenprint [17] is one of best candidate to do this.

Gutenprint

Gutenprint is a package of high quality driver for thousands of printers, including both laser and inkjet printer, from brands such as Canon, Epson, Sony or Olympus. Though dealing with a large amount of different printers, Gutenprint common core code base is shared between several printer families. This core controls from top most common GUI to lower level of dithering algorithm, from image rasterization to printing command dispatcher [16]. Therefore, a change made for on a specific target printer can be ported seamlessly to another printer with minimum or none of code rewriting. Beside the strength of an open-source project, that flexibility is the most important reason why we chose to work with Gutenprint. Currently, Gutenprint support over 1300 inkjet, dye sublimation and laser printers. It can be used with all common UNIX print spooling systems by means of either CUPS (Common UNIX Printing System) or Ghostscript. This guarantees that although Gutenprint has not supported Microsoft Windows OS yet, it can run easily on all UNIX-like systems such as Linux, BSD (Berkeley Software Distribution) or Macintosh OS X.

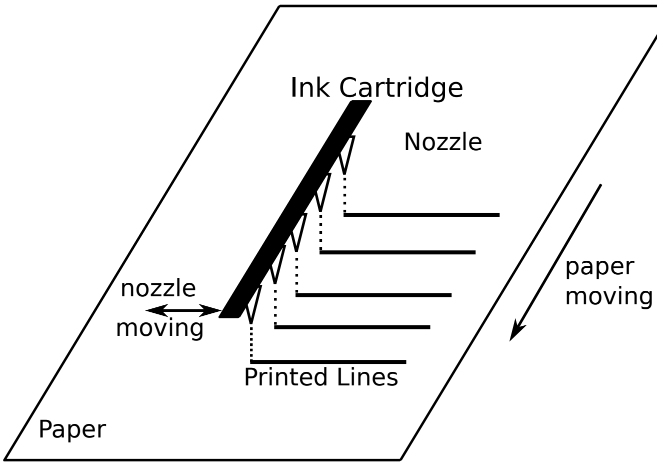


Fig. 3.3: Inkjet printing mechanism

3.5 Implementation of Auto Overprinting

In our research, we targeted Epson printer - EP-905A as Gutenprint has great support for this model. And it is very easy to purchase this Epson printer at that moment. Moreover, since we need to reload the ink with silver nano-particle ink, it is much simpler with EP-905A thank to its cheap empty ink tank.

Basically, the inkjet printing mechanism is that the print head (the ink cartridge) will keep moving from one edge of the paper to the opposite edge. While moving like that, the nozzles will deposit ink droplets into surface of the paper (as you can see at the Figure 3.3). We call this a "pass".

If we can let the print head stay at the same vertical position (means that the paper is not moving), print the same content, for several passes, auto overprinting will be realized. As Gutenprint control printing process from rasterization to printer commands sending, it is possible that we can implement this using Gutenprint.

In order to modify Gutenprint driver for EP-905A printer, we need to modify Epson driver module inside Gutenprint. One of the files that control behavior of a Epson printer is `escp2-driver.c`. In this file, function `void stpi_escp2_flush_pass()` will continuously send printing commands to the printer. Since this function controls the commands which are sent to the printer, most of print head behaviors can be adjusted by tackling this function. By simply adding a loop, we can make the printer overprint as many times as we want. Following is the modified source code of this function:

```
escp2_privdata_t *pd = get_privdata(v);
for (i=0; i<pd->overprint; i++){
  for (j=0; j<pd->channels_in_use; j++){

    ...
    // printing commands are generated here
    ...

    // Check if overprint enough, if enough, go to next pass (print head will be moved
    to next vertical position to start a new pass)
    if(i == pd->overprint-1){
      lineoffs->v[j] = 0;
      linecount->v[j] = 0;
    }
  }
}
```

Listing 3.1: Overprint - function `stpi_escp2_flush_pass`

Here, the struct `stp_vars_t *v` contains all the settings of the printer. The value of overprinting time was set to variable `overprint` in this struct by user through another GUI function which is not necessary to be mentioned here. The function `get_privdata(v)` will return a struct which contains the setting of a general Epson printer. The inner loop:

```
for (j=0; j<pd->channels_in_use; j++){...}
```

will generate printing commands based on designed pattern image. These commands will be continuously sent to the printer to control the print head movement. `pd->channels_in_use` is just the number of ink tank that the printer has. In this modification we do not have to care about this value. The outer loop:

```
for (i = 0; i< pd->overprint; i++){...}
```

will repeat generating and sending printing commands. Thus, we have the overprinting. In other words, for each line of printing, the print head will move back and forth for a specific number of times. This number of overprinting time will be set by user from Gutenprint's parameters dialog. The modification for this GUI elements are trivial and too long to be listed here. They can be found in the source code stored on GitHub repository. Source code of Gutenprint with overprinting for Epson inkjet printer family is stored on GitHub repository at `https://github.com/tung-akg/gutenprint-overprint.git`

To show the flexibility of Gutenprint, we have tested this overprinting on another printer, the Epson WF–3011. Epson WF–3011, with modified Gutenprint, can overprint immediately without any code rewriting.

3.6 Resistance with Overprinting

3.6.1 Experiment

There are many factors that affect the conductivity of the silver nano-particle ink printed pattern like the properties of media, substrate used in media, quality of the ink, the connectivity of silver nano-particles, the thickness of the printed pattern. Here, we focused on the thickness of the pattern and the connectivity among silver nano-particles. These 2 factors can be improved by over-printing technique introduced above and by adjusting printing density. The more we overprint, the thicker the pattern is, and the better connectivity among silver nano-particles is. This results in a better conductivity. Experiment environment:

- Printer: Epson EP–905A
- Driver: Gutenprint–5.2.9 – modified to implement overprinting
- Media: Mitsubishi Paper Mills Limited Photo Paper – NB–RC–3GR120
- Silver nanoparticle ink: Mitsubishi Paper Mills Limited Silver Nano-particle Ink NBSIJ-MU01
- Printed pattern: horizontal rectangle size 1.5 mm x 150 mm as Figure 3.4

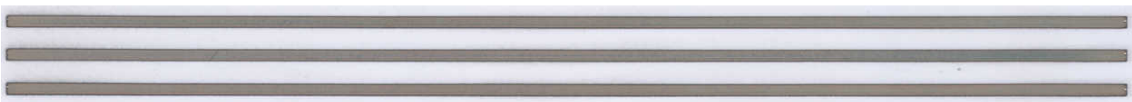
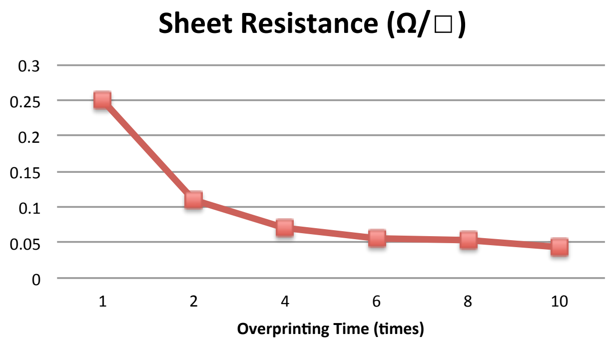
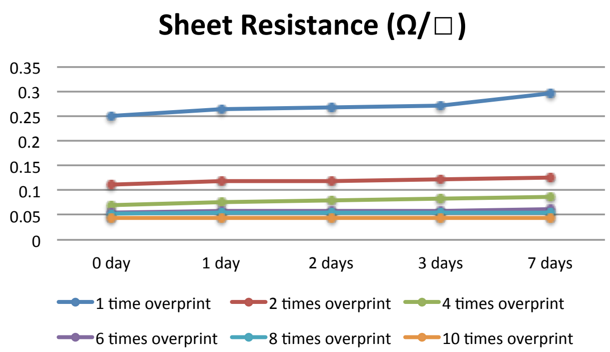


Fig. 3.4: Printed pattern used to measure sheet resistance

3.6.2 Result



(a) Change of sheet resistance depends on number of overprinting time



(b) Change of sheet resistance with different overprinting time after several days

Fig. 3.5: Sheet resistance after overprinting

After printing, we immediately measured the sheet resistance of the pattern without exposing to high humidity atmosphere. The data showed that the sheet resistance was quite high for 1 and 2 times overprinting or even non-conductive in case of 4, 6, 8, 10 times of overprinting. The reason was that after printing, the whole silver nano particle is not fully connected. The chemical sintering happened only to the silver nano-particles on the first layer, which has direct contact to the coated layer on the substrate. The latter added silver nano-particles layers did not have such reaction. As a result, the conductivity was decreased.

To solve this, we have exposed the printed pattern to high humidity atmosphere. This is a known technique for accelerating the process of chemical sintering by adding water[42]. For each case of overprinting time, we measured the sheet resistance immediately after exposing to high humidity for 75 minutes. Figure 3.5 (a) shows the change of sheet resistance (co-responding to the overprinting time of 1, 2, 4, 6, 8, 10 times) after exposing to moisture for 75 minutes. The sheet resistance was significantly decreased to $0.11\Omega/\square$ by overprinting 2 times and was continuously decreased to $0.043\Omega/\square$ after overprinting 10 times. There is an additional point here is that the necessary moisture exposing time depends on the number of overprinting time. While conducting the experiment, we noticed that for 10 times overprinting, 75 minutes moisture exposing is needed, but for 2 times overprinting, 45 minutes is enough (Table 3.1).

The more we overprint, the more silver nano-particle ink are added to the pattern. Therefore, the humidity exposing time needs to be increased. During conducting the experiment, when we tried to overprint for 4 times (or more), the pattern right after printing was not conductive at all. Humidity exposure was necessary. For each case of overprinting, there is a different humidity exposing time that will make the sheet resistance minimum.

Another point here is that the sheet resistance decreases slowly when overprint for 6, 8 or 10 times. That is because the connectivity of silver nano-particles is going to be "saturated." As a result, the sheet resistance does not drastically decreased after 6 times overprinted.

Beside of measuring the sheet resistance right after steaming, we also measured it after 1 days, 2 days, 3 days and more. According to our previous results, without overprinting, printed pattern's sheet resistance

Overprint Time	Humidity Exposing (min)	Minimum Sheet Resistance (Ω/□)
2	45	0.100
4	75	0.072
6	75	0.055
8	75	0.053
10	75	0.043

Table 3.1: Sheet resistance for different overprinting time at different humidity exposing time

will increase several days after printing. Figure 3.5 (b) shows that when overprinted, the sheet resistance was quite stables after printed. We can see that the change of sheet resistance was decreased when we increase the overprinting time. In the case of 8 times or 10 times overprinting, sheet resistance was almost the same through 7 days.

3.7 Resistance with Overprinting and Print Density

One of the disadvantages of overprinting is that it takes quite a lot of time overprinting. For example, 10 times overprinting will take at least 30 minutes to finish. It is also worth to mention that, according to our observation, depend on the printer, the maximum number of command can be sent to the printer is limited. The reason is probably the limitation of memory buffer on the printer. Therefore, we also try to increase the amount of ink deposited on to substrate without too many time of overprinting. It turns out that, in Gutenprint, we can easily adjust the density of printing process. The printing density decides the amount of ink deposited in an area unit. As a result if this printing density is increased, the connectivity between silver nano-particles will be increased. Based on this, we have made the experiment to see the change of sheet resistance in responding to the change of printing density.

3.7.1 Density Adjustment without Overprinting

In this experiment, we tried to confirm the effect of printing density adjustment on sheet resistance. The pattern at Figure 3.4 would be printed once (no overprint) with each different values of printing density (value of 1, 2, 4, 6 and 8). The printed pattern will be immediately exposed to moisture for several minutes.

The blue line in Figure 3.6 is the change of sheet resistance after moisture exposure. The sheet resistance decreased from $0.25\Omega/\square$ (value from previous experiment - without adjustment of density) to $0.15\Omega/\square$ when printing density is 1. It continued to decrease to $0.085\Omega/\square$ for printing density of 8. This proved that the printing density adjustment did help to increase the conductivity of silver nano particle ink pattern.

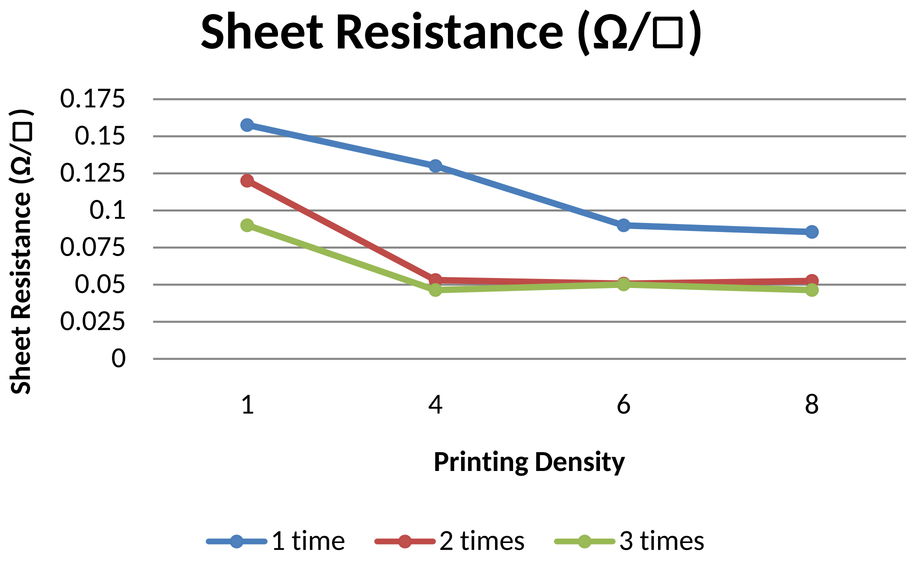


Fig. 3.6: Change of sheet resistance depends on Density and Overprinting time

3.7.2 Density Adjustment with Overprinting

One of the trade-offs to get better conductivity with overprinting was that the printing time will be longer. 6-time-overprinting will take 3 times longer than just overprinting for 2 times. It depends on the printer but for the one we used in the experiment (Epson EP–905A), it may sometimes take 30 minutes for 10-time-overprinting. In the experiment this time, we tried to use overprint along with printing density adjustment to see if we could achieve the same good sheet resistance with less overprinting time. Again, the pattern in Figure 3.4 would be overprinted for 2 and 3 times. For each case, we tested the conductivity of the pattern with different values of printing density parameter (1, 2, 4, 6 and 8).

The result was very good even with only 2 times of overprinting. While it takes 6 times of overprinting without printing density adjustment to get the sheet resistance the value of 0.05Ω/□, setting printing density parameter to value of 4 and use 2-time-overprinting was enough to obtain the same value of sheet resistance. That means the printing time would be 3 times faster. In the previous experiment of overprinting, we had reached the value of 0.043Ω/□ with 10 time overprinting. By adding density adjustment, we could reach this value by setting printing density parameter to 8 and just have to use 3 times overprinting only.

3.8 Applications

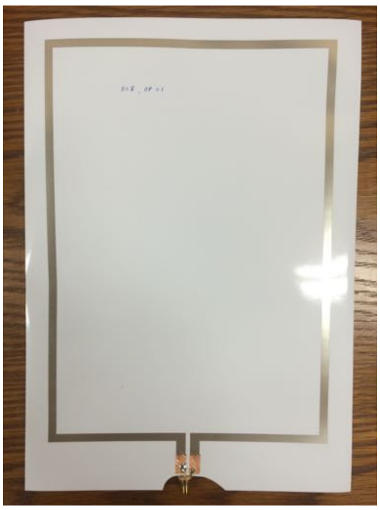
3.8.1 Q-factor in Wireless Power Transmission

We have been using Instant Inkjet Circuits for printing coupling coils for WPT. Being able to rapidly print and reprint the coil enabled us to both quickly try new coil design and shorten the trials-and-errors iteration. However, one of the biggest problem of Instant Inkjet Circuits for WPT is its resistance. The quality factor or Q-factor in WPT is calculated as follows:

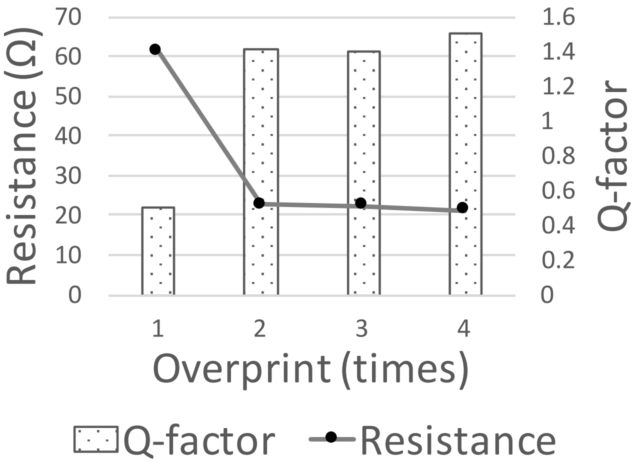
$$Q = \frac{\omega L}{R}$$

where Q is quality factor of the coil, L and R are respectively inductance and resistance of the coil.

High resistance compare to bulk metal significantly reduces the Q-factor in power transmission. By using overprinting and density adjustment to reduce the resistance of conductive inkjet printed coil (as illustrated in Figure 3.7), we have succeed in increasing this Q-factor from 0.5 to 1.5.



(a) Overprinted coupling coil



(b) Changing of Q-factor

Fig. 3.7: Overprinting to improve Q-factor in Wireless Power Transmission

3.8.2 Coil for Pressure Sensor

Instant Inkjet Circuits has been used to fabricate flexible passive pressure sensor [43]. The sensor is basically a RLC circuit in which resistance R is resistance of the conductive inkjet printed pattern. The coil L and capacitor C are made so that a change of pressure on the sensor leads to the change of capacitance C. With each value of capacitance C, the RLC circuit has a different co-responding resonant frequency. Using a Vector Network Analyzer (VNA) to sweep through a range of frequency, we can detect this resonant frequency by searching for the point at which phase of the circuit reaches it minimum. The sensitivity of this measurement depends on Q-factor of the pressure sensor $Q_{sense} = \frac{1}{R}\sqrt{\frac{L}{C}}$, where RLC are respectively resistance, inductance and capacitance of the sensor [43].

In order to increase the sensitivity and accuracy of the sensor, it is necessary to increase this Q-factor. The most appealing approach is to reduce the resistance of the printed pattern. With the support of overprinting and print density adjustment, we can significantly improve this Q-factor of the pressure sensor. As illustrated in Figure 3.8, compared to printing only 1 time, overprinting for 3 times dramatically improved the sharpness at the bottom of the graph.

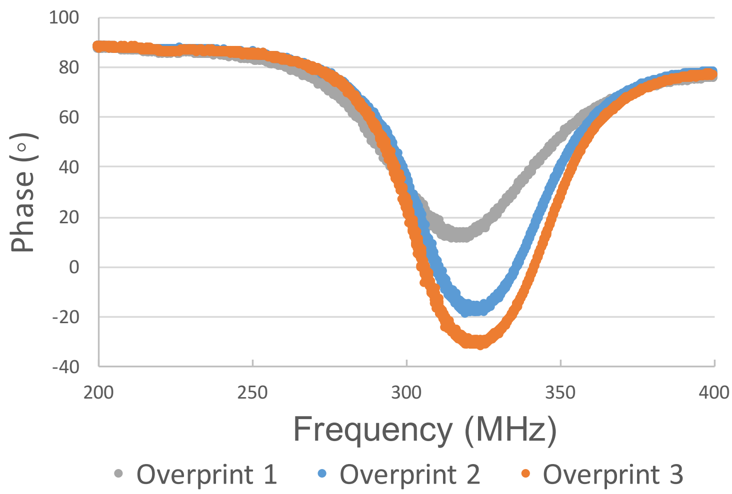


Fig. 3.8: Q-factor of Pressure Sensor is improved using overprinting and print density adjustment

3.9 Conclusion

In this chapter, we have discussed about tweaking an open-source printer driver, named Gutenprint, to improve performance of Instant Inkjet Circuits.

- Gutenprint is an open-source printer driver for more than 1300 inkjet, dye sublimation and laser printers.
- A modification in Gutenprint can be seamlessly applied to many other brands of printer as long as supported by Gutenprint. In case of knowing the specification of a new printer, user can easily add that new printer to Gutenprint supported list.
- By tweaking Gutenprint code base, we have succeed in implementing auto overprinting mechanism on Epson EA–905A inkjet printer. This modification was also directly applied to another printer Epson WF–3011 without any requirement of code rewriting.
- This auto overprinting technique, with printing density adjustment, can help to reduce the sheet resistance of Instant Inkjet Circuits printed pattern to as low as $0.043\Omega/\square$.

The realization of overprinting ink-jet printer can be marked as a sign of the possibility in controlling printer head by only driver modification (which is much simpler than modification of printer's firmware). With this success, we are confident that there are many more complex modifications and interesting applications of conductive ink-jet printer in rapid prototyping.

Chapter 4

Double Layer for Flexible Electronic Circuit

Instant Inkjet Circuits by silver nano-particle ink realized home-brew electric circuit fabrication. However, current method can support only single-layered patterns, and conventional inter-layer connection methods are not suitable. In this paper, we will evaluate various easy-to-use inter-layer connection methods by making via holes, especially the ones made by different drilling mechanisms. We show that the felting needle is the best candidate as it can establish good conductivity immediately after nano-particle ink is printed into the hole, without using any curing process.

4.1 Related Works

4.1.1 Electro-plating PCB vias

For traditional PCBs, in order to fabricate multi-layered circuits, different electronic nets are formed on separated layers and they are connected using via holes. These via holes are made by drilling tiny holes on the surface of the PCB and filling them with a highly conductive material (typically, copper). A widely used method to fill these holes is electro-plating. Drilled PCB via holes will be rinsed and electroplated in an electrolytes composed of copper sulfate and sulfuric acid, so that conductive material will stick to the inner wall of the drilling holes [41]. Although this method has the advantages of low cost and simple operation, it involves in working with chemical substances which are hazardous and difficult to be used in the rapid prototyping with flexible substrates like paper or film.

4.1.2 Conductive adhesive

Another approach to filling a via hole without involving in chemistry process is to fill it with conductive adhesives [25, 21]. In this method, tiny holes will be drilled in PCB substrate and a squeegee will pass through this surface, fill the drilled holes with the conductive adhesive. This can make via holes with resistance as low as 0.3Ω. However, due to the use of the conductive adhesive, the whole sample needs to be cured in a high temperature during at least 30 minutes. This is troublesome and time consuming.

4.1.3 Silver nano-particle ink and sintering

Emergence of new conductive materials at nano size has enabled us to fabricate a conductive pattern more conveniently. Along with this, laser beam has also been investigated and applied to drill via holes on a PCB substrate [14]. By printing silver nano particle ink on an array of laser drilled micro size holes, we can have an interconnection “microvia” structure on the flexible substrate [12]. In this method, after laser drilling and silver nano particle ink inkjet printing, hole array was cured at high temperature for at least 2 hours. This step is important to make the filled holes become conductive. The use of the laser cutter to drill tiny holes is a barrier for this method to approach normal users (to whom possession of a laser cutter is not common). And again, the silver nano particle ink used in this method required thermal sintering, which is not always a convenient way to conduct. Moreover, high temperature curing might affect characteristic of some flexible substrates.

4.1.4 Silver nano-particle ink and rivet

In another attempt to make double sided circuit with silver nanoparticle ink, a copper rivet has been used to connect 2 circuits in the front and the back sides of paper substrate [5]. Although this method can help to establish vertical interconnection between 2 circuits, the resistance of the connection is still high at 1.45Ω. Moreover, using rivet requires the applying of silver epoxy to guarantee the contact between copper rivet and printed silver nano-particle ink. This is neither time efficient nor robust.

In our approach, we focus on implementing double sided circuit with a via hole in Instant Inkjet Circuits. The uniqueness of Instant Inkjet Circuits is that it uses silver nano particle ink which does not require thermal sintering or curing after printing. Printed pattern will be chemically sintered at room temperature and become conductive as soon as coming out from the printer. Chemical sintering at room temperature relies on the contact of the silver nano particle ink and special coating layer on the surface of the printed substrate. Our work would be trying to preserve sintering-free characteristic of Instant Inkjet Circuits while making interconnection in double sided circuit. Based on this, we aim at bringing an automatic printing circuit maker to every hobbyist's hand. Toxic materials (chemical substances like strong acids), harmful conditions (like high temperature, high power laser, etc.) should be avoided. We plan to realize an easy-to-use desktop sized system with low electrical power consumption which allows to reduce production cost and turnaround time. Entry level solution might be a low cost special pen to manually make double sided circuit interconnections. A final solution should be a full-automatic system with a specially designed computer-aided design software to print double sided circuits.

4.2 Approaches to Double Sided Flexible Circuit

4.2.1 Office Supplies Approach

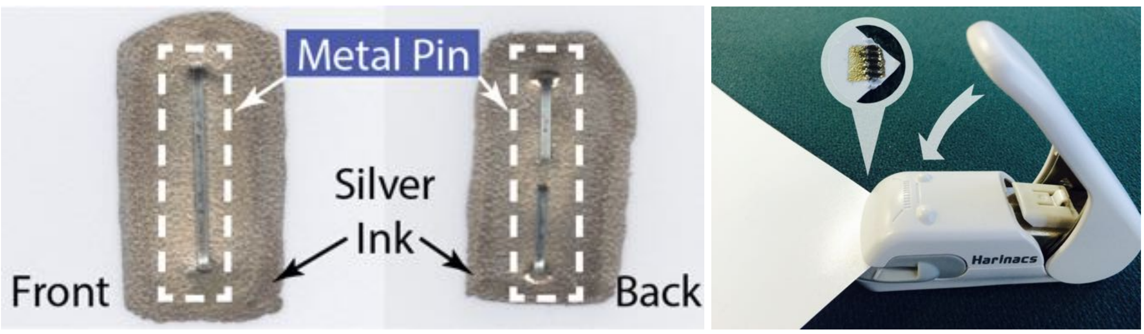
One of the simplest ways to make interconnections for double sided circuits in Instant Inkjet Circuits is to use office supplies, tools like a stapler (with metal pins) or a crush-style needle-less stapler.

A stapler with metal pins

This was the first option that we have thought of when we tried to make interconnections between 2 sides of paper substrate. We simply made this connection with a metal pin from a stapler as Figure 4.1 (a). A quick measurement showed that the resistance of an interconnection made by stapling is 6.3Ω. However, this interconnection is not durable due to the loosening by time at contacting point between the metal pin and silver nano particle ink. After 3 months, the resistance of the same sample was increased to ten-mega-ohm order. Moreover, with a normal stapler, we can only make the interconnections which are not too far from the substrate edge due to the size of the stapler.

Crush-Style Needle-less Stapler

A crush-style needle-less stapler is one kind of staples that does not have any metal pin. It uses pressure to press separated paper together [23]. At the place of pressing, 2 sides of the paper will be crushed and entangled so that when filled with the silver nano particle ink, this entanglement will help to bind the ink from both sides of the paper (Figure 4.1 (b)). The resistance of the interconnection made by the crushing stapler, as our observation, is more stable than the metal pin stapler's interconnection. The resistance of the interconnection increased from less than 3Ω right after painted with silver ink to 15Ω after 3 months. However, it also bears the limitation of the stapler size. We can only make the crushing interconnections at



(a) Front and Back of a interconnection made by metal pin from an office stapler

(b) Interconnection made by crush-style (needle-less) stapler

Fig. 4.1: Office supplies approach via hole

places where are closed to the edge of the substrate.

4.2.2 Via-hole Approach

As mentioned above, via hole has been long used as a solution for interconnection in the multi-layered circuit. It is natural to think of using via holes in the Instant Inkjet Circuits. By comparing approaches to make interconnection for double sided circuits (Table 4.1), we can see that drilling via hole should be selected as its superior over other methods. A stapler or a crush-style needle-less stapler results in large interconnection footprints and cannot make interconnection, far from the edge of the substrate. In contrast, a laser drill gives small footprint and flexibility in the positioning of the interconnection, however, it consumes a huge amount of energy and is difficult to miniaturize the apparatus. Standing out from these, drilling via hole mechanically can safely make small footprint and is flexible in positioning of interconnection without consuming energy.

The challenge is how to not only optimize the via hole quality, but also retain the sintering-free characteristic of the Instant Inkjet Circuits. Coating layer on the substrate acts an important role in making the printed pattern conductive. It is necessary to have this coating layer in both edge and inner wall of the via hole. To achieve this goal, drilling operation is evaluated and optimized. We will focus on evaluating differences of the via holes made by different hole openers (drill bits, hole punch drill bits, and felting needles).

Approach	Footprint	Position	Energy	Danger
Stapler	Large	Near Edge	No	No
Crush	Large	Near Edge	No	No
Laser	Small	Any	Huge	Yes
Via Hole Drill	**Small**	**Any**	**No**	**No**

Table 4.1: Comparison of approaches to interconnection for double sided circuits

4.3 Interconnection using Via-hole

This section will discuss about experiment with via-hole made by several different type of hole openers.

4.3.1 Experiment Preparation

Substrate

Instant Inkjet Circuits can work with commercially available single sided photo paper, especially with dedicated paper from Mitsubishi Paper Mills. In order to evaluate the double sided circuit, double sided photo paper from Mitsubishi Paper Mills has been chosen as the substrate (Figure 4.2). Slightly different from single sided photo paper shown in Figure 2.4, double sided photo paper from Mitsubishi Paper Mills is added another layer of the special coated porous layer on the other side of the paper. Thus make it conductive printable on both sides. This type of paper shows great surface adhesiveness and conductivity with sheet resistance after printing, according to our measurement, is 0.56Ω/□.

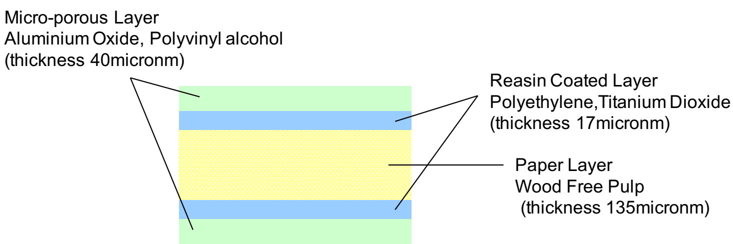
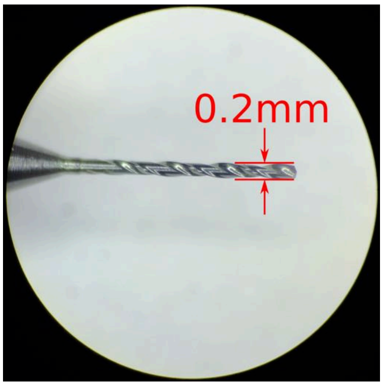


Fig. 4.2: Structure of Mitsubishi Paper Mills' double sided paper [38]

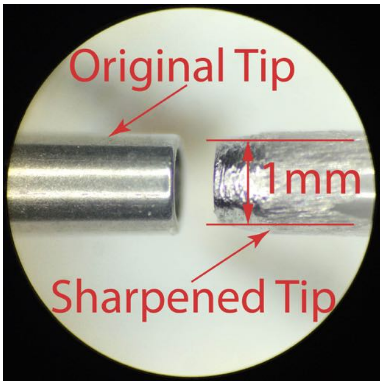
Hole Opener

Hole opening mechanism affects the hole structure, thus, affects the via hole's characteristics. Choosing a suitable hole opener is one of the most important tasks to optimize the via hole quality. In our experiment, we have tried 6 different types (and sizes) of the hole openers as follows:

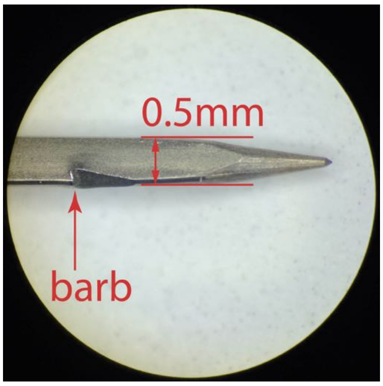
- Drill Bits: Tamiya Ultra-Fine Drill Bit item number 74044 [39] with diameters φ0.5mm, φ0.8mm and Unimax Drill Bits C-UMD 2020-025 [40] with a diameter φ0.2mm (Figure 4.3 (a)).



(a) Drill bit φ0.2mm, φ0.5mm, φ0.8mm



(b) Hole punch drill bit φ0.5mm, φ1mm



(c) Triangular felting needle with barbs

Fig. 4.3: Hole opener

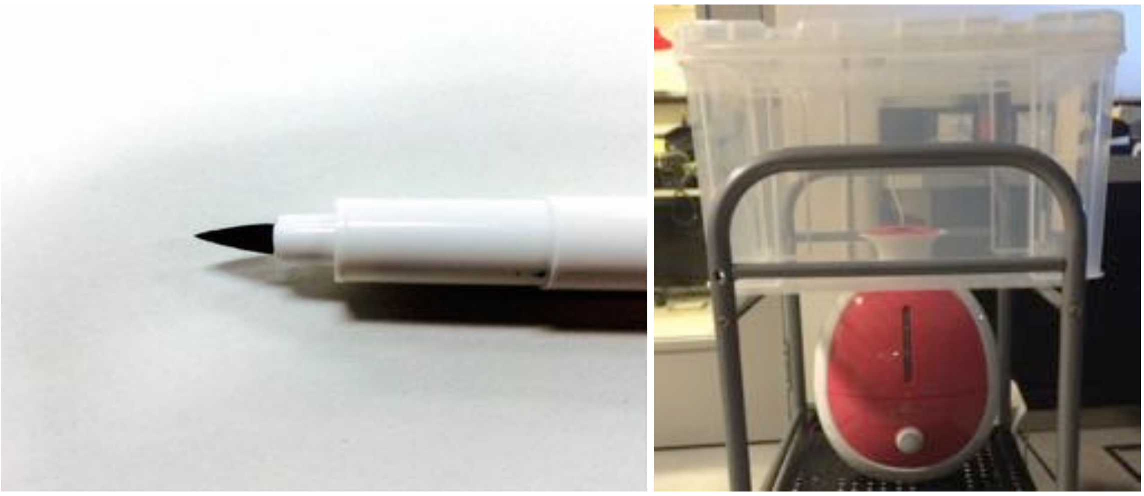
- Hole Punch Drill Bits (modified from mechanical pencil tips): diameters φ0.5mm and φ1mm. Tip of a mechanical pencil is sharpened by grinding with the electronic grinding router so that it becomes a sharp hollow puncher (Figure 4.3 (b)). Typical diameter (i.e. 0.5mm) of a mechanical pencil tip is for inner diameter. Therefore, holes made by these modified mechanical pencil tips will be slightly larger than stated diameters (equal to the outer diameter).

- Felting Needles: Felting needle is a special needle which has barbs along its body. This type of needle is typically used to entangle non-woven fabric. In our experiment, we used Clover Felt Puncher 58-607 [11] to open hole on paper substrate (Figure 4.3 (c)). This felting needle has a triangular cross-sectioned with 0.5mm edge length.

Room Environment

According to our previous observation, environment temperature and humidity do have a slight impact on the resistance of the printed pattern. Experiments conducted during winter and summer, or between different climate may result in different results. The environment during the experiments is as follows:

- Temperature T = 20°C



(a) Silver nano particle ink filled AgIC brush/marker

(b) Ultra-sonic water humidifier

Fig. 4.4: Ink filler and humidifier

- Humidity H = 20% ~ 30%.
- Humidifier: moisture exposure is a well-known method to accelerate chemical sintering in Instant Inkjet Circuits [4, 20]. In our experiment, some samples, after hole opening and ink filling, will be exposed to humidity (H ≈ 100%) generated by an ultra-sonic water humidity maker (Figure 4.4 (b)) for 5 minutes.

Conductive Ink

Silver nano particle ink with part number NBSIJ–MU01 from Mitsubishi Paper Mills [29].

Software

In order to control the amount of ink deposited by the printer, Gutenprint [17] driver version 5.2.10 for Fedora 20 operating system [13] was used to adjust the printing parameters. Among many printing parameters, printing density is one of the simplest way to adjust the amount of deposited ink. Printing density in Gutenprint driver is a coefficient used to define the size of droplet for each printed dot. Modern home inkjet printer uses micro piezoelectric nozzles which allow to eject ink onto medium at different droplet sizes. The Micro Piezoelectric print heads in Epson printers support upto 5 different sizes of ink droplet [36]. For each printing dot, pre-dithering and dithering algorithm in Gutenprint will decide the size of the droplet based on the input value of that dot [16]. Each range of the input value corresponds to a specific droplet size. Larger input value results in bigger droplet size. Density parameter acts as a multiplier for this input value. Setting "Density = 2" does not mean it will print at double density but it will double the input value of each printing dot before choosing droplet size. Thus, a smaller range input value can be multiplied into larger range and results in choosing larger droplet size for the corresponding printing dot. By default, this parameter receives values in range from 0 to 8.0. However, for the simplicity of the experiment, in this paper, we will only focus on integer values of density parameter (from 1 to 8).

4.3.2 Experiment Conduction

Hole opening mechanism

We have 3 types of hole openers, which are drill bits (different diameter), hole punch drill bits (different diameter) and felting needles. For each type, we have a hole opening operation as Figure 4.5:

- Drill Bit, Hole Punch Drill Bit: clock-wise rotate and push down
- Felt Needle: push down and pull up

3 modes of filling ink

After drilling holes, we need to fill them with the silver nano particle ink. We will use an AgIC brush [1] (Figure 4.4 (a)) and an Epson WF-3011 [37] printer to fill in the opened hole. The reason to choose an Epson inkjet printer was that besides compatibility to silver nano particle ink, it is easier to control Epson printer with modified open source Gutenprint printer driver. As mentioned above, we focus on printing density from 1 to 8, however, as our observation, printing with "Density" greater than 2 results in a wet printed pattern. In other words, the printed pattern will get dirty and smeared after coming out from the printer. Therefore, we will stop at 2 modes of printing with "Density" value set to 1 and 2. In total, for filling ink, we have 3 modes:

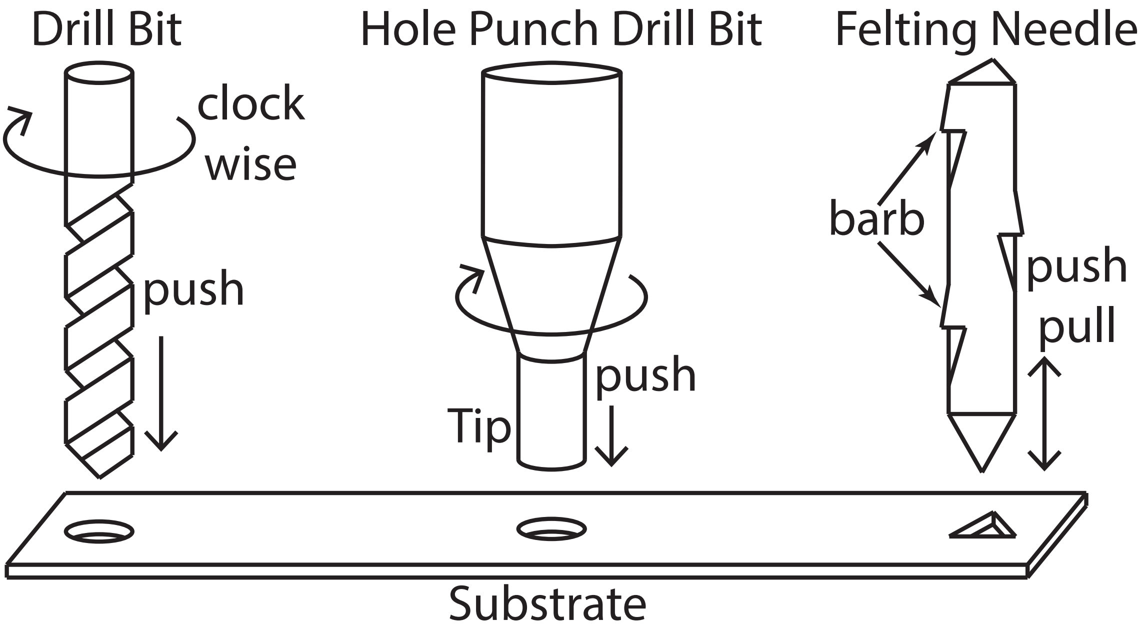


Fig. 4.5: Hole open mechanism

- Brush: paint drilled holes with the silver ink brush
- Print with “Density = 1”
- Print with “Density = 2”

Types of via hole processes

For each mode above, we have 6 types of processing via holes as follows:

- Process 1: hole open - ink fill (no humidify)
- Process 2: hole open - ink fill - humidify
- Process 3: hole open - ink fill - wait 24 hours - humidify
- Process 4: pre-ink - hole open - ink fill (no humidify)

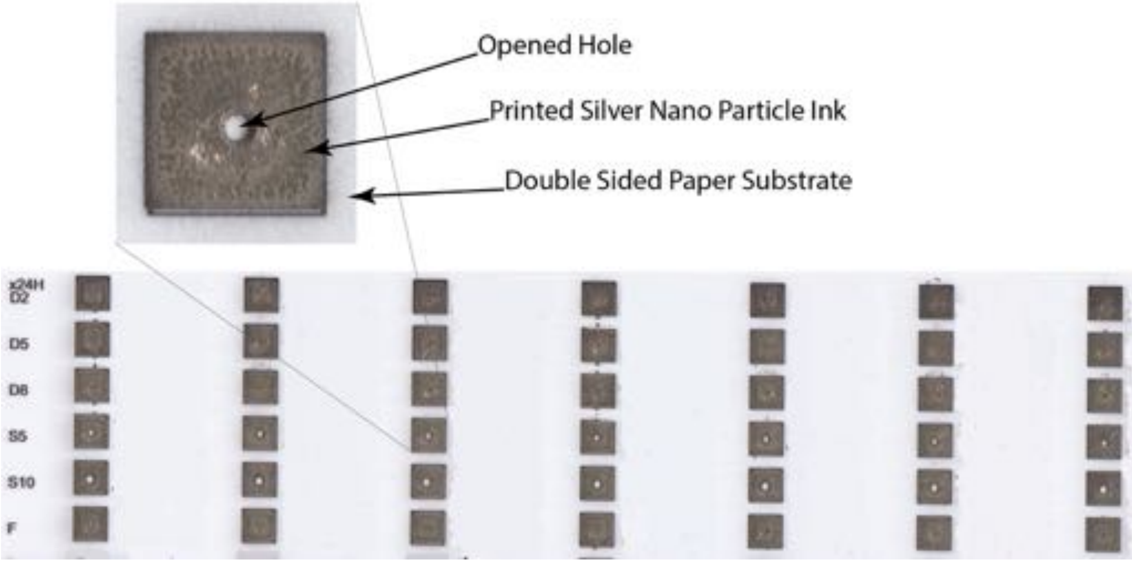


Fig. 4.6: Samples on paper substrate after hole opening and ink filling

- Process 5: pre-ink - hole open - humidify
- Process 6: pre-ink - hole open - wait 24 hours - humidify

In the last 3 processes, before opening hole, we paint the hole opener (drill bit/hole punch drill bit/felt needle) with the silver ink brush, expecting that this will help to bring the silver ink into the inner wall of the opened hole. We call this pre-inking.

As we have 3 modes of giving ink, 6 types of via hole processes and 6 types of different hole openers, we have totally 108 types of samples. For each type of sample, we will make 7 samples (7 holes) - Figure 4.6. In total, we will have 756 samples to be evaluated.

Measurement

In this experiment, we focus on the resistance of the via hole. A typical 4-probe multimeter (Tonga TH2821 LCR Meter [9]) was used to measure the via hole resistance immediately after ink filling, after 1 day, 2 days, 3 days, and 5 days. Measurement schedule is listed in Table 4.2 (○: measure, ×: skip).

Measurement Time	No Humidify (Process 1&4)	0h - Humidify (Process 2&5)	24h - Humidify (Process 3&6)
Immediately	○	○	○
After Humidify	×	○	×
1 day	○	○	○
After Humidify	×	×	○
2 days	○	○	○
3 days	○	○	○
5 days	○	○	○

Table 4.2: Measurement schedule for different samples

○ - measure, × - skip

- All samples will be measured immediately after printing.
- Samples of Process 1 and Process 4 (No Humidify) will be measured after 1 day, 2 days, 3 days, and 5 days.
- Samples of Process 2 and Process 5, after immediate measurement, will be humidified and measured resistance after humidifying, after 1 day, 2 days, 3 days, and 5 days.
- Samples of Process 3 and Process 6, after immediate measurement, are left at room environment for 1 days and then measured again. After that, these samples are humidified and measured again after humidifying, after 2 days, 3 days, and 5 days.

4.3.3 Result

Ink filling and Via hole resistance

After measuring all the samples for 5 days, the first thing we observed was that printing with "Density = 2" gave the best result in term of resistance. In 252 samples printed with "Density = 2", 93.65% number of samples were conductive with resistance $R < 100\Omega$. In the case of printing with "Density = 1" and painting the via hole with the brush, these values are 13.49% and 39.68% respectively. For stricter conditions, $R < 10\Omega$, and $R < 1\Omega$, the via holes filled by printing with "Density = 2" still showed the best performance (more details in Figure 4.7). This conforms to common thought that the more silver nano particle ink we

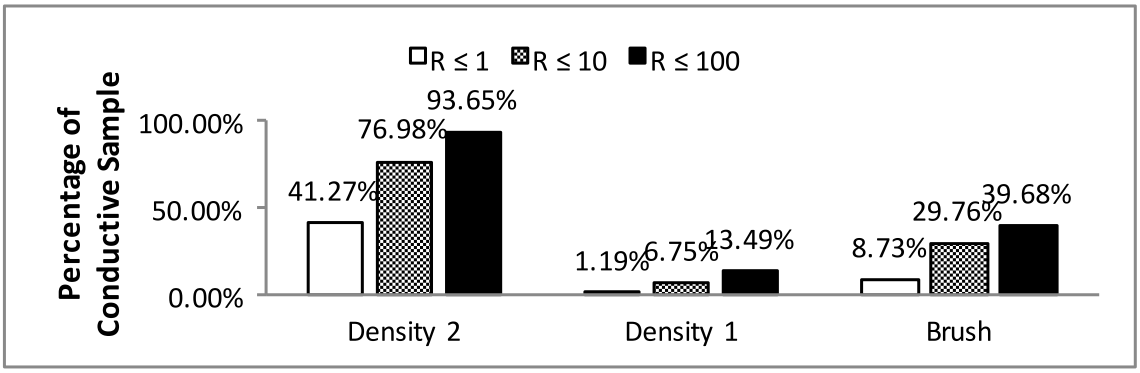


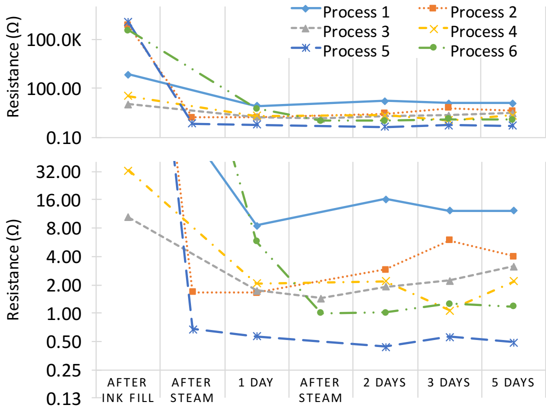
Fig. 4.7: Percentage of conductive samples

add, the better via hole conductivity is. In the following parts, we will only focus on evaluating via holes which were printed with “Density = 2”.

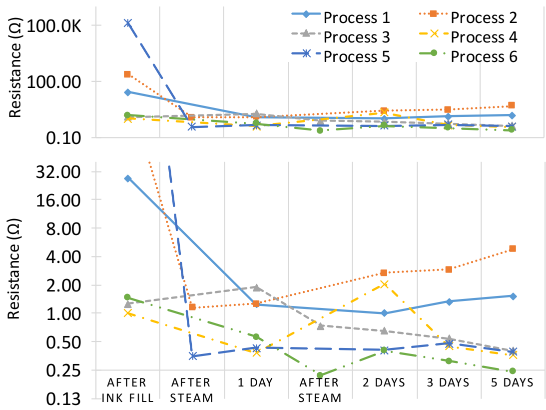
Hole opener and via hole resistance

For each type of the sample, the median of 7 via holes will be used to plot the resistance graph as Figure 4.8.

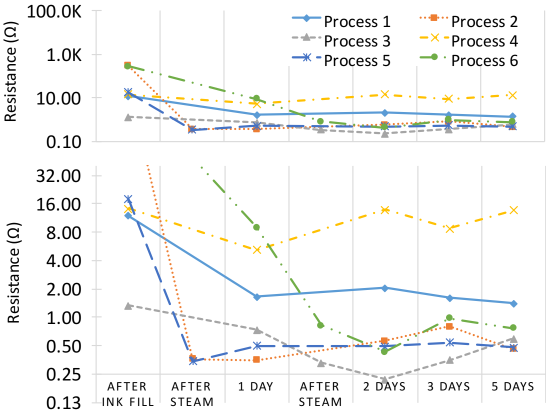
Across 6 types of the hole openers, there is a common point that, via holes made by Process 4, 5 and 6 (with pre-ink before opening hole) are not conductive immediately after the printing. The resistances are in the mega ohm order of magnitude. More analysis and experiment are necessary to fully explain this, but there is a hypothesis that the pre-inking before opening hole will bring a small amount of silver nano particle ink into the inner wall of the hole. This small amount of ink will be chemically sintered by strands of coated material inside the hole. However, since this amount of ink is too little, it cannot establish full conductivity inside the hole. After opening, the hole will be filled with a larger amount of silver nano particle ink by printing. However, since the strands of coating layer have been used to sinter previously, the latter amount of ink is not fully sintered. And this, after all, leads to a non-conductive via hole. On the other hand, via holes made by Process 1, 2 and 3 (without pre-ink) establish conductivity right after printing. Resistances of these samples are in the hundred ohm order of magnitude.



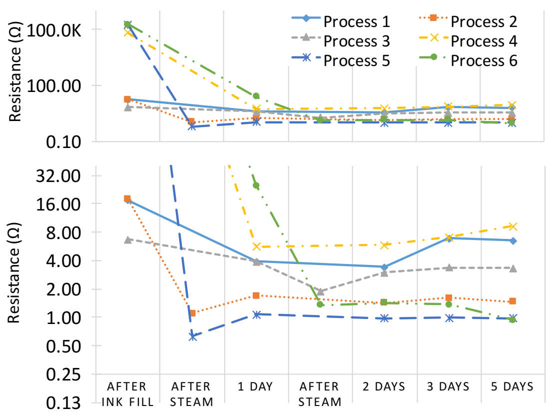
(a) Resistance of via holes made by ϕ0.2mm drill bit & print "Density = 2"



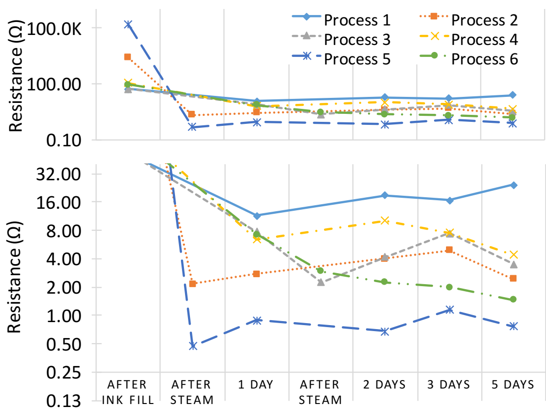
(b) Resistance of via holes made by ϕ0.5mm drill bit & print "Density = 2"



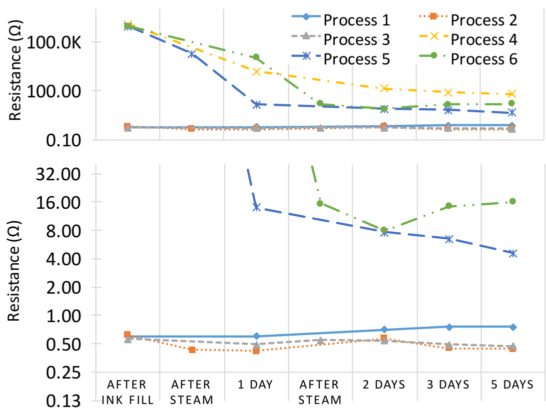
(c) Resistance of via holes made by ϕ0.8mm drill bit & print "Density = 2"



(d) Resistance of via holes made by ϕ1mm hole punch drill bit & print "Density = 2"



(e) Resistance of via holes made by ϕ0.5mm hole punch drill bit & print "Density = 2"



(f) Resistance of via holes made by Felting Needle & print "Density = 2"

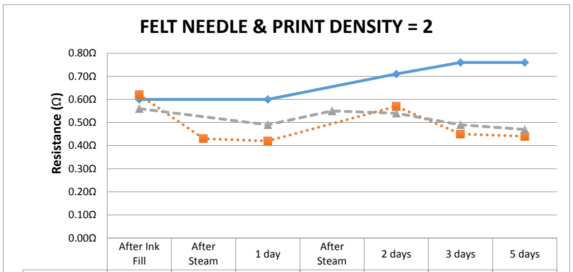
Fig. 4.8: Median resistance of via holes made by different hole opener and filled with silver nano particle ink by inkjet printing with "Density = 2". In each sub-figure, *upper graph*: full logarithmic scale base 10; *lower graph*: zoomed-in to see small resistance values at logarithmic scale base 2

Although conductivity was not well established immediately, the resistance of all the samples has significantly decreased after exposing to moisture by the ultra-sonic water humidifier. This is an expected result as adding water is a well-known technique to accelerate the sintering process and improve the conductivity of the printed pattern [4, 20]. In the case of samples made by Process 3 and 6 in which the via holes were left in the room environment condition for 24 hours before exposing to moisture, the conductivity of via holes have been well established due to moisture existing in the air. After the first 24 hours, the resistances of these samples were in the ten ohm order of magnitude. When these samples were exposed to moisture by the humidifier, their conductivity was significantly improved. Median resistance was decreased to around 1Ω. Later measurements after 2 days, 3 days and 5 days showed that the resistance of samples were stable during the time.

Results above were generally right for all samples (made by drill bits ϕ0.2mm, ϕ0.5mm, ϕ0.8mm, hole punch drill bits ϕ0.5mm, ϕ1mm, and felting needles). However, there were samples which consistently established conductivity right after printing with resistance $R < 1\Omega$. They are via holes made by the felting needles (Figure 4.8 (f)). In this figure, for via holes made by Process 1, 2 or 3, median values of resistances right after printing were less than 1Ω (0.6Ω, 0.62Ω and 0.56Ω respectively). This is especially different from via holes made by other hole openers (Table 4.3).

Process	Drill 0.2 mm(Ω)	Drill 0.5 mm(Ω)	Drill 0.8 mm(Ω)	Puncher 0.5 mm (Ω)	Puncher 1 mm (Ω)	Felting Needle (Ω)
1	700	27	12	52	17.4	**0.6**
2	740K	230	300	2.5K	18	**0.62**
3	10.5	1.27	1.33	53.34	6.68	**0.56**
4	32.78	1	14.2	110	67K	1.3M
5	1.2M	137K	17.8	150K	170K	960K
6	366K	1.46	273	88.9	190K	930K

Table 4.3: Median values of resistance via holes made by different hole openers. Measurements were made immediately after printing with “Density = 2”



	After Ink Fill	After Steam	1 day	After Steam	2 days	3 days	5 days
Process 1	0.60Ω		0.60Ω		0.71Ω	0.76Ω	0.76Ω
Process 2	0.62Ω	0.43Ω	0.42Ω		0.57Ω	0.45Ω	0.44Ω
Process 3	0.56Ω		0.49Ω	0.55Ω	0.54Ω	0.49Ω	0.47Ω

Fig. 4.9: Median value of resistances of via holes made by felting needle with printing "Density = 2", measured during 5 days

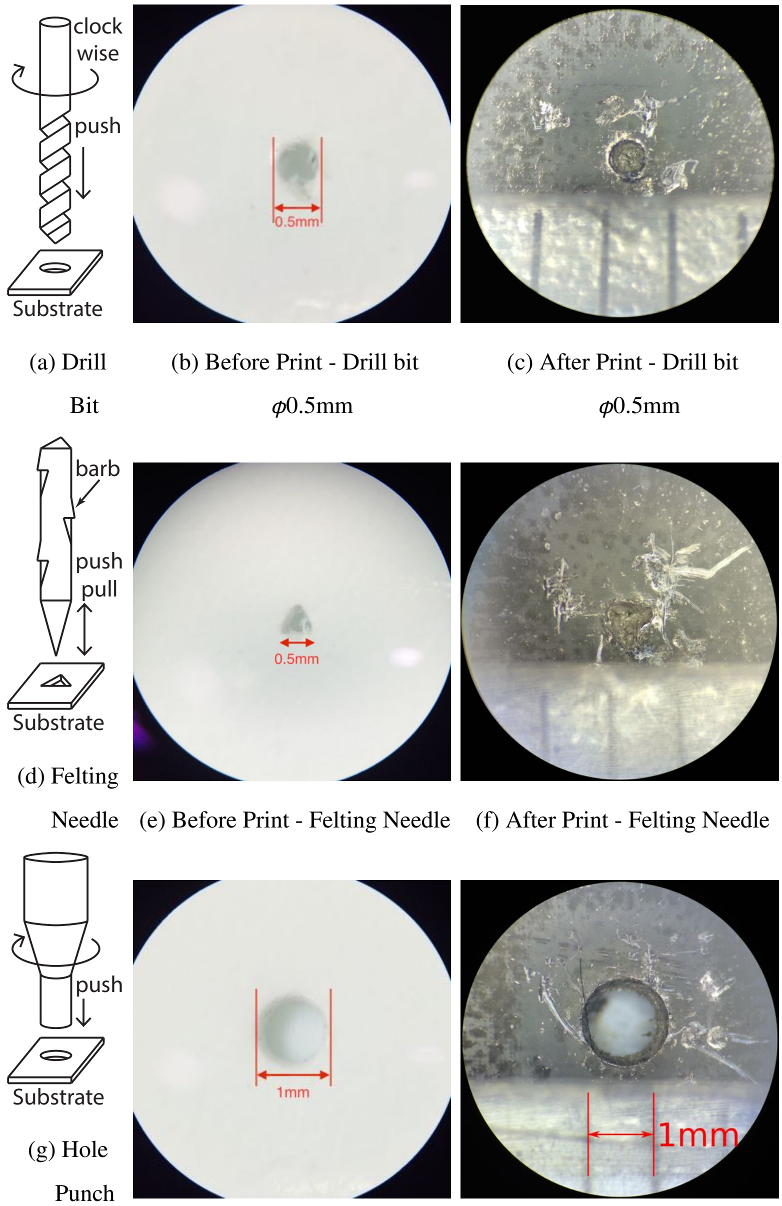
Drill bits φ0.2mm, φ0.5mm, φ0.8mm, hole punch drill bits φ0.5mm, φ1mm can also establish conductivity immediately after printing. However, the resistances were not consistent and considerably higher than the ones made by the felting needle.

As having lowest immediate resistance after printing, felting needle via holes without pre-inking (Process 1, 2 and 3) are promised to have the best conductivity after all. Figure 4.9 shows that via holes' conductivity have been improved after humidifying and the resistances are stably less than 1Ω through 5 days. Our measurement on the same samples after 6 months showed that the resistances of felting needle via holes are increased to 1.65Ω. Compare to other interconnections like the ones made by staplers mentioned in the beginning of this paper, the durability of via holes made by felting needle are much more superior. In the case of no humidifying samples (Process 1 samples), although resistances were higher than the ones that have been humidified, they are also stable and keep resistance at 0.7Ω. This is an important result as Process 1 is the simplest process but resistances of via holes are still low and stable.

4.3.4 Via-hole Structure

In order to have a better understanding about the structure of the via holes made by the drill bits, hole punch drill bits and felting needles, via hole samples have been observed using an optical microscope.

Figure 4.10 are magnified images of via holes made by drill bits, felting needles and hole punch drill bits before and after printing.



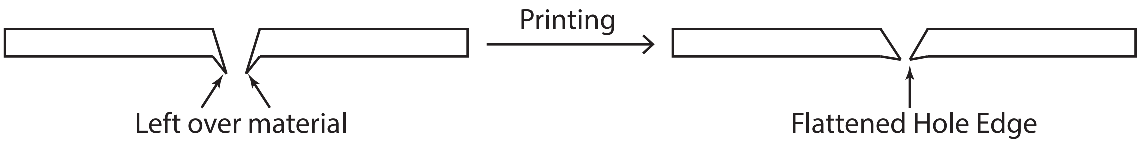
(a) Drill Bit (b) Before Print - Drill bit φ0.5mm (c) After Print - Drill bit φ0.5mm

(d) Felting Needle (e) Before Print - Felting Needle (f) After Print - Felting Needle

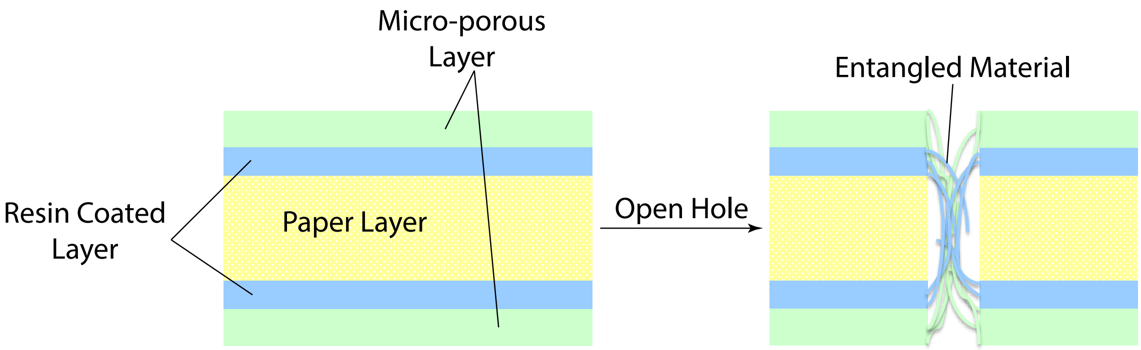
(g) Hole Punch Drill Bit (h) Before Print - Hole Punch Drill Bit φ1mm (i) After Print - Hole Punch Drill Bit φ1mm

Fig. 4.10: Via hole structure

(a) Edge structure of holes made by hole punch drill bit before and after printing



(b) Edge structure of holes made by drill bits or felting needles before and after printing



(c) Entanglement of substrate material after hole opening

Fig. 4.11: Via-hole structure

It is obvious that the shape of the via holes made by different hole openers are not the same. There is a special point that, the via holes made by a hole punch drill bit are completely through-the-hole. This is because hole punch drill bit used cut-off style to open holes on the paper substrate (Figure 4.11 (a)). In this type of via hole, conductivity will be established through only the silver nano particle ink on the inner wall of the hole. There should be a note here is that the via hole structure may become smoother if sharply filed hole punch drill bits are used instead of modified mechanical pencil tips, which have some jags and not so sharp blade. However, we do not have any data to indicate which type of the structures has a good conductivity.

In the case of via holes made by drill bits and a felting needles, although they were also through-the-holes before printing, the holes had been covered after printing. The reason is that the drill bit or the felting needle did not completely cut off the material part inside the hole. After opening a hole, this left over substrate material still sticks to the edge of the hole and make it a rising/falling edge hole as illustrated in Figure 4.11 (b).

While printing, the paper feeding mechanism of the inkjet printer will put drilled substrate through a chain of the feed rollers. These rollers will press and cover the opened hole with the remaining substrate material mentioned above. This covering leads to more messiness of the coating strands entanglement – Figure 4.11 (c). Due to this, covered holes can hold a larger amount of ink and have better chemical sintering than through holes (in case of hole punch drill bit types). As a result, the via holes made by drill bits and felting needles have better conductivity than the ones made by hole punch drill bits.

4.4 Handy Drilling Pen

A handy drilling pen aims at hobbyists and makers who want to manually make a double sided circuit. A simple tweak to attach a drill bit to chuck of an electric eraser [35] will help to make hole opening operation more convenient and consistent (Figure 4.12, 4.13). As the substrate is paper, the torque generated by motor in the electric eraser is more than enough to open a hole. This opened hole can be filled by the AgIC silver nano particle ink brush or by printing with an inkjet printer. Although this is not an optimized solution, it can be used as a handy tool for double sided circuits which require just a few drilled holes.

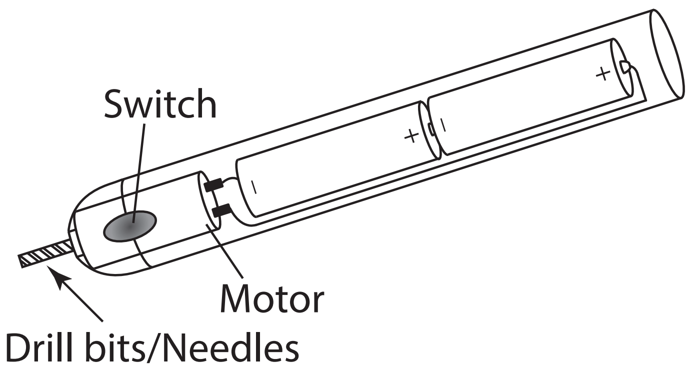
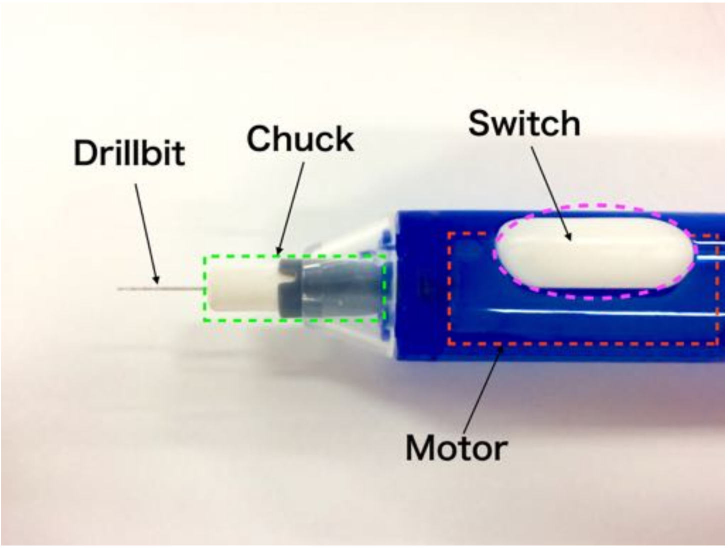


Fig. 4.12: Drilling pen for making via-hole with drill bits



(a)

(b)

Fig. 4.13: Drilling pen in use

After making drilling pen with electric eraser rotated motor, a small tweak can help us to make a handy pen for felting needles. A 3D printed chuck for holding a felting needle can be attached to a solenoid actuator. This solenoid actuator makes the felting needle to move linearly along the body of the pen. With a sponge mattress underneath the paper substrate, our solenoid pen can easily open a via-hole on the paper.

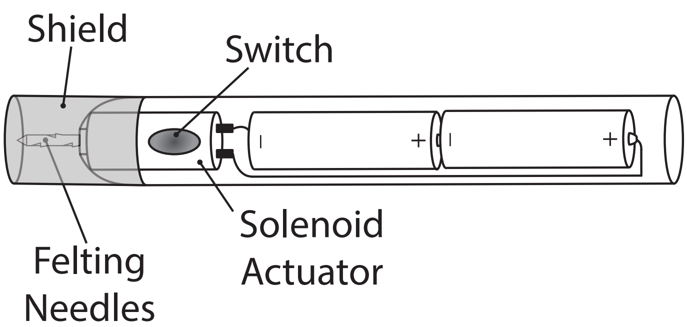


Fig. 4.14: Felting pen for making via-hole with felting needles

4.5 Applications

With the support of double side circuits, we can use Instant Inkjet Circuits to make a lot of applications. Following examples are just very basic use cases which are enabled by double sided circuits.

4.5.1 LED Matrix

Instant Inkjet Circuits can be easily used to light up a chunk of LED. However, due to the nature of single layer, it used to be impossible to implement an LED matrix with Instant Inkjet Circuits. By using double sided photo paper and the via hole technique described in this paper, we can quickly print a conductive pattern and attach LEDs to make an LED matrix on the paper (Figure 4.15). The realization of LED matrix in Instant Inkjet Circuits open a path to rapidly fabrication of pixelated display using conductive printing technology.

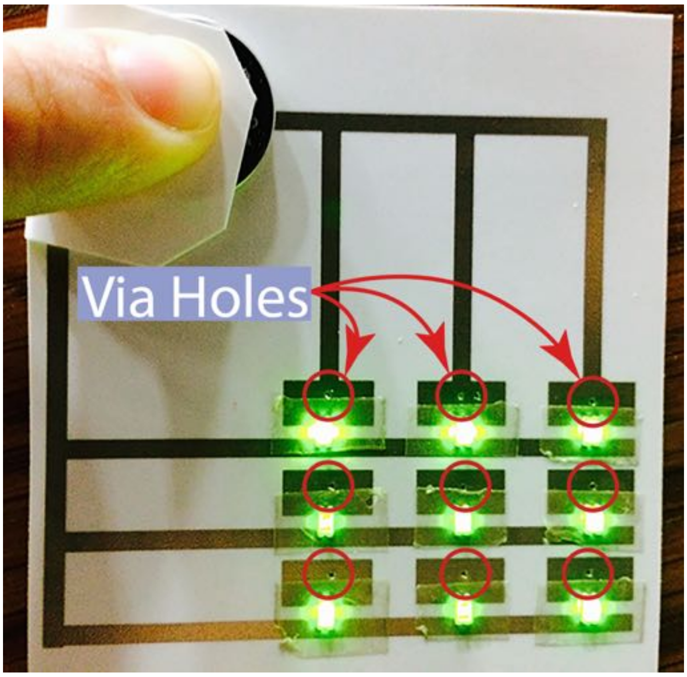
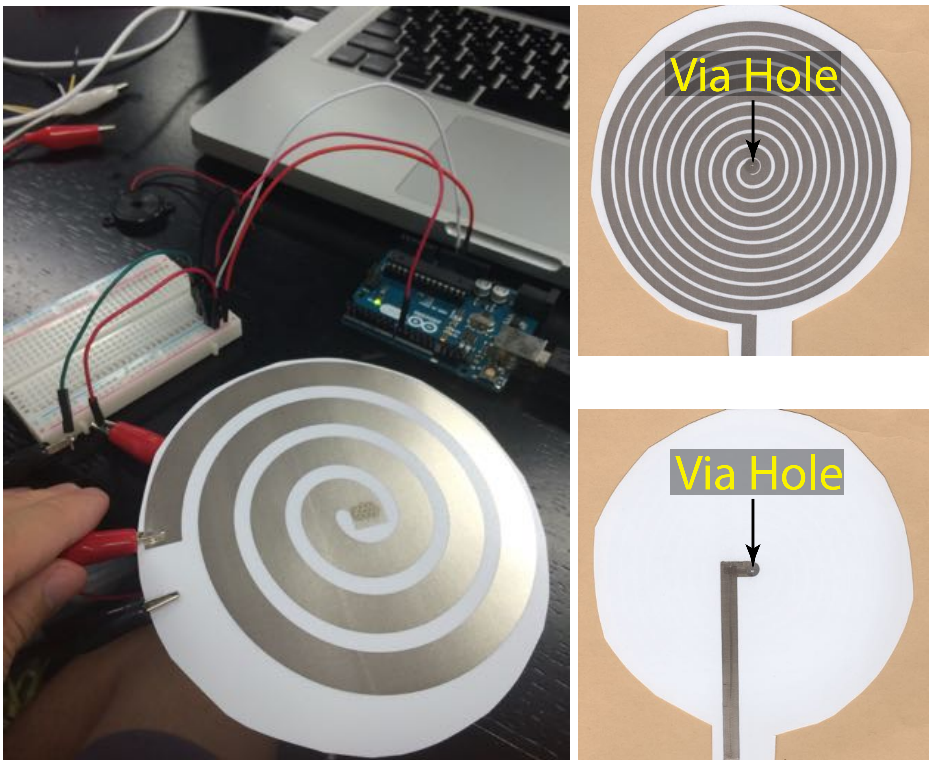


Fig. 4.15: LED matrix

4.5.2 Paper Printed Speaker

A paper speaker is an interesting application of electronic rapid prototyping [18]. A conductive spiral coil will be fabricated on a thin substrate. This substrate will be put closed to a permanent magnet and act as a membrane that vibrates and moves the air to create sound. In some designs, a printed conductive spiral coil needs to be wired one end inside-out with an additional insulated layer [18]. By using a via hole, the spiral coil can be wired inside-out through the other side of the paper substrate as Figure 4.16 (b).



(a) Paper Speaker

(b) Speaker Coil - Front & Back

Fig. 4.16: Paper speaker made by double layer coil

4.5.3 Tune-able RFID Coil

RFID tag has been widely used in the real life with many applications for near field communication. In order to miniaturize a tuneable RFID antenna, a printed inductor in the shape of a coil is usually added. In current Instant Inkjet Circuits, it is not possible to connect 2 ends of the coil which is important to make this type of RFID antenna to work. With the support of a via hole, we can easily connect 2 ends of the coil in the same manner as the coil for paper speaker mentioned above. Figure 4.17 is a coil inductor for an RFID tag printed with Instant Inkjet Circuits and connected by via holes.

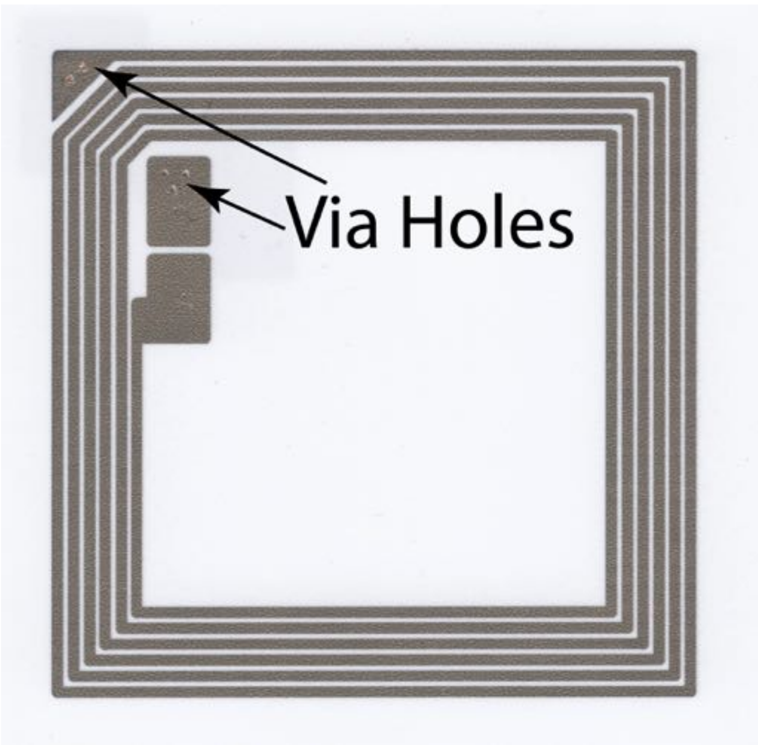


Fig. 4.17: RFID coil inductor

4.5.4 Hide wiring pattern in artwork

One of widely used applications of Instant Inkjet Circuits is to create digital artworks such as drawing electronic pictures, cards, or paper works. In such applications, it is sometimes necessary to hide the wiring pattern in order to draw user's attention to colorful drawing. With double sided paper and via hole, all wiring pattern can be easily put on 1 side, the another side will be used solely for artwork drawing. Figure 4.18 is a simple application which helps to train children on classification skill. The front side is a colorful drawing of several animals that children need to divide them into different groups by drawing lines with a silver ink brush. The backside is printed with silver nano particle ink and via holes are made so that an LED will light up if dividing lines are drawn correctly.

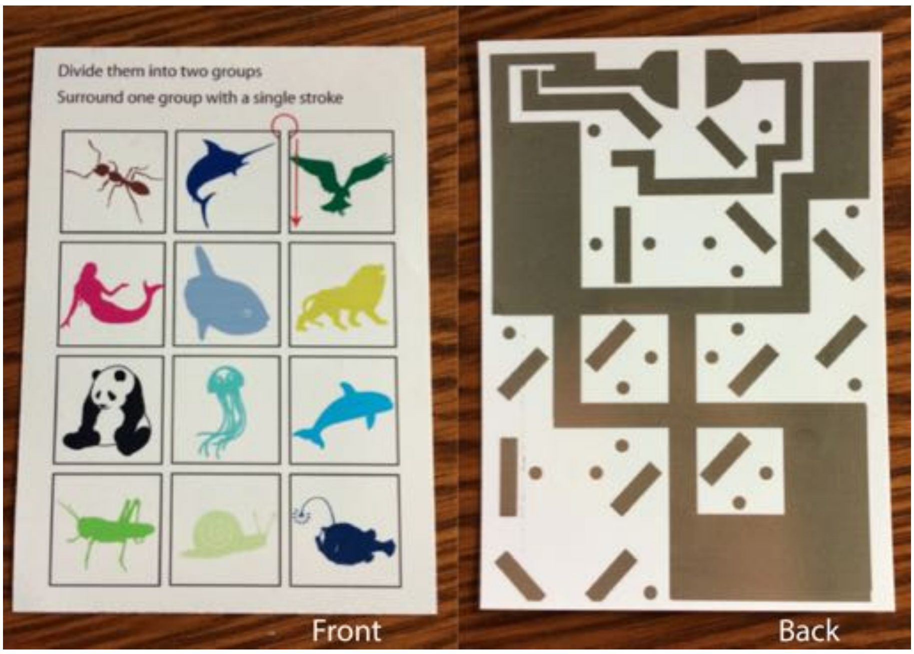
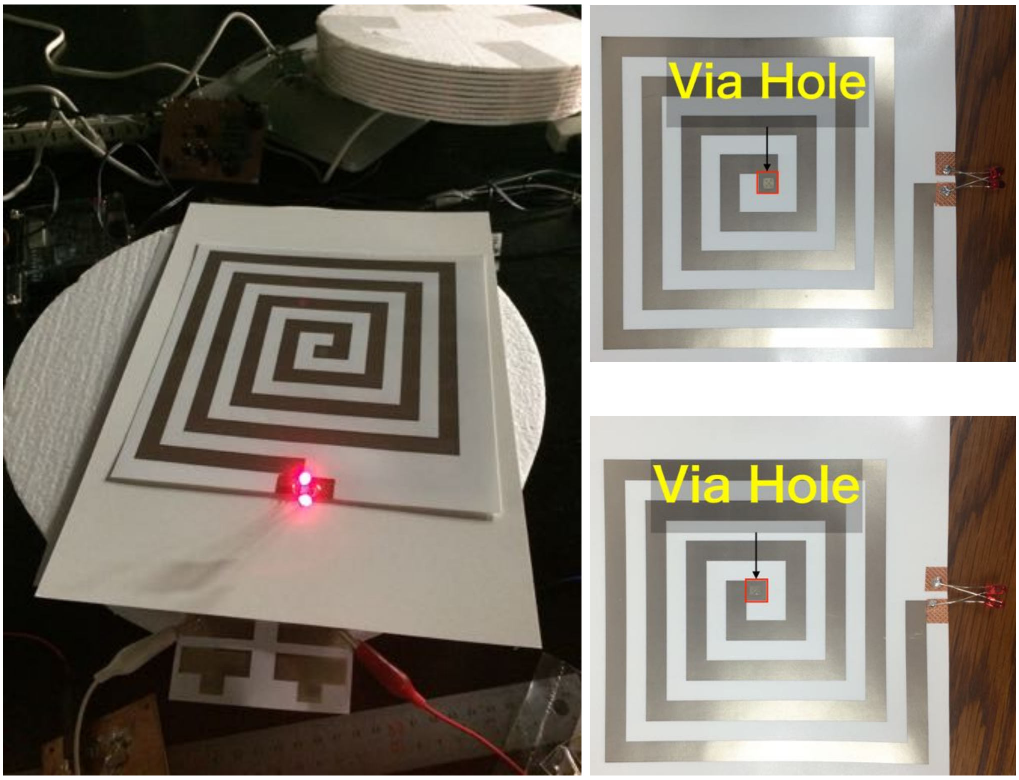


Fig. 4.18: Hiding wiring on the other side of paper

4.5.5 Wireless Power Transmission Antenna

Wireless Power Transmission (WPT) has become an intensive research trend recently. There are a lot of works about improving the efficiency of WPT. One of the critical factors which affect performance of a WPT system is the coupling coils. These coils should have low resistance and multiple number of turn. Prior to double sided circuit for Instant Inkjet Circuits, although coil's resistance problem can be solved by techniques mentioned in Chapter 2, we could only make 1-turn-coil on paper substrate, thus limited the application of rapid prototyping in designing WPT system. With via-hole and double sided circuit, we can make multiple turn coil as Figure 4.19.



(a) WPT Coil Inductor (b) Speaker Coil - Front & Back

Fig. 4.19: Paper speaker made by double layer coil

4.6 Conclusion

In this chapter, we presented several approaches to double sided circuits for the Instant Inkjet Circuits. The key to double sided circuits is interconnection between 2 sides of the substrate. Beside simple, but not robust approach using office supplies (a metal pin stapler and a crush-style needle-less stapler), we evaluated another solution using via holes made by several hole openers like drill bits, hole punch drill bits and felting needles. The use of these tools with sintering-free silver nano-particle ink to make via holes is far simpler than other methods like laser drill or using conductive adhesive. The structure of the drill bits, hole punch drill bits and, especially, felting needles, help to entangle strands of the coating layer between 2 sides of the substrate through the opened hole. This entanglement improves chemical sintering of the silver ink inside the hole, makes it a conductive via hole.

Beside advantages of being a fast, simple, effective method, double sided circuit for Instant Inkjet Circuits is facing a disadvantage from the inaccurate paper feeding mechanism in commodity desktop inkjet printer. Even with an auto-duplex inkjet printer, in which, after printing the first side, the paper is automatically rolled back to print on the other side, there is still misalignment. The paper feeding and rolling back mechanism of these inkjet printers is not accurate enough. It heavily depends on the brand of the inkjet printer and characteristics of the paper substrate, but as our observation on Mitsubishi Paper Mills double sided paper and Epson WF-3011 printer, misalignment is about 0.5mm $\sim$ 1mm. A temporary solution for this problem is to design patterns of the 2 sides with offset in mind. In the future, misalignment will need to be eliminated in order to make an automatic double sided circuit printer.

By elaborating methods to make interconnections for double sided circuits with Instant Inkjet Circuits, we have:

- Evaluated the resistance of the via holes made by different hole openers: drill bits, hole punchers and felting needles.
- Presented a simple yet the best setting to make via holes: use a felting needle to open hole on the paper substrate and then fill this hole with silver nano particle ink by printing with “Density” on Gutenprint driver set to 2.

- Explained the mechanism to have conductive via hole immediately after printing at room condition - the entanglement of material inside the hole.
- Made a handy drilling pen to make hole opening more convenient and consistent.
- Presented some applications that via hole has enabled us to easily make with the Instant Inkjet Circuits.

Chapter 5

Conclusions

5.1 Summary

As the title has already stated, this work focused on discussing about some tools and techniques that support to improve performance of conductive inkjet printing technology, especially for Instant Inkjet Circuits. The emergence of conductive inkjet printing and Instant Inkjet Circuits have opened the gate for anyone from a novice to an expert to rapidly make electronic circuits. The rapidness is important in the sense that it helps to shorten the pace of product design iteration so that a prototype can be refined in no time for a better version.

Instant Inkjet Circuits, from its arrival, enjoyed great adoption from most applications. However, its limitation in electrical conductivity and the lack of multi-layered circuits support have narrowed the range of application scenarios.

5.1.1 Tweaking printer driver for advancing printed pattern characteristics

By tweaking an open-source printer driver (Gutenprint), we have succeed in implementing an auto-overprinting mechanism, along with printing density adjustment, to bring down the sheet resistance of printed pattern from about 0.25Ω/□ to 0.04Ω/□. With this technique, we can print highly conductive pattern on paper without any misalignment as in manual overprinting. This has enabled us to improve the performance of a variety of sensors and antennas such as capacitive based pressure sensor or energy harvesting antenna. Besides being effective in improving electrical conductivity, auto-overprinting has shown the potential of software approach in advancing Instant Inkjet Circuits and in general, conductive inkjet printing. It is possible to gain more control of commodity inkjet printer to make it a better electronic circuit fabricator. Once implemented, such changes can be easily applied to thousands of printers from other brands with minimum or none of code revision.

5.1.2 Double sided layered circuit for Instant Inkjet Circuits

In addition to tweaking printer driver to improve conductivity of printed pattern, we also proposed a simple method to rapidly make via-holes, electrical interconnections between 2 sides of the paper substrate, to realize double sided circuits with Instant Inkjet Circuits. One of the most important characteristics of Instant Inkjet Circuits is its capability of establishing electrical conductivity at room environment almost immediately after printing. Therefore, our proposal aimed at making a low resistance via-hole while retaining room temperature sintering of Instant Inkjet Circuits. Based on the fact that there are entanglements of substrate material inside a hole made on a piece of paper substrate, we selected several type of hole openers such as drill bits, hole punchers and felting needles to make the hole. After that, the hole is filled with silver in using conductive ink marker or inkjet printer. Observation showed that a hole made by felting needles, after filled silver nano-particle ink by a inkjet printer at Print Density = 2 will give the lowest resistance, as low as 0.7Ω.

5.2 Future Work

The following could be regarded as future work.

(I) *Printable resistance*: beside reducing as much as possible the sheet resistance of printed pattern, it is sometime necessary to increase it. More precisely, in many applications, we would like to print a resistor with specific resistance value. By adjusting printing density in Gutenprint as described through previous chapters, we can find the relationship between printing density parameter and the resistance of printed pattern. Along with changing the dimension of the printed pattern (length and width), we can gain more flexibility on printing specific valued resistor using Instant Inkjet Circuits.

(II) *Automatic Double Sided Circuits Silver Instant Inkjet Printer*: We are excited about finding some ways to integrate via hole making mechanism to an inkjet printer so that we can have a fully automatic double sided circuit fabricator using Instant Inkjet Circuits technology. This integration is possible if we can attach a solenoid mechanism with a felting needle to print head of the printer. Conductive pattern can be designed on any Computer-Aided Design (CAD) software which supports double sided and multilayered circuit design (e.g. EAGLE [7]). A modified driver might be required to print the CAD data with a home inkjet printer.

(III) *Automatically Fix Misalignment for Double Sided Circuits*: As mentioned from the conclusion of chapter 4, filling via-hole made on paper substrate using printer requires the re-feeding of the substrate. However, the tray based paper feeding mechanism in commodity inkjet printer is not accurate that it causes misalignment of 0.5 mm between 2 sides. Though this can be improved by adding offset to printed data during designing phase, it is tedious and sometime frustrated. Since these misalignment depend on the brand of the printer as well as the thickness of the substrate, we can modify printer driver so that the printer will adjust print-head's offset based on printer and media information.

(IV) *Multi-layered Electronic Circuits on Single Sided Substrate*: Overprinting implementation described in chapter 3 has opened the possibility to improve characteristics of conductive inkjet printed patterns with software approach. Interconnection through via-hole described in chapter 4 has shown a effective hardware approach to double sided and multi-layered electronic circuits with Instant Inkjet

Circuits. The next step might be implementation of multi-layer electronic circuits with the use of overprinting. Along with loading inkjet printer ink tanks with different conductive materials and insulating inkjetable materials, a appropriately revised Gutenprint can help to print different materials at the same position of the same substrate, thus, fabricating a multi-layered electronic circuit.

(V) *Design support tool*: There is a fact that many users of Instant Inkjet Circuits are non-expert users. They are graphic designers, non-experience hobbyists or even kids. Most of these users do not have much experience on designing electronic circuits. It would be great to have a assistant tool that is integrated into common used graphical designing tools (such as Adobe Illustrator or InkScape). This tool can help to auto route simple electronic schematics, self check for any wiring mistake. This tool will also benefit expert user by automatically generate tedious period pattern like Intedigitated Capacitor or meander pattern for resistor.

Publications

International Conferences

[1] T. D. Ta, M. Fukumoto, K. Narumi, S. Shino, Y. Kawahara, and T. Asami, "Interconnection and Double Layer for Flexible Electronic Circuit with Instant Inkjet Circuits," UbiComp '15, September 2015, pp. 181-190.

International Demos

[2] T. D. Ta, K. Narumi, Y. Kawahara, "Assistant Tools and Techniques for Conductive Inkjet Printing Technology," Proc. of ACM UbiComp 2015, GadgetShow Plus Demo, Osaka, Japan, Sept. 2015.

[3] T. D. Ta, Y. Kawahara, "Implementation of via hole and multi-layered circuit with Instant Inkjet Circuit," Microsoft Research Asia Faculty Summit, Asia Faculty Summit, Beijing, China, Oct. 2014.

Domestic Workshops

[4] T. D. Ta, W. Wei, Q. M. Duong, Y. Kawahara, and T. Asami, "Tweaking Printer Driver for Improved Conductivity in Instant Inkjet Circuits," Information Processing Society of Japan (IPSJ), Ubiquitous Computing System, UBI42, pp. 1-4, 2014.

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