Interconnection and Double Layer for Flexible Electronic Circuit with Instant Inkjet Circuits

Tung Ta
The University of Tokyo
7-3-1 Hongo, Bunkyo-ku,
Tokyo, Japan
tung@akg.t.u-tokyo.ac.jp

Masaaki Fukumoto
Microsoft Research
Beijing, China
fukumoto@microsoft.com

Koya Narumi
The University of Tokyo
7-3-1 Hongo, Bunkyo-ku,
Tokyo, Japan
narumi@akg.t.u-tokyo.ac.jp

Shigeki Shino
Mitsubishi Paper Mills
Kyoto, Japan
shino_shigeki@mpm.co.jp

Yoshihiro Kawahara
The University of Tokyo
7-3-1 Hongo, Bunkyo-ku,
Tokyo, Japan
JST PRESTO
kawahara@akg.t.u-tokyo.ac.jp

Tohru Asami
The University of Tokyo
7-3-1 Hongo, Bunkyo-ku,
Tokyo, Japan
asami@akg.t.u-tokyo.ac.jp

ABSTRACT
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.

ACM Classification Keywords
B.m. Hardware: Miscellaneous

Author Keywords
Instant Inkjet Circuits; Conductive Ink; Inkjet-printing; Double Sided Circuit; Via Hole; Drill/Needle.

INTRODUCTION
Multilayered circuit boards have been used for a long time in fabricating electronic devices. The advantage of the multilayered circuit is that it can reduce the complexity of the circuit routing. Additionally, in many circuit designs, it is impossible to wire without multilayered circuit support. Multilayered circuit is not simply stacking separated single circuits. It is necessary to have interconnections among these stacking circuits. The most popular method to connect layer-to-layer in multilayered circuit is to use via hole. Via hole is a mature technique which is regularly used in printed circuit board (PCB) fabrication.

UbiComp '15, September 7–11, 2015, Osaka, Japan.

ACM 978-1-4503-3574-4/15/09...$15.00.
http://dx.doi.org/10.1145/2750858.2804276

For recent years, development of rapid prototyping tools for electronic circuits has brought researchers, makers, and hobbyists many powerful tools to fabricate electronic circuits [3, 8, 14, 18, 19]. Printing technology has been developed for decades to increase resolution, printing speed, deposit precision, etc. Nowadays, we can easily print large area with high resolution in a short time and at acceptable prices. Along with the development of printing technique, the emergence of the new conductive materials has made electronic circuit fabrication much simpler. In Instant Inkjet Circuits [18], it takes less than 1 minute to print a conductive pattern with a home available inkjet printer and sintering-free silver nano particle ink. The printed pattern is flexible, durable and can establish conductivity almost immediately right after printing. Instant Inkjet Circuits also has the advantage of low-cost in prototyping. It is stated in [18] that Instant Inkjet Circuits costs only about 5 US cents per meter for a 1mm wide trace. Many interesting applications have been proposed with the use of conductive inkjet ink in rapid prototyping [9, 12, 25]. A problem of the Instant Inkjet Circuits is that it supports only a single layer circuit board. In this paper, we will focus on the implementation of the double sided circuit for Instant Inkjet Circuits using via hole interconnections.

RELATED WORKS

Electro-plating PCB vias
For traditional PCBs, in order to fabricate multilayered 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 [30]. 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.

Conductive adhesive

Another approach to filling a via hole without involving in chemistry process is to fill it with conductive adhesives [7, 20]. 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.

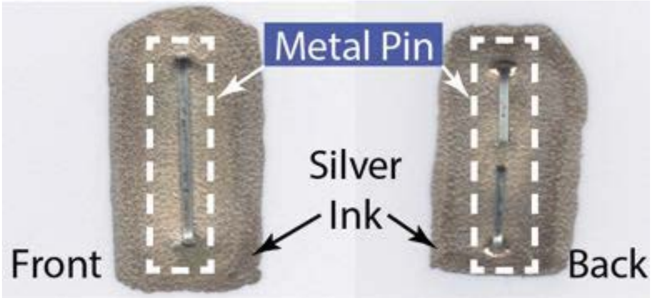
Silver nanoparticle ink and sintering

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 [11]. 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 [10]. 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.

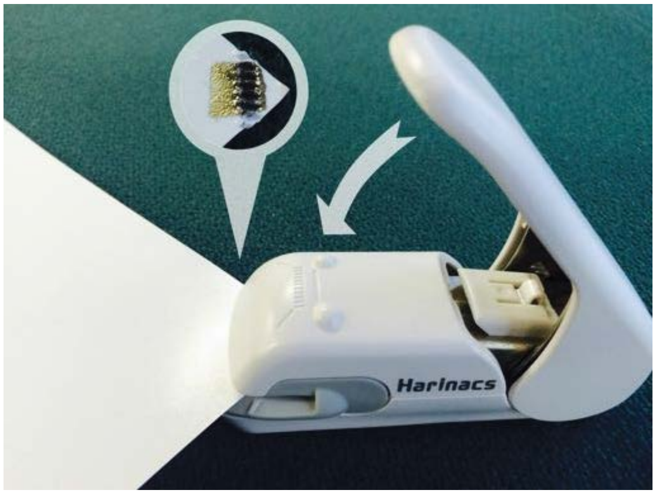
Silver nanoparticle ink and rivet

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 [2]. 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 nanoparticle 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



(a) Interconnection made by metal pin from an office stapler



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

Figure 1. Office supplies approach via hole

should be a full-automatic system with a specially designed computer-aided design software to print double sided circuits.

APPROACHES TO DOUBLE SIDED FLEXIBLE CIRCUIT IN INSTANT INKJET CIRCUITS

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 needleless 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 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 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 places where are closed to the edge of the substrate.

Via hole approach

As mentioned above, via hole has been long used as a solution for interconnection in the multilayered 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 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).

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 2). This type of paper shows great surface adhesiveness and conductivity with sheet resistance after printing, according to our measurement, is 0.56Ω/□ - ohm per square [1].

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 1. Comparison of approaches to interconnection for double sided circuits

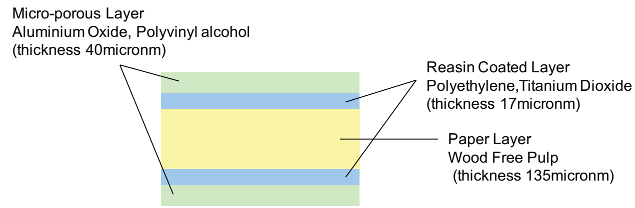
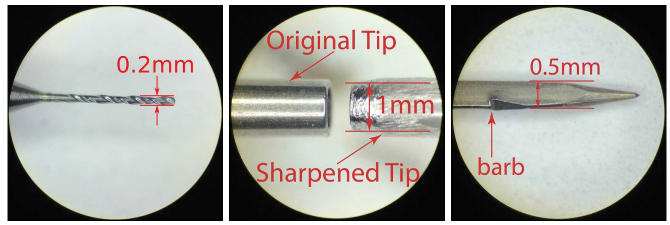


Figure 2. Structure of Mitsubishi Paper Mills' double sided paper



(a) Drill bit φ0.2mm, φ0.5mm, φ0.8mm **(b) Hole punch drill bit φ0.5mm, φ1mm** **(c) Triangular felting needle with barbs**

Figure 3. Hole opener

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 [17] with diameters φ0.5mm, φ0.8mm and Unimax Drill Bits C-UMD 2020-025 [29] with a diameter φ0.2mm (Figure 3 (a)).
- 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 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 [21] to open hole on paper substrate (Figure 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

[1]Ω/□ is the unit used to represent sheet resistance. This unit is dimensionally equal to an ohm. It is loosely thought of as "ohms per aspect ratio"

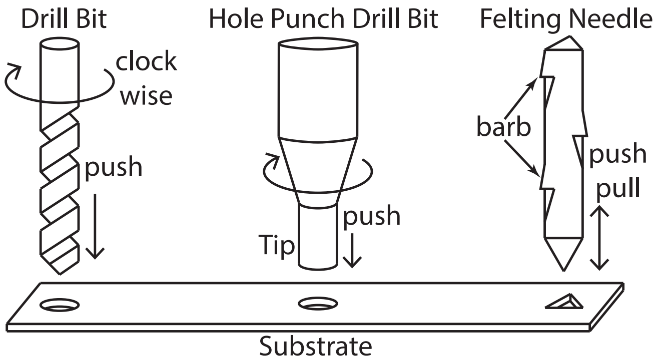


Figure 4. Hole open mechanism

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

(b) Ultra-sonic water humidifier

Figure 5. Ink filler and humidifier

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
- Humidity H = 20% $\sim$ 30%.
- Humidifier: moisture exposure is a well-known method to accelerate chemical sintering in Instant Inkjet Circuits [1, 18]. In our experiment, some samples, after hole opening and ink filling, will be exposed to humidity (H $\approx$ 100%) generated by an ultra-sonic water humidity maker (Figure 5 (b)) for 5 minutes.

Conductive Ink

Silver nano particle ink with part number NBSIJ–MU01 from Mitsubishi Paper Mills [24].

Software

In order to control the amount of ink deposited by the printer, Gutenprint [13] driver version 5.2.10 for Fedora 20 operating system [26] 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 ink-jet 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 [5]. For each printing dot, pre-dithering and dithering algorithm in Gutenprint will decide the size of the droplet base on the input value of that dot [27]. 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 0.1 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).

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:

- 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 [15] (Figure 5 (a)) and an Epson WF-3011 [6] 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:

- 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)
- 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 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 [22]) 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 2. (○: 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.

EVALUATION

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 7). This conforms to common thought that the more silver nano particle ink we add, the better via hole conductivity.

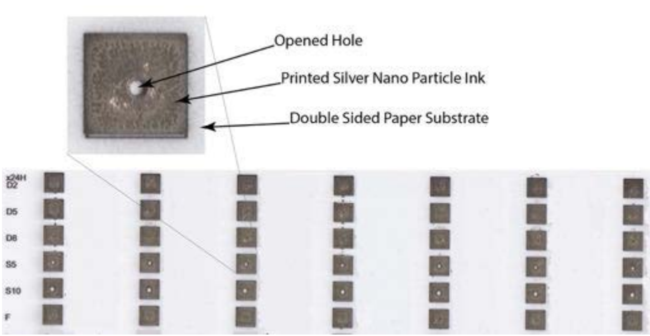


Figure 6. Samples on paper substrate after hole opening and ink filling

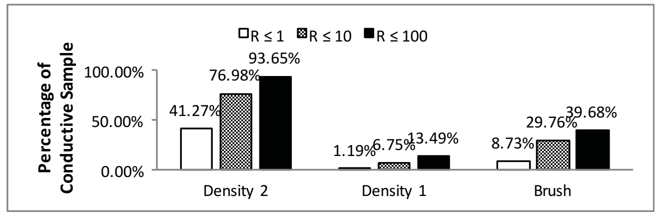


Figure 7. Percentage of conductive samples

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

Hole opener and via hole resistance

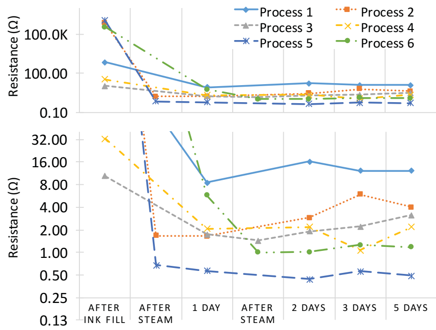
For each type of the sample, the median of 7 via holes will be used to plot the resistance graph as Figure 8.

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.

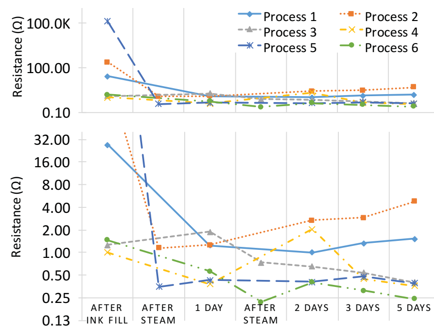
Although conductivity was not well established immediately, the resistance of all the samples has significantly decreased after exposing to moisture by the ultra-sonic water humidifier. This is an expected result as adding water is a well-known technique to accelerate the sintering process and improve the conductivity of the printed pattern [1, 18]. 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

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	○	○	○

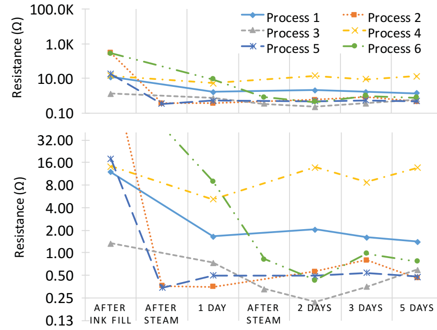
Table 2. Measurement schedule for different samples
○ - measure, × - skip



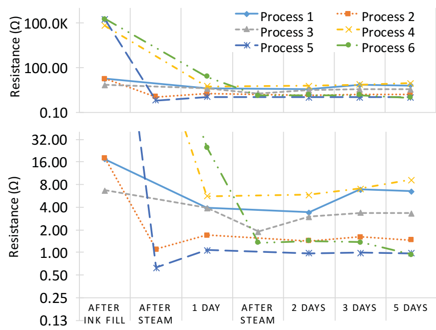
(a) Resistance of via holes made by ϕ0.2mm drill bit & print "Density = 2"



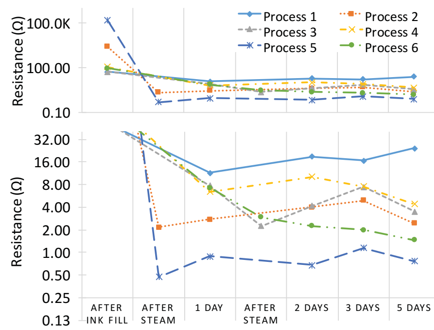
(b) Resistance of via holes made by ϕ0.5mm drill bit & print "Density = 2"



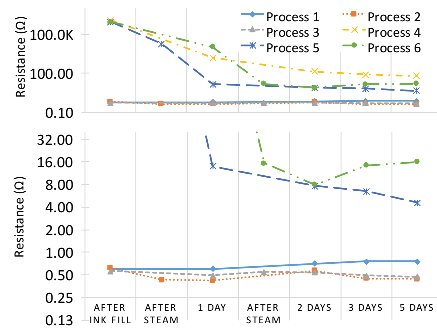
(c) Resistance of via holes made by ϕ0.8mm drill bit & print "Density = 2"



(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"

Figure 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 subfigure, *upper graph*: full logarithmic scale base 10; *lower graph*: zoomed-in to see small resistance values at logarithmic scale base 2

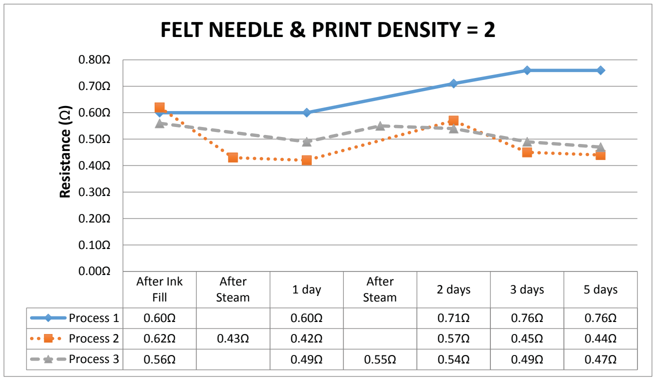
Process	Drill 0.2mm (Ω)	Drill 0.5mm (Ω)	Drill 0.8mm (Ω)	Puncher 0.5mm (Ω)	Puncher 1mm (Ω)	Felting Needle (Ω)
1	700	27	12	52	17.4	**0.6**
2	740K	230	300	2.5K	18	**0.62**
3	10.5	1.27	1.33	53.34	6.68	**0.56**
4	32.78	1	14.2	110	67K	1.3M
5	1.2M	137K	17.8	150K	170K	960K
6	366K	1.46	273	88.9	190K	930K

Table 3. Median values of resistance via holes made by different hole openers. Measurements were made immediately after printing with "Density = 2"

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.

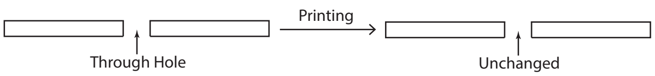
Results above were generally right for all samples (made by drill bits ϕ0.2mm, ϕ0.5mm, ϕ0.8mm, hole punch drill bits ϕ0.5mm, ϕ1mm, and felting needles). However, there were samples which consistently established conductivity right after printing with resistance $R < 1\Omega$. They are via holes made by the felting needles (Figure 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 3). 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 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

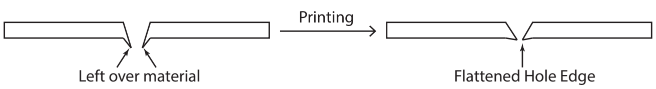


	After Ink Fill	After Steam	1 day	After Steam	2 days	3 days	5 days
Process 1	0.60Ω		0.60Ω		0.71Ω	0.76Ω	0.76Ω
Process 2	0.62Ω	0.43Ω	0.42Ω		0.57Ω	0.45Ω	0.44Ω
Process 3	0.56Ω		0.49Ω	0.55Ω	0.54Ω	0.49Ω	0.47Ω

Figure 9. Median value of resistances of via holes made by felting needle with printing "Density = 2", measured during 5 days



(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

Figure 10. Edge structure before and after printing

Process 1 is the simplest process but resistances of via holes are still low and stable.

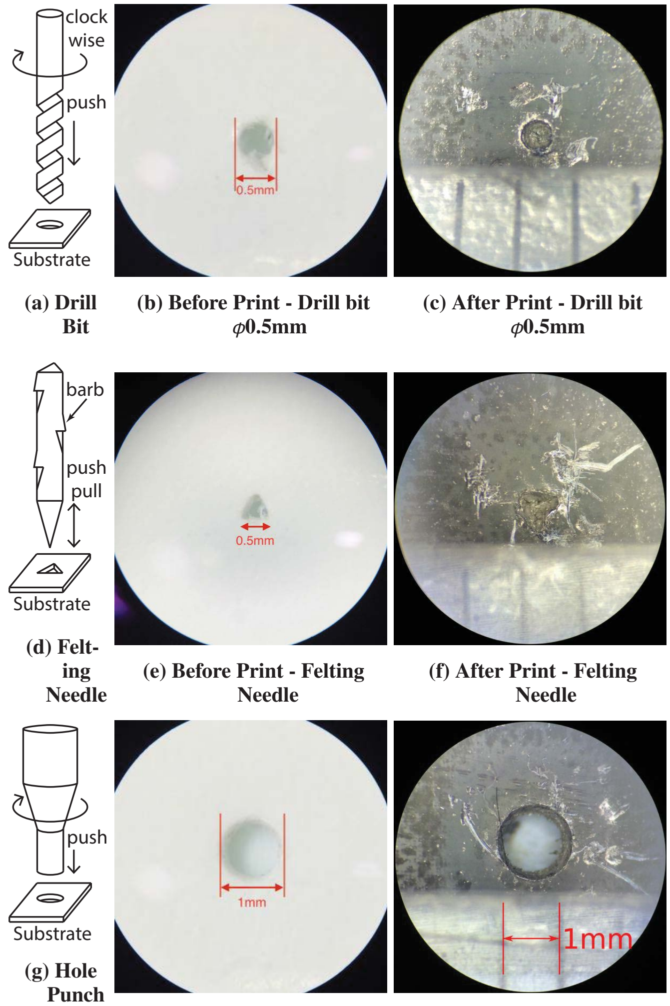
VIA HOLE STRUCTURE

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 and compared using an optical microscope.

Figure 11 are magnified images of via holes made by drill bits, felting needles and hole punch drill bits before and after printing.

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 10 (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



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

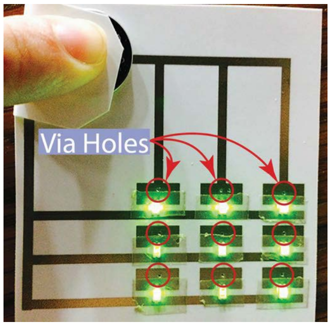
(d) Felting Needle **(e) Before Print - Felting Needle** **(f) After Print - Felting Needle**

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

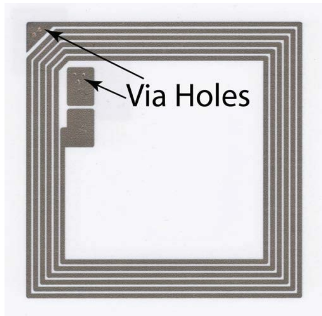
Figure 11. Via hole structure

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 (Figure 10 (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. 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.

Between drill bit via holes and felting needle via holes, our experiment showed that the via holes made by felting needles can give lower resistance. This is the result of the differences between structure of drill bits and felting needles. Along the body of a felting needle, there are tiny barbs that are better at entangling strands of coating material between 2 sides of

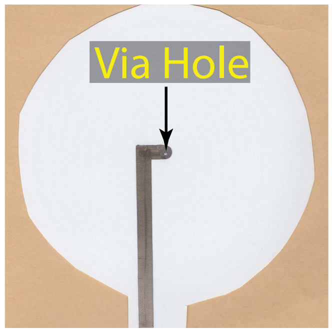


(a) LED matrix



(b) RFID coil inductor

(c) Speaker Coil - Front



(d) Speaker Coil - Back

Figure 12. Applications of double sided circuit

the paper substrate. These entangled strands will sinter the printed silver nano particle ink inside the via hole. More entanglement promises more thorough sintering which is an important factor to have better conductivity of the silver nano particle ink printed pattern.

APPLICATIONS

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 12 (a)).

Paper printed speaker

A paper speaker is an interesting application of electronic rapid prototyping [28]. 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 [28]. By using a via hole, the spiral coil can be wired inside-out through the other side of the paper substrate as Figure 12 (c), 12 (d).

Tunable RFID tag inductor

RFID tag has been widely used in the real life with many applications for near field communication. In order to miniaturize a tunable 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 12 (b) is a coil inductor for an RFID tag printed with Instant Inkjet Circuits and connected by via holes.

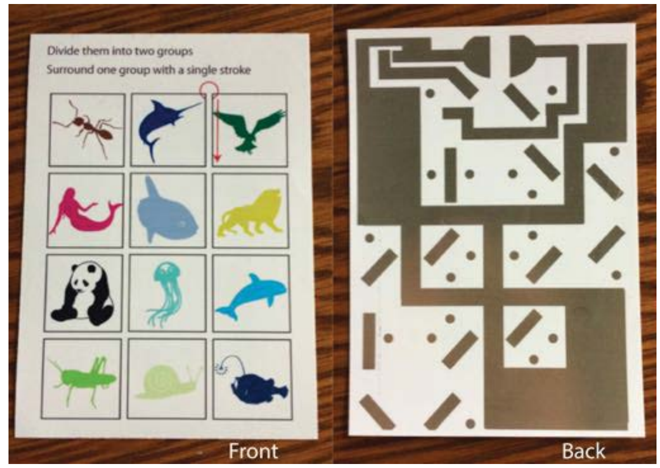


Figure 13. Hiding wiring on the other side of paper

Hide wiring pattern in artwork

One of widely used applications of Instant Inkjet Circuits is to create digital artworks like drawing electronic pictures, cards, paper works, etc. 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 other side will be used solely for artwork drawing. Figure 13 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.

DISCUSSION

Practical issues

By implementing via holes on the double sided paper, a double sided circuit can be easily fabricated with Instant Inkjet Circuits. After opened, the hole will be filled with conductive ink by an inkjet printer. However, as the printer used in Instant Inkjet Circuits is a home available inkjet printer, there is always misalignment of the printed pattern between 2 sides of the paper. 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.

Future works

In the future, we want to have a more detailed investigation on the characteristics of the via hole made by drill bits, hole punch drill bits and felting needles. Besides resistance which was evaluated in this paper, current load, parasitic capacitance and inductance are also important properties that need to be evaluated.

As for the hole opener structure, the felting needle has shown its best performance in making conductive via holes. However, in our experiment, we have just used only one type of the felting needle. By adjusting the arrangement of the barbs along the body, it is possible to optimize the felting needle structure for opening via holes on the paper substrate. Besides, we also aim at building a complete tool-set to fabricate double sided electronic circuit, starting with a low-cost entry level solution and going to develop an advanced solution.

Entry level solution - Handy Auto-Push Drilling Pen

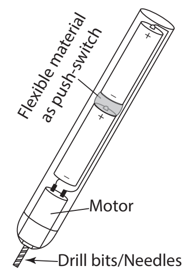
A handy auto-push drilling pen aims at hobbyists and makers who want to make a double sided circuit manually. A simple tweak to attach a drill bit or a felting needle to chuck of an electric eraser [4] will help to make hole opening operation more convenient and consistent (Figure 14 (a)). An additional push-switch can be added to the chuck of the electric eraser so that the user just needs to push the drilling pen on the paper substrate to open a via 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 applied as a quick-fix for a double sided circuit with a few drilled holes.

Automatic Double Sided Circuit Silver Instant Inkjet Printer

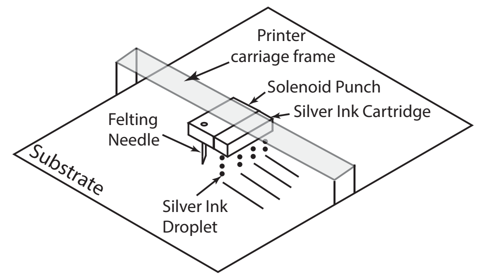
We are excited about finding some ways to integrate via hole making mechanism to an inkjet printer so that we can have a fully automatic double sided circuit fabricator using Instant Inkjet Circuits technology. This integration is possible if we can attach a solenoid mechanism with a felting needle to print head of the printer (Figure 14 (b)). Conductive pattern can be designed on any Computer-Aided Design (CAD) software which supports double sided and multilayered circuit design (e.g. EAGLE [16]). A modified driver might be required to print the CAD data with a home inkjet printer.

CONCLUSION

In this paper, 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.



(a) Handy auto-push via-hole making pen



(b) Fully automatic double sided circuit printer (combined with paper flipping mechanism)

Figure 14. Future plans of home-brew double sided circuit maker

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 drill bits, hole punch drill bits 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.
- Presented some applications that via hole has enabled us to easily make with the Instant Inkjet Circuits
- Pointed out a research direction to make a fully automatic double sided circuits fabricator with the Instant Inkjet Circuits.

We believe that a double sided circuit is the first step for us to implement a multilayered circuit with Instant Inkjet Circuits. Other users will find it easier to make more complex electronic circuits with the double sided Instant Inkjet Circuits.

ACKNOWLEDGMENTS

This work is a project in Core Project program of Microsoft Research. We would like to thank Microsoft Research Asia for providing generous supports to this research. We also would like to thank Mitsubishi Paper Mills for providing double sided photo paper - a remarkably important part of this research.

REFERENCES

1. Henrik Andersson, Anatoliy Manuilskiy, Tomas Unander, Cecilia Lidenmark, Sven Forsberg, and Hans-Erik Nilsson. 2012. Inkjet Printed Silver Nanoparticle Humidity Sensor With Memory Effect on Paper. *Sensors* 12, 6 (2012), 1901–1905.
2. Henrik A. Andersson, Anatoliy Manuilskiy, Stefan Haller, Magnus Hummelgard, Johan Siden, Christine

Hummelgard, Hakan Olin, and Hans-Erik Nilsson. 2014. Assembling surface mounted components on ink-jet printed double sided paper circuit board. *Nanotechnology* 25, 9 (2014). http://stacks.iop.org/0957-4484/25/i=9/a=094002

3. BareConductive. n.d. BarePaint. (n.d.). Retrieved July 22, 2015 from www.bareconductive.com.
4. Sakura Color Product Corp. n.d. Electric Eraser. (n.d.). Retrieved July 22, 2015 from http://sakuraofamerica.com/electric-eraser.
5. Seiko Epson Corporation. 2010. An Epson White Paper - Epson Micro Piezo Print Head Technology. (September 2010). Retrieved July 22, 2015 from http://www.epson.co.in/resource/mediacenter/technology_resources/white_papers/printer/Micro%20Piezo%20White%20Paper.pdf.
6. Seiko Epson Corporation. n.d. Epson WF-3011 printer. (n.d.). Retrieved July 22, 2015 from http://www.epson.co.th/epson_thailand/en/printers_and_all_in_ones/inkjet/product.page?product_name=Epson_WorkForce_WF-3011.
7. LPKF Laser & Electronics. n.d. LPKF ProConduct - Chemical Free Through Hole Plating. (n.d.). Retrieved July 22, 2015 from http://www.lpkf.com/products/rapid-pcb-prototyping/through-hole-plating/chemical-free.
8. ElectronInks. n.d. CircuitScribe. (n.d.). Retrieved July 22, 2015 from http://www.electroninks.com.
9. Karagozler Mustafa Emre, Ivan Poupyrev, Yuri Suzuki, and Gary K. Fedder. 2013. Paper Generators: Harvesting Energy from Touching, Rubbing and Sliding. In *Proc. UIST '13*. ACM Press, 23–30.
10. Tomasz Falat, Jan Felba, Andrzej Moscicki, and Janusz Borecki. 2011. Nano-silver Inkjet Printed Interconnections through the Microvias for Flexible Electronics. In *Proc. IEEE-NANO*. IEEE, 473–477.
11. Eric K. W. Gan, H. Y. Zheng, and G. C. Lim. 2000. Laser Drilling of Micro-Vias in PCB Substrates. In *Proc. EPTC*. IEEE, 321–326.
12. Nan-Wei Gong, Jurgen Steimle, Simon Olberding, Steve Hodges, Nicholas Edward Gillian, Yoshihiro Kawahara, and Joseph A. Paradiso. 2014. PrintSense: A Versatile Sensing Technique to Support Multimodal Flexible Surface Interaction. In *Proc. CHI '14*. ACM Press, 1407–1410.
13. Gutenprint. 2014. Open Source Printer Driver Gutenprint 5.2.10. (20 May 2014). Retrieved July 22, 2015 from lhttp://gimp-print.sourceforge.net.
14. Steve Hodges, Nicolas Villar, Nicholas Chen, Tushar. Chugh, Jie Qi, Diana Nowacka, and Yoshihiro Kawahara. 2014. Circuit stickers: peel-and-stick construction of interactive electronic prototypes. In *Proc. CHI '14*. ACM Press, 1743–1746.
15. AgIC Inc. 2014. AgIC Marker. (2014). Retrieved July 22, 2015 from http://agic.cc/en.
16. CadSoft Inc. n.d.a. EAGLE Computer-Aided Design. (n.d.). Retrieved July 22, 2015 from http://www.cadsoftusa.com.
17. Tamiya Inc. n.d.b. Tamiya Ultra-Fine Drill Bits. (n.d.). Retrieved July 22, 2015 from http://www.tamiyausa.com/items/tools-accessories-80/tools-74000/fine-drill-set-74044.
18. Yoshihiro Kawahara, Steve Hodges, Benjamin S. Cook, Cheng Zhang, and Gregory D. Abowd. 2013. Instant inkjet circuits: lab-based inkjet printing to support rapid prototyping of UbiComp devices. In *Proc. UbiComp '13*. ACM Press, 363–372.
19. Yoshihiro Kawahara, Steve Hodges, Nan-Wei Gong, Simon Olberding, and Jurgen Steimle. 2014. Building Functional Prototypes Using Conductive Inkjet Printing. *Pervasive Computing* 13, 3 (2014), 30–38.
20. Ryszard Kisiel, Artur Markowski, and Marcin Lubiak. 2002. Conductive Adhesive Fillets for Double Sided PCBs. In *Proc. POLYTRONIC*. IEEE, 13–16.
21. Clover Mfg Co. Ltd. n.d.a. Needle Felting Tool Refill Needle (Heavy Weight Needle). (n.d.). Retrieved July 22, 2015 from http://www.clover-mfg.com/pdf_en/Needle-Felting-Tools_En.pdf.
22. Changzhou Tonghui Electronic Co. Ltd. n.d.b. TongHui TH2821 Portable LCR Meter. (n.d.). Retrieved July 22, 2015 from http://www.globalmediapro.com/att/a/2/6/c/a26cn0/th2821.pdf.
23. Kokuyo S&T Co Ltd. 2014. Harinacs Press. (9 October 2014). Retrieved July 22, 2015 from http://techon.nikkeibp.co.jp/english/NEWS_EN/20141009/381577/.
24. Mitsubishi Paper Mills. 2013. Silver Nano-particle Ink NBSIJ–MU01. (2013). Retrieved July 22, 2015 from http://www.k-mpm.com/agnanoen/agnano_ink.html.
25. Simon Olberding, Nan-Wei Gong, John Tiab, Joseph A. Paradiso, and Jurgen Steimle. 2013. A Cuttable Multi-touch Sensor. In *Proc. UIST '13*. ACM Press, 245–254.
26. Fedora Project. 2013. Fedora 20. (17 December 2013). Retrieved July 22, 2015 from http://docs.fedoraproject.org/en-US/Fedora/20/html/Installation_Guide/index.html.
27. The Gutenprint Project. 2003. The Developers Guide to Gutenprint. (7 November 2003). Retrieved July 22, 2015 from http://gimp-print.sourceforge.net/gutenprint-developer-manual.pdf.
28. High-Low Tech. n.d. Paper Speakers. (n.d.). Retrieved July 22, 2015 from http://highlowtech.org/?p=1372.
29. Union Tool. n.d. Unimax Drill Bits C-UMD 2020-025. (n.d.). Retrieved July 22, 2015 from http://www.uniontool.com/cgi-bin/pdfs/metalworking/c-umd.pdf.
30. Ming-Yao Yen, Ming-Hung Chiang, Hsu-Hsin Tai, Hsien-Chang Chen, Kwok-Wai Yee, Crystal Li, Elie Najjar, Mark Lefebvre, and Betty Xie. 2013. Advanced Thin Copper Electroplating Process for HDI Microvia Filling Application. In *Proc. IMPACT*. IEEE, 245–250.