Tweaking Printer Driver for Improved Conductivity in Instant Inkjet Circuits

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Abstract

We have proposed "Instant Inkjet Circuits" that allows users to print circuits using a home inkjet printer. The benefits of using this technique were the cost effectiveness, widely available toolset and very short time of fabrication. However, default setting of an inkjet printer can only print less complex circuits. Without controlling the printing process, it is hard to improve the performance of the printed circuit/pattern. For example, the sheet resistance of printed pattern, which was reportedly about 0.19 ohm per square(Ω/□)[1], has limited the performance and the usage range of this technology. For instance, we have been using an inkjet printed antenna in researching of Wireless Power Transmission for a long time. However, the resistance of 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 this paper, we improved the conductivity by over-printing. We tweaked the open source printer driver named Gutenprint which can be used in many ink-jet printer brands. In addition to over-printing, we also adjust the printing density to see how the sheet resistance changes. According to our measurement results, the sheet resistance of ten times overprinted pattern was successfully decreased to 0.043Ω/□.

1 Introduction

There are several ways to control the behavior of a printer. First one is trying to modify the hardware of the printer. This seems to be very hard and may endup with making a new printer. In this case, the development and testing will be troublesome and costly. Second thought is modification 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 applicable range. Normally, neither hardware or firmware modification could be applied to a printer brand other than the one on modifying. That means, a modification on Canon printer, probably can not be applied to a Epson printer. In order to overcome these, an easier method is to modify the driver used to control printer on OS level. Gutenprint is one of best candidate to do this. Gutenprint is an opensource driver used to control hundreds of popular ink-jet printer brands like Epson, Cannon, Brother etc.

With some small changes inside Gutenprint driver, we realized overprinting - a technique help to improve conductivity of the printed pattern. By common sense, when the thickness of a printed pattern is doubled, its resistance will be halved. According to our previous result[1], when printing a solid pattern of rectangle with dimension of 1.5mm x 150.0mm, the sheet resistance can be calculated by the formula $R_s = RW/L$ where R is the measured resistance in Ω and W and L are width and length of the pattern. Printing this pattern on photo paper with silver nanoparticle ink will give the lowest sheet resistance of 0.19Ω/□[1]. Previous work also mention about how to reduce the sheet resistance by reprintting the pattern. However, this re-printing, in which the paper is re-fed back to the paper tray for re-printing the same pattern again, results in misalignment of the print (about 0.5mm). This narrows the use of this technique in "wider traces"[1]. Our overprinting technique helps to decrease sheet resistance without any misalignment.

In this paper, we will introduce modification of Gutenprint in order to realize overprinting without re-feeding the paper after printing. Thus, we can overprint multiple times without making misalignment on the print. We see this modification as the first step to "hack" a commodity home inkjet printer and use it as a substitute of expensive "material printer." In addition to over-printing, printing density is also a factor which affect the conductivity. By trying to adjust the printing density, we hoped to improve printed pattern conductivity without too many times of over-printing.

2 Related works

Conductivity has always been the big problem in printing antenna[3]. In the paper at [3], the authors using silver nanoparticle 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 work was using laser to sinter the silver nano-particle ink pattern. The conductivity has been improved but the minimum sheet resistance was still 0.16Ω/□[4]. Moreover, this method needs the involvement of laser which is quite troublesome. A known technique for accelarating the chemical sintering process of silver nano-particle ink and improving its conductivity is trying to add water by exposing the printed pattern to a high humidity[1]. This is good technique and we will use it in addition to our proposed method. In the same paper[1], overprinting by refeeding paper has been proposed. The conductivity was improved, however, there was misalignment (0.5mm)[1] in printed pattern between each time of printing. In our work, the conductivity will still be improved without any misalignment.

3 Over-printing Implementation

In our experiment, we used the newest version of Gutenprint (version 5.2.9) and an Epson printer - EP-905A. The reason we chose this model is that it was easy to buy at that time and Gutenprint supports this printer. 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 1).

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 serveral times, over-printing will be realized. We will 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 the behavior of printer is `escp2-driver.c`. In this file, function `void stpi_escp2_flush_pass()` will continously send printing commands to the printer. Since this

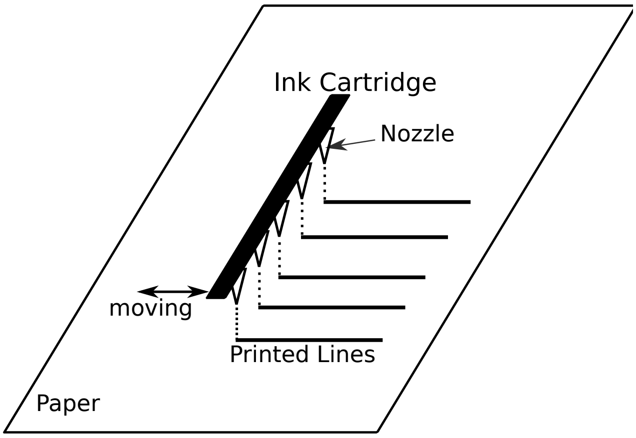

Figure 1: Inkjet printing mechanism

function controls the commands 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:

Listing 1: Overprint - function `stpi_escp2_flush_pass`

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

    ...
    // command 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;
    }
  }
}
```

Here, the struct `stp_vars_t *v` contains all the settings of the printer. The value of oveprinting time was set to variable `overprint` in this struct by user through another GUI function which is not neccessary 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 (set by user).

4 Improving Conductivity of Ink-jet Printing Silver Ink Pattern

4.1 Measurement Parameter

There are many factors that affect the conductivity of the silver nanoparticle ink printed pattern like the properties of media, substrate used in media, quality of the ink, the connectivity of silver nanoparticles, the thickness of the printed pattern. Here, we focused on the thickness of the pattern and the connectivity among silver nanoparticles. These 2 factors can be improved by overprinting technique introduced above and by adjusting printing density. Experiment environment

- Printer: Epson EP-905A
- Driver: Gutenprint-5.2.9 - modified to implement overprinting
- Media: Mitsubishi Photo Paper - NB-RC-3GR120
- Silver nanoparticle ink: Mitsubishi Silver Nanoparticle Ink NBSIJ-MU01
- Printed pattern: horizontal rectangle size 1.5mm x 150mm as Figure 2

Figure 2: Printed pattern used to measure sheet resistance

4.2 Over-printing Measurement Result

After printing, we immediately measured the sheet resistance of the pattern without steaming, the data showed that it was very high for 1 and 2 times overprinting or even non-conductive in case of 4, 6, 8, 10 times of overprinting. The reason of this was that after printing, the whole silver nano particle is not fully connected. As a result, the conductivity was decreased. To solve this, we have exposed the printed pattern to moisture. This is a known technique for accelerating the process of chemical sintering by adding water[1]. For each case of overprinting time, we exposed for 75 minutes and measure the sheet resistance immediately after steaming. Figure 3 shows the change of sheet resistance (coresponding to the overprinting time of 1, 2, 4, 6, 8, 10 times) after exposing to moisture for 75 minutes. The sheet resistance was signicantly 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 that the neccesary 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.

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." When overprint for 6 times, the deposited silver nano particle ink has reach the state of almost fully connected. 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 will increase serveral days after printing. Figure 4 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.

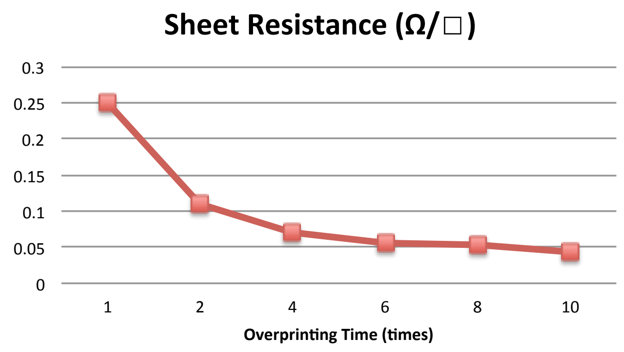

Figure 3: Change of sheet resistance depends on number of overprinting time

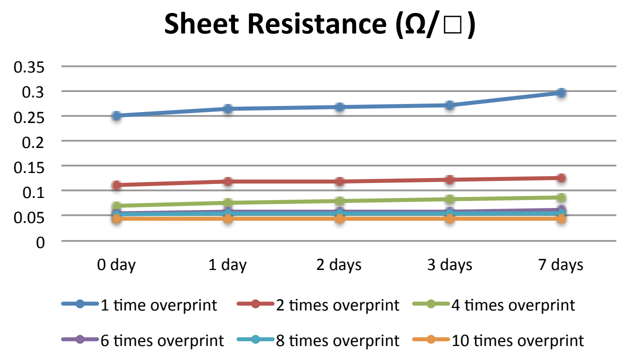

Figure 4: Change of sheet resistance after several days

4.3 Density Adjustment Measurement Result

The printing density decides the quantity 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. Base on this, we have make the experiment to see the change of sheet resistance in responding to the change of printing density.

Density Adjustment without Overprinting In this experiment, we tried to confirm the effect of printing density adjustment on sheet resistance. The pattern at Figure 2 would be printed once (no overpint) 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 serveral minutes.

The blue line in Figure 5 is the change of sheet resistance after moisture exposure. The sheet resistance decreased from 0.25Ω/□ (value from previous experiment - without adjustment of density) to 0.15Ω/□ when printing density is 1. It continued to decrease to 0.085Ω/□ for printing density of 8. This proved that the printing density adjustment did help to increase the conductivity of silver nano particle ink pattern.

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 sometimes may take 30 minutes for 10-time-overprinting. In this time experiement, 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 2 would be overprinted for 2 and 3 times. For each case, we tested the pattern's conductivity with different value of printing density parameter (1, 2, 4, 6 and 8).

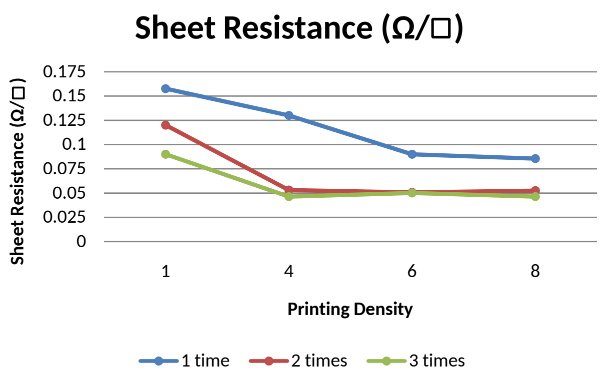

Figure 5: Change of sheet resistance depends on Density and Overprinting time

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 give 0.05Ω/□. 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.

4.4 Discussion

As we stated above, overprinting can help to improve the conductivity of silver nanoparticle ink printed pattern. The more we overprint, the better conductivity we get. Thus, this technique allows ink-jet printer to be applied in antena or very low power circuit fast prototyping. Besides, the realizing 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 have confidence on much more complex modifications and interesting applications of ink-jet printer in *in-lab prototyping*.

5 Conclusion and Future Work

In conclusion, our work in this paper was trying to modify open-source ink-jet printer's driver - Gutenprint. We consider this as a first step to transform a home used ink-jet printer to a farbrication machine. Using the modified driver, we have tried to improve the conductivity of silver nanoparticle ink printed pattern. The result was very good when the sheet resistance was reduced to a stable value of 0.043Ω/□. Not stopping at adjusting the number of overprinting time parameter only. Using Gutenprint, we have also adjusted the density parameter, which decide the ink's drop size, to improve the conductivity without increasing number of overprinting time. Thus, the printing time will be shortened (about 3 times shorter than overprinting only).

In the future, we will solve overprinting's weak points. Current overprinting method has a weak point that when we overprint a large pattern, there will be a lot of ink deposited at the same place. Since there are too much ink, the pattern will not get dried while comming out of the printer. We have a plan to put a small "heater" into the printer so that the ink will be heated while printing. Another weak point of current overprinting method is that after overprinting, pattern needs to be exposed to moisture for accelerating the chemical sintering - which make the pattern conductivity. It would be nice if we can put some moisture in the pattern while printing. In order to do that, an premise option will be to load an ink tank with water and use it to put moisture into the pattern.

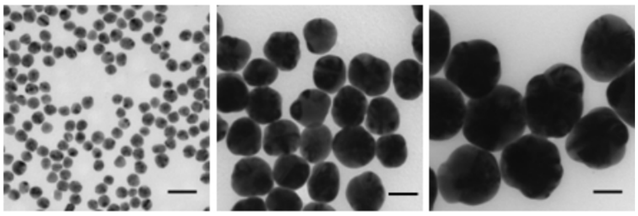

Figure 6: Silver nano-particles[2]

Along with solving weak points, we will try to implement a mechanism that allows ink-jet printer to print multiple circuits/patterns on a same media surface. This can be realized by loading an isolation material into an ink tank and use it to isolate different circuits. Currently, beside of repeating printing commands for overprinting, we could already assign ink tank to each printing command so that each command can use different ink color to print. Therefore, we believe that it is possible to print multi-layered circuits and make the laboratory *rapid farbrication* even faster and cheaper.

Appendix A

In 4.2, we have mentioned why the sheet resistance did not decrease drastically after overprinting too much (more than 6 times). Theoretically, if we double the thickness of a conductive pattern, its resistance will be halved (or its conductivity will be double). However, this did not happen in our experiment. The reason is that overprinting twice does not guarantee to double the thickness of the pattern. When printed, the silver nano particles is not fully connected. It looks like that there are some distances among silver nano particles[2] (Figure 6), and these distances decrease the conductivity of the pattern. In order to lower the affection of this problem, a technique was trying to add water by steaming the pattern after printing. This technique has worked very well until it reached its limitation and the conductivity did not increase further. Overprinting technique has solved this limitation by adding more ink into the printed pattern. This technique does not only increase the thickness of the printed pattern but also decrease the distances among silver nano particles, thus, increase the chance that these particles are connected by moisture exposure.

Appendix B

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

Overprint Time	Moisture Exposing (min)	Minimum Sheet Resistance (Ω/□)
2	45	0.1
4	75	0.072
6	75	0.055
8	75	0.053
10	75	0.043

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