Printing functional low-cost micro devices with 45-micron wide lines using a hacked desktop printer

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***Abstract*— Functional micro devices with a 45 micron line-width were printed using a low-cost desktop printer for the first time. Modified software and hardware were used to access individual nozzles of the printer. The printed devices were made out of silver nanoparticle ink. The optimization for continuous lines was done for the following parameters: substrate surface energy (contact angle), temperature for sintering, cooling rates for continuity of lines. The software and hardware of the printing process were further developed to print various 2D micro heater devices. The resistivity of the printed and sintered silver lines were found to be 13.5 times and 17.5 times of their bulk value on hydrophilic and hydrophobic substrates respectively. A temperature increase of 60°C of the micro-heater is also demonstrated.**

Keywords—silver nanoparticles; micro devices; inkjet printing; micro heater; sintering; substrate; conductivity; contact angle.

I. INTRODUCTION

Additive manufacturing by printing materials is becoming ubiquitous for bottom-up approach of making devices including micro electro mechanical systems (MEMS) based sensors and actuators [1]. These devices are more reliable compared to their macro models. When compared to traditional fabrication methods, additive manufacturing by printing reduces the fabrication costs, is more flexible, and prototype friendly. For the reasons mentioned, scientists worldwide try to find out a simple and low-cost method to produce MEMS. To produce MEMS by inkjet printing, nanoparticle ink is printed in the desired format and sintered to fuse the nanoparticles to obtain desired reproducible characteristics [2].

Currently a certain amount of micro-drop printers exists, but the resolution of these printers is too low to be able to produce micro devices [3]. On the other hand, Fujifilm [4] has achieved smaller sized droplets in the range of 1-35 picolitre, but these printers are rather expensive($54500) when compared to the desktop printer(€50) used in this work.

The software of a low-cost commercial desktop printer (EPSON XP-235) has been hacked to access individual printhead nozzles [5]. An attempt to integrate y-motion into the printer was also made [6,7]. Eventually, it was possible to control individual nozzles by external electrical signals, and a stand-alone printhead with x-y-motion system was built to allow printing 2D shapes [8]. The system still needed to be modified to be able to print functional micro devices. Firstly, the electrical signals were not of an appropriate shape to actuate the piezos of the nozzle in a reproducible manner. Secondly, the printhead purged at the beginning, after every 90 droplets and at the end of printing, which made it impossible to print shapes involving more than 90 droplets of ink.

In this work, we addressed the second problem. Functional micro devices were printed and tested with a line width of approximately 45 μm, using a low-cost commercial printer. This is the first time ever to print such small lines with a low-cost desktop inkjet printer. Initially, the parameters for printing optimum lines and the sintering parameters were experimentally determined. Then the thermal stresses caused by cooling down after sintering were studied. The printed patterns were characterized using white light interferometry and the conductivity was measured by four-point-probe method. Finally, we designed and printed various micro scale devices. They were characterized for their electrical and thermal properties.

This research has been done in the context of a Bachelor End Project (BEP) at the department of Precision and Micro systems Engineering by a group of 4 third-year Bachelor students.

II. MATERIAL & METHODS

During the entirety of this research, numerous materials were used in order to get the various experiments to work. These materials and methods are summed up below.

A. Printing silver nanoparticle ink

For the line morphology a hacked desktop Epson Expression Home XP-235 printer and Metalon JS-B25P silver inkjet ink were used to print lines on untreated soda-lime microscope glass substrates with a constant droplet size (average of 50μm in diameter). In order to get relevant conductive lines, experiments were done varying the droplet spacing in the range of 20-30% of the droplet diameter resulting in continuous lines with evenly distributed particles. After printing, the samples were visually inspected using a Omax trinocular metallurgical microscope and then sintered. The substrate was sintered at 260°C [9] for 10 minutes on a preheated Stuart US150 hotplate, but further in the research the sintering parameters were changed for better results. To decrease the line width, the substrate was treated with trichloro(octyl)silane to form a surface assembled monolayer of silane molecules and increase hydrophobicity. The line length, thickness, and width were then determined using the Bruker white light interferometer GTK1-10-096. It was also used to make 3D models of the line as well as determine the contact angle of the silver ink droplets on both clean and hydrophobic substrates.

Four-point-probe method was used to measure the resistivity of thin sheet materials which helps to eliminate contact resistance. These measurements were done using a Signatone SP4 four-point-probe, a Keithley 2400 Sourcemaster to regulate the current and a Keithley 2182 NanoVoltMeter to measure the voltage drop. As the line width was too small to physically place the probe points on the line, four 18 nm thick Au/Pd electrodes were sputter coated on the glass sample[7] so that contact with the line was made. With the current and voltage drop known, the resistance was measured using ohm's law. When the cross-sectional area of the line and the distance between the probes is known, then the resistivity can be calculated as well

B. *Printer hardware modification:*

The hardware used is from the previous BEP group[5,8], but it still needed to be modified to be able to print different 2D designs. The purging problem was solved by blocking the print signal at the moment of purging using a mechanical switch at the purging station.

Another mechanical end-switch was placed on the opposite side of the purging station. It was used to improve the synchronization between the x-y-motion system and the printhead control program. This sensor is responsible for the motion stage going to the next printing position.

C. *Printing and testing functional devices*

After the lines for both clean and hydrophobic substrates were optimized in order to be both continuous and conductive, multiple heater designs were made in fusion with G-code and interpolated in a python code to achieve the needed drop spacing. An experimental setup was made for measuring the temperature change and the resistance of the devices. The setup consisted of a Thorlabs 30cm x 30cm breadboard with a 3D printed sample holder, and a total of four probe needles. In this setup the four-point-probe measuring method was made using the probe needles on the micro heater. The current was provided by a Keithley 2400 Sourcemaster, the voltage drop was measured using the Voltcraft VC860 Multimeter and the temperature change was measured using a FLIR A35 thermal camera. Multiple loading cycles were used to eventually reach the saturation point of the heater, resulting in its resistance not changing anymore.

III. Results

A. *Line morphology:*

1) *Uniformity of the printed lines:*

In order to obtain uniformly printed lines, many lines were printed on various substrates with different droplet spacings. To explain the behavior of the printed lines, a dimensionless quantity is desirable. In this case, the droplet spacings are given in terms of physical radius and dimensionless quantity, the y-ratio [10], which is the ratio of droplet spacing to footprint radius.

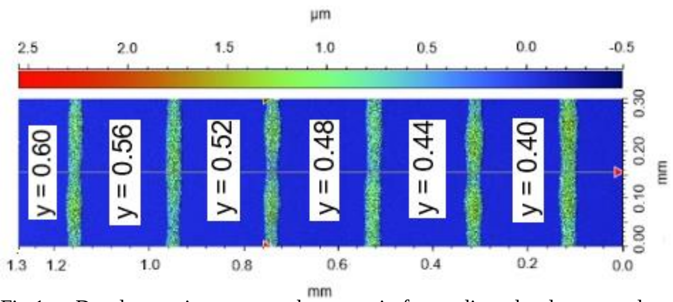

Fig.1. Droplet spacing expressed as y- ratio for medium droplets on a clean substrate.

Fig. 1 illustrates the lines that have been printed on clean glass with different y-ratios. It is shown that the uniformly printed line has y-ratio of 0.48. For hydrophobic glass, uniform lines have been achieved for a y-ratio of 0.91. The receding values of the y-ratio can be used if the same ink and substrates are used. The uniform line needs to be continuous in order for it to be conductive.

2) *Printed line dimensions:*

Many droplets were printed and characterized by white light interferometry resulting in an average contact angle of $4.62° \pm 0.86$ for a clean glass substrate, and $82.6° \pm 0.80$ for a hydrophobic substrate. As a result, the line width printed with the optimum y-ratio for both clean and hydrophobic glass were approximately 70µm and 40µm respectively.

3) *Sintering:*

After achieving continuous and uniform lines, sintering was still needed in order to obtain conductive lines. The previous BEP groups recommended to sinter the samples on a 260°C hotplate for 10 minutes [9]. Unfortunately, these settings resulted in no conductivity. To achieve better conductive lines, discontinuities should be decreased, and thus by trial and error, an improved sintering time, temperature and cooling time was achieved:

- Hydrophobic glass: sintering at 250°C for 5 minutes, and cooling on the hotplate for 8 minutes when turned off
- Clean glass: sintering at 200°C for 5 minutes and cooling on the hotplate for 7 minutes

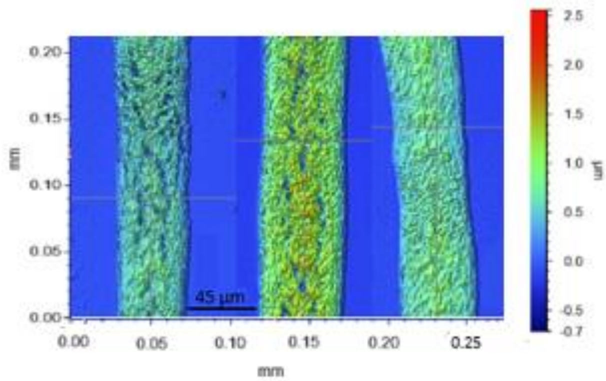

Fig. 2. Discontinuities in sintered lines, from left to right decreased cooling speed.

B. *Resistivity of the printed lines:*

Due to the thickness of the printed lines, the resistivity had to be measured using the four-point-probe method. Furthermore, two layers were needed for untreated glass substrate, as single layer printing did not show conductivity. The resistivity of the lines and their value compared to bulk resistivity value are given in the table below.

Table I. Line Resistivity

Substrate	Resistivity, ρ, $x10^{-7}$ (Ω·m)	Increase compared to bulk resistivity
Untreated glass, 2 layers	2.13±0.04	13.5 x
Hydrophobic	2.78±0.04	17.5 x

C. *Printing micro heaters:*

Depending on the previous printing parameters and after improving the x-y stand-alone motion system, it was possible to print various micro devices. Different heater designs were printed. Fig. 3 shows a spiral heater that was printed on a hydrophobic substrate with 0.91 y-ratio. The temperature measurements are shown in Fig. 4. But due to the reflection of different components this measurement was inaccurate so the experiment was only used for the measurement of the temperature difference which was unaffected by the reflection.

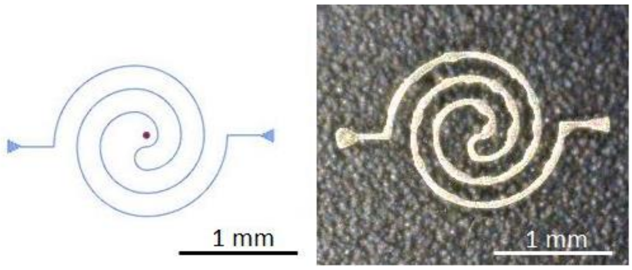

Fig. 3. Printed spiral heater and design.

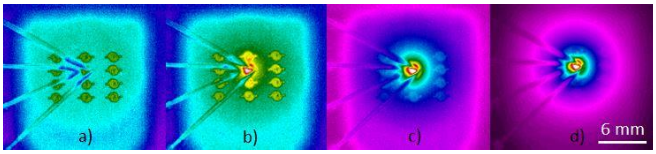

Fig. 4. Testing one of the 12 micro heaters, heating up, a) I=0mA, ΔT=0.0°C, b) I=15mA, ΔT=3.8°C, c) I=30mA, ΔT=14.9°C, d) I=50mA, ΔT=52.0°C.

D. *Thermal characterization and resistance measuring of printed heaters:*

In order to describe the thermal characterization of the printed heaters, nine spiral heaters were printed on hydrophobic substrates. After sintering, the heater dimensions could be determined by white light interferometry, resulting in a width of 44.7±2.50µm and a total length of 5.11 mm. Using the thermal camera, the thermal behavior of the printed micro heaters was characterized. The resistance and the associated difference in temperature was measured at various currents ranging from 5 to 50 mA with increments of 5 mA. Fig. 5 shows both the temperature difference and the increased resistance with increasing current for the average of the 9 heaters.

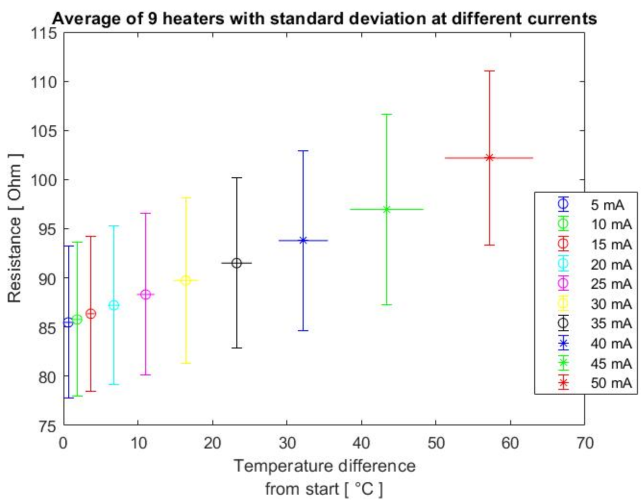

Fig. 5. Average of 9 heaters with standard deviation at currents from 5 to 50 mA with increments of 5 mA.

E. *Additional sintering by applying high current:*

After putting a current of 70mA through a micro heater the maximum temperature measured was around 160°C. This temperature was high enough to sinter the line and decrease the resistance of the heater. After three cycles of heating and cooling down, using a current of 70mA, the resistance did not change significantly anymore. This method of sintering resulted in a decrease of 16.3% in resistance.

F. *Parallel printing of multiple devices:*

The next challenge was to print multiple devices using multiple nozzles in parallel. At the moment of writing, only 30 nozzles can be controlled and therefore, as can be seen in Fig. 6, only 4 micro heaters could be printed simultaneously in 5 minutes and 35 seconds.

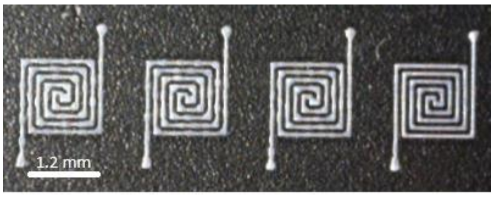

Fig. 6. Four micro heaters printed in parallel.

IV. DISCUSSION

A. *Printed line dimensions:*

In the case where the ink, the droplet size and the printhead height are constant, next to the droplet spacings that were determined earlier, the printed line width was still affected by the material used as a substrate. In other words, the deposited droplet will have a footprint diameter d_{con}, which is influenced by its initial diameter and the equilibrium contact angle θ_{eqm} between the ink and the substrate surface [10]. This relation is shown below.

$$d_{con} = d_o \sqrt[3]{\frac{8}{tan\frac{\theta_{eqm}}{2}\left(3+\tan^2\frac{\theta_{eqm}}{2}\right)}}$$

d_{con}*: the droplet* footprint diameter, θ_{eqm}: the contact angle, d_0: the initial droplet diameter.

The droplet footprint increases with decreasing contact angle and is approximately $3d_0$ at a contact angle of 10° [10].

B. *Discontinuity in sintered lines and thermal stress*

It was observed that thermal stresses, caused by rapid cooling, were the cause of the discontinuities. To understand the effect of the cooling speed of the printed tracks, samples have been cooled at different temperatures, very fast (-4 ºC), quite fast (room temperature at 22.3 ºC), and gradually cooled (temperature range from 250 ºC to 22.3 ºC). Fig. 2 illustrates that the samples that were gradually cooled down had the best form and less discontinuities.

The duration and the temperature of the whole process is critical. It should be enough for evaporation of the organic solvent (Ethylene Glycol) and adhesion between the silver nanoparticles to occur, but still be able to achieve small scale (approximately 45µm) printing, without flowing of the lines due to melting. Here the material of the substrate plays an important role. It takes more time before the silver nanoparticles start to flow if the substrate is hydrophobic because of the lower surface energy of the substrate [10].

Indeed, it was not possible to make an obvious relation between these parameters, but after plenty of experiments it was possible to achieve the ideal parameters that can be used if the same inks and the same substrates are used. After sintering, reprinting another line on top of the previous line, with the same parameters and sintering them again, was a good solution to achieve a conductive line on the untreated glass substrate. A single layer was not enough for conductivity. The diameter of the printed line on the clean glass substrate was approximately doubled when compared to the line printed on the hydrophobic substrate.

C. Repeatability printing on hydrophobic surface

It was not always possible to print continuous lines on the hydrophobic substrates. Instead of a line the NP ink sometimes formed large droplets. This issue prevented the research to run smoothly. There are many different variables that could be the reason of this issue, but at this point it is still unknown, so it could be a topic for further research. One of the reasons could be the room temperature, as one time when the room temperature decreased, it became possible to print on the hydrophobic substrate again. The other reason could be the concentration of the Ag nanoparticles in the ink. Namely there was noticeable difference in the samples printed using a recently filled ink cartridge and the one that was filled a few weeks earlier.

D. Stopping the printer from purging

The printer sends digital signals, through two data cables, to the printhead to select which nozzles need to print. A third digital signal is responsible for sending print commands for each nozzle. When the data signals are high(3.6V) at the moment a print command is send the corresponding nozzle print. When these signals are low(0V) the corresponding nozzle will not print. These signals are kept low using mechanical end-switches and pull-up resistors. Even though the printhead is not inside the printer, the carriage of the printhead still moves. When purging, the carriage moves to the purging station and the end-switches, one for each data cable, are placed inside the printer at the purging station only blocking the signals when purging and not during printing.

E. Parallel printing of multiple devices

The space in between two nozzles is 211 µm, at the moment of writing it is only possible to use 30 nozzles. So, the space between the first and the last nozzle is 29 x 0.211 = 6.119 mm. The total space divided by the width shows how many devices could be printed. The color row (90 nozzles) and the black row (90nozzles) have a distance of 3 mm. When it is possible to control all 180 nozzles and the length of the device is not bigger than 3 mm, it is possible to parallelly print even more micro devices. With the dimensions of the spiral from Fig. 3, this would be a total of 30 micro devices. For this purpose, a total of 4 cartridges of silver ink will be eventually needed.

V. Conclusion and Recommendations

Conductive lines were printed at a scale that has not been achieved before with desktop commercial office inkjet printers. The conductivity that was achieved was quite low when compared to a larger scale of printed lines, but it was a successful beginning for further research. The purging problem had been solved and the hardware system is now able to print more than 90 droplets. As a result, various rectangular and circular micro devices have been printed. In addition, the performance of these printed micro heaters was tested and documented as well. Finally, it was possible to print multiple devices in parallel.

For further research a higher conductivity is desired, this can be achieved by improving adhesion between the printed particles, a higher concentration of silver ink or using a ink which does not need sintering.

VI. Acknowledgment

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VII. Reference

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