Journal of Materials Science & Surface Engineering, 6(1): 739-742
ISSN (Online): 2348-8956; 10.jmsse/2348-8956/6-1.2

Rapid Prototyping of Flexible Printed Circuits and Printed Membrane Switches

Lutz Sommer . David Skopek

Albstadt-Sigmaringen University, Germany.

ABSTRACT

This study investigates the possibility to use low-cost desktop printed circuits as a replacement for conventional circuits. Firstly the authors examine whether such circuits which are fabricated with this technology and under laboratory conditions, withstand one million cycles of operation under real test conditions. Particular attention is being paid to the ability to print resilient electro-conductive traces and patterns onto flexible substrates such as PET, PC and PVC films and photo paper with low investment costs. Secondly, the authors examine the possibility to improve the printability of such circuits. It is demonstrated that it's possible to fabricate resilient membrane switches under laboratory conditions that exceed one million switching cycles under real conditions with this technology. Furthermore, the improvement of printability by plasma activation could be confirmed. Based on these results, the authors prove that an off-the-shelf desktop printer and available electro-conductive ink achieve remarkable results.

ARTICLE HISTORY

Received 18-09-2017
Revised 22-11-2017
Accepted 24-11-2017
Published 06-01-2018

KEYWORDS

Low-Cost printer,
Printed electronics,
Switches,
Conductive ink,
Circuits

Introduction

The subject of the work is the improvement of switches which are installed in control panels for lifts. Current push buttons have switching elements that are mounted on circuit boards and include a metal plate or a metal dome for switching (Interlift, 2015). An alternative concept is e.g. to use membrane switches for switching. Since the invention of the PCB from *Paul Eisler*, there has been continuous development with respect to printing technology, electro-conductive inks and paints and input options for electronic devices e.g. buttons and touch screens (Interlift, 2015); (BBSB, 2015); [1].For example, *Bare Conductive* (n.d.) uses electric paint to brush wires and sensors onto paper, wood, plastic, glass or textile fabrics connecting electronic components (e.g. a LED) with each other. In combination with their *Touch Board* the electric paint can also act as a capacitive sensor [2]. *Russo et al.* (2011) developed an electro-conductive silver ink for use in off-the-shelf roller ball pens [3]. These silver ink pens are used to draw directly traces and circuits on flexible substrates like paper. *Coelho, Hall, Berzowska* and *Maes* (2009) present a series of techniques for building circuit boards, sensors, actuators, emissive displays and silkscreened speakers by embedding electro-conductive inks and smart materials (e.g. LEDs and microcontrollers) directly and seamlessly into sheets of hand-made paper during the papermaking process [4]. G*ong, Hodges* and *Paradiso* (2011) apply a conductive inkjet technology to print onto a roll of flexible substrate. They use this technology to produce versatile and cost-efficient sensing surfaces with scalable length that is constrained only by the size of the roll. Some advantages of this method are the production of low-cost and large-surface-area printed capacitive sensors and various types of RF antennas [5]. A new approach which is barely discussed and considered for the manufacture of printed electronics is the embossed film printing also known as hot stamping[6]. In this process, metal is accurately vapor-deposited onto a foil carrier so that the metal particles are very close together and establish a homogenous conducting layer on the nanoscale [6].

Stempien, *Rybicki, Rybicki, Kozanecki* and *Szynkowska* (2015a) expose a method of deposition of intrinsically conducting polymers on different textile fabrics by reactive inkjet-printing. They assert that this method is very simple and can be carried out with electro-conductive, water-based inks [7]. Another research carried out by *Stempien*, *Rybicki, Rybicki* and *Lesnikowski* (2015b) addresses the production of a stable and printable, silver-based ink for inkjet printing of textile substrates. Using appropriate water-soluble inks enables sintering at low temperature under 90 °C during inkjet printing of textile [8]. The authors state that the surface resistance gradually recedes with each additional printed silver layer so that they achieved surface resistances from 0.155 to 0.622 Ω/sq. Moreover, the printed patterns have a good resistance to bending, flexing, washing and dry-cleaning [8]. *Kawahara, Hodges, Cook, Zhang, & Abowd* (2013) present a cheap, fast and accessible technology premised on inkjet printing for rapid prototyping of flexible PCBs and other functional electronic devices such as uniquely-shaped capacitive sensors and antennas. The authors emphasizes that there is, unlike other printing methods, no curing process with expensive and special equipment needed. The ink dries immediately after the printing process, when it was printed onto an appropriate substrate (e.g. coated paper). One of the prime insights of this work is the possibility to print electronics with conventional desktop inkjet printers along with electro-conductive inks for acquisition costs of round about US$ 300 [9]. However, Kawahara et al. (2013) noticed that the chemical sintering of silver inks and therefore the conductivity of the printed traces is strongly influenced by the surface roughness and the surface treatment, for example, coating. Based on the statement from Kawahara et al. (2013) it could be argued, that the quality of such a printed trace depends on the combination of these different variables. In other words, there is a need to test such combinations under special circumstances.

Corresponding Author: Lutz Sommer, Tel: (0049) 7571732953
Email: sommer@hs-albsig.de

Most of the existing research is based on laboratory test, which are helpful for developing laboratory prototypes. Beside such tests, it is also reasonable to test such printed traces under real conditions. The aim of the present paper is to test both. Hypothesis 1 deals with the influence of plasma activation on the printability of a surface:

Hypothesis 1: If a low-energy surface gets plasma activated, then not only the surface energy will increase but also the curing of silver inks that are printed onto the substrate will be significantly supported and accelerated.

Hypothesis 2 deals with the question of durability of such printed traces under real conditions. According to the recommendations of an internal standard for testing switches of a German manufacturer of switching elements [1] we pose the following hypothesis:

Hypothesis 2: If you use traces printed with a low-cost desktop printer as switching elements, then you can generate one million switching cycles with a piston force of approx. 32 N (= average) without any malfunctions.

Experimental

Method

For testing *Hypothesis 1* we used the following equipment: (1) DSA25 from Krüss: In order to determine the behavior of the different and partially surface pre-treated substrates regarding wetting and printability, the surface energies of each substrate was ascertained with the *DSA25* from Krüss. The test liquid, which was used for this, was distilled water. (2) Femto low pressure plasma system from Diener: Since untreated PVC and PC substrates turned out to be non-printable because of their very low surface energies, it was tried to modify and enhance the surface energies of these substrates by means of plasma pre-treatment. In this work, the plasma surface activation was carried out with a *Femto* low pressure plasma system from *Diener electronic GmbH+ Co. KG* using the settings which are listed in the Tables 1, 2 and 3.

Table 1: Applied settings for the plasma surface activation

Parameter	Setting
Process gas	Air
Gas flow	45 sccm
Treatment time	3 min
Performance	100%

Table 2: Tested substrates without plasma treatment

Substrate	Source
Circuit Paper, Circuit PET Film	AgIC
Photo paper	Bot Factory
Premium Photo Paper	Kodak
Novele	Nova Centrix
3G Clear PET, 3G White PET	Method Electronics

Table 3: Tested substrates before and after plasma treatment

Substrate	Source
3G Opaque PET	Method Electronics
Novele	Nova Centrix
Lexan 8B35	Krick
SK-M, White, Matt	
SK-M, White, High Gloss	
SK-MGK, Glossy	Renolit Contact
White, Matt	
White, High Gloss	

For testing *Hypothesis 2* we used the following equipment: (4) Switches: The membrane switches were printed with the *Brother MFC-J6710DW*. The membrane switch pattern was designed by using *Microsoft Word 2013*. The following Fig. 1 shows the design of the upper and lower switching layer of the membrane switch.

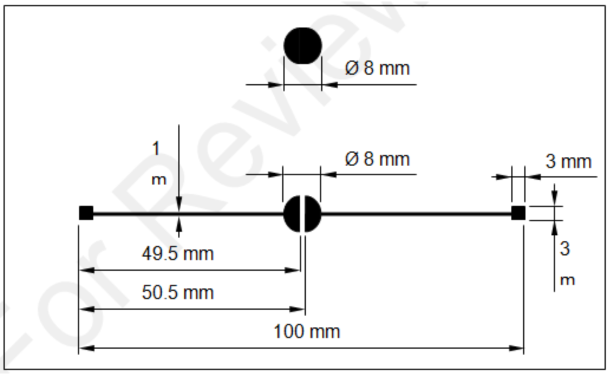

Figure 1: Design of the switching cycle test pattern (upper and lower layer)

Substrate: *Novele™* substrates from *Nova Centrix* using the following print settings recommended in the *AgIC Printing System Start Guide*. The recommended Brother print settings from AgIC (2016) are: Media Type "Brother Photo Paper BP61"; Print Quality "Best"; Color Mode "Active"; Orientation "Portrait". After printing the test pattern of the lower switching layer, two connecting wires were glued with the electro-conductive glue from *BotFactory* onto the contact pads of the pattern. The specimens were then put into a *MemmertS25* oven to cure the glue. In order to go easy on the substrates, the curing temperature was set to ca. 60 °C and the curing time to 120 minutes which is also recommended by BotFactory; (6) Ink: The AgIC Circuit Printer Cartridge Set were used. AgIC provided a Circuit Printer Cartridge Set whereby the silver ink has already been poured into a set of 3 *Brother LC71* (US) resp. *LC1240* (Europe) cartridges (yellow, cyan and magenta). For printing, the *Circuit Printer Cartridge Set* only had to be inserted in the *Brother* printer; (7) Switching cycle test: The membrane switches were then assembled and put into *a* test facility [1] which was used to determine the reachable switching cycles. The test facilities equipped with two short-stroke pneumatic cylinders (= Material number 0822406401 from *Aventics Rexroth Pneumatics)* with cylinder bore diameters of 12 mm, strokes of 10 mm and a maximum operation pressure of 10 bar.

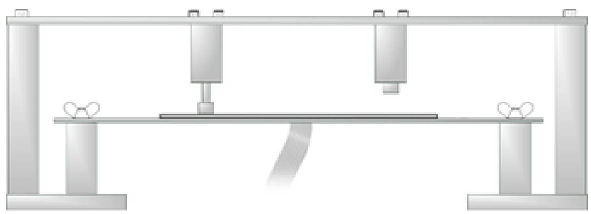

Figure 2: Test arrangement of the switching cycle test

In order to ascertain the switching cycles of the membrane switches, the internal company standards from *Schaefer* were adopted. For testing their electromechanical switches, *Schaefer* sets the pressure to 3 bar. From this value the measured piston force is approx. 32 N. The glued on connecting wires of the lower switching layers were connected with an Arduino Uno by way of two breadboards.

Results and Discussion

Hypothesis 1 deals with the question, whether it is possible to improve significantly the curing process of low-energy surfaces via plasma pre-treatment. For testing the *Hypothesis 1* we received the following results: The results of the measurement regarding the surface energies of substrates without plasma activation are listed in Table 4.

Table 4: Surface energy of the different substrates without plasma activation

Substrate	Contact Angle	Surface Energy
AgIC - Circuit Paper	47.29°	54.7mN/m
AgIC - Circuit PET Film	40.71°	66.3mN/m
BotFactory - Photopaper	31.47°	63.1mN/m
Kodak - Premium Photo Paper	30.68°	63.5mN/m
Method Electronics 3G Clear PET(enhanced adhesion)	02.67°	>72.0mN/m
Method Electronics 3G White PET (enhanced adhesion)	02.09°	>72.1mN/m
Method Electronics 3G Opaque PET (enhanced adhesion)	68.24°	42.4 mN/m
NovaCentrix - Novele™ (PET)	09.93°	>71.0mN/m
Krick - Lexan 8B35 Folie (PC) Velvet surface	86.82°	30.8mN/m
Krick - Lexan 8B35 Folie (PC) Matt surface	74.95°	38.1mN/m
Renolit Contact SK-M weiss, matt (PVC)	75.23°	38.0mN/m
Renolit Contact SK-M weiss, high gloss (PVC)	79.61°	35.2mN/m
Renolit Contact SK-MGK, 180 µm (PVC)	74.14°	38.7mN/m
Renolit Contact SK-MGK, 185 µm (PVC)	91.51°	27.9mN/m
Renolit Contact Weiss Matt, 185 µm (PVC)	75.82°	37.6mN/m
Renolit Contact Weiss Matt, 200 µm (PVC)	85.97°	31.3mN/m
Renolit Contact Weiss Hochglanz (PVC)	77.29°	36.7mN/m

Traces that were printed on substrates with surface energies lower than 43 mN/m didn't cure under ambient conditions. Hence, it was tried to support the curing on these substrates by increasing their surface energy via plasma activation. As shown in the Table 4, the surface activation of the substrates with low-energy surfaces achieved good results. It was possible to enhance the surface energy of each substrate by a clear margin. However, the plasma surface activation of the substrates didn't remain stable over time under our test conditions. Rather, as also shown in the Table 5, the surface activation vanished under ambient conditions after a couple of hours.

Figure 3 contains the measured resistances and calculated resistivities of traces which were printed with the *Brother* printer and the *AgIC Circuit Ink*. Only seven substrates, which were not plasma treated and still had surface energies higher than 50 mN/m, enabled the curing of the ink. The lowest resistivity with a value of 262.24 mΩ/sq. could be detected on the *NC Novele™* substrate after 15 min of curing. The printability of the plasma pre-treated substrates was investigated 48 hours after surface activation. Unfortunately, the treated substrates remained unprintable and the ink did not cure. Based on the results it could be concluded that Hypothesis 1, which deals with the question what happens when a low-energy surface gets plasma activated in regard to the surface energy and the curing of silver inks that are printed onto the substrate, is not confirmed. On the one hand, the surface energy was increased after plasma activation but only for a couple of hours; on the other hand the curing of the silver ink was still not significantly supported in our case. This indicates, that the quality of low-cost printed switches cannot be significantly improved by investments in low-cost plasma activation technology solely. In other words, the quality of low-cost printed membrane switches cannot be increased easily to the highest level with low investments. Adequate investments in pre and after treatment as well as an optimized process flow (e.g. process time) are key success factors in printing of membrane switches for professional use.

Table 5: Surface energy of plasma activated substrates

Substrate	Contact Angle & Surface Energy after plasma activation	48 hours later
Krick - Lexan 8B35 Folie (PC), Velvet surface	40.72° ≙58.4mN/m	61.35° ≙46.4mN/m
Krick - Lexan 8B35 Folie (PC), Matt surface	35.02° ≙61.4mN/m	55.84° ≙49.8mN/m
Renolit Contact SK-M weiss, matt PVC)	55.59° ≙49.9mN/m	68.19° ≙42.3mN/m
Renolit Contact SK-M weiss, high gloss	55.49° ≙50.0mN/m	65.16° ≙44.1mN/m
Renolit Contact SK-MGK, 180 µm (PVC)	38.74° ≙59.5mN/m	59.44° ≙47.6mN/m
Renolit Contact SK-MGK, 185 µm (PVC)	47.59° ≙54.6mN/m	63.55° ≙45.1mN/m
Renolit Contact Weiss Matt, 185 µm PVC)	52.89° ≙51.5mN/m	75.96° ≙37.5mN/m
Renolit Contact Weiss Matt, 200 µm (PVC)	49.30° ≙53.8mN/m	68.94° ≙41.9mN/m
Renolit Contact Weiss Hochglanz (PVC)	51.55° ≙52.3mN/m	67.19° ≙42.9mN/m

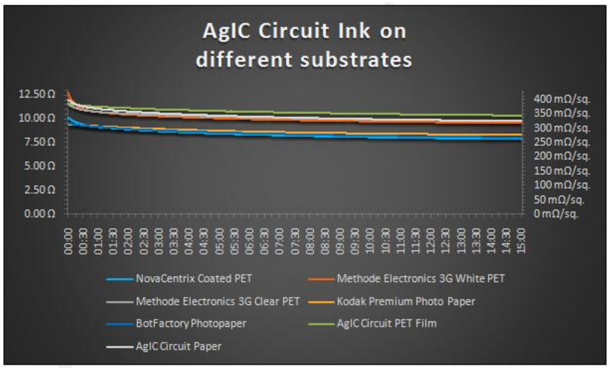

Figure 3: Change in resistivity during curing of the AgIC Circuit Ink on different substrates

Hypothesis 2 deals with the question, whether the switches withstand 1 million switching cycles without malfunctions. The first four prototypes reached and even outperformed one million switching cycles. Figure 4 displays the resistance behavior over switching cycles of the tested switches.

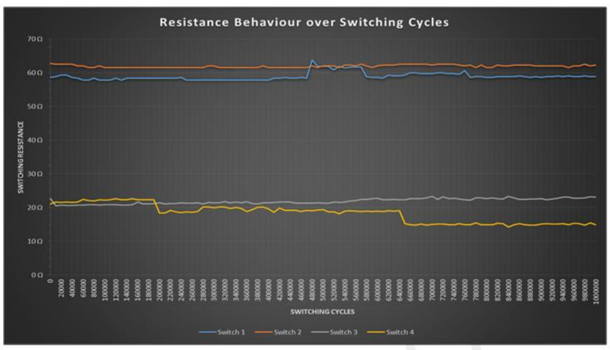

Figure 4: Change in resistance of the membrane switches during switching cycle test

Despite the fact that the switches were working without malfunction, it needs to be stated, that the silver traces became partially detached from the PET substrates, as illustrated below:

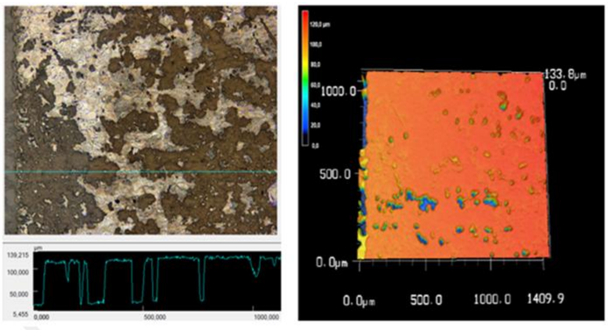

Figure 5: Detached silver traces after 1 million switching cycles as a laser image and displayed in 3D, illustrated with a Keyence 3D laser microscope VK-X200. The maximum film thickness of the silver ink is 133,8 µm

It can be seen, that some areas of silver layer are unimpaired whereas other areas came off. Zone 1 shows area with more or less intact silver traces, zone 2 shows areas with slight detachments and zone 3 shows areas which are more or less destroyed.

However, this hypothesis could be confirmed with regard to the functionality as a switch. The switching cycle tests demonstrated that it is indeed possible to fabricate membrane switches that are able to withstand and even surpass one million cycles of operation. The production is carried out with low-cost desktop printers (in this case, the *Brother* printer with *AgIC's* silver ink) and under laboratory conditions. In consequence, membranes switches can be utilized as switching elements, if following tests continue confirm and corroborate the first outcomes. The test facility hits the switches with a force of approx. 32 N. This fact emphasizes the results even more, because commonly applied actuation forces for non-tactile membrane switches only reach from 1 to 5 N ± 0.8 N. It is also remarkable that the resistances behaved relatively constant and didn't increase noticeably during and after the endurance test.

Conclusions

This result of the paper at hand could be seen as quite interesting with regard to cost effective printing of membrane switches for the future due to the factor that a smart combination of ink, process flow, treatment and surface generates a remarkable quality. In other words, there is - beside higher investments in High-Tec printing technology or treatment alternative to achieve quality for professional use with adequate investments.

As limitation could be seen the range of the measured resistances of each test sample and test series. This area varied during the switching cycle test, because the electro-conductive glue didn't cure uniformly and also the applied quantity varied. A further factor of influence was the different lengths of the connected cables that were used. It is recommended to use a more constant and reliable connection method than the current one. Furthermore it could be seen, that the silver traces started to detach partially from the PET substrate after 1 million cycles. Due to this fact, we recommend to start further investigations to figure out different opportunities to enhance the stability of the silver ink. In the end, it can be said that on the one hand desktop and low-cost printers could be feasible alternatives to high-cost laboratory or industrial printers concerning rapid prototyping of flexible circuits under special circumstances, on the other hand it could be argued that there is room for improvement with regard to the adhesion of silver ink on the substrates. The *Brother MFC-J6710DW* printer combined with *AgIC's Circuit Printer Cartridge Set* could be seen as a promising example of low-cost rapid prototyping for non-professional use.

References

1. Schaefer GmbH, We want to be the best – in everything we do!, n.d.. [Online]. Available: http://www.ws-schaefer.de/en/company/portrait/. [Accessed 18 12 2015].
2. Bare Conductive London, n.d.. [Online]. Available: http://www.bareconductive.com/. [Accessed 16 December 2015].
3. Analisa Russo, Bok Yeop Ahn, Jacob J. Adams, Eric B. Duoss, Jennifer T. Bernhard, Jennifer A. Lewis, Pen-on-Paper Flexible Electronics,Advanved Materials*,* 2011, 23, 3426 - 3430.
4. Marcelo Coelho, Lyndl Hall, Joanna Berzowska, Pattie Maes, Pulp-Based Computing: A Framework for Building Computers Out of Paper, CHI'09 Extended Abstracts on Human Factors in Computing Systems, 2009, 3527 - 3528.
5. Nan Wei Gong, Steve Hodges and Joseph A. Paradiso, Leveraging Conductive Inkjet Technology to Build a Sclable and Versatile Surface for Ubiquitous Sensing,Proceedings of the 13th international conference on Ubiquitous computing, 2011,45 - 54.
6. Alexandra Lyashenko, Untersuchung des Prägefoliendrucks im Hinblick auf die Anwendung im Elektronikbereich, 2014, 1-197.
7. Zbigniew Stempien, Tomasz. Rybicki, Edmund Rybicki, Marcin Kozanecki and M. I. Szynkowska, In-situ deposition of polyaniline and polypyrrole electroconductive layers on textile surfaces by the reactive ink-jet printing technique,Synthetic Metals*,* 2015, 202, 49-62.
8. Zbigniew Stempien, Edmund Rybicki, Tomasz Rybicki and Jacek Lesnikowski, Inkjet-printing deposition of silver electro-conductive layers on textile substrates at low sintering temperature by using an aqueous silver ions-containing ink for textronic applications,Sensors and Actuators B: Chemical*,* 2016, 224, 714-725.
9. Yoshihiro Kawahara, Steve Hodges, Benjamin Cook, Cheng Zhang, Gregory Abowd, Instant Inkjet Circuits: Lab-based Inkjet Printing to Support Rapid Prototyping of UbiComp Devices, ACM International Conference on Ubiquitous Computing - UbiComp '13 , 2013.

Contents lists available at http://www.jmsse.org/ & http://www.jmsse.in/