INTUITIVE

INnovative Network for **T**raining in To**U**ch **I**nterac**TIVE** Interfaces

Grant agreement: #861166
Start date: 2019-10-01

H2020-MSCA-ITN-2019
End date: 2024-03-31

Deliverable reporting document

Deliverable no: D4.9		WP: 4
Deliverable name: Embedded integration of sensors/electronics at various depths in soft substrates	Type: Report	Dissemination level: Public
Due Delivery date: 31 May 2023		Date delivered: 29 May 2023

Description:
Integration of sensors at various depths in soft substrates – towards 3D integration of sensor distribution.

Deliverable D4.9: Embedded integration of sensors/electronics at various depths in soft substrates

The first step towards integration of electronics on soft substrates is the fabrication of the interconnect patterns on the substrates. Here we studied the properties of screen-printed silver interconnects on various soft substrates.

Printing technologies are revolutionizing the field of flexible electronic by enabling devices such as high-speed transistors [1, 2], various types of sensors [3, 4], foldable displays [5], various radio-frequency identification (RFIDs) tags [6] and circuits [7] etc. They provide cost-effective routes for processing diverse functional and electronic materials/inks at temperatures that are compatible with various soft and flexible substrates [8, 9]. Printed flexible devices/circuits are advantageous as they can conform over irregular and curvy surfaces which is needed for the advancement of applications such as wearable systems [10, 11], soft robotics [12], electronic-skin [13-16], and healthcare monitoring systems [17, 18]. During practical applications these devices may operate under repeated cycles of mechanical deformations such as bending, stretching, and twisting. The module performance could vary due to the stresses induced by these deformations [19-21]. The contact points between the devices and substrates, especially for rigid substrates, and the interconnection layout must endure the mechanical stresses to ensure reliable performance of the flexible modules. Therefore, there is a need to study the: (i) response of flexible systems under various mechanical deformations, (ii) understand the failure/fracture mechanism(s), and (iii) propose appropriate solutions to mitigate the adverse impact of mechanical deformations on the performance of flexible electronic systems.

Among various components on a flexible electronic system, the stable and mechanically robust metal electrodes for interconnects are crucial. The reliable low-resistive interconnects are critical to realise hybrid (heterogeneous integration) flexible systems [22, 23] that combine printed electronics and silicon technologies. Due to the differing elastic properties, the interconnects are more vulnerable to mechanical stress compared with the soft functional materials. The resistivity of printed electrodes/interconnects could also vary under mechanical deformation, and this could directly affect the device performance and the reliable operation of the entire flexible system. For instance, increase in the resistivity of the printed metal interconnects after bending cycles has been shown to decrease the transistors field effect mobility [23]. Therefore, strenuous efforts are on-going to investigate the reliability of metal interconnects under bending [21, 23] and stretching [24] as well as modelling the device behaviour. Whilst these works are steps in the right direction, there is need to systematically analyse the endurance of these devices, particularly the interconnects, for large number of bending and twisting [19, 20].

In this work, we have assessed the endurance of screen-printed silver interconnects on commonly used soft and flexible substrates. Screen printing was chosen to fabricate the interconnects as this technology has received considerable commercial attention recently owing to its capability of printing large area modules, with a variety of inks ranging from conductive materials to dielectrics, on a variety of substrates ranging from plastic to glass and ceramics, with minimum feature size of approximately 100 mm. It is widely used commercially to print RFID tags, electrodes on solar cells and various wearable devices. It has significant advantages over traditional metal deposition techniques in terms of throughput and cost of production. In screen-printing, the factors that determine the resistance of the printed interconnects are their dimensions, concentration of conducting material in the ink and adhesion of ink with the substrates. For most of the practical applications, the constraints on the width of the interconnects provide little room for optimization. Instead, the thickness of the interconnects can be increased to decrease the resistance. However, the increased thickness of the interconnects could lead to lesser bending and can also make them more susceptible to bending/twisting strains. Motivated by these factors, in this work, we investigate the endurance of screen-printed silver interconnects on polyethylene terephthalate (PET), polydimethylsiloxane (PDMS), Polyimide (PI) and paper substrates under mechanical bending and torsional loading.

The paper, PET and PI substrate samples were commercially obtained. The PDMS thin films were prepared by spin coating a 10:1 (Elastomer: Binder) solution on PET at 1000 rpm for 60 seconds and subsequently annealing at 60 C for 2 hours. An Aurel C920 Screen printer was used for printing silver lines with Dupont PE828 silver ink (having sheet resistivity of <25 mOhm/sq./25 mm and density of 2.5 g/cc) and squeeze pressure of 17 N. The resistance of the silver lines was measured by using a Keysight-34465A Digital multimeter. The bending and twisting endurance measurements were done using a Yuasa bending and twisting endurance setup. The bending tests were done with a bending radius of 10 mm. For torsional endurance testing, the samples were twisted over an angle of 80° (40° clockwise and counterclockwise twisting about the median relaxed state).

A. Base resistance of screen-printed interconnects on various soft substrates.

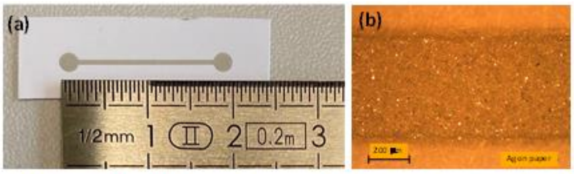


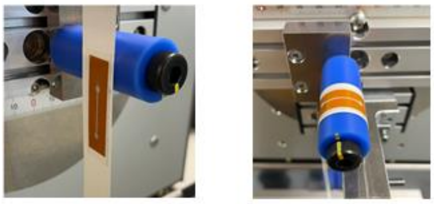
Fig. 1. An image showing the 2 cm long screen-printed Ag lines on paper substrate used for endurance test.

The base resistance of 2 cm long screen-printed Ag lines over various commonly used soft substrates are presented in Table 1. The resistance in general decreased with the number of coatings of ink during screen printing. For single coating of silver ink, the variability in resistance is approximately 11% (1.8 ± 2 Ω). For PET samples with five coatings of silver ink, the resistance dropped sharply by 58%, as compared to single coating of silver. This can be attributed to the increase in thickness of the interconnects due to 5 coatings. But this trend is not similar for other substrates. For PDMS and paper substrate, on 5 coatings, the resistance dropped by 12% and 27% respectively, while for polyimide sample there was no difference in the resistance of the interconnects with the number of coatings of the silver ink. The lowest resistance of 0.7 ohms was achieved for 5 coatings of silver ink on PET, followed by paper (1.3 Ω), PDMS (1.4 Ω) and polyimide (2 Ω) in the increasing order. As the squeeze pressure and substrate to screen distance is same for all the samples, the dimensions of the Ag lines are expected to be same. The variation in resistance can be due to the difference in surface roughness of the substrates and can be ascertained further with Atomic Force Microscopy (AFM) measurements. Also, the run-to-run variability of these resistances are high and better comparison between surface properties of substrate and base resistance of interconnects printed on them requires statistical data. In this work, we have limited our study to the endurance tests of single coated samples only. The next sub-sections present the bending and torsional endurance of these printed interconnects.

TABLE I: Resistance of screen-printed 2-cm silver lines on Paper, PET and PDMS substrates.

Substrate	**Resistance (Ω)**	
	Single coating	**Five coatings**
PET	1.7	0.7
PDMS	1.6	1.4
Paper	1.8	1.3
Polyimide	2.0	2.0

B. Bending endurance of Ag lines on various soft substrates.


(a) Relaxed sample (b) Sample under bending

(c) Sample under torsional strain

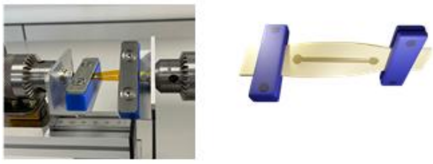


Fig. 2. Setup for measurement of (a, b) bending and (c) torsional endurance.

The endurance tests of a 2-cm silver interconnect printed on PET, PDMS and paper were carried out for over 4000 bending cycles with a bending radius 10 mm. The resistance of the Ag-on-paper sample monotonically increased, from an initial resistance of 2.6 ohms to 29.9 ohms after 4000 bending cycles as shown in Fig. 3. Although the increase in resistance was not linear, the ΔR increased with the number of bending cycles. This suggests that the breakpoints/micro-cracks in the Ag interconnect keeps increasing with the repeated bending strain cycles. Also, at the micron scale there can be continuous delamination of the Ag line from the paper substrate due to its fibrous nature. For the PET and PDMS samples however, after an initial increase till 500 cycles, the resistance stabilized at a constant value up to 4000 cycles. This suggests that due to bending strain, initially some breakpoints were formed in the interconnects, but they are not propagating any further over repetition of the bending strains. Definite conclusions can be drawn by statistical analysis and accessing the variation of the surface roughness and morphology of the substrate and the interconnect over the bending cycles.

C. Torsional endurance of Ag lines on various soft substrates.

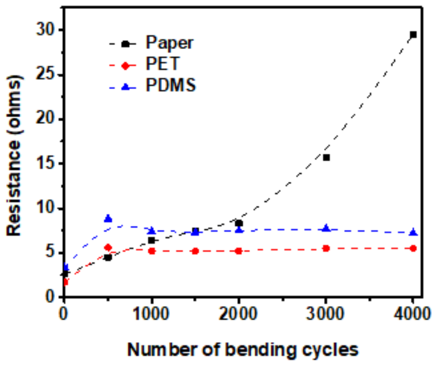


Fig. 3. Bending endurance (r = 10 mm) tests of screen-printed silver lines on different soft and flexible substrates.

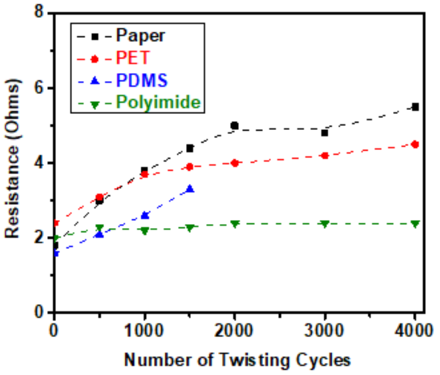


Fig 4. Torsion endurance tests (twisting angle = 80°) of screen-printed silver lines on different soft and flexible substrates.

The torsional endurance tests of Ag interconnects printed on PET, PDMS, paper and PI were also carried out for 4000 twisting cycles over an angle of 80°. As compared to bending tests, where only one type of stress (tensile or compressive) is present at a time, during twisting, some part of the sample is under tensile stress while another part is under compressive stress at the same time. However, the pattern of degradation of the interconnects under twisting stress is similar to the bending stress. Although the base resistance on paper is lower than PI, a continuous increase in the resistance is seen in the case of paper with the twisting cycles contrary to the PI sample whose resistance stabilized after an initial 20% increase. For PDMS samples, the resistance of the interconnect increased till 1500 cycles and delaminated from the substrate when further twisted. For paper, similar to the trend observed for bending, there is a continuous increase in resistance with the number of twisting cycles, while for PET, the resistance approximately stabilized after 1000 twisting cycles.

In conclusion, the base resistance and endurance of screen-printed silver interconnects are heavily dependent on the substrate. For PET substrate, there is a 60% decrease in base resistance for 5 coatings of silver ink as compared to single coating, while for polyimide, there was no change in resistance with the number of coatings. The lowest resistance of 0.7 ohms was achieved on PET substrate. Ag on PET and PDMS fares well against bending stresses, after an initial increase, their resistances got stabilized. While for Ag on paper, the resistance kept increasing monotonically with the number of bending cycles. In the case of torsional stress, Ag on polyimide exhibited best endurance against torsional stress with only 20% increase in resistance over 4000 cycles, compared to 205% increase in resistance in Ag on paper samples. For the PDMS substrate, the silver interconnect delaminated after 1500 twisting cycles. To optimize the performance of these printed interconnects, their thickness and interaction with the surface of the substrate must be studied carefully. Also, suitable encapsulation can increase the endurance of these interconnects, which will be the focus of our future work.

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