Dang, W., Lorenzelli, L., Vinciguerra, V. and Dahiya, R. (2017) Hybrid Structure of Stretchable Interconnect for Reliable E-skin Application. In: 2017 IEEE 26th International Symposium on Industrial Electronics, Edinburgh, UK, 19-21 Jun 2017, pp. 2093-2096. ISBN 9781509014125(doi:10.1109/ISIE.2017.8001579)

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Hybrid Structure of Stretchable Interconnect for Reliable E-skin Application

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***Abstract*—This paper presents the methodology for realisation of stretchable interconnects based on hybrid thin film stack of spray-coated conductive polymer PEDOT: PSS and evaporated gold (Au) film. The PEDOT: PSS film, with its properties in electrical conductivity and mechanical softness, serves as a stress release buffer in the layered hybrid structure. With the serpentine-shape design, the stretchable interconnects can accommodate larger deformation in comparison with a straight line. The correlation between interconnects' morphology (i.e. cracks propagation) with their electrical behaviour has been studied through microscope in along with electrical characterisation under external strain. Furthermore, a comparison in failure strain among different serpentine-shaped designs has been studied. Higher level in stretchability of interconnects can be achieved with a larger arc degree in design. The fabricated stretchable interconnects can accommodate significant deformations up to 72% external strain while maintaining electrically conductive.**

Keywords—PEDOT:PSS, PDMS, Conductive polymers, Stretchable interconnects, Spray coating.

I. INTRODUCTION

Recent research on stretchable electronics has grown exponentially driven by a widen scope of various applications such as wearable electronics [1, 2], flexible electronics [3, 4] and e-skin in robotics [5, 6] etc. Many innovative technologies have been developed to impart new features to electronic devices such as the ability to withstand extreme mechanical conditions comprising bending, twisting and stretching movements [7]. Currently, one popular strategy is to build up a network of traditional silicon-based electronics with stretchable interconnects. The proper engineering design in geometries of interconnects can help to re-distribute the location of the concentrated strain and further mitigate the destructive effect from the strain [8, 9]. Novel 'smart' material, on the other hand, reveals nature of both electrical conductivity and mechanical softness [10, 11] that can further advance the field. One of the representatives of such materials is the nanocomposite which embed highly conductive fillers into soft polymer matrix [11, 12]. Another branch of 'smart' materials is the organic conductive polymer, such as Poly(3,4-ethylenedioxythiophene)-Poly (styrenesulfonate) (PEDOT: PSS). They draw the attention by researchers because of their ability of maintaining electrical properties while being mechanically soft. [13] The PEDOT: PSS is a conductive polyelectrolyte complex. The conductive part is the positive charged PEDOT while the PSS part is to balance the doping charges and makes PEDOT easier to be dispersed in water. [14] Although PSS contributes to a better dispersion of PEDOT in water, it blocks the connection of conductive PEDOT molecules and lower the resulting electrical conductivity in the film. In order to enhance the conductivity of PEDOT: PSS film, the pristine PEDOT:PSS solution is often mixed with polar solvent like isopropanol (IPA), methanol and ethylene glycol etc. [15, 16] However, the achieved electrical conductivity of PEDOT:PSS film is still weak compare to the metal films.

This paper is organised as follows: A brief state of the art of PEDOT:PSS film as electrode in stretchable electronics' applications is presented in section II. The experiments of proposed methodology are presented in section III. This is followed by results and discussion in section IV. Finally, the summary of results and future scope of the research are given in section V.

II. STATE OF THE ART

The intrinsic elastic property of the conductive polymer PEDOT:PSS provokes its utilisation in stretchable electronics. The secondary-doped PEDOT:PSS film, which is deposited on stretchable elastomers (i.e. PDMS) can withstand external strain up to 188% and a cyclic strain of 30% [14, 17]. With this supreme mechanical property, PEDOT:PSS has been applied in fabricating wearable electronics [16, 18] and stretchable solar cells [19]. However, PEDOT:PSS is sensitive to aqueous

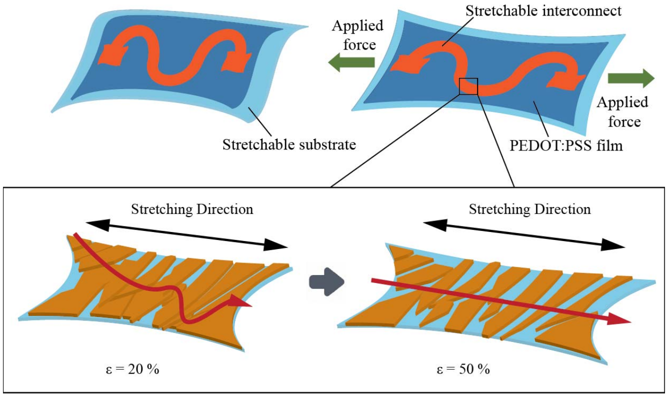


Figure 1: Schematic representing the effect under an applied strain in interconnect with underlying layer of PEDOT:PSS. The electrical conducting path can be built not only from metal islands but also from underlying PEDOT:PSS film within certain external strain.

environment. Both electrical and mechanical behaviours can be compromised with the variations in humidity in the air or during further microfabrication process such as etching and photolithography [20, 21].

In this work, a metal layer is deposited on top of the PEDOT: PSS film as a protective layer from water and chemicals. In the meanwhile, the metal film highly enhances the electrical conductivity of the hybrid structure. Furthermore, the PEDOT:PSS film is served as a stress release buffer between the brittle metal film and soft elastic substrate. As described in *Figure 1*, the cracks generated in top metal film due to the external strain will not immediate lead to a break in electrical connection. The metal islands still partially connect and build the electrical conducting path. Up to a certain level of strain, the electrical conducting path will disconnect. Compared to the structure with only metal-based conducting film, the underlying PEDOT:PSS film in the hybrid structure will keep the separated metal islands electrically connected. The achieved stretchable interconnects is able to accommodate up to 72% external strain.

III. EXPERIMENTS

A. *Organic conductive polymer deposition*

From the viewpoint of mechanics (*Equation 1*), the concentrated stress σ generated by axial tension F is in reciprocal of the cross-section area A. This indicates that the thickness of the deposited film plays an important role in deciding the stretchability of resulting film.

$$\sigma = \frac{F}{A} \qquad (1)$$

The deposition process of spin-coating reported in the literature gives a relatively low thickness (around 100 nm) [13]. To obtain a thicker film, spray-coating process with a 0.4 mm inner diameter of nozzle (NanoNC, Korea) is chosen in this study. To help the water-dispersed PEDOT:PSS (Sigma-Aldrich, Italy) solution to easily spread on PDMS substrate, 5% IPA is mixed with purchased PEDOT:PSS solution. In order to further increase the contact angle between the PEDOT:PSS solution with the hydrophobic surface of PDMS. A short time period of oxygen plasma (10 s) treatment is applied. The achieved PEDOT:PSS film is illustrated in *Figure 2*. To adjust deposited layer with low electrical resistance, multiple runs of spray are required. Confirmed with optical interferometry, each run of spray coating results in a 200-300 nm–thick PEDOT:PSS film.

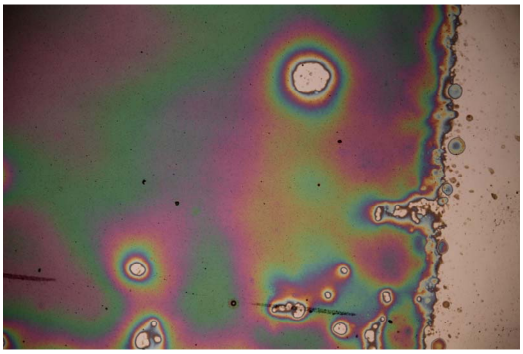


Figure 2: Microscope image of spray-coated PEDOT:PSS on PDMS substrate after 10 s oxygen plasma treatment.

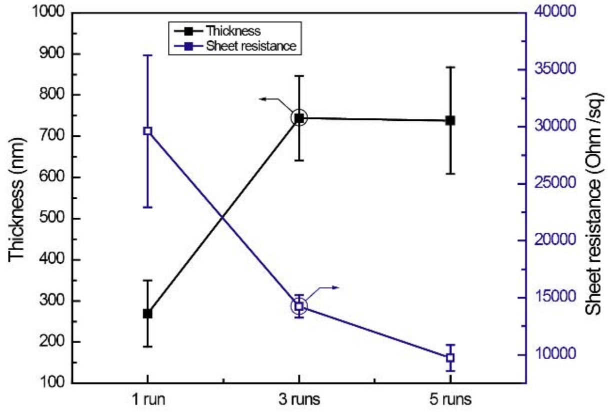


Figure 3: Measurements in sheet resistance and thickness of spray-coated PEDOT:PSS layer.

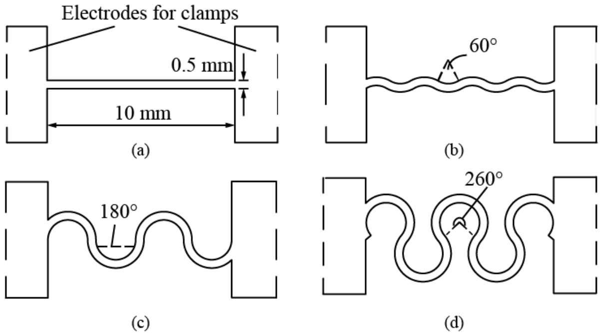


Figure 4: (a-d) Schematic of interconnect patterns with different arc curvature (a) straight (b) 60° (c) 180° and (d) 260°.

However, the further increase of the spray runs, for example, from three runs to five runs, does not increase the thickness as presented in *Figure 3*. The sheet resistance of PEDOT:PSS film was examined by sheet resistance measurement machine (Napson, Japan). The results indicate a dramatic reduce in sheet resistance while increasing the runs of spray.

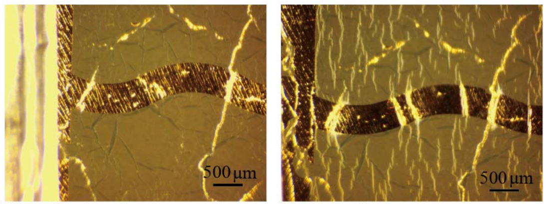
B. *Metal layer deposition and structure patterning*

The highly conductive metal stack film composing Ti/Au (10nm/100nm) is evaporated on top of the PEDOT:PSS film. Followed by the steps of photolithography and wet etching, the serpentine-shape of stretchable interconnects are patterned according to the designs shown in *Figure 4*.

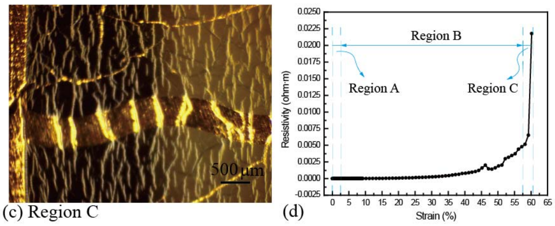
IV. RESULTS AND DISCUSSION

A. *The cracks propagation trend*

The electrical response of interconnect under an applied strain is measured by a custom-made uniaxial stretching setup equipped with multimeter (Keithley 2700). The minimum step for one-end's stretch movement is 0.01 mm. The overall resistance is recorded through Labview program. *Figure 5* (a-d) depict the change in film's morphology in corresponded to the



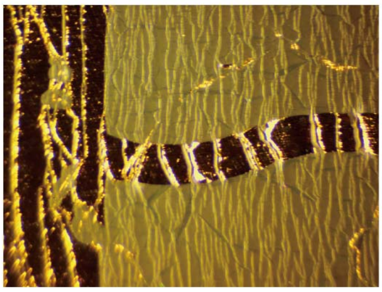
(a) Region A (b) Region B



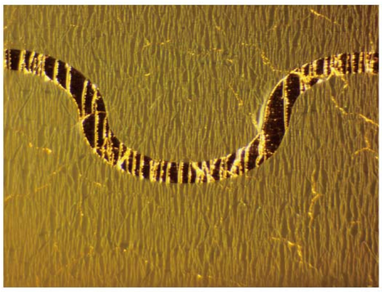
(c) Region C (d)

Figure 5: (a-c) Optical images on the trend in crack propagation with an increasing of external strain, (d) the electrical response respects to the regions with different crack density.

(a) Curvature 60 degree



(b) Curvature 180 degree



(c) Curvature 260 degree

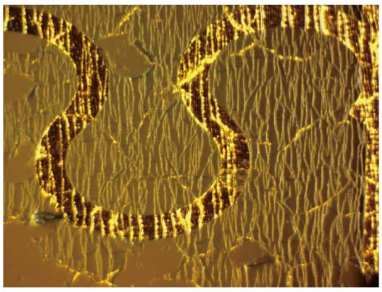


Figure 6: Optical images of interconnects under failure strain with different design in curvature (a) 60° (b) 180° and 260°.

change in resistance of interconnect under applied strain. When the sample is under external strain, the generated cracks propagated from top metal (Au) (Region A) to intermediate layer (PEDOT:PSS) (Region C). In Region A (0-2.5%), the cracks are majored in Au film which contribute to the change in resistance. Up to a certain point, the cracks start to appear in the intermediate layer (PEDOT:PSS) as indicated in Region B. The number of cracks in PEDOT:PSS film is increasing along with the increase in external strain, the cracks separate metal film to detach further and leave the the overall resistance is 10-50 times higher than before. When PEDOT:PSS film starts to break (Region C), the resistance will rise to the range of MΩ. The proposed interconnects will remain conductive until being elongated 60-70% longer than original length.

B. The influence of interconnect's curvature design

The curved design in interconnect routings not only re-distributes the concentrated strain while the interconnect is under stretched, but also provides longer overall length which allows more freedom for movements. Here we have various degree of the interconnect arc curvatures including 60°, 180° and 260°. *Figure 6* compared these three designs while being stretched to their maximum degree (or failure strain). The straight-line design has a limited stretchability of 1.2%. However, the contribution of large curvatures helps to increase the stretchability up to 72%.

V. CONCLUSION

The organic conductive polymer PEDOT:PSS film has been deposited on the PDMS substrate with an optimised spray coating parameter. The deposited PEDOT:PSS film is served as a stress release buffer between the top metal film and PDMS substrate. Its mechanical softness endures more degree of external strain compare to the brittle metal film. In this way. It can provide the electrical path when cracks generated in the metal film. To further increase the stretchability of interconnects, they designed shape is like serpentine. The larger degree of curvature contributes to more stretchability in interconnects. The achieved stretchable interconnects will be integrated with flexible sensors for realizing large-area conformable electronics.

ACKNOWLEDGEMENT

This work was supported by the European Commission under grant agreement PITN-GA-2012-317488-CONTEST and Engineering and Physical Sciences Council (EPSRC) Fellowship for Growth – Printable Tactile Skin (EP/M002527/1).

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