Screen-Printed Mechanical Switch Based on Stretchable PU-Foam Film

J. Tolvanen, J. Hannu, J. Palosaari, M. Nelo, H. Jantunen

A screen-printed mechanical switch based on an electrode structure on stretchable PU-foam film, Platilon U 4021, combined with a piezoelectric actuator, Smart Material MFC M-4010-P1, is proposed. The minimum actuation voltage of the prepared component is 300 V. The measured resistance was 2 Ω while closed and > 0.5 TΩ when open. The electrode structure endured on average of up to 15.5 M cycles with movement ≥ 100 times greater than the ≤ 1 µm required for actuation. The results suggest that the switch could be advantageous for various e-textile applications.

Introduction: Printed electronics have progressed rapidly during the recent decade. The most traditional technique used in printing electronics is screen printing. Its benefits include low cost, simplicity and versatility, as it can be used on almost any surface, e.g., polymers, textiles, ceramics and metals, and it can also be applied to non-flat and/or irregular surfaces [1].

Recent research on various switching devices has been focused on devices fabricated with MEMS and NEMS technology, which can be flexible in some cases [2-4]. At the same time, mechanical switches are favoured over electrical ones due to their ability to preserve desired functionality with substantially enhanced performance [2]. However, switches that are highly flexible, thin, single-layered and operated by stretching or electrostatic actuation are very rare. The closest application of such a device that the authors found was a stretchable fabric switch that could be operated by a releasable action of stretching and/or pushing, causing electrically conductive strips integrated into the fabric to come into contact with each other and activate the device [5].

This article proposes a screen-printed electrode structure on stretchable PU-foam film (PUFF; Platilon U 4021). This substrate material has benefits, like outstanding mechanical, chemical and thermal properties with good adhesion to foams and inks. The structure was also combined with a piezoelectric actuator (Smart Material MFC M-4010-P1) to form a switch. The component's fabrication and electrode structure were optimised and characterised while initial reliability testing of the electrode structure was done.

Screen-printed switch: The component was fabricated by attaching a PUFF-electrode structure (PUFF-e) to a Smart Material MFC M-4010-P1 piezoelectric actuator (P1) with two-sided tape (Fig. 1*a*). The attachment was done while the PUFF-e was stretched. PUFF-e's can be actuated in multiple ways, e.g. by stretching or vibrating the structure, and in this case a piezoelectric actuator was chosen. As a voltage is applied between the P1's electrodes it bends, closing an incision (Fig. 1*b*) and forming a contact between two sides of a conductive pattern. Thus, in its initial state the PUFF-switch (PUFF-s) is in an open state.

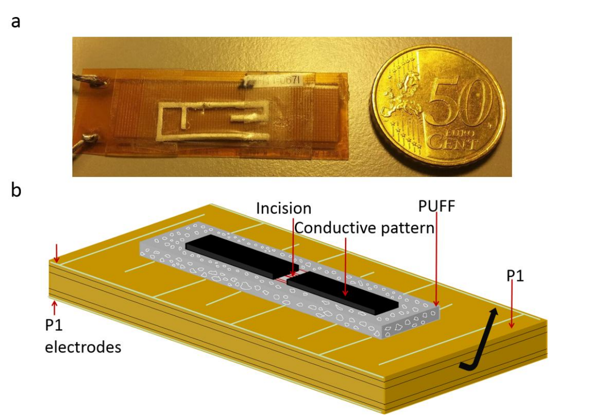

Fig. 1 *Fabricated PUFF-s (a) and structural 3D image of its attachment (b). As a voltage is applied, the P1 bends in the direction of the black arrow, closing the incision.*

The P1 'elongates' 1400 ppm when the voltage changes from -500 V to +1500 V, which correlates with a 36.5 nm change in length per volt for the active region of the P1. Table 1 shows the measurement results for the prepared component.

Table 1: Operation of the PUFF-s as the actuation voltage changes.

Actuation voltage: (V)	Closed resistance (Ω)	Open resistance (TΩ)
1300	0.8	> 0.5
1000	2	> 0.5
300	2	> 0.5
200	10	> 0.5
100	20	> 0.5

The 100–1300 V change in voltage correlates with a movement of 2.8–36.4 µm. Thus, at the minimum reliable actuation voltage of 300 V, the change in length of the P1 was 8.4 µm. When the operating voltage decreased towards 100 V, the contact resistance of the component increased. In addition, the movement required with the P1 to switch between the open and closed states is significantly greater than by stretching the PUFF-s with a micrometre screw (≤ 1 µm), as noted in the next paragraph. The determining factors of these phenomena were attaching the PUFF-e's to tension in the initial state and bending the P1 during elongation as the component was actuated, respectively. Nevertheless, in the best scenario, the minimum operating voltage needed to elongate the piezo-actuated component could be as low as ≤ 36 V, as shown in the following paragraphs.

Structure and fabrication of PUFF: The screen-printed and fabricated structure on PUFF is presented in Fig. 2. In the initial state the incision was closed (Fig. 3*f*) and the PUFF-e was connected. When the PUFF-e was stretched (Fig. 3*e*), the contact switched off as the width of the incision increased, thus abruptly increasing the measured resistance.

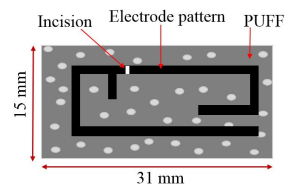

Fig. 2 *Top view of the PUFF-e design. Scale 1.5:1 vs. a real PUFF-e.*

The PUFF-e's were fabricated on film with a thickness of 100 µm (Fig. 3*a*). The PUFF was processed by laser-cutting the surface with an LPKF Photolaser U3 to make a partial incision with about 60 laser sweeps (Fig. 3*b*). The settings of the laser-cutting parameters must be carefully chosen since the structural and mechanical properties of the PUFF should not suffer and the desired incision depth (80–90 µm) should be reached. Also, PUFF can slightly melt due to heat generated during laser-cutting.

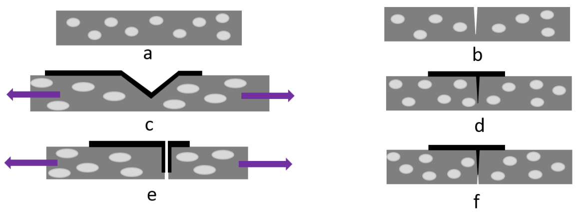

Fig. 3 *Process flow (a–f) and a sample under stretching (e).*

Next a conductive pattern of DuPont 5064H silver conductive paste was screen-printed onto the surface of the PUFF while the samples were stretched (Fig. 3*c*). The samples were released before curing at 130 °C for approximately 12 minutes (Fig. 3*d*) as keeping the surface smooth during stretching was harder than without stretching, and in some cases strenuous stretching combined with curing stressed the samples excessively to permanent failure. The paste was chosen due to its lower curing temperature that the PUFF can withstand (140 °C) without permanent deformation. The purpose of stretching the samples during fabrication was to open the incision to enhance spearing of the paste.

Eventually the incision through the gap in the PUFF was made while stretching the sample (Fig. 3*e*).

Characterization of PUFF: The resistance and capacitance of the PUFF-e's were measured as a function of change in length. As the PUFF-e's were stretched 1 µm or less with a micrometre screw, the resistance values of the samples changed abruptly, from approximately 2 Ω to 1 TΩ (Fig 4). All the individual samples were set to be equal to 1 µm, since it was difficult to accurately measure distances smaller than 1 µm. Simultaneously, the capacitance decreased abruptly to below 1 pF and the values eventually flattened out to a value close to 0.5 pF as stretching was further increased. The amount of stretching required to switch was reduced by decreasing both the length of the incisions and the width of the conductive line to 1 mm. It should be kept in mind that further downsizing is not a viable option for the current fabrication method, as the final cutting of the incision is done by hand.

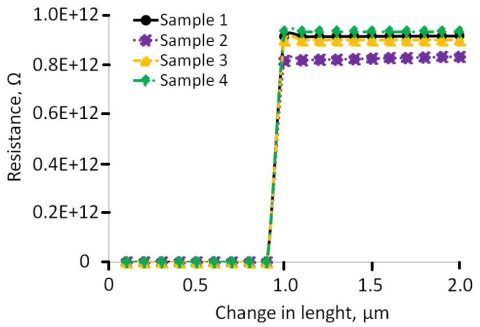

Fig. 4 *Resistance measurements of individual samples 1–5 as a function of change in length.*

A Brual&Kjaer 4810 Mini Shaker (MS) with maximum displacement of 6 mm was used to test the operating speed of the PUFF-e. The samples were attached from one side of the contact to the MS while the end was attached to a stand at an angle of 45 degrees with respect to the MS. Thus, it was possible to stretch the PUFF-e by adjusting the frequency, voltage and gain of the measurement system. The repeated and releasable action of stretching worked well at the tested frequencies up to 140 Hz, but it was not possible to accurately and reliably measure the resistance values. The ratio of open to closed state times during operation was approximately 2 to 1 in the observed cases, which possibly can be explained by the elasticity of the material.

Optimisation and initial reliability analysis: Optimisation of the fabrication was done by using imaging with an optical microscope. Spreading of paste was not found to be uniform in all the observed cases. The depth of the incision was seen to correlate with this problem; thus, as the number of laser sweeps increased to about 60, the total depth of the incision increased and further enhanced the spearing of the paste. This reduced problems with the angle of contact of the actuation part during operation. In addition, it further improved the measurement results by reducing variation (Fig. 4). As a result, the contact sides were less sensitive to changes in the angle of contact during operation as the surface area of the paste increased. This also improved the reliability of the contact. However, a major source of variation between the observed samples originated from the final incision (Fig. 3*e*), which had a larger impact on the measurement results than spearing of the paste.

Reliability testing of the PUFF-e's was done by using the MS at a frequency of 140 Hz while the number of cycles was up to 25 M. For each individual sample, multiple measurement points were taken. The movements of the PUFF-e's were measured optically with a laser beam. The reliability testing results in Fig. 5 show measured on-resistance versus the number of cycles between 0 and 25 M. A failure in the reliability testing was observed as a change in resistance from the initial value of the sample due to mechanical wearing. There is no real definition for resistive failure in the literature. However, it is obvious in these cases that as the on-resistance value increased to ≥ 5 Ω due to repetitive stretching, the contact became significantly harder to form. The repetitive stretching gradually increased the distance of the incision in the closed state and the connection eventually disappeared permanently as a result. It was observed that even a low number of cycles can rapidly start to wear out the PUFF-e's if the movement of the sample is ≥ 300 µm. However, as the movement of the samples was reduced to a value of 100–130 µm, the reliability of the PUFF-e's increased to an average of 15.5 M cycles, taking into account the sample variation (Fig. 5).

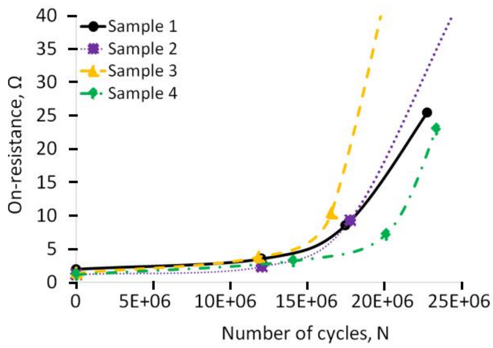

Fig. 5 *Measured on-resistance values versus number of cycles for 25 million cycles with PUFF-e's with movement of 100–130 µm.*

Yet, the movement was still multiple times greater (≥ 100) than the minimum amount required to switch between the open/closed states with a micrometre screw (≤ 1 µm). Thus, the reliability of the PUFF-e's could be further increased by decreasing the movement.

Conclusion: As the results suggest, the PUFF-s requires a 300 V actuation voltage to switch its low resistance (2 Ω) to high (> 0.5 TΩ), enabling the open and closed state, respectively. The benefits of the PUFF-s are flexibility, thin structure and a simple, low-cost manufacturing process. The reliability of the PUFF-s was relatively good compared with other mechanical switches. Also, the reliability can be further increased by reducing the movement. In the near future, the size of the actuation part should be minimised and the reliability of the fabrication method should be improved to find alternative ways to make the final incision. Regardless, the fabrication method is highly capable of producing switches. Various e-textile applications or cosmetic electronics could benefit, where actuation could be achieved, e.g. by movement of joints or limbs in humans or animals.

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References

1. Izdebska, J. and Thomas, S.: 'Printing on Polymers: Fundamentals and Applications' (William Andrew 1st Edition, 2015)
2. Park, E.S, Chen Y., Liu, T.K and Subramanian, V.: 'A New Switching Device for Printed Electronics: Inkjet-Printed Microelectromechanical Relay', NanoLett., 2013, **13**, pp. 5355-5360, doi: 10.1021/nl4028632
3. Pan, Y., Yu, F. and Jeon J.: 'Fully-polymeric NEM relay for flexible, transparent, ultra-low power electronics and sensors', MEMSYS., 2015, 28th IEEE International Conference, pp. 940-943, doi: 10.1109/MEMSYS.2015.7051115
4. Sun, J. Wang, W., Muruganathan, M. and Mizuta H.: 'Low pull-in voltage graphene electromechanical switch fabricated with a polymer sacrificial space' Appl. Phys. Lett, 2014, **105**, doi: 10.1063/1.4891055
5. Marmaropoulos, G., Vu, G. and Pulford, K.: 'Stretchable fabric switch', https://www.google.com.ar/patents/US20060251854, US 20060251854 A1 2006 January 2016