Bhattacharjee, M., Soni, M. and Dahiya, R. (2019) Microchannel Based Flexible Dynamic Strain Sensor. In: 2019 IEEE International Conference on Flexible and Printable Sensors and Systems (FLEPS), Glasgow, UK, 08-10 Jul 2019, ISBN 9781538693049 (doi:10.1109/FLEPS.2019.8792317).

Microchannel based Flexible Dynamic Strain Sensor

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I. Summary And Motivation

The dynamic measurement of strain is needed in several applications where frequent bending is experienced. For example, in the case of robotics and prosthesis, the strain sensors could indicate the bending of fingers or hand joints[1, 2]. Likewise, it is needed to detect the damages to interconnects due to frequent bending in the flexible and wearable electronics[3-5]. To this end, microchannel based technology can provide an efficient solution. This paper presents a flexible microfluidic channel-based sensor for the detection of dynamic strain. The sensor has been developed using Polydimethylsiloxane (PDMS). The micro-channel (dia~175 µm), fabricated using replica molding technique, was made conductive by filling with poly (3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT: PSS) polymer. The developed strain sensor was subjected to various strains, which led to changes in the channel diameter and hence the resistance. We observed about 3 order ($\Delta R/R$ ~2800) increase in the resistance (R) value for 10% applied strain ($\Delta L/L$, L= length of sensor) This lead to a gauge factor (GF = $(\Delta R/R)/(\Delta L/L)$) of ~280 for 10% applied strain, which is better (~70 times) than reported polymer based strain sensors [6-9].

II. Advances over Previous Work

The advances in wearable and flexible sensors and systems are making it possible to monitor in real time a range of parameters such as pH [10, 11], provide energy autonomous solutions [12-14], and analyze biomedical data [10]. Among others, the strain sensing has attracted major attention due to applicability in soft robotics. Several strain and stress sensor have been developed using nanostructured materials such as nanowires [15], CNT [16], nanoparticles [17]. Most of these devices exhibit piezoresistive properties and thus for a small strain the material shows a change in electrical conductance [18]. There are several conductive polymer-based strain sensors reported in the recent past [19, 20]. Among them the polymer PEDOT:PSS has gained attention owing to good electrical and structural properties and several strain sensors have been developed using PEDOT:PSS conductive polymer [21, 22]. The developed strain sensors are mostly fabricated by printing polymers between two electrodes. However, these sensors become inefficient due to environmental effects such as excessive use, temperature, humidity etc. Of late, microchannel based strain sensors have been developed using 3D printed techniques [23]. However, the fabrication of multiple channels with uniform dimension is the challenge yet to be overcome. Moreover, the development process in these kinds of sensors is complicated. In this regard, our recent work [24] demonstrated a CNT based stretchable strain sensor, fabricated using dielectrophoresis (DEP) technique which requires an external voltage of 10-15V during material deposition. The sensor showed 2 order change in resistance for an applied strain up to 11%. However, the proposed sensor demonstrates a simpler fabrication technique which does not require any external power in material deposition with 10 times superior performance.

III. Results and Methodologies

*A. Materials***:** PDMS has been procured from Sigma Aldrich, and PEDOT: PSS was procured from Merck, UK. The other necessary consumables were procured from local vendors.

*B. Fabrication***:** The strain sensor was fabricated with PDMS using replica molding technique. Firstly, the PDMS and the cross-linker was mixed in 10:1 ratio and then degassed inside a vacuum desiccator for 1 hr before pouring it inside the circular mold of diameter 5.5 cm. The channel was introduced during molding using a metal wire. The mold was placed in a convection oven for 2 hrs at 70ºC. Conducting polymer PEDOT: PSS was injected into the microchannel using a syringe and dried for another 3 hrs at 70ºC. The process of injection and curing was repeated 3 times. The optical image of the sensor is shown in Fig. 1(c).

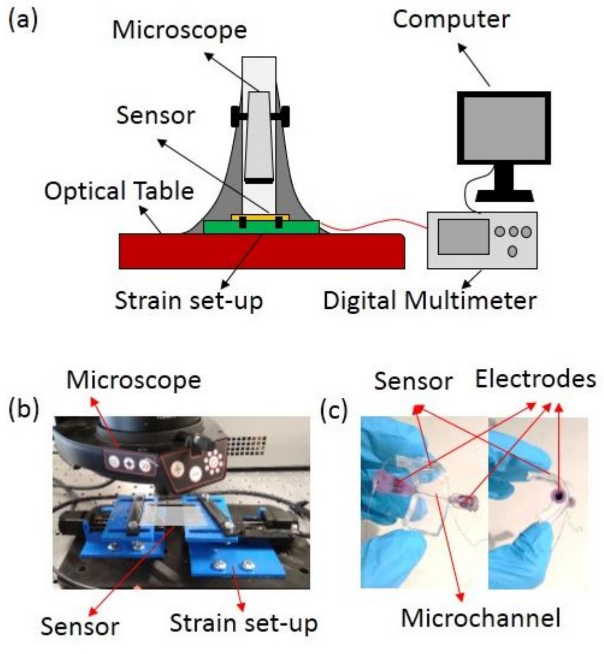

Fig. 1: (a) The schematic diagram of the experimental set-up; (b) the strain measurement set-up employed in the experiments; (c) the optical image of the flexible sensor.

*C. Characterization***:** The sensor was characterized using a digital multimeter (Agilent 34461A) and a LabView enabled strain generation set-up. The set-up which was able to move back and forth, with varying velocity, to generate uniaxial strain in the device-under-test (DUT) as illustrated in Fig.1 (a-b). The sensor was mounted on this set-up and electrical connection was taken out using thin metallic wires connected to both ends of the DUT. A maximum of 10% strain was applied with a velocity of V_S = 0.1 mm/s. The measurement set-up is illustrated in Fig. 1 where Image (a) shows the schematics of the experimental set-up and image (b) shows the real image of the strain generation set-up.

*D. Results***:** The response of the sensor was measured as the resistance (R_S) value across the DUT. Fig. 2(a) shows the response of the sensor for a maximum strain of 10%, applied dynamically at a speed of V_S = 0.1 mm/s i.e. each second 0.1 mm of displacement took place in each shaft of the strain generation set-up. It was observed that the resistance of sensor increases with the increase in the strain before reaching a maxima and then reduces to the initial level when brought back to the relaxed state as illustrated in Fig. 2(a). The increase in the strain while shafts are moving apart is termed as forward cycle (FC) and the reverse motion is termed as backward cycle (BC), as shown schematically in Fig. 2(b). One complete cycle, which consists of a forward and a backward movement, is magnified and shown in Fig. 2(c).

The change in the resistance due to the applied strain is mainly because of the change in the dimension of the microchannel as shown schematically in Fig. 3(a-b) and the corresponding micrographs are shown in Fig. 3(c-d). The increase in the diameter of the channel along the direction of applied force (in the direction of X-axis as shown in Fig. 3(b)) created a more resistive path due to the local detachments and cracks in polymer materials and thus a higher resistance was achieved. It is interesting to see that the sensor recovers faster as compared to the forward cycle. This can be attributed to the faster material rearrangement inside the microchannel in backward cycle. The PEDOT: PSS polymer material retracts and rearranges back to its relaxed position faster to create the more conductive path as the material retains the memory of the original positions for a small deformation due to the inherent elastic nature. Table 1 shows the performance comparison between the proposed sensor and different flexible strain sensors reported in prior art.

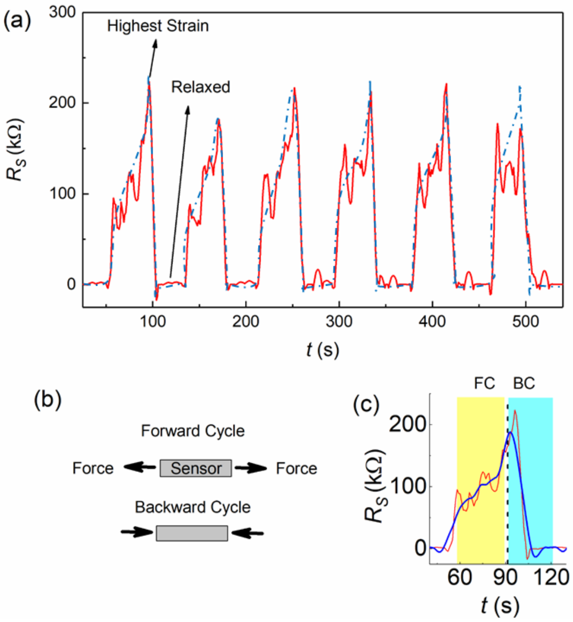

Fig. 2: (a) Response of sensor under a dynamic strain of 10% at a rate of 0.1 mm/s velocity; (b) the schematic illustration of forward (FC) and backward cycle (BC); (c) the single cycle of response for forward and backward strain cycle.

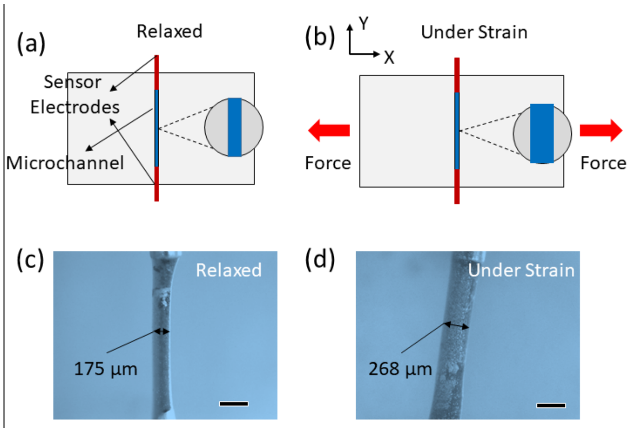

Fig. 3: (a) and (b) the schematic diagram of the sensor under relaxed and strained condition; (c) and (d) the microscopic images of the fabricated microchannel under relaxed and strained conditions.

TABLE I. PERFORMANCE COMPARISON OF DIFFERENT FLEXIBLE STRAIN SENSORS

Material	**Gauge Factor (GF)**	**Strain Range**	**Ref.**
Natural Rubber/CNT	43.5	100%	[7]
PDMS/CNT	142	30%	[6]
Ecoflex/Pt	42	185%	[9]
Ecoflex/CNT	48	400-700%	[8]
PEDOT:PSS	286	10%	This Work

IV. CONCLUSIONS

A microchannel based ultrasensitive strain sensor was developed using conductive PEDOT: PSS to determine the dynamic strain cycle. The micro-channel was fabricated using replica molding technique with a channel diameter of 175 µm. The response of the sensor was based on the change in the effective dimension and polymer detachments and cracks due to the applied strain. The sensor showed a 3 order increase in resistance with *GF* ~280 for a 10% applied strain in perpendicular to the channel length towards X-axis. The studies with thin PDMS films and other polymer or composite materials can be performed in future to improve the performance of the sensor.

ACKNOWLEDGMENTS

This work was supported by European Commission through North West Centre for Advanced Manufacturing (H2020-Intereg-IVA5055).

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