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Flexible Strain Sensor with NFC Tag for Food Packaging

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Abstract— In this work we present a polymer-based flexible strain sensor integrated with an NFC tag to detect strain by means of a visual LED indicator. The sensor was fabricated using conductive polymer poly (3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) as an active material inside a flexible and transparent polymer Polydimethylsiloxane (PDMS) microchannel. The strain sensor changes its resistance at different bending conditions, showing up to three order increase in resistance for ~100□ bending. A custom-developed passive NFC tag with an LED connected in series to the strain sensor is powered from an NFC reader to detect strain in a semi-quantitative way. The light intensity of the LED indicator is modulated according to the strain level, showing maximum brightness (~67 lux) for relaxed or no strain condition, and being almost OFF (~8 lux) for the maximum strain condition. The potential application of the NFC-based strain sensor system in food package for spoilage detection is also presented.

Keywords— Flexible Strain Sensor, NFC Tag, Smart Packaging.

I. INTRODUCTION

Smart sensors, serving as the interface between the digital and physical worlds, are opening interesting avenues for remote monitoring of environment, agriculture and healthcare applications [1-3]. The combination of smart sensors, with increased computational power and wireless connectivity, increasingly, by 5G networks, will enable new ways to analyse data and gain actionable insights. In this regard, several physical sensors have been developed for temperature [4-6], pressure [7, 8], strain [9, 10] and humidity [11, 12] sensing. There is an increasing trend to wirelessly acquire the sensor data using technologies such as Radiofrequency Identification (RFID), Near Field Communication (NFC) and Bluetooth. With RFID technology, it is also possible to have battery-less wireless communication. However, Ultra-High Frequency (UHF) RFID systems usually require the use of specialised equipment and reader antennas [13]. In that regard, NFC has advantage. NFC is a specialized subset within the family of RFID technology for short-range wireless systems in the High Frequency (HF) band, mainly focused on secure identification applications [14]. A distinct advantage of NFC over generic RFID lies in the peer-to-peer (P2P) communication that can be achieved between NFC tags and NFC-enabled smartphones, which makes this technology within the reach of any individual user [15, 16]. For this reason, various physical and chemical sensors have been integrated with NFC to create wireless sensor platforms for applications such as smart packaging, wearable health and modified atmosphere packaging (MAP) for food monitoring applications [16-19].

The use of NFC-tag–based system for food packaging is particularly attractive, given that nearly a third of all food is wasted worldwide and the rapidly growing challenges for food security. Much of it is still safe to eat, but consumers throw it away because it is close to or beyond its printed expiration date. That waste could be mitigated if food were packaged with a sensor that monitored its spoilage in real time. With NFC based sensor system it is possible to detect the food spoilage at an extremely early stage. In future, such systems could lead to automated decision-making, where the best course of action is automatically implemented with smart labels triggering an internet connected device; for example, a robot in supermarket.

In most food packages, presence of gases such as oxygen could indicate the loss of quality and shelf-life of the food, since it is the origin of the oxidation of the content or the microbial growth [20]. The inflated or swollen food package, might be an initial sign of bacterial activity within the package, which leads to discoloration, nutritional loss and final food spoilage [21]. The bulge in food package, as a result of gases, can be detected by using an appropriate strain sensor integrated in the package. Generally, strain sensors convert mechanical deformation into electrical signal. Primary data of the sensor are converted to strain using the so-called strain factor. Among various transduction mechanisms such as piezoelectricity, triboelectricity or optical methods, resistive and capacitive sensing are the most commonly used [22, 23]. Conventional strain sensors used in manufacturing processes are stiff and therefore not adequate to detect small deformations in food packages [24], but flexible strain sensors can address this issue [25]. The flexible substrates such as polyamide (PI), polyethylene terephthalate (PET), polyethylene naphtholate (PEN), etc. are light and conformable and have been used for sensor applications in different fields such as robotics [3, 26], health and environmental monitoring [27-29]. These sensors can be fabricated using a variety of approaches such as printing methods [30, 31], conductive fabrics [32, 33] or polymer-based materials [6, 34].

Herein, we present a microchannel-based flexible strain sensor integrated with an NFC tag to detect in a semi-quantitative way the applied dynamic strain. The sensor comprises of PDMS channel filled with conductive polymer PEDOT:PSS and the change of the its resistance at different bending (or strain) conditions modulates the light intensity of the LED indicator. The system could be used in food packaging

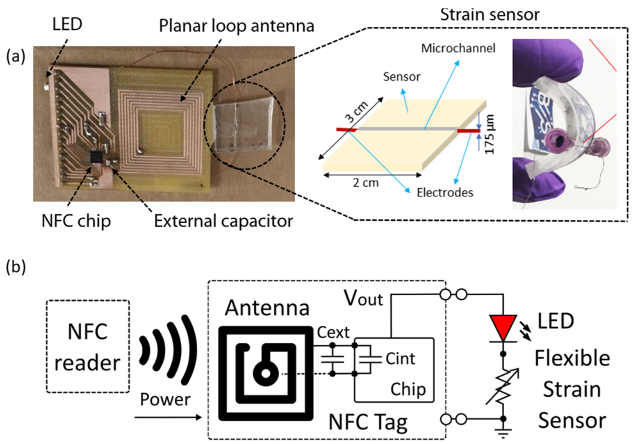

Fig. 1. Optical images (a) and schematic diagram (b) of the developed strain sensing system, including NFC tag, reader and sensing module.

for early detection of bacterial activity through strain sensors measuring the bulge or swelling of package.

II. MATERIALS AND METHODS

A. *Strain sensor*

The PDMS and PEDOT:PSS used to fabricate the strain sensor were procured from Sigma Aldrich. The polymer PDMS and crosslinker were mixed at 10:1 ratio and poured into a circular mould (dia 5.5 cm) and then the mixture was degassed for 1 hr using desiccator. Then the mould was cured at convection oven for 2 hrs at 70□C. After the microchannel fabrication, whose detailed manufacturing process is available in a previous work [35], conductive polymer PEDOT:PSS was injected into the microchannel. Then, the electrodes were dried and fixed using metal wires. The schematic diagram and the optical image of the fabricated sensor are shown in Fig. 1(a).

B. *NFC interface*

The designed tag antenna consists of a Printed Circuit Board (PCB) planar coil matched to the internal capacitor of the NFC transponder chip RF430FRL154H (Texas Instruments, Dallas, Texas, USA). The tag was fabricated on FR4 substrate using a mechanical milling machine model ProtoMat S103 (LPKF Laser & Electronics AG, Garbsen, Germany).

The tag was designed to resonate at 13.56 MHz, which is the frequency compatible with NFC applications. Therefore, it can be operated with any NFC-enabled smartphone. Considering the input capacitance of the RFID chip at 13.56 MHz (C_{int}~35 pF), the required inductance value is L~3.9 µH according to the resonance frequency of a parallel LC tank circuit, which is given by $\omega_0=1/(LC)^{1/2}$. To reduce the antenna dimensions, a 1.85 µH squared planar inductor was designed with N=7 turns and dimensions of 26 mm^2, with 400 µm conductor width and 350 µm interspacing between the tracks. An external capacitor of 39 pF was then placed in parallel to C_{int} to achieve resonance at the desired frequency. With RFID reader providing an adequate RF electromagnetic field, the tag can provide a regulated voltage of ~2 V and an output current up to 500 µA. These are enough to power the LED indicator. As shown in the schematic diagram of Fig. 1(b), the strain sensor is connected in series with the LED indicator, thus modulating the LED light intensity as a function of the resistive variation in the sensor due to the strain. Such changes can give the user a visual semi-quantitative indication of the strain level. The dimension of the tag was ~6×5 cm^2, where the antenna had dimensions of ~2.6×2.6 cm^2, the chip area was ~2×2 mm^2, and the sensor was fabricated on ~3×2 cm^2 substrate.

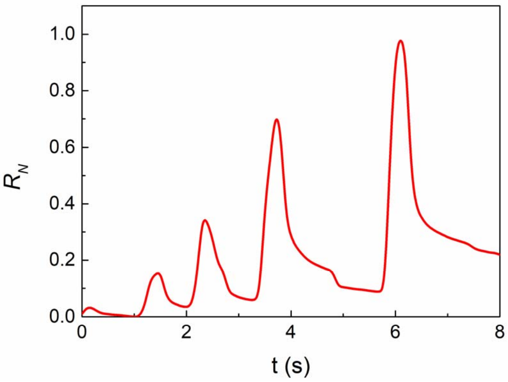

Fig. 2. The temporal normalized resistance (R_N) response of the fabricated sensor.

C. *Experimental setup*

A digital multimeter (Agilent 34461A) connected to a LabVIEW application was used to characterize the strain sensor in terms of resistance as a function of the strain level. Impedance frequency characterization of the tag was carried out using an Agilent 4294A Precision Impedance Analyzer along with a 42941A impedance probe kit (Keysight Technologies, Santa Clara, CA, USA). A TRF7970A NFC/RFID Booster Pack from Texas Instruments was used as the reader, although the tag can be also operated using an NFC-enabled smartphone. Preliminary tests confirm that a smartphone is able to generate the required voltage to drive the LED. To characterize the LED light intensity variation when the strain sensor changes its resistance due to the bending, a generic lux-meter mobile application was used.

III. RESULTS AND DISCUSSION

A. *Sensor characterization*

The developed strain sensor is resistive, which means that its resistance increases with the increase in strain value. Fig. 2 shows the temporal normalized resistance (R_N) response of the strain sensor, which was measured by bending it to different angles. The response was calculated using normalized resistance of the sensor where the maximum strain, in this case, was correlated to the maximum change in the resistance.

B. *Electromagnetic performance of antenna*

Fig. 3(a) shows the experimental measurements inductance (L) and quality factor (Q) of the PCB coil without the RF430FRL154H chip. The measured inductance at 13.56 MHz was 1.82 µH, very close to the designed value. In addition, the quality factor achieved using a FR-4 substrate is higher than 75, enough for this type of applications, and the self-resonance frequency is much higher than 13.56 MHz, about 58 MHz in our case. From this frequency onwards, the reactive part of the impedance adopts a capacitive behaviour, meaning that the

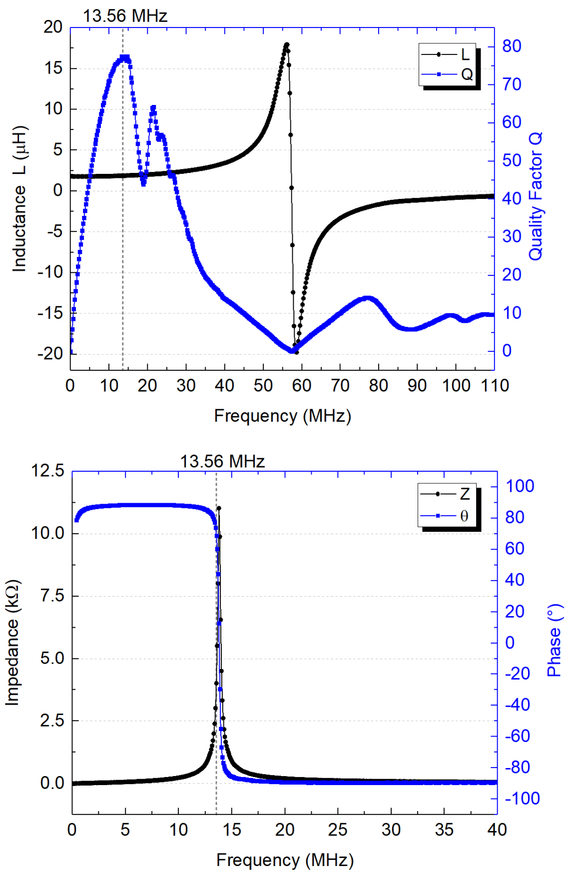

Fig. 3. (a) Measured frequency response of the planar inductor in terms of inductance and quality factor; and (b) measured impedance and phase of the parallel LC circuit.

inductance value becomes negative. Since we operate far below the self-resonance frequency of 58 MHz, the coil can be considered valid for our requirements. Once the RF430FRL154H chip and the external capacitor were attached to the PCB, the resonant circuit was completed. Thus, a new frequency characterization was carried out by measuring the impedance (Z) and phase (θ) of the parallel LC resonant circuit. As can be observed in Fig. 3(b), the measured resonant frequency is very close to the desired working frequency.

C. Strain sensing

The corresponding light intensity values were measured using a lux-meter mobile application for the different strain conditions. For each case, Fig. 4 shows the brightness of the LED connected to the sensor in series as illustrated in Fig. 1. The intensity of the LED decreased significantly once the sensor underwent bending. The LED brightness was highest (~67 lux) for relaxed or no strain condition, while the LED was found to be almost OFF (~8 lux) for the maximum strain condition. Figure 4 also shows the decrease in the intensity of the LED brightness with the increase of bending angle. As a proof of concept, an example of application of NFC-based strain sensor system attached to a food package for meat spoilage detection is shown in Fig. 5. Under normal conditions (i.e., when the product is suitable for consumption), the LED will be ON with the maximum brightness level when an RFID reader approaches the tag. The growth of bacteria in the food package will lead to gases and hence the swelling of package. In such scenario, the inflated package will increase the resistance of the strain sensor and the LED will be OFF when the RFID reader is approached, meaning that the food is unfit for consumption. Intermediate levels of the LED brightness can reveal the different spoilage levels that the food might be suffering due to bacterial activity.

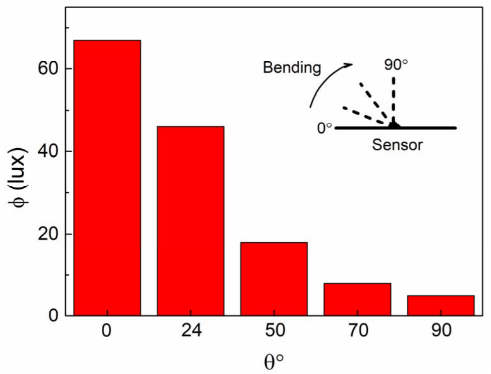

Fig. 4. LED brightness (ϕ) variation with bending of the sensor.

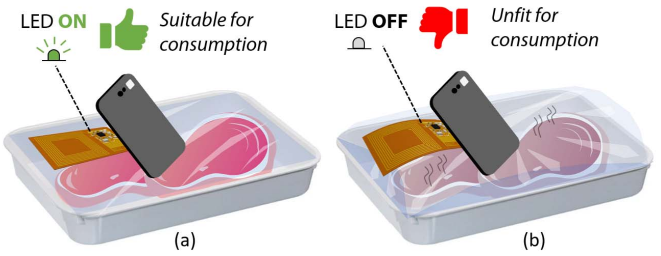

Fig. 5. Example of the application showing the NFC strain sensor tag attached to a food package for meat spoilage detection. The LED will be (a) ON if the product is suitable for consumption, or (b) OFF if the food is unfit for consumption.

IV. CONCLUSIONS

This paper presents a flexible strain sensor integrated with an NFC tag to detect strain in a semi-quantitative way. The sensor is fabricated using a flexible polymer PDMS microchannel and conductive polymer PEDOT:PSS injected into the channel as the active material. The sensor showed a maximum of three order increase in resistance for ~100□ bending. The resistive strain sensor was then connected to a custom-developed NFC tag system containing an LED indicator, whose light intensity is modulated as per the strain level. As future scope of this work, a flexible version of the NFC tag system will be developed to achieve a better integration with the package and demonstrate its applicability to food spoilage detection in Intelligent Packaging (IP) systems.

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REFERENCES

[1] H. R. Lim, H. S. Kim, R. Qazi, Y. T. Kwon, J. W. Jeong, and W. H. Yeo, "Advanced Soft Materials, Sensor Integrations, and Applications of Wearable Flexible Hybrid Electronics in Healthcare, Energy, and Environment," *Advanced Materials,* p. 1901924, 2019.doi: 10.1002/adma.201901924.

[2] R. Dahiya, D. Akinwande, and J. S. Chang, "Flexible Electronic Skin: From Humanoids to Humans [Scanning the Issue]," *Proceedings of the IEEE,* vol. 107, no. 10, pp. 2011-2015, 2019.doi: 10.1109/jproc.2019.2941665.

[3] R. Dahiya *et al.*, "Large-Area Soft e-Skin: The Challenges Beyond Sensor Designs," *Proceedings of the IEEE,* vol. 107, no. 10, pp. 2016-2033, 2019.doi: 10.1109/jproc.2019.2941366.

[4] T. Q. Trung, S. Ramasundaram, B. U. Hwang, and N. E. Lee, "An All-Elastomeric Transparent and Stretchable Temperature Sensor for Body-Attachable Wearable Electronics," *Adv Mater,* vol. 28, no. 3, pp. 502-9, Jan 20 2016.doi: 10.1002/adma.201504441.

[5] M. Dankoco, G. Tesfay, E. Bènevent, and M. Bendahan, "Temperature sensor realized by inkjet printing process on flexible substrate," *Materials Science and Engineering: B,* vol. 205, pp. 1-5, 2016.doi: 10.1016/j.mseb.2015.11.003.

[6] M. Soni, M. Bhattacharjee, M. Ntagios, and R. Dahiya, "Printed Temperature Sensor Based on PEDOT:PSS - Graphene Oxide Composite," *IEEE Sensors Journal,* pp. 1-1, 2020.doi: 10.1109/jsen.2020.2969667.

[7] E. S. Hosseini, L. Manjakkal, D. Shakthivel, and R. Dahiya, "Glycine-Chitosan-Based Flexible Biodegradable Piezoelectric Pressure Sensor," *ACS Appl Mater Interfaces,* vol. 12, no. 8, pp. 9008-9016, Feb 26 2020.doi: 10.1021/acsami.9b21052.

[8] N. Yogeswaran *et al.*, "Piezoelectric graphene field effect transistor pressure sensors for tactile sensing," *Applied Physics Letters,* vol. 113, no. 1, p. 014102, 2018.doi: 10.1063/1.5030545.

[9] D. Zymelka, T. Yamashita, S. Takamatsu, T. Itoh, and T. Kobayashi, "Printed strain sensor with temperature compensation and its evaluation with an example of applications in structural health monitoring," *Japanese Journal of Applied Physics,* vol. 56, no. 5S2, 2017.doi: 10.7567/jjap.56.05ec02.

[10] M. A. C. Angeli, F. Nikbakhtnasrabadi, P. Vena, and R. Dahiya, "Geometry dependent application of stretchable printed antenna," in *2019 IEEE International Conference on Flexible and Printable Sensors and Systems (FLEPS)*, 2019, pp. 1-3: IEEE, doi: 10.1109/FLEPS.2019.8792245.

[11] M. Bhattacharjee, H. B. Nemade, and D. Bandyopadhyay, "Nano-enabled paper humidity sensor for mobile based point-of-care lung function monitoring," *Biosens Bioelectron,* vol. 94, pp. 544-551, Aug 15 2017.doi: 10.1016/j.bios.2017.03.049.

[12] M. Bhattacharjee and D. Bandyopadhyay, "Mechanisms of humidity sensing on a CdS nanoparticle coated paper sensor," *Sensors and Actuators A: Physical,* vol. 285, pp. 241-247, 2019.doi: 10.1016/j.sna.2018.11.034.

[13] P. Escobedo, M. A. Carvajal, L. F. Capitan-Vallvey, J. Fernandez-Salmeron, A. Martinez-Olmos, and A. J. Palma, "Passive UHF RFID Tag for Multispectral Assessment," *Sensors (Basel),* vol. 16, no. 7, p. 1085, Jul 14 2016.doi: 10.3390/s16071085.

[14] Z. Cao *et al.*, "Near-Field Communication Sensors," *Sensors (Basel),* vol. 19, no. 18, p. 3947, Sep 12 2019.doi: 10.3390/s19183947.

[15] P. Escobedo *et al.*, "General-purpose passive wireless point–of–care platform based on smartphone," *Biosensors and Bioelectronics,* vol. 141, p. 111360, 2019.doi: 10.1016/j.bios.2019.111360.

[16] W. Dang, L. Manjakkal, W. T. Navaraj, L. Lorenzelli, V. Vinciguerra, and R. Dahiya, "Stretchable wireless system for sweat pH monitoring," *Biosens Bioelectron,* vol. 107, pp. 192-202, Jun 1 2018.doi: 10.1016/j.bios.2018.02.025.

[17] P. Escobedo *et al.*, "Flexible Passive near Field Communication Tag for Multigas Sensing," *Anal Chem,* vol. 89, no. 3, pp. 1697-1703, Feb 7 2017.doi: 10.1021/acs.analchem.6b03901.

[18] T. B. Nguyen, V. T. Tran, and W. Y. Chung, "Pressure Measurement-Based Method for Battery-Free Food Monitoring Powered by NFC Energy Harvesting," *Sci Rep,* vol. 9, no. 1, p. 17556, Nov 26 2019.doi: 10.1038/s41598-019-53775-1.

[19] P. Marsh *et al.*, "Flexible Iridium Oxide based pH sensor Integrated with Inductively Coupled Wireless Transmission System for Wearable Applications," *IEEE Sensors Journal,* pp. 1-1, 2020.doi: 10.1109/jsen.2020.2970926.

[20] P. E. Araque, I. M. P. de Vargas Sansalvador, N. L. Ruiz, M. M. E. Rodriguez, M. A. C. Rodríguez, and A. M. Olmos, "Non-invasive oxygen determination in intelligent packaging using a smartphone," *IEEE Sensors Journal,* vol. 18, no. 11, pp. 4351-4357, 2018.doi: 10.1109/JSEN.2018.2824404

[21] J. K. Brecht, S. A. Sargent, P. E. Brecht, J. Saenz, and L. Rodowick, "Protecting Perishable Foods During Transport by Truck and Rail," ed, 2019.

[22] J. Heikenfeld *et al.*, "Wearable sensors: modalities, challenges, and prospects," *Lab on a Chip,* vol. 18, no. 2, pp. 217-248, Jan 16 2018.doi: 10.1039/c7lc00914c.

[23] R. Dahiya and M. Valle, *Robotic Tactile Sensing: Technologies and System*. Dordrecht: Springer Science + Business Media, 2013.

[24] J. Hughes and F. Iida, "Multi-Functional Soft Strain Sensors for Wearable Physiological Monitoring," (in eng), *Sensors (Basel),* vol. 18, no. 11, p. 3822, Nov 8 2018.doi: 10.3390/s18113822.

[25] D. Y. Wang *et al.*, "High performance flexible strain sensor based on self-locked overlapping graphene sheets," *Nanoscale,* vol. 8, no. 48, pp. 20090-20095, Dec 8 2016.doi: 10.1039/c6nr07620c.

[26] W. Navaraj and R. Dahiya, "Fingerprint ‐ Enhanced Capacitive ‐ Piezoelectric Flexible Sensing Skin to Discriminate Static and Dynamic Tactile Stimuli," *Advanced Intelligent Systems,* vol. 1, no. 7, p. 1900051, 2019.doi: 10.1002/aisy.201900051.

[27] L. Manjakkal, D. Shakthivel, and R. Dahiya, "Flexible printed reference electrodes for electrochemical applications," *Advanced Materials Technologies,* vol. 3, no. 12, p. 1800252, 2018.doi: 10.1002/admt.201800252.

[28] L. Manjakkal, S. Dervin, and R. Dahiya, "Flexible potentiometric pH sensors for wearable systems," *RSC Advances,* vol. 10, no. 15, pp. 8594-8617, 2020.doi: 10.1039/D0RA00016G.

[29] L. Manjakkal, D. Szwagierczak, and R. Dahiya, "Metal oxides based electrochemical pH sensors: Current progress and future perspectives," *Progress in Materials Science,* vol. 109, p. 100635, 2020.doi: 10.1016/j.pmatsci.2019.100635.

[30] G. Rosati, M. Ravarotto, M. Scaramuzza, A. De Toni, and A. Paccagnella, "Silver nanoparticles inkjet-printed flexible biosensor for rapid label-free antibiotic detection in milk," *Sensors and Actuators B: Chemical,* vol. 280, pp. 280-289, 2019.doi: 10.1016/j.snb.2018.09.084.

[31] L. Manjakkal, B. Sakthivel, N. Gopalakrishnan, and R. Dahiya, "Printed flexible electrochemical pH sensors based on CuO nanorods," *Sensors and Actuators B: Chemical,* vol. 263, pp. 50-58, 2018.doi: 10.1016/j.snb.2018.02.092.

[32] Y. K. Kim, S.-H. Hwang, S. Kim, H. Park, and S. K. Lim, "ZnO nanostructure electrodeposited on flexible conductive fabric: A flexible photo-sensor," *Sensors and Actuators B: Chemical,* vol. 240, pp. 1106-1113, 2017.doi: 10.1016/j.snb.2016.09.072.

[33] A. Pullanchiyodan, L. Manjakkal, S. Dervin, D. Shakthivel, and R. Dahiya, "Metal Coated Conductive Fabrics with Graphite Electrodes and Biocompatible Gel Electrolyte for Wearable Supercapacitors," *Advanced Materials Technologies,* 2020.doi: 10.1002/admt.201901107.

[34] S. J. Park, J. Kim, M. Chu, and M. Khine, "Highly flexible wrinkled carbon nanotube thin film strain sensor to monitor human movement," *Advanced Materials Technologies,* vol. 1, no. 5, p. 1600053, 2016.doi: 10.1002/admt.201600053.

[35] M. Bhattacharjee, M. Soni, P. Escobedo, and R. Dahiya, "PEDOT: PSS microchannel based highly sensitive stretchable strain sensor," *Advanced Electronic Materials,* 2020.doi: 10.1002/aelm.202000445.