Degradable nanofibers-based capacitive pressure sensor for underwater monitoring

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***Abstract*—This paper presents a degradable nanofibers-based sensor for underwater pressure monitoring applications. The presented capacitive pressure sensor uses polyhydroxy butyrate (PHB) nanofibers as the dielectric material. The sensor is encapsulated in polyimide (PI) to prevent moisture permeation during the operation. The fabricated device is tested in air and water ambient under dynamic and static conditions. The sensor showed a sensitivity of 3.87 kPa^{-1} with excellent linearity (99.8%) and stability, and low hysteresis of 1.3 %. The fabrication process used here could also be replicated to develop flexible pressure sensors for underwater wearables.**

Keywords*—*Degradable nanofibers, electrospinning, pressure sensor, underwater monitoring, flexible electronics.

I. Introduction

Pressure sensors are widely used in underwater applications such as oceanic exploration using robots and wearable suits [1, 2]. The sensors in these applications should be capable of operating over a wider range of pressure (for deeper exploration). Further, flexible form factors are desired so that they can be easily attached to curved surfaces of marine vehicles and diving suits. A wide range of pressure sensors based on transduction mechanisms such as piezoresistive, piezoelectric, triboelectric and capacitive etc., could meet these requirements [3-7] Among these, the capacitive sensors are preferred due to their high sensitivity, lower hysteresis, less susceptibility to noise and simple readout electronics. However, due to high pressures in underwater ambient, the capacitive sensors require suitable encapsulation to prevent water from permeating. Further, the materials (e.g., encapsulation, conductive electrodes, dielectric etc.) they often use are either non-degradable or partially degradable. Some of these materials contribute to microplastics in water [8, 9] and hence to the higher incidence of mortality among marine animals. Such issues raise the demand for sensors based on materials that are degradable naturally into useful by-products [10]. In this regard, the polymers such as polyvinyl alcohol (PVA) [11], polycaprolactone (PCL) [12], starch [13], polyhydroxy butyrate (PHB) [13], silk [14] etc. have attracted considerable attention in recent years, and this is also the focus of capacitive pressure sensors presented in this paper.

The flexible and lightweight capacitive pressure sensor presented in this paper uses a dielectric layer based on biodegradable polyhydroxy butyrate (PHB) nanofibers. The nanofibers were obtained using electrospinning. Unlike conventional methods such as wet etching with dip coating [1], drop casting [3], and rolling [2] etc., electrospinning is a simple and cost-effective approach which also allows easy control over fiber dimensions and tuning of their properties [15]. The electrospun nanofibers offer several advantages, including a higher aspect ratio, which is ideal for sensing [16]. Therefore, the electrospinning technique has been used in this paper to develop the PHB nanofibers for the dielectric layer of the capacitive pressure sensor. The developed sensor exhibited a linear response for a pressure range of 0 to 100 kPa when tested in air. The sensor was tested underwater at different depths (0 to 60 cm) equivalent to a pressure of 6kPa. The observed results indicate the suitability of the fabricated sensor towards various underwater pressure sensing applications.

This paper is organised as follows: Section II discusses the materials and fabrication method for the capacitive sensor. Section III details the characterisation and performance of the sensor in the air and underwater ambient. A summary of the key results is given in Section IV.

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II. Materials and Methods

A. *Design of the capacitive sensor*

The device consists of three layers; a nanofibers-based dielectric layer which is sandwiched between two electrodes (Aluminium foil and conductive textile), as depicted in Fig 1(a). All layers have the same design, i.e., 20 mm long, 15 mm wide, and an extended square contact pad of 5mm. The device was encapsulated with PI tape (25 × 25 mm).

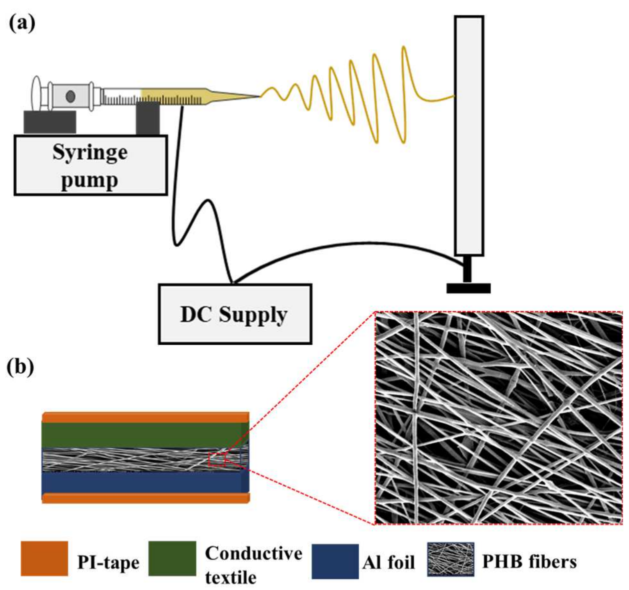

Fig. 1. (a) Schematic illustration of electrospinning setup, (b) schematic illustration of the capacitive sensor's design with SEM image of the PHB electrospun nanofibers at 20 µm scale.

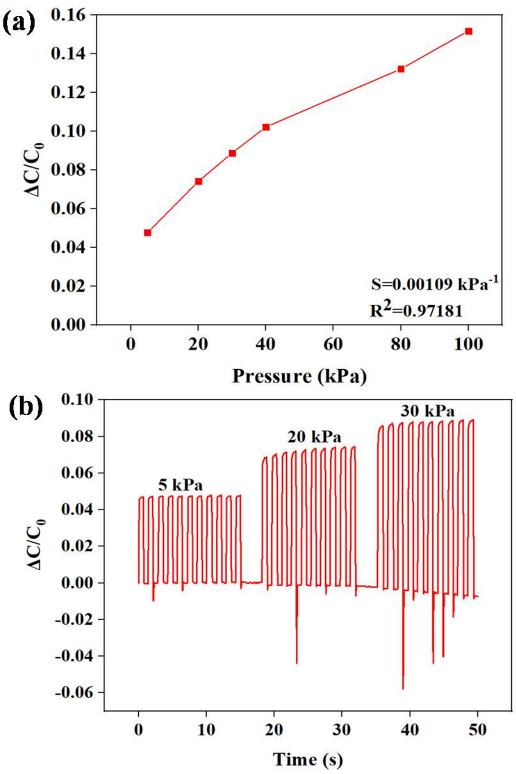

Fig. 2. (a) Sensor response for the pressure range 0-100 kPa, and (b) its stability under different cyclic loadings (5 kPa -30 kPa)

B. Material Preparation

1.2 g of PHB (m.w: 550 Kg/mol) was mixed with 10 mL of Chloroform: Ethanol (9:1 v/v) and stirred at 200 rpm overnight at 60 ℃.

C. Device Fabrication

The solution was put into a 20 mL syringe and placed in the flow pump of the electrospinning setup (TL-PRO, TONGLI TL, Nanshan, Shenzhen, China). A stainless-steel needle (20G) was connected to the syringe at 12 cm from a grounded flat collector, covered with aluminium foil. The flow rate of the pump was 1.5 mL/h, and 17 kV was applied during electrospinning. The experiments were conducted at room temperature. After electrospinning, a conductive textile was attached on top of the nanofibers based dielectric layer. Finally, the device was encapsulated with PI tape.

III. Results and Discussion

A. Performance and Evaluation

The as-fabricated sensor was tested in air and water ambient. For the air conditions, the device was placed on a load cell and its output were recorded at different pressures applied with a linear motor. The pressure applied on the sensor was measured by the load cell. The linear motor is controlled by a custom-made LabVIEW software. A square probe (dimensions 0.7 cm × 0.7 cm) was affixed to the linear motor during the application of pressure. For the underwater conditions, the sensor was placed on a wooden stick and manually moved to different depths in a water tank. Eq. 1 was used to calculate the water pressure at different depths.

$$P = \rho_w g h \quad (1)$$

where ρ_w is the water density (1000 kg/m^3), g is the gravitational constant (9.81 m/s^2), and h is the depth of the fluid column. For both air and water conditions, the relative change of the sensor capacitance was obtained using a Keysight (E4980AL) LCR meter. The capacitance of the sensor changes during the underwater conditions at various depths. When the depth of water changes, the water pressure induces compression on the capacitive sensor, which in turn causes a change in capacitance. This might be either due to a change in the distance between the electrodes or a change in the dielectric layer, which reflects the underwater pressure value.

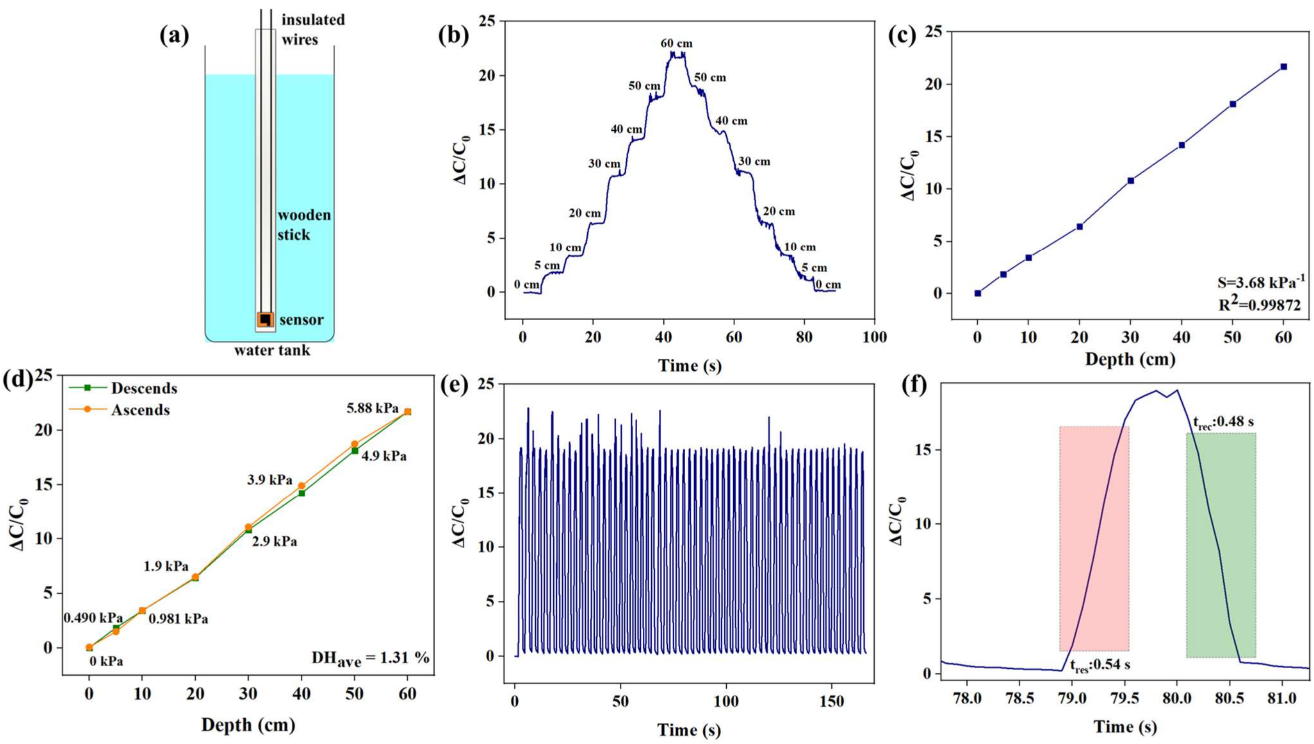

Fig. 3. (a) Schematic illustration of the capacitive sensor in the water tank, (b) response during ascending and descending conditions, (c) sensor response for the depth range (0-60 cm), (d) hysteresis of the capacitive pressure sensor, (e) cyclic repeatability at 60 cm and (f) response and recovery time of the capacitive sensor.

B. *Air conditions*

The performance of the sensor was first evaluated under air conditions to examine its stability and capacitive behaviour. Fig 2(a) shows the relative change of capacitance of the sensor under loading conditions for the range 0-100 kPa. The sensor exhibited good sensitivity of 0.00109 kPa^{-1} ($R^2 = 0.97181$). Fig 2 (b) illustrates the capacitive response of the device for 10 cyclic loadings, lasting 3 s for each applied pressure (5 kPa, 20 kPa and 30 kPa). The sensor showed excellent stability with a minor downwards trend for all the cyclic loadings-unloading cycles. This minor downwards trend may be attributed to the custom-made testing setup.

C. *Underwater conditions*

The performance of the encapsulated sensor was also analysed in the water environment. The sensing performance is analysed up to 60 cm depth using a tap water filled tank (with a depth of 60 cm) as shown in Fig. 3 (a). The sensor was attached to wooden stick and connected to LCR meter using the insulated copper wires. The sensing performance is analysed using a step wise response (at 5, 10, 20, 30, 40, 50 and 60 cm depths) as shown in Fig. 3 (b). The response ($\Delta C/C_0$) of the sensor is observed in range of 1.842 to 21.70 for the considered depths ranging from 5 cm to 60 cm, as shown in Fig. 3 (c). The sensor shows a sensitivity (S) of 3.68 kPa^{-1}. This enhanced sensitivity could be explained on the basis of change in dielectric constant properties and compression of the sensor in water environment. The performance of the sensor is evaluated after 12 weeks and a slight variation in the performance is observed. The observed variations at 5 cm and 60 cm depths are found as ~6 % and ~9 %, respectively. The average hysteresis (as shown in Fig. 3 (d)) of the sensor was also analysed using the step wise response and it was found to be 1.3%. Further, the cyclic repeatability of the sensor was carried out at 60 cm depth, as shown in Fig. 3(e). The response and recovery times of the capacitive sensor are calculated at 60 cm depth, as depicted in Fig. 3(f). The response and recovery times are found as 0.54 s and 0.48 s, respectively. The obtained results indicate a highly repeatable performance of the presented sensors. Table I presents a comparative analysis of our sensor with other capacitive sensors reported for underwater applications. The reported sensors were developed with different techniques. The data clearly shows excellent figures for the presented sensor as compared to the previous reports.

TABLE I. COMPARATIVE TABLE OF CAPACITIVE PRESSURE SENSORS FOR UNDERWATER APPLICATIONS

Fabrication Method	Dielectric Layer	Sensitivity [kPa^{-1}]
Drop casting [3]	Porous PDMS	0.005 (0-40 kPa)
Deep coating/wet etching [1]	Wet-tissues-coated with carbon nanotubes (CNTs)	0.2 (<6 kPa) 0.05 (>8 kPa)
Drop casting [17]	Porous PDMS	0.0018 (0-25 kPa) 0.0007 (25-200 kPa) 0.0004 (200-300 kPa)
Blade-casting [7]	Porous PDMS/ZnO NWs	0.717 (0-50 Pa) 0.360 (50-1000 Pa) 0.200 (1000-3000 Pa)
Electrospinning [This work]	PHB nanofibers	3.68 (<6 kPa)

IV. CONCLUSION

In this work, a degradable nanofibers-based capacitive pressure sensor is presented along with the evaluation of its suitability for underwater pressure monitoring applications. The sensor is developed using electrospun PHB nanofibers-based dielectric layer, aluminium and conductive textile as electrodes materials and PI as encapsulation layer. The presented sensor exhibits sensitivities as 0.00109 kPa^{-1} (in range 0 – 100 kPa) and 3.68 kPa^{-1} (towards 0 - 60 cm depth), for air and underwater conditions, respectively. The observed results indicate the suitability of the presented sensor for underwater pressure monitoring. The presented sensor is partially degradable – thanks to the use of conductive textile and PHB based dielectric layer. In future, we will develop fully degradable device by replacing the aluminium electrode and encapsulation layer with suitable degradable environmental friendly materials.

REFERENCES

[1] C. C. Vu and J. Kim, "Waterproof, thin, high-performance pressure sensors-hand drawing for underwater wearable applications," Science and Technology of Advanced Materials, vol. 22, no. 1, pp. 718-728, 2021.

[2] M. Zhang et al., "Self-Powered, Electrochemical Carbon Nanotube Pressure Sensors for Wave Monitoring," Advanced Functional Materials, vol. 30, no. 42, p. 2004564, 2020.

[3] E. S. Hosseini, M. Chakraborty, J. Roe, Y. Petillot, and R. S. Dahiya, "Porous Elastomer Based Wide Range Flexible Pressure Sensor for Autonomous Underwater Vehicles," IEEE Sensors Journal, vol. 22, no. 10, pp. 9914-9921, 2022.

[4] M. Ntagios and R. Dahiya, "3D Printed Soft and Flexible Insole with Intrinsic Pressure Sensing Capability," IEEE Sensors Journal, pp. 1-1, 2022, doi: 10.1109/JSEN.2022.3179233.

[5] G. Khandelwal and R. Dahiya, "Self-Powered Active Sensing Based on Triboelectric Generators," Advanced Materials, vol. 34, no. 33, p. 2200724, 2022.

[6] O. Ozioko, H. Nassar, and R. Dahiya, "3D Printed Interdigitated Capacitor Based Tilt Sensor," IEEE Sensors Journal, vol. 21, no. 23, pp. 26252-26260, 2021.

[7] G.-W. Hsieh, L.-C. Shih, and P.-Y. Chen, "Porous Polydimethylsiloxane Elastomer Hybrid with Zinc Oxide Nanowire for Wearable, Wide-Range, and Low Detection Limit Capacitive Pressure Sensor," Nanomaterials, vol. 12, no. 2, p. 256, 2022.

[8] J. R. Jambeck et al., "Plastic waste inputs from land into the ocean," Science, vol. 347, no. 6223, pp. 768-771, 2015.

[9] A. Cózar et al., "Plastic accumulation in the Mediterranean Sea," PloS one, vol. 10, no. 4, p. e0121762, 2015.

[10] M. Chakraborty, J. Kettle, and R. Dahiya, "Electronic Waste Reduction Through Devices and Printed Circuit Boards Designed for Circularity," IEEE Journal on Flexible Electronics, vol. 1, no. 1, pp. 4-23, 2022.

[11] G. Ge et al., "Stretchable, Transparent, and Self-Patterned Hydrogel-Based Pressure Sensor for Human Motions Detection," Advanced Functional Materials, vol. 28, no. 32, p. 1802576, 2018.

[12] M. A. U. Khalid et al., "A highly sensitive biodegradable pressure sensor based on nanofibrous dielectric," Sensors and Actuators A: Physical, vol. 294, pp. 140-147, 2019.

[13] H. Liu et al., "Flexible and Degradable Multimodal Sensor Fabricated by Transferring Laser-Induced Porous Carbon on Starch Film," ACS Sustainable Chemistry & Engineering, vol. 8, no. 1, pp. 527-533, 2020.

[14] Y. Liu, L.-Q. Tao, D.-Y. Wang, T.-Y. Zhang, Y. Yang, and T.-L. Ren, "Flexible, highly sensitive pressure sensor with a wide range based on graphene-silk network structure," Applied Physics Letters, vol. 110, no. 12, p. 123508, 2017.

[15] F. E. Ahmed, B. S. Lalia, and R. Hashaikeh, "A review on electrospinning for membrane fabrication: Challenges and applications," Desalination, vol. 356, pp. 15-30, 2015.

[16] W. E. Teo and S. Ramakrishna, "A review on electrospinning design and nanofibre assemblies," Nanotechnology, vol. 17, no. 14, p. R89, 2006.

[17] S. Dervin, E. S. Hosseini, and R. Dahiya, "Porous Elastomer based Soft Pressure Sensor for Autonomous Underwater Vehicles," in 2021 IEEE International Conference on Flexible and Printable Sensors and Systems (FLEPS), 20-23 June 2021 2021.