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Porous Elastomer based Wide Range Flexible Pressure Sensor for Autonomous Underwater Vehicles

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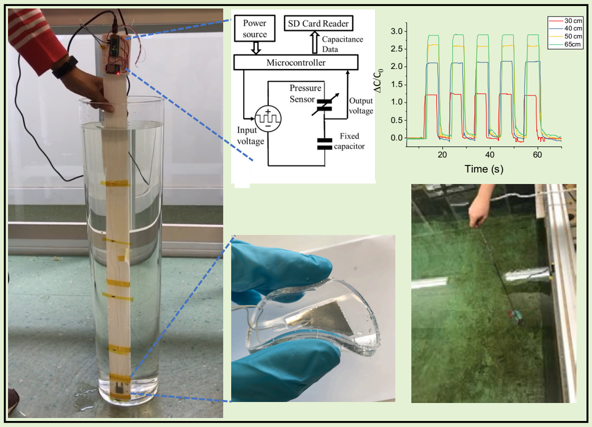
***Abstract*—This work presents the design and implementation of a porous polydimethylsiloxane (PDMS)-based wide-range flexible pressure sensor for autonomous underwater vehicles. The capacitive sensor, with porous PDMS as dielectric, is encapsulated in bulk PDMS polymer. The fabricated sensor was evaluated over a wide pressure range (0-230 kPa), which is similar to pressures experienced up to approx. 24m below the sea level. The sensors showed linear response when tested in air and near-linear response (98%) when submerged in water. The sensor showed much higher sensitivity (0.375 kPa^{-1}) in water than in the air environment. However, the sensor exhibited the performance and sensitivity similar to the air condition (0.005 kPa^{-1}) when the readout electronics (encapsulated inside a watertight enclosure) was also submerged inside the water along with the sensor. The fabricated sensor also exhibited fast response and recovery time (190 ms), as well as excellent repeatability and stability (no drift) over tested range of 50 loading and unloading cycles. These results demonstrate the suitability of presented sensors for potential use in applications requiring a wide range of pressure, particularly the underwater robotics where real-time pressure monitoring is critical for autonomous operation.**



***Index Terms*—Microstructure dielectric; wide-range pressure sensor; flexible electronics; robotics; capacitive pressure sensor**

I. Introduction

Recently, there has been a growing interest in applying Autonomous underwater vehicles (AUVs) for real-time and remote monitoring of underwater environments as well as environmental inspection and surveillance operations [1, 2]. One of the most indispensable sensors found on board AUVs is the pressure sensors, which is needed to detect local pressure variations to help the AUV avoid obstacles, maintain a desired depth underwater, and calibrate other sensors when their response changes with pressure [3]. For this, a reliable, robust, flexible, lightweight, and surface-mountable sensing systems is needed to be deployed on AUVs to continuously monitor water pressure. This pressure measurements are also needed to understand the relation between the water level and other parameters such as pH, temperature and salinity etc. in water [4].

In recent years, several flexible and conformable pressure sensors have been developed using various mechanisms, including piezoresistive, capacitance, piezoelectric, etc. [5-8]. Among these, capacitive-based pressure sensors offer several advantages, including simple design and low-cost fabrication routes, fast response, long-term stability, suitability for static and quasi-static pressures and less sensitivity to interfering temperature and humidity [9-11]. In addition, capacitive structures provide a passive form of sensing and consume low power. Despite this, the use of flexible capacitive sensors for underwater pressure measurement applications remains relatively unexplored. Ideally, the sensors for underwater pressure monitoring should have a good sensitivity over wide pressure range and properly packaged with robust, biocompatible and soft materials.

Herein, we present a flexible and conformable capacitive

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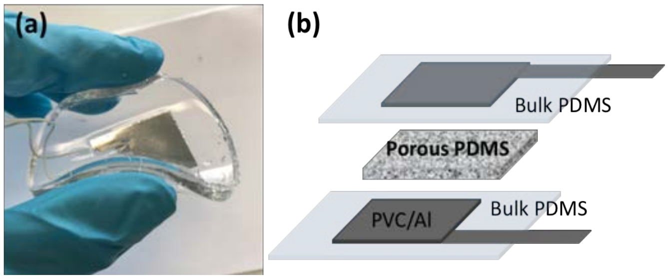

Fig. 1. (a) Image of fabricated soft pressure sensor. (b) Schematic showing the structure of fabricated pressure sensor.

pressure sensor developed by sandwiching a porous elastomer between flexible PVC substrates with Aluminum (Al) electrodes on them. The pressure sensor is packaged in bulk PDMS, as shown in Fig. 1. PDMS is a biocompatible polymer and does not decompose in water [12]. As explained in Sec. III, the porous PDMS was fabricated by annealing PDMS and NH_4HCO_3 mixture. The pressure sensor was characterized in different conditions: a) air, b) small water tank, and c) water pool. In the water environment, the sensor was sensitive to the water depth, with a fast (190 ms), near-linear response (98%) and good sensitivity (0.005 kPa^{-1}) over a wide pressure range. However, the performance of the sensor was different when the connecting wires were in contact with water compared to the situation where wires were encapsulated in a watertight enclosure. The fabricated sensor shows good flexibility with linear response up to the 20 mm bending radius and can be deployed on the curved hull of an underwater vehicle or on underwater structures of interest. These sensors can also easily be integrated into a complete monitoring system that includes an Arduino-based interface circuit for sensor readout that could be integrated with the sensor after proper packaging. The work presented in this paper extends the preliminary results presented during IEEE FLEPS 2021[13]. The extended work presented here includes encapsulation of the pressure sensor to be able to test it in the water environment. Therefore, a detailed characterization of the sensor in water have been conducted. In addition, the designed interfacing circuit allows real-time monitoring of the water pressure by the submersing sensor at varying depth.

This paper is organised as follows: The state of art related to soft capacitive sensors is presented in Section II. This is followed by the discussions in Section III related to the materials and methods used in this paper. The details of the sensor fabrication, characterisation, electronic components and readout circuit design used for the pressure sensing device are also presented in this section. The results related to sensor's performance in air and water conditions are described in Section IV and finally the key outcomes are summarised in Section V.

II. STATE OF THE ART

A wide variety of soft and conformable capacitive pressure sensors have been reported in literature for a range of applications. These sensors normally consist of two parallel flexible and conducting electrodes, separated by a soft dielectric layer based on different elastomeric formulations [14]. In all these sensors, the dielectric layer deforms in response to pressure stimuli, which results in change in the thickness or permittivity of the dielectric material between the two electrodes and hence causes a change in the capacitance. Considering this, the selection of dielectric material is crucial to achieve the desired dynamic range and sensitivity. Soft dielectric elastomers such as Ecoflex and silicone-based elastomeric polymers (e.g., polydimethylsiloxane (PDMS)) have been widely used as dielectric layers in capacitive pressure sensors [15]. PDMS is one of the most attractive dielectric layers due to its excellent mechanical strength, tunable elasticity, flexibility and conformability, and high dielectric properties [16]. PDMS is also environmentally friendly and demonstrates high chemical stability in water with low sensitivity to temperature and humidity [12, 17]. On the other hand, this silicone-based polymer has an high elastic modulus (~ 1 Mpa) and hardly squeeze under pressure, which means PDMS-based capacitive sensors will have limited sensitivity range under pressure [18].

In our previous work we have shown that the sensitivity of a bulk PDMS based pressure sensor is low (0.0008 kPa^{-1}) particularly in high pressure level (10-160 kPa) and it reaches to saturation level in higher pressure [5]. In this regards, different material design strategies have been investigated to expand the detection range and improve sensitivity in PDMS-based capacitive sensors. For example, the dielectric properties of PDMS elastomer layers have been modified by creating micro or nanostructured features such as pyramids, pillars, and pores structures [18-21]. The sensitivity tends to increase in porous PDMS due to two reasons. Firstly, the air gaps or porous formed in micro or nanostructured elastomers achieve a high compressibility compared to the bulk PDMS under the same applied external pressure and, thus, enhance the sensitivity. Secondly, the applied pressure causes an increase in the volume fraction of the PDMS to the air in the porous layer and followed by considerable changes in the effective dielectric constant of porous PDMS composites [22-24]. Such porous dielectric layers have been fabricated previously using sacrificial particles such as sugar or salt that dissolve in water or decomposition reaction with chemicals such as NH_4HCO_3 or $NaHCO_3$ [23, 25-27]. Chemical decomposition provides highly deformable porous PDMS with uniform porosity compared to the dissolution of sacrificial particles. In the second approach, some particles may be trapped inside the polymer and cannot be taken out through water dissolution.

Due to its simplicity and versatility, chemical decomposition process has been used to develop tuneable and highly sensitive flexible capacitive sensors which can be integrated with a range of flexible electronics and robotics technologies [28]. A few studies in the literature have reported the resistance [29] and capacitance [30] based flexible pressure sensors for underwater environment. However, they have been mainly been used for applications such as imaging [31] and wearables [29, 30] in the underwater environment, and not necessarily to measure the water pressure itself. For this reason, the sensors have been tested in a limited water depth and low-pressure range (usually

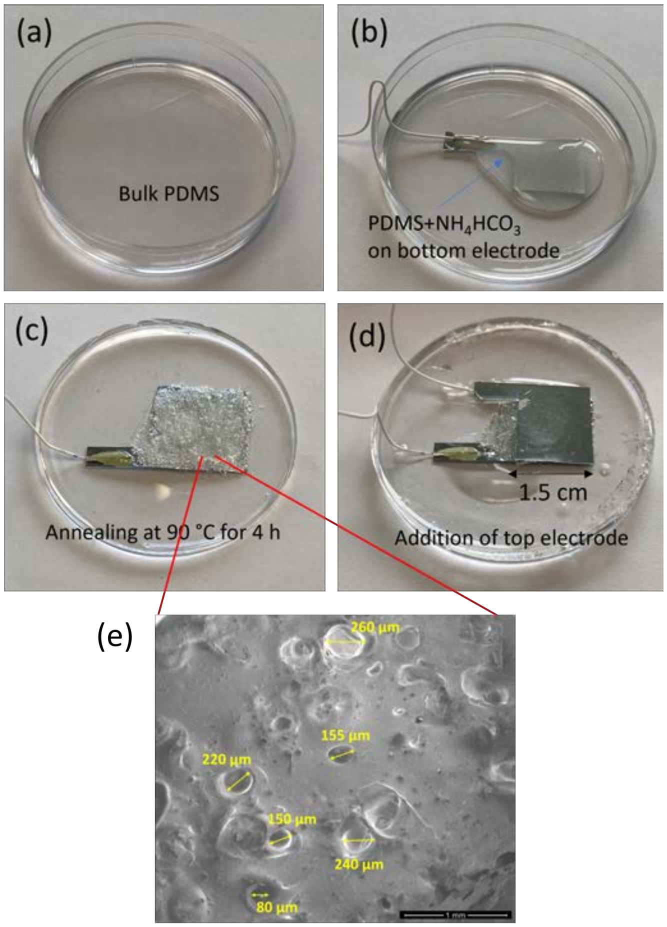

Fig. 2. (a-d) Photographic images showing fabrication steps of porous PDMS-based capacitive pressure sensor packaged with PDMS. (e) SEM image of the porous PDMS layer.

<10 kPa) [32]. An array of solid PDMS based capacitive pressure sensing system is another example that displays excellent performance in deep sea-water [33]. In comparison to multiple fabrication and lithography steps needed for these solid PDMS based capacitive sensors, the PDMS foam-based sensors presented here are developed with a simple fabrication technique that involves metal deposition on a polymer sheet and low temperature annealing of the polymer solution. Our results show that even a single porous PDMS-based capacitive pressure sensor would be promising for water pressure monitoring over a wide pressure range. Further, the sensitivity of the developed sensor can be tuned by optimizing the porosity and thickness of the dielectric layer, as discussed in Section IV.

III. MATERIALS AND METHODS

A. Sensor Fabrication

The preparation process of the packaged porous PDMS-based flexible pressure sensor is illustrated in Fig. 2. First, the top and bottom contact electrodes were prepared by depositing an 100nm thick layer of Al on PVC substrates using electron-beam evaporation. The wires are attached to the Al layer electrode, using a commercial conductive Ag ink. For underwater testing, the pressure sensor needs to be packaged to prevent water from entering the pores of the porous PDMS, as this affects the performance. For this purpose, the pressure sensor is encapsulated with PDMS elastomer. Therefore, the pressure sensor and packaging layer of PDMS were fabricated at the same time to seal the sensor, (see Fig 1). Firstly, a layer of bulk PDMS (10:1w/w polymer and curing agent) is cured in a Petri dish (Fig. 2a). An Al coated PVC film was placed on the PDMS layer as the bottom electrode, and a mixture of PDMS and ammonium bicarbonate (NH_4HCO_3) in a 4:1 (w/w) ratio was drop cast on the Al/PVC (Fig. 2b). Then, the sample was annealed at 90 °C for 4 h to decompose NH_4HCO_3 into NH_3, H_2O, and CO_2, forming microstructured PDMS film with high porosity and a thickness of about 1mm (Fig. 2c). PDMS solution was in contact with the electrode this decomposition and as a result the porous PDMS got attached to the electrode. Fig. 2e shows the SEM image of the porous layer. The pores are distributed relatively uniformly, with a size of about 220 µm. The other Al/PVC film was placed on top, then the PDMS solution is dispensed on topsides and was cured to package the sensor fully (Fig. 2d). Figure 1b shows the schematic of the encapsulated pressure sensor. The dimension of each sensor is 1.5 cm × 1.5 cm, and the thickness of the dielectric layer is 1 mm. For similar sensor packages, a constant amount of PDMS (3 gr) was added in a mould to cover the sensors. Since the dimensions of the sensors and mould were fixed, the thickness of PDMS capsulation is expected to be similar for all sensors.

B. Sensor characterization

For initial characterization of the sensor in the air, the porous capacitive sensor was firmly attached to a 1004 aluminium single point low-capacity load cell. Contact pressures ranging from 0–230 kPa were uniformly applied to the fabricated sensors, using a disk-type compression fixture with a diameter of 8 mm, attached to a computer-controlled linear motorized stage with a resolution of ~0.1 mm. The static response of the sensor under stepwise loading and unloading of 0–30 kPa in the air was also obtained using a load cell. In the water environment, the water pressure is proportional to the water depth as per the following formula: $P = \rho_w g h$. Where ρ_w is the density of water, g is the gravitational acceleration and h is the depth of the water. Water density depends on the surrounding temperature and the existence of impurities in the water. Five sensors have been tested to check the repeatability which is discussed in section IV. For consistency, the encapsulated sensors were used in both air and water.

The readout electronics has been designed using off-the-shelf components and a commercial Arduino microcontroller that communicates with an interfacing program to read the sensor's capacitance changes in the water environment. In addition, an E4980AL precision LCR meter (Keysight Technologies, Santa Clara, CA, USA) and a custom-made LabVIEW program were used as a reference measurement technique to record the capacitance changes of the sensors in the air and water environment and to compare the output of the developed device.

C. Design of interfacing circuit

An interfacing circuit was designed for the capacitive pressure sensor to collect the data in underwater environment.

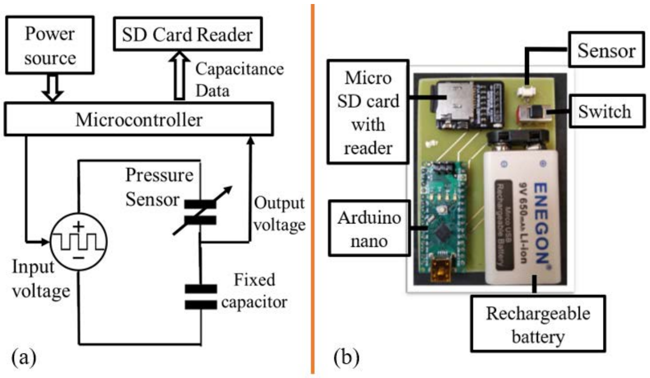

Fig. 3. Interfacing circuit for the capacitive pressure sensor: (a) block diagram, (b) PCB implementation

To this end, we have used a ccommercial ATmega328P microcontroller IC in Arduino Nano to read the capacitance and store its value in a SD data card. The interfacing circuit is quite simple. A square pulse voltage (V_1) is generated by the microcontroller and applied across the test capacitive pressure sensor (C_1) and a fixed capacitor (C_2). Output voltage (V_{out}) is measured across the fixed capacitor and calculated as:

$$V_{out} = \frac{V_1 \times C_1}{C_1 + C_2}$$

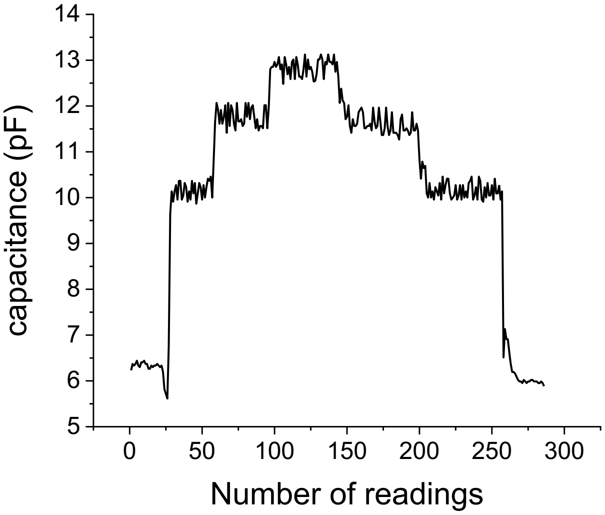

Fig. 4. Output of the electronic device showing capacitance change in pF with the change in water level.

As the Arduino operates at 5V maximum, value of V_1 a 0 to 5 V pulse. The circuit was also simulated in SPICE software and the circuit simulation gives the value of fixed capacitor as 24-30 pF. Output voltage across this fixed capacitor is fed to the microcontroller, which is programmed to calculate the capacitance and store the value in the SD card. Block diagramand PCB implementation of the circuit is shown in Fig. 3a and 3b respectively. The fixed capacitance C_2 in simulation is not present in hardware implementation as the Nano board has a comparable stray capacitance which is utilized in programming to show the final output. A rechargeable 9V battery powers the device for underwater standalone measurements. When this circuit is tested with the designed capacitive pressure sensor dipped in water, microcontroller shows the capacitance changes with the change in water level. For a repetitive measurement, the interfacing circuit shows an error of ±0.5% with the actual value shown in LCR meter. A continuous measurement of capacitance with the change in water level for one of the sensors is shown in the Fig.4. The data is shown by the microcontroller at every 0.2 s interval and 286 number of readings are plotted.

IV. RESULTS AND DISCUSSION

A. *Performance of the sensor in the air*

Fig. 5a presents the relative change in capacitance ($\Delta C/C_0$) of the packaged porous PDMS based pressure sensor under continuous loading and unloading. C_0 is the initial capacitance of the unloaded sensor, and C_{max} is the capacitance as a function of applied pressure, varying in pressures ranging from 0−200 kPa. Fig. 5b demonstrates the capacitance changes when the static pressure of 0−30 kPa is applied and removed in a stepwise manner. In this case, the sensor is tested in the air ambient, it shows a stable capacitance value for each step with very low hysteresis and also fast response/recovery time (190 ms). This means that PDMS fully restored after pressure loading due to the elastic and soft nature of porous PDMS. Five sensors were fabricated under the same condition to evaluate the repeatability. These dimensions of the dielectric layer, electrodes and PDMS packaging was similar in these sensors. Fig. 5c shows their sensitivity in the 0-230 kPa pressure range in the air. The porous elastomer-based soft pressure sensor demonstrated a near-linear response (98%) with a 130%

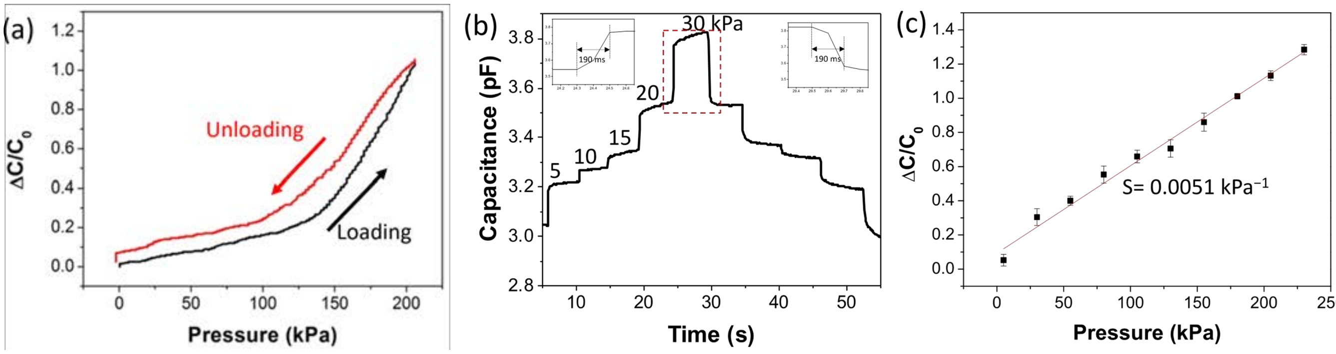

Fig. 5. (a) Variation of capacitance ($\Delta C/C_0$) of the porous PDMS based soft pressure sensor under continuous loading and unloading of 200kPa pressure. (b) Static response of the sensor under stepwise loading and unloading of 0–30 kPa. The insets show the response time of the pressure sensor for both loading and unloading. (c) The sensitivity of sensors in the 0-230 kPa pressure range in the air.

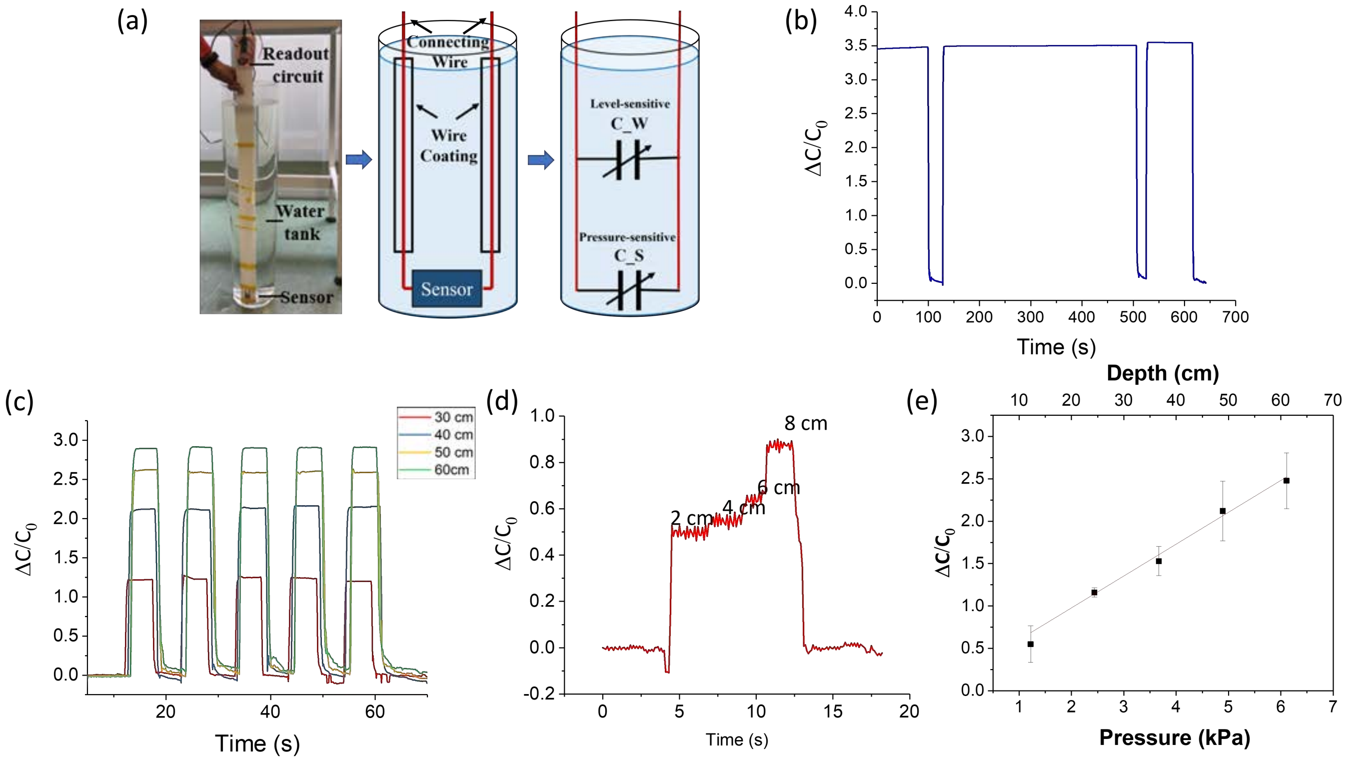

Fig. 6. (a) The sensor dipped in a water tank, and modeling of the level-sensitive and pressure-sensitive capacitance inside the water (b) The stability of the sensor response in the 70 cm depth of the water for few minutes and fully recovered to its initial state when it is taken out of the water. (c) The capacitance change (*$\Delta C/C_0$*) of the sensor under repeated dip cycles in the water, and (d) The detection limit of the sensor in water. (e) The sensitivity of sensors in the 0-62 cm water depth.

relative capacitance change in the air. The pressure sensitivity (S) is defined as $S = \delta(\Delta C/C_0)/\delta p$, where p is the applied pressure. The sensor exhibited a sensitivity of 0.0051 kPa^{-1}. The relative permittivity of the porous PDMS is between the relative permittivity of PDMS ($\varepsilon_{PDMS} = 2.7$) and the air ($\varepsilon_{air} = 1$), as it depends on the ratio of the air in the porous layer. Thus, the applied pressure causes an increase in the volume fraction of the PDMS, followed by increasing in the effective dielectric constant of the porous PDMS composite and also significant change in the thickness of the porous layer. Therefore, the capacitive pressure sensor with the porous PDMS dielectric layer showed an improved sensitivity and a wide measurement range because it requires a relatively high pressure to completely close the pores in the dielectric layer and the permittivity of the dielectric layer reach a saturation value. In the maximum pressure that we applied here (230 kPa) the sensor did not reach the saturation level yet.

Further, the porous PDMS is soft, and its elastic modulus is known to be much lower than the PDMS [34]. Sensor performance was measured in three different bending conditions (bending radii 10 mm, 20 mm, and 40 mm). As illustrated in Fig. S1, the deviation in sensor performance is 5.8% with the change in radius of around 88%. The sensor gives a linear response up to the 20 mm bending radius.

B. Performance of the sensor in the water environment

The performance of the same sensor was evaluated in the water environment. The sensor was packaged with the bulk PDMS to prevent water from entering into the pores of porous PDMS. Firstly, the performance of the sensor was tested in a water tank filled with tap water with a depth of about 70 cm. The sensor was connected to the electronic circuit through 1-meter cables and the packaged sensor was dipped in the water tank for up to depth of 70 cm (Fig. 6a) while the electronic readout was out of the water (see the setup in video file S1). The capacitive sensor's response and sensitivity were obtained. The sensor compresses under the pressure from water and its capacitance value changes due to changes in the thickness and dielectric constant properties of the porous PDMS. Fig. 6b shows the capacitance change response of the sensor under 70 cm water depth for few minutes. The sensor's response was stable at the defined water level, and it fully recovered to its initial value after removing from the water tank with negligible hysteresis effect.

Fig. 6c shows the change of capacitance and response of the sensor when it descends and ascends in different depths of the water (30, 40, 50 and 60 cm). Similarly, to the applying pressure in air condition, the sensor's performance is the same during five times loading and unloading at each water depth. Fig. 6d shows the detection limit of the sensor in water which shows that sensor can detect the water level as low as 2cm.

Fig. 6e shows the change of capacitance of five sensors (fabricated in the same condition and similar dimensions) in the different depths of the water. A linear correlation between water level and the sensor output was obtained. In the water depth of 0-62 cm, the sensor demonstrated an increase in capacitance from around 6 pF to 25 pF, resulting in an overall relative

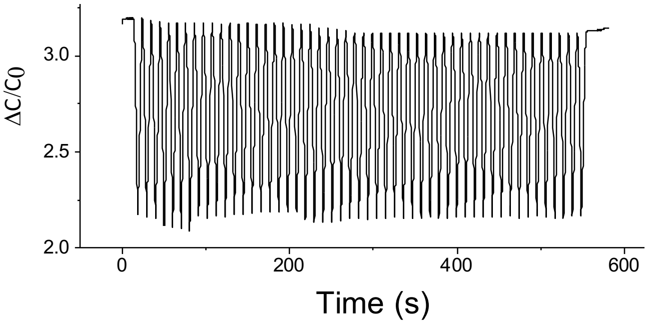

Fig. 7. The sensor response under cyclic loading and unloading for 50 cycles.

capacitance change of ~300%. The sensor also exhibited ~98% linear response with a high sensitivity of 0.375 kPa^{-1} in the 0-62 cm water depth.

The stability of the sensor was examined with cyclic loading and unloading from 45 to 65cm water depth. As shown in Fig. 7, the sensor maintained a stable response of $\Delta C/C_0$ under 50 cycles with negligible hysteresis, demonstrating a good durability in water. The slight drift in the response can be handled by better controlling the position of the sensor in the water in each cycle and suitable readout electronics, which needs further investigation. It may be noted that the $\Delta C/C_0$ changed quickly and reversibly, indicating that the porous elastomer-based soft pressure sensor had stable responses.

From above it is clear that the porous PDMS-based soft pressure sensor can provide a linear response with good sensitivity over a wide pressure sensing range. However, the sensor demonstrated a more sensitive response in water environment compared to the air. This is because of the two parallel cables that are dipped in water along with sensor to collect the data. These cables have conductive copper wire as the core and an insulated coating as shell. These cables introduce additional capacitance with copper wires acting as the electrodes and the insulation - water – insulation forming a composite dielectric medium. As the sensor goes deeper in the water, the additional capacitance introduced by the cables also increases. This level-sensitive variable capacitance C_W can be modelled along with the sensor capacitance C_S, as shown in Fig. 6a. Because of the additional variable C_W, the sensor demonstrated a greater sensitivity in water environment compared to the air. For real applications such as using the sensor to measure water depth or using it to control the depth of an underwater robotic vehicle, the additional response due to C_W can be compensated from the overall response. Alternately, the wireless data acquisition could be explored to prevent the introduction of additional variable capacitance.

In this work, the actual sensitivity of the sensor in water media is obtained by eliminating the wires effect. This is be achieved by encapsulating wires and electronics inside a watertight enclosure and exposing only the sensor to the water. We implemented this scheme as shown in Fig. 8a. The wires connections pass through the holes on top of the box they were sealed with epoxy (Fig. 8a). The box goes in different depths of the water pool for continues monitoring of water pressure (Fig. 8b). Fig. 8c shows the sensitivity of the sensor in different water depths (up to 400 cm) when the electronics and wires were placed in a watertight box to eliminate the additional capacitance mentioned above. In this case the change of capacitance was found to be much lower with increasing water depth. This sensitivity of the sensor was 0.005 kPa^{-1} (Fig. 8c), which matches the sensor's performance in the air (0.0055 kPa^{-1}) in Fig. 5c.

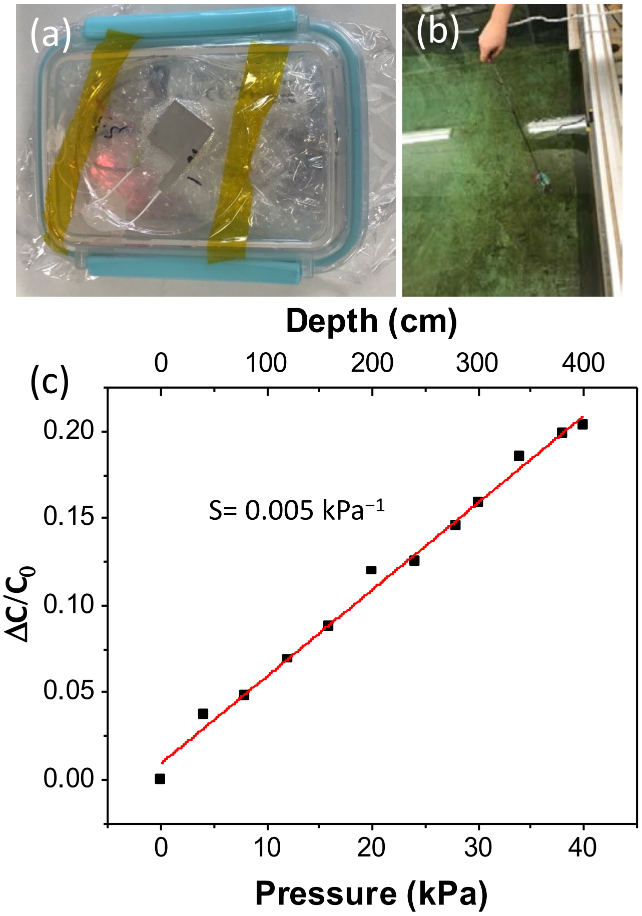

Fig. 8. (a) The electronics and wires placed inside a watertight enclosure and sensor exposed to the water (as in the case of underwater vehicles). (b) The image from real experiment conducted in deep water tank. (c) The response of the sensors at varying depths. d

The sensor performance can be further improved by optimizing the size and distribution of pores in the dielectric layer by varying the NH_4HCO_3 content in the polymer solution and/or adding sacrificial particles to introduce a hierarchically structured porous PDMS layer [25]. The thickness of the dielectric porous PDMS can be optimized as well to achieve both high sensitivity and wide-range pressure sensing. In addition, capacitive sensors made from other soft dielectric polymers such as a liquid metal elastomeric foam [34][35] or 3D porous Ecoflex [23], can be investigated. Furthermore, arrays of multiple sensors connected in parallel can improve the sensitivity of the sensor. The sensor can thus be used to monitor a wide range of different static and quasi-static pressure values experienced in applications ranging from human activity monitoring to surface-mountable skins for flexible electronics and robotics, including those that can generate the 'feel' of harsh water environments.

V. CONCLUSIONS

In summary, a soft and conformable capacitive pressure sensor was fabricated by sandwiching a porous PDMS dielectric layer between two Al coated flexible PVC sheets. We investigated the performance of the fabricated sensor in water for up to 4 m depth. The fabricated sensor could detect water pressures with stable response and good sensitivity. The sensor presented excellent performance in water with a near-linear response (98%) and a sensitivity of 0.005 kPa^{-1} in 0-40 kPa pressure regimes. The sensor also exhibited good repeatability and high durability in water. The fabricated flexible capacitivee pressuree sensors can be integrated with a range of flexible electronic and robotic technologies, including underwater sensing and surveillance. Our future aim is to deploy this flexible porous capacitive pressure sensor on marine robots for continuous water pressure monitoring and depth sensing in real-world water environments.

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