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Flexible Hydrogel Capacitive Pressure Sensor for Underwater Applications †

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Abstract: This paper reports development of a novel, flexible hydrogel based capacitive pressure sensor. It features a simple design of hydrogel thin film sandwiched between two gold electrodes. The sensor shows linear increase in output with increase in pressure. The microporous network of hydrogel enables high water retention while its flexible and stretchable structure ensures usage over large areas. These factors, combined with its stability in water, make it an ideal candidate for underwater applications. Further, the physical and chemical properties of hydrogels can be tailored to tune the capacitance to specific sensing needs. Flexible arrays of capacitive sensors with hydrogel hold great potential for underwater smart skin applications.

Keywords: capacitive; hydrogel; pressure sensor; smart skin

1. Introduction

Hydrogels are three dimensional crosslinked networks of hydrophilic polymers capable of retaining large volumes of water. They are either chemically or physically crosslinked and possess unique structural and mechanical properties that can be tailored to specific requirements. These tunable soft hydrogels can be used as a dielectric layer between two electrodes to fabricate capacitive pressure sensors. These hydrogel based sensors find applications as soft actuators, transducers, tactile and chemical sensing, etc. [1–4]. Owing to their water-retaining property and stability within water, hydrogel based capacitive sensors can be employed for sensing underwater flows. In addition, the excellent acoustic impedance match to water makes them promising as capacitive pressure or acoustic transducer [5]. Underwater sensing faces certain limitations such as robustness of sensors in harsh environments, biofouling, corrosion, and inability to sense over large areas for high throughput sensing [6]. An array of hydrogel based capacitive sensors with patterned electrodes presents a good prospect for constructing surface mountable, flexible smart skins for underwater vehicles.

Dimethylacrylamide (DMAA) based hydrogels have been widely investigated for biomedical and pharmaceutical applications because of its hydrophilic and biocompatible nature with associative properties [7,8]. These hydrogels, when synthesized by self-crosslinking in the presence of free radical initiators, exhibit excellent toughness and extensibility while having high swelling. These mechanical properties and the hydrophilic nature of DMAA are highly desirable to develop a sensor for underwater applications. Moreover, the crosslinking conditions are mild at room temperature. To the best of our knowledge, DMAA polymer hydrogel based capacitive pressure sensor has not been developed in the past. A thin film of hydrogel was prepared and placed between two chromium/gold (Cr/Au) electrodes to develop a simple, flexible yet robust capacitive pressure

sensor. This paper aims to study the sensing performance of this hydrogel sensor as a potential candidate for smart skin applications.

2. Experimental Section

2.1. Hydrogel Synthesis and Characterization

The self-crosslinking ability of DMAA was used for thin film hydrogel synthesis as described previously [8]. Briefly, 33 wt % DMAA was dissolved in deionized (DI) water and nitrogen (N_2) gas was bubbled through this solution for 45 min to remove dissolved oxygen. Potassium perfulfate (KPS), 1 mole % with respect to DMAA in solution, was added and N_2 gas was continued to bubble through the solution for another 15 min. *N,N,N′,N′*-tetramethylethylenediamine (TEMED) was then added and the solution was kept at room temperature to allow polymerization reaction (crosslinking) to continue for 24 h. After crosslinking, hydrogel film was immersed in DI water for 5 days to reach swelling equilibrium. The water swollen hydrogel film was used for sensor testing experiments. For morphological characterization of DMAA hydrogel, the water swollen film was dipped in liquid nitrogen for few seconds for rapid quenching and then lyophilized for 72 h. The dry hydrogel film was gold coated for 80 s and examined under scanning electron microscope (SEM) (JSM 6360A Jeol, Japan) at 5 kV acceleration voltage.

2.2. Sensor Fabrication and Testing

For sensor fabrication, firstly two electrodes were prepared by sputtering a Cr (20 nm)/Au (100 nm) layer on silicon substrate. A connecting wire was attached to each of the electrodes using conductive epoxy EPO TEK H20E (Epoxy Technology Inc., Billerica, MA, USA). The water swollen hydrogel was placed between these two electrodes and the electrodes were connected to a DC power supply of 5 V through a resistor as shown in Figure 1. The hydrogel film sensor was characterized for sensing ability by collecting its response to applied pressures. Pressures were applied on the hydrogel film via top electrode at fixed intervals and the sensor output was collected by National Instruments data acquisition (NI-DAQ) system USB–6289 M-series and recorded using LABVIEW software system.

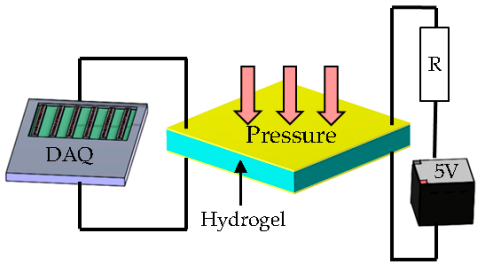

Figure 1. A schematic showing the experimental set up of hydrogel capacitive pressure sensor.

3. Results and Discussion

Free radical polymerization of DMAA, in the presence of KPS and TEMED initiators, results in self-crosslinking of DMAA chains to form a hydrogel with superabsorbent property and high mechanical strength [8]. A thin film of hydrogel was prepared by this polymerization reaction, swollen in water, and used to develop the capacitive pressure sensor. Figure 2 is a schematic representation of the hydrogel network with crosslinking points and water-filled pores. The water swelling behavior and mechanical properties of hydrogel can be controlled by varying crosslinking conditions and concentrations of DMAA and KPS.

The morphology of hydrogel was observed using SEM. Figure 3 shows a SEM image of lyophilized hydrogel film sample. It shows porous network structure indicating its ability to absorb and retain large volumes of water inside its matrix. These large pores ensure high water retention,

and thereby the polymer's stability for underwater environment. Thus, the properties of high water swelling and mechanical strength of DMAA hydrogel facilitate the development of a robust capacitive pressure sensor for underwater sensing applications.

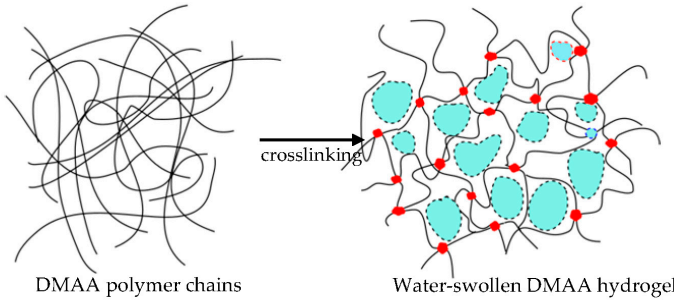

Figure 2. A schematic showing DMAA polymer chains and self-crosslinked flexible hydrogel structure with crosslinking points (red) and water molecules (blue) entrapped within its network.

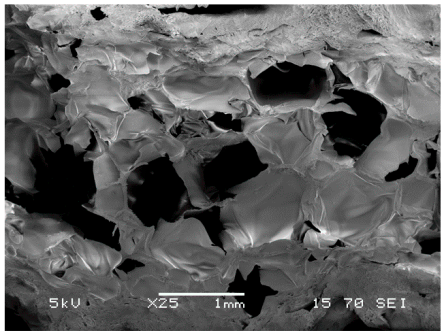

Figure 3. Scanning electron micrograph of DMAA hydrogel showing large pores in the network.

Figure 4a shows the sensor response to a pressure of 250 Pa applied on the hydrogel film. As pressure is applied, the hydrogel film is pressed, bringing the two electrodes closer. The reduction in gap results in increase in capacitance and this in turn gets reflected as the change in the voltage output. A sharp dip was observed in the output upon application of pressure. During recovery, the original baseline could not be reached due to the viscoelastic nature of hydrogel having low relaxation times. Further, with increase in pressure, the output was found to increase linearly with a slope of 0.135 mV/Pa as shown in Figure 4b.

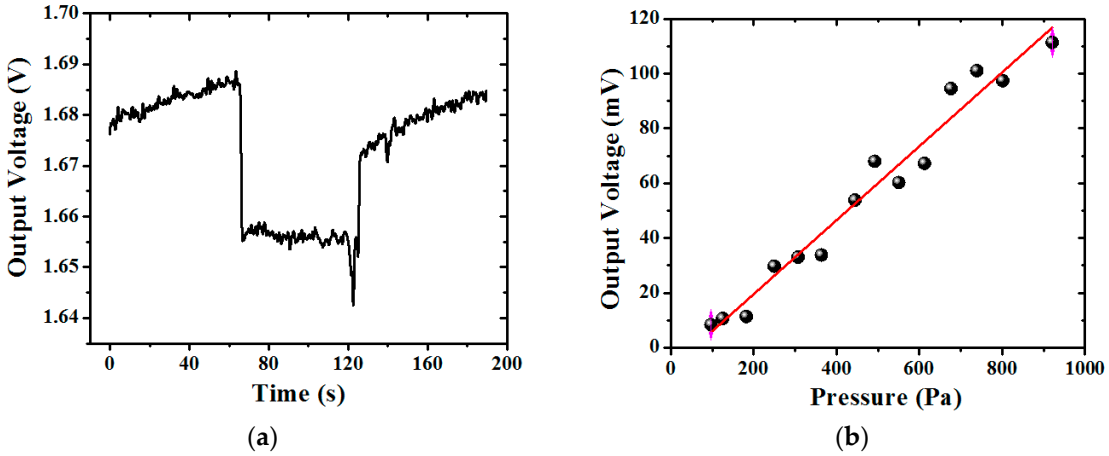

Figure 4. Sensor response to applied pressure (**a**) Sensor output plot showing a sharp dip and recovery in response to the application and removal of a pressure of 250 Pa, respectively; (**b**) Sensor response showing a linear increase in the output with increase in applied pressure.

For underwater sensing and smart skin applications, we propose fabrication of a sensor array with multiple electrodes and a hydrogel thin film embedded within. Figure 5 shows the proposed design for a sensor array with hydrogel incorporated between patterned electrodes. Each pair of bottom and top electrode together with the hydrogel film would comprise a pressure sensor. Such an array of sensors mounted on a surface, can provide variation of pressure across the surface.

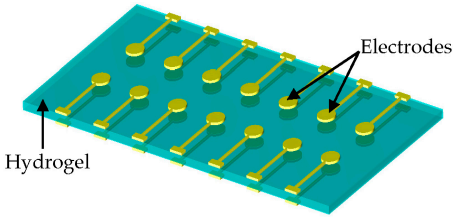

Figure 5. Schematic of the proposed design of hydrogel capacitive pressure sensor array with patterned electrodes on top and bottom surface of hydrogel.

4. Conclusions

Hydrogels are promising materials to develop capacitive pressure sensor for underwater applications. In this work, we developed a simple, low cost, easy to fabricate hydrogel pressure sensor using flexible and robust DMAA hydrogel thin film sandwiched between Cr/Au electrodes. The hydrogel has high water retention ability owing to large pores in its network. In response to applied pressure, the sensor output was found to increase linearly. The hydrogel will be further investigated for its swelling and mechanical behavior to optimize the sensitivity and efficiency of the overall sensor. This hydrogel sensor, besides underwater vehicles sensing applications, would also find applications in soft robotics, biomedical devices, and optoelectronics.

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Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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