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Novel Supercapacitor-Based Force Sensor Insensitive to Parasitic Noise

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Abstract

Traditional capacitive sensors suffer from significant parasitic noise when used in liquid environments or inside the human body. The parasitic noise overwhelms the force response of the sensor and makes it impossible to calculate the absolute force experienced by the sensor. This article focuses on the development of a supercapacitor based force sensor that is immune to parasitic noise. The supercapacitor consists of co-planar electrodes and a solid state ionic gel electrolyte on a deformable membrane. Force exertion causes deformation of the electrolyte membrane, increases its area of contact with the electrodes, resulting in a change of capacitance. The sensor is sealed, waterproof, and shows absolutely no changes in capacitance when immersed in water or enclosed in extracted sheep tissue. At the same time, its force sensitivity of $0.13 \mu\text{F/N}$ exceeds the 0.3 pF/N sensitivity of a traditional capacitive sensor by 6 orders of magnitude. The developed sensor could have many biomedical applications in which parasitic capacitance is a serious challenge.

Index Terms

Supercapacitors; force sensors; parasitic capacitance; liquid environment

I. INTRODUCTION

1.1 Background

Capacitive sensors have low temperature hysteresis, high sensitivity and low power consumption ([1]–[4]). In capacitive force sensors, the force is translated into a change in the distance between two parallel-plate electrodes. By measuring the real-time capacitance between the electrodes, the force can be calculated. Figure 1(a) shows a parallel plate capacitive sensor. In addition to the electric field in between the parallel plates, the device also has *fringe* capacitance due to the electrical field lines at the edges of the device. When a capacitive sensor is immersed in a liquid environment or is placed inside a human or animal body, the fringe capacitance becomes very significant due to the high dielectric constant of the surrounding medium. As shown in Figure 1(b), the surrounding in vivo environment

causes an additional capacitance called as parasitic capacitance which can cause a large error in the relationship between force and the measured capacitance value. In fact, parasitic capacitance in water or tissue can be several times as large as the nominal capacitance due to force for a conventional capacitive sensor ([5]–[7]). Due to the existence of the fringe electric field around the electrodes, parasitic noise is inevitable in these conventional sensors.

The error due to parasitic capacitance can be compensated by measurement of background capacitance in the absence of loads and subsequent subtraction of this value, but this is only possible when the parasitic noise is static. In biomedical in-vivo applications of the capacitive sensors, the interference from human tissues on the fringe electric field of the sensor can cause highly dynamic parasitic noise, which can greatly contaminate the sensor signal and cannot be eliminated by subtraction.

This paper pertains to a supercapacitor-based force sensor, in which the parasitic capacitance can be negligible due to the fringe field being extremely small. Such a sensor would be extremely valuable for accurate measurement of force in water and in human body environments.

In a supercapacitor, the capacitance is created by using a pair of electrodes and an electrolyte ([8]–[11]). A basic form of a supercapacitor is shown in Figure 1(c), consisting of two electrodes and an electrolyte solution in between. The application of a voltage across the electrodes enables the flow of ionic current between the electrodes, due to the presence of the electrolyte. A supercapacitor is governed by the same fundamental equation as a traditional capacitor in which capacitance can be described by

$$C = \frac{\epsilon A}{d} \quad (1)$$

where A is the geometric surface area of the electrode; ϵ is the relative permittivity of the dielectric material; and d is the distance between two oppositely biased electrodes. However, in a supercapacitor, the oppositely charged particles are separated from each other by a distance equal to just the size of 1 or 2 layers of atoms. This is because, as shown in Figure 1(c), the positive and negative ions in the electrolyte separate from each other forming positive and negative layers of charges at the negative and positive electrodes respectively. The electrode-electrolyte interface at each electrode results in a double layer formed between the electrolyte ions and the electronic charges on the electrode ([12], [13], [14]). Hence, d in Eq. (1) is the double layer atomic thickness, which is very small (of the order of Angstroms), making the fringe field and the resulting parasitic capacitance extremely small.

1.2 The use of a supercapacitor as a sensor

In a supercapacitor, the distance between the positive and negative charges at each electrode is of the order of the size of 1 or 2 layers of atoms. Unlike a traditional capacitor, the distance d does NOT change in a supercapacitor based sensor. Instead the area A needs to change in response to force. In a previous supercapacitor based sensor, researchers used a

liquid electrolyte and the contact area between this liquid and the electrode changed in response to force ([16]). Figure 2 shows a schematic example of a supercapacitive sensor in which a drop of electrolytic fluid is squeezed between two electrodes. A force on the electrodes causes the drop to be squeezed, resulting in a change in the contact area between the electrolyte and the electrodes. This results in a change in capacitance, which serves as a measure of the applied force. Here, the surface of the electrodes needs to be treated so as to be superhydrophobic. This ensures that the electrolyte does not “stick” to the electrodes and moves quickly in response to applied force, without any hysteresis.

The disadvantages of the droplet based supercapacitive sensor include the fact that the sensor cannot be easily miniaturized and the need for an expensive hydrophobic coating. In addition, the effect of gravity on the droplet will limit its applicability in non-planar applications, and the sensor will have limited shelf life due to liquid evaporation.

Other supercapacitive sensors have also been explored [15], but they have never before been shown to work accurately in liquid and/or tissue environments. The use of a supercapacitive sensor in liquid environments needs it to be both sealed so as to prevent fluid leakage into the sensor and to also be immune to parasitic capacitance. This letter develops a design for such a sensor and demonstrates its performance.

II. SENSOR DESIGN AND FABRICATION

A novel solid-state supercapacitor based force sensor that does not use liquid droplets is developed. The proposed supercapacitive sensor consists of 3 layers which are the bottom layer with the two parallel electrodes, the spacing layer and the top layer with solid electrolyte transferred on (Figure 3(a)). Two gold electrodes were fabricated by first evaporating gold on the polyimide (PI) substrate and then patterning using photolithography and wet etching technique. The planar layout of the two electrodes on the same substrate make the alignment easier during bonding. The spacing layer is made of PDMS (Polydimethylsiloxane) by molding. The solid electrolyte is essentially a ionogel, in which the ionic liquid (IL) can move freely in the matrix of the UV-curable polymer gel. An IL, 1-ethyl-3-methylimidazolium tricyanomethanide [EMIM] [TCM] (IOLITEC Inc.), a prepolymer solution, consisting of PEG diacrylate (PEGDA, $M_w = 575 \text{ g mol}^{-1}$) monomers (Sigma-Aldrich) and a photo initiator of 2-hydroxy-2-methylpropiophenone (HOMPP, Sigma-Aldrich) were mixed at a ratio of 50:40:10wt%. The mixture was drop-cast on a slide with Kapton tape defined boundaries and covered by another slide on top. Then it was put under a UV lamp ($265 \mu\text{W}/\text{cm}^2$) and exposed for 1min. The cured solid electrolyte film was transferred onto a clear PET (Polyethylene terephthalate) film (Dura-Lar, 0.003inch) as the top flexible layer. For bonding, the three layers were treated with oxygen plasma first, and then a thin layer of uncured PDMS was brushed on the bonding surfaces. At last, they were pressed together and left on a hotplate at 75°C for 12hr. The sensor was fully sealed and protected from water leaking-in. The effective sensing area was $10 \text{ mm} \times 13 \text{ mm}$ and the chamber formed by the spacing layer had a depth of 0.7 mm. A photograph of the as-fabricated sensor is shown in Figure 3(b).

The supercapacitive sensor was fixed to a slide and tested by applying forces on it using a force gauge (Handpi, Digital Force Gauge) both in air and in water. The capacitance changes were recorded using a capacitance meter (Rigol 3058E). A soft rubber was put on top of the sensor to generate a distributed force. For the test in water, the whole device was immersed in water in a shallow container. The normal force from water is negligible (less than 0.01N).

In order to compare the supercapacitor's performance with a more traditional sensor, a conventional capacitive force sensor was also fabricated (Figure 4(a)).

The capacitive sensor also consists of three layers which are the bottom layer with one electrode, an insulation layer on top of the electrode, a spacing layer and a top layer with the other electrode. The copper electrodes were patterned on PI/Copper substrate (DuPont™ Pyralux® AC) using wet etching technique. On one electrode, a thin PDMS layer was brushed for insulation. The spacing layer is obtained using the same molding method as on the supercapacitor. The top and bottom layer were stacked together and aligned face to face with the spacing layer in between as shown in Figure 4(a). The bonding method is same as described for the supercapacitor. The as-fabricated conventional capacitive sensor is shown in Figure 4(b). The dimensions of the conventional sensor are approximately the same as those of the supercapacitive sensor.

III. RESULTS AND DISCUSSION

The test results for the supercapacitive sensor are shown in Figure 5. As the force increases, the contact area between the solid electrolyte and the electrodes underneath increases, resulting in a change in capacitance, as shown earlier in Figure 3 (c). The sensitivity of the supercapacitive sensor is around 0.13 μ F/N. In comparison of the response in air and water, there isn't any obvious capacitance change due to operation inside water. In other words, the sensor has negligible parasitic capacitance.

The results for the traditional capacitive sensor are shown in Figure 6. As the force increases, the distance between two electrodes decreases, thus increasing the capacitance. The sensitivity of capacitive sensor is approximately 0.3pF/N which is much lower than that of the supercapacitive sensor. More importantly, after immersion in water, the capacitance of the sensor increases by as much as 50%, which is caused by parasitic noise. A huge offset in measured capacitance can be seen in Figure 6 between the in-water and in-air values.

A larger range of forces is shown in Figure 6 because of the lower sensitivity of the sensor. Both sensors had approximately the same operating range of force measurement.

In order to further investigate the different influence of parasitic capacitance on the supercapacitive sensors and capacitive sensors, the two sensors were also tested in four additional scenarios as described below:

Scenario 1: A steel tweezer was placed over the sensors (1–2mm away from the top of the sensor)

Scenario 2: A human finger was used to approach the sensors (1–2mm away from the top of the sensor)

Scenario 3: The two wires which collect current from the two electrodes were untwisted.

Scenario 4: The sensors were placed inside extracted real sheep tissues. (The tissues were carefully wrapped around the sensor to make sure no pressure is applied on the sensing area, but the sensor itself is enclosed by the tissue)

The results from the four scenarios are shown in Figure 7. As shown in the figure, when a finger approaches or a metal tweezer is moved close to the traditional capacitive sensor, its capacitance increases significantly, which means an additional parasitic capacitance is created in these two scenarios. That makes the sensor sensitive to interferences and limits its use in many circumstances. Besides, the capacitance of the traditional sensor became smaller after the wires were untwisted. The parasitic noise from the wires is not negligible, since the capacitance of the conventional sensor is low. When put inside the real sheep tissues, the capacitance jumped to nearly twice of the original capacitance. That limits capacitive sensors in in-vivo use, like bio-sensors. However, in case of the supercapacitive sensor, the capacitance remained exactly the same in all four scenarios, with no change whatsoever.

IV. CONCLUSIONS

A novel solid state supercapacitor based force sensor has been developed and successfully fabricated using an ionic gel solid electrolyte and planar electrodes. Also, a similarly-sized conventional capacitive sensor was fabricated to compare its performance with that of the supercapacitive sensor. Tests have been conducted on these two sensors in air and in water, as well as in other typical use scenarios. Results show that while the conventional capacitive sensor suffers significantly from parasitic noise and has significantly lower sensitivity, the new supercapacitor-based force sensor is completely immune from parasitic capacitance. Furthermore, its force sensitivity of $0.13 \mu\text{F/N}$ exceeds the 0.3 pF/N sensitivity of the conventional capacitive sensor by 6 orders of magnitude! This indicates that the supercapacitor based sensor could be highly suitable for biomedical in-vivo applications. In future work, the supercapacitive sensor will be miniaturized and applied for in-vivo use in an actual biomedical application.

References

1. Kasahara T, Mizushima M, Shinohara H, Obata T, Futakuchi T, Shoji S, Mizuno J. Simple and Low-Cost Fabrication of Flexible Capacitive Tactile Sensors. *Jpn J Appl Phys.* 2011; 50:016502.
2. Lei KF, Lee K-F, Lee M-Y. Development of a flexible PDMS capacitive pressure sensor for plantar pressure measurement. *Microelectron Eng.* 2012; 99:1.
3. Yu H, Guo B, Haridas K, Lin T, Cheong JH, Tsai ML, Yee TB. Capacitive micromachined ultrasonic transducer based tilt sensing. *Appl Phys Lett.* 2012; 101:153502.
4. Kang BS, Kim J, Jang S, Johnson FRW, Therrien RJ, Rajagopal P, Roberts JC, Piner EL, Baik KJLNGC, Gila BP, Abernathy CR, Pearton SJ. Capacitance pressure sensor based on GaN high-electron-mobility transistor-on-Si membrane. *Appl Phys Lett.* 2005; 86:253502.
5. Eswaran P, Malarvizhi S. MEMS Capacitive Pressure Sensors: A Review on Recent Development and Prospective. *Int J Eng Technol.* 2013; 5:2734.
6. Ahmadi M, Rajamani R, Timm G. Flexible Distributed Pressure Sensing Strip for a Urethral Catheter. *J Microelectromechanical Syst.* 2015; 24:1840.

7. Suter JD, Hohimer CJ, Fricke JM, Christ J, Hanseup K, Evans aT. Principles of Meniscus-based MEMS Gas or Liquid Pressure Sensors. *J Microelectromechanical Syst.* 2013; 22:670.
8. Karakaya M, Zhu J, Raghavendra AJ, Podila R, Parler SG, Kaplan JP, Rao AM. Roll-to-roll production of spray coated N-doped carbon nanotube electrodes for supercapacitors. *Appl Phys Lett.* 2014; 105:263103.
9. Jang Y, Jo J, Jang H, Kim I, Kang D, Kim K-Y. Activated carbon/manganese dioxide hybrid electrodes for high performance thin film supercapacitors. *Appl Phys Lett.* 2014; 104:243901.
10. Jung H, Ve Cheah C, Jeong N, Lee J. Direct printing and reduction of graphite oxide for flexible supercapacitors. *Appl Phys Lett.* 2014; 105:53902.
11. Jang Y, Jo J, Woo K, Lee S-H, Kwon S, Kim K-Y, Kang D. 2D all-solid state fabric supercapacitor fabricated via an all solution process for use in smart textiles. *Appl Phys Lett.* 2017; 110:203902.
12. Hu S, Rajamani R, Yu X. Flexible solid-state paper based carbon nanotube supercapacitor. *Appl Phys Lett.* 2012; 100:104103.
13. Notarianni M, Liu J, Mirri F, Pasquali M, Motta N. Graphene-based supercapacitor with carbon nanotube film as highly efficient current collector. *Nanotechnology.* 2014; 25:435405. [PubMed: 25301789]
14. Zhang Y, Rajamani R. High-voltage thin-film supercapacitor with nano-structured electrodes and novel architecture. *Technology.* 2016; 4:55.
15. Nie B, Li R, Cao J, Brandt JD, Pan T. Flexible Transparent Iontronic Film for Interfacial Capacitive Pressure Sensing. *Adv Mater.* 2015; 27:6055. [PubMed: 26333011]
16. Nawi, MNM., Manaf, AA., Rahman, MFA., Arshad, MR., Sidek, O. 2013 IEEE SENSORS. Baltimore, MD: 2013. One side electrode type fluidic based capacitive pressure sensor; p. 1

Figure 1.

(a) Fringe electric field and parasitic capacitance on a capacitive sensor; (b) Equivalent electric circuit; (c) Schematic representation of a supercapacitor.

Figure 2.

Electrolyte droplet based supercapacitor force sensors

Figure 3.

(a) Structure of the supercapacitive sensor; (b) photograph of the as-fabricated supercapacitive sensor (c) illustration of sensing mechanism

Figure 4.

(a) Structure of the capacitive sensor; (b) photograph of the as-fabricated capacitive sensor

Figure 5.
Response of supercapacitive sensor to applied force in air and in water

Figure 6.
Response of a traditional capacitive sensor to applied force in air and in water

Figure 7.
Four test scenarios