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Transparent Flexible Active Faraday Cage Enables In Vivo Capacitance Measurement in Assembled Microsensor

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Abstract

Capacitive micro-sensors such as accelerometers, gyroscopes and pressure sensors are increasingly used in the modern electronic world. However, the in vivo use of capacitive sensing for measurement of pressure or other variables inside a human body suffers from significant errors due to stray capacitance. This paper proposes a solution consisting of a transparent thin flexible Faraday cage that surrounds the sensor. By supplying the active sensing voltage simultaneously to the deformable electrode of the capacitive sensor and to the Faraday cage, the stray capacitance during in vivo measurements can be largely eliminated. Due to the transparency of the Faraday cage, the top and bottom portions of a capacitive sensor can be accurately aligned and assembled together. Experimental results presented in the paper show that stray capacitance is reduced by a factor of 10 by the Faraday cage, when the sensor is subjected to a full immersion in water.

Index Terms

MEMS; pressure sensors; Faraday cage; Stray capacitance

I. INTRODUCTION

Micro-sensors that measure pressure, force, touch or motion have seen significant developments recently [1]–[10]. Several of these new micro-sensors are based on capacitive transduction [7], [8], [9] and [10]. In particular, capacitive sensors are frequently used in accelerometers and gyroscopes [9]. Many researchers are also studying the use of micro-sensors in biomedical applications where flexible devices that can function in the circulatory or urinary system and even in the brain to measure pressure, temperature, electrical and chemical measurements will be needed in the future [11]–[16].

Capacitive pressure sensors are highly sensitive and also have superior low-drift properties with temperature and humidity, compared to those of piezo-resistive devices. But capacitive

sensors suffer from an inherent problem that has been rarely recognized or addressed in literature – They suffer from significant stray capacitance induced by the body during in vivo applications. Hence, in vivo biomedical applications of such sensors typically measure dynamic variables, rather than absolute (or static) values [10], [17], [18].

This letter addresses stray capacitance by developing a Faraday cage that encloses the sensor and is utilized electrically during capacitance measurement to shield against fringe fields from the human body. The letter shows how the Faraday cage can be made transparent so as to enable assembly of separately fabricated sensor components, and can yet function effectively.

II. STRAY CAPACITANCE

For a parallel plate capacitor with large electrode area, electrical field is almost uniform between the electrodes and the capacitance is given by:

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

where C is the capacitance, ϵ is the permittivity of the dielectric material between the electrode plates, A is the common area between the electrodes and d is the distance between the electrodes. In Equation (1), the fringe electric fields at the edges of the plate are neglected. This assumption holds well when the common area between the electrodes is very large compared to the distance between the plates. In real life, however, fringe electrical field outside the capacitor penetrates neighboring materials, as shown in Figure 1a and builds additional capacitance which is called stray capacitance. If the capacitor's lateral dimensions are not much larger than the distance between the electrodes, this stray capacitance cannot be ignored anymore. The latter is the case in micro-fabricated capacitive sensors where the thickness of the sensor can be between 10 and 100 microns, while the lateral dimensions are of the order of 100 – 500 microns. Due to the large dielectric constant of water and tissues that surround the sensor during in vivo applications (Figure 1a), the magnitude of the stray capacitance can be relatively large (10s of pico Farads, pF) compared to the direct response of the sensor to force (0.1–10 pF).

To measure sensor capacitance in real time, a capacitance to digital converter (CDC) chip such as the Analog Devices IC chip AD7147 is often utilized. This 16 bit $4 \times 4 \text{ mm}^2$ chip can be connected simultaneously to 12 capacitors and can measure a capacitance change of up to $\pm 8 \text{ pF}$ relative to ground in real time. The capacitance is measured by sending a 250 kHz square wave signal to charge and discharge the capacitors and measuring the time constant for the same.

In order to eliminate stray capacitance for in vivo applications, this letter proposes that the sensor be covered by an active Faraday cage, as shown in Figure 1b. The Faraday cage consists of a highly conductive material that surrounds the entire sensor. Figure 1a shows a schematic of the original sensor consisting of parallel plate electrodes made of copper on a polyimide substrate. The fringe electric fields outside the sensor are illustrated in Figure 1a.

To eliminate stray capacitance from being measured by the CDC chip, this letter proposes that the active square wave voltage supplied to the electrode for purposes of capacitance measurement be simultaneously supplied to the Faraday cage, as shown in Figure 1b. The Faraday cage voltage $V_{acs}(t)$ is then driven to the same voltage potential as the sensing electrode $V_s(t)$ at all times, to make the capacitance between the Faraday cage and the sensing electrode to be zero. Then any capacitance created by external fringe fields between the Faraday cage and neighboring materials will not affect the capacitance measurement. In the ideal case the stray capacitance can be completely reduced to zero in this case. Figure 1c shows the fringe electric fields being confined entirely to stay within the Faraday cage by using this active shielding technique.

Note that while the use of a Faraday cage to protect humans from lightning and other similar applications are well known, the use of a transparent thin Faraday cage which is supplied an active capacitive sensing voltage to shield a micro-sensor from stray capacitance is a novel technique that is being proposed for the first time in this letter.

III. DESIGN AND FABRICATION OF A SHIELDED CAPACITIVE SENSING STRIP

A flexible sensing strip with 9 capacitive force sensors on it is fabricated (Figure 2b). Being an ultra-thin flexible sensing strip, it can be adhered to catheters that can be used in urology, endoscopy and other in vivo applications. The flexible capacitive pressure sensing strip is made of three separate layers: top, middle and bottom. The top and bottom electrodes contain copper electrode on a polyimide substrate while the middle polymer layer serves as the glue and separator between the top and bottom electrodes. The middle layer is made of PDMS. The three layers need to be aligned with respect to each other and then assembled to create the sensor.

The schematic of an individual capacitive sensor on this sensing strip is shown in Figure 2a. A photograph of the fully fabricated sensing strip with all 9 sensors on it is shown in Figure 3a. The overall dimensions of the top layer of electrodes in the sensing strip is approximately $7\text{ cm} \times 3\text{ mm}$, with micro-fabricated built in features inside each sensor of $20\text{ }\mu\text{m}$ resolution.

The electrodes on both top and bottom layers are created by using a substrate of polyimide with pre-deposited copper on it, purchased from DuPont (AC091200EV from DuPont Flexible Circuit Materials Group) [21]. The $9\text{ }\mu\text{m}$ thick copper on the $12\text{ }\mu\text{m}$ polyimide substrate is patterned to create both the top and bottom electrodes as well as the circuitry for the CDC chip. The CDC chip and associated electronic components are integrated with the sensing strip to reduce the length of the traces between the sensing electrodes and the chip. This also avoids having a separate connector device in between the sensor and chip, as shown in Figure 3a–b.

PDMS (Sylgard 184) is used to make the middle layer which is the structure between top and bottom layers to keep the distance between the electrodes (Figure 2a). The high

flexibility of the assembled sensing strip will allow it to be mounted on catheters for recording pressure distribution in real time inside body's cavities and in between tissues.

Transparency

To make a Faraday cage for protecting the capacitive signal due to pressure from stray capacitance, the deposition of a thin enclosing layer of highly conductive metal, such as gold, is needed [19]. However, when the three layers need to be assembled together to create the sensor, they have to be aligned accurately with respect to each and then bonded to make the sensing strip. Deposition of gold after the sensor has already been assembled can be considered. However, since deposition of gold in a thermal evaporating machine happens in near-vacuum at very low pressure (1.3×10^{-6} Torr), it is highly risky to place the assembled sensing strip in an evaporating machine to deposit the conductive film on it. The air that is encapsulated inside the individual sensors will expand under vacuum and could delaminate the assembled sensing strip. Hence, the Faraday cage had to be fabricated and included on the outer surfaces of both the top and bottom electrode layers *before* assembly. The Faraday cage then had to be made transparent to be able to see the alignment marks on the three layers for assembling the layers. In order to achieve transparency in the gold layer, it was etched to create a gold mesh through which the underlying layers are visible.

The mesh was designed to have a continuous array of openings of size $60 \times 60 \mu\text{m}^2$ to make the Faraday continuous and conductive, but at the same transparent. First the electrodes in copper are made (Figure 4b) on the copper side of the polyimide substrate. Then the Faraday cage is made on the backside of the polyimide substrate. For gold deposition, the polyimide layer is AMI cleaned and baked to evaporate the residual humidity. Then a 20 nm adhesion layer of Ti is deposited on the backside of polyimide (Figure 4c) in a CHA evaporator machine followed by deposition of 400 nm gold (Figure 4d). The bonding strength of gold and polyimide can be verified by sticking and peeling of a Kapton tape. Then to pattern the Faraday cage, a masking layer from s1813 photoresist was made by photolithography techniques (Figure 5e). The masking layer was a mesh with tiny square shape windows of $60 \times 60 \mu\text{m}^2$ and trace thickness of $30 \mu\text{m}$. Then the setup was immersed in gold etchant GE6 for 30 sec (Figure 4g) followed by BOE 10:1 for 10 sec to etch and pattern Ti under the gold layer (Figure 4f). Finally the s1813 masking layer was peeled off in acetone (Figure 4i). Figure 5 is a SEM photograph of the fabricated mesh.

The Faraday cage needs to be connected to the alternating voltage of the sensing CDC chip and needs to be subsequently covered by an insulation layer. So after bonding together the top and bottom layers, the polymer PDMS was further coated and cured on the Faraday cage.

In order to understand why a transparent mesh can be used as the Faraday cage, instead of a continuous layer of gold, consider the following calculation of electrical resistance of the film. Using the gold film thickness of 400 nano-meters, an effective width of one-third of the actual $400 \mu\text{m}$ width of the film (due to the mesh holes), and a length equal to the length of each sensor, the equivalent resistance is found to be

$$R = \frac{\rho \ell}{A} = \frac{2.44 \times 10^{-8} \times 4000 \times 10^{-6}}{0.4 \times 10^{-6} \times 0.33 \times 400 \times 10^{-6}} = 1.85 \, \Omega \quad (2)$$

Thus, the resistance of the gold layer is quite low, in spite of it being a very thin transparent mesh with large holes.

IV. RESULTS AND DISCUSSION

Two assembled sensors, one with an active Faraday cage on it and the other one without a Faraday cage, were tested in DI water. The results for all individual sensors of each of the sensing strips are shown in Figure 6a–b. In Figure 6a, region 1 consists of the time when the sensor is dry and outside DI water, region 2 consists of the time when the sensor is immersed in water and region 3 consists of the time when the sensor has been removed from water but is still wet with residual water. The residual water creates stray capacitance in region 3 since the water dries up slowly. The immersion in water and subsequent removal are repeated several more times. Region 4 represents the last time that the sensor is pulled out of the water. It can be seen in Figure 6a that when the sensing strip is not shielded by the Faraday cage, the values of the stray capacitance due to the water range from 25 fF to 375 fF (femto Farad).

Then the same test is repeated in DI water with a sensing strip covered by an active Faraday cage, as shown in Figure 6b. Again, in region 1 the sensor is outside DI water and the readout is zero. Then the strip is immersed in DI water (region 2) and taken out (region 3). It can be seen in Figure 6b, that the parasitic capacitance has dropped dramatically by factor of ~10 compared to Figure 6a for the sensor without the Faraday cage. It ranges from only 5 fF to 42 fF. Again, there is an offset in region 3 relative to region 1. It is because after removing the sensor from water, it is still covered by a layer of water that creates stray capacitance which would gradually go to zero after drying for a long time.

From Figure 6a–b, it can be concluded that the addition of the active Faraday cage highly reduced the stray capacitance, but did not eliminate it. The reasons for the stray capacitance not being completely eliminated include:

- a. The low thickness of the golden enclosure (400 nano-meters) which limits its conductivity
- b. The presence of electrical resistance due to the Faraday cage being a mesh with an effective width that is $1/3^{\text{rd}}$ of the width of a continuous film, again resulting in a loss of conductivity and hence a voltage drop across the Faraday cage
- c. The lack of a Faraday cage on the sides of the sensor, due to the fact that the Faraday cage was deposited on the top and bottom electrodes only.

Although the stray capacitance could not be completely eliminated, its reduction by a factor of 10 due to the active Faraday cage technique will highly reduce the error in the sensor readings. It should be noted that the insulation PDMS layer on the sensor by itself does not reduce stray capacitance but the Faraday cage does do.

V. CONCLUSIONS

A golden, thin, transparent flexible Faraday cage was micro-fabricated on the outer layer of a flexible pressure sensing strip to shield the capacitors from stray capacitance. The shielding is achieved by supplying the voltage from the capacitance sensing chip simultaneously to both the positive sensor electrode and the Faraday cage. Transparency is achieved by patterning the gold cage to create a see-through mesh. The transparency enables the top, middle and bottom layers of the sensors to be aligned accurately and then assembled together. The performance of the active Faraday cage was evaluated by testing the sensors through immersion in DI water and comparing the results with those from the sensor without a Faraday cage. It was shown that adding the Faraday cage decreases the stray capacitance by a factor of ten. Future improvements to the sensor can include layer-by-layer sensor fabrication without assembly so that the Faraday cage does not have to be transparent. In this case the Faraday cage can be designed to have lower resistance and better performance.

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Figure 1.

(a) Fringe electric field in a capacitor without a Faraday cage, it bends towards human tissue that is in close proximity (b) Faraday cage is actively driven to have the same potential as the sensing electrode, (b) Electric field is separated from the outside world by adding the active Faraday cage, (d) Equivalent circuit of a shielded capacitive sensor with the active Faraday cage.

Figure 2.

(a) Structure of each capacitive pressure sensor: top and bottom electrodes are etched into 9 μm copper on polyimide substrate, distance between the electrodes is kept by middle PDMS layer, (b) Array of 9 capacitive sensors on a sensing strip

Figure 3.

(a) Schematic of top and bottom layers of the sensing strip, (b) Actual assembled sensing strip with 9 pressure sensors.

Figure 4.
Fabrication steps of the Faraday cage and sensor strip

(b)

Figure 5.
SEM image of the fabricated transparent Faraday cage: dark area is gold and bright area is polyimide.

Figure 6.

(a) Tests of the sensor without an active Faraday cage in DI water, (b) Tests of the sensor with active Faraday cage in DI water