A Multifunctional Capacitive Sensor for Stretchable Electronic Skins

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***Abstract*—We present a stretchable and multifunctional capacitive sensor made of gold thin films embedded in silicone rubber. The mechanical compliance of the gold films and silicone membranes allow the device to be bent, folded, or stretched without damage, making it a suitable candidate for electronic skin applications. The device can detect strains up to 20%, human touch, and pressure up to 160 kPa, and reliably function when it is held stretched or relaxed.**

***Index Terms*—Capacitive sensor, pressure measurement, strain measurement, stretchable electronics, touch sensor.**

I. Introduction

THE observation of human tactile performance and the physical nature of biological tissues and skin suggest that an artificial electronic skin should be fabricated with soft, compliant materials and designed to detect simultaneously several macroscopic stimuli such as mechanical pressure, stretch, temperature or pain. Using stretchable metallization, we have developed a unique capacitive sensor capable of registering strain (up to 20%), pressure (up to 160 kPa), and finger touch. The sensor is made of silicone rubber and can conform to curved shapes or move in tandem with the skin as it stretches over a finger joint.

Thin gold film conductors evaporated on silicone rubber are stretchable: they can reversibly stretch up to twice their length [1], cycle a quarter million times to tens of percent strain [2], withstand radial stretch to 14% strain [3], while maintaining good electrical conduction. The initial sheet resistance of a 50-nm-thick gold film on silicone is typically 12 $\Omega/\square$. However, the change in their electrical resistance with applied strain is not linear [2], and depends on maximum applied strain and number of cycles. We found that stretchable metallization can be used to prepare electrodes and conductive tracks of stretchable capacitive sensors allowing for a reliable measure of strain, pressure and touch. In this letter, we present experimental data on each functional mode of the stretchable sensor, and show that such a device has potential for sensory electronic skins.

II. Experimental

A. Sensor Design and Modes of Operation

The stretchable sensor is designed as a 2 mm^2 overlapping plate capacitor separated by a 0.5 mm thick PDMS (polydimethylsiloxane, Sylgard 184, Dow Corning) dielectric layer. Strain and pressure are detected through the change in dimensions of the overlapping electrodes and thus in the plate capacitance [4]. Interconnects (1×11 mm $\mathrm{W} \times \mathrm{L}$) provide touch sensitivity through electric field fringing effects [5].

Electrodes and interconnects are made of 50-nm-thick gold films (on top of a 5-nm-thick adhesive chromium layer) patterned on both sides of the 0.5 mm thick PDMS membrane using a metallic shadow mask. The structure is subsequently embedded between two 0.5-mm-thick PDMS membranes, and irreversibly bonded using oxygen plasma treatment.

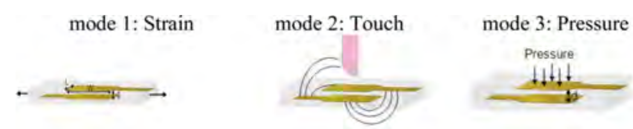

Fig. 1. Stretchable sensor functional modes.

Fig. 1 presents a sketch of the capacitive sensor in each of its functional modes: strain (mode 1), touch (mode 2) and pressure (mode 3). We assume the PDMS is incompressible. We define $C_{\mathrm{sensor}}, C_0, C_{\mathrm{f1}}$, and C_{f2} as the sensor capacitance, the plate electrodes capacitance, the fringing capacitance in the PDMS overlay, and the fringing capacitance through the medium directly above the sensor, respectively.

In mode 1 (strain), a large ($>1\%$) strain is applied in the plane of the device. C_0 increases with the applied stretch as the surface area $\mathrm{L} \times \mathrm{W}$ of the electrodes increases and the PDMS thickness T decreases. Changes in C_{f1} and C_{f2} are negligible compared to C_0. Therefore the sensor capacitance C_{sensor} increases as C_0 with the applied strain.

In mode 2 (touch), an object or the user finger is in contact with the top surface of the sensor, disturbing the fringing electric field above the sensor. No pressure is applied, the sensor is not geometrically deformed; C_0 and C_{f1} remain constant and so C_{sensor} changes with C_{f2}. The sensor functions by detecting small changes in the electric field between its top electrode and the object in its proximity [5]. When the material in contact with the sensor is electrically insulating ($\varepsilon > \varepsilon_{\mathrm{air}}$), or conducting but floating (larger conducting surface area), C_{sensor} increases with C_{f2}. On the other hand, if the sensor is touched by the user's finger (or an earthed, conducting medium), C_{sensor} decreases as C_{f2} is minimized by the charge being grounded.

In mode 3 (pressure), a pressure (P) is applied normal to the sensor surface, squeezing the elastomer stack thus reducing the gap between the electrodes. When the object is just touching the sensor surface (and no pressure is applied on the sensor), the sensor initial capacitance is that obtained in the touch mode (mode 2). Then, C_{sensor} increases with the applied pressure (as C_0 and C_{f1} do). When the stretchable sensor is held stretched, C_{sensor} reaches a new baseline value C' (mode 1), and both modes 2 and 3 can be detected.

B. Sensor Characterization

The capacitance of the sensor is recorded using an Analog Devices (EVAL-AD7152) evaluation board operating in differ-

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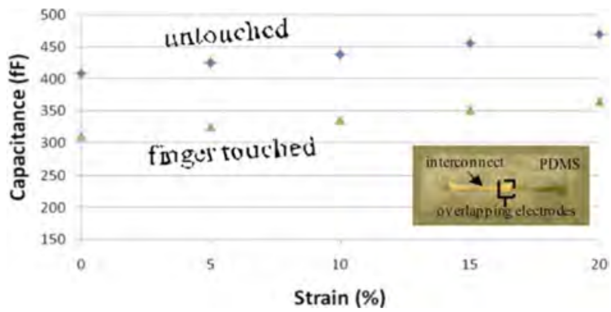

Fig. 2. Sensor response to applied uniaxial strain (top curve) and combined human touch with strain (bottom curve). Inset shows a top view of the device.

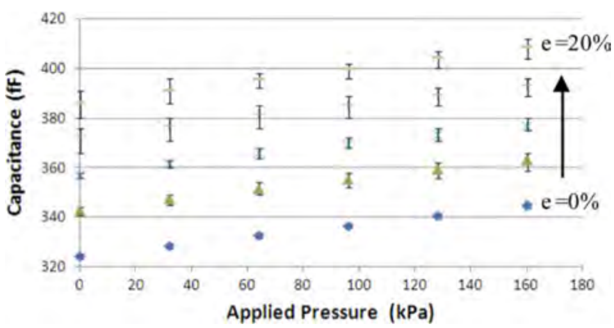

Fig. 3. Sensor response to applied pressure and strain. Each pressure cycle is repeated three times. The error bars indicate the maximum and minimum recorded capacitance.

ential mode to remove the capacitance of the measuring wires and compensate for the interconnect resistance. The excitation voltage is ± 1.65 V in amplitude oscillating at 32 kHz. The sensors are mechanically stretched in increments of 5% strain up to 20% in a customized uniaxial stretcher [2]. Using a 6.3 mm $\oslash$ Teflon® post and loading it in 100 g increments, controlled pressure is applied. A glass stage is placed underneath the device during the measurements to prevent bending and further stretching. Loading over 700 g (225 kPa) at 20% strain resulted in device failure. To simulate human touch, a grounded metallic plate is used as a load interface.

III. Results

Fig. 2 shows a picture of the stretchable sensor and depicts the sensor response in mode 1 and combined modes 1 and 2. The sensor capacitance C_{sensor} is plotted as a function of the applied strain when the sensor is freestanding (top curve) and when the user delicately touches the top surface of the sensor (bottom curve).

The initial sensor capacitance (at 0% strain) is 409 fF, and drops by $\Delta C_{\text{touch}} \sim -100$ fF upon finger touch. When the Teflon post is in contact with the sensor surface, C_{sensor} increases by approximately 5 fF. The sensor exhibits a linear response to strains up to 20% (slope $\sim$ 3 fF/%) with hysteresis less than ± 0.5 fF deviation for each measured strain increment. Its gauge factor is 0.75 and remains the same when the device is simultaneously stretched and touched.

The sensor response to pressure loading is illustrated in Fig. 3. At $P = 0$ Pa, the grounded metallic plate is in contact with the sensor top surface: $C_{\text{sensor}} \sim 324$ fF, which is close to the initial value when the sensor is finger touched. Each loading cycle from 100 to 500 g is repeated three times. The sensor response is linear and reproducible with a sensitivity of $\sim$13 fF/100 kPa.

The pressure cycle is then repeated with the sensor held stretched at 5%, 10%, 15%, and 20% uniaxial strain. The sensor response remains linear; its pressure sensitivity increases from 13 fF/100 kPa to 14 fF/100 kPa with increasing applied strain, and shows a maximum deviation (at 160 kPa) of 5 fF between single trials. Applying pressure with the Teflon post induces slightly larger pressure sensitivity from 14 to 17 fF/100 kPa at 0% and 20% strain, respectively.

The sensor reliably operated in all three combined modes.

IV. Discussion

Modes 1 and 3 act to increase C_0. Planar stretching and normal pressure both induce an increase in electrode surface area and a reduction of the plate dielectric thickness T. Therefore, the device's sensitivity to pressure and strain are intertwined. C_0 can be modelled as an ideal plate capacitor as follows:

$$C_0 = \frac{\varepsilon_r \varepsilon_0 W(1-\nu e_L)L(1+e_L)}{T(1-\sigma/E)(1-e_L)} = \frac{\mathrm{f}(e_L)}{1-\sigma/E} \qquad (1)$$

where ε_0 is the free-space permittivity (F/m), e_L is the uniaxial strain, and σ is the applied pressure (Pa). The elastomer's Young's modulus, Poisson ratio and dielectric constant are $E = 1$ MPa, $\nu = 0.5, \varepsilon_r = 2.7$, respectively. We assume the surface area covered by the finger or object applying the pressure is much larger than the electrode surface area, i.e., $\mathrm{f}(e_L)$ only increases with the applied strain. The pressure sensitivity of the sensor increases when the sensor is stretched. When $e_L = 0\%$, the calculated pressure sensitivity is 14 fF/100 kPa. When $e_L = 20\%$, it increases to 16 fF/100 kPa. This is in agreement with our experimental data (Fig. 3). Experimental values are marginally lower than the analytical ones because the fringe capacitance C_{f1} is not taken into consideration in the model.

We have demonstrated that stretchable metallization can be reliably integrated for capacitive sensing, and that it can be readily interfaced with commercial transducer electronics (for example, the Analogue Devices AD7147 system readily interfaces with up to 13 input sensors and provides fF resolution). Using conventional lithography and an array design, such stretchable sensor technology could be integrated into large area sensory skins capable of registering the shape of the object in contact with the e-skin and the pressure with which it is applied. Sensing modes will function when the e-skin is bent or stretched over complex shaped structures. The sensor fabrication can be scaled up to large area and conformable pixel like surfaces using conventional lithography. Finally individual pixels may be further engineered to reduce or enhance their sensitivity to one or two sensing modes producing localized sensitivity to pressure or strain on the electronic skin.

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