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Fabrication and Characterization of Bending-Independent Capacitive CMOS Pressure Sensor Stacks

Abstract: Artificial limbs, equipped with miniaturized tactile sensors, can handle objects with more dexterousness. Next to detecting forces, the sensor devices are also able to measure temperature. With this additional information, the touched objects can be better characterized. As such sensors, active CMOS-based capacitive pressure sensors are used in this work. The Sensors are thinned to 20–30 μm target thickness to make them bendable. One challenge of such thin sensors is the strong dependence of the output signal upon bending. To compensate this dependency, two sensors were mounted back to back. This allows a numerical adjustment of the two characteristic sensor output signals to mechanical stress curves. After electrically contacting of the stacks with a 15 μm thin polyimide foil substrate, the bending dependence of the stacks was characterized with a four-point bending procedure. By this characterization the dependency of the pressure sensor output signal on the height of mechanical stress was determined. Both sensor output signals show an inverted behavior under the same mechanical stress which confirmed prior simulation results with the same setup. Based on this information, a numerical method for compensating the bending dependence was successfully proven.

Keywords: smart skin, flexible electronics, CMOS pressure sensor, four-point bending test, dicing by thinning.

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1 Introduction

Touch sensing in robots would help in understanding the interaction behaviours of a real-world object. Recognizing

the properties of an object, e.g. its weight and stiffness, how it deforms on contact and how it moves when pushed, provides crucial information for many tasks that involve manipulation and gripping of objects in the environment [1]. So, for new generations of robots tactile sensing is a key technology that enables the robots to operate in an unstructured environment and in close interaction with humans [2].

In addition to robotics, tactile sensors can also be used in the biomedical field, e.g. prosthetics. These days, most prosthetic limbs are not able to restore a natural sense of touch. A possibility to restore this is using a Smart Skin, an artificial skin that is applied over the prosthesis. These prostheses provide a feedback to the patient that is essential for precise handling of objects [3]. Smart Skin applications are under active research. There are passive tactile sensor arrays based on capacitive [4] or resistive [5] measurements with a corresponding spatial resolution as the human skin, but usually they can just measure mechanical forces.

For the realization of the sensitive skin, we propose embedding thinned miniature, ultra-low power active CMOS pressure sensors into a stretchable and flexible skin coating of the prosthetic. Advantages of integrating active CMOS sensors are the possibility to measure multiple physical properties (here: pressure, temperature), scalability, ability to place the sensors almost anywhere and to connect the sensors to a digital network, which minimizes the wiring effort [6].

The challenge of integrating thinned capacitive CMOS pressure sensors into a stretchable substrate is that the capacitance value of the pressure sensor is strongly depending on bending [7]. In general, it cannot be determined whether the signal change was caused by a pressure change or a bending of the sensor. In this paper, we describe the fabrication and characterization of two thinned pressure sensors which are connected back to back. In case of bending this sensor stack, one sensor will be stretched and the other one compressed. By comparing the two inversely influenced output signals, it is possible to eliminate the bending-influence and it proofs the numerical compensation presented in [8].

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2 Fabrication and Characterization

2.1 Fabrication

For fabricating the pressure sensor stacks, three process steps have to be performed – thinning, stacking and forming of an electrical contact. The process of thinning the capacitive pressure sensors to a target thickness of 20 – 30 μm follows the procedure already shown in [7].

Subsequently, two thinned pressure sensors are connected back to back via flip-chip bonding to form a sensor stack. The mechanical connection is done using an epoxy resin based one-component SMD adhesive (Panacol Elsolol Structalit 5605). To not destroy the CMOS surface of the sensors, the force during bonding is set to a minimum of 0.5 N. A good adhesive distribution could be achieved with a dip-coating process and an adhesive thickness of about 5 μm .

Finally, the stack is electrically contacted. This is done by a polyimide foil with integrated conducting lines. The polyimide foil is mechanically and electrically connected to the stack with an isotropic conductive adhesive (Panacol Elsolol Elecolit 325) using also flip-chip bonding with minimal forces. Figure 1 shows a produced pressure sensor stack. For the characterization of the bending dependence of the sensor stack, the stack has the geometry of $1.385 \times 12.7 \times 0.055 \text{ mm}^3$. The actual sensor stack that will later on be integrated into the Smart Skin has the dimensions of $1.385 \times 2.56 \times 0.055 \text{ mm}^3$. The larger geometric dimensions allow an accurate handling during the characterization without affecting the bending dependence.

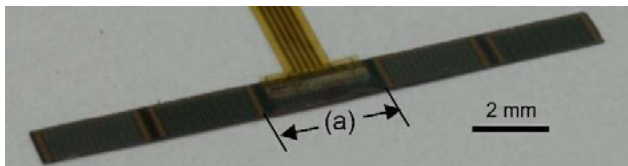


Figure 1: Electrically contacted pressure sensor stack with a thickness of about 55 μm (a) in a bulk for bending purpose.

2.2 Characterization

The stacks are characterized in two ways: first by a mechanical shear test of the bond of the two sensors and second by a four point measuring setup, which was constructed for this purpose. The reason for the four-point bending test is that between the two loading pins a constant

bending moment arises and that there are no transverse forces in this area [9].

The pins of the bending set-up were 3D-printed on resin base. The distance between the load pins is 2.4 mm, between the shoulder pins 4.8 mm. To measure the bending forces, a force sensor was integrated into the set-up. All components, including the measuring set-up for the sensor output values, are integrated into a pressure chamber. With that, bending tests can take place under different ambient pressures.

In Figure 2 a four-point bending test on a pressure sensor stack is shown. The applied force F leads to a deflection of the sensor stack, which has its maximum w_{max} in the middle of the stack. The deflection is calculated according to the equation

$$w_{\text{max}} = z + \frac{3}{64} \frac{F}{\eta E b h^3} l^3 \quad (1)$$

where z corresponds to the traversing distance of the loading pins, l is the distance between the supporting pins, b and h are the width and thickness of the stack, E is the Young's modulus of silicon and η is a numerical correction factor that combines the linear and non-linear beam theory [10].

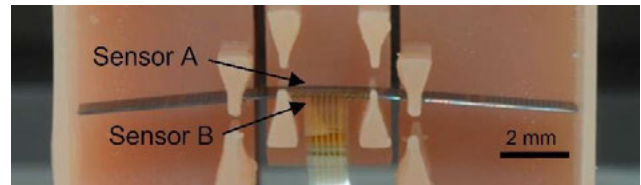


Figure 2: Four-point bending set-up. The sensor whose pressure cans are pointing upwards is marked with the suffix A, the opposite with the suffix B

The shear tests proved that the adhesive bond is more stable than the silicon. Before releasing the adhesive bond, the sensors are destroyed under shear stresses of around 70 N/mm². Though the normal breaking stress of silicon is 5 GPa but due to the fabrication and thinning processes of the silicon chips it can be strongly reduced [11]. A schematic and a zoom in of the adhesive bond are shown in Figure 3.

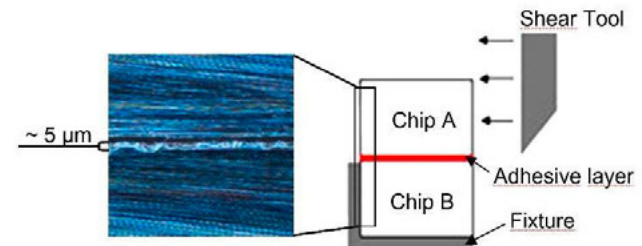


Figure 3: Schematic of a shear test of a stacked sensor

3 Results

3.1 Reference measurements without bending

In order to investigate the general output behaviour of the sensor stacks, reference measurements without bending load were carried out first (see exemplary results of stack 4 in Figure 4). For this purpose, the stacks were placed in the measuring set-up and the chamber pressure was varied from 1000 to 1400 hPa. In this range the sensors were calibrated to ± 1000 pressure values (pressure values in arbitrary units). The maximal pressure range is ± 4095 pressure values. With the calibration in between ± 1000 pressure values, the output signal is less sensitive to pressure. Since the pressure sensor has a limited output range, an initial calibration with half the value range results in approximately doubling the bending compensation range. In that case, a trade-off between sensitivity and bending compensation range must be chosen.

3.2 Measurements under four-point bending

After the calibration, four-point bending tests were carried out. For this, the sensor stacks were bent up to $400\ \mu\text{m}$ in both directions under variable ambient pressures which is equal to a bending radius of around 18 mm (see Figure 5).

As expected, a higher ambient pressure leads to a shift in the output curve upwards (from the front curve to the back ones in Figure 5), a higher deflection to a more sensitive output curve (Figure 5 from left to right). It can also be seen that the output behaviour of the two sensors are mirrored on the y-axis. This is because the two sensors are arranged mirror-inverted. Sensor A is for positive deflections of the stack in compression and sensor B for negative. Therefore, both output signals rise under compression and fall under stretching.

This can be explained by the bending behaviour of capacitive pressure cells. A compression of the substrate under the pressure cell causes the pressure-sensitive diaphragm to deflect in the direction of the counter electrode. A reduced diaphragm distance leads to an increase in the capacitance and thus to an increase in the output signal. When stretching the substrate, the inverse effect occurs, where the membrane is clamped more firmly, which leads to an increased diaphragm distance and thus to a reduced output signal.

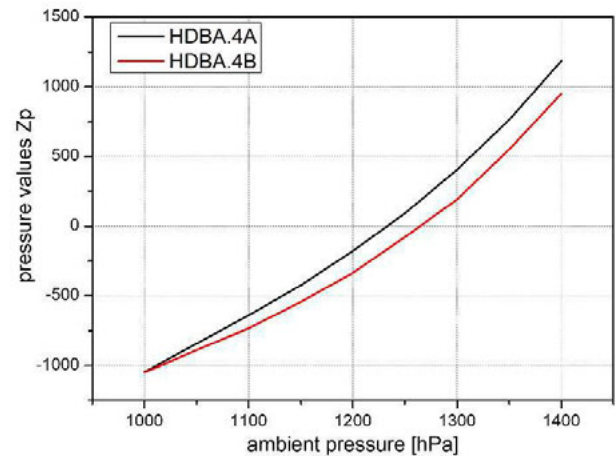


Figure 4: Pressure dependence of the sensors of stack 4 without bending load. Z_p in arbitrary units.

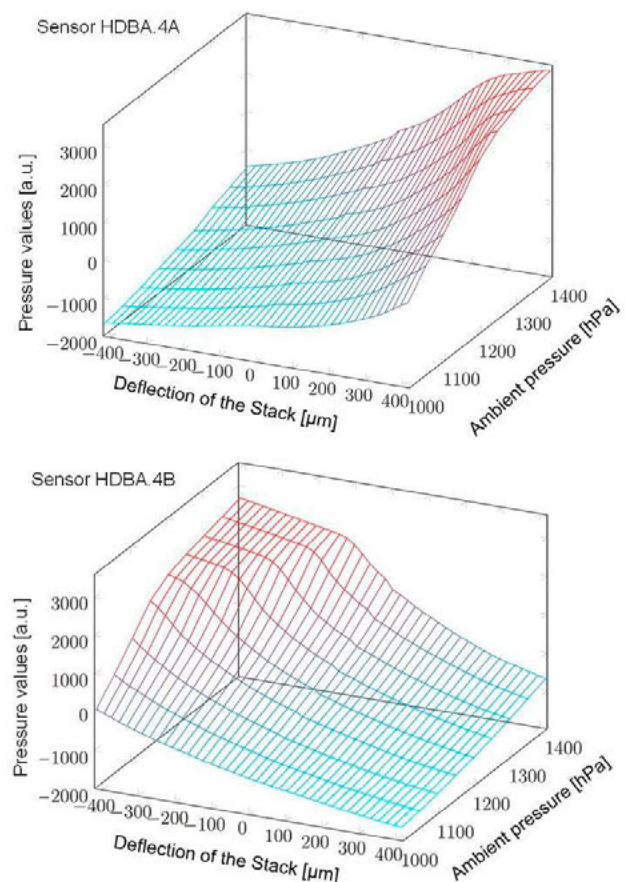


Figure 5: Dependency between pressure values and deflection of the stacks at different ambient pressures. Top: output signals for sensor HDBA.4A; Bottom: output signals for sensor HDBA.4B.

Especially in the area of compression at sensor B a rapid gradient change can be seen. Sensor A also shows this behaviour, but under stronger compressions. This behaviour is typical for capacitive pressure sensors which leave the intended pressure range. The reason for this is the beginning of bearing of the membrane of the pressure cells at the bottom electrode.

The sensors used are designed for a maximum pressure of 1400 hPa, but without deflection. When leaving the intended pressure range, there is an abutment of the diaphragm at the counter electrode which counteracts the rise of the sensor signal. As a result of the pre-deflection of the diaphragm in the direction of the counter electrode, this effect occurs earlier under compression of the substrate.

Therefore, the two output characteristics are not identical. This might be due to the scattering of the sensor thicknesses, which deviate by a few micrometres after the thinning process. At the same time, the sensors have a mechanical preload due to the thinning. If two unequal-thick sensors are connected, then the resulting stack has also a mechanical preload. This preload increases the mechanical stress in one direction and reduces it in the other.

Nevertheless, the compensation method shown in [8] does not exactly require the same sensor behaviour. With the results of this work the compensation method of the bending influence could be proven.

4 Conclusion

A manufacturing process for the fabrication of capacitive CMOS pressure sensor stacks was successfully developed. The stacks with a single sensor thickness of less than 30 μm are flexible and functional even under bending.

In four-point bending tests, the signal output behaviours of the stacks were investigated. The promising results confirm that with the selected sensor arrangement both a bending compensation and a determination of the actual deflection can take place.

For this reason, a numerical compensation method was developed at the institute prior [8]. With that, the stacks are e.g. suitable for Smart Skin applications and can help to achieve accurate force detection on curved prosthesis.

Author Statement

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