Screen-Printed Resistive Pressure Sensors: Influence of Electrode Geometry on the Performance and on Cross-Sensitivity to Strain and Temperature

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Abstract. Fully screen-printed resistive pressure sensors have attracted rising attention in recent years. The possibility to fabricate them on any substrate as well as their low thickness and overall flexibility allow their application on curved surfaces or for material integrated sensing. However, these applications often apply additional loads other than only pressure to the sensors. A major concern is the cross-sensitivity of the sensors to strain. Thus, this work investigates the influence of the electrode geometry used for screen-printed pressure sensors on the device performance and on the cross-sensitivity to strain. It is shown, that the performance as well as the cross-sensitivity to strain are affected by electrode setup and orientation. The pressure sensitivity increases with the number of interdigital electrodes. The cross-sensitivity to temperature is not affected by the electrode setup.

1. Introduction

Common silicon-based pressure sensors use either the piezoresistive or capacitive sensing principle and are fabricated by well-established silicon micromachining technologies [1]. Even though the lateral dimensions as well as the functionality of the sensors have been improved, the major disadvantages of silicon-based pressure sensing, namely the limited reducibility of height and the brittleness, have not yet been addressed. Therefore, in recent years fully screen-printed resistive pressure sensors have attracted increased attention. These sensors can be fabricated on almost any substrate and have a very low height, allowing them to even remain flexible. Thus, they can be applied to non-planar surfaces [2–4] or in material integrated sensing [5, 6].

Figure 1. Rendered image of fully screen-printed pressure sensor on flexible substrate as reported in [7]. The pressure sensitive layer is shown semi-transparent in order to make the underlying interdigital electrodes visible.
Figure 1 shows a rendered image of a sensor, which has been presented by us previously in [7]. The sensor consists of a flexible Polyimide substrate, interdigital electrodes and the pressure sensitive layer. The pressure sensitive layer is shown semi-transparent to make the electrodes visible.

2. Working Principle
Conductive polymers consist of a polymer matrix filled with conductive particles (e.g. carbon black). The electrical properties are defined by the filler material, shape and volume content. In [8], we have shown the impact of filler content on the conductance. Figure 2 (left) shows the regime of resistance in dependency of filler content. Generally, the mechanism of current flow can be divided into 3 regions, where region I describes the non-conductive region. In region II the current flow is defined by quantum tunneling, whereas an ohmic behavior occurs in region III. Pressure sensitivity is achieved by compression of the polymer matrix and a resulting decrease in distance between electrical filler (see Figure 2 (right)) [9]. The regions of the graph shown in Figure 2 determine the sensitivity of the sensor. In region II very high sensitivity can be achieved [10].

![Resistance vs Filler Content](image1)

**Figure 2.** The resulting resistance of different current flow mechanisms. Region I: no current flow, region II: current flow due to quantum tunneling, and region III: current flow due to ohmic behavior (left). Illustration of pressure sensitivity due to compression of the polymer matrix (right). Adapted from material datasheet (ECI 7004LR E&C) and [9].

When pressure is applied to the surface of the sensor, the resistance will be altered due to the compressibility difference between conductive filler and polymeric matrix. Due to the negligible deformation of the conductive filler, the resulting change in resistance is depending on the deformation of the polymeric matrix [9]. The change in interparticle separation causes a change in resistance and can be calculated by

\[
\frac{R}{R_0} = \frac{s}{s_0} \exp \left[ -\frac{4\pi}{h} \sqrt{2m\varphi(s_0 - s)} \right] \tag{1}
\]

where \( R_0 \) is the resistance, and \( s_0 \) the interparticle separation before applied pressure, \( h \) Plank’s constant, \( \varphi \) the height of the potential barrier between the conductive particles, and \( m \) the electron mass. The change in interparticle separation, due to applied pressure, can be calculated as

\[
s = s_0 (1 - \varepsilon) = s_0 \left(1 - \frac{\sigma}{K}\right) \tag{2}
\]

where \( \varepsilon \) is the strain of the polymer matrix, \( \sigma \) the applied stress, and \( K \) the compressive modulus of the polymer matrix [9]. From equation 2 it can be assumed that antecedents for strain other than pressure will also affect the signal.

3. Device Design and Fabrication
In this work, the functional layers are printed directly on inflexible PMMA substrates with 3 mm thickness, 30 mm width and 100 mm length. Those substrates can directly be used to determine the strain sensitivity of the sensors by pull testing. Thus, issues in mounting flexible Polyimide-foil based
sensors to a rigid substrate for pull testing are avoided. We expect no difference in sensor performance due to the change of substrate. Four sensors are printed on each substrate allowing to characterize all four simultaneously.

The fabrication steps for the presented sensor are depicted in Figure 3. The whole fabrication is done by manual screen-printing. In step (a), electrodes are printed on the substrate using a SEFAR Type 180/305-27 PW screen and Sun Chemical CHSN8013 Conductive Silver paste. The wet layer thickness of the electrodes is estimated to be 14 µm according to [11]. The electrodes are cured for 30 minutes at 90°C in an oven. In step (b), the pressure sensitive layer is printed on top of the electrodes using a SEFAR Type 54/137-64 PW screen and a 4:1 mixture of non-conductive Henkel NCI 7002 E&C paste and conductive carbon filled Henkel ECI 7004LR E&C paste. The ratio of the pastes determines the concentration of conductive particles in the insulating matrix and, thus, influences the device performance according to theory. The ratio, which we chose, is designed to make the sensors work in region II of the theoretical model (figure 2). The wet layer thickness of the pressure sensitive layer is estimated to be 35 µm. The electrodes are well covered by the pressure sensitive layer as the layer thickness is approx. three times higher. Copper wires are conductively glued to the contact pads of the sensors using the Sun Chemical CHSN8013 Conductive Silver paste. The paste is again cured at 90°C for 30 minutes.

The aim of this work is to investigate the influence of the electrode geometry on the device performance and on the cross-sensitivity to strain and temperature. Therefore, devices with 3 different electrode geometries as depicted in Figure 4 are fabricated. Each electrode geometry is fabricated in vertical and horizontal orientation respectively.

The electrode geometries are expected to show different cross-sensitivity to strain depending on their orientation. For geometries 1, 3 and 5, particle separation in the pressure sensitive layer is increased when strain is applied, whereas for geometries 2, 4 and 6, there is an additional increase in the distance between the electrodes. Thus, electrodes 2, 4 and 6 are expected to be more sensitive to strain.

4. Device Characterization
Three device characteristics of the sensors are determined: pressure sensing performance, strain cross-sensitivity and temperature cross-sensitivity. All characteristics are determined for each electrode
geometry. The resistance of the sensors is recorded using a Keithley 2000 multimeter with a Keithley 2001 Scan multiplexer extension card.

4.1. Pressure Sensing Performance
For the determination of pressure sensitivity, the sensors are placed in a stainless steel vacuum chamber with wire feed-through ports. Pressure is applied by compressed air. The pressure is controlled using a Druck DPI 510 pressure controller. The pressure is increased from 0 to 6 bar relative to ambient pressure in steps of 0.1 bar. Exemplary results for all electrode geometries are shown in Figure 5. As similar but 90° tilted electrodes show the same pressure sensitivity, only one graph per two similar electrode geometries is shown.

![Geometries 1&2](image1.png)

**Geometries 1&2**: Applied Pressure / bar

![Geometries 3&4](image2.png)

**Geometries 3&4**: Applied Pressure / bar

![Geometries 5&6](image3.png)

**Geometries 5&6**: Applied Pressure / bar

**Figure 5.** Relative change in resistance versus applied pressure for each electrode geometry pair. Black marks are the measured values and the red dashed line is a linear approximation.

The electrode geometries 1&2 and 3&4 show similar pressure sensitivity. However, the electrodes 1&2 have a much more steady decrease in resistance with increasing pressure. The pressure sensitivity of geometries 5&6 is much higher than for the other geometries and shows the least fluctuation in signal. Obviously, the number of electrodes strongly effects the pressure sensitivity, whereas, the overlap improves the fluctuation of the signal.

4.2. Cross-Sensitivity to Strain
The sensitivity of the sensors to strain is determined in a pull test. The PMMA substrates are installed in the fixtures of a DINA-MESS pull testing machine. The pull test can be executed either distance or force controlled. Force control allows much lower strain rates, thus, force control is chosen to execute the tests. The applied force is increased with a rate of 5 N/s up to a maximum of 1000 N. This results in a maximum strain of approx. 0.3%. The direction of applied strain is indicated in Figure 4.

The relative change in resistance versus the applied strain is exemplary shown in Figure 6 for all electrode geometries. Sensors with vertically oriented electrodes are shown in the left column and with horizontally oriented electrodes in the right column respectively. All graphs show a mostly linear correlation between change in resistance and applied strain. However, the sensors with horizontally
oriented electrodes show on average a 15% to 25% higher sensitivity to strain. It can also be seen that
the sensors with similar orientation each show similar sensitivity to strain. Therefore, it can be
concluded that the number of electrodes as well as the electrode overlap have only minor influence on
the strain sensitivity.

Figure 6. Relative change in resistance versus applied strain for each electrode geometry. Black marks
are the measured values and the red dashed line is a linear approximation.

4.3. Cross-Sensitivity to Temperature

The sensitivity to temperature of the sensors is tested on a hotplate. In order to reduce heat loss due to
convection or radiation, the sensors are covered by a lid. The temperature is increased from room
temperature to 100°C in steps of 5°C. After each increment, the hotplate and sensors are given time to
settle to a stable temperature. All electrode geometries show a very similar behaviour when exhibited
to temperature. The relative change in resistance versus the applied temperature is exemplary shown in
Figure 7. Surprisingly, the resistance decreases linearly up to a temperature of approx. 50°C. Above
50°C, the resistance increase mostly linearly with temperature. However, in the temperature range up
to 100°C the magnitude of the relative change in resistance is less than 0.1%.
Figure 7. Relative change in resistance versus applied temperature.

5. Conclusion and Outlook
The electrode geometry and orientation has a large influence on the performance and cross-sensitivity to strain of screen-printed resistive pressure sensors. The pressure sensitivity increases dramatically by using multiple electrodes over single electrodes. In order to decrease the cross-sensitivity to strain, the electrodes have to be oriented in a way that prevents the electrode distance to be increased by applied strain. Thus, the electrode orientation must be chosen according to the application of the sensor and the application-specific direction of strain.

In future work, additional electrode setups will be investigated as well as the behaviour of the sensor when pressure and strain are applied simultaneously. In addition to the device characterization we plan to use the sensors for material integrated sensing in rubber elastomer parts.

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