Tactile CMOS-Based Sensor Array for Applications in Robotics and Prosthetics

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1 Introduction

For a human the hand is the main mean to manipulate its surroundings. Mechanoreceptors, which are embedded in the skin, provide information about the texture of an object and the contact between hand and object. They exhibit a great dynamic range and can detect small and high forces. The spatial resolution at which touch can be detected lies in the millimeter range for the fingertips. The information that these mechanoreceptors provide, i.e. the location and the magnitude of contact forces is essential for the dexterous handling of objects. This can easily seen by the fact that many everyday activities are difficult for people suffering a decrease or lack of cutaneous force sensitivity[1]. Apart from detecting forces the skin is also able to measure other physical properties like temperature.

Developing a technical equivalent to the human skin is of great scientific interest. A system equipped with such a skin will be able to mimic the human ability to handle objects of different sizes and shapes and to adapt to new previously unknown objects. Humanoid robots, for example, shall one day be able to perform tasks in unstructured scenarios like acting as household service robots. So at least their hands have to be equipped with sensors to measure the contact forces. Equipping the whole body of a robot with tactile sensors will be beneficial as this allows for detecting accidental contacts, which is an important safety feature to protect nearby humans from injuries.

Another possible application for a technical skin is to enhance prostheses. A variety of hand prostheses have been developed: from simple grippers to more sophisticated myo-electric anthropomorphic hands[2] that can be controlled by muscle activity in the residual limb. However, these prostheses don't provide touch sense feedback. Without feedback gripping and moving objects requires constant visual supervision. Consequently, means of providing such a feedback are under active development. Approaches range from tactile displays[3] to stimulating afferent nerves[4].

The commonly used passive arrays based on capacitive[5] or resistive[6] measurements provide a resolution that is comparable to that of a human hand but cannot measure additional parameters like temperature. Therefore, we suggest using active CMOS based sensors to develop an artificial skin. They can measure a multitude of physical quantities and the integration of analog and digital electronics allows transmitting the measured values over a digital network. Employing the network approach greatly reduces the required wiring effort compared to connecting each sensor individually. Additionally, on chip self tests,

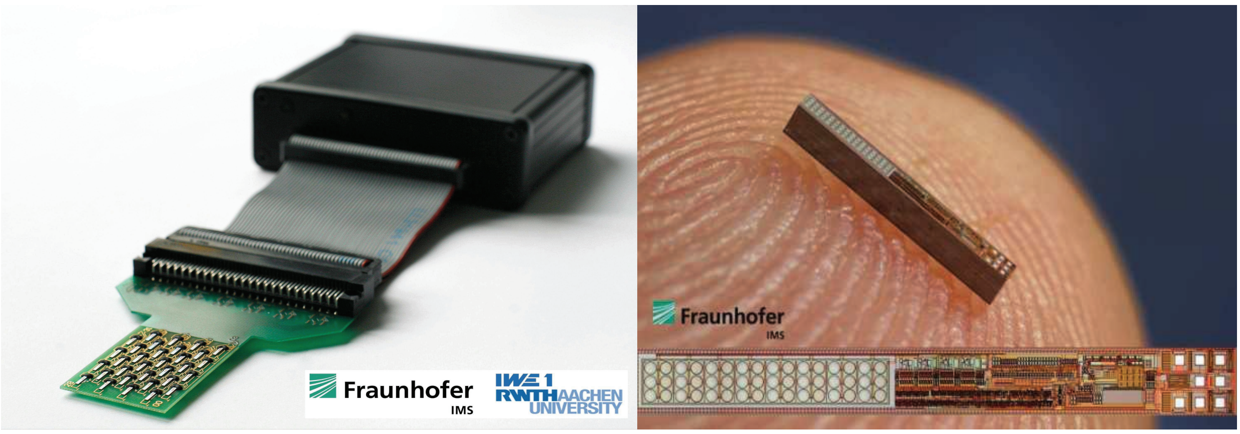

Figure 1: a) Tactile array on a rigid substrate and read out electronics b) CMOS integrated capacitive pressure and temperature sensor on a fingertip. In the close up view three regions can be distinguished: The pressure sensitive membranes on the left, the integrated electronics in the middle and the contact pads on the right

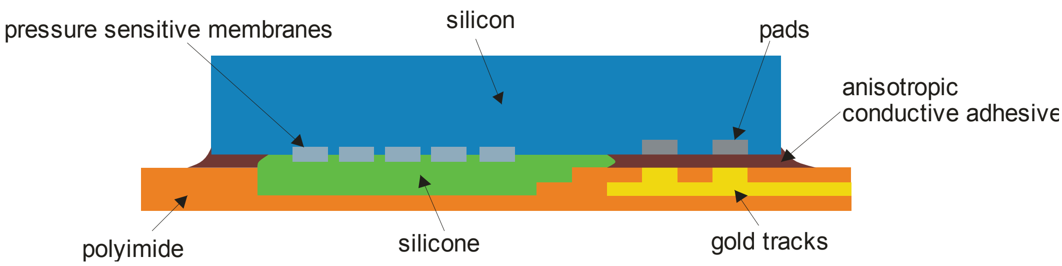

Figure 2: Thin pressure sensor chip mounted on polyimide foil.

redundancy and sleep functions can easily be integrated. If the thickness of silicon is reduced to below 50 µm the normally brittle material becomes flexible and the sensors can be applied to curved surfaces.

In the following sections the design and fabrication of a tactile sensor array using CMOS integrated pressure sensors is presented. The system concept is proven using rigid sensors and substrates and a way to achieve very thin and possibly bendable sensors is shown.

2 Design and Fabrication

2.1 Design

The flexible tactile sensor array is developed in two steps. Firstly, the system is developed using sensors with normal thicknesses on a rigid substrate to evaluate the suitability of the sensors to measure tactile events. This is shown in Figure 1. The sensor that is used is a CMOS integrated capacitive pressure and temperature sensor (Figure 1b) similar to the one presented in [7]. It is 5.5 mm long, 0.55 mm wide and 0.73 mm thick. The sensors are glued on top of a custom printed circuit board. Electrical connections are made via wire bonding and the bond wires are protected by epoxy. The black box in Figure 1a is the read out electronic unit that can be connected to a standard PC via USB. For tactile measurements the pressure sensors are covered with a layer of silicone.

For a flexible system every part that is used has to be flexible as well. Therefore, a thin polyimide film has been chosen as the carrier. Figure 2 shows the design. The silicon sensor chip is glued onto the polyimide foil with an anisotropic conductive adhesive that also provides the electrical connection between the chip's pads and the gold conductors. Under the pressure sensitive membranes the polyimide is only 5 µm thick and the cavity is filled with a silicone to ensure optimal pressure transmission. The membranes may not be covered with epoxy glues as they stiffen the membranes and lead to sensor failure.

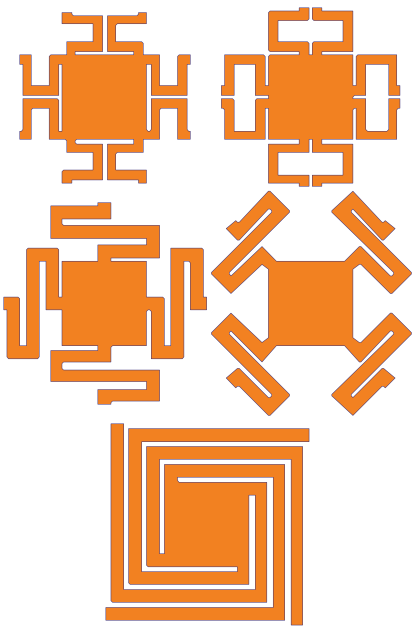

Figure 3: Different spring structures that were simulated.

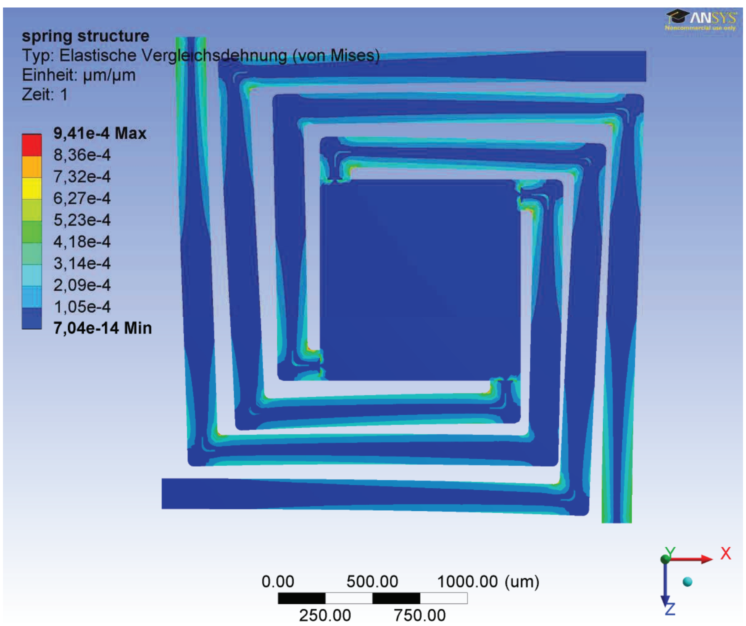

Figure 4: ANSYS simulation of the polyimide spring structure. The chip is glued with its pad onto the island in the middle. The island is connected to the main polyimide foil via long slender beams.

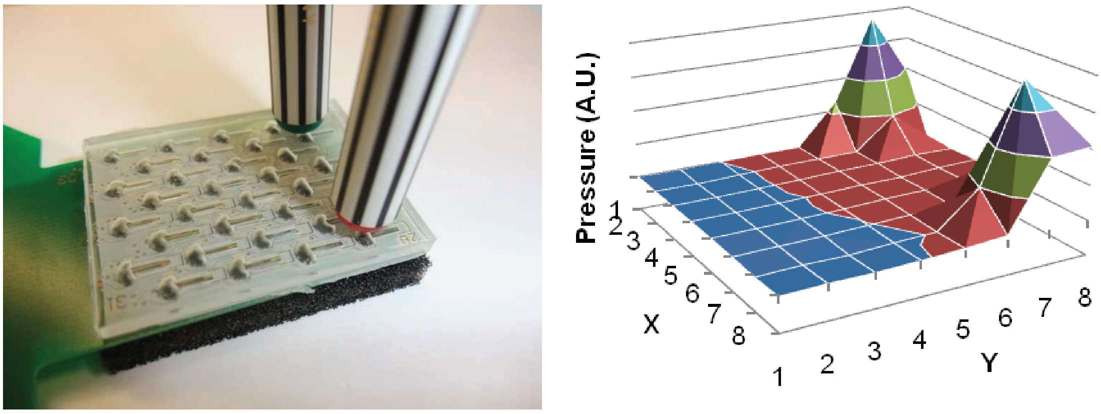

Figure 5: First evaluation of the rigid tactile sensor array. The sensor chips were embedded in a sheet of silicone and forces were exerted onto the silicone. The measured pressures are given in arbitrary units because the sensors hadn't been calibrated before the experiment.

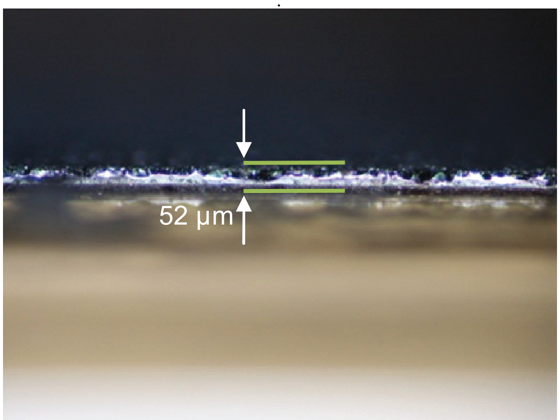

Figure 6: Side view of a sensor after thinning.

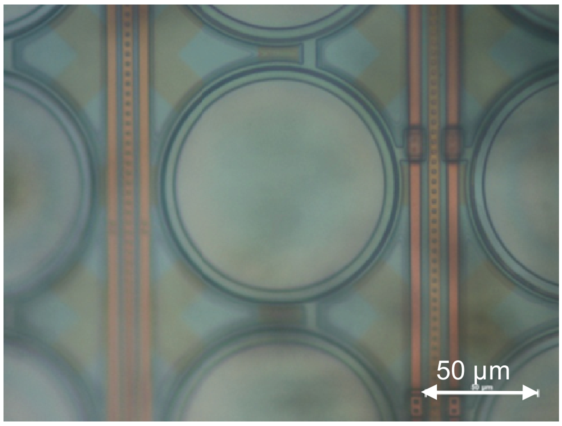

Figure 7: View of a sensor membrane through the polyimide foil after thinning. No visible damage.

When the sensor chip is attached to the carrier substrate at two sides external stresses applied to the substrate will propagate to the sensor chip and affect the pressure measurement. Thus, at least one side has to be decoupled from the polyimide foil. Several spring like structures were considered (see Figure 3) and simulated with the ANSYS finite elements simulation software. Figure 4 shows a simulation of the spring structure that exerts the least force on the sensor chip. The spring beams were modeled as a stack of a 5 µm polyimide foil, 5 µm gold tracks and again a 5 µm polyimide foil. Young's modulus was assumed to be 8.5 GPa for polyimide and 78.5 GPa for gold. The Poisson's ratio is assumed to be 0.31 and 0.42, respectively. The outer ends of the spring beams were held at a fixed position and a displacement of 10 µm was imposed on the middle island as a benchmark to compare different designs. The structure with the least reaction force was considered the best. For the structure shown in Figure 4 the reaction force is 529.54 µN at 10 µm displacement.

2.2 Fabrication

The sensors are thinned after being glued to the polyimide foil. Therefore, the foil is fabricated on a 3 mm thick glass substrate that is four inch in diameter. The glass substrate is stable enough to be mounted to the lapping jig later in the process. First, an aluminum sacrificial layer is evaporated onto the glass substrate. After that, polyimide is spin coated and patterned. Chromium and gold are evaporated as a plating base and pads and conductors are made by electroplating gold. A layer of polyimide, another layer of gold and a final layer of polyimide follow. An anisotropic conductive adhesive is dispensed at the sites specified in Figure 2 and the sensor chip is flip chip bonded to the polyimide foil. Subsequently, the adhesive is cured. A low viscosity silicone is dispensed into the gap between the pressure sensitive membranes and the polyimide foil and cured. To avoid chip breakage during lapping the chips are embedded in a wax. After lapping the protecting wax is dissolved and the chip is covered by a resist prior to etching the sacrificial layer. As a last step the resist is dissolved in acetone.

3 Experiments and Discussion

The rigid tactile array presented in Figure 1 was covered with a sheet of silicone and different load were applied. One example is shown in Figure 5. It can be clearly seen that the CMOS integrated pressure sensors can be used for a tactile sensor array when embedded in silicone. Additionally, these experiments prove the functionality of the read out electronics.

Thinning experiments have shown that it is possible to lap capacitive pressure sensors down to about 50 µm without visible damage to the membranes (Figure 6 and Figure 7). Protecting the sensor chips by embedding in wax is crucial for successful thinning. As the sensor chip is very narrow it can be easily tilted during lapping. This results in chipping of the edges and finally the complete destruction of the chip. After lapping the chip surface is very rough. To achieve bendability stress relief etching and polishing have to be employed.

4 Conclusion

A new tactile sensor array using CMOS pressure sensors has been presented. The first measurements conducted with rigid substrates and sensors have proven the suitability of these sensors for tactile applications. The first thinning experiments have provided promising results as the membranes have been left intact by the thinning process. Electrical and mechanical characterization of the thinned sensor chips has to follow.

Acknowledgements

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