978-1-5386-2092-2/18/$31.00 ©2018 IEEE

Design and fabrication of a flexible capacitive coplanar force sensor for biomedical applications

Andrea Bodini[1], Stefano Pandini[2], Emilio Sardini[1], Mauro Serpelloni[1]
[1]Dep. of Information Engineering, University of Brescia, Brescia, Italy
[2]Dep. of Mechanical Engineering, University of Brescia, Brescia, Italy
a.bodini004@unibs.it

Abstract— **Flexible capacitive sensors are acquiring more importance in nowadays applications. They are being used in a wide variety of fields, from fingerprints reading to force sensing, from cell growth evaluation to touch sensing. In the biomedical field, research is pushing towards micrometer scale capacitive sensors, requiring a complex fabrication process. This project aims at the design of an easy-to-use and low-cost capacitive force sensor for biomedical applications. For this purpose, a coplanar geometry is studied, developed and few prototypes were fabricated. In the current configuration, sensors' size is 4 mm thick, with a diameter of 8.5 mm but different sizes can be adopted as well. Furthermore, the capacitive sensor is made by a wafer of 3 different polymeric layers, in which is inserted a flexible polyimide PCB (130 μm thick). The prototypes were tested with a maximum force of 1 N, but wider range are permitted. In the current configuration, the tested sensors have a sensitivity of 172 fF/N, a resolution of 80 mN, a hysteresis of 20 fF and the percentage of nonlinearity is 1.087%. Its field of application could vary from sitting posture sensing, insole pressure sensor, tongue pressure monitoring, tactile pressure and many other biomedical applications in which a soft surface is needed.**

Keywords— capacitive sensor; pressure sensor; coplanar sensor; PVS; silicon; sensor; force sensor.

I. Introduction

Force or pressure measurement is a key feature in many applications, manipulative robots [1],[2], augmented reality [3], surgical operations [2][4], breast cancer recognition [5][6], and many others. This kind of sensors are based on different physical principles, piezo-resistivity, capacitance, diffraction and many others. The most used are resistive and capacitive sensors. Resistive sensors are usually made by resistance-varying pastes, which are generally affected by temperature drift, thermal noise and hysteresis. Capacitive sensors made their fortune with their employment in the consumer market of the smartphones, and the wide penetration of touch-sensing technologies also in manufacturing and automotive industries. Unlike resistive sensors, they are less sensitive to temperature variations and thermal noise. Their behavior is strictly dependent from the dielectric type and the armors shape. Capacitive pressure sensors are nowadays employed in many different fields, starting from biology, for example for intraocular pressure measuring [7], to harsh environments industrial application [8] for proximity detection. As a consequence of the polymer industry growth, more attention was put on flexible capacitive sensors [5-15,18-22], usually involved in force detection. One of the drawbacks of this technology is the need of having two conductive plates divided by a dielectric [5-13,20], which drives to an intrinsic difficulty in the wafer construction and in the bonding. Furthermore, more and more often easiness in fabrication and the possibility of employing it in water-filled environments is required. These constrains are given by keeping in touch with the biomedical field, where these sensors are supposed to work in. State of the art reports lots of capacitive force sensors, but they are made in micrometrical scale, using hard-to-reproduce techniques. Capacitive coplanar sensors are adopted extensively in touch-sensitive interfaces, sensibly facilitating the fabrication process of the PCBs, avoiding the need of physical buttons shortening the bill of materials (BOM) and easing the interface with the user also in high-moisture environments. These systems can measure a variation of the capacitance value due to the electric field variation around the electrodes. They are used for tracking fingers movements, gesture recognition, proximity detection, etc. In [17] many hints to deep understand capacitive-touch interfaces are reported. These sensors are easy to fabricate and with the right technical arrangements, they can work in high moisture environments. In [18], a deep study on coplanar capacitor shaping and dimension, with a different final purpose is reported. These studies shown a great sensitivity to environments variations by the spiral shaped coplanar capacitors, with a high zero-capacitance value. However, force or pressure measurements are not implemented restricting the application fields to industrial or consumer, they are gaining more importance also in the medicine, rehabilitation therapies and tele-monitoring.

In this work, a capacitive coplanar force sensor is proposed, it is designed with a full biocompatibility for being employed in a variety of biomedical environments. Its particular shape increases the sensitivity to the force applied in a specific direction, removing the interferences coming from the opposite side. The sensor surface is made on a 130 μm flexible polyimide substrate, stacked between three layers, two of ethylene vinyl acetate (EVA) and one of poly vinyl siloxane (PVS). These dielectric layers contain the electric field lines, reducing the capacitance variation when approaching the sensitive surface. A force application to the deformable surface reduces the distance from the sensitive area, causing a capacitance variation. This sensor then offers a low-cost alternative to aforementioned polymer-based capacitive force sensors, reducing the fabrication process complexity using standard flex PCB technologies.

This project is co-financed by the EULO foundation, as a price winning project of the "Bando EULO" 2016.

978-1-5386-2092-2/18/$31.00 ©2018 IEEE

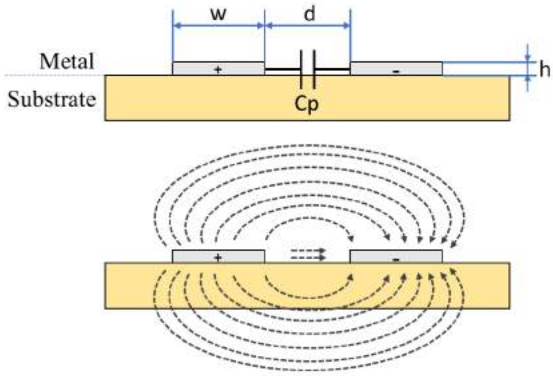


Fig. 1: Basic coplanar capacitor size and principle, where Cp is the intrinsic capacitance, w is the path width, d is the distance between them and h is the height of the metal layer.

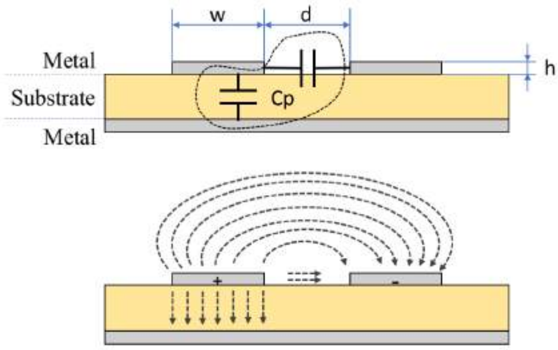


Fig. 2: Coplanar capacitor with ground plane, Cp is then the parallel between the two intrinsic capacitances, increasing the direct capacitance value.

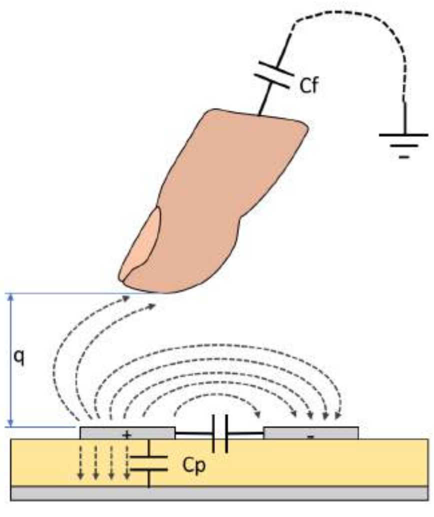


Fig. 3: When a finger (for example) approaches the coplanar capacitor, the capacitance value of the finger will change the total capacitance value of the sensor and it becomes Csens = Cp + Cf. The capacitance variation is linked to the distance between the finger and the sensing element.

II. Sensor Design

A. Working principle

Coplanar capacitors are usually characterized by a small width (w) versus a short height (h), divided by a distance (d) as shown in Fig. 1. The capacitance value is usually made by the combination of two different components, the direct capacitance value and the capacitance due to fringing effect. Direct capacitance is the one evaluated only between the plates, fringing capacitance is evaluated outside the borders. In this particular case, the direct capacitance value should be lesser than the fringing's. The electric field of a simple coplanar capacitor has the peculiarity of permeate the space in both directions from the electrodes, making it sensible to perturbations as above as below it. This is for the intrinsic symmetry of the free electric field lines. Shaping the capacitor in a particular way, it is possible to limit this effect, guiding the lines in a preferred path. In the present configuration, the sensor is designed to be more sensitive to one-side interaction. That could be obtained placing a ground plane on the side we would blind to variations. In

Fig. 2, the working principle of a coplanar capacitor with a ground plane is shown; electric field lines are more condensed in the upper side than in the lower, making the lower side blind, or less sensitive, to proximity variations. This kind of operation also increases the intrinsic capacitance value of the capacitor Cp, improving the reading operations. In [17], a deep explanation of this phenomena is given, there are also some guidelines for touch panels PCB design. When approaching to these sensors for example with a finger, as shown in Fig. 3, or with something with an intrinsic capacitive behavior, the total capacitance read from the sensitive area is the sum of the two components Cp and Cf. The capacitance of the fingers, read by the sensor, is linked to the distance (q) between them. Placing an elastic material with a dielectric constant higher than the air on the sensitive area, it is possible to convoy the electric field lines in this layer, reducing their scattering.

B. Capacitor shaping and material selection

Capacitor shape was designed in order to obtain the maximum faces area, and then increase the initial capacitance value. As reported in [18], the circular shape of the spiral is the best trade-off between the area of the plates and total sensor space occupation. In [18], the spiral capacitor is used for the characterization of surrounding materials, in particular multilayered dielectric structures; its shape gives both a higher output signal strength and a better accuracy in material characterization than the simple disk-and-ring configuration. Mixing the concepts reported in [17] and [18] a sensor was designed as a spiral with a radius of 8.5 mm, a 3D representation of the spiral is shown in Fig. 4. The elastic material chosen for being placed on the sensing element is a particular poly-vinyl siloxane (PVS). This material is widely used in dental clinics as mold for the dental impressions. In this particular case, the choice was between two materials, one with a typical hardness of 8 shore A, and the second with a 16 shore A. The materials involved are the "Elite Double 8" and the "Elite Double 16Fast" by Zhermack (www.zhermac.com). Because this material refuses to bond with glues as cyanoacrylates, it becomes mandatory to find something to keep all the layers tight. For this reason, the choice felt on the enclosing the structure between two

978-1-5386-2092-2/18/$31.00 ©2018 IEEE

layers of ethylene vinyl acetate (EVA), by a thermoforming process. This also guarantees a completely hermetic enclosure, for the employment in high moisture environments.

C. Sensor fabrication

Sensor prototypes were fabricated on a flexible substrate. A polyimide layout laminated with copper was used to fabricate the two coplanar electrodes and the ground plane on the bottom. The substrate is a 25 μm layer of polyimide on which are glued two 35 μm copper layers. Then the copper is protected with an enclosure of polyimide, reaching a total thickness of 171 μm, including glues, resist and other fabrication-specific materials. The drawn sensor follows the shape shown in Fig. 4, with a maximum diameter of 8.5 mm. The sensor was bonded with two wires and encapsulated between two EVA layers, each 1.5 mm thick. The encapsulating process is made through a thermoforming process which reduces the thickness of the materials of near 25%. This enclosing technique hermetically seals the sensor from the environment. It prevents capacitance variation due to moisture changes in the surrounding environment. The EVA layers become then more or less 2.25 mm thick. Making a choice between the two PVS materials, required a series of tests. We have put a 2 mm layer on the sensing area and measured which produces the greater capacitance variation. Trials then reported a complete blindness to low intensity force variations (< 1 N) of the 16 shore A PVS, forcing the choice of the 8 shore A silicon. Fig. 5 shows a schematic representation of the layered sensor in (a) and a picture of the fabricated flexible PCB in (b). Copper spiral dimensions are, referring to these reported in Fig. 2, w = 0.203 mm (8 mils) and d = 0.1778 mm (7 mils), with a maximum diameter of 8.5 mm. For clarity, in Fig. 5 (a) is depicted a general representation of the wafer structure, the materials involved for the flex PCB fabrication are not reported.

III. Preliminary Experimental Results

The fabricated prototypes were tested under an INSTRON® 3366 machine to obtain a relationship between capacitance variation and applied force. An impedance analyzer HP4194A was used to measure the capacitance during tests. The starting capacitance C_0 of the encapsulated sensor, including the cables parasites, was 16.5 pF. As a first step, the sensor was tested with a force of 1 N, further analyses will examine its behavior with stronger loads. The test was made with a metal tip, left electrically floating. In Fig. 6, the evolution of the force value seen from the INSTRON load cell and the simultaneous capacitance reading of the impedance analyzer are reported. Picture clearly depicts the presence of parasites on the capacitance value, indeed there is a difference between the C_0 value of the 3rd trial and the others. This behavior is probably due also to the movements of the PVS layer inside the EVA enclosure after a stress application. There is also a difference in the ΔC between the 3rd and the other measures. This is due to the different position of the INSTRON tip on the sensor. Further investigations are undergoing to obtain a full characterization of the sensor behavior against different force applications, in terms of orthogonality and displacement from the center of the spiral. Test1 and Test2 reports instead a similar response, pretty comparable to the force curve read by the INSTRON machine. There is also an unexpected behavior of the load cell, this could be due to a possible overheating.

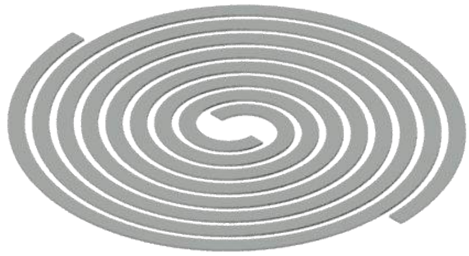
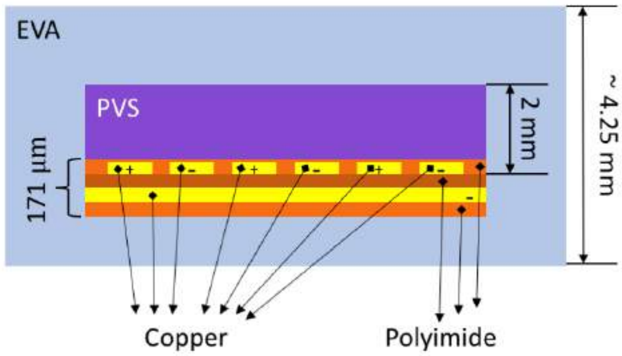
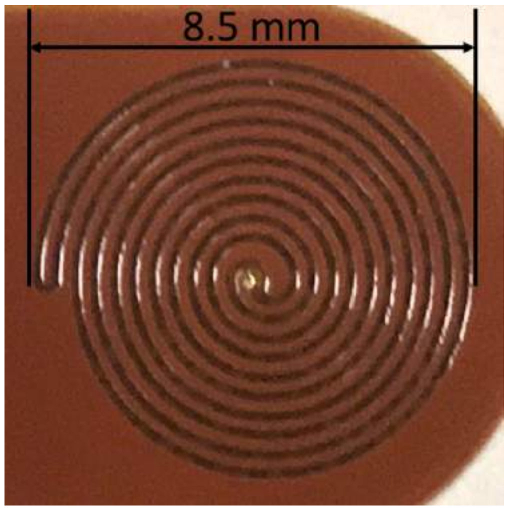


Fig. 4: Coplanar capacitor spiral design



(a)



(b)

Fig. 5: (a) Section of the sensor. The widths are, copper 35 μm, polyimide 25 μm, PVS 2 mm and EVA 3 mm. The total sensor height equals to EVA's. (b) A picture of the polyimide machined layer, where, referring to Figs.1 and 2, the dimensions are w = 0.203 mm and d = 0.1778 mm. The maximum diameter of the spiral is 8.5 mm.

Looking the upper side of Fig. 6, the initial force value is different from the last, and this behaves as a straight line over time. This drift is automatically erased drawing a picture as Fig. 7. In Fig. 7, the results of three different runs of the force test are shown. In Test1 and Test2, the force is applied in the same point,

978-1-5386-2092-2/18/$31.00 ©2018 IEEE

in the Test3 it was near the edge. The sensor behavior reveals low hysteresis, with a maximum value of 20 fF.

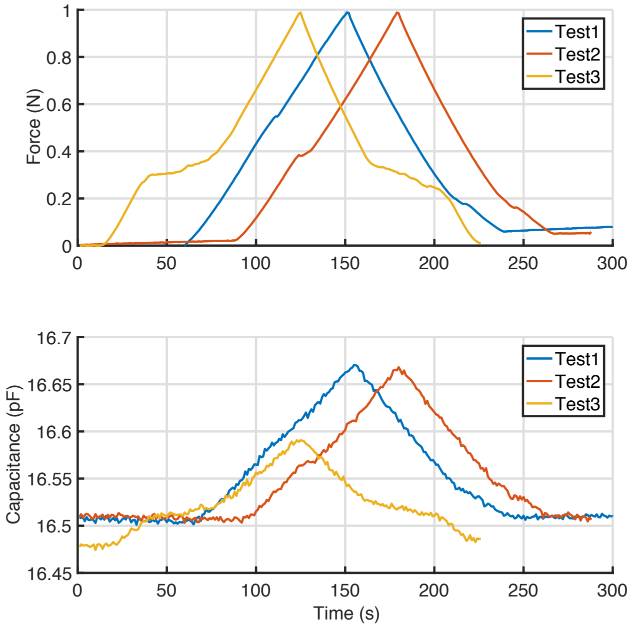


Fig. 6: Force values measured by the INSTRON load cell and the variation in the capacitance value of the sensor measured by the impedance analyzer.

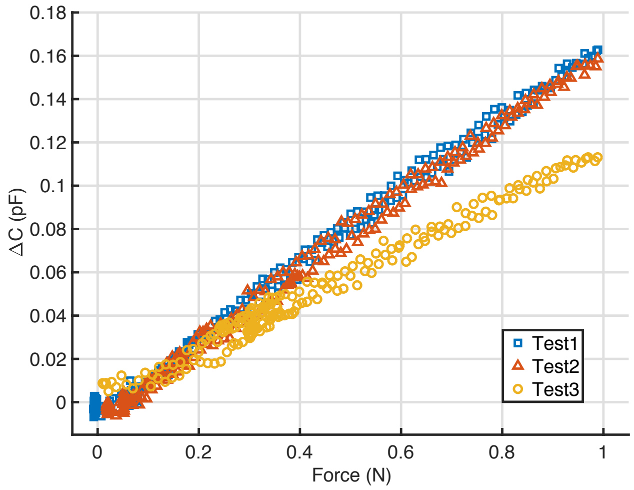


Fig. 7: Capacitance variation versus force. Test1 and Test2 are two different runs of the same test, maintaining the same force application position. Test3 is obtained moving the force application position from the spiral center

It also has a sensitivity of 172 fF/N, a resolution of 80 mN and a zero drift of -5.5 fF. When moving from the center of the sensor, the sensitivity decreases. In this particular case, it reduces its value of a 32.7%. It could be linearized with a first order polynomial approximation, with a R^2=0.9798 and a standard deviation of the residuals σ=4.9 fF in tests 1 and 2. This corresponds to an uncertainty on the estimated force of about $\varepsilon_F = 64.07\, mN$. In terms of percentage of nonlinearity, the sensor shown a 1.08%. If the force is not equally distributed on the sensor's surface, the sensor is also sensitive to the position of force application point. Test3 reveals that the response to a force applied outside the center gives a different capacitance variation. This extent the possible application fields also to the position detection through placing arrays of sensors. Further analyses are ongoing in order to obtain a complete characterization in respect to the tip positions.

IV. Conclusions

A low-cost capacitive pressure sensor has been designed, fabricated and tested. Preliminary results are reported with an applied force with a maximum intensity of 1 N. Because of its geometry it is sensitive only to a one-direction stimulus and it could also act as a position sensor, varying its maximum capacitance variation against the position from the center of the spiral. Applying a force of 1 N it gives a variation in the capacitance with a good repeatability and a low hysteresis, in the order of 0.02 pF. It has shown a sensitivity of 172 fF/N, a resolution of 80 mN and a low zero drift. This sensor is fabricated using standard methodologies involved in the flex PCB construction, avoiding the need of expensive ad-hoc methods. Further analyses are needed in order to obtain a sensor characterization in terms of long-time stability, linearity and resolution. The thermoforming technique involved in the sensor construction permits to hermetically seal sensors from the outside environment. This prevents any capacitance value variations due to moisture changes. Anyway, a deep environmental calibration of the sensor is undergoing to evaluate the effect of the temperature on sensors behavior. Deeper investigations are also needed on the dimensions and the sensor capacitance variation with a non-floating INSTRON tip.

References

[1] Y. Wei, Q. Xu, "Design of a PVDF-MFC Force Sensor for Robot-Assisted Single Cell Microinjection", IEEE Sensors Journal, pp. 3975-3982, vol. 17, no. 13, July 1,2017.

[2] Y. Dai, A. Abiri, S. Liu, O. Paydar, H. Sohn, E. P. Dutson, W. S. Grundfest, R. N. Candler, "Grasper integrated tri-axial force sensor system for robotic minimally invasive surgery", Engineering in Medicine and Biology Society (EMBC), 2017 39th Annual International Conference of the IEEE, 11-15 July 2017, Seogwipo, South Korea.

[3] J. Kim, Y-H. Kwak, W. Kim, K. Park, J. J. Pak, K. Kim, "Flexible Force Sensor Based Input Device for Gesture Recognition Applicable to Augmented and Virtual Realities", 14th URAI, 28 June – 1 July 2017, Maison glad Jeju, Jeju, Korea.

[4] S. Kim, C. Kim, S. Park, D-Y. Lee, "A 3-DOF sensor to estimate the force applied to the tip of a surgical instrument", 18th ICAR, 10-12 July 2017, Hong Kong, China.

[5] T. Nagatomo, N. Miki, "Three-axis capacitive force sensor with liquid metal electrodes for endoscopic palpation", IET Micro & Nano Letters, pp. 564-568, vol. 12, iss. 8, August, 2017.

[6] J. Fernandes, H. Jiang, "Three-Axis Capacitive Touch-Force Sensor for Clinical Breast Examination Simulators", IEEE Sensors Journal, pp. 7231-7238, vol. 17, iss. 22, 2017 IEEE Journals & Magazines.

[7] D. Ha, W. N. de Vries, S. W. M. John, P. P. Irazoqui, W. Chappell, "Polymer-based miniature flexible capacitive pressure sensor for intraocular pressure (IOP) monitoring inside a mouse eye", Biomed Microdevices (2012), 14:207-215, Springer Science+Business Media.

[8] Lee et al., "Dual-mode Capacitive Proximity Sensor for Robot Application: Implementation of Tactile and Proximity Sensing Capability on a Single Polymer Platform Using Shared Electrodes", IEEE Sensors Journal, vol. 9, no. 12, pp. 1749-1755december 2009

[9] S. C. B. Mannsfeld, B. C-K Tee, R. M. Stoltenberg, C. V. H-H. Chen, S. Barman, B. V.O. Muir, A. Sokolov, C. Reese, Z. Bao, "Highly sensitive flexible pressure sensors with microstructured rubber dielectric layers",

Nature Materials, vol. 9, pp. 859-864, October 2010, Macmillan Publishers Limited.

[10] Zhuo et al., “High Sensitivity Flexible Capacitive Pressure Sensor Using Polydimethylsiloxane Elastomer Dielectric Layer Micro-Structured by 3-D Printed Mold”, IEEE Journal of the Electron Devices Society, vol. 5, no. 3, pp. 219-223, May 2017

[11] H-C. Yu, C-L. Cheng, P-H. Wu, S-J. Li, “Elastic Capacitive Tactile Array Pressure Sensor System”, Sensors and Materials, vol. 29, no. 7 (2017), pp. 885-895, MY Tokyo

[12] H. Qin, Y. Cai, J. Dong, Y-S. Lee, “Direct Printing of Capacitive Touch Sensors on Flexible Substrates by Additive E-Jet Printing With Silver Nanoinks”, ASME Journal of Manufacturing Science and Engineering, vol. 139, March 2017.

[13] E. Pritchard, M. Mahfouz, B. Evans III, S. Eliza, M. Haider, “Flexible Capacitive Sensors fot High Resolution Pressure Measurement”, Proceedings of SENSORS 2008, Lecce, Italy

[14] S. Guo, J. Guo, W-H. Ko, “A Monolithically Integrated Surface Micromachined Touch Mode Capacitive Pressure Sensor”, Sensors and Actuators, pp. 224-232, vol. 80, 2000, Elsevier.

[15] Y. Joo, J. Yoon, J. Ha, T. kim, S. Lee, B. Lee, C. Pang, Y. Hong, “Highly Sensitive and Bendable Capacitive Pressure Sensors and Its Application to 1 V Operation Pressure-Sensitive Transistor”, Advanced Electronic Materials, Mar 15 2017, John Wiley and Sons.

[16] S. Chaurasia, P. Sen, N. Bhat, “Using Dielectric Droplets to Improve Sensitivity of Capacitive Sensors Suitable for Tactile Sensing”, Proceedings of the 12th IEEE International Conference on Nano/Micro Engineered and Molecular Systems, 2017, Los Angeles, USA.

[17] R. Seguine, M. Lee, “Layout guidelines for PSoC™ CapSense™”, AN2292, Cypress Semiconductor, 2005

[18] T. Chen, N. Bowler, “Design of Interdigital Spiral and Concentric Capacitive Sensors for Materials Evaluation”, Review of Progress in Quantitative nondestructive evaluation, 7-2012, Denver, USA http://lib.dr.iastate.edu/cnde_conf/15/

[19] B. Zhuo, S. Chen, & X. Guo. ,”Micro structuring polydimethylsiloxane elastomer film with 3D printed mold for low-cost and high sensitivity flexible capacitive pressure sensor. *2017 IEEE Electron Devices Technology and Manufacturing Conference, EDTM 2017 - Proceedings*, *8*(31), 148–149. https://doi.org/10.1109/EDTM.2017.7947545

[20] W. H. Ko, Q. Wang, “Touch mode capacitive pressure sensors”, *Sensors and Actuators, A: Physical*, *75*(3), 242–251. https://doi.org/10.1016/S0924-4247(99)00069-2

[21] T. H. N. Dinh, P.-Y. Joubert, E. Martincic, E. Dufour-Gergam, “Polymer-based flexible capacitive pressure sensor for non – invasive medical monitoring applications.” *MeMeA2014*, *8622*(1), 270–274. https://doi.org/10.1109/MeMeA.2014.6860070

[22] M. Magni,B. Saggin, D. Scaccabarozzi, M. Tarabini, “Measurement of force and pressure distribution in walking for prosthesis design”. *2016 IEEE International Symposium on Medical Measurements and Applications, MeMeA 2016 - Proceedings*. https://doi.org/10.1109/MeMeA.2016.7533797