3D Printed Capacitive Pressure Sensor with Corrugated Surface

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***Abstract*— In this work a novel 3D printed capacitive pressure sensor with a corrugated surface is presented. The design composed of top and bottom plates. The sensor is 3D printed using a commercially available polymer material and then coated with Cr and Au with sputtering process. The dimensions of produced structure that designed is 11×11×4.6mm^3. Due to the corrugated surface, the area of the plates is increased 19.46% compared to a standard flat surface parallel plate capacitive sensor in the same bulk area. The design process of the sensor, simulation and the experimental results are given and explained in detail. The performance of the sensor is tested with various pressure levels between 0 Pa and 8.88 kPa. The experimental results show that the capacitance range of the sensor is 2.7 pF-4.3 pF. The maximum sensitivity of the sensor is obtained as 0.14 pF / kPa. The results confirm that the presented capacitive sensor can be utilized for carrying out pressure measurements.**

I. Introduction

The performance of various micro-electro-mechanical-systems (MEMS) applications depend upon devices and micro-structures with an alternating thickness. Standard micromachining technologies including surface micromachining [1], bulk micromachining [2] and lithography, electroplating, and molding (LIGA) [3] are not able to form curved three-dimensional (3D) surfaces and therefore can not always pattern the required profiles of micro-structures. Even though there are several different reported methods claiming to pattern out-of-plane curved surfaces on polymer and silicon substrates namely micro-stereo lithography [4] or inclined/rotated UV lithography [5], they are not fully capable of producing real 3D micro-structures with a low-cost and in quick fashion.

Recently, there has been an interest in 3D printing technology which is also referred as additive manufacturing (AM) especially in the development of various MEMS because of its excellent fine feature detail, low-cost, low-waste and quick-prototyping capabilities [6], [9]–[11]. AM techniques such as fused deposition method, stereolithography or selective laser sintering employs deposition of materials layer-by-layer as oppose to conventional fabrication processes. Moreover, different from the planar micro-fabrication processes, AM fully enables the depth profile shaping of MEMS structures.

Different capacitors or capacitive sensor structures that are fabricated using 3D printing technology were previously shown in literature [6]–[8]. This work focuses on the design and fabrication of a novel capacitive pressure sensor that exploits the AM to depth-shape the plates of the sensor and hence enhance the performance of the MEMS device.

This paper is organized as follows. Section two explains the proposed capacitive pressure sensor design and elaborate its working principles. Moreover, it theoretically demonstrates how a parallel-plate capacitive sensor with a corrugated surface has an increased sensing performance. Section three fully describes the implementation process along with a discussion of the used fabrication material. Section four characterizes the devices by giving experimental results and discusses the performance of the proposed system. Finally, concluding remarks and outlook are provided.

II. Proposed Design

The proposed 3D printed corrugated sensor design together with the related design parameters is shown in Fig. 1. The proposed design is composed of two plates; namely *top* and *bottom* plates. The top plate is designed to act as a membrane that deflects with an applied pressure. If the plates of the proposed 3D printed sensor are coated with a conductive material, a parallel plate type capacitive pressure sensor structure can be achieved. Moreover, as it is depicted in Fig.1, the top plate contains legs interlocked with the holes located at the bottom plate to restrain only the vertical deflection of top plate, by preventing the top plate from lateral motion under an applied pressure.

The capacitance value of the proposed sensor geometry can be calculated by;

$$C = \int_A \int \frac{\epsilon_o \epsilon_r dxdy}{d(x,y) - \Delta(x,y)} \qquad (1)$$

where C is the capacitance value obtained under a differential pressure, ϵ_r is the relative dielectric constant of dielectric material that located between the top and bottom plates, ϵ_o is the dielectric constant, $d(x,y)$ is the distance between plates and $\Delta(x,y)$ is the function that models the deflection of the top plate [19]. When a mechanical force or pressure is applied on the top plate, the top plate deflects and the distance between plates alters accordingly. The nominal distance between the plates under no applied pressure is denoted with $d(x,y)$ in equation (1). For a standard parallel plate capacitor, $d(x,y)$ is a constant value.

Equation (1) clearly shows that the capacitance value of the proposed design is linearly depended to the surface area of the plates. It is important to note that the surface area and

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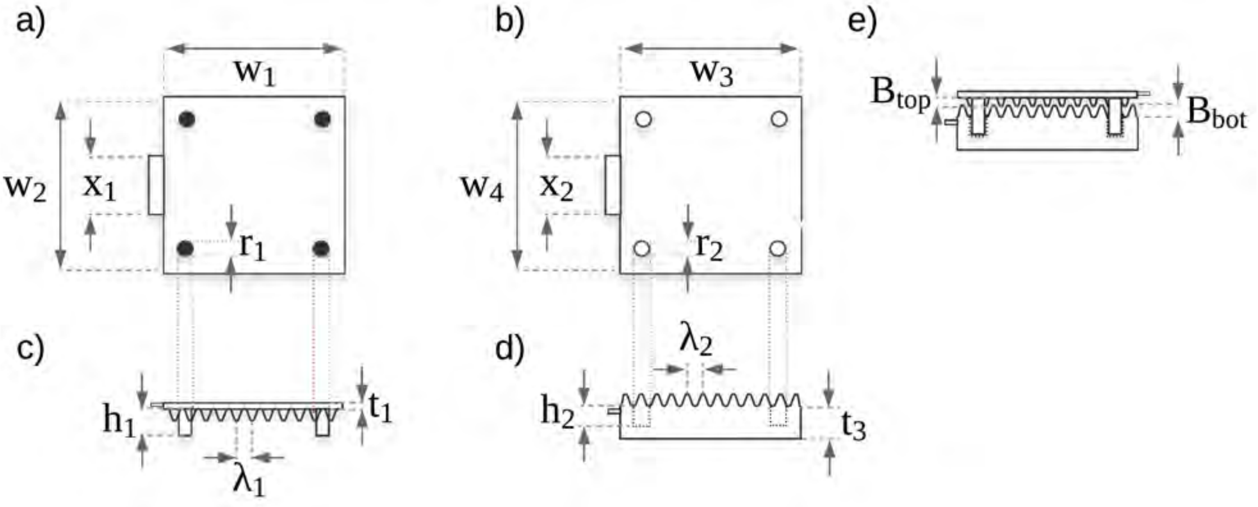

Fig. 1: Display of the proposed design and its related parameters. a) Top view of the top plate. b) Top view of the bottom plate. c) Profile view of the top plate. d) Profile view of the bottom plate. e) Overall recommended design

the related capacitance increase is advantageous, since higher valued capacitive sensors is desired for large full-scale range and designing compact read-out circuits. In order to attain an augmentation of capacitance value, the surface area of the plates must be increased. Such a maximization in surface area can be acquired in a controlled manner by modeling the surface of the plates with a two-variable-function $f(x, y)$. In the proposed design, to maximize the surface area in the same limited plate perimeter the following sinusoidal function is employed in both x, and y axes of the top and bottom plate surfaces;

$$f(x, y) = B(\sin(\frac{2\pi}{\lambda_x}x) + \cos(\frac{2\pi}{\lambda_y}y)) \quad (2)$$

which results in corrugated top and bottom plate surfaces. In (2), B is the wave amplitude and λ_x and λ_y defines the wave length for x and y dimensions respectively [20]. Top and bottom plate surfaces that are modeled using equation (2) is illustrated in Fig.2.

The increase in the amount of the proposed surface area can be computed by considering a nominal distance $d(x, y)$ and deflection $\Delta(x, y)$ functions between plates in equation (1). The distance between plates for the proposed capacitive sensor depends on the parameters of the applied surface function (2), thus, it varies along the x and y axes. The function for computing the distance between plates can be elaborated as;

$$d(x, y) = h_1 - h_2 - f_{top}(x, y) + f_{bot}(x, y) \quad (3)$$

where h_1 and h_2 are illustrated in Fig. 1. $f_{top}(x, y)$ and $f_{bot}(x, y)$ express the surface function (2) for top and $bottom$ plates respectively.

III. Implementation of the Proposed Structure

Parameters with the dimensions listed in Table I are applied to the design for 3D printing implementation. In

TABLE I: Dimensions of the proposed design

Parameters	Dimensions (μm)	Parameters	Dimensions (μm)
w_1	1.1×10^4	w_2	1.1×10^4
w_3	1.1×10^4	w_4	1.1×10^4
x_1	550	x_2	550
r_1	1.4×10^3	r_2	1.6×10^3
h_1	1.85×10^3	h_2	1.1×10^3
t_1	300	t_3	2.5×10^3
λ_1	200	λ_2	200
B_{top}	300	B_{bot}	500

order to prevent pull-in, the amplitudes, B_{top} and B_{bot}, of the surface function (2) are limited. With the given dimension for the proposed geometry , a surface area increase of *19.46%* is achieved compared to a generic flat-surface parallel-plate capacitive sensor with the same bulk geometry.

Finite-element-method (FEM) simulations of the design are carried out to determine the bending behavior of the top plate. For FEM simulations, COMSOL simulation tool is utilized. The results are shown in Fig.3. A pressure of 2.8 kPa is applied to the center of the top plate surface in the simulations and a peak deflection of 3.77 μm is acquired.

The proposed sensor is printed with an Objet 260 Connex 3D printer with fused deposition modeling. VeroClear RGD810 polymer material is used as the fabrication ma-

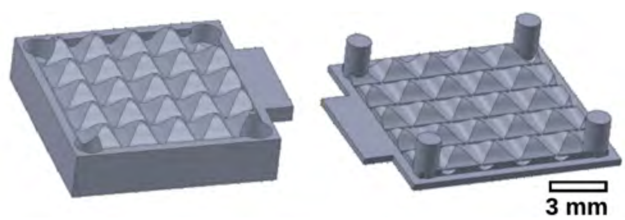

Fig. 2: CAD image of the proposed top and bottom plate surfaces.

TABLE II: Material properties of the Veroclear RGD810

Parameters	Values
Young's Modulus(MPa)	$2000-3000$
Coefficient of Elongation(%)	$10-25$
Tensile Strength(MPa)	$50-65$
Flexural Strength(MPa)	$75-110$
Flexural Modulus(MPa)	$2200-3200$
Polymer Density(g/cm^3)	$1.18-1.19$

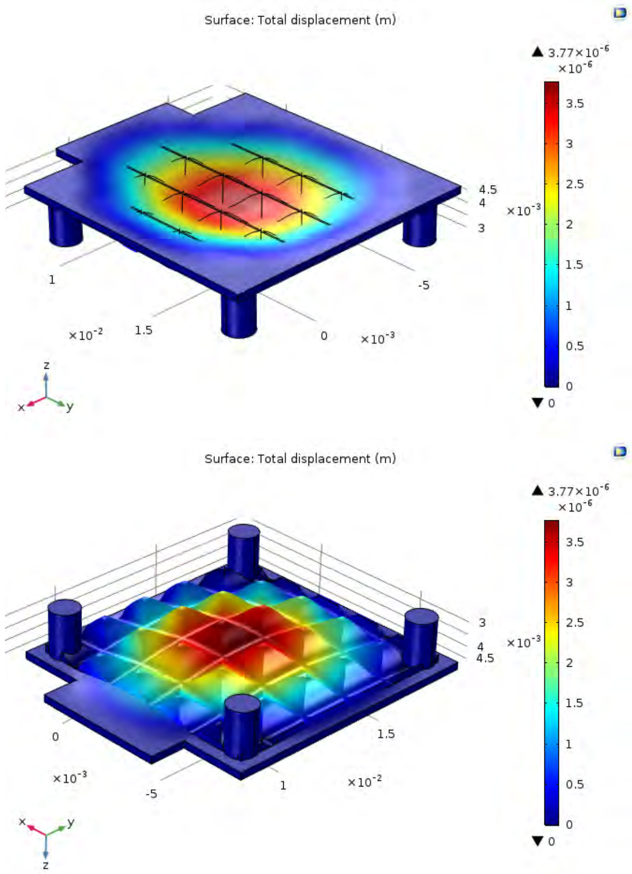

Fig. 3: FEM simulation results showing 3.77 μm peak displacement of the top plate under 2.8 kPa differential pressure.

terial [12]. The material properties of the used fabrication material is given in Table II. Printed polymer sensor is strip-off from the support material by immersing it into a 40% NaOH solution for approximately 16 hours. Following to that, to establish the electrical connections and provide the conductive surface, the sensor surfaces are coated with 10 nm thick Cr and 115 nm thick Au using a sputtering process, respectively. For creating electrical connection to the sensor, copper wires are attached to the plates of the sensor using silver epoxy. Fabricated capacitive sensor with the dimensions of $11 \times 11 \times 4.65$ (mm) is shown in Fig. 4.

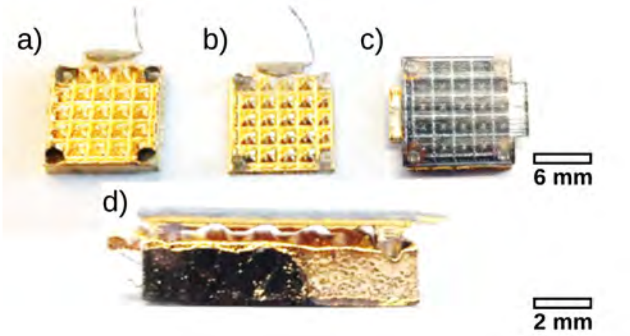

Fig. 4: Implemented 3D printed capacitive sensor a) fabricated bottom plate, b) fabricated top plate, c) assembly of the fabricated bottom and top plates, d) profile view of the assembled sensor.

IV. Experimental Results

In the experiments, the fabricated sensor is tested under seven different pressure levels (i.e. 0 Pa, 0.71 kPa, 1.42 kPa, 2.13 kPa, 2.84 kPa, 3.55 kPa, 5.33 kPa, 8.88 kPa), while the sensor is connected to GWINSTEK-LCR 814 LCR meter for measuring the capacitance change. The result of the measurements is shown in Fig. 5. The nominal capacitance of the sensor when there is no applied pressure is measured as 2.7 pF, and the maximum capacitance when pull-in occurs is measured as 4.3 pF. An exponential behavior over the pressure level is observed due to increasing electric field strength between the plates. The sensitivity of the sensor also varies due to the exponential behavior. The maximum sensitivity is obtained as 0.14 pF/kPa in the 0.71 kPa to 2.13 kPa pressure range.

The parasitic series resistance is also a very important factor that limits the performance of the capacitive sensors. Therefore, together with the capacitance measurements, the parasitic series resistance of the sensor is also measured and calculated. The factors that effect the resistance value of the proposed sensor are resistivity properties of the coated metal, copper wires used and the resistivity of the silver epoxy used to bond the wires to the sensor. Due to the chromium is used only as a buffer and chromium surfaces of the plates are coated smoothly and stably with gold, only gold metal affects the obtained results in both capacitance and resistance measurements. The parasitic series resistance, R, can be calculated from the following equation [18];

$$R = \rho \frac{l}{A_{cs}} \quad (4)$$

where ρ is the electrical resistivity of the conductive material, l is length of the conductive material and A_{cs} is the cross-sectional area of the specimen. According to equation (4), the parasitic resistance value of the sensor is calculated as 2.1 Ω in the nominal condition.

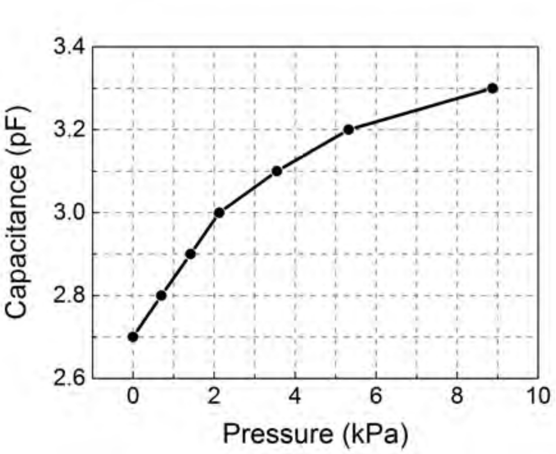

Fig. 5: Experimental capacitance-applied pressure results of the fabricated sensor under pressures between 0 Pa to 8.88 kPa.

V. Conclusion

In this work,a novel 3D printed capacitive pressure sensor with a corrugated surface is presented. The design process of the sensor, simulation and the experimental results are given and explained in detail. The design composed of two plates namely top and bottom. The assembled sensor is $11\times11\times4.6\text{mm}^3$ of size. After confirmation of the design with FEM simulations, the sensor is fabricated on a 3D printer using a commercially available polymer material. The residual support material on the 3D printed structure is etched out from the surfaces of the plates by applying a caustic solution to the print for 16 hours. In the next step, the polymer print is coated with the conductive metals those are 10 nm thickness Cr and 115 nm thickness Au with sputtering process. The performance of the sensor is tested with various pressure levels between 0 Pa and 8.88 kPa. The experimental results show that the sensor exhibits an exponential behavior. The nominal capacitance of the sensor when there is no applied pressure is measured as 2.7 pF, and the maximum capacitance when pull-in occurs is measured as 4.3 pF. The maximum sensitivity of the sensor is obtained as 0.14 pF / kPa in 0.71 kPa to 2.13 kPa range. The experimental results also confirm that the presented capacitive sensor can be utilized for measuring pressure levels.

VI. Acknowledgement

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