

# Study on Optimization of Capacitive Pressure Sensor Using Coupled Mechanical-electric Analysis

Ciprian Ionescu<sup>1)</sup>, Paul Svasta<sup>1)</sup>, Cristina Marghescu<sup>1)</sup>, Marina Santo Zarnik<sup>2)</sup>, and Darko Belavič<sup>2)</sup>

<sup>1)</sup> Center for Technological Electronics and Interconnection Techniques, University “Politehnica” of Bucharest, Romania

<sup>2)</sup> HIPOT-RR, Šentjernej, Slovenia

ciprian.ionescu@cetti.ro

**Abstract:** *The object of the paper is a pressure sensor realized in thick-film technology developed at “Jožef Stefan” Institute. This pressure sensor is also the object of a common project which has the goal to optimize the sensor design acting mainly on layout parameters. Some of the sensor parameters are determined by the LTCC process, for instance the thickness of diaphragm whose thickness is a multiple of foil thickness. The novelty in the proposed paper is the use of specific simulation tools to give an estimate of sensor output characteristics. Using this technique it is possible to optimize the layout and construction of the sensor. The finite-element simulation is used to outline the output characteristic: capacitance versus pressure. This simulation implies the coupled field analysis from mechanical deflection of sensor diaphragm to electrical field quantities, in this case the capacitance. The analysis will take into account beside geometrical parameters the temperature dependence of materials properties. This fact will give a better appreciation of real life behavior of manufactured sensors, and can suggest some specific packaging methods.*

## 1. INTRODUCTION

The work to this paper is derived from a joint project between University Politehnica Bucharest and Josef Stefan Institute from Ljubljana. The need for study in this field of sensors has been determined by the market for capacitive pressure sensors. The demand has been on a steady rise for the last couple of years due to their low cost and stability. The basic structure (most common structure) of a capacitive pressure sensor comprises two parallel electrodes with one fixed electrode and one electrode bonded to a diaphragm [2]. The value of the capacitance is determined by the distance between electrodes, the area of the electrodes and the nature of dielectric. This paper focuses on a capacitive pressure sensor realized in thick-film technology. The employed dielectric is air. Pressure on the diaphragm will have as effect a deflection which will in turn lead to a change in the value of the capacitance. The proposed sensor architecture can be observed in fig. 1. The sensor's characteristics depend on the construction, the dimension and the material properties of the sensor structure. Virtual prototyping tools allowed the

simulation of different geometrical parameters dimensions and temperature dependence. The ANSYS<sup>TM</sup> provides a wide range of tools to perform this multi-field analysis.

## 2. CAPACITIVE PRESSURE SENSOR THEORY

The pressure sensing element in this type of sensor is a deformable diaphragm. It influences the behavior of the sensor [2]; and having this in mind a discussion of the different diaphragm types is appropriate when choosing a sensor design. The following types of diaphragms are commonly used: small deflection diaphragms (the maximum deflection is smaller than 30% of the thickness of the diaphragm), medium deflection diaphragms, membranes (very thin diaphragms) or bossed and corrugated diaphragms which can be used for large deflections. The behavior of the diaphragm will depend on many factors as the deflection range compared to diaphragm thickness. At small deflections (<10% of diaphragm thickness) the pressure-deflection relationship is assumed to be linear. As the pressure increases, the rate of deflection decreases and the pressure-deflection relationship will

become nonlinear. As a rule of thumb, a deflection of 12% of diaphragm thickness will produce a terminal nonlinearity of 0.2%; a deflection of 30% produces a nonlinearity of 2% [2].

The presented sensor architecture is based on a circular edge/clamped small deflection diaphragm. The deflection in this case can be expressed as:

$$\begin{aligned} y(r) &= \frac{3P(1-\nu^2)(R_d^2-r^2)^2}{16Et^3} = \\ &= y_0(R_d^2-r^2)^2 \end{aligned} \quad (1)$$

In the assumption that the fringing field is neglected the capacitance can be calculated as follows:

$$C(P) = \varepsilon_0 \varepsilon_r \int_0^{2\pi} d\theta \int_0^{R_d} \frac{rdr}{D_0 - y(r)} \quad (2)$$

where  $y(r)$  is the deflection at the position  $r$  from the center when a pressure  $P$  is applied,  $E$  is the elasticity (Young) modulus,  $\nu$  is Poisson's ratio,  $t$  is the thickness and  $R_D$  is the radius of the diaphragm.  $C(P)$  is the value of the capacitance when a pressure  $P$  is applied. The following factors influence this value: the permittivity of vacuum -  $\varepsilon_0$ , the relative permittivity -  $\varepsilon_r$ , the radius of the electrode -  $R_e$ , the distance between electrodes at no deflection -  $D_0$  and  $y(r)$  - the deflection. It is possible to give a closed form to the integral (2) by replacing  $y(r)$  from (1). In order to simplify the calculation we introduce a dimensionless parameter  $\beta=y_0/D_0$  and we change the variable from  $r$  to  $x$  as follows:

$$r = \sqrt{\beta}(R_d^2 - r^2) \quad (3)$$

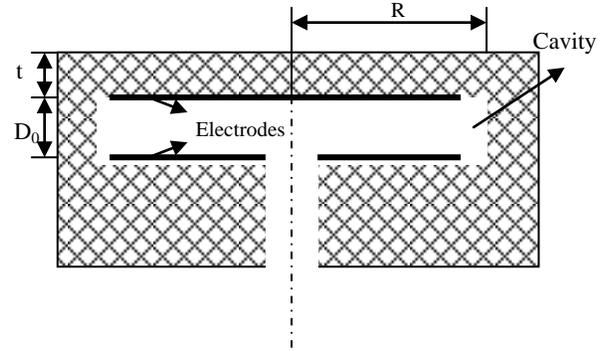
This gives

$$C(P) = \frac{\pi\varepsilon_0}{\sqrt{\beta}D_0} \int_{\sqrt{\beta}R_d^2}^0 \frac{dx}{x^2 - 1} \quad (4)$$

and it gives finally:

$$C(P) = \frac{\pi \cdot \varepsilon_0}{2D_0\sqrt{\beta(p)}} \ln \left| \frac{\sqrt{\beta(p)}R_d^2 + 1}{\sqrt{\beta(p)}R_d^2 - 1} \right| \quad (5)$$

We make the observation that this is valid when the pressure is applied from the top of the membrane. In the situation when the pressure is applied from below, from the cavity, the deflection ratio is similar and so the capacitance change, but the closed form expression of the capacitance is different because of the plus sign at the denominator in (2) and hence, it contains the arctan(x) function not logarithm.



**Fig. 1** Sensor architecture

This analytical approach has only the advantage of phenomenological analysis of sensor behavior with respect to the influence of geometric and material factors, but is only a starting point in design. The actual capacitance is in a considerable amount determined by the presence of the dielectric, or other saying the fringing field from the parallel plate capacitor cannot be neglected as will be shown.

The sensor's sensitivity is defined by the initial capacitance, the geometry and the flexibility of the diaphragm [3]. The sensor's response is the fractional change in capacitance.

The proposed sensor should be realized on low-temperature-cofired-ceramic (LTCC) with the electrodes made from Ag/Pd (3:1 proportion) and a metal (brass) tube as pressure inlet.

When building the model the following material constants were used for LTCC:

Characteristics	Value
Density ( $\rho$ )	3.1 [g/cm <sup>3</sup> ]
Thermal expansion coefficient (TEC)	5.8x10 <sup>-6</sup> [1/K]
Thermal conductivity (k)	3.3 [W/mK]
Elastic modulus (E)	110 [GPa]
Temperature coefficient of elastic modulus (TCE)	-240x10 <sup>-6</sup> [1/K]
Poisson's ratio ( $\nu$ )	0.17

**Tab. 1.** Characteristics of LTCC (Du Pont 951).

For the Ag/Pd electrodes the following values were used:

Characteristics	Value
Density ( $\rho$ )	10.9 [g/cm <sup>3</sup> ]
Thermal expansion coefficient (TEC)	17.7x10 <sup>-6</sup> [1/K]
Thermal conductivity (k)	393 [W/mK]
Elastic modulus (E)	92.5 [GPa]
Poisson's ratio ( $\nu$ )	0.38

**Tab. 2.** Characteristics of Ag/Pd deposition.

For these values and the above mentioned equations a *MathCAD* mathematical worksheet was created. The deflection at different positions on the diaphragm was calculated for several values of the pressure. By modifying the material constants it is possible to compare the differences in the sensor's response when the sensor is realized on different materials. We are interested in modification of dimensions in order to find a better output response or a better thermal behavior.

### 3. THE FINITE ELEMENT MODEL (FEM)

An analysis using ANSYS has three basic steps: Pre-processor – when the geometry, materials, loading, and boundary conditions are defined, Processor – the mathematical model is constructed and solved, and Post-processor – the displacements and stresses are displayed and analyzed.

For this model a top-down approach was used – the volumes that define the component were defined first.

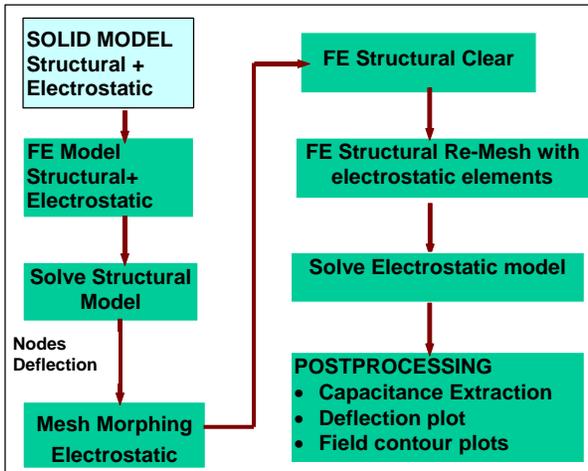
Since the modification of the model data was necessary a parametric model was constructed in order to facilitate this approach (the dimensions were defined as parameters whose value can be easily changed). The units must be consistent for all the defined dimensions.

Three material models were defined: one for the LTCC ceramic, the second for the air and the third for electrostatic LTCC.

We have the intention to realize a model that should give the output variable, in this case the capacitance in function of the input physical quantity, in this case the pressure using the same simulation environment.

The ANSYS program offers coupled electrostatic-structural analysis but only in this sense when from electrostatic analysis the forces are sent for a structural displacement computation. This is not our case. For our analysis the steps to be followed make use of another feature of the program which is called “mesh morphing”.

The model at the beginning contains the block of LTCC ceramic modeled as structural element in which there is an air cavity modeled as electrostatic air, so no influence for the structural domain. After the structural analysis the displacement obtained at the membrane interface are transferred to the volume that models the cavity using the morphing feature. Only the coordinate of the nodes are changed, the solid model elements (volumes, surfaces) are kept as initial. Supplemental, the program keeps track of the nodes, so they are still associated with the surfaces, even there was a movement from initial position. The membrane operates at relatively small deflection ratio so in this case there is no need for non-linear problem activation. For large deflections this feature offers more accurate results. After the morphing process, the volume of the LTCC block is cleared from the structural mesh and is re-meshed with electrostatic elements having the relative permittivity of 7.8. Now it is possible to do the electrostatic analysis on a model that contains the cavity and the LTCC together, but the coordinates of the membrane are taken from the structural analysis. The flow diagram of the simulation process is presented in figure 2.

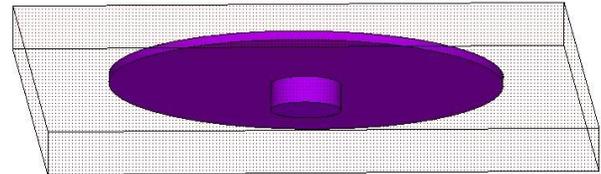


**Fig. 2** Flow process for the structural -electrostatic simulation.

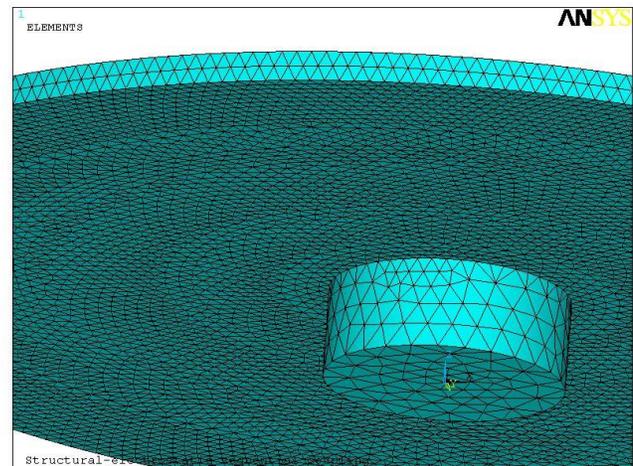
Regarding the simulation flow, all the steps are contained in one single batch file which can simplify considerably the simulation process with different input values.

For the electrostatic solution the capacitance was computed (electrostatic analysis) using the *CMATRIX* macro-command. This command extracts the self and mutual capacitance terms for multiple conductor systems. No loads are applied to the model. The conductors are considered to be perfect so it is not necessary to apply a finite element mesh on them. Only the dielectric shall be meshed. In order to extract the capacitance the conductor nodes at the boundary of the conductors and the dielectric regions are grouped in components, in this case we have two conductors so two components shall be created (since we know the dimensions we can select all nodes at a certain height). The component name must contain a common prefix. This is followed by a numerical suffix. After meshing the dielectric and grouping the nodes in components, the *CMATRIX* macro is invoked. This requires as input the following: a *symmetry factor* (can be 1 if there is no symmetry), the node component prefix name, the number of conductor node components, the *ground key* option, and a name for the stored matrix of capacitance values. The command shall store the capacitance matrix also in a text file (extension .txt). This file shall share the name of the matrix. We have computed the capacitance also in a different way, based on energy stored in elements. The both methods give results identical up to the fourth position after coma.

Initially a structural analysis was performed in order to compute the effects of the pressure on the model. In this case the only load defined was the pressure which was applied on the solid model, on areas. This approach has several advantages that recommend it – mesh modifications that are made do not affect the applied loads and the solid model has fewer elements than the finite element model. The solid model is presented in fig. 3 and a part of the FEM model in fig. 4.



**Fig. 3.** Solid model of the sensor.



**Fig. 4.** Detail of the solid model with elements being visible.

The model was a full 3D meshed with tetrahedral elements, SOLID 92 and SOLID 123, structural and electrostatic, respectively.

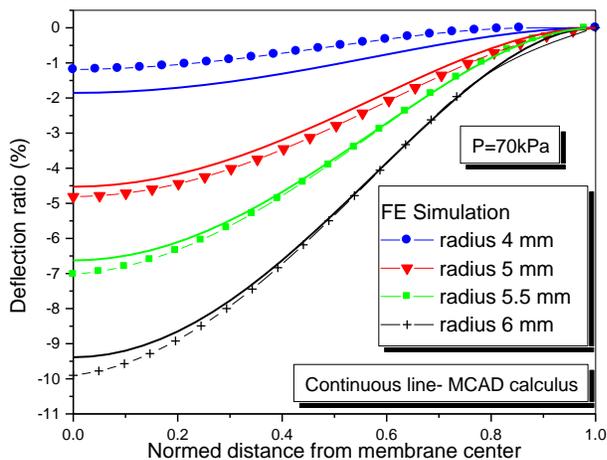
A coupled analysis was performed as well: structural (load pressure surface load – a distributed load applied over a surface) and thermal strain (load temperature – body load a volumetric load). The loads are applied on the solid model volumes and areas.

The deflection of the membrane was read by using the so called path operations in which a variable from the model is plotted against a path defined in the model. The path in this case was the radius of the diagram. The deflection was then plotted and

compared to the values calculated using formulae or if available with the measured data.

#### 4. MEASUREMENT AND SIMULATION RESULTS

The FEM analysis on membrane deflection has revealed a low percent of defection for small diameter membranes. Other calculations have been done using the theoretical approach, relation (1). Some of the results are presented in fig. 5.

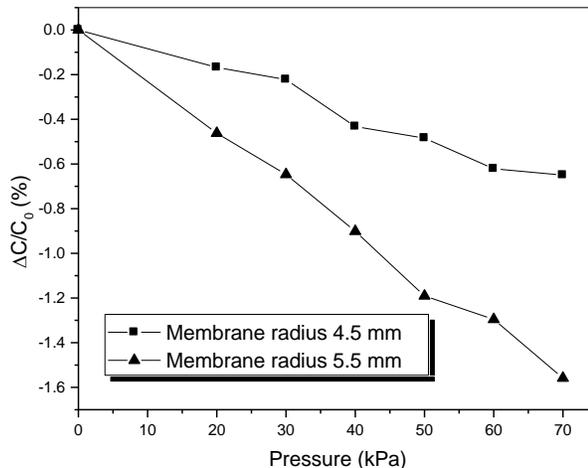


**Fig. 5.** Membrane deflection for different radii, FEM and analytical formula.

We can see little differences between the two families of curves which can derive from the material data of the LTCC which is not easy to be determined. On the other hand, it can be seen that larger membrane can bring more advantages over smaller membranes. A 6mm radius membrane can still be used in the small deflection domain.

Regarding the capacitance determination from the model, values about 4.3 pF were found for 4.5mm diameter membrane. These values differ with 0.3-0.4 pF from the measured values and differ with more than 2pF from the values computed with relations (2) or (5). This is supposed to be caused by the LTCC dielectric with a permittivity of 7.8 units.

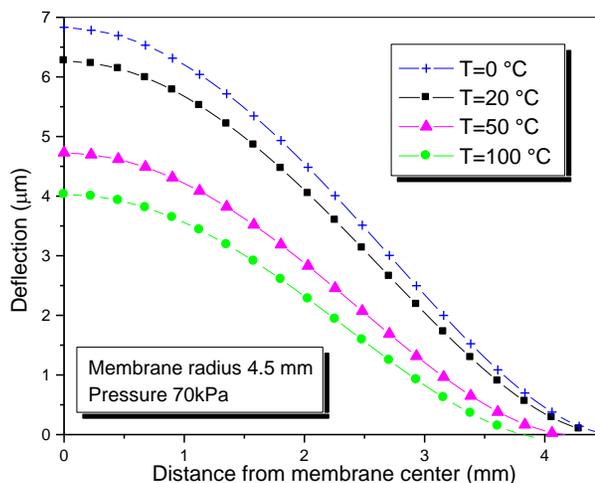
More variants of radius parameter were tried. In figure 6 we present the relative capacitance change for two membrane dimensions.



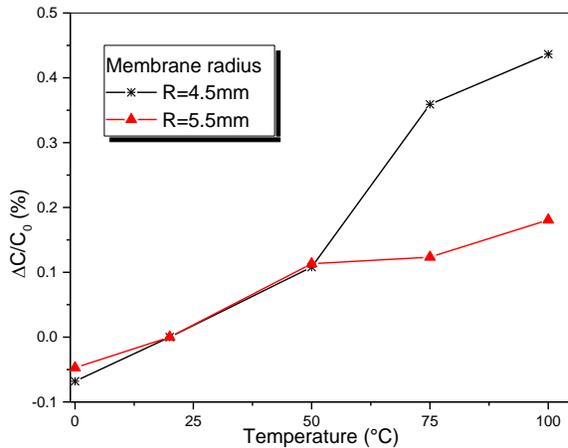
**Fig. 6.** Sensor output characteristic, relative capacitance change.

As expected, larger diameter membrane can determine higher sensor sensitivity

The influence of temperature was taken into account by realizing a series of simulations for deflection and capacitance at different constant temperatures applied to all model entities. The thermal expansion coefficient of the LTCC was now taken into account. In figure 7 we present the influence of temperature on membrane deflection and in figure 8 the influence on capacitance change.



**Fig. 7.** Influence of temperature on membrane deflection for a given pressure.

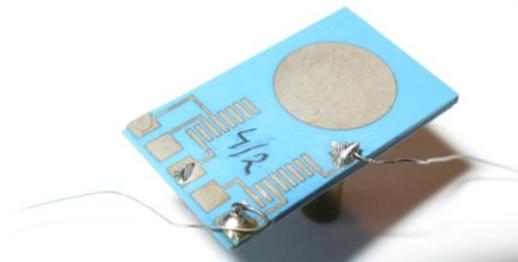


**Fig. 8** Relative capacitance change referred to 20 °C in function of temperature for two membrane radii.

The effect on deflection is in the sense of reducing the maximum deflection, and hence some increase in capacitance if the pressure is applied from inside the cavity. Larger membrane seems to behave more stable related to capacitance, as in fig. 8.

In conclusion, we have established a procedure to simulate the sensor behavior from mechanical field to electrostatic field having the pressure as input variable and capacitance as output variable.

We establish the influence of the temperature in the sense of reducing the deflection and thus the output capacitance. We suggest a better behavior for a larger membrane. The slovenian partner has already produced a few sensors using the foil thickness of 0.2mm and a membrane radius of 4.5 mm. A picture of this structure with the measurement wires can be seen in figure 9.



**Fig. 9.** Photo of a sensor with a 4.5 mm membrane.

The measured capacitance lies between 4.73-4.65 pF, slightly different from our simulation. The

pressure dependence and temperature behavior seems to be in accordance from the first measurements. In the following we will try to include more temperature effects in the model, especially for LTCC material. The relatively small output signal of this sensor makes appropriate the use of specialized measurement circuits that in many cases are driven by microcontrollers. In these situations, the non-linear effects can be easily removed. Regarding the optimization of the sensor, we did not find an optimal solution. We can recommend a membrane radius of 5.5 to 6 mm to be employed. Other factors of influence as membrane thickness and cavity gap are technology determined by the green tape employed in the process.

## ACKNOWLEDGMENTS

This paper is a result of activities that took place in the frame of a project (DAPST) funded by The Romanian National Authority for Scientific Research (ANCS).

## REFERENCES

- [1] ANSYS 6.1 Theory, Reference Manual documentation.
- [2] Stephen Beeby, Graham Ensell, Michael Kraft, Neil White, "MEMS Mechanical Sensors", Artech House , 2004, Cap.6.
- [3] J.I. Pavlič, Marina Santo Zarnik, Darko Belavič, "Feasibility study of a ceramic capacitive pressure sensor", *Proceedings. Ljubljana: MIDEM – Society for Microelectronics, Electronic Components and Materials*, 2006, pp.95-100
- [4] Darko Belavič, Marina Santo Zarnik, Mitja Jerlah, Marko Pavlin, Marko Hrovat, Srečko Maček, "Capacitive thick-film pressure sensor : material and construction investigation", *Proceedings of the XXXI International Conference of IMAPS Poland 2007, Rzeszów, Krasieczyn, Poland, September 23-26, 2007*, pp.249-253.
- [5] Darko Belavič, Marina Santo Zarnik, Srečko Maček, Mitja Jerlah, Marko Hrovat, and Marko Pavlin, "Capacitive Pressure Sensors Realized With LTCC Technology", *ISSE 2008 Proceedings*, , May 7-11, 2008, pp. 271-274.
- [6] L.K.Baxter, "Capacitive Sensors", [www.capsense.com](http://www.capsense.com)