Optimized behavioral model of a pressure sensor including the touch-down effect

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ABSTRACT

The complexity of microsystems is steadily increasing due to the scaling of microelectronic as well as for example mechanical, optical or fluidic devices. In order to be able to get good designs fast, one has to apply simulation as well as optimization tools extensively. An exact model of the system under investigation is the necessary basis for these evaluation methods.
Looking at micromechanical devices, the touch-down, the moment moving elements touch any static parts of the system, has a major influence on the overall system performance. Hence one definitely needs to consider the systems behavior in touch-mode. With the so far known approaches it has not been possible to include this effect into system evaluations efficiently. This paper presents a method for including the touch-down effect into behavioral models of microsystems which can be used for modelbased design optimizations.

Keywords: pressure sensor, touch-down, behavioral model, optimization

SYSTEM UNDER INVESTIGATION

A capacitive absolute pressure sensor fabricated with surface micro machining [5] is investigated. This fabrication technology allows a monolithic integration of a signal preprocessing unit being necessary because of the very small signals that have to be evaluated.

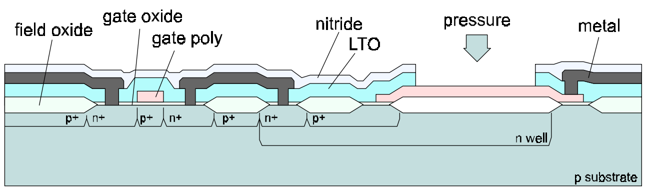

Fig. 1: Schematic cross section of the sensor chip

Fig. 1 shows a schematic cross section of the sensor including an integrated NMOS-Transistor. Using this technology, the NMOS layers are used for manufacturing the sensor system. The structure of the pressure sensor (Fig.1) is composed of a movable electrode (the sensors membrane), the implanted n-well as backplate electrode and the pressure chamber between them. There is a thin oxide layer on top of the counter electrode which results from the etching of the chamber.

MODELING THE TOUCH-DOWN EFFECT

Difficulties with modeling the touch-down effect

One of the most difficult objectives in modeling micro electromechanical devices depending on the movement of membrane structures is the consideration of the touch-down effect. It appears, whenever the movable electrode touches the oxide at the counter electrode. In the touch-mode the counter electrode is isolated from the movable electrode by the thin oxide layer. This will play an important role in the behavior model.
So far no analytical solution including the touch-down effect has been found. The difficulty is that one would have to solve a partial differential equation with changing border conditions. There have been solutions using finite element formulation [6] or 3D coupled simulations between electrostatic and mechanical elements [7], but none of these solutions is practical for system simulations and especially not for model based system optimizations.

Including the touch-down in a behavioral model

The calculation of the membranes deflection is based on the theory of large excursions for quadratic plates with clamped edges [1]. In [2] it is supposed to calculate the membranes excursion

$$\omega(x,y) = \omega_0 \cdot \left(1 + c_1 \cdot \frac{x^2 + y^2}{\left(\frac{a}{2}\right)^2} + c_2 \cdot \frac{x^2 \cdot y^2}{\left(\frac{a}{2}\right)^4}\right) \cdot \cos\left(\frac{\pi x}{a}\right) \cdot \cos\left(\frac{\pi y}{a}\right) \quad (1)$$

ω_0: excursion of the middle point of the membrane, a: length of membrane edge, x, y: geometric coordinates

The excursion of the middle point ω_0 of the plate results from the pressure that acts on the membrane. The expression (1) is valid until the membrane touches the counter electrode. Afterwards the shape of the bending line deviates extremely from (1), which results in an error in the calculation of the sensors capacity. Since this capacity is used to make conclusions about the extern pressure, errors

will occur in the developed system, for the design is partially based on wrong calculations.
In order to be able to include the touch-down effect into a behavioral model, the membrane as well as the lower electrode have to be divided into s × s partial areas (Fig. 2) and hence form s × s partial capacitors. This way it is possible to detect the touch-down of each partial plate by evaluating the deflection $\omega_m(x_i, y_i)$ at its mid point.

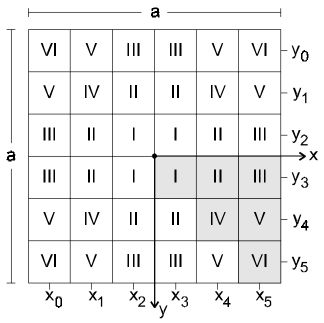

Fig. 2: Partitioning membrane and electrode into partial areas (here 6 × 6)

The capacitance of the partial plates can be calculated by using the approximation of a plate capacitance. The distance between the plates of one partial capacitance is set to be the distance $h - \omega_m(x_i, y_i)$ between the mid point of the membrane and the counter electrode at the point (x_i, y_i), where h is the height of the pressure chamber. Until the touch-down is reached, the calculation of $\omega_m(x_i, y_i)$ is based on the known theory formulated in equation (1). In touch-mode the deflection $\omega_m(x_i, y_i)$ is constantly set to h, hence the distance is equal to zero.

$$\omega_m(x_i, y_j) = \begin{cases} h - \omega(x_i, y_j) & \text{for } \omega(x_i, y_j) < h \\ h & \text{for } \omega(x_i, y_j) \geq h \end{cases} \tag{2}$$

Fig. 3 shows the plate deformation one gets using this approach.

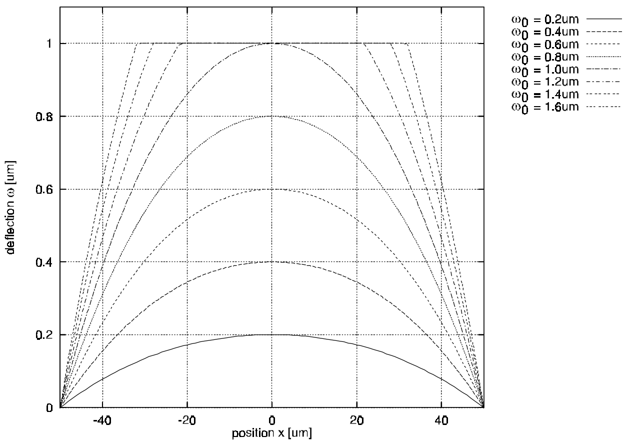

Fig. 3: Plate deformation before and after touch-down

One can see (Fig. 3) that due to this crude approximation the bending line is cut of once the touch-mode for one plate is reached.

The total deflection capacitance is calculated by

$$C_{total} = \sum_{i=0}^{s-1} \sum_{j=0}^{s-1} \frac{C_{pox} \cdot C_p(x_i, y_j)}{C_{pox} + C_p(x_i, y_j)} \tag{3}$$

where C_{pox} is the partial oxide capacitance and $C_p(x_i, y_j)$ is the partial deflection capacitance that can be calculated by

$$C_p(x_i, y_j) = \varepsilon_0 \frac{(a/s)^2}{h - \omega_m(x_i, y_j)} \tag{4}$$

In order to reduce the error made due to the discretization a partitioning of 100 × 100 is used. Making use of the given symmetry of the bending line, the number of necessary calculations can be reduce immensely. As pointed out in Fig. 2 for a partitioning of 6 x 6 plates only the gray shaded areas would have to be considered.

Although it is possible to detected the touch-down with the above proposed solution (Fig. 4), there is still a big discrepancy between measurement and model looking at the touch-mode itself. Therefor the calculation of the bending line had to be modified further.

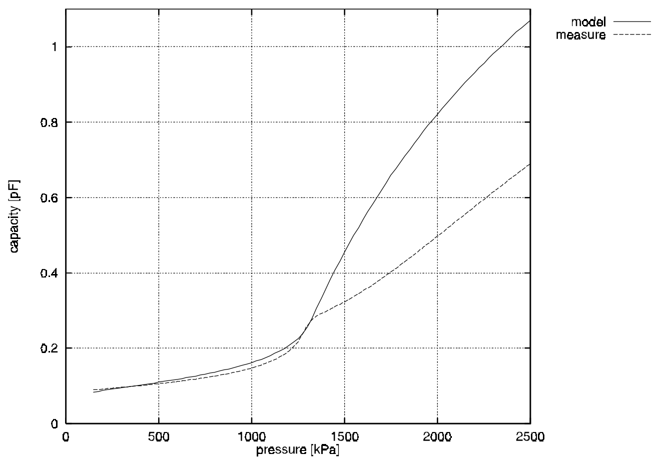

Fig. 4: Calculation result for limited deflection of partial plates

Modified empirical solution for the calculation of the bending line in touch-mode

This empirical modification only affects the case after touch-down has occurred. The plate deformation should have the form of the corrected characteristic shown in Fig. 5. This can be achieved by applying correction displacements d_x and d_y to the coordinates x_i and y_i of each plate that depend on the deflection in the middle point ω_0 of the sensor membrane:

$$d_x(x_i) = c \cdot (\omega_0 - h) \cdot \sin\left(2\pi \frac{x_i}{a}\right) \qquad (5)$$

c: non physical parameter

The correction displacement d_y for y is calculated analogous. The parameter c is a non physical parameter which determines the slope of the capacitance characteristic after touch-down. The displacement after touch-down $\omega_a(x_i, y_j)$ of the partial plate at coordinates x_i and y_j is the value of expression (1) for the excursion of the middle point of the plate at touch-down $\omega_0 = h$ at the corrected coordinates $x_i+d_x(x_i)$ and $y_j+d_y(y_j)$:

$$\omega_a(x_i, y_j) = \omega(x_i + d_x(x_i), y_j + d_y(y_j))\Big|_{\omega_0=h} \qquad (6)$$

Fig. 5 shows this relation in x-direction for $y = 0$ at two points x_i and x_n. Because the coordinates x and y run from $-a/2$ to $a/2$ the displacement is positive within the negative range and negative within the positive range.

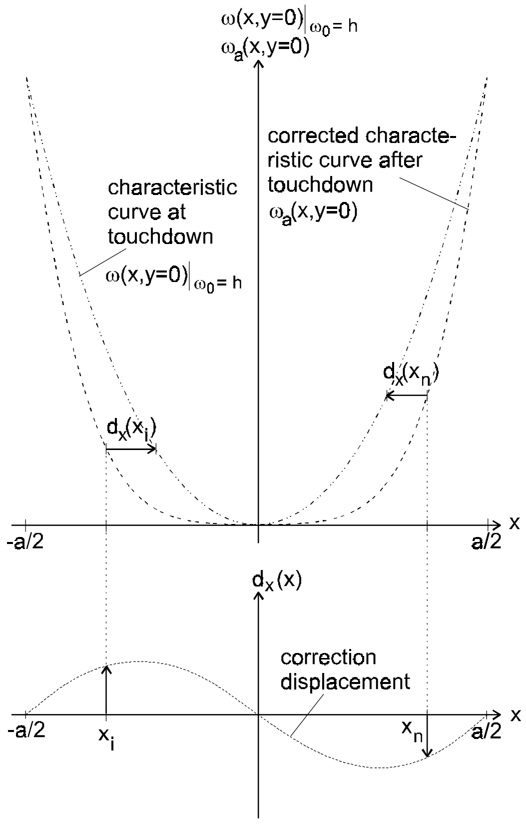

Fig. 5: Correction of the plate deformation after touch-down by using a correction displacement d_x

Using again a partitioning of 100 × 100 for the modified calculation of the bending line in touch-mode, the calculated characteristic curve of the sensor capacity (given in Fig. 6) corresponds very good with the measured data (Fig. 7).

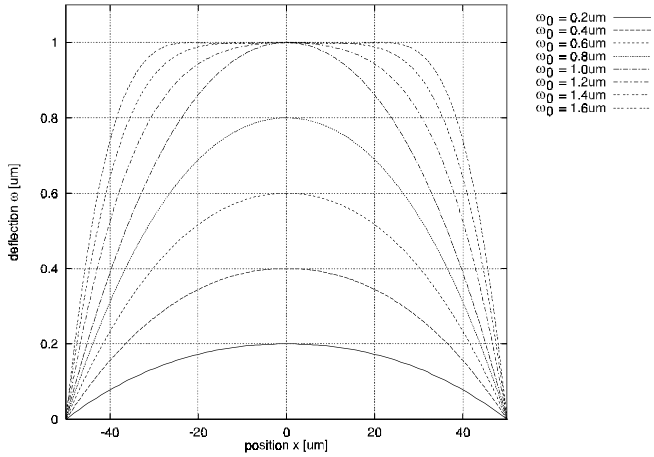

Fig. 6: Plate deformation before an after touch-down

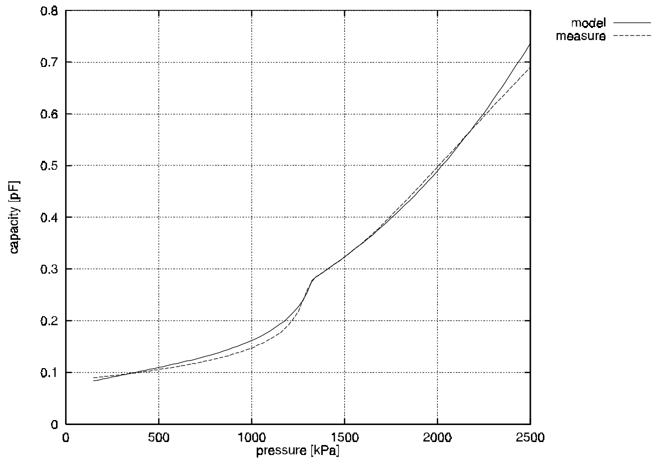

Fig. 6: Measurement and optimized calculation of the capacity

OPTIMIZATION

Regarding the design process of microsystems, optimization is necessary for carrying out design optimizations. Mathematical algorithms are very powerful tools for supporting the design process of microsystems. They may point out new solutions and sometimes the results may only be achievable by using automatic methods since theory does not give enough information about the problem under consideration.

Mathematical Optimization Algorithms

Choosing algorithms applicable for the problems occurring during the design process of microsystems one has to firstly classify the problems to be expected. Most likely the quality function will be a linear one depending on more than one variable. Furthermore the quality function is not formulated analytically but is inherent to the model which is the basis for the design optimization. The variables of the quality function will have to meet implicit as well as explicit constraints. These consideration lead to the conclusion that it would be most appropriate to use nonlinear programming strategies being able to consider constraints. Using deterministic approaches has a major advantage over evolutionary ones regarding the number of function evaluations, which is the most time critical task in model based design optimization.

Two deterministic constrained optimization approaches were applied to the design optimization of the pressure sensor: Rosenbrocks strategy of rotating coordinates which uses a partial interior penalty function [3] and the Complex Strategy of Box [3] including the changes being made by Guin [4].

Design optimization regarding the sensors sensitivity

Since the new approach for modeling the touch-down effect as well as the behavior in touch-mode has proven to simulate the capacitance correctly it can be integrated into the behavioral system model of the pressure sensor and serve as a reliable basis for design optimizations.

One of the most critical tasks in developing micro-mechanical sensors are their small output signals. Therefor one tries to get the largest sensitivity possible. Sensitivity is defined here as change in capacitance per change in pressure.

$$S = \frac{\partial C}{\partial p} \tag{7}$$

The optimization task was to maximize the sensitivity depending on the geometrical layout of the sensor. The quality function therefor depends on the length of the edges

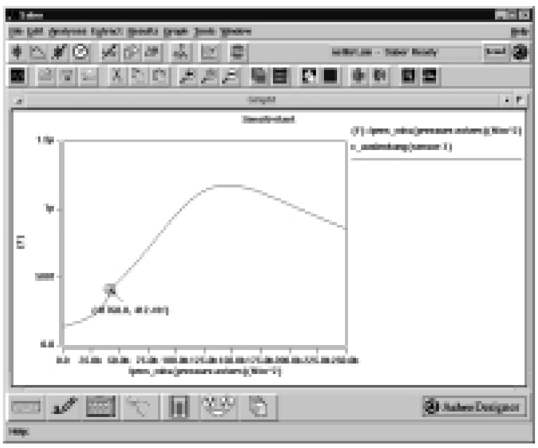

Fig. 7: Capacitance of the optimized pressure sensor

of the membrane, the thickness of the membrane and the height of the pressure chamber. This seems to be a trivial task but for one thing one does not know in the beginning how the touch-down will influence the overall system performance and if one does want to either use the sensor in touch-mode or not in touch-mode it is hard to decide how to layout the sensor in order to achieve the desired goal.

By applying the above mentioned mathematical methods (Fig. 7) the touch-down has clearly been moved out of the range of operation which is 70kPa to 150kPa. It occurs at around 50kPa, hence the system is totally operated in touch-mode. Corresponding to [8] this is the most favorable mode of operation of capacitive pressure sensors for industrial applications for the output is nearly linear then.

SUMMARY

In this paper a model of a capacitive pressure sensor was presented, which includes the touch-down effect as well as the touch-mode. Good correspondence between measurement and theory were achieved. Based on this model design optimizations were carried out using direct mathematical optimization methods. These optimizations lead to design considerations that have already proven to be successful according to [8]. Hence the proposed modeling approach can be used as a reliable basis for design optimizations of capacitive pressure sensors.

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