Investigation of Cross-coupling and Parasitic Effects in Microelectromechanical Devices on Device and System Level

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ABSTRACT

With progressing monolithic integration of entire microelectromechanical systems on one chip fabricated by standard IC technology we have to cope with the problem that the operation of embedded transducer elements is considerably affected by cross-coupling and parasitic effects. Referring to a BiCMOS-integrated capacitive pressure sensor as an illustrative example, we demonstrate that a detailed coupled-field analysis on the device level is indispensable to understand the interplay of various effects which contribute to the sensor output. On the basis of this analysis we are able to build a physically-based macromodel for the predictive simulation of the system performance.

Keywords: coupled-field finite element analysis, small signal analysis, macromodel, cross-coupling effects, MEMS

1 MOTIVATION

Progressing integration of entire microelectromechanical systems (MEMS) on single chips fabricated by industrial standard IC technologies as used in microelectronics often leads to device structures of high complexity. Since their fabrication is subjected to specific process and design rules such as, e.g., predefined layer sequences or doping profiles in the substrate, parasitic structures cannot be avoided which affect the sensor signal and are not separable from it by measurements alone. Therefore, a dedicated numerical analysis on device and system level is required to identify all effects contributing to the sensor signal, to get comprehensive insight into the device behavior and eventually to calibrate the device [1]. Detailed device studies should then lead to physically-based compact models which enable the device engineer to perform predictive simulations for design optimization [2].

2 PROBLEM DEFINITION

In this work we investigated a fully BiCMOS-integrated pressure sensor [3] as an illustrative example of parasitic cross-couplings. The sensor (see fig. 1) is realized as polysilicon membrane with a boss located in the middle. The pressure-induced deflection of the membrane is detected by reading out the change of the capacitance between membrane and the counterelectrode formed by n$^+$/n^{++}-implantations in the silicon substrate. In parallel, a reference structure with a non-deflectable membrane is used for calibration.

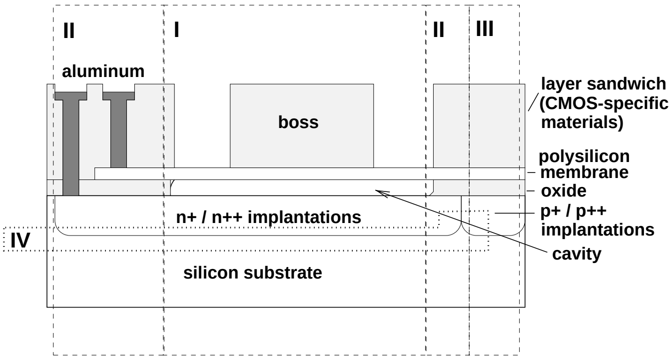

Figure 1: Cross-sectional view of the pressure sensor. The read-out capacitance is realized between polysilicon membrane and n^{++}-implantation. The dashed lines indicate regions where parasitic small signal capacitances are located: MIS-junctions - air/n^{++} (region I), field oxide/n^{++} (region II), field oxide/p^{++} (region III) - and pn-junctions (region IV).

For a comprehensive characterization of sensor and reference structure we carried out static and dynamic measurements. The capacitance change caused by the action of external pressure as well as that affected by an voltage applied between membrane and counterelectrode was measured for varying device geometries using a LCZ-meter. To obtain the differential capacitance change we subtracted the capacitance of the reference structure. Additionally, we completed the mechanical characterization by determining the eigenfrequencies of all sensors.

The sensor signal is strongly affected by variations of the mechanical parameters and built-in prestresses in the sandwich-like layer sequences, the electromechanical

	sensor#1	sensor#2	sensor#3	sensor#4
$f_{meas.}$	1.9 MHz	2.0 MHz	2.1 MHz	1.4 MHz
$f_{lit.}$	2.3 MHz	2.4 MHz	2.7 MHz	1.6 MHz
$f_{extr.}$	1.9 MHz	2.0 MHz	2.2 MHz	1.3 MHz

Table 1: Fundamental frequency of varying sensor geometry. Comparison between measurement $f_{meas.}$ and FEM (parameters from literature $f_{lit.}$, extracted parameters $f_{extr.}$)

coupling between membrane and counterelectrode, and the cross-coupling and parasitic electrical effects in the silicon substrate. Therefore we had to combine mechanical and electro-mechanically coupled FEM simulations with electrical device simulation followed by a small signal analysis in order to get a proper description of the device function which enables us to build a macromodel on a physical basis for the entire sensor chip.

3 NUMERICAL SIMULATION

3.1 Mechanical Simulation

First, as a basis for our investigations, a suitable set of material property and geometry data was extracted from mechanical FEM simulations combined with measurements of the static pressure characteristics and spectral analysis for varying sensor geometries. The mechanical simulations were carried out using a standard finite element simulator. It shows that the agreement between the simulated and the measured mechanical behavior significantly improves when the new extracted parameter set is substituted for the previously used default parameters taken from literature (see fig. 2 and table 1).

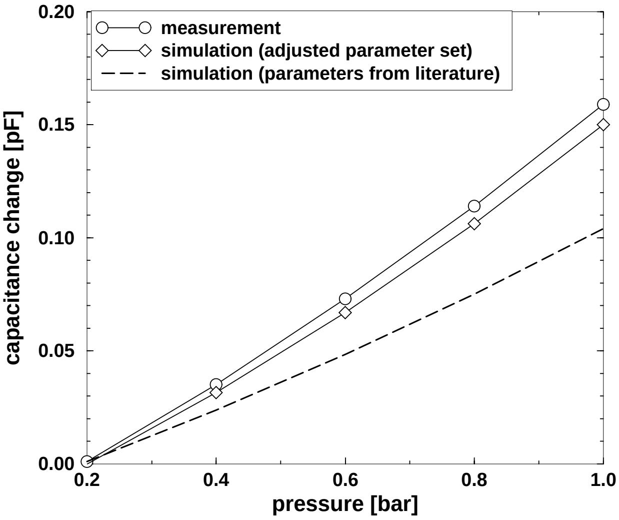

Figure 2: Capacitance change caused by the action of external pressure for one typical sensor geometry (sensor#1). The extracted process-specific parameter set yields good agreement with the measured data and serves as basis for further investigations.

3.2 Electrical Simulation – Small Signal Analysis

In a second step, we performed electrical device simulations of the reference structure including numerical small signal analysis as described in [4] to gain insight in the nature of the parasitic capacitances. The results of the simulations are shown in fig. 3. The measured data are fairly well reproduced when the lateral diffusion between p^{++}- and n^{++}-regions is properly taken into account, despite the fact that only a rough estimate of the interface and surface charges was known. Our studies reveal that the sensor characteristics is strongly affected by an intricate interplay of the various MIS-structures and pn-junctions in the silicon substrate, which are illustrated in fig. 1. The spatial distribution of electrons and holes makes evident that the steps in the CV-curve cannot be explained by a simple overlay of typical MIS-capacitor characteristics alone, but are rather strongly influenced by electrical shorts between different regions in the substrate caused by electron or hole channels developing at the respective threshold voltages. This is nicely illustrated in fig. 4, where the hole and electron concentrations are shown for a voltage of -20 V and +12 V, respectively, applied to the polysilicon membrane.

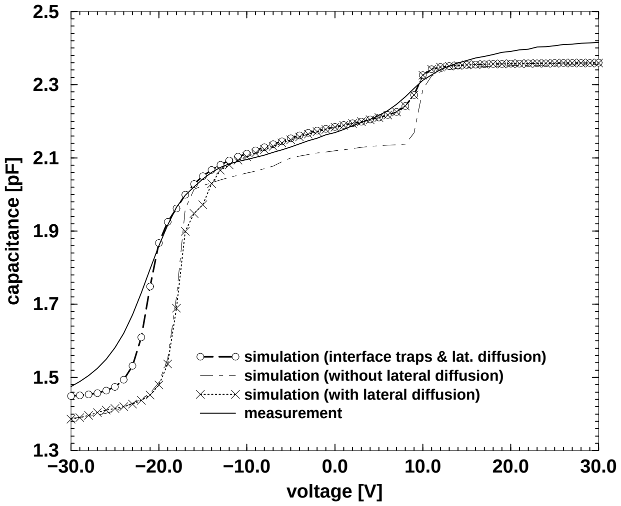

Figure 3: CV-characteristics of the reference structure (voltage ramped at the membrane, small signal frequency 100 MHz). The steps are mainly caused by electron or hole inversion channels which short the p^+- and n^+-region (see fig. 4).

3.3 Influence of the Parasitic Capacitances on the Sensor Signal

The effect of electrical parasitics on the sensor output signal has been calculated using a geometric configuration that is determined from the balance of electrical and mechanical forces along the interface between cavity and the self-consistently displaced membrane. To this end, a fully coupled electromechanical FEM simulation had to be performed for each voltage step, followed by a small signal C(V) extraction with the self-consistent membrane deflection. The difference capacitance between deflected and reference structure constitutes the sensor signal marked by the crosses in fig. 5. The significantly better agreement with the measured signal shows clearly that the fully coupled inclusion of all distributed parasitics is essential and indispensable.

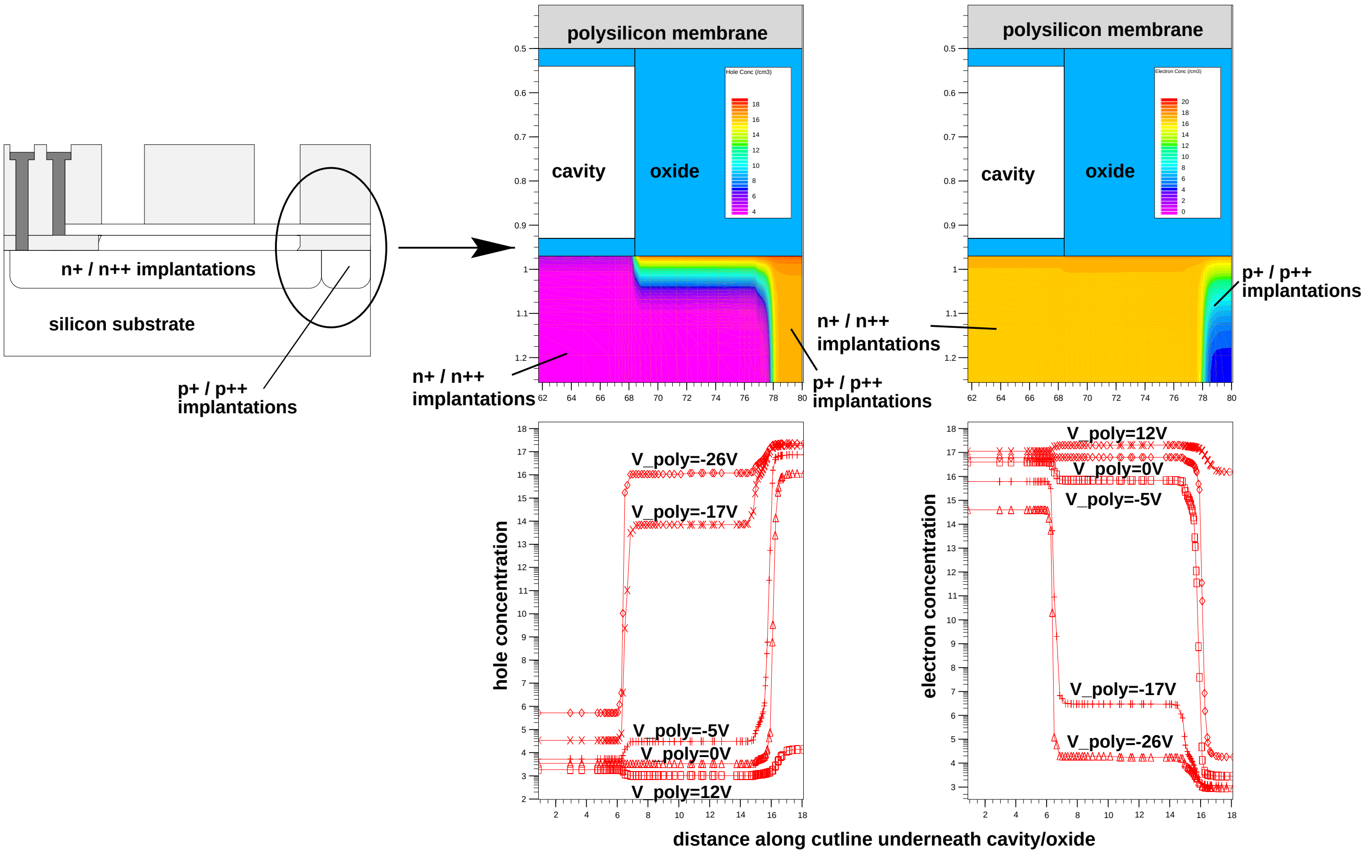

Figure 4: Results of electrical device simulation: hole (left) and electron (right) concentration. For V$_{poly}$ <-20 V, a hole inversion channel develops which shorts the p$^+$- and n$^+$-region (left). Analogous for electrons at V$_{poly}$ >10 V (right).

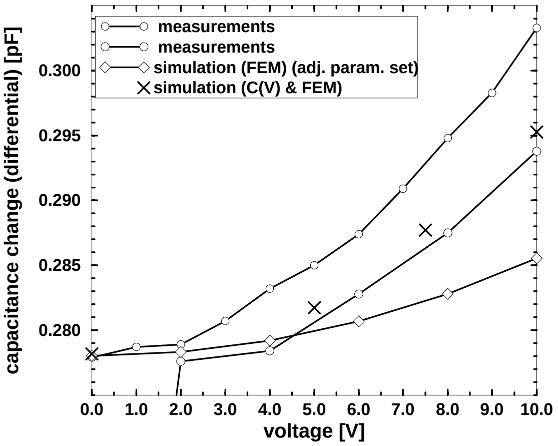

Figure 5: Relative capacitance change versus applied voltage (the reference signal is subtracted from the sensor signal). Crosses indicate the result of cross-coupled electrical and mechanical simulations leading to a much better agreement with the measured CV characteristics than a merely electro-mechanical FEM simulation without inclusion of parasitic effects. This underlines the intricate interweaving of the electrical and mechanical parts.

3.4 Macromodel

Based on these accurate device simulations on the continuous-field level, we are now able to describe the sensor signal in terms of the equivalent circuit model displayed in fig. 6. The model reflects the above-discussed interplay of all the physical effects contributing to the sensor signal and builds the starting point for a physically-based macromodel of the sensor chip.

The MIS capacitors are modeled as plate capacitors in

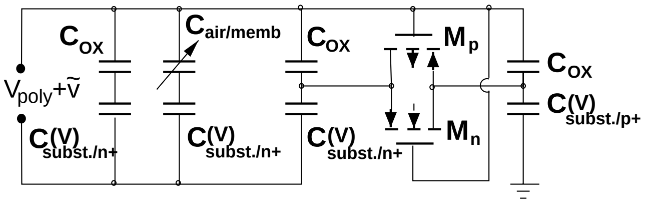

Figure 6: Equivalent circuit model of the sensor. The sensor operation is mainly determined by fixed oxide capacitances and by variable capacitances in the substrate. The above mentioned electron and hole inversion channels are realized by MOS-transistors of n-type (M$_n$) or p-type (M$_p$), respectively.

series with variable capacitors in the silicon substrate. The CV characteristics of the MIS capacitors can be described by a physically-based analytical model according to [5] which accurately reproduces the results of the small signal device simulation shown fig. 7 for a MIS structure (air as isolator, n^{++}-substrate) as typical example.

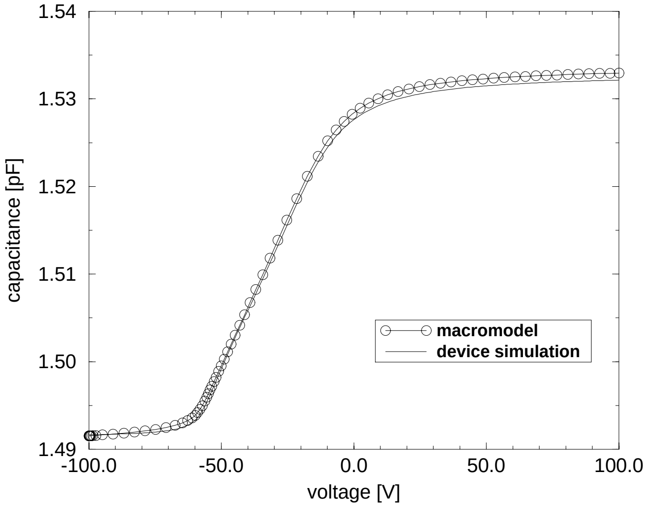

Figure 7: CV-characteristics of a MIS capacitor (air as isolator, n^{++}-substrate) as typical example. Comparison between macromodel (circles) and device simulation.

The MOS-transistors represent the above-mentioned electron and hole inversion channels, respectively, and act mainly as switches that short the n^{++}- and p^{++}-regions in the silicon substrate at the respective threshold voltages, which results in an additional contribution to the measured capacitance (steps in CV curve of fig. 3). The sensor membrane itself is modeled as a mechanical mass-spring system which is calibrated by electromechanically coupled FEM simulations. To model the entire system a circuit simulator with an analog hardware description capability is used.

4 CONCLUSIONS

For a fully BiCMOS integrated capacitive pressure sensor we exemplified that numerical simulation on device level is necessary to understand and estimate all the interweaving effects and parasitics that are unavoidable by the integration into standard microelectronic processes and affect the sensor function. It became apparent that the detailed analysis on the continuous-field level is a complicated and lengthy way, but worthwhile, because it is this detailed information which enables us to build a physically-based macromodel. This in turn, is the prerequisite to model the entire sensor chip and to perform effective and fast simulations for design optimization.

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