Parasitic Extraction Methodology for MEMS Sensors with Active Devices

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***Abstract*—Nowadays, the demand for a MEMS development/design kit (MDK) is even more in focus than ever before. In order to achieve a high quality and cost effectiveness in the development process for automotive and consumer applications, an advanced design flow for the MEMS (micro electro mechanical systems) element is urgently required. In this paper, such a development methodology and flow for parasitic extraction of active semiconductor devices is presented. The methodology considers geometrical extraction and links the electrically active pn-junctions to SPICE standard library models and subsequently extracts the netlist. An example for a typical pressure sensor is presented and discussed. Finally, the results of the parasitic extraction are compared with fabricated devices in terms of accuracy and capability.**

***Index Terms*—MEMS, parasitic extraction, electrostatic analysis, pressure sensor**

I. Introduction

For the design of analog and digital integrated circuits (IC), it is a common practice to use process development/design kits (PDK), provided by the foundries. Besides characterized and parametrized devices with their SPICE models and layout geometry, such PDKs also include the data for the design rule check (DRC), the layout versus schematic (LVS) and the parasitic extraction (PEX). The idea of such standardized collections of foundry-specific library elements and verification data was introduced by Mead and Conway [1]–[3] in the late 1970s.

Within MEMS design, e.g. for a pressure sensor (Fig. 1), PDKs have to additionally consider the interaction between mechanics and electronics. Klaus et al. suggest in [4] a model-based design strategy of the overall system co-simulations of mechanics and electronics on various hierarchy levels such as system, device, and layout. Schröpfer et al. highlight in [5] MEMS component libraries for circuit simulators which can be customized for a given MEMS fabrication technology.

Meanwhile, several MEMS PDKs are available (e.g. [6], [7]), which promise the reliable design of different MEMS elements. Nevertheless, they are not sufficiently sophisticated enough for the design of customized and highly optimized MEMS elements. The design flow of such MEMS elements typically consists of the simultaneous development for the mechanical parts, the process technology and the electrical design (Fig. 2).

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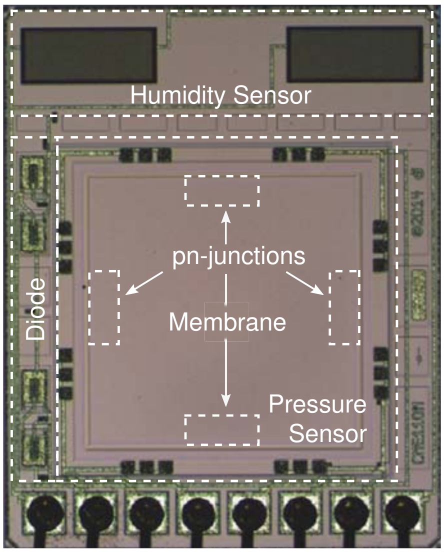

Fig. 1. Environmental sensor BME680 with pn-junctions [8], representing the piezo resistors of the Wheatstone-Bridge in the pressure sensor.

Due to this simultaneous design approach, “floating boundary” conditions have to be considered in a MEMS development kit (MDK), e.g. changes in the process as depicted in Fig. 2. Therefore, an MDK with fixed boundary conditions is impractical for the design of highly optimized MEMS elements. For this reason, we suggest an MDK framework which is developed simultaneously in the design process.

One feature of such an MDK is the electrostatic analysis. It includes the parasitic extraction from the wiring and the electrostatic behavior of the functional elements. Hald et al. [9] show that a common field-solver for the design of ICs can be used for a satisfying electrostatic analysis of MEMS sensors. The parasitic extraction presented in [10]–[12] handles the case that the MEMS does not include active devices such as diodes. In this paper, we propose an extension of the extraction flow presented in [9] to also include customized models of active devices in MEMS. With our extension, we enable the electrostatic analysis of MEMS environmental sensors such as the BME680 depicted in Fig. 1. This sensor includes active devices, as for example, the pressure sensor piezo resistor

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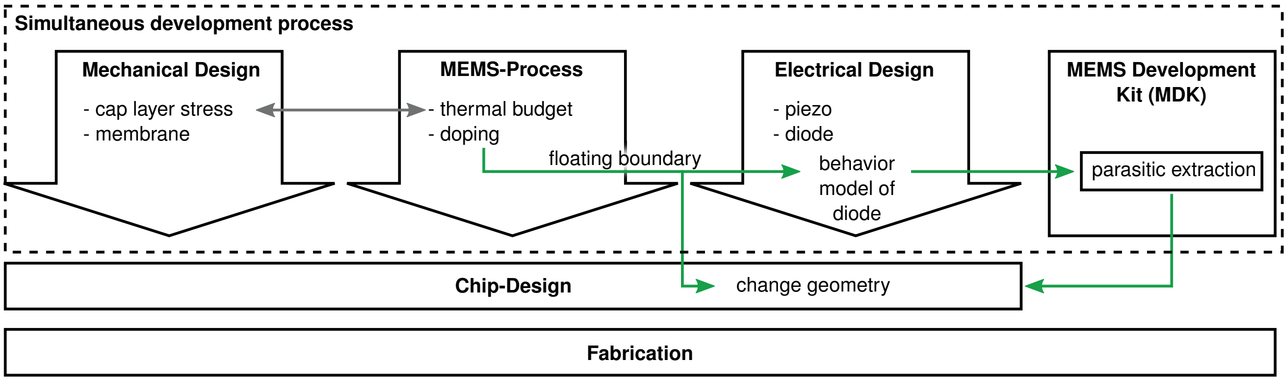

Fig. 2. Our design flow proposal for MEMS elements, featuring the simultaneous development of the mechanical design, the process technology and the electrical design. Due to the floating boundary conditions, the MEMS development kit (MDK) considers a parallel development of process technology and design. We highlight the influence of doping as floating process boundary to the electrical design and the chip-design in the figure.

elements in the Wheatstone bridge or the temperature diode.

The paper is organized as follows: Our extended electrostatic extraction flow is described in Sec. II, followed by the description of the custom device models in Sec. III. The extraction of the device parameters is presented in Sec. IV. In Sec. V we verify our approach with a comparison of simulated and measured data for a MEMS pressure sensor. The paper ends with a summary and an outlook in Sec. VI.

II. Parasitic and Geometrical Device Extraction

As described in Sec. I, a typical MEMS environmental sensor (see Fig. 1) includes besides the wiring and the micro mechanical structures (e.g. membrane), multiple diodes which have to be modeled within the electrostatic analysis. To include customized device models of active devices, we propose an extension of the extraction flow as presented in [9].

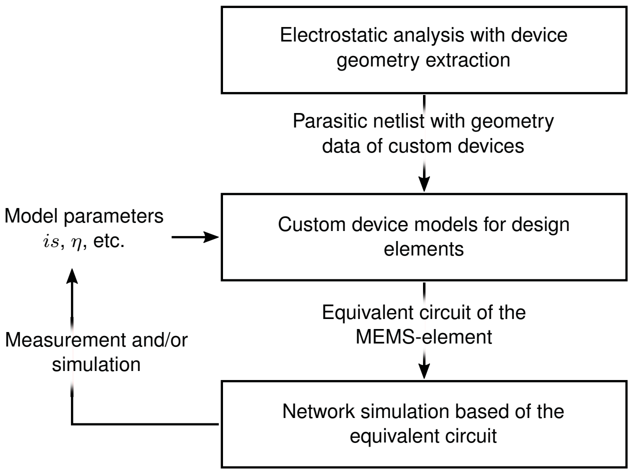

Fig. 3. Our electrostatic analysis flow for MEMS pressure sensors with active device elements.

As depicted in Fig. 3, our electrostatic analysis flow begins with a geometrical layout extraction. This is a well known procedure from the design of ICs. During this geometrical extraction, the used commercial field-solver calculates the parasitic capacitances and resistors caused by the wiring. In regions where the active devices are placed the extraction software extracts only geometrical properties as area or perimeter and reports them as custom device elements. This means the software is not able to extract the parasitics of the electrical part from the active device. The calculated parasitics and geometry properties of the customized devices are exported into a SPICE netlist. In the second step (Fig. 3), the netlist data are mapped to simulation models which have a one-to-one relation to the custom devices from the electrostatic analysis. Combined with the extracted parasitics, they represent a complete equivalent electric circuit of the MEMS element.

Besides the geometrical data of the layout, the customized device models further need fabrication process dependent parameters (Fig. 2). The definition of these device models and the source of these parameters are described in Sec. III and IV, respectively.

III. Custom Device Models

As shown in Fig. 1, a pressure sensor consists of piezo resistors and temperature sensing components. Both, the piezo resistors and the diodes contain active semiconductor structures such as pn-junctions. The piezo pn-junctions are reverse biased while the temperature sensing elements use forward biased pn-junctions.

As mentioned in Sec. II, a common field-solver for the parasitic extraction is not able to describe the behavior of such devices. Therefore, it is necessary to model these active semiconductor components as custom devices in the extraction and the network simulation (Fig. 3).

For example, the bridge pn-junctions elements are modeled as standard diode model (SPICE level 1 model) of the SPECTRE environment. Each piezo element may contain multiple diode devices to predict accurately the voltage drop across the bridge from V_{DD} to GND.

The temperature diode pn-junctions are modeled by identical diode devices, concentrating on the most important/dominant junctions. These were extracted by the simulation methodology presented in [13]. Caused by the fact that the temperature diode is a bipolar transistor applied as transdiode, more than one diode device is required to consider the buried collector as additional parasitics with respect to the substrate. Finally, a single device containing all the necessary elements is created to accurately represent the temperature sensing element.

IV. Device Model Parameters

When the models for the bridge and temperature sensing elements are defined (Sec. III), they require geometry data from the layout and process dependent parameters. These need to be fed into the level 1 model of the SPICE pn-junction representation (Fig. 3). Here, we suggest various possibilities to account for the required values as shown in Table I.

TABLE I
Excerpt of SPICE diode model parameters [14]

	name	**parameter**	**unit**	**default**	**example**	**area**
1	IS	saturation current	A	1.0e-14	1.0e-14	*
2	RS	ohmic resistance	Ohm	0	10	*
3	N	emission coefficient	-	1	1.0	
4	TT	transit-time	sec	0	0.1ns	
5	CJO	zero-bias junction capacitance	F	0	2pF	*
6	VJ	junction potential	V	1	0.6	
7	M	grading coefficient	-	0.5	0.5	

In general, all parameters are already available by default parameters within the SPICE diode model of the simulator environment. However, these parameters do not represent the behavior within a MEMS process. This is because dopings, thermal budgets, and process flow itself are not comparable to classical IC processes. Nevertheless, they might be similar and are a good starting point to build a first running parasitic extraction flow.

The first possibility one may consider is feeding the model with measurements for each component of Table I. This is, of course, a cost-intensive and time-consuming procedure. However, if it is done for a released process, this might be an useful way and solution. MEMS, as said in the introduction, contain floating boundary conditions. This means that simultaneous engineering is applied: Design and process push each other. Therefore, the probability of process changes during development are likely and such a measurement and characterization only makes sense during the last development phase.

Another possibility is explained in [13], where a simulation methodology is applied for process and device simulation for active semiconductor structures in MEMS. This flow offers various advantages. Once it is calibrated, a prediction for process and design changes are possible. The simulation results are then used to feed the required parameters.

Furthermore, additional information can be incorporated into the geometrical extraction, e.g. lateral and vertical diffusion behavior of pn-junctions. One can apply such information to improve the precision of the area and perimeter.

In summary, the three described methods for the derivation of the SPICE parameters (Table I) are qualitatively evaluated in Table II. Default parameters are not sufficient accurate for an electrostatic analysis. Device simulations are useful in an early sample phase, when no silicon is available. Performing measurements represent the most accurate method to account for the precise parameter derivation, but it is also the most cost and time intensive method.

TABLE II
Qualitative evaluation of the methods for the derivation of the SPICE parameters (Table I) in terms of time, cost and accuracy by +, 0 and -.

	Device simulation	Measurement	Default values
Time	0	-	+
Cost	0	-	+
Accuracy	0	+	-

V. Verification

The verification was performed using the reverse biased pn-junctions of the pressure sensor. There, a full set of characterization data for several million samples is available including the SPICE model parameters of Table I as CJO, M, RS, IS, N, etc., to feed the SPECTRE simulation environment.

The parameters were fed into the Cadence simulation environment, where PEX is applied, and the final parasitic extraction of the pressure sensor for the given layout is accomplished. Additional information such as lateral and vertical well diffusion from process and device simulation [13] were taken into account for the calculation of the effective area and perimeter.

In addition, an AC device simulation of the pn-junction was performed for comparison. The results are presented in Fig. 4. Here, one can clearly observe a good agreement between the PEX, device simulation, and measurements. Some slight differences in the curvature are visible between measurements and predictions. However, the prediction covers a huge range and the results are in the order of the expectation from the measured devices. Furthermore, tolerances have not been taken into account for the prediction and deviations between theory and reality are unavoidable.

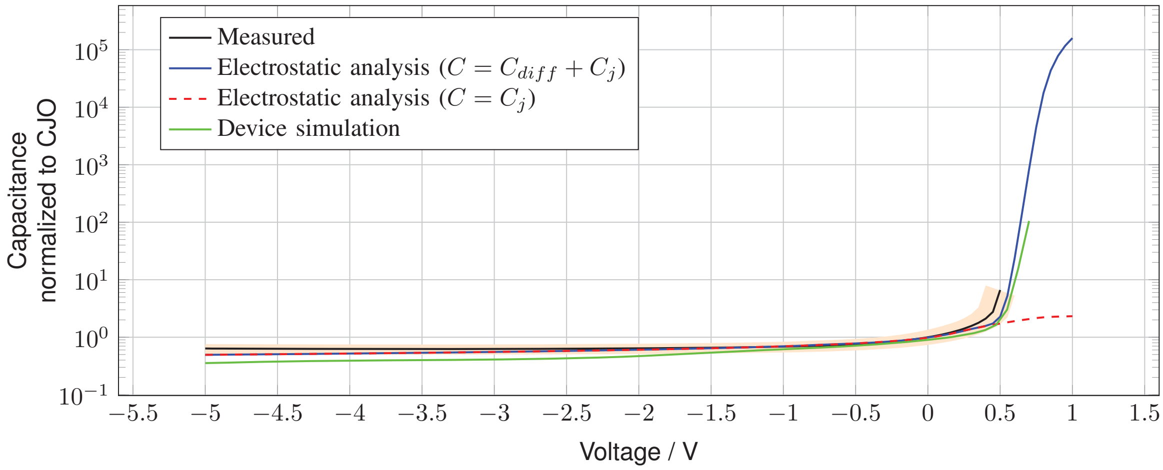

Fig. 4. Comparison of the measured and simulated junction capacitance of a pn-junction. The capacitance is normalized to the CJO (zero-bias junction capacitance) of the measured data. The orange band around the measured data visualize the possible statistical deviations of the measurements. C_j is the junction capacitance and C_{diff} is the diffusion capacitance.

VI. Summary and Outlook

In this paper we proposed an extension of the electrostatic extraction flow for MEMS as published in [9]. This extension is required in order to extend the electrostatic analysis (common in IC design) to active devices. Consequently, this analysis can now be applied for MEMS design as well. Here, active devices are commonly used in MEMS pressure or environmental sensors, as, for example, the pressure sensor piezo resistor elements or the temperature diode.

Besides our extension of the electrostatic analysis flow for MEMS devices, we discuss the definition of custom device models and the source of the device model parameters for the SPECTRE simulation. In case that no data of a characterization are available, we suggest to predict the device model parameters using a device simulation (e.g. [13]).

Our flow has been verified by comparing measurement data, device simulation data and the results of our SPECTRE simulation of the extracted netlist of a reverse biased pn-junction on a MEMS pressure sensor.

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