A Novel Polygon-Based Circuit Extraction Algorithm for Full Custom Designed MEMS Sensors

Axel Hald*, Johannes Seelhorst*, Mathias Reimann*, Jürgen Scheible† and Jens Lienig‡
*Automotive Electronics, Robert Bosch GmbH, Tübinger Str. 123, 72762 Reutlingen, Germany, Email: axel.hald@de.bosch.com,
†Reutlingen University, Robert Bosch Center for Power Electronics,
‡Dresden University of Technology, Institute of Electromechanical and Electronic Design, www.ifte.de

***Abstract*—In contrast to IC design, MEMS design still lacks sophisticated component libraries. Therefore, the physical design of MEMS sensors is mostly done by simply drawing polygons. Hence, the sensor structure is only given as plain graphic data which hinders the identification and investigation of topology elements such as spring, anchor, mass and electrodes. In order to solve this problem, we present a rule-based recognition algorithm which identifies the architecture and the topology elements of a MEMS sensor. In addition to graphic data, the algorithm makes use of only a few marking layers, as well as net and technology information. Our approach enables RC-extraction with commercial field solvers and a subsequent synthesis of the sensor circuit. The mapping of the extracted RC-values to the topology elements of the sensor enables a detailed analysis and optimization of actual MEMS sensors.**

I. INTRODUCTION

Over the past few years, the development of a library-based MEMS design flow, similar to schematic driven IC design flows, has come into the research focus (e.g. [1]–[5]). The general idea of this approach is to provide a process design kit (PDK) with fully parametrized elementary MEMS components (e.g. rigid plate, beams, combs, springs) integrated in a MEMS design environment, which is compatible to IC design environments ([1], [5]). The aim of this attempt is to enable small and fabless companies to develop their own MEMS devices for low volume applications, independently from MEMS process suppliers.

In high volume products there is a maximum demand for robustness and reliability as well as ambitious requirements for cost reduction, which mainly include more area reduction. To comply with these conflicting objectives, it is necessary to make extensive use of all available degrees of design freedom. This level of optimization requires a polygon-based design approach. It cannot be achieved with today's library-based MEMS design approaches due to several limitations, for example the insufficient precision of their component models. In consequence, geometry and net information of a sensor are only given by polygons and text labels.

Additional problems arise from the fact that the mechanical MEMS core is electrically connected at its bottom side. Therefore, the wiring is realized in an additional conductive layer, which leads, together with core internal parasitics, to considerable parasitic RC effects. Hence, the parasitic electrostatic RC effects have to be analysed and optimized in detail during the design phase. Unfortunately, this is in conflict with the polygon-based design strategy which does not provide any information about the sensor elements such as the masses, springs, electrodes or wires (compare Fig. 1). The lack of information is caused by the fact that the physical design is done by simply drawing polygons. The polygons are merged into nets, which are defined by text labels on the external contact pins. Therefore, commercial parasitic extraction tools can only analyse the entire MEMS structure as a black box. The extracted circuit is reduced to the coupling capacitances between these nets by summing up the extracted capacitances of all polygons on each net. The upper part of Fig. 1 shows the extracted circuit of an acceleration sensor, with three external pins, resulting from such an extraction.

Our approach divides the sensor nets into several sub-nets by a rule set R to enable a detailed analysis and optimization. These sub-nets are separated by net separation devices, e.g. zero ohm resistors, which can be identified by commercial RC-extraction tools. We call these special sub-nets ”sensor topology elements”. These elements are a meaningful segmentation of a sensor which are not required to be equal to component library elements. The topology elements, which are separate sub-nets, are represented as sub-nets in the extracted circuit of a commercial RC-extraction tool. This provides a geometrical mapping between the sensor polygons and the extracted capacitances. The lower part of Fig. 1 shows the circuit of the same acceleration sensor extracted with our structure recognition algorithm. In this paper we present a rule-based structure recognition algorithm, which identifies sensor topology elements by a rule set R. The algorithm starts from a user defined initial segmentation given by a few marker layers. After the rule-based segmentation and identification of the topology elements, the electrostatic RC-extraction is performed by a commercial field solver.

Using the library-based design flow, a layout versus schematic (LVS) approach is presented in [6]. The LVS algorithm is

978-1-5090-0490-4/16/$31.00 2016 IEEE

Please quote as: A. Hald, J. Seelhorst, M. Reimann, J. Scheible, J. Lienig "A Novel Polygon-Based Circuit Extraction Algorithm for Full Custom Designed MEMS Sensors", Proc. of the 13th Int. Conf. on Synthesis, Modeling, Analysis and Simulation Methods and Applications to Circuit Design (SMACD 2016), Lisbon, Portugal, 27-30 June 2016.

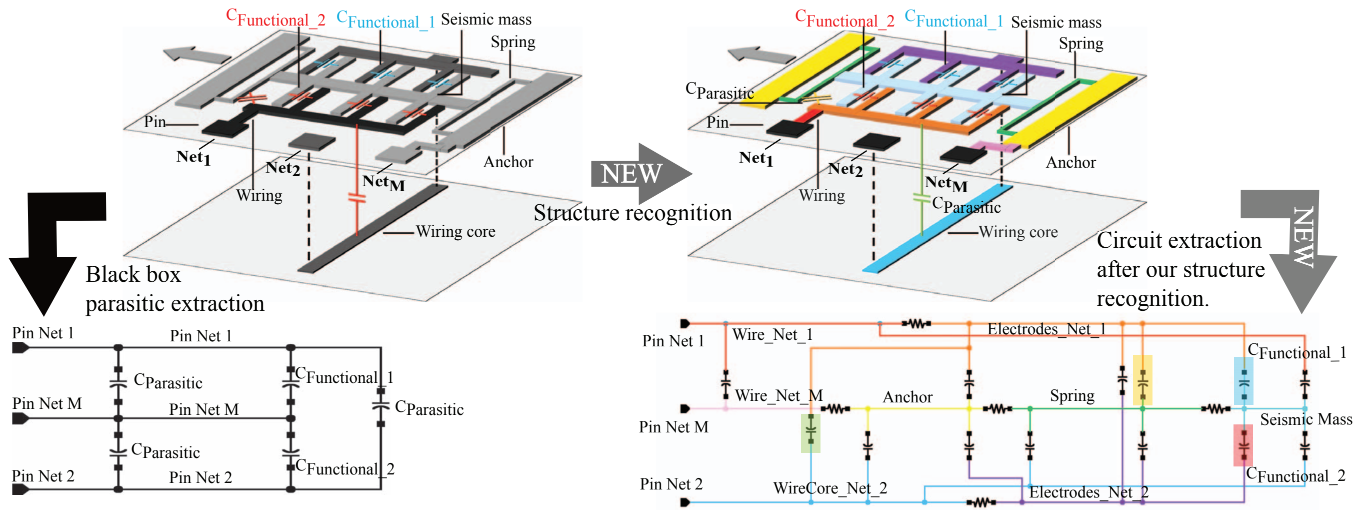

Fig. 1. Left: Acceleration sensor with conventional black box parasitic extraction. Right top: Acceleration sensor after our new structure recognition method. The sensor topology elements are represented in different colours. Right bottom: Circuit extraction after structure recognition. The recognized sensor topology elements are represented by sub-nets with the according colour. The sub-nets are connected by dummy resistors.

based on a polygon recognition algorithm which maps the recognized elements to the component library elements. The component library is essential for this approach, hence, it is not applicable to polygon-based designs.

The problem is refined and the general idea of the algorithm is presented in Section 2. Section 3 describes the structure recognition algorithm. Section 4 shows a demonstration of the algorithm on a real sensor, and the impact of the new circuit extraction method to the design flow. The paper closes with a summary in Section 5.

II. PROBLEM CLARIFICATION AND GENERAL IDEA

Due to the continuously changing sensor geometries, the goal is to develop a topology recognition algorithm, which is independent of a MEMS sensor's geometry. The general idea of our approach is a rule-based separation of the sensor topology elements such as spring, anchor, mass and electrodes which are based on the characteristic sensor principles of the MEMS itself.

A MEMS sensor S is a set of $n \in \mathbb{N}$ layers L

$$S := \{L^1, \dots, L^n\} \tag{1}$$

The layers $L^1, \dots, L^n$ contain $m_i \in \mathbb{N}$ polygons p

$$L^i := \{p^i_1, \dots, p^i_{m_i}\} : p^i_j = \{p^i_{j_1}, \dots, p^i_{j_t}\} : p^i_{j_v} \in \mathbb{R}^2 \tag{2}$$

with $1 \le j \le m_i, t \in \mathbb{N}, 1 \le v \le t$

Remark: Structures which are connected on one layer L^i are represented by one polygon p^i_j.

Remark: Every polygon p^i_j on layer L^i belongs uniquely to a net which is defined by a text label.

A set of sensor topology elements T of one layer L^i is defined by

$$t^i \in T^i : t^i \subseteq p^i_j \in L^i, 1 \le i \le n, 1 \le j \le m_i \tag{3}$$

in which the sensor topology elements $t^i \in T^i$ are a disjoint decomposition of the polygons $p^i_j, 1 \le j \le m_i$. The sensor topology elements are an arbitrary decomposition of the layers L^i.

$$\dot{\bigcup_{t^i \in T^i}} t^i = L^i, 1 \le i \le n \tag{4}$$

The goal is to derive a set of topology elements T which represents the sensor S by a rule system R from the input geometry. The rule system R is an arbitrary set of $s \in \mathbb{N}$ rules r^1, r^2 and r^3

$$R = \{r^1_1, \dots, r^1_{s_1}, r^2_1, \dots, r^2_{s_2}, r^3_1, \dots, r^3_{s_3}\} \tag{5}$$

with $s_1 + s_2 + s_3 = s$. The rules r^1, r^2 and r^3 are defined as follows:

i) relation between/combination of polygons on layers:

$$r^1 : (L^i, L^j) \rightarrow L^{new} \tag{6}$$

ii) selection of polygons on a layer:

$$r^2 : (L^i, \text{constraint}) \rightarrow L^{new} \tag{7}$$

iii) deformation of polygons on a layer:

$$r^3 : (L^i, \text{operation}) \rightarrow L^{new} \tag{8}$$

with $1 \le i, j \le n$.

With key elements defined by the design, it is possible to derive useful sensor topology elements with a rule system R (5) from the polygons of the sensor. The design key elements depend on the sensor type (e.g. pressure sensor, acceleration sensor or yaw rate sensor) and the predefined rule system R (5). Both have to be set up once per sensor type. The key elements are an initial segmentation of the polygons. Starting from the key elements, the algorithm refines this segmentation and defines the relationships between the polygons with the rule system R (5). Hence, the selection of the key elements affects the recognition of the sensor topology elements.

The key elements could also be identified by a pattern matching rule r_4. Because of the polygon-based design approach, that key patterns for the pattern matching rule r_4 would have

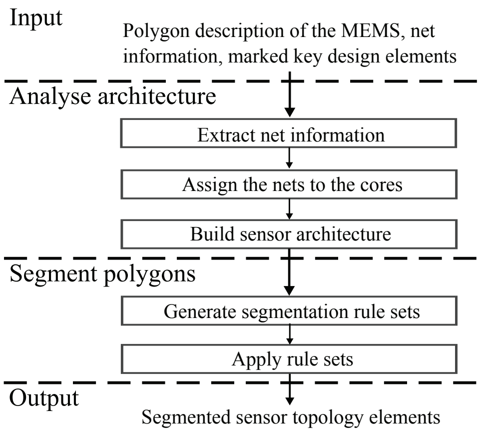

Fig. 2. Our structure recognition flow.

to be redefined again for every new MEMS sensor, and due to arbitrary polygon structures a misinterpretation could not be ruled out. In our approach, the manual definition of the key elements allows a flexible structure recognition, that enables typical topology elements to be recognizable by the algorithm.

For example, typical MEMS inertial sensors contain a net (Net_M) with a moveable electrode and two nets (Net_1, Net_2) with detection electrodes (e.g. acceleration sensor, Fig. 1). Based on the working principle, we know that there is a specified layer L^i (2) whose polygons of the Net_M have to represent springs, one or more seismic masses, and an anchor point.

In the case of an in plane moveable seismic mass, each electrode on Net_1 or Net_2 has to be a structure very close and parallel to the moveable electrodes on Net_M. (A detailed description of the working principle of inertial sensors is given in [7]).

With the springs as design key elements, it is possible to derive all main sensor topology elements by a rule system R (5). For example, the seismic mass can be derived by the following two rules:

1) The seismic mass has to touch the springs (rule type r^1 (6): L^i touch $L^{springMarker} = L^{new}$).
2) The seismic mass must not be connected to any other structure or layer (rule type r^1 (6): $L^i \cap L^j = \emptyset$).

A demonstration of the algorithm is given in Section V.

III. STRUCTURE RECOGNITION ALGORITHM

The main flow of our structure recognition algorithm is depicted in Fig. 2, and described in detail in the following subsections.

A. Input

The algorithm demands a polygon description of the MEMS sensor geometry as input, for example in a standard GDS format with net information. The algorithm needs additional marking layers, which identify well defined key sensor topology elements. These key elements depend on the sensor type.

B. Architecture Analysis

For the recognition of the sensor topology elements, it is necessary to analyse the sensor architecture.

This process starts with the extraction and analysis of the net information. The naming convention of typical MEMS sensors normally follows the function purpose of the net connected to the bondpad. Thus informing us what kind of sensor is analysed (e.g. acceleration sensor, yaw rate sensor or pressure sensor), and additionally it gives us information about the architecture (e.g. the number of detection nets of an acceleration sensor).

Afterwards, the process technology is identified by the layer stack. The layer stack itself defines the connectivity of the different sensor topology elements.

In the special case of a multi channel inertial MEMS sensor, the sensor can contain several cores in which each core is represented by one seismic mass. For a correct topology recognition, it is necessary to distinguish between inertial sensor cores with one, two, or three sensing axes. The nets with the detection electrodes are identified by the net information analysis. The algorithm associates these nets to their corresponding seismic mass.

Based on this information it is possible to build the sensor architecture. Due to the known working principle and the analysed sensor architecture, the algorithm decides which sensor topology elements are expected.

C. Segmentation

The next step is the segmentation of the input polygon representation of the MEMS sensor into the expected topology elements, which are found in the architecture analysis. The segmentation is performed on the basis of predefined rule sets, which are automatically selected, customized, and synthesised to a rule system R (5) by the segmentation algorithm. The predefined rule sets are valid for a special type of sensor (e.g. acceleration sensor) and are independent of the sensor geometry.

After the segmentation, all expected topology elements t^i are derived and connected by net separation devices.

D. Output

The algorithm maps the derived polygon representation of the topology elements to unique output layers, and marks them with the according text label. An example is given in the middle part of Fig. 3.

IV. ELECTROSTATIC RC-EXTRACTION AND CIRCUIT SYNTHESIS

On the basis of the output of the structure recognition algorithm, a commercial field solver can perform the electrostatic RC-extraction. Because of the net separation devices, the derived lumped elements are interpreted as individual nets. Typically, the net separation devices are represented as zero ohm resistors. Now, the result of the field solver is a more detailed netlist which contains the resistances and capacitances of the sub-nets, and the coupling capacitances between all

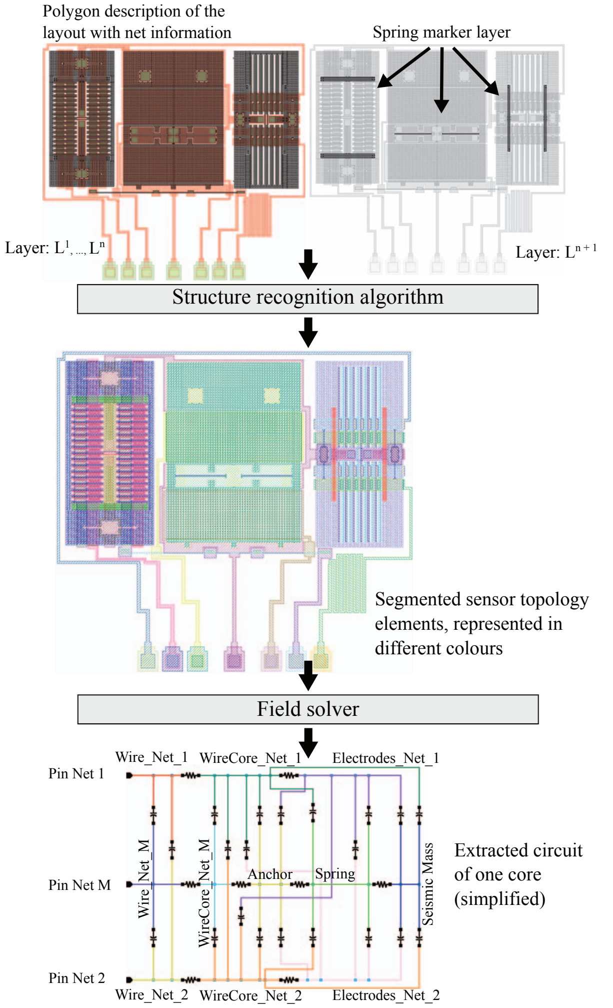

Fig. 3. Structure recognition applied to a three-axis acceleration sensor.

these sub-nets. Based on this information, it is possible to distinguish clearly between functional and parasitic coupling capacitances, and to assign them to the sensor polygons.

In the end, the output netlist of the field solver can be synthesized into a schematic with a commercial layout tool for further simulations.

V. DEMONSTRATION

An example of the working principle of the recognition algorithm is given in Fig. 3. The algorithm is applied to a three-axis acceleration sensor. The upper left part of Fig. 3 shows the input polygon description of the sensor with the net information, and the upper right part the marker layer which marks the positions of the six springs. The structure recognition algorithm returns a GDS-File, which contains the segmented sensor topology elements. The individual topology elements are represented in different colours in the lower part of Fig. 3. With the sensor topology elements, a commercial field solver performs a detailed RC-extraction. The extracted circuit looks like the one shown in the lower right part of Fig. 1. The topology elements can be located in the extracted circuit and in the polygon description of the sensor. Hence, it is possible to optimize the symmetry of the nets due to parasitic RC-effects in detail.

TABLE I
RESULT OF A CIRCUIT EXTRACTION FOR A TYPICAL THREE-AXIS ACCELERATION SENSOR

	Black box	Polygon-based
Time	Manual segmentation > 30 min	Rule-based segmentation < 5 min[a]
Number of nets	7	36 (depends on the rule sets)
Back annotation and optimization	Restricted to nets	Up to sub-net (topology element) level
Transferable (to other designs)	Manual segmentation needed for every new design	Defined rule sets usable for each new design

[a] Including manual definition of marker layers and runtime of the algorithm with predefined rule sets

In Table I, through the application of a three-axis acceleration sensor (the sensor is shown in the upper left part of Fig. 3), the state-of-the-art black box parasitic extraction is compared to our novel circuit extraction algorithm.

The table shows, that the algorithm enables a fast and detailed optimization of today's full custom designed MEMS sensors.

VI. SUMMARY

The presented algorithm allows a semi-automatic parasitic extraction of a detailed, meaningful circuit from a polygon-based MEMS sensor design. The correlation of the extracted topology elements to the sensor polygons enables a detailed analysis and optimization of the parasitic RC-effects. The achievement is the basis for further analytical methods, and it paves the way to a deeper analysis of current MEMS sensors. Further work will include the co-simulation with the signal processing ASICs with compliance of electrostatic parasitic RC-effects.

The algorithm has been demonstrated on a MEMS acceleration sensor; however, the general idea works for all MEMS sensors that have a characteristic sensor topology and working principle. Only a special initial rule set and some key topology elements have to be defined in order to successfully run the algorithm.

REFERENCES

[1] M. Meiners, M. Sommer and H. Graeb, "Schematic driven MEMS design", *SMACD*, Seville, 2012, pp. 117-120.
[2] X. Zhao, Y. Tan, G. Lu and X. Li, "IP library-based general and visualized MEMS device simulation and verification tool", *NEMS*, Xiamen, 2010, pp. 207-210.
[3] W. Xiaoyu, Y. Linghui and X. Song, "Research on micro-electromechanical system computer aided design", *EMEIT*, Harbin, Heilongjiang, China, 2011, pp. 1556-1559.
[4] C. Zhang, Z. Jiang, D. Lu and T. Ren, "3D MEMS design method via SolidWorks", *NEMS*, Zhuhai, 2006, pp. 747-751.
[5] G. Schröpfer, G. Lorenz, S. Rouvillois and S. Breit, "Novel 3D modeling methods for virtual fabrication and EDA compatible design of MEMS via parametric libraries", *Journal of Micromechanics and Microengineering*, vol. 20, number 6, 2010, pp. 064003.
[6] B. Baidya and T. Mukherjee, "Layout verification for mixed-domain integrated MEMS", *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, 2005, vol. 24 (4), pp. 563-577.
[7] L. Franz, "Mechanical microsensors", *In: MEMS: A Practical Guide to Design, Analysis, and Applications*, Springer Berlin Heidelberg, 2006, pp. 523-566.