Modeling and Simulation for MEMS Design, Industrial Requirements

R. Neul

Robert Bosch GmbH, Stuttgart, Germany, reinhard.neul@de.bosch.com

ABSTRACT

The development process of today's products is dominated by demands like 'product performance', 'quality', 'time to market', 'development cost', 'development risk' etc., while the products' complexity is increasing. Design methods for MEMS devices are discussed, which particularly use modeling and simulation techniques. The objectives of these methods are to optimize the function of the devices and to minimize development time and cost by avoiding unnecessary design cycles and foundry runs. Bosch is using MEMS mostly in the field of automotive sensors, which already experiences a notable growth rate. It is estimated that this growth will go on in the future [2,14]. Therefore efficiency of the development process is quite an important issue.

Keywords: MEMS, development process, design methods, modeling, simulation, design flow.

1 DESIGN METHODS FOR MEMS

The objective of the presented paper is to discuss methods to accelerate and improve the development process of micro electromechanical sensor systems using modeling and simulation techniques.

To emphasize the difference between design of MEMS and pure electronic devices, a comparison between MEMS design and standard IC design is recommended. Especially with digital ICs we have the most advanced design automation. In this segment we have a 'kit-like' modeling and design approach using basic elements, whose behavior is well known. Most of the testing is done in simulation before manufacturing the components. 'First silicon right' is very common.

With analog and digital ICs (mixed signal) there is a less automated, but well understood design approach. This is because we have a wider variety of basic elements on the field of mixed signal ICs and simulation methods are more complicated.

In the MEMS domain (mixed nature or mixed domain) there is the least automated design process, characterized by many design cycles, which often require complete foundry runs. Design of MEMS is even more complicated because of the various participating subsystems from different physical domains.

2 DEVELOPMENT PROCESS

Development of MEMS sensors has to undertake a trade-off between the system's specifications, the properties and capabilities of the sensing element as well as the signal evaluation circuit. In the case of MEMS devices this trade-off is influenced by the available technology's properties. (**Figure 1**). Every aspect depends on each other and is influenced by the others.

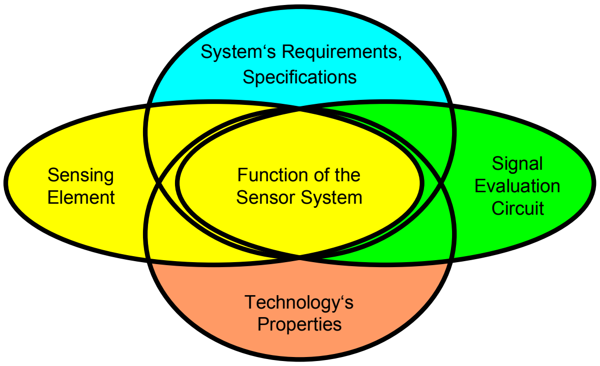

Figure 1 Design trade-off for MEMS sensors.

The development process of any technical system is briefly shown in **Figure 2** (see also [10]).

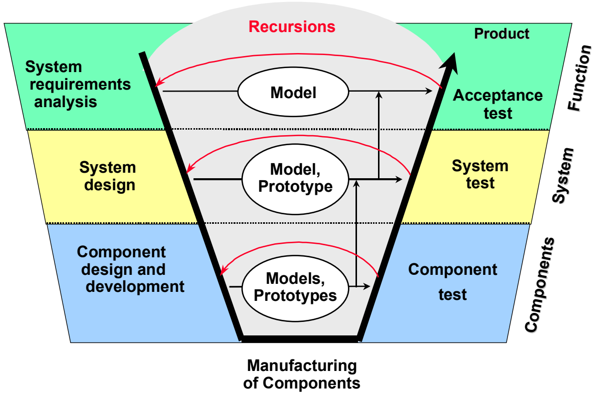

Figure 2 V-shaped model of the design process.

It starts with a system requirements analysis followed by the design on system level. Subsequently the system is decomposed into components and the components are designed and developed. At this stage the manufacturing of the components is started. If thereafter the component tests are passed, the parts are assembled and the whole system is tested. After the following acceptance test, this process leads to the final product.

A real development process is not as straightforward as described before, because component, system and acceptance tests usually reveal problems that need to be solved. In that case designers have to go back on the particular level to component design, system design or even to system requirements analysis. This is a recursive process which has to be repeated until all tests are satisfied. The loops within the design process are time-consuming and cause additional cost. Especially the design process of micro electromechanical sensor structures is commonly characterized by a large number of foundry runs and time-consuming experimental set-ups to get a detailed overview of the sensor's behavior. The only means to avoid them is to use simulation techniques during the early phases of the design process to do the testing as far as possible before manufacturing the components. Therefore modeling and simulation methods play an important role in the design and development process.

3 MODELING AND SIMULATION

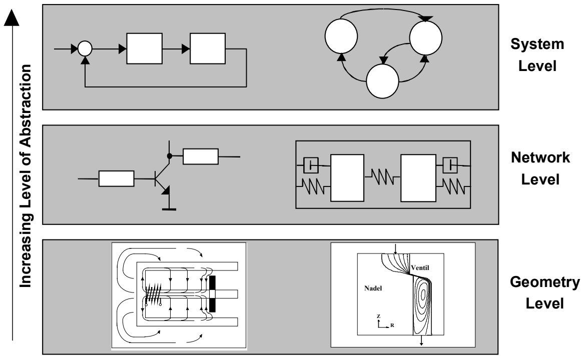

Figure 3 Modeling on different levels of abstraction.

Modeling and simulation methods can be briefly subdivided into three different levels of abstraction (see **Figure 3**). The lowest level of abstraction, here denoted by "Geometry Level", is close to reality. There, physics is described by partial differential equations. This level is the domain of finite element or boundary element solvers or related methods. Due to their high accuracy they are well suited to calculate stress distributions, distortions and natural frequencies of MEMS structures. But they also cause considerable computational effort. Thus, these methods are used to solve detailed problems, where needed. The simulation of whole sensor systems and in particular transient analyses are therefore done using methods on higher levels of abstraction. The network level is the domain of e. g. circuit and multi-body simulators. On that level physics is described by systems of differential algebraic equations. In spite of the higher level of abstraction, modeling of the components is near to physics, because we can still recognize physical parts, e. g. resistors and transistors or masses and springs (see e.g. [5,6,7,15]). The highest level of abstraction, here denoted by “System Level”, is the domain of system level simulators, which use block diagrams from control engineering and signal processing or state charts for the description of digital systems. The level to be used depends on the particular question that arises in the design process of MEMS. Every level has its own advantages and can’t be omitted.

4 DESIGN FLOW

There are two basic approaches to organize the design procedure: bottom up and top down. At a very early development stage of a technology, when we are still deep on a research level, most design procedures are bottom up. But if the used technologies are getting more and more mature and we know about the technology’s capabilities and properties, we have to come to a top down approach in developing products, because this approach fits much better into an industrial development process.

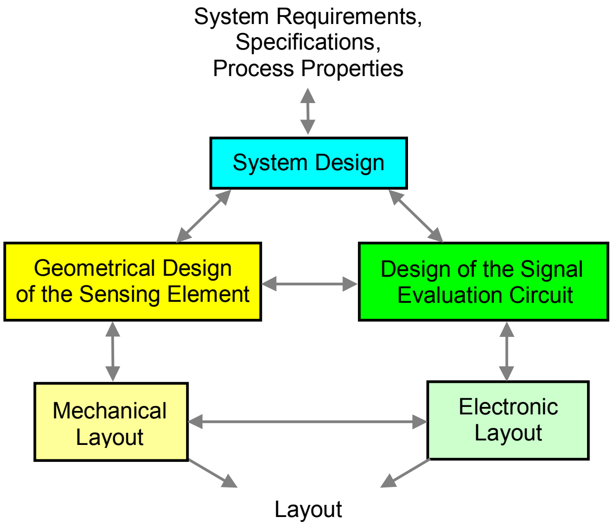

Figure 4 A brief workflow for designing MEMS sensors.

A brief representation of a design flow is shown in **Figure 4**. It starts in a top down style with system requirements and specifications and we have to bear in mind the properties of the available processes.

The system design uses methods and tools from the system level in **Figure 3**, ensuring the overall performance of the product under development and taking into account all influences and dependencies between the subsystems. In general, the methods and tools from the system level have the ability to deal with complete systems. Examples can be found e. g. in [13]. It is strongly recommended to take testability issues into consideration already at this level.

After finishing the system level design, the partitioning of the system into subsystems is carried out. In case of MEMS sensors there can be single chip as well as dual or even more chip approaches. All approaches have their particular benefits and drawbacks.

Figure 5 MEMS pressure sensor from Bosch.

Bosch is actually manufacturing an increasing variety of different kinds of automotive MEMS sensors, such as accelerometers for passenger restraint systems [11], angular rate sensors for vehicle dynamics control [8], roll over protection and navigation systems [1,15,16], pressure sensors [4,12] and air flow sensors for engine management systems etc. **Figure 5** shows a pressure sensor which is used at the intake manifold of an automotive engine as an example for a single chip device and **Figure 6** is a dual chip gyro for passenger restraint and navigation systems.

After partitioning into subsystems according to **Figure 4** the micromachined and the electronic subsystems are designed. The methods and tools usually used are from network respectively geometry level in **Figure 3**. In general these methods and the appropriate tools are not capable to deal with complete sensor systems. This is the reason why a back annotation step is necessary from design of the sensing element and the signal evaluation circuit on component level back to system level, ensuring that all changes made do not compromise the complete system's proper performance. For this back annotation step we need appropriate behavioral models for system simulation. They can be obtained either by back annotating parameters or by generating reduced order models.

Next steps are the layouts of micromechanical and electronic parts of the system. Even at this stage changes are taking place, which need to be back annotated to the component level and also to the system level, if necessary. In the electronic field the back annotated parameters for instance are specific capacitances, which are not known before layout. In mechanical micromachining the specific parameters are also capacitances as well as masses, moments of inertia, thermal capacities and conductivities, etc.

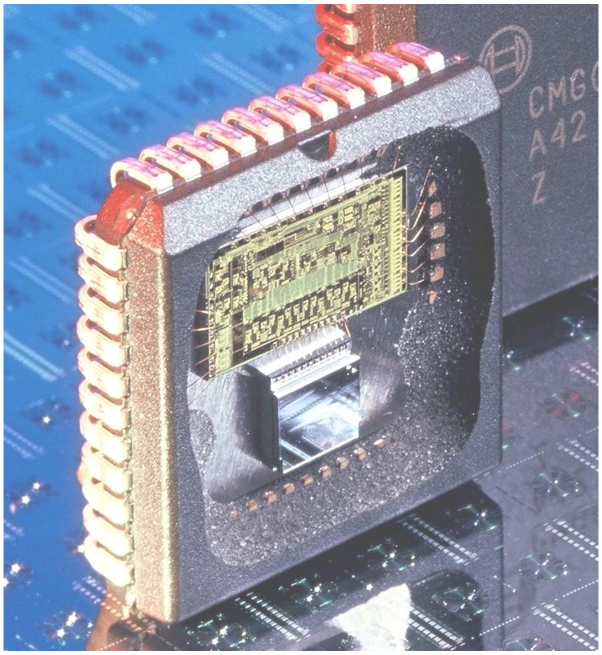

Figure 6 MEMS gyro from Bosch.

5 DESIGN OBJECTIVES

A further view on the design process of MEMS at Bosch is outlined in **Figure 7** (for details see [12,17]). The MEMS devices have to meet certain functional parameters, e. g. scale factor, offset and their temperature coefficients, nonlinearity, hysteresis, noise, resolution and cross sensitivities. Besides that, we are also interested in reliability and yield of the devices. The set of functional parameters is depending on a set of model parameters, which consists of process parameters, material parameters and geometrical parameters. All model parameters act as input parameters for the design procedure as well as for the manufacturing process. Material parameters are influenced by the process steps and their parameters, whereas geometrical parameters are determined by process parameters and the actual design.

The advantage of this approach to the design process is the possibility to perform a special kind of sensitivity analysis [17], where we can determine certain measures for the influence of each model parameter to each functional parameter, leading to a deep insight into the influence, which is critical for a particular design. Knowledge about these critical influences already at an early design phase is essential for keeping recursion loops in **Figure 2** small.

6 CONCLUSION

Design methods and appropriate tools as previously outlined already have reached a certain level, but still aren't at that grade of maturity known from microelectronics. Thus, there is still research and development work to be done. The requirements besides powerful solvers for precise simulation results, which also need to have predictive capabilities, are accurate and reliable models. The spectrum of the necessary investigations start from modeling of MEMS relevant physical effects, material properties and the properties of technological processes. Due to the fact that MEMS devices consist of parts from different physical domains, solvers able to handle these domains simultaneously are needed. Furthermore, methods to generate behavioral models are important. These models should be capable to be used in system level simulations. Last but not least tools are needed, which seamlessly fit into an industrial design and work flow and which have appropriate interfaces to existing EDA and silicon foundry environments.

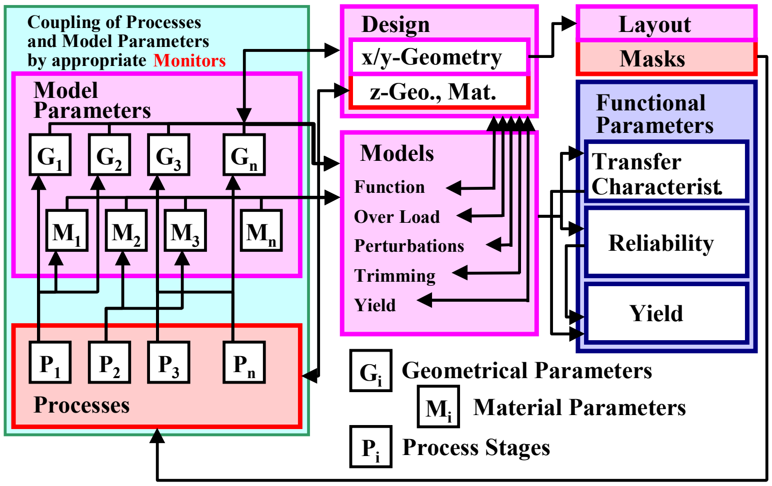

Figure 7 Objectives in design flow.

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