Design Automation for MEMS/MST

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Abstract

In this paper we only summarized some of the design automation topics in the MEMS field that are still of the main concern of MEMS design groups. The MEMS designers will be confronted with large variations in process steps, unknown material property data and even the lack of design kits for existing foundries. In addition the MEMS device will have to be packaged in some way. We encourage to include package design considerations as early as possible in the MEMS device design process. We believe that this can be structured by using software tools for this as well, we have shown this by marketing the Kyocera Standard packaging library with software.

Understanding different modelling levels gives a clearer picture of where design automation tools can be used, how the different results are communicated between different modelling levels and how all this is captured in existing tools.

1 Introduction

Design Automation for MEMS/MST has become a specialized area faced with challenges not seen in other Design Automation Areas such as Electronic Design Automation (EDA) and Mechanical Design Automation (MDA). Examples are the complex coupled three dimensional physics, unknown physical material properties but also the diversity of engineering backgrounds of the MEMS Design software tool users. In addition the MEMS market itself is not yet large enough to support the development of completely dedicated software.

In this paper we will present Design Automation solutions for the technical problems MEMS/MST engineers are faced with within the product development cycle. First we will present a systematic modelling sub-division taken from MicroSystemDesign by Senturia [1]. This classification of modelling problems will provide the background for MEMS Design Automation selection criteria. Secondly we will address several of the design topics engineers are faced with in prototyping and production and the possible implementation of Design Automation solution for this. These software tools must be seen as an aid in order to facilitate and speed up the solution of complex issues. We will discuss areas such as physical material properties, packaging, and system design.

2 Modelling, a method of communicating in a mathematical language.

The modelling levels for Microsystems presented in [1] are not unique nor a new concept but it gives a clear framework for understanding different Design Automation tools. Four modelling levels are defined as system level, device level, physical level and process level.

2.1 System level modelling

The interactions of the MEMS component with its environment and electronics can be modelled and simulated on the system-level. We can even state that only for a few limited cases such interactions can be modelled on the physical level where strict simplifications in the models are needed to achieve results.

There are two approaches to system level modelling. Either using a Model-based design method or a hardware description language (HDL). In mathematical terms this relates to working with block diagrams or Ordinary Differential Equations (ODE). Some software tools also allow the user to use both at the same time. The Matlab-Simulink environment is an example of Model-based design and Verilog-AMS, Eldo or Saber are examples of HDL-based design. The clear advantages here are the complexity of designs that can be modelled and the fast simulation times.

Block Diagram tools have a clear input-output definition with operations on the information flow going through the blocks. The main disadvantage is that there is no conservation of energy inherent in the programming. This is overcome by the HDL based tools in which the elements or component models are defined in through and across variables such as Voltage and Current for the electrical domain.

On a System level an electronic component such as an OpAmp can be modelled either on a “macro-model-level” or on a “transistor-level”. Similarly MEMS components can be modelled in much the same way. If we refer back to paragraph 2, a MEMS device can be composed of different fundamental building blocks such as mechanical beams, plates, detection electrodes, or more complex building blocks such as complete electrostatic comb-drive configurations. We can interpret these building blocks as MEMS "components". In much the same way as electronic components, the MEMS components can be modelled either on the "macro-model-level" or "transistor-level". The difference being that the macro-models are descriptive models usually extracted from multiple field-solver simulations, e.g. Finite Elements, and the MEMS "transistor-level" models are models where the physical equations are written in Ordinary Differential Equations or scalar equations. For example the bending or torsion of a mechanical beam is written as F=Kx where F is a 12x1 Force vector, x a 1x12 displacement vector and K a 12x12 beam stiffness matrix. The mechanical model can be extended to include the Damping and Stiffness matrices as well.

An additional advantage of system level modelling is that it is not necessary to know all details of the complete design. It is possible to incorporate simple analytical functions, so called look-up tables or even measured graphs as models before such detailed information is available.

2.2 Device level modelling

Single MEMS devices are often large and complex compared to IC-devices. It is sometimes difficult to capture the physics or behaviour in terms of ODE's. On the other end it is often to cumbersome to use Partial Differential Equations (PDEs) like in Physical Modelling (next paragraph). In these cases it is possible to use Macro-Modelling, Compact Modelling or Reduced Order Modelling approaches which we place under the Device level modelling. One important prerequisite is that the extracted models must be compatible with the System-level models.

2.3 Physical modelling

The Physical level of modelling is probably the best known in Mechanical engineering and MEMS engineering. It refers to the abundance of field solvers for any physics ranging from solving Finite Element Models for mechanics, Navier-Stokes, or Maxwell equation just to name a few. Other discretization techniques are Boundary Element methods, Finite Volume and Volume of Flow Methods.

2.4 Process modelling

Process simulation consists of 3D numerical simulation of process chemisctry and physics to produce accurate models after material addition and subtraction (mostly depositing and etching). Typically process simulation for MEMS is limited to the simulation of wet chemical anisotropic etching of crystal silicon and calculation of doping profiles created by implantation and diffusion. The considerable variety of process steps in MEMS fabrication, the large number of unknown inputs, and the complexity of the calculations, render other process simulation extremely time consuming or in most cases just not possible - due to the lack of adequate simulation tools.

As a result, MEMS CAD tools favour the process emulation approach, which takes 2D masks and a description of the fabrication process to create a geometric 3D solid model. These models are build rather quickly and can subsequently be used for physical modelling.

Because 3D solid modelling depends on complex solid modelling mathematics, process emulation usually is limited to a certain degree of geometrical complexity and in addition it can, on occasion, fail to produce a model. Other recent techniques such as the "voxel-based emulation" (volumetric pixel) do not have this limitation and are robust to 2D-mask errors, it is possible to build highly detailed, realistic-looking virtual prototypes.

3 MEMS Foundry Access

Efficient and high-yield manufacturing is a crucial component of any commercial MEMS product development effort. Due to the novelty of a majority of MEMS devices, the development of standard MEMS processes for manufacturing are either unavailable or have taken a significant time for development.

3.1 MEMS Manufacturers

MEMS manufacturing companies are currently pursuing two kinds of business models. Under the first category fall the so called OEMs (Original Device Manufacturers). These companies design and manufacture a complete product (MEMS component or MEMS enabled module) and sell it to specific customers as well as to the open market through distribution channels. The second category include open foundries, which provide technology services in the form of fabrication processes. This business model often implies a new process development for a new product development. In some cases standard processes can be re-utilized, which are also offered on a MPW (Multi-Project-Wafer) basis.

Independent of the business model, each company is developing its own process. And the standardization of the core processing steps is needed. For OEMs the presence of a standard technology can provide an answer to the customer second sources request; for open foundries the availability of a standard simplifies enormously the path to industrialization. The standardization is especially important for fabless MEMS design-houses to enable the design into a standard and well-known process similar to CMOS based IC design.

3.2 Material Properties

The availability of characterized processing effects and reliable material properties will determine how and when MEMS are volume-production ready. Since MEMS devices are essentially mechanical, their design requires that the corresponding material properties are understood and accurately characterised. For this purpose specific material property test structures can be used to identify the critical material properties, such as Young's modulus, stress and stress gradient, fracture strength, electrical conductivity, dielectric permittivity, thermal coefficient of expansion and stiction.

These material property characterisation structures should be regularly placed along with process characterisation structures at specific locations on test and prototype wafer lots. A sub-set of these test structures is typically used to monitor run-run variations and obtain statistical process data. The detailed material property information should have been previously correlated with simulation models of the test structures and is available to be considered in the design cycle.

3.3 Virtual Prototyping and Manufacturing Analysis

The ability to gain insight into the sources of manufacturing performance variation without actually fabricating devices is extremely cost effective and efficient and common in the IC industry, where a single fab run is typical. On a system model level, the parametric MEMS models enable statistical analysis (e.g. Monte Carlo) of a design considering statistical distributions of material and process tolerances. This type of "virtual manufacturing analysis" enables the designer to verify manufacturability based on given fabrication constraints.

Detailed process emulation (see paragraph physical modelling) allows virtual prototyping. The virtual fabrication of a MEMS device enables designers and process engineers to visualize the effects of design and process modifications before fabricating an actual device. The used method can be used to predict and visualize effects such as mask misalignments; determine under-etched conditions, it emulates the blurring of sharp corners due to lithography effects and engineers can view geometry "inside" the device which would be very difficult to do with a physical prototype.

3.4 Design Kits

In practice a process design kit would contain the essence of material and process information. For instance this data contain parameters such as layer thickness, Young's modulus, Poisson's ratio and stress gradient that have been well defined within the tolerances of the specific manufacturing process. The design kit would automatically set these constraints for the designer allowing other design parameters to be varied during the evaluation of designs. This certainly influences the product development process substantially as only those designs that can be manufactured, which are perfectly compatible with the manufacturing constraints. MEMS design groups of OEMs have their internal design kit or customized design environment. For open foundries relying on design houses, design kits provide an easier access to the manufacturing processes allowing the design of MEMS with confidence using established and characterized fabrication processes.

4 Packaging, where do package considerations enter your MEMS design flow ?

A well recognized commercialisation barrier for MEMS enabled products has been and continues to be packaging. This is a significant technological problem in the MEMS industry, and has resulted in custom packaging for each application, leading to higher overall package cost. Packaging of MEMS components differs significantly from the packaging of microelectronics, which is well established, primarily because unlike microelectronics, the functional specification of the MEMS chip is critical to the design of the package. Industry experts also recognize that a "lack of attention" may be a contributing factor to the overall problem both within organizations, as well as externally by industry vendors and suppliers. Today there are new options for reducing MEMS packaging costs and ultimately bring MEMS devices to market faster.

No matter where Package considerations enter your design cycle, if this can be brought forward it will be of commercial significance. This is both true in IC-design and in MEMS-design. Different organizations have established their own work-flow determined by the history of the company which includes the current knowledge on available personnel and design automation tools. Of course it is important to bring "experts" into the design-flow. It is important to realize that they do not only bring their expertise on package-design but also their own work "habits". For the second point it is extremely hard to stay "up-to-date" on current capabilities on Design Automation Tools. Evaluations cost time of the expert and in addition the software tools are often evaluated by comparing current work "habits" and alternative modelling and simulation are often very foreign to the work-flow. However, having an open mind for work-flow enhancement considerations can have significant cost saving in the complete design-cycle.

4.1 How to capture Packaging information in mathematical models ?

Whether a custom package solution is considered or a standard package, the problem remains that in order for the packaging considerations to move up the design-flow-chain some mathematical modelling is required. In most organisations the only feasible or known solution to this problem is to model the package using physical models. In other words, to consider full finite element simulations of the complete or partial package. This approach causes the package considerations to be incorporated into the device or component design at a late stage. It also forces the organisation to have Finite Element Modelling and simulation experts. Very often the tasks are very time consuming because of the Macro-size of the package compared to the MEMS device. In addition to this not much time is spend on considerations that will make it possible to reuse the simulated results in future projects.

4.2 Package-MEMS Co-Design

It is possible to capture Package models for reuse. First it needs to be realised where the package model is reused. If we refer back to Paragraph 2, there are the options of reuse in Physical models, Device models or System models. Here the later two can be considered simultaneously since they will be implemented in system models.

In any case it will be advantages to build up a library of known models and simulation results of packages for reuse. The options are to store complete Physical field simulations on packages, extracted compact models of these simulations, or Reduced Order models. All this data can be reused in a MEMS-device or component design study on either the physical field solver level or the system level.

Package material properties are a large part of the problem of capturing package knowledge, but this is not much different from the MEMS-material knowledge problem.

4.3 Standard Open Tool Packages

Until now there was no simple way of sharing detailed package design data in the early stages of the MEMS design process. Recent availability of a set of standard open tool IC packages within an existing MEMS CAD tool environment will deliver to designers detailed package design data in a easy-to-use, accessible environment. The package CAD data is supported by the package supplier directly and will be available in the form of a library of different packages of various size and type, and which are easily modified to custom designs. Through the availability of open tooled packaging solutions from Kyocera, (both package and MEMS) designers now have significantly more choices for initial package selection i.e. in terms of chip size, number of electrical connection, etc., and to consider the effects of packaging early in the design phase. With access to the package geometry and materials data in a MEMS design environment, both package and MEMS designers could communicate design information more effectively.

4.4 Custom Package Libraries

For custom packages the software solutions available are limited to the standard Mechanical Engineering tools such as Solid Modelling tools and Finite Element analysis tools. One can however consider trying to set up and control the custom package design process in such a way that the data can be easily reused in future design or design iterations. The methods listed under the Standard Open Tool packages can also be employed internally. Creating a more structured way within the company.

4.5 Conclusions

There are still many design automation challenges on the road for MEMS design. Some challenges are related to converting the existing expectations of MEMS designers to new modelling fields. Many still believe that for physical analysis and mechanical analysis in particular, finite element simulations are the only way. But in fact, over the last 10 years many alternate modelling levels and techniques have been made available that take into account more the work environment of the MEMS designers rather than just focussing on 3D solid model simulations. Other challenges that still exist are related to the manufacturing of MEMS, here the foundries can start to rely on design automation tools that can capture their process capabilities and process results for the MEMS engineer. Now also the packaging of MEMS can be included in the MEMS design process, this is possible for Standard Packages and custom packages.

[1] S.D. Senturia: "Microsystem Design". Kluwer Academic Publishers 2001. ISBN-0-7923-7246-8

[2] Eric Parker and Tushar Udeshi, "Exploiting self-similarity in geometry for voxel based solid modeling," Proceedings of the eighth ACM symposium on Solid modeling and applications, Seattle, Washington, USA, June 2003

[3] Gerold Schröpfer, Mark McNie, ea, "Designing manufacturable MEMS in CMOS compatible processes: methodology and case studies", Proceedings of SPIE Photonics Europe 2004, Strasbourg, April 2004