Transactions on the Built Environment vol 12, © 1995 WIT Press, www.witpress.com, ISSN 1743-3509

Simulation tools for micro electro mechanical systems

B. Folkmer,[a] H. Sandmaier[b]
[a]*Department of Microsystems Technology, Frauhofer Institute for Solid State Technology, D-80686 München, Germany*
[b]*Institute of Micro & Informations Technology, Hahn-Schickard Society, D-78052 Villigen-Schwennigen, Germany*

Abstract

The application of simulation tools in MEMS design allows a quick and accurate prediction and optimization of specific system functions using a variety of sophisticated simulation programs on high end computer systems: e.g. finite element analysis for structural mechanics, thermal- and electrical field calculations or network and state simulators for simulations at system level as well as tailored programs for certain classes of sensors and actuators.
The calculation of the system characteristics, considering coupled physical effects and distributed behaviour, generally is more complex since the necessary tools and know how, related to history, have been developed in different engineering sciences. Beside an overview on the state of the art in MEMS simulation this paper describes a new approach, using a combination of state models and field simulations on component and system level.

1 Introduction

Microelectromechanical systems will play a key role for modern products in the future. Miniaturisation and integration are tuning cumbersome basic devices into tiny and intelligent microsystems. Since we are looking at multidisciplinary technology which joins various fields such as micromechanics, microelectronics, microsensor and microactuator engineering in a system approach, large investment and know how is required.
The complexity of silicon based MEMS still continues to expand. High integration levels of subsystems lead to coupling in different physical effects. The only way to verify a certain design is to build it and test it [1]. Therefore, in

Transactions on the Built Environment vol 12, © 1995 WIT Press, www.witpress.com, ISSN 1743-3509

the engineering process -from first idea to a reliable MEMS product-, the number of design cycles increases cost and time-to-market.
For microelectronics powerful tools exist on process, device and circuit level. However, many of these tools are inapplicable to aid for MEMS design, since generally three-dimensional structures have to be considered.
Several software packages have been developed for sensor and actuator design [2-8]. However these tools are limited to certain classes of devices.
On the other hand, there exist numerous general purpose simulators for numerical calculations on structures, e.g FEM tools, or on function -, behaviour -, or on device level. Usually those tools are applied within the design process for analysis of special problems (see Fig. 1). High effort is spend on adequate coupling conceptions for application of those tools to general MEMS simulation [1-18].
There is still an increasing need for software tools to assist designers of micro devices and microelectromechanical systems in a variety of tasks including device simulation, design verification, design optimization, mask layout, process planning, etc.

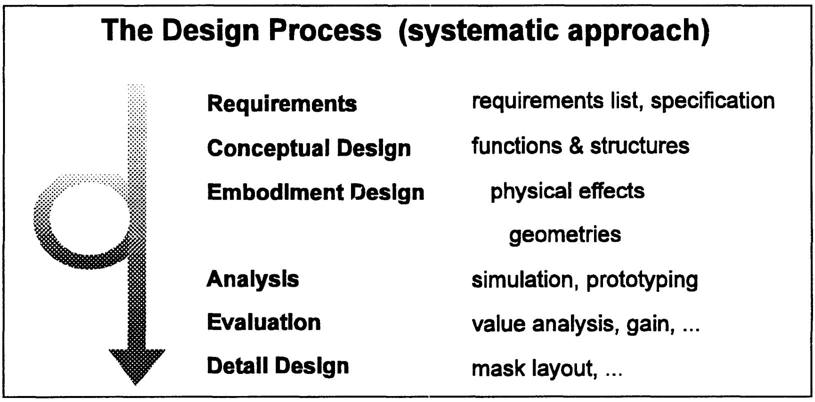

Figure 1: Sketch of the MEMS design process

2 State of the art

The development of special programs for MEMS simulation started in the early 80th focusing on pressure sensors. Then the increasing use of numerical simulation tools at research institutes and large companies has led to a considerable improvement of the characteristic of micro sensor devices. Today some stand-alone programs are available solving special problems. These simulation tools run in most cases on workstation or PC platforms. The tools were primarily developed to improve sensor design and layout [2-7]. SENSIM,

Transactions on the Built Environment vol 12, © 1995 WIT Press, www.witpress.com, ISSN 1743-3509

CAPSIM, CAEMENS-D, SENSOR, NM/SESES, MEMCAD, to mention some, use analytical approaches and/or the more general finite element method (FEM) to simulate the output characteristics of sensors for mechanical, thermal or magnetic quantities. Most of these tools offer access to a simple database and provide menu driven interfaces to other simulation tools. The database usually contains material properties and performance data. The communication between different simulation packages is realized by file transfer. E.g. the program SENSOR [5] provides an automated macro model generator to represent a mechanical and temperature loaded sensor by an HSPICE™ subcircuit or by ELDO™ modelcards. The lumped parameters supporting the macro model are extracted after simulation of the specific device (see Fig. 2). This way, simplified simulations of the output characteristic of a sensor device, even considering a system environment, are possible with restricted consideration of physical couplings. Depending on the tool biasing effects due to temperature shift, packaging, passivation, etc., nonlinear behaviour and/or on chip integration are implemented.

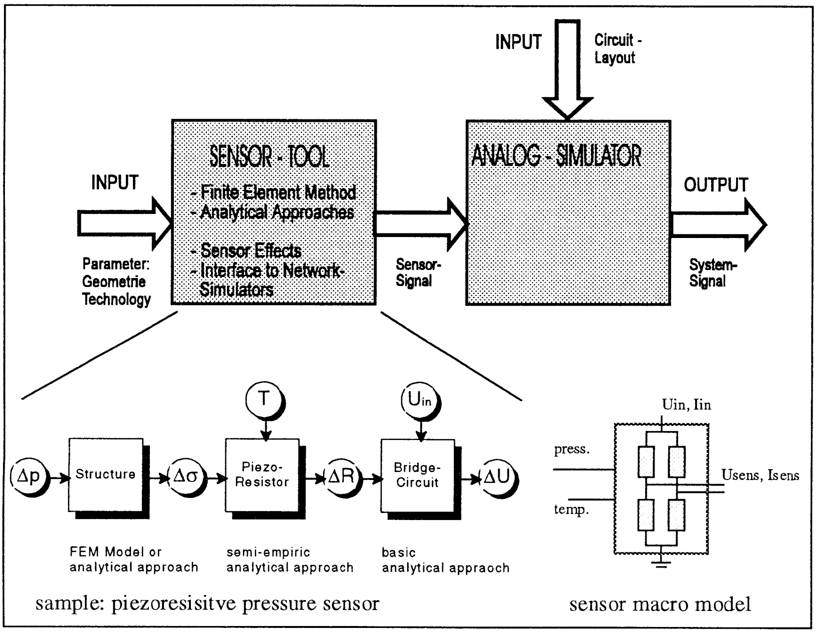

Figure 2: MEMS simulation applying the SENSOR tool

In the field of actuators too, tailored software packages were developed. Running on a PC-system, the simulation tool PUSI allows to simulate and optimize the complex dynamic behaviour of a micropump [8].

Transactions on the Built Environment vol 12, © 1995 WIT Press, www.witpress.com, ISSN 1743-3509

Several groups developed process simulation tools for 3-D structures in silicon. The programs OYSTER [9] and MEMBUILDER [10] concentrate on the problem of creating a 3-D geometric model from an integrated process description and mask data. Other process simulation tools focus on the modelling of anisotropic etching [11-13]. In some cases anisotropic etching simulators are implemented in design systems [14].
The existing tailored tools usually focus on special sensors or actuators. Physical couplings are commonly disregarded as long as they are not an essential part of system function.

3 MEMS Simulation

For the optimization of MEMS its of importance, that a simulation tool supports fast estimation of the characteristic quantities and dimensions of the system. Therefore rough calculations at system level, division into subsystems and free definition of couplings are essential demands.
Modelling may start at the geometry level, i.e with 3-D analysis (FEM, BEM, FDM, etc.). Coupling of different physical effects is possible at this level therotically, but usually limited by hard- and software due to the high number of degrees of freedom to be calculated. Introducing macro models at a higher level which are fed with extracted parameters (thermal conductivity, stiffness, etc.) from 3-D calculations allows the coupling of generalized degrees of freedom (temperature-heatflow, force-velocity). Good modelling predicts the conservation of energy or power.

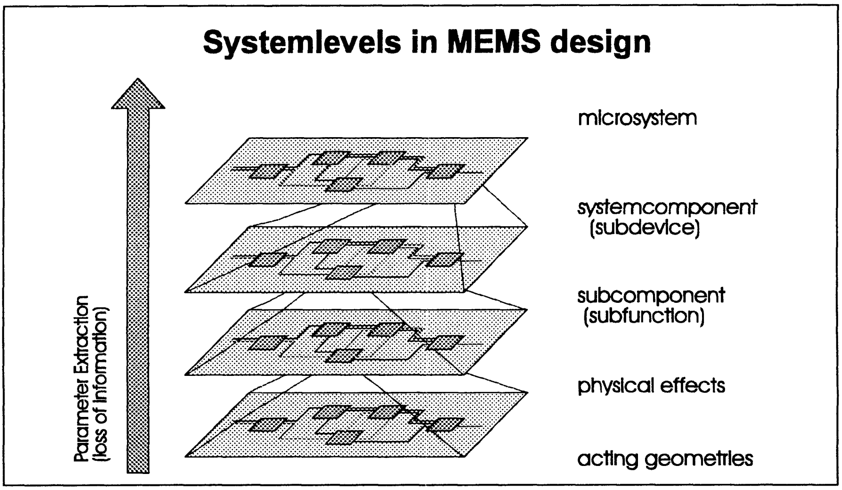

Figure 3: Systemlevels in MEMS design and simulation

The authors suggest a top down approach to support the design process. The most simple models at system level are behavioural. Complexity can quickly be expanded to increase accuracy by considering architecture and behaviour of the subsystems. To take advantage of an ideal mathematical engine, the VHDL 1076.1 analog hardware description language allows free definition of system architecture and model behaviour [15-16]. Mixed technology design is supported. Different disciplines, electrical, thermal, mechanical, etc., are described by different *NATURES* of conversation laws in only one model.

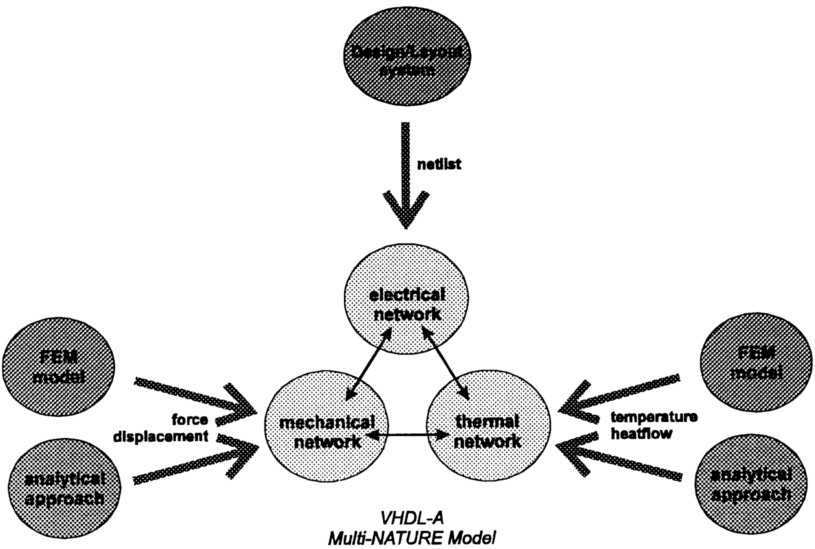

Figure 4: Behavioural MEMS model on system level with different energy *natures*, implemented in VHDL-A, supported by generalized data from structure simulations

Usually parameters should be known before simulation because they refer to those inputs to a model that are not related to its degrees of freedom. VHDL-A description allows that degrees of freedom of one discipline (e.g. temperature at transducer location in the thermal network) acts as a parameter in another discipline, which may change during simulation (e.g. temperature for a piezoresistor model) [15]. Therefore physical cross couplings can easily be generated at nearly all modelling levels.

Lumped parameters to support the description of the distributed 3-D structure behaviour can be obtained by finite-element calculations for each discipline. Integration over the considered areas/ volumes allows the calculation of the numerical values for the generalized degrees of freedom. Then parameters of each model are determined by inversion of the characteristic set of equations.

Transactions on the Built Environment vol 12, © 1995 WIT Press, www.witpress.com, ISSN 1743-3509

As an example we modelled a piezoresistive pressure sensor with HDL-A, a pre-implementation of VHDL-A, to study the thermo-mechanical coupling effects due to self-heating. The system behaviour was determined by ELDO. The FEM calculations were carried out with SAMCEF and ANSYS.

Regarding Fig. 5 it is obvious that in a MEMS-CAD environment sensorics, actuatorics, signal conditioning, packaging, quality management, etc. have to be implemented. Furthermore, different technologies and their relevant data, e.g. material and process parameters and geometry restrictions have to be store in some kind of common database for MEMS simulation tools.
The application of a set of consistent MEMS-CAD tools allows the designer quick and accurate optimization and prediction of the characteristics of the MEMS as well as the determination of the parameters for mask layout and the technological realization.

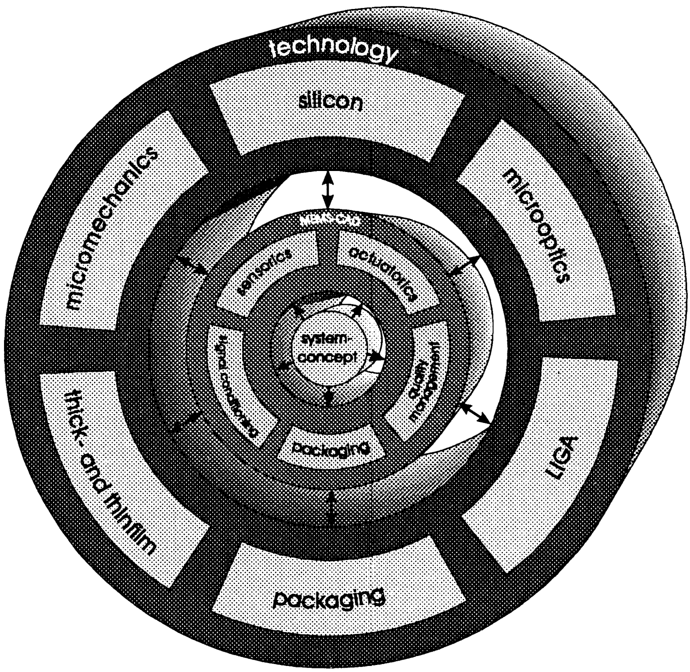

Figure 5: Manifolds of technology and research fields to be considered in a MEMS CAD and simulation environment.

4 Conclusion

The presence of new enhanced numerical simulators together with a mixed-signal-hardware-description-language allows efficient modelling of the architecture and behaviour of MEMS on different system levels as well as inclusion of physical cross coupling. 3-D structure behaviour can be considered by extracting lumped parameters from FEM simulation. A top-down approach, from system level via physical effects to structure level supports the synthesis of new solutions as part of the design process.
Much more effort is necessary in developing a modular simulation environment and standard technology processes with the parameters stored in a database open to MEMS simulators. New testing environment has to be supported to provide fast and easy access to material properties which are highly related to each individual technology process. Improving the simulation environment for MEMS still offers interesting challenges.

Acknowledgements

Major parts of this work were carried out within the project „Application Specific Integrated Sensors (ASIS 2S)“. The authors would like to thank the german federal ministry for education, science and technology (BMBI) for financial support.
Special thanks to Mr. P. Groth (TSE GmbH, Reutlingen) and Mr. D. Pabst (ANACAD GmbH, Ulm) for valuable discussion and support in FEM- and HDL-A system simulation.

References

1. Senturia, S., CAD for microelectromechanical systems, Transducers '95 & Eurosensors IX, Vol. 2, pp. 5-8, *Proc. of the 8th Int. Conf. on Solid-State Sensors and Actuators,* Stockholm, Sweden, 1995
2. Lee, K.W. & Wise K.D. SENSIM: A simulation program for solid-state pressure sensors, *IEEE Trans. Electron Devices*, 1982, Vol. ED-29, No. 1, pp. 34-41.
3. Puers, B. , Petersen E. & Sansen W., CAD tools in mechanical sensor design (CAPSIM), *Sensors & Actuators*, 1989, 17, pp. 423-429.
4. Zhang, Y., Crary, S.B & Wise, K.D., Pressure sensor design and simulation using the CAEMENS-D module, pp. 32-35, *Tech. Dig. IEEE Solid-State Sensor and Actuator Workshop,* Hilton Head SC, USA, 1990.
5. Folkmer, B., Offereins, H.-L., Sandmaier, H. , Lang, W., Groth, P. & Pressmar, R., A Simulation tool for mechanical sensor design (SENSOR), *Sensors & Actuators*, 1992, 32, pp. 521-524.
6. Senturia, S., Harris, R., Johnson, B., Kim, S., Nabors, K., Shulman, M. & White, J., A computer-aided design system for microelectromechanical systems (MEMCAD), *Journal of Microelectromechanical Systems*, 1992, Vol. 1, 1, pp. 3-13.
7. Schwarzenbach, H., *NM/SESES: Programsystem for semiconductor sensor simulation*, prospect of NM Numerical Modelling GmbH, CH-8800 Thalwil, Schwitzerland, 1993.

8. Zengerle, R., Richter, M., Brosinger, F., Richter, A. & Sandmaier, H., Performance simulation of microminiaturized membrane pumps, Transducers '93, pp. 106-109, *Proc. of the 7th Int. Conf. on Solid-State Sensors and Actuators,* Yokohama, Japan, 1993.
9. Koppelman, G.M., OYSTER: A three-dimensional strutural simulator for micromechanical design, *Sensors & Actuators*, 1989, 20, pp. 179-185.
10. Osterberg, P. & Senturia S., MEMBUILDER: An automated 3D solid model construction program for microelectromechanical strutures, Transducers '95 & Eurosensors IX, Vol. 2, pp. 17-20, *Proc. of the 8th Int. Conf. on Solid-State Sensors and Actuators,* Stockholm, Sweden, 1995
11. Koide, A., Sato, K. & Tanaka, S., Simulation of two dimensional etch profile of silicon during orientation-dependent anisotropic etching, pp. 216-220., *Tech. Dig. IEEE Micro Electro Mechanical Systems Workshop,* Nara, Japan, 1991.
12. Sequin, C., Computer simulation of anisotropic etching, Transducers '91, pp. 106-109, *Proc. of the 6th Int. Conf. on Solid-State Sensors and Actuators,* San Francisco, USA, 1991.
13. Buser, R. & de Rooij, N., CAD for silicon anisotropic etching, pp. 216-220., *Tech. Dig. IEEE Micro Electro Mechanical Systems Workshop,* Nara, Japan, 1991.
14. Buser, R., Crary, S. & Juma, O., Integrating the anisotropic-silicon-etching program ASEP within the CAEMENS CAD/CAE framework, MEMS '92 , pp. 133-138, *Proc. of the Int. Conf. on Micro Electro Mechanical Systems,* Travemünde, Germany, 1992
15. Shi, R. & Vachoux, A., VHDL-A Design objectives and rationale, in *Current Issues in Electronic Modeling*, eds Levia, O., Berge, J.-M. & Rouillard, J., Issue 2, Kluwer Academic Publishers, 1995
16. Krolikoski, S., Sharon, P., Smith, D., ed. al., *VHDL 1076.1: Technical Seminar '95*, technical note of Analogy GmbH, München, Germany, 1995
17. D. Pabst, Stand der Systemsimulation und Kopplungsmöglichkeiten zu FEM, in Bayerischer Forschungsverbung f. technisch-wissenschaftliches Hochleistungsrechnen (ed Wachutka, G.), *Proc. of Numerische Simulation von Mikrostrukturen und elektronischen Baulelementen Workshop,* Günzburg-Reisensburg, Germany, 1995.
18. Ulrich, J., Füller, H. & Zengerle R., Static and dynamic flow simulation of a KOH-etched micro valve, Transducers '95 & Eurosensors IX, Vol. 2, pp. 17-20, *Proc. of the 8th Int. Conf. on Solid-State Sensors and Actuators,* Stockholm, Sweden, 1995