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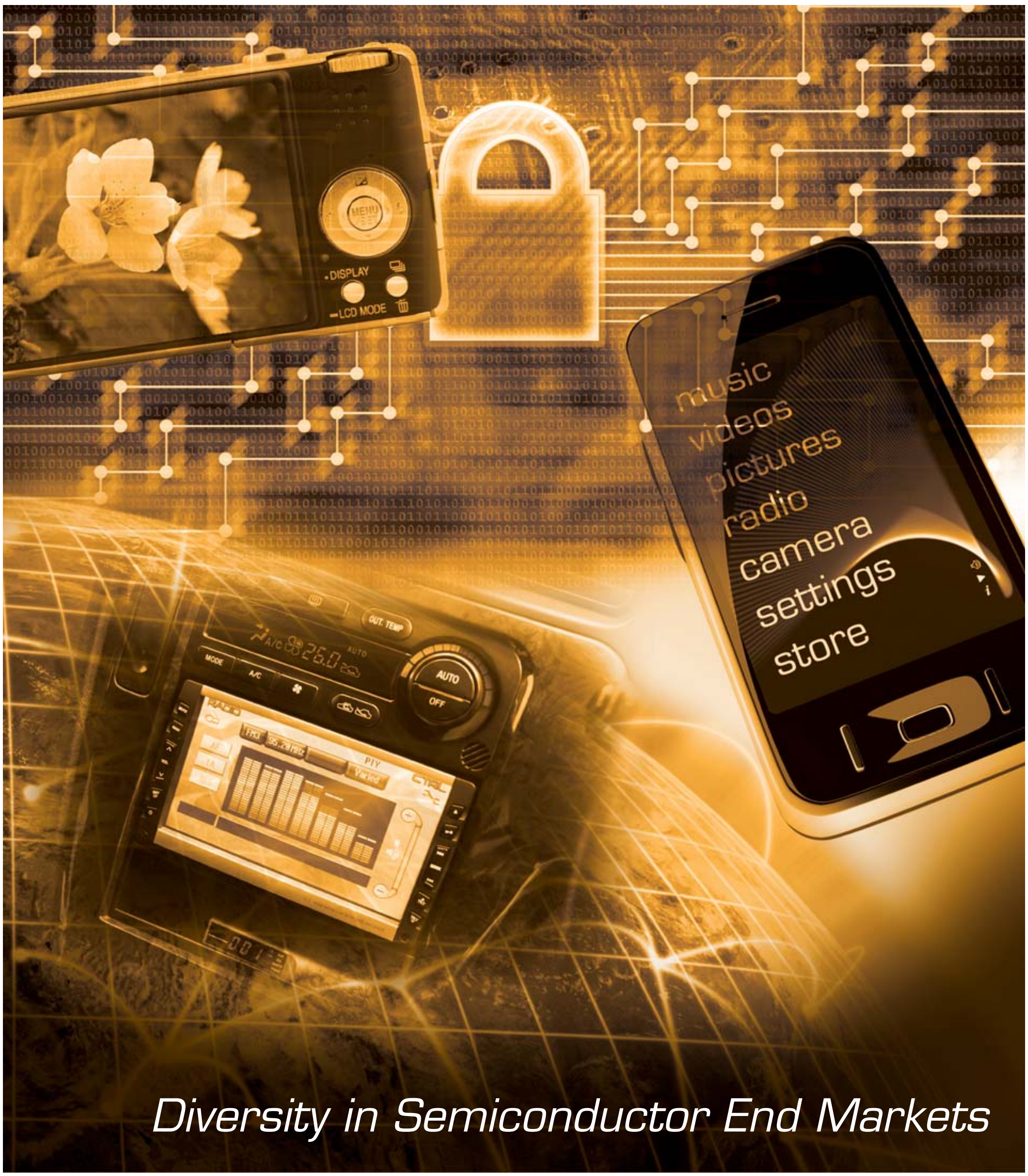

Diversity in Semiconductor End Markets

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Development of High-Performance and Reliable Next-Generation Systems Based on Emerging MEMS Technology

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Microelectromechanical systems (MEMS) are finally becoming attractive for many industrial applications; their potential range of use is continuously increasing. The next generation of industrial applications will require optimal systems with high resolution, miniaturization and reliability, thereby forcing system integrators to combine both sensors and application-specific ICs (ASICs) in a feedback arrangement implemented as a system-in-package (SiP).

The real challenge consists in guaranteeing performance and yield for the SiP. As high-performance multi-domain systems slowly emerge, innovation and new design techniques are required to reach robustness and testability goals.

This article presents a method which can be used to guarantee that the multi-domain system will be in conformance with its specification and explains why performing an assessment of a virtual fabrication process is mandatory to evaluate robustness and reliability. It describes a design chain that can be used to ensure the correlation between simulations and silicon measurements of a multi-domain system.

Advanced Modeling Techniques and Libraries

MEMS as mechatronic systems integrate a complex combination of microelectronic (ME) analog and logic blocks with electrical devices and non-electrical mechanical structures (MS) for sensing or actuation. To gather system behavior, the complete system must be modeled and simulated as a whole. To meet this challenge in adequate time without sacrificing accuracy, a behavioral modeling methodology is used. At this stage, it is doable for the system's analog and mixed-signal components, as ME traditionally provides models at both the behavioral and the structural levels. The latter level enables model verification versus silicon measurement, and the worth of such a pair of models is at par with the capability to prove their equivalence. Meanwhile, the challenge for MEMS governed by mechanical domains is providing a structural model in tune with measurements on silicon and compatible with ME models.

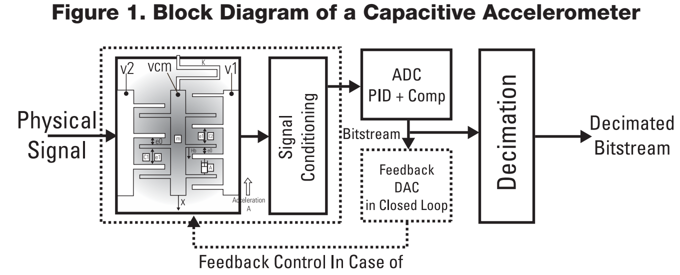
Behavioral modeling for electronic parts in MEMS devices is based on component models representing complex functions for conditioning, modulation (analog-to-digital conversion) and filtering the signal coming from the sensor, including amplifiers, integrators and differentiators.

The model for a MEMS MS is based on the composition of basic physical effect models which occur in or between single components of micromechanical devices as felt in the electrical domain. One advantage of this kind of structural modeling for a MS is the high reusability of already-modeled, validated effects. This approach is beneficial to the designer, as it can be decided whether an effect will be taken into account, thereby actively influencing simulation accuracy and speed. Another advantage is that no knowledge of the ME+MS system's model equation is necessary, as it is automatically built inside the simulator by combining the needed effect models.

A Practical Illustration of an Accelerometer

An accelerometer will be used to demonstrate the modeling technique previously discussed. Figure 1 shows a scheme of a typical capacitive sensor with its associated electronics. A seismic mass is connected through a meander spring to the housing and so builds a spring-mass-damper system. Conductive plates are attached to the substrate on one side. With the counter plates attached to the movable mass on the other side, they form capacitors. These capacitors change capacitance according to the position of the seismic mass in non-linear relation to an external acceleration applied to the device. The resulting change in capacitance is detected and processed by connected electronics.

Figure 1. Block Diagram of a Capacitive Accelerometer



The accelerometer is modeled from its basic physical effects (i.e., those selected physical effects considered relevant are modeled in very high-speed IC hardware description language-analog and mixed-signal (VHDL-AMS)) like the inertia of masses in translational moving bodies, the spring effect of a beam, damping effects or the electrostatic attraction between two conductive plates.

Both mechanical and electronic parts can be built from their own basic component libraries. Each basic model has been designed and validated carefully. For instance, in the electronic library, each component must respect design constraints and topology assembly rules to facilitate their connections within the rest of the chain. Topology rules are constituted of geometrical constraints such as spacing, width, and position between sensitive and aggressive signals.

It becomes easy for the system-on-chip (SOC) designer to build their ME+MS system from these model libraries and check that the architecture and application schematics fulfill system requirements.

Performance Assessment and Robustness Analysis

These modeling techniques and libraries enable the SOC designer to describe all mechanical and electrical coupling domains into a homogeneous overall behavioral model. Even if each domain keeps its specific language, simulation and measurement methods, using a multi-level simulator, a MEMS-based SOC designer can simultaneously handle both analog/mixed-signal structural models and high-level languages such as VHDL-AMS so that mechanical and electronic behavior can be modeled in a coherent framework using physically meaningful parameters.

An MS' performance is comprised of two properties: sensitivity and noise level. An MS' characteristics strongly affect the system's feasibility, stability (in the case of closed-loop ME+MS), performance and, naturally, its implementation. For a capacitive accelerometer, the ME+MS designer must consider, in addition to noise level and sensitivity, other sensor properties, such as mass and stiffness constants, in both open-looped and closed-looped systems to ensure system reliability.

The unique solution for performance assessment is to adopt a hierarchical approach, gathering library blocks and multi-level verification, and to use a high-level modeling language, such as VHDL-AMS, to perform jitter simulation and provide an acceptable level of jitter that guarantees the specification of dynamic range for a given architecture. SPICE simulations are also used for the architecture's sub-elements to guarantee, by design, the overall performance.

By taking this approach, the assessment of the tolerance margin of each domain, with respect to the acceptable fabrication variations of the other, can be performed. From an electronics point of view, a MEMS-based SOC designer can provide acceptable margins to define a range of acceptable sensors and vice versa. From a mechanical point of view, the noise budget can be defined for the electronics family.

Multi-Domain Simulation for Yield Prediction

The fabrication of MEMS underlies manufacturing process variations inducing variations such as the geometric dimension of a MS (i.e., due to under-etching, material property variation, doping/temperature variations, etc.). Thus, fabrication yield depends on the nominal—the optimal—design within its parameter tolerance range and distribution functions.

Today, there is strong demand for decreasing MEMS structure sizes. As a sequel, the fabrication process' tolerance range decreases as well. The fabrication process must become more accurate, and the tolerance range of each process step must be well-defined and controlled. Running a Monte Carlo simulation, which consists in multiple simulation runs of the complete MEMS design, each run with a different set of parameter values according to their statistical distributions allows one to predict fabrication yield.

Indeed, any electrical measurement has an associated distribution. In the case of an accelerometer, the variation of the sensor structures as geometric elements in x,y directions are applied with normal or Gaussian distribution and different tolerances. This normal distribution is defined by a mean value and a standard deviation or sigma.

Since the design of the chosen sensor structure is insensitive to thickness variation, no distribution function is applied. For simplification, the material parameter's specific weight, the dielectric constant and the beam's elastic modulus are controllable in the process and are considered constant in this simulation. The normal distribution function defined in the statistical analysis package SAE J2748 is applied on the parameters in the accelerometer architecture, which are then passed to the effect model instances. To be precise, the SAE J2748 package is useful in defining the statistical variation of electrical, electronic, mechanical component and sub-system parameters.

The model previously described is used to determine the MEMS device's resonance behavior. The accelerometer model is instantiated in a simple testbench, and the small-signal Monte Carlo analysis is initialized. Figure 2a shows the small-signal Monte Carlo analysis of a MS with 50 random runs. With this simulation, it is possible to detect whether the processed accelerators perform in an acceptable range or not. For each random run, it is possible to extract the applied device parameters for further design optimization. This helps to value the fabrication process for an expected yield or if a design optimization becomes necessary.

Figure 2b shows the result of the reachable performance with a standard deviation defined for a given resonance distribution of the electromechanical part.

Figure 2a. Monte Carlo Results for a Mechanical Part

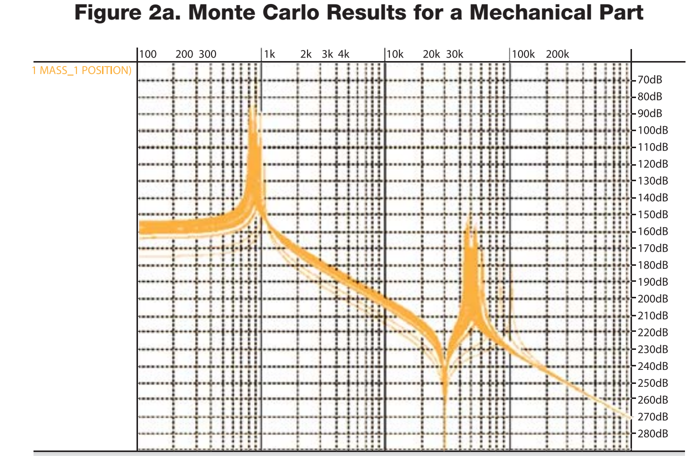


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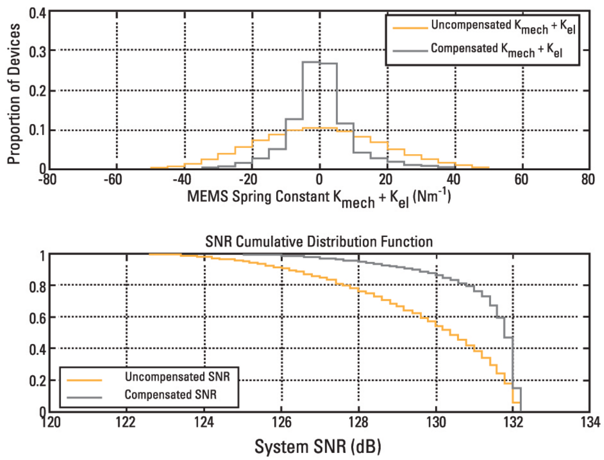
Figure 2b. Yield Analysis of the MEMS System with σ = 200Hz



The Virtual Fabrication Process as the Unique Solution to Facilitate Market Success

Right-on-first-pass is the golden objective of any system integrator faced with a diversity of local flaws and interfacing hurdles. The priority is to minimize the risk of detecting bugs at the silicon stage. This requires a skillful mixing of simulations and silicon qualifications. The aim is to identify the main critical parameters or innovative design parts and to correlate simulations and silicon measurements on those parts.

The virtual fabrication process is the unique solution to increase yield by selecting the most robust architectures and to accelerate time-to-market for innovative MEMS. Indeed, in those applications, the main challenge is validating worst-case configurations in a multi-domain system.

The objective is to check the conformity of measurements with different tolerance templates specified for jitter, loop stability (in the case of a closed-loop system), power supply and noise reference. More than respecting specifications, it permits to assess design margins.

Direct Application to the Calibration Process and Industrial Test

The modeling technique previously described can be used to increase system reliability—sensor and electronics—and interest in several market segments. Indeed, it is important to understand how the system can be calibrated: either by self calibration using embedded error compensation structures or by a software calibration sub-routine.

Thanks to the design chain, it is possible to determine the parameters which may change and cause a performance loss in the ME+MS system.

To continue with the accelerometer example, each electronic component has gain, offset, linearity, power supply or temperature behavior to add to the sensor behavior. By performing a sensitivity analysis of the ME+MS system with the simulation models previously described, the ME+MS-based SOC designer can tune the most effective compensation mechanism and then optimize the calibration of both sensor and electronics.

Practical Experience

The combination of an electromechanical basic effects library, an electronic element library and an effective mixed-signal multi-level simulator enables graphic modeling and simulation of high-performance multi-domain systems.

Applying distribution functions on simulation model parameters helps determine where design or process optimizations are necessary to bring system behavior within an acceptable range. Simulation runs of an optimized design with parameters that match the fabrication unit's process variations allow for the prediction of yield of final MEMS devices. Right-on-first-pass is no longer black magic.

The next stage will be to differentiate the levels of behavioral and structural modeling for a MEMS MS and to introduce their automatic verification of equivalence. ■

About the Authors

Dr. L.M. Vosskaemper received a diploma of engineering from Gerhard Mercator University of Duisburg, Germany in 1997. Thereafter, he started his Ph.D. studies at Gerhard Mercator University in close co-operation with Dolphin Integration and the Fraunhofer Institute for Microelectronic Circuits and Systems (IMS), Duisburg. Since 2000, he has worked full time at Dolphin Integration. In 2003, he became development manager for the SAXO product line. His main task is the coordination of modeling activities of micro systems for system simulation purposes. You can reach Dr. L.M. Vosskaemper at mems@dolphin.fr.

Lucille Engels received a master's degree in electrical engineering from the Polytechnical National Institute of Grenoble, France in 1999. She went directly to Dolphin Integration, Meylan, France to work in logic design for mixed-signal CODECs and in mixed-signal SOC integration. As development manager for the SOC integration product line, since 2007, she has been involved in Dolphin's innovative concepts and practices needed to concretely enable mixed-signal SOC integration in multi-domain systems—starting with early floorplanning to solve power consumption and noise issues, mastering multi-level equivalence checks between models, and completing virtual fabrication and virtual test processes. You can reach Lucille Engels at soc.europe@dolphin.fr.