

8

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Design, Modeling, and Simulation

1.0 CAD for MEMS Requirements.....	323
2.0 Verification and Validation.....	330
3.0 The Evolution of MEMS CAD.....	331
4.0 The MEMS CAD Market.....	333
5.0 Conclusion.....	334
6.0 References.....	335

EXECUTIVE SUMMARY

Microsystems Technology (MST) or Microelectromechanical systems (MEMS), by their very nature as sensors and/or actuators, must interact with their environment. This need for interaction implies the interaction of various physical energy domains. The goal of MEMS device design is to understand and control the effects of these energy domains so that a useful function can be performed. The performance of a useful function more often requires communication with a larger system, requiring the MEMS device to be integrated in a larger system design. In addition, the device or system must be packaged in a manner that is appropriate to the application. Finally, the system must be verified and validated (qualified).

The requirements for a true CAD environment for MEMS must encompass and integrate all these levels of design: device, system, package, and validation. In addition to modeling of the MEMS devices and systems, there may also be requirements for modeling of the fabrication processes, including etch and deposition processes and packaging processes. Work has been done, over more than a decade, by various groups and companies, to construct pieces of such a CAD environment. Some of the pieces are reasonably mature, while others are less so. In the last couple of years, integrated tools that could be called a MEMS CAD environment have emerged. Figure 1 shows an example of design flow for a MEMS CAD environment.

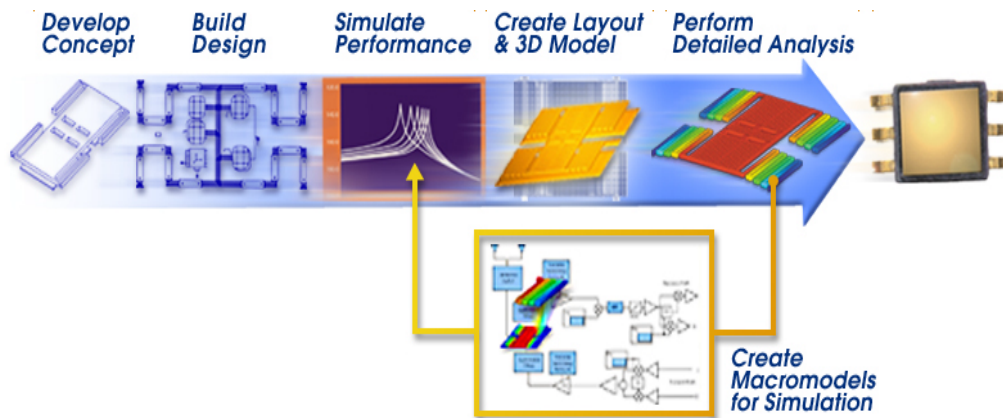


Figure 1. An Example Design Flow for MEMS CAD (courtesy of Coventor, Inc.)

Figure 2 attempts to capture a global view of MEMS design and simulation requirements and their interrelationships. In particular, it captures the requirements for initial conditions based on the fabrication process; environmental knowledge that governs the required simulation boundary conditions, and geometric and mesh descriptions of the actual components. Detailed constitutive models capture the underlying material, physical and chemical behavior. Computational science needs include advanced solution algorithms; detailed formulations of the governing continuum and non-continuum transport and mechanics equations. Finally, validation is needed of each and all of these requirements.

The technical challenges of constructing a workable CAD environment for MEMS are considerable, however, there are other challenges as well. In order to support a commercial market for these complex software tools, the size of the potential customer base must be sufficient to amortize the considerable ongoing development costs. The current state of MEMS'

maturity and market penetration do not yet clearly demonstrate a scalable market for MEMS CAD.

This roadmap chapter intends to look more closely at the technical and market issues surrounding current MEMS CAD tools and examine the requirements for development of future systems.

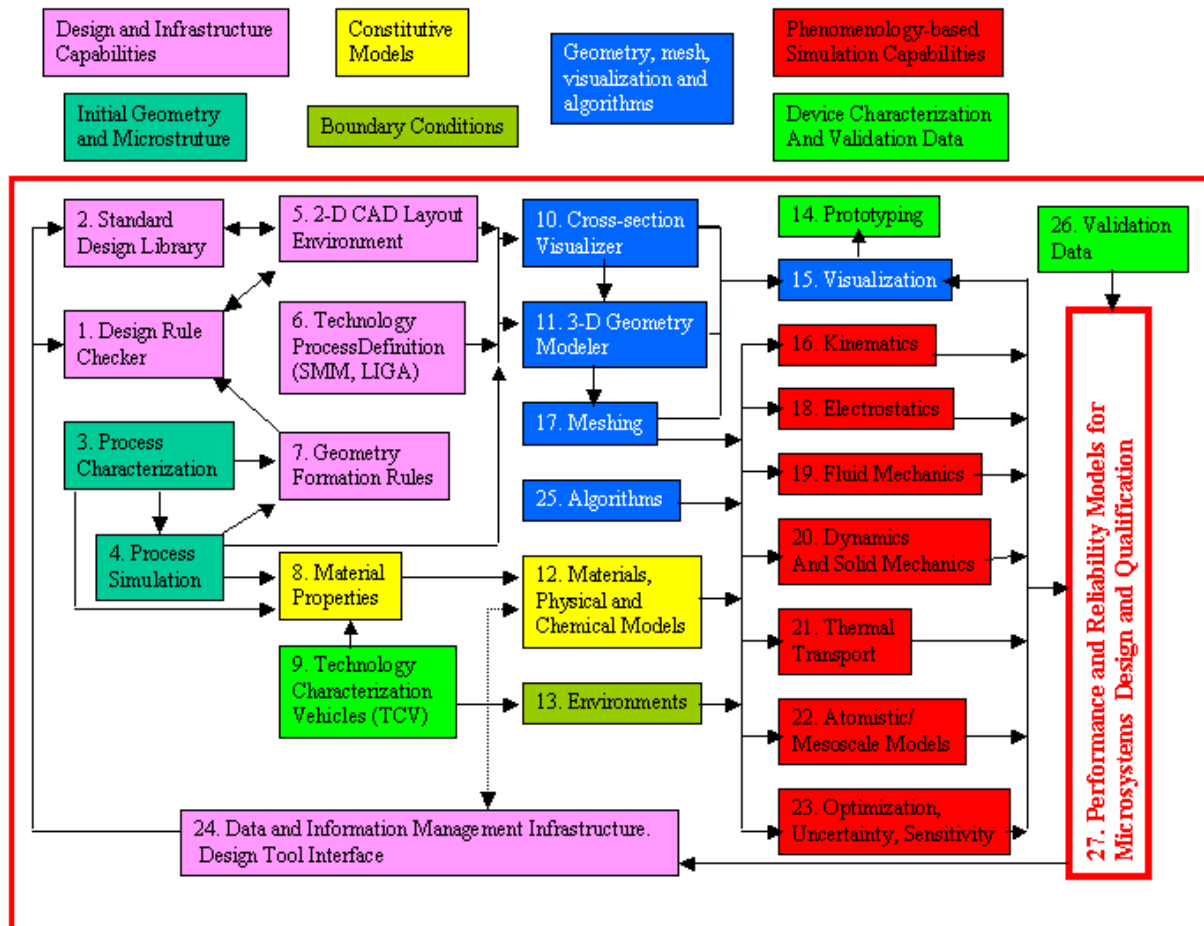


Figure 2. Interdisciplinary Strategy of Science Based Modeling and Simulation of MEMS/MST (from Hermina, Sandia National Laboratories)

1.0 CAD for MEMS Requirements

1.1 Layout, Fabrication Simulation, and Solid Model Generation

The first requirement for a CAD environment for MEMS is the ability to construct appropriate drawings and solid models. Since many MEMS are created using many of the same layer based fabrication techniques that are used to construct VLSI circuits, the basic geometric definition is generally done using a set of 2-D mask drawings. Sophisticated layout tools exist in VLSI circuit CAD environments that can be used for MEMS. However, there are some difficulties with their use. In particular, VLSI layout tools are built to support the rectangular, or “Manhattan” geometries found in typical circuit layout. Their ability to create circular or other free-form shapes is very limited. Second, the data structures are built based on the ultimate use of the layout, which is to produce a fabrication mask. These masks are constructed using line-segment and vertex data. Thus, the typical layout tools store their data in this way. If one intends to also use the data for discretized physical simulations (i.e. FEM analysis), this is a poor data structure to use. More appropriate are structures that retain the true curve data such as are used in mechanical design automation (MDA) CAD packages. At the same time, layout output must be compatible with the electronic design automation (EDA) requirements of mask making vendors. Several vendors currently support layout tools that are designed to support the hybrid EDA/MDA requirements of MEMS.

The construction of basic 3-D solid models is reasonably straightforward because MEMS materials are formed in discrete layers. The difficulty comes in emulating the etching processes. These etches can etch through or partially through one or more layers, and they can etch with isotropic or anisotropic profiles. Further, the specific details of the final geometric shape are heavily dependent on specific etch parameters and the previous wafer history. Given this variability, it is very difficult to simulate shapes for all etch chemistries and their possible etch parameters. As a consequence, physical etch simulators for the broad array of MEMS etching techniques have not been commercially developed.

One area where etch simulation has been developed is the class of wet anisotropic silicon etches that etch along defined crystal planes (Hubbard, 1994). These simulators allow users to visualize the effects of anisotropic wet etching, including corner compensation, etch stops, and higher-order etch planes (see Fig. 3). These simulators rely on an underlying database of orientation dependent etch rate data. This data is hard to develop experimentally, particularly in light of all the environmental interactions with etch rate. Also, the characteristic shape and morphology of the etch front at under-etched convex corners cannot be satisfactorily explained by the commonly used models of the etching mechanism. Researchers from Munich University of Technology have found a way to predict the shape and morphology of anisotropically etched Si structures by new step-flow models of 3D structuring (Horn, 2000).

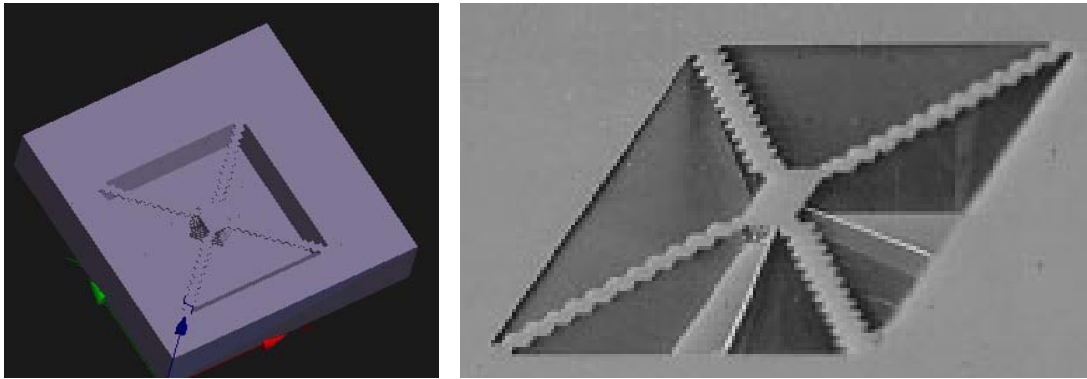


Figure 3. Comparison between the Geometry Generated by AnisE® (Corning IntelliSense) and a SEM of the Actual Etched Device.

Without the ability to simulate etch shapes, some broad assumptions must be made to classify and simplify the etch shapes used to construct a solid model. This may seem like a significant limitation. However, such geometrical simplifications are almost always necessary when constructing a solid model for a complex 3-D object. If such simplifications were not made, the meshing would be too complex and the simulation would be too time (and memory) consuming to be practical. The art of this type of simulation is to understand which physical features affect device function and must be kept, and which can be simplified away. The typical simplification for MEMS solid model generators is to assume that all etches have straight wall profiles through the material thickness. This approach works reasonably well for many etch types, including RIE type dry etches. Adding the ability to support sloped sidewalls extends the capability to anisotropic wet etches. Isotropic etches, which will cause undercutting of the non-etched layers must be generated by more complicated means if the undercut shape is important. Often the entire layer can simply be removed if its presence is not important to the desired simulation. Otherwise, extra material layers and etches can often be used to generate adequately similar geometry at the cost of generating mask layouts and/or process steps that are not part of the actual process flow. Also, manual modifications can be made in the 3-D solid model domain if necessary.

1.2 Physical Simulation

In order to perform accurate physical simulation on arbitrarily complex 3-D geometries, a discretized computational method, such as the Finite Element Method (FEM) or the Boundary Element Method (BEM), is generally required. Tools employing such methods are widely used in mechanical analysis. The difficult part of successfully using this type of analysis is in discretizing, or meshing, the 3-D geometry. This difficulty is compounded by the fact that different energy domains often require different meshes. For example, in electrostatic-structural problems, FEM is typically used to solve the structural problem, while BEM is used for the electrostatic domain. BEM is preferred for the electrostatic calculation because it does not require meshing of the exterior electrostatic volume as FEM would.

Automatic 3-D meshers are a relatively young technology and are generally poorly tuned for the type of material aspect ratios and geometries typical of MEMS devices. Automatic meshing

tools are becoming available for MEMS, but, in general, user involvement in the meshing is still required. Also becoming available are adaptive meshing tools. These start with a crude mesh that is easy to generate automatically and then improve it based on some computational accuracy metric. The difficulty here is to devise accuracy metrics that are broadly applicable. Research into other techniques, such as mesh morphing is ongoing (Zhulin, 2000).

Due to the large difference in size scale between the material thickness dimension and the planar dimensions typical of MEMS devices, MEMS device meshes tend to have a very large number of elements. For standard FEM or BEM implementations, this often results in impractical simulation times or memory requirements. As a consequence, more sophisticated, accelerated computational methods are generally required (Nabors, 1991). A significant added complexity is that these accelerated methods are often specific to a physical energy domain (e.g. electrostatics) and thus different methods may be required for a multi-domain simulation.

The most important aspect of physical simulation for MEMS is the need for coupled, self-consistent simulations of multiple energy domains. MEMS devices are almost always transducers of some type. This means that a true simulation of their behavior must correctly account for the interaction of these energy domains. There are numerous methods of coupling solvers to obtain self-consistent solutions. Each has its pros and cons with respect to accuracy, speed, memory usage, and convergence. In addition, this coupling puts constraints on the relationship between meshes generated in each coupled energy domain. This can further complicate the meshing problem.

As MEMS become integrated in more and more complex domains, such as RF and Optics, it becomes increasingly difficult for a given tool suite to integrate the needed application specific functionality. In this situation, the desire is to transfer models and simulation results to other tools (for example, HFSS for RF, and Code V for optics). For example, this would allow RF simulations to be performed on an accurate electromechanically deformed MEMS structure. Such transfers do not allow self-consistent coupled solutions, so care must be taken where coupled interactions might occur. In order for a truly cross-disciplinary environment to evolve, file format and transfer standards will need to evolve. This will be a difficult evolution to instigate because the MEMS market is, in general, too small to motivate domain specific tool vendors to participate in standardization.

1.3 Material Properties and Initial Conditions

The accuracy of any physical modeling is dictated by the accuracy of the material property data and the initial state inputs (Bart, 2000). Both the material properties and the initial states of devices are determined during the fabrication process because this determines the material's microstructure. This microstructure takes on added significance at the microscale where grain size can become comparable to part dimensions. In these situations, material properties can become highly non-uniform and anisotropic. The properties of interest include the mechanical, electrical, and thermal properties, residual stresses, material microstructure, surface condition, chemical composition, and many others. Since accurate determination of these material properties is critical to simulation accuracy, using bulk material properties often leads to erroneous results. Thus, design and simulation must include materials understanding gained from direct test-structure measurement. Additional diagnostics such as AFM, SEM, TEM and ion beams are used to characterize surface and bulk morphology which form the basis for

characterizing behavior such as stiction, friction, wear, elasticity, fracture toughness and many other surface and bulk constitutive properties.

In general, it is much too complex to predict material behavior directly from physical principals. One commercial tool addresses the problem of material property prediction (MEMaterial® from Corning IntelliSense). This tool incorporates a large database of published material property versus fabrication parameter data. This data is used to predict material parameters by extrapolating the database to the user's inputs. Since these parameters can be very dependent on local fabrication details, improved accuracy can only come from local measurements.

Measurement of these material properties and states has been difficult in MEMS for several reasons. First, typical thin-film materials do not retain the same properties as their bulk material properties. Second, and more importantly, the properties for a given deposited film vary substantially with the specific details of the local deposition process. For example, they often vary throughout the thickness of the film owing to lattice mis-matches. Third, the material properties are difficult to measure accurately. In order to try to address some of these measurement difficulties, modifications of standard material measurement methods have been used (Sharpe, 1997). These methods are often based on the measurement of deflections of simple mechanical structures such as cantilever beams or fixed-fixed beams. Such structures can be used in cases where the films of interest are consistent with the construction of the test device. However, in many cases MEMS structures are composed of compound material stacks. One can obtain aggregate properties by building test structures from the same stack. Such aggregate properties do not, however, allow the extraction of individual properties for the materials in the stack. It is these individual properties that are required for full simulation flexibility in order to perform design trade-offs and optimization. Methodologies that allow the extraction of individual material parameters from complex film stacks require the use of modeling to correlate results of test-structure simulation to measurements (Bart, 2002).

1.3.1 Constitutive Models

Constitutive models describe the basic material behavior and subgrid physics below the modeled scales. These models are based on fundamental material properties, as described above. Microsystems can introduce many unique constitutive model requirements as a result of their small scale. These challenges arise because of the large surface-to-volume (S/V) ratios of microsystems and because of non-continuum phenomena arising from their small scale. Large S/V ratios increase the dominance of surface forces. These include the following phenomena:

- Adhesion/stiction
- Friction/wear
- Surface tension and viscous forces
- Electrostatic charge
- Aerodynamic damping

Non-continuum phenomena occurs at a small scale, giving rise to the need for new classes of constitutive models. For example, where thermal conductivity was once required, scattering coefficients for phonons may now be required. These non-continuum phenomena arise when the fundamental scale of the relevant phenomena transport, e.g. the distance a phonon travels

between collisions, approaches the characteristic scale of the device being modeled. These non-continuum phenomena have been observed, at the microscale, for gas-dynamics, thermal transport and bulk material properties.

Accurate simulations of microsystem performance require that we characterize the dominant constitutive phenomena. Much of this work must be performed experimentally through carefully instrumented experiments that can characterize these phenomena as a function of critical parameters such as environmental conditions, surface morphology, and known material characteristics.

In current design practice, it has been found empirically that continuum assumptions hold in most cases for micron-scale devices. However, a full set of constitutive models is not available because, in many cases, the governing physics is not understood, or we do not have diagnostics with sufficiently high spatial and temporal fidelity. With continued increases in the performance of computers, work is ongoing in the area of constitutive model generation by performing simulations of atomic and molecular scale processes that can be used to generate constitutive models.

1.4 Package Simulation

Another important coupled interaction in MEMS devices is the interaction between the device and its package. This interaction often generates package requirements that are fundamentally different from typical integrated circuit (IC) package requirements. These requirements create packaging challenges that are far more complex than in typical IC packaging. Even for ICs, package design is a complex multidisciplinary job. It includes design of the package proper (or several layers of packaging), die-attach, and electrical interconnect both inside the package and from the package to the board level. This system must be designed not only to offer the proper interaction and protection from the environment, but also to have appropriate fatigue and reliability behavior. Physics based simulation, such as FEM analysis, can provide some basis for examining these behaviors and their effect on the IC. In the case of MEMS, such simulation becomes even more critical due to the increased modes of interaction and sensitivity of MEMS devices to their environment.

Areas of interaction that are common to both ICs and MEMS include electro-magnetic interference, heat generation, shock survivability, etc. Areas where MEMS are often much more sensitive than ICs are: package and thermal induced stresses, optical energy flux, shock and vibration transmission, hermeticity, material out-gassing, contact with dirty or corrosive atmospheres, etc. Typical failure mechanisms in microelectronic packaging include fatigue of interconnections, corrosion, metal migration, electromigration, thermomigration, current leakages, cyclic creep, etc. (Hannemann, 1994). In MEMS systems this list expands to include similar fatigue and shock induced failure of the MEMS components.

Because of these complex MEMS package-device interactions, the package can often require significant design effort and typically costs more than the MEMS component itself. Indeed, if the package-device interactions are not well understood, the device performance can be compromised or even fail completely. Therefore, it is very important that MEMS devices and their packages be co-designed in an environment where the package-device interactions can be simulated and understood (Bart, 1998). In addition, a single MEMS device can potentially be

repackaged for multiple applications. In this case, a way to quickly analyze the effects of different packages on the device is important.

In addition to the complex physical domains that are required to simulate package-device interactions, there are also modeling challenges. One fundamental problem is the large difference in the size scale between a MEMS device and its package. Any combined device-package Finite Element Method (FEM) model with resolution appropriate to accurately model the device will easily exceed practical computational resources. Even when such a “Brute Force” solution can be computed, the need for numerous simulations to explore the design space makes such combined models of limited use.

One method for overcoming mesh scaling incompatibilities is by sub-modeling. This is a method often used in FEM analysis that allows for an increase in resolution in specific regions of the structure. A related modeling technique has been demonstrated which allows extraction of parameterized behavioral package models (Bart, 2000). This approach allows for a separate analysis of the package and device. An appropriately meshed package model is simulated under the external influence of interest (e.g. temperature) and a parametric compact model is extracted. The package-induced effects on a device can then be simulated through the application of the package compact model to the device simulation. Not only does this method allow coupled simulations with appropriately scaled FEM models; it allows the creation of package model libraries that can be used in combination with new or existing device models. This can facilitate the increased use of off-the-shelf packages and the cost effective re-packaging of devices for multiple applications.

1.5 System Level Simulation

Much of the promise of MEMS comes from their ability to be integrated with signal conditioning circuitry into complex systems. To ensure proper functioning of such an integrated system, simulation and verification at the system-level is required. This can reduce the need for prototype fabrication and test iterations and significantly reduce time-to-market. Current state-of-the-art VLSI design environments benefit from several decades of evolution of system level tools for the rapid design and verification of integrated circuits. It is impractical to consider reconstructing such systems for MEMS. Rather, appropriate MEMS models must be integrated into these systems.

Performing full 3-D physical simulation within each time step of a typical system simulator (such as SABER, MATLAB, or SPICE) is prohibitively time-consuming and numerically impractical. Hence, in order to simulate the appropriate system level dynamic behavior efficiently, a reduced-order model or "Macro-model" of the MEMS subsystem must be obtained and employed in the system-level simulator. Such a system model typically has many fewer degrees of freedom than a FEM/BEM model of the device, and therefore the simulations require much less computation time, but can be less accurate.

Early MEMS designers used handcrafted models in their circuit level simulations (Bart, 1996). As micro-systems become more complex and the need for models with large numbers of coupled degrees-of-freedom (DOFs) increases, the use of automated tools for generating macro-models becomes increasingly important. Early macro-modeling techniques were rather limited (Fedder, 1996). More recently, commercial systems have started to appear.

Current systems employ two basic methods for macro-model construction (Romanowicz, 2000). The first method, sometimes called nodal analysis (NA), is similar to the method used in VLSI circuit simulators. It contains a library of MEMS elements that can be joined in a schematic capture tool. The MEMS elements encompass the behavior of the device and signals in multiple energy domains. Once a schematic exists, a multi-domain netlist can be extracted and simulations can be performed using an ODE network simulator such as Saber, Cadence Spectre, or Spice. Recently, the use of high-level hardware description languages (HDLs) like VHDL-AMS or Verilog-A, have gained popularity (Iyer, 2001; Romanowicz, 2000). The model elements can be as primitive as a beam segment or as complex as an entire functional device unit. Figure 4 shows the connection of individual elements to form a torsional mirror model. The underlying model can take many forms such as tables, analytical models, equivalent circuits, etc. and can be expressed in various languages. Analytic expressions are the most common, with geometric and material parameters that must be supplied by the user. This type of model cannot capture the full free-form geometric complexity that could be built. In addition, the underlying analytic models are often approximations. Thus, this type of modeling can have limited accuracy. However, it has the power of very quick simulation and ease of parameterization using physical parameters that correlate with the designer's intuition (Casinovi, 2001). Thus, it can provide a powerful iterative design tool. Also, the element libraries can be expanded and customized by users to more closely fit their device or accuracy needs (Clark, 2002).

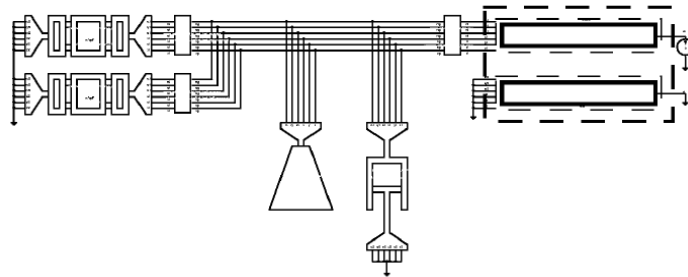


Figure 4. System Level Schematic of an Electrostatic Torsional Mirror (Coventor Inc.). The Model contains two Torsional Springs, a Moment of Inertia, a Damper, and an Electrostatic Transduction (gap).

Given a parameterized library of devices, optimization algorithms can be utilized to specify device geometries and process parameters given a set of system level constraints. An example is the automatic determination of the spring lengths, plate geometries and number of comb teeth in a resonator structure given the resonant frequency and area constraints. Multi-parameter, non-linear optimization is necessary. Optimization of MEMS devices is a challenge due to the multiple scales and strong non-linearities in the device behavior. As in most optimizations, avoidance of local minima is an issue. Technology exploration can also be done with optimization tools. Comparison of actuation methods can be quickly explored given a set of technology constraints. Statistical analysis can also be performed at the system level. Device parameters must be described with a statistical distribution and the system level behavior in response to parameter variation can be determined. Sensitivity analysis can be used to determine the parameters with the largest effect on system performance. MEMS vendors do not typically supply "Process Corners" as is done routinely in the VLSI world.

The second general macro-model construction mechanism is to construct a model based on a combination of automatic reduction and on curve fits of physical simulation (i.e. FEM) data (or experimental data if available) (Zaman, 1999). This mechanism can be quite time consuming to construct the model, but can yield very high accuracy (see Fig. 5). Such models are very useful for final verification. However, they are not easily parameterizable, so they are not well suited to early design iteration.

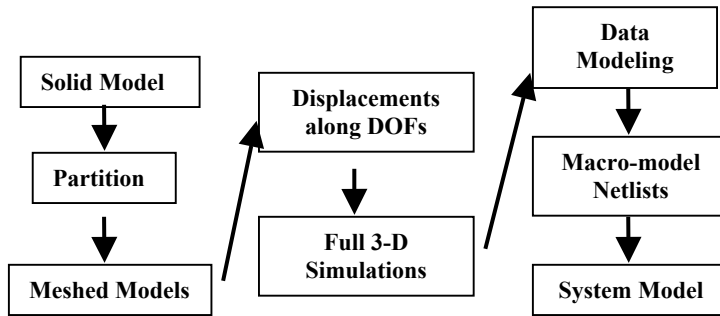


Figure 5. Basic Sequence for Constructing a Device Macro-model Based on Fitting of 3-D Simulation data.

In all reduced order macro-model generation there is the issue of how to decide which degrees of freedom to keep in a given model. The desire is to keep the minimum number that captures all the relevant dynamics. Unfortunately, there is no specific method for determining this other than sound engineering judgment.

1.6 Reliability

One area that has hindered the wider introduction of microsystems into commercial products is the lack of understanding and capabilities for predicting the lifetime and reliability of MEMS. Such predictive capabilities require detailed knowledge of how material properties age and how a component will perform off its design point for a wide variety of environmental situations. Currently, there are few physical models available for use by designers or CAD tool providers. Further fundamental scientific research will be required.

2.0 Verification and Validation

The area of CAD for MEMS that is least developed is design verification. Verification refers to the ability to verify that all of the models and design representations (i.e. layout, solid model, schematic, etc.) are correct and self-consistent. Similar to VLSI designs, MEMS designs can be large and complex. The opportunity for human error to escape notice in such a system is very large. Thus, the ability for MEMS to be produced cost effectively will increasingly depend on the ability of software verification to reduce errors that cause design iteration cycles in the fab.

An important verification issue is the checking of the design for violation of foundry design rules. Automatic design rule checkers test the design against rules such as spacing, overlap and

minimum width of structures. Some rules are context dependent and depend on the type of MEMS structure being designed. For example, there may be a minimum distance from the ground plane to the stator of a motor or the number and placement of etch holes on a plate that is to be released. MEMS CAD tools have made use of VLSI design rule checkers to perform such checks, but there have been problems with this approach. Because the VLSI checkers were created for mostly 90-degree angle designs, they are not very efficient and accurate at checking MEMS designs, which are highly curvilinear. The VLSI checkers often report false errors at curved segments. New algorithms and methods have been applied as modifications to the basic checker by several researchers to address these issues.

Simple verification techniques such as testing for appropriate symmetry and for correct electrical connection have been examined (Zaman, 1999). More complex functions such as correlation of a layout to a mechanical schematic have been postulated. In VLSI systems a netlist describing the devices used and their interconnections can be derived from the physical layout. This is possible because rules for recognizing the primitive devices from mask objects have been created for the commonly used devices; transistors, capacitors, resistors and inductors. MEMS offer a much richer set of primitives and so far no robust recognition algorithms have been put forth. Researchers have made progress for a class of inertial devices, but commercial extractors have had to rely on a different approach. This approach treats the MEMS device as a black box where the connections to other devices may be extracted but the device itself must be specified by hand. Layout versus schematic checks have also been extended to MEMS, where the comparison is made for multi-domain netlists. In addition to the intended devices created in the layout, extractors can be used to represent elements forming parasitic devices present in the layout. For example, in electrical layouts unwanted capacitances, resistances and inductances are often present. In MEMS these parasitic elements must be generalized to multiple domains. System simulation must be run on the netlist with parasitics to verify any changes in system function due to the presence of these parasitics.

Validation is fundamentally an experimental process used to confirm the accuracy of the computational model and technique in representing the real phenomena. As such, measurements of sufficient temporal and spatial fidelity are required. Validation requirements become very stringent for modeling and simulation capabilities when used to qualify the performance of a microsystem.

Validation is required at all levels of the CAD environment. The individual submodels or constitutive models within a simulation capability must be validated. The simulators and their coupled-physics interaction must be validated. In addition, the solid-model representation, mesh, boundary or environmental conditions, and initial state or conditions must all be validated for each application. Finally, the integrated model consisting of all of the above in conjunction with the representation of the conservation equations that are used to simulate the problem of interest must be validated.

3.0 The Evolution of MEMS CAD

A new generation of design tools that combine aspects of electronic design automation (EDA) with the mechanical, thermal, and fluidic computer-aided design (CAD) is envisioned for the future. The development of an integrated EDA/CAD solution for MEMS structures, offering a continuous top-to-bottom design flow, would bring the benefits of MEMS to the entire design industry. The use of the right design methodology will greatly enhance reusability and efficiency

while reducing cost and risk, still considered the main barriers to wider introduction of these technologies in many applications.

The focus in CAD for complex MEMS design in the future will be on 1) sensitivity analysis and validation, 2) mechanical modeling extensions, 3) computational advances, 4) user-interface and layout improvements, 5) design synthesis and optimization, and 6) distributed computation. The following sections examine the future outlook for some of these areas.

3.1 Electronic Design Automation (EDA)

The implementation of EDA for MEMS design is dependent on the successful integration of the workflows of the system engineer and the component engineer. The system engineer is accountable for schematic capture, simulation, layout, design-rule checking, etching verification, and cross-section viewing. The component engineer provides finite element modeling (FEM), which may be translated to an analog HDL model to enable validation of full system functionality, and libraries at various levels that are tied to the schematic driven layout feature of the system engineer (Karam, 1998). Most important for the successful integration of MEMS will be the seamless integration of MEMS design tools with IC design tools so that product development, from concept to output of files for mask making, can occur in an integrated manner.

An important issue for the future is the interoperability of CAD tools and standards for data exchange. Lack of standards has and will continue to hamper the adoption of CAD tools. Lack of standard fabrication processes, which in the short term allows MEMS foundries to provide added value, makes it difficult for system designers and fabless design houses to utilize MEMS quickly and efficiently. This is also true for MEMS CAD vendors who must spread their resources very thinly. This lack of standardization also makes the creation of design kits difficult. In the integrated circuit industry, model parameters are exchanged in a standard fashion. Making progress in this area will require the collaboration of foundries, CAD tool vendors and users. Because MEMS is still the domain of experts and involves the collaboration of a large multidisciplinary team, there is no standard design or work flow. Unlike the top-down design flow found in the design of large digital systems, MEMS design is more like a spiral where requirements are iterated between package, MEMS, and electronics designers. Design might begin with innovation at the process, device or system level and hence the CAD tool must be flexible enough to handle multiple entry points and design flows. Because of the variety of MEMS devices, the lack of standardization, and the value added in the details of the device design, system designers cannot currently take advantage of predefined, characterized libraries as is done in digital design. This state of affairs allows for richness in device design, but makes it hard for system designers to innovate, as they must possess considerable device specific knowledge. As a consequence, many library elements provided in current MEMS CAD environments are more akin to examples than true fully parameterized general design elements.

3.2 Platforms and Distributed Computation Models

Contemporary MEMS design problems often embody significant levels of complexity that make it unwieldy for a single designer to work alone. The continuing growth of knowledge and supporting information and ever increasing complexity of design problems has led to increasing specialization. Wide-area networks and the Internet-based WWW allow work in distributed

teams with remote design servers. MEMS CAD systems running on these design servers could support a large-scale group of users/designers. Users would not need special hardware or software to consult these services. Thus, multiple users/designers in different locations would be able to use the same CAD tool and design a MEMS device or system together. With the advent of the Internet and WWW, it is expected that one of the focal research areas in the MEMS design community will be on the development of a WWW-based design framework/platform for collaborative MEMS design (Zha, 2002). An Internet-based simulation environment using a browser-based client and a back-end server is expected to be used by the MEMS design industry by 2007 (Wilson, 2000).

With the continued evolution of high-speed networking, object oriented programming and high performance computing, it is anticipated that interactive, distributed design infrastructures will become more prevalent. Within this infrastructure, component design, manufacturing process design, and optimization of design and process will occur concurrently across multiple platforms driven by a designer at his desktop. These complex distributed simulation tools will share a common interface permitting interoperability of modules and allowing rapid implementation of new and enhanced design and manufacturing modules. This capability will dramatically reduce the design cycle time for new microscale components.

4.0 The MEMS CAD Market

When trying to project the potential size of the CAD for MEMS market, an analogy with the VLSI CAD market is often cited. Here a rule of thumb that is often used is that the market for VLSI CAD tools is on the order of a few percent of the semiconductor market. There are two difficulties in using this type of model for MEMS. First, the MEMS market is not a mature market. The majority of companies that are designing MEMS do not have a current MEMS product. Thus, the majority of design work might be classified as R&D as opposed to product design. As a consequence of this immaturity, most companies have only a small number of designers and can often only justify one or two seats of a complex and expensive software product.

The second problem is that the size of the MEMS market is not easily quantifiable. Many market studies have been produced over the last several years that show widely varying market sizes. One reason for these differences is differing assumptions about how much of the final system to count. Studies that wish to predict the overall effect of MEMS tend to count the value of the full systems that use MEMS. On the other hand, if one is interested in understanding the ability of the market to support a MEMS CAD industry, it is more appropriate to look only at the value of the MEMS chips themselves. These values can be tens or hundreds of times smaller than the value of the entire system.

The costs of developing a sophisticated CAD environment for MEMS are on the same order as those required for other sophisticated VLSI or mechanical CAD systems. The key to the profitability of such systems is the ability to amortize this large development cost over a large base of installed seats. At the current moment, it is estimated that there are fewer than 1000 commercial MEMS designers in the world. This is a small market over which to amortize the significant development costs. (The academic market would represent a significant increase in the number of designers, but academic software licenses are typically steeply discounted, so this does not represent a significantly increased revenue source.) This is especially true if this market must be shared among competitive products. The consequence of this small market is that the

tools must be expensive, but at the same time, the profit margins that they provide are small. Also, the cost of sales is high because of the need for highly trained applications engineers and because the large effort expended on each customer represents the sale of only one or two seats. It is difficult to judge the current state of profitability of MEMS CAD tool vendors because, to date, no company has reported profitability from MEMS CAD tool sales alone.

Given the complex tool requirements, the small market size, and the high cost of sales, what is the future outlook for MEMS CAD environments? The main hope espoused by practitioners over the years has been that the MEMS industry will grow large enough to support independent MEMS CAD companies. At the same time, these CAD design environments for MEMS are enabling the growth of the MEMS market. The availability of good CAD tools allows greater use of MEMS in systems, which, in turn, supports more tool purchases. However, this feedback can have an accelerating or a decelerating effect on growth. Although it is impossible to know how large the market will grow, it is clear that the evolution of the MEMS market has been slow over the past 15 years and shows no dramatic signs of accelerating at this time. The question is, can the MEMS CAD tool providers support the development of their tools for long enough to allow the MEMS device market to grow big enough to support them?

Another evolution for MEMS CAD would be absorption into more mainstream VLSI or mechanical design packages. This would allow improved integration and a reduction of development effort by using already developed tools. In fact, this is just an extension of what is done now, where MEMS CAD environments use many 3rd party tools that would be too expensive to produce internally. More importantly, it would provide a financial reservoir from which to continue the development while waiting for the MEMS market to grow larger.

5.0 Conclusion

MEMS design is a complex, interdisciplinary job. It requires sophisticated CAD tools to simulate the interactions of the various physical domains. Considerable progress has been made in developing such tools. However, more development is required before the average design engineer can successfully use these tools. In order to reduce the required sophistication of the MEMS designer, CAD for MEMS systems will need to continue to move more toward system level tools that can be successfully used by system designers and not require MEMS experts. This will require increasing integration with commercial simulation tools. Further, verification tools will need to evolve significantly to find errors that are inevitable in such complex systems. If simulation is to have impact in both design and qualification of microsystems, our scientific understanding, as manifest in constitutive models and physical representations, must continue to improve. In addition, we must develop the necessary experiments and diagnostics to validate all phases of our models, from constitutive models, initial and boundary conditions to fully integrated multi-physics capabilities. This includes the development of “Standard” metrology methods.

At this time it is unclear how the MEMS CAD industry will evolve. Figure 6 postulates one possible timeline. What is clear is that without CAD tools to support a more standard (and simple) design flow, MEMS design will remain in the realm of Ph.D. level engineers and this will suppress its growth into a mainstream technology.

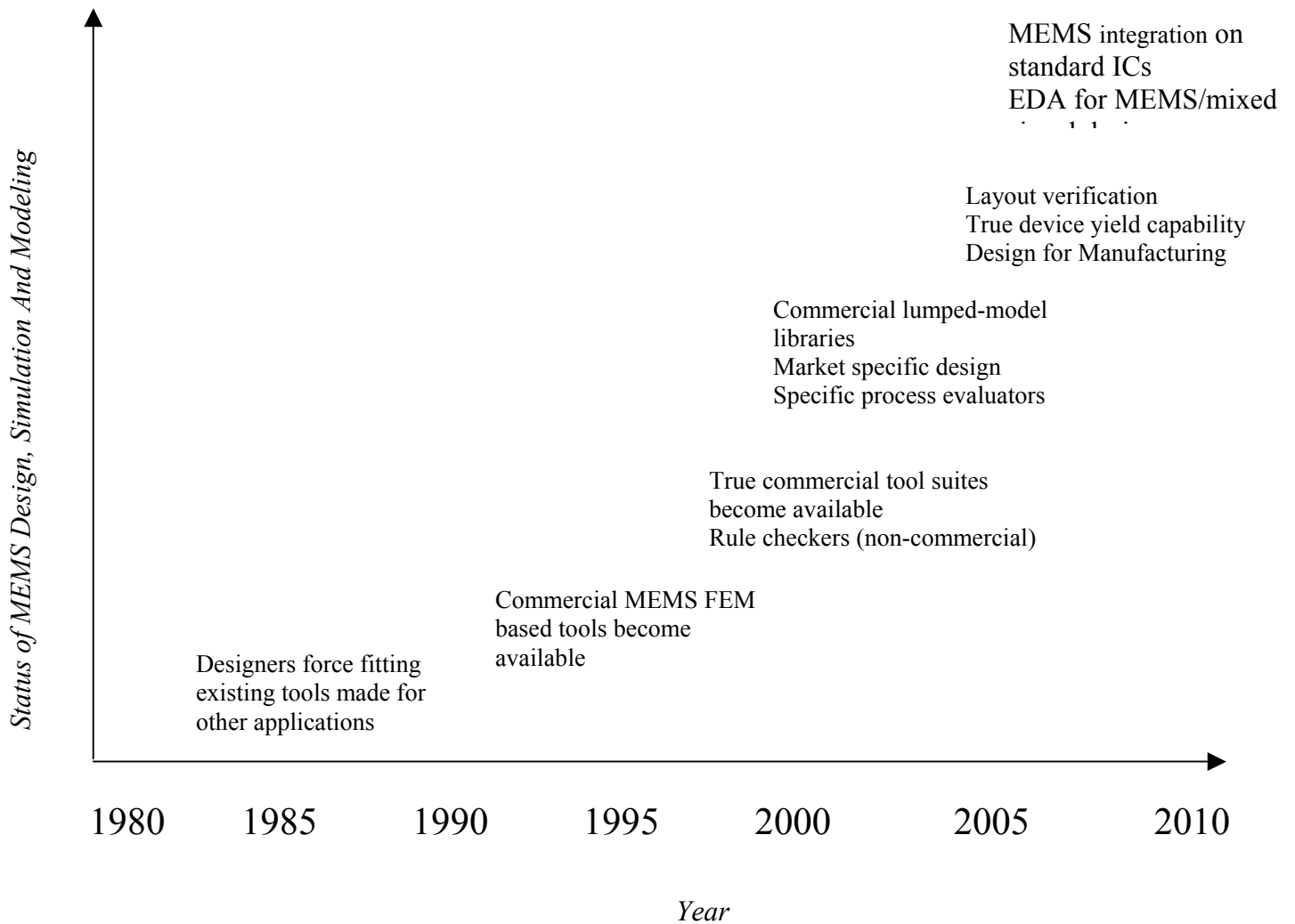


Figure 6. A MEMS Design, Simulation and Modeling Timeline

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