INCORPORATING CAD FOR MEMS TOOLS INTO THE ACADEMIC ENVIRONMENT

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ABSTRACT

Preparing engineers to work in industries such as telecommunications, biomedical, instrumentation, or aerospace necessarily involves the teaching of MEMS (Micro-ElectroMechanical Systems) technology. Through the use of CAD for MEMS tools, universities are able to teach concepts which could not be studied in traditional software packages. Such concepts include the MEMS fabrication process flow, anisotropic etching behavior, process dependence on material properties, and the coupling of electrostatic and mechanical device behavior. Software allows students to simulate and virtually prototype devices before entering into expensive and time intensive fabrication. These simulation capabilities give them the freedom to develop devices quickly within a digital environment and enable the teaching of more MEMS concepts than is typically feasible solely with fabricated devices.

This paper presents examples of classroom activities utilizing CAD tools for MEMS. Also presented are examples of the benefits of CAD tools for MEMS as communication platforms in research partnerships between universities and industry.

INTRODUCTION

Historically, CAD tools for MEMS were complicated and difficult to learn because they integrated existing traditional commercial code as core building blocks [1]. This approach required students to learn the GUI and capabilities of a handful of different tools. As the CAD tool industry has matured, self-consistent CAD tools for MEMS have been developed which have rapidly increased the learning curve, making them viable for academic use.

Due to increased ease of use, CAD tools for MEMS have become a valuable part of the academic environment. To be valuable, however, the incorporation of such tools must be undertaken carefully. Each aspect of the academic environment, coursework and research, requires a variety of elements to facilitate this integration.

Used as part of a course, a CAD tool must be easy to learn, as the time spent learning the program necessarily reduces the students' productivity. In addition, the CAD provider must train the professor and student staff in the use of the tool. MEMS engineers must also frequently support academic institutions in the preparation of classroom exercises, homework problems, and design projects. Finally, having customer support available for students can lessen the burden on the faculty and contribute to an overall positive experience.

University research groups require similar but slightly different resources to maximize the benefit from a CAD tool for MEMS. Again, as with all software programs, ease of use and access to training enable students to maximize the time spent pursuing their research. Also, readily available customer support alleviates down-time and can introduce new concepts to students. A key element in the support of research groups, though, is access to the many publication opportunities offered to commercial companies. Whether authored solely by the academic institution or in partnership with a commercial company, these joint efforts publicize both the commercial company and the work being done at the university.

A COMPLETE PACKAGE

In academia, MEMS research typically has been dominated by electrical and mechanical engineering departments [2]. Currently, more and more universities are opting for a multi-disciplinary approach to MEMS teaching by incorporating mechanical, electrical, materials, process, and industry applications personnel from throughout the university. An optimal CAD tool for MEMS must address all of these elements. In addition, the software becomes most valuable to universities if it can incorporate all aspects of MEMS design – mask layout, process simulation, and device analysis – while remaining within academic pricing constraints.

Example 1.

Figure 1 shows a yaw-rate sensor developed by students at the University of Windsor, Canada. The mask layout was generated in IntelliSuite™. A process table was also generated in the CAD package, utilizing the available process step database. From the mask layouts and process table, a three-dimensional model was created automatically. Finally, this model was analyzed to optimize and validate the design. This work was done prior to any device fabrication, saving time and money on prototyping.

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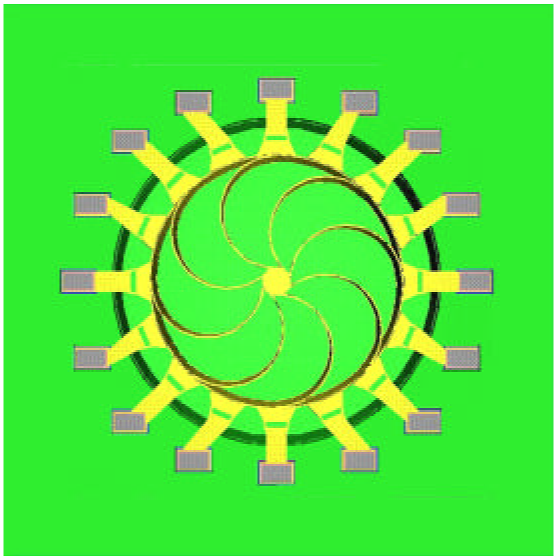

Figure 1 Yaw-rate sensor in the IntelliSuite™ design environment, developed at the University of Windsor, Canada

MASK LAYOUT

Creating the two-dimensional mask layout is the first step in device design. Masks, in conjunction with fabrication deposition and etching processes, will define the three-dimensional geometry of the structure. A variety of mask layout software packages, MEMS specific or otherwise, are available (AutoCAD® [4], L-Edit Pro™ [5], Virtuoso Layout Editor [6], IntelliSuite™ Mask Layout). Standard features include the ability to construct a variety of mask component shapes, to efficiently manipulate those shapes, and to create multi-level mask files. An important feature is the ability to transfer the mask data to fabrication simulation, device analysis, and mask vendors using standard file formats such as GDSII, CIF, and DXF.

GDSII is a standard electrical design file format, CIF is an academic file format, and DXF is a standard mechanical design file format. By providing translation to each of these standard formats, a CAD package enables communications between MEMS personnel with mechanical and electrical backgrounds.

PROCESS SIMULATION

Device physics analysis is at the core of any CAD tool for MEMS, but it is process simulation capabilities that set these tools apart from standard FEA tools. Process simulation can be defined to include everything up to device physics analysis: fabrication simulation, virtual prototyping, and design communication.

Fabrication Simulation

Three components are at the core of fabrication simulation: a process database, a thin film material database, and standard foundry templates.

Process Database.

Process databases include standard process steps which may exist at any fabrication facility, such as material deposition, wet and dry etching, wafer bonding, and mask definition steps. A sequence of these steps, along with the mask geometries, is used to generate a three-dimensional structure for analysis. These databases can also be customized to include unique or proprietary processes performed for a particular company or at a particular fabrication facility. In the case of academia, they can be limited to include only those process steps available to students.

Each process step typically includes the machine parameters (pressure and temperature of deposition, doping concentration, gas partial pressures, etch time, etc.) and any required data, including material properties and mask layouts. The structure generated from these process steps is limited in accuracy by the accuracy of the available process data. Conformal deposition and process-induced effects are captured in the development of a three-dimensional structure. An example of conformal deposition is shown in Figure 2 where the suspended structure's topology is made up of a number of steps. Examples of process-induced effects include curvature or a change in natural frequency resulting from internal stresses in a material layer.

Thin Film Material Database.

Thin-film material databases give students ready access to material properties, such as Young's modulus, Poisson's ratio, dielectric constant, intrinsic stress, etc. Thin-film material properties differ from bulk material properties and are often difficult to find. Unlike bulk material properties, thin-film material properties vary significantly as a function of fabrication machine settings. This difference makes it important for students to understand the nature of these properties and incorporate the correct values in their designs. Because of their size, MEMS structures can be more sensitive to incorrect material property values than macro-structures. The use of bulk or otherwise incorrect material property data can produce results which have little relevance to actual results, no matter how accurate the numerical simulation model is.

Standard Foundry Templates.

Standard foundry templates assist students in the design of devices for fabrication at any of the facilities available for university prototyping. These templates, or design kits, are available either standard or via separate purchase from the CAD provider. They consist of a pre-constructed process sequence and require only the mask layouts as input.

Fixed process flows include Standard MEMS's, IntelliSense's, Sandia's SUMMiT, and Cronos' MUMPs processes, for example. Cronos' MUMPs process is very popular for university prototyping, because of low cost, low volume, and regularly scheduled fabrication runs. By providing standard process templates, CAD tools facilitate quick simulation, even for students who may not yet be as familiar with processing technology.

In addition, the relatively lengthy turnaround time for fabrication typically results in only one run per semester, or a maximum of three during the year if run in succession. For research groups, the time and number of fabrication runs required before a working device is created can be significantly reduced by utilizing CAD tools for MEMS to optimize designs prior to the first fabrication run.

Example 2.

Figure 2 shows the IntelliSuite™ simulation model of an RF switch developed at Stanford University [7]. The switch was developed using the MUMPs foundry template [8] with the analysis results used to characterize material properties. The steps in the beam are generated as a result of the emulation of conformal deposition.

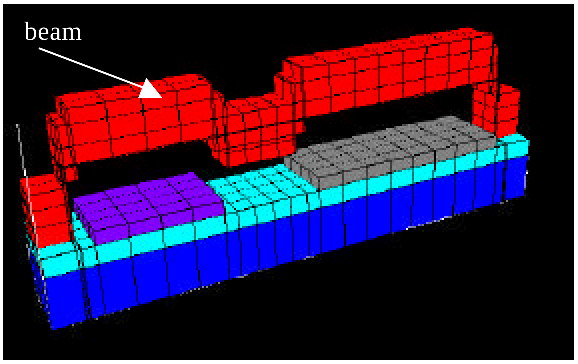

Figure 2 RF switch developed at Stanford University [7] using the MUMPs foundry template showing conformal deposition

Virtual Prototyping

Unlike traditional macro-world mechanical devices and components, the design and functionality of a MEMS device is directly and significantly impacted by the way in which the device is fabricated, i.e. the process sequence which is used. Thus, for MEMS design, it is essential to consider fabrication effects. These can include residual stresses in material layers, changed material properties from doping or other processes, lack of corner compensation mask features, or process non-idealities.

Once a process flow is generated from a process database or via the use of a standard template, virtual prototyping is of great benefit to students. This capability enables students to visualize the device at each step of the fabrication process. Here they can modify the process and/or geometry and see the effect of the modification without multiple fabrication runs. Process tolerances and mask compatibility can also be studied in detail in the digital environment.

Example 3.

Figure 3 shows virtual prototyping of an electro-thermal actuator from the University of California, Berkeley within the IntelliSuite™ design environment. The actuator was developed using the MUMPs process. From the top down are two early intermediate steps, a later intermediate step, and the final structure.

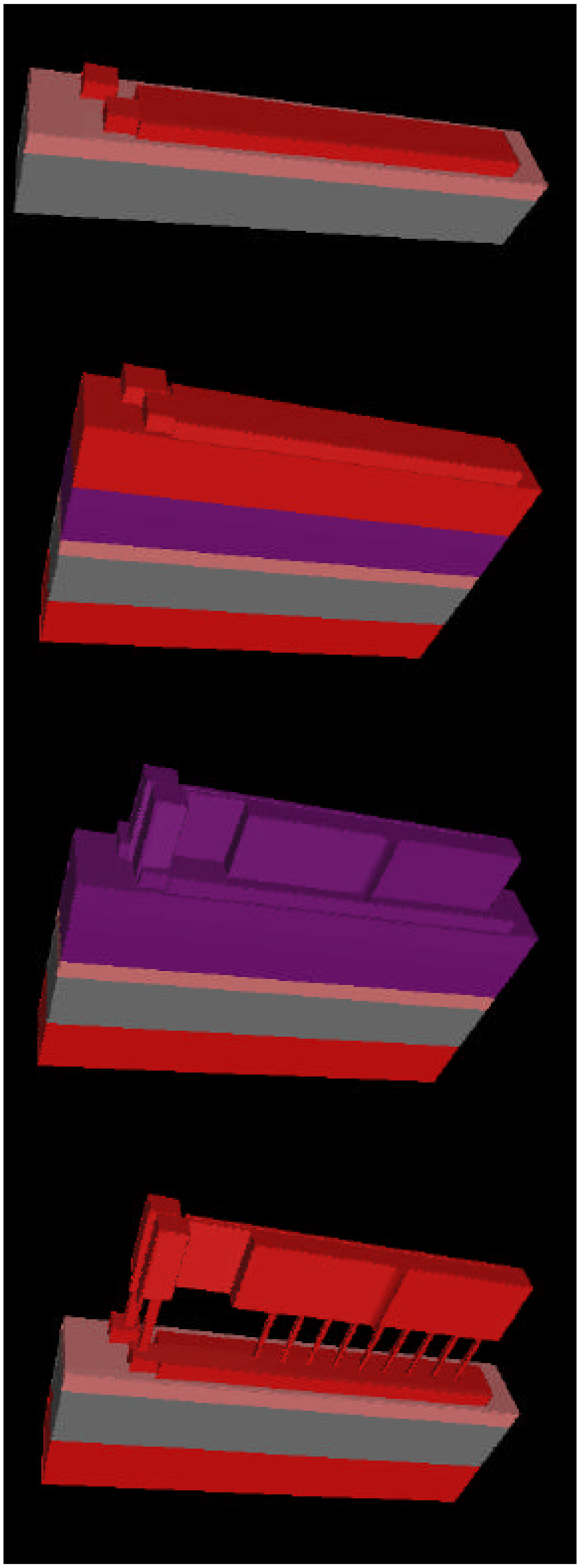

Figure 3 Process steps for the University of California, Berkeley's electro-thermal actuator

Example 4.

Figures 4 and 5 illustrate a silicon anisotropic etch simulation in which corner compensation and mask compatibility is studied. Starting with the top structure's upper right corner compensation feature and proceeding counter-clockwise, the length of the feature is increased. The lower structure in Figure 4 illustrates corner compensation features which are the same length as the corresponding feature on the top structure, but wider. Figure 5 shows the 3D result of the etched silicon using the mask in Figure 4. One can see that the two uncompensated corners (lower right) are etched until rounded, while the largest corner compensation feature (bottom structure, lower left feature) protects and leaves a square corner. The remaining corners are etched based on the size of the associated corner compensation feature.

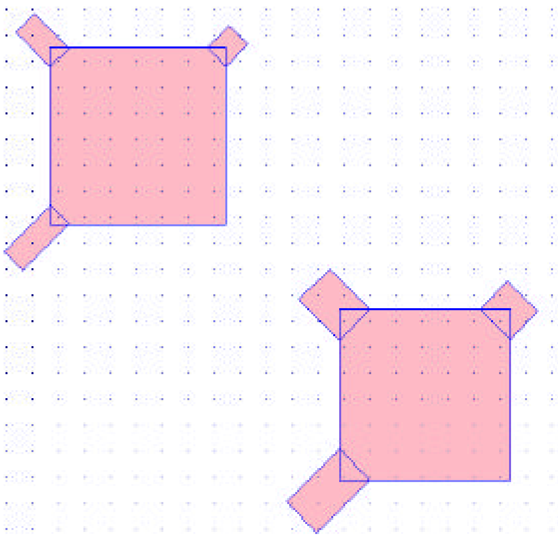

Figure 4 Mask layout showing corner compensation features

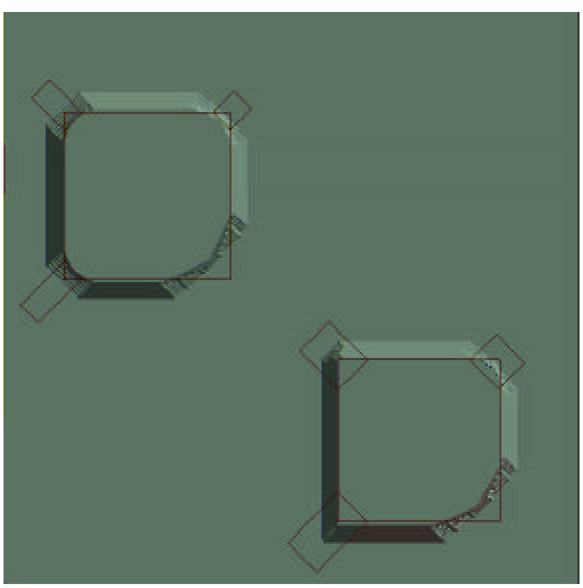

Figure 5 AnisE® corner compensation simulation results showing the final etched silicon

By enabling students to study anisotropic etching in the virtual environment, AnisE® gives future fabrication engineers intuition about bulk silicon etching that they would not otherwise gain without numerous, time consuming and costly fabrication runs.

Design Communication

The ability to rapidly exchange design files among different collaborative research groups is essential for efficient device design. The process table can also be used as an instrument of communication between such design teams. A single file, consisting of process steps and mask layouts, can be transferred between groups for the development of specific aspects or consultation on designs. This can be particularly useful for university groups developing designs for corporations. Using such a communications platform, the students can perform the primary design activities and easily receive guidance from the company's MEMS engineers.

DEVICE ANALYSIS

As discussed above, the core of any CAD tool for MEMS is its performance analysis capabilities. While some device analysis can be performed within the context of a standard FEA tool, CAD tools for use in MEMS design should also include coupled thermo-electro-mechanical, fluidic, and electromagnetic analysis capabilities, as these solvers are needed for today's MEMS designs.

There are two device analysis aspects of CAD tools for MEMS which distinguish them from standard FEA tools. One is the coupling of non-mechanical (e.g. electrostatic, electromagnetic, or fluidic) and mechanical solvers. While some passive MEMS devices do exist, most include multi-physics aspects which necessitate coupled solvers to accurately account for the interplay between the effects. The second aspect is mesh generation from the process sequence in conjunction with the ability to later independently refine the electrostatic and mechanical meshes.

Once masks and a fabrication sequence are defined, CAD tools for MEMS should generate a three-dimensional structure for analysis. Typically, this consists of the automatic generation of a coarse finite element mesh. This finite element mesh also defines the default electrostatic mesh. This can be of great assistance to students by eliminating the need to draw each element and create a compatible finite element mesh.

Example 5.

Figures 6 and 7 show a thermally actuated beam developed at Texas Christian University [9]. The switch was modeled in IntelliSuite™ using the MUMPs foundry template [8]. Figure 6 shows the solid model, while Figure 7 shows the coarse mesh which was automatically generated by the CAD tool for MEMS.

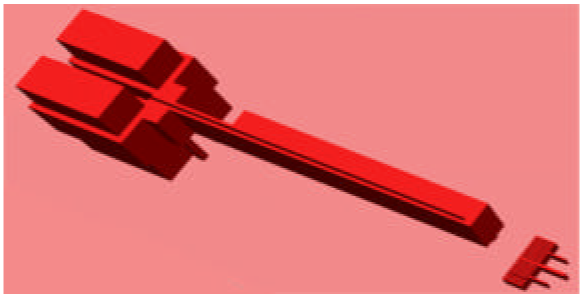

Figure 6 Solid model of a thermally actuated beam developed at Texas Christian University [8]

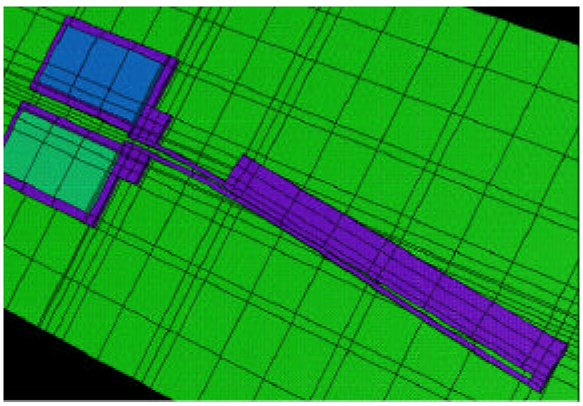

Figure 7 IntelliSuite™ simulation of TCU's thermally actuated beam showing the generated coarse mesh [8]

Inside an analysis module, the finite element and electrostatic meshes can be independently refined in areas of interest [10]. Typically, the finite element mesh is refined in areas of high mechanical deformation while the electrostatic mesh is refined in areas of high electrostatic charge. This interactive mesh refinement can be used to illustrate the areas of mechanical and electrostatic significance in the structure. This method also enables students who have mastered these concepts to analyze larger and more complex structures.

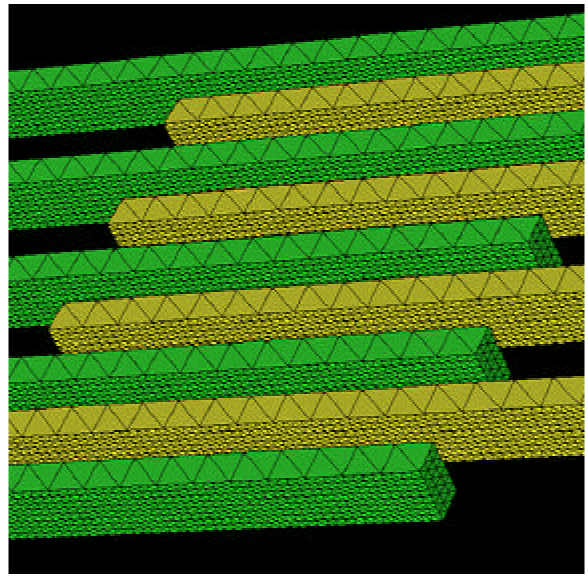

Figure 8 Independent refinement of the electrostatic mesh on comb drive fingers

Example 6.

Figure 9, a gripper developed for a Senior Project at San Jose State University [11], shows a structure that benefits from independent mesh refinement. Mechanical mesh refinement is performed along the beam supports while electrostatic mesh refinement is performed on the comb fingers.

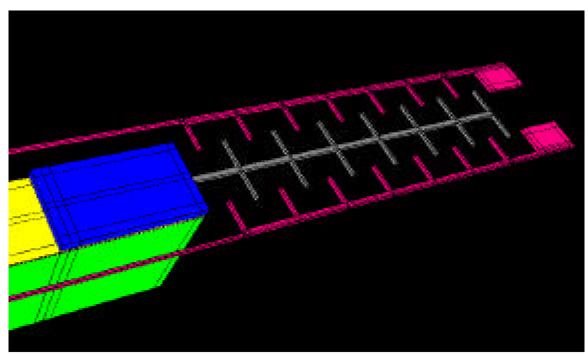

Figure 9 MEMS gripper developed in IntelliSuite™ at San Jose State University [11] illustrating areas of necessary mechanical mesh refinement

Students must also determine, through convergence studies, the number of iterations required for a particular device and the degree of mesh refinement necessary to produce accurate results. For structures requiring coupled analysis, mesh refinement studies are best done when independent mesh refinement is available. In contrast to MEMS design tools, macro-scale design tools which do not simulate non-mechanical behavior usually do not consider this type of iterative convergence accuracy.

Example 7.

Figure 10 shows the analysis results from a micro-flapper valve from Oregon State University's IE 506 Term Project [12]. The valve allows fluid flow in one direction and restricts the flow in the opposite direction. Unique for a MEMS device, it is made of stainless steel, fabricated using an ESI 4420 laser micro-machining system. The figure shows the sample valve created as an example for use during the student design projects.

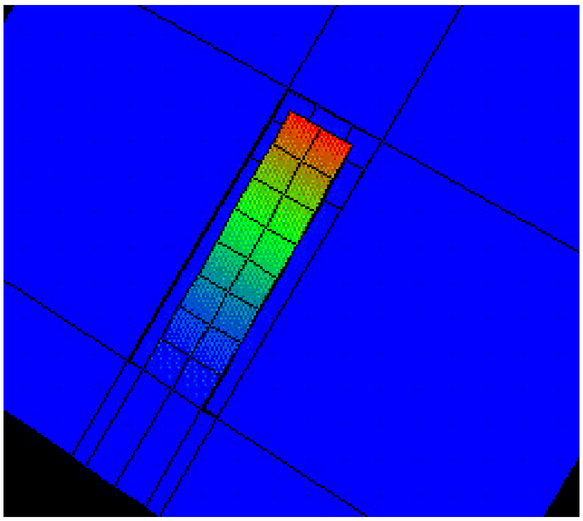

Figure 10 Micro-flapper valve from Oregon State University, showing displacement resulting from fluidic pressure loads

Many universities have standard FEA tools in-house which students have learned to use. When such tools pre-exist at a university, three concerns about CAD tools for MEMS must be overcome if the university is to maximize the benefits from a CAD for MEMS tool. First, the cost of a new tool must remain feasible for universities. Second, the new tool should be able to work with the existing tools so that students' current designs can be easily transitioned into the new design environment. Finally, the new tool must be easy to learn and use, or students will return to using what they already know, even at the cost of MEMS specific functionality.

CONCLUSION

CAD tools for MEMS can be a valuable addition to a university MEMS program, but only if certain criteria are met. These include low cost, access to training, ease of use, support from the provider, and added benefit over existing software at the academic institution. The value of a software tool is also determined by the quantity and quality of the included features. CAD tools for MEMS can add this value by providing a complete solution, keeping academic constraints in mind.

CAD for MEMS tools enable students to learn concepts faster by reducing the need for time consuming and expensive fabrication runs. Virtual prototyping and other fabrication simulation aspects teach Microfabrication techniques, while analysis and optimization capabilities increase the likelihood of fabricating working devices.

To be a valuable addition to industry, students must learn about MEMS specific phenomena. This includes the design details, such as process induced effects or corner compensation, as well as design approaches, such as interactive mesh refinement and process tolerance studies. By allowing students to study such phenomenon outside of the laboratory, CAD tools for MEMS are a valuable asset to and a necessary feature of university MEMS programs.

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