# Utilizing Existing TCAD Simulation Tools To Create Solid Models for the Simulation Based Design of MEMS Devices

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**This paper gives an overview of MEMS simulation and the computational requirements in the field from the prospective of creating realistic geometry based on process simulation. We motivate the needs for such geometry, and discuss in detail one approach to create pseudo 3-D geometry from 2-D process simulation. Three different methods to perform booleans critical to the pseudo-3D technique are discussed in detail.**

## Introduction

Micro-Electro-Mechanical Systems (MEMS) offer dramatic new functional capabilities. Analysis of MEMS is a challenge; the structures are geometrically complicated, electro-mechanically coupled, and inherently three-dimensional. The multi-domain physics for MEMS includes: electrical, mechanical, and fluidic interactions. Effects of each domain need to be accurately simulated to correctly predict device performance. In addition, IC-based fabrication techniques require the modeling of complex material behavior and processing such as etching, deposition, and thermal processes such as diffusion (and oxidation).

Two quite different modeling methodologies are being pursued among the MEMS community. The "homogeneous" approach is to develop tightly integrated component simulation tools and design methodology. Alternatively, a "heterogeneous" approach is one that wraps distinctly different end-user software packages to create a "meta" tool. The MEMCAD system is one well known example that uses commercial and other academic tools (ABAQUS, IDEAS, and Fastcap).

Currently available heterogeneous implementations have limitations especially in the area of creating and utilizing complex geometry. A geometry server is demonstrated, based on a solid modeler (Shapes), that permits the efficient integration of process simulation results into a portable geometric model. The incorporation of *hp*-adaptivity is critical for analysis of many components. The present work demonstrates simulations where complex geometry is used in an environment that provides sophisticated anisotropic *hp*-adaptivity (ProPHLEX).

## Previous utilization of Solid Modeling in TCAD

There have been efforts in the past to use solid modeling for VLSI applications (Wang, 96)(Yu, 95). These methods rely on the user providing simulation results, sweeping options, and process flow information. The major difference between the approach described in this paper and the other efforts is that the process simulation is run automatically for the user. In addition to being run automatically, the process simulation input is actually generated from the geometry as the model is being built. The goal is to automate the process.

## Geometry Modeling Support

Robust 3-D process simulators do not currently exist to model deposition and etching. A new pseudo 3-D physical process simulation approach is demonstrated which is fully integrated with traditional geometric capabilities. The technique used to create 3-D physical geometry consists of five major steps (see Figs. 1-10):

1) Create an initial geometry.

2) Cut the geometry into "slices" in the x and y planes.

3) Perform 2-D physical simulation on the "slices" using SPEEDIE .

4) For the results in each direction, create a solid.

5) A boolean addition (union) of the solids from the cuts in both directions is then performed to generate the final 3-D profile.

The resulting profile is incorporated into the solid model, and can be manipulated in subsequent steps by geometric operations and additional physical depositions. The RF switch shown (Fig. 10) was created using this technique. The entire device was created by the user defining only the mask specification (.CIF file) and a simple process flow. One physical deposition step was performed in conjunction with multiple geometric etches to achieve the final shape. Notice the rounded corners on the top of the switch due to the physical process simulation, while the sharp edges are the result of geometric etching.

## Challenges in Unioning Objects in the Solid Modeler

An unexpected difficulty in turning the conceptual approach detailed above into a working code was step 5 of unioning the resulting solid from the cuts in the “x” and the cuts in the “y”. In the end, three different techniques were attempted. First, the use non-rational b-splines (NURBS) was investigated. Second, a special geometric definition referred to as a “web geometry” was used. Finally, we utilized a B-rep triangulized surface representation. Each of these techniques had distinct advantages and disadvantages, but in the end robustness issues made the only viable choice the B-rep triangulized surface representation.

**NURBS**

The main advantage of using the union of the two NURBS is that it yields a smoothing of the intersection of x plane and y plane simulations. This topological smoothing of the 3-D effects is the best that can be achieved without full 3-D simulation. Major computational cost savings is thereby achieved. The drawback with using NURBS is that the union of the NURBS is a complex intersection problem, which the solid modeler being used cannot handle in a robust fashion. For more details on the use of NURBS, see (Wilson, 98).

**“Web” Geometries**

Traditional geometric modeling systems have focused on modeling and manipulating smooth objects of the kinds used in industrial design and manufacturing applications. However, numerous application areas exist where solid modeling manipulation is needed for discrete data sets such as motion simulation, GeoPhysical modeling, and bio-medical modeling. In an effort to address these applications, one solid modeling package has developed a special data structure to handle the applications which they refer to as “web” geometries (Shapes). For example, recent work has demonstrated the usefulness of “web” geometries in the field of vascular modeling (Taylor, 96).

A “web” is conceptually defined by a set of patches sewn together in a mesh structure. In this application, it can also be thought of as a closed surface mesh defining a solid region. An important requirement of the web structure is the property of coherence between adjacent patches - also referred to as patch coherence. This implies that patches can only intersect at the corners or along a complete edge. The requirement of coherence is also required by most forms of analysis such as finite-element analysis. It is coherence that significantly increases the computational efficiency of the web structure over the data structure described below.

Unfortunately, current implementations of web geometries in the solid modeling package cannot handle the complex union operations needed for the pseudo-3D technique outlined in this paper. This currently rules out the use of web geometries, but software improvements may lead to their use in the future.

**Boundary Representation of a Solid**

SHAPES represents all geometric objects using a representation known in the solid modeling community as a Boundary Representation (B-rep). In a B-rep, you define objects as regions on underlying curves or surfaces enclosed by specified boundaries. An example would be a rectangular plane which can be represented by an infinite plane and a series of four line segments which bound the plane. For the current purpose, if one defines a complete closed boundary using a surface mesh, then this can be used as the boundary of an infinite 3-space to represent a solid.

It is important to note that coherence is not required when using this method to represent a solid, only that the surfaces used as the boundary do actually close the region. This has two important implications. First, the boundary can be described in a more general way. Second, it is in turn more computationally expense than a “web” geometry to calculate intersections and boolean operations.

In a sense, this method represents the lowest level representation of a solid geometry permissible in commercial B-rep solid modeling kernels. It appears to be very robust. The images of the RF switch given in this paper were created using the B-rep technique. The drawback to the current implementation is that it is computational expense. To give ballpark time estimates, the B-rep representation can require hours to create a solid while “web” geometries time is on the order of minutes for a solid defined by several thousand surface panels.

**Challenges in Geometry - Corners and Number of Slices in the x and y directions**

While corner effects for VLSI may be critical, in some MEMS structures of interest corner effects play a less dominate role. Fig. 12 indicates the current performance of the method at a corner. As you would expect, the method predicts reasonable cover on the step, but inaccurately predicts no coverage in the region labeled “beta”. One possibility being explored to address this problem is using an extra "angled" slice plane (show as a dotted line) which would give a more reasonable result in this region.

The other significant area for improvement is to automatically detect the number of cut planes being used in the x and y directions. Currently, the user specifies the total number of cut planes in the x and y direction and the program uses uniformly spaced cuts. This causes two potential difficulties in that the certain features could be missed if insufficient refinement is used and that unnecessary simulation is also performed due to the non-optimal spacing of the cut planes. The image shown of the RF switch was created using 40 x 40 uniformly spaced cuts, while with non-uniform spacing this number could be reduced to 6 x 6 for the same level of accuracy.

**Issues Involved in Mesh Generation for Finite Element Analysis**

One of the critical components in the simulation of a MEMS device is the ability to generate a reasonable mesh for analysis. Some believe that generating a mesh for the electrostatic region surrounding a device is difficult and time consuming (Cai, 1993). Indeed, meshing must be integrated with the solid model to streamline and simplify the process. In addition, if finite element analysis is to be used for the simulation of both the electrostatics and the solid mechanics of a MEMS device (as described below), it is necessary to have a mesh generator that is capable of meshing multiple, geometrically complex regions.

The reasons given above lead to our use of the mesh generation tools developed under the lead of Mark Sheppard at RPI (SCOREC). The RPI mesh generator is based on the octree mesh generation technique and interfaces directly with the solid modeler. Fig. 13 shows three views of the mesh of the RF switch. The mesh of the device and the air region is quite complicated and would be difficult for a user to create using a highly-interactive tool such as PATRAN or I-deas. The use of automatic mesh generation increases the need for a safeguard of an insufficient mesh for analysis. This facilitates the use of *hp*-adaptivity as described below.

**Extensions in Simulation**

Important multi-physics interactions and numerical requirements that need to be addressed in dynamic response simulation of MEMS systems are a key focus of prototype simulation development efforts. Current progress includes the demonstration of a versatile framework to test MEMS requirements for solving coupled systems of equations using ProPHLEX as a prototype vehicle. The solution of coupled elastostatic-electrostatic equations is demonstrated based on a relaxation scheme; ongoing work is targeted to exploit *hp*-adaptivity using gradient based error predictors. Fig. 11 shows the Von Mises stress for the electrostatically actuated RF switch. Stress concentrations occur at the inner corners due to the sharp edges. Note that a similar result would have been seen at the top edges if geometric deposition had been performed. Physically based simulation, however, indicates rounded corners will appear and thus no stress concentration will be observed at the top corners. This is in better agreement with experimental results.

**Future work**

Robustness issues in the area of solid modeling will continue to be addressed. Improvements are in the works to reduce the number of 2-D SPEEDIE simulations performed. In the area of mesh generation, work will continue to utilize the full power of the mesh generation tools and to generate the best possible meshs for analysis. In addition, to solve for required design parameters such as pull-in voltage for the RF switch will require remeshing at least the air region surrounding the switch. In simulation, better approaches to solving the coupled system will be evaluated.

**Acknowledgments**

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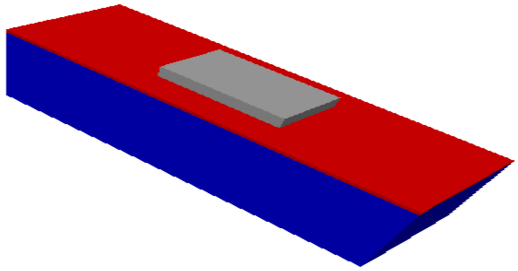

**Fig. 1: Initial geometry on which physical deposition is to be performed.**

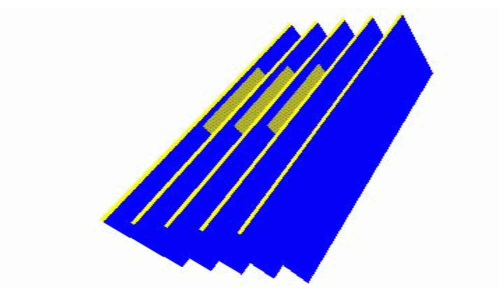

**Fig. 2: Initial slices of the geometry in the x-direction.**

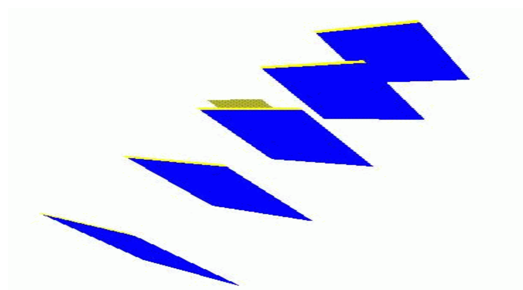

**Fig. 3: Initial slices of the geometry in the y-direction.**

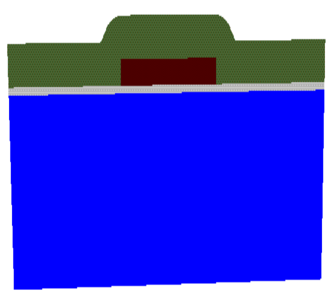

**Fig. 4: Representative cross section showing simulated (SPEEDIE) deposition.**

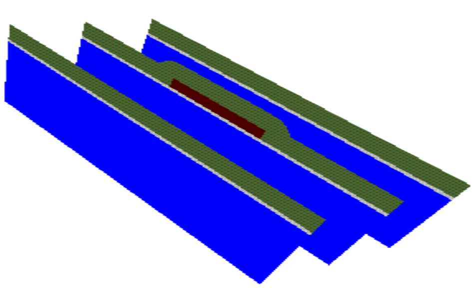

**Fig. 5: Three representative slices in the x-direction showing the simulated deposition.**

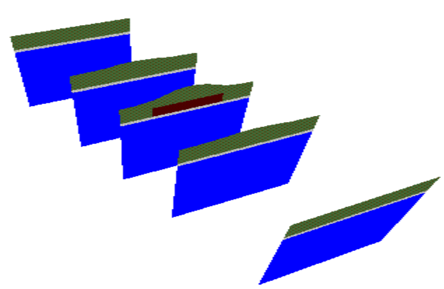

**Fig. 6: Five representative slices in the y-direction showing the simulated deposition.**

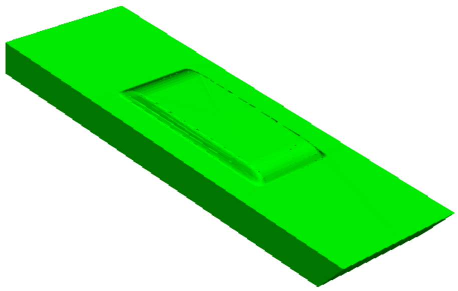

**Fig. 7: The solid representing the deposition due to the slices in the x-direction.**

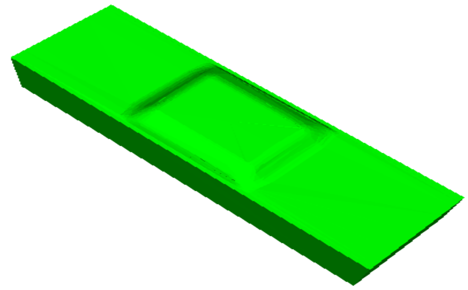

**Fig. 8: The solid representing the deposition due to the slices in the y-direction.**

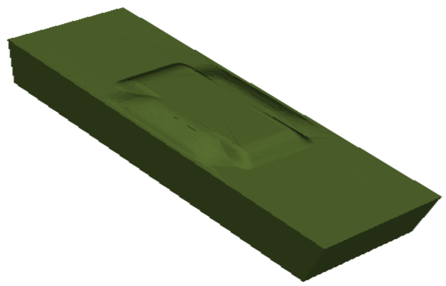

**Fig. 9: The union of the solids shown in Fig. 7 and Fig. 8 which is the pseudo 3-D deposited layer.**

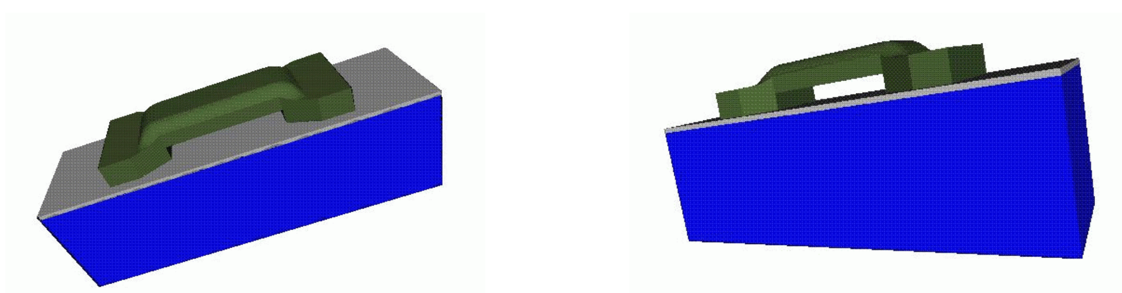

**Fig 10: A view of the RF switch created using two geometric depositions, two geometric etches, and one simulated deposition.**

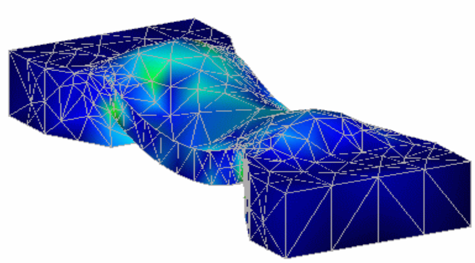

**Fig 11: Von-Mises stress distribution of the electrostatically actuated RF switch.**

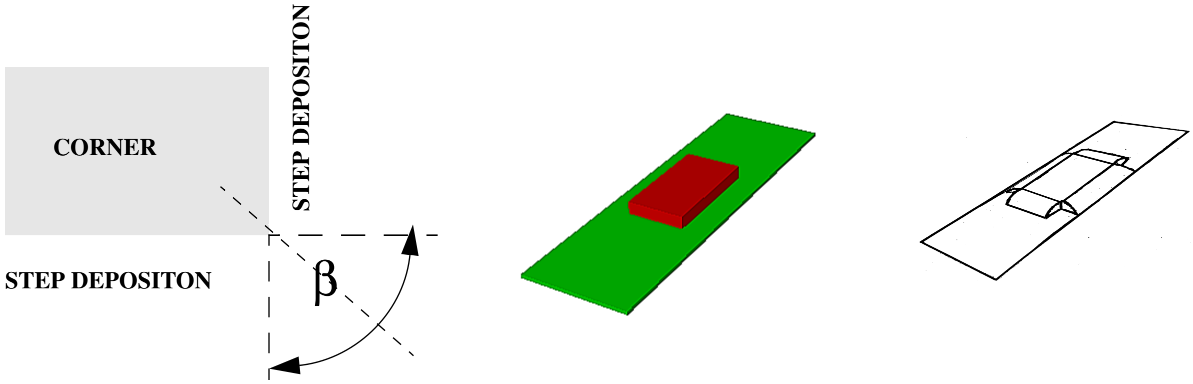


**Fig. 12: (a) schematic showing top view. (b) before pseudo-3D deposition. (c) after pseudo-3D deposition.**

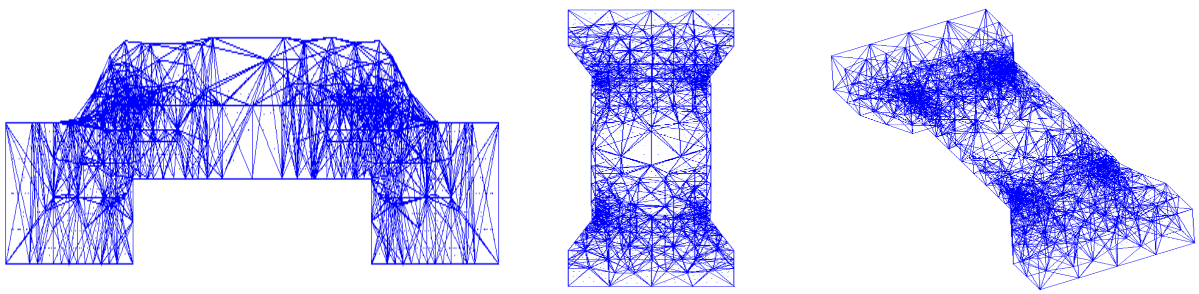

**Fig. 13: Three different views of the mesh for the actuated material of the RF switch.**