Intelligent Automatic Meshing Of Multilayer CMOS Micromachined Structures For Finite Element Analysis

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ABSTRACT

In this paper, we describe an automatic technique for meshing multilayer CMOS micromachined structures for Finite Element Analysis (FEA) from device layout. The technique is based on a 3D canonical representation of the different CMOS layers and feature recognition of plate masses, springs, beams and comb drives within the surface micromachined MEMS device. Manual meshing of devices for FEA is very tedious for multilayer structures as each layer must be separately meshed and subsequently merged. FE modeling experts tend to use heuristics derived from past experience and knowledge of structural features to improve mesh quality. We present a technique that tries to replicate this approach by detecting various MEMS features, and then meshing them based on an user-supplied rules file. This approach results in a FEA mesh that is computationally more efficient that conventional automeshers that have no knowledge of the geometry. The resulting computation time is found to be an order of magnitude faster than uniform meshing, with less than 5% difference in accuracy.

Keywords: CMOS micromachined structures, finite element analysis, automatic meshing, 3D canonical representation.

INTRODUCTION

Finite element analysis (FEA) is an important tool for the design of MEMS devices. Low-cost, high performance MEMS devices require integrated electronics/MEMS processes, which have led to the development of CMOS micromachining technologies that additionally have the capability of including multilayer surface micromachined devices. Exploiting such processes for novel electrostatic and thermal actuators and sensors have made FE modeling of such devices very tedious. Device structural optimization is difficult as a new FE model must be constructed for each design iteration. FE modeling experts tend to use heuristics derived from past experience and knowledge of structural features to obtain good FE models. The interdisciplinary nature of MEMS results in limited past meshing experience for most designers. This paper describes a tool developed to enable novice designers to make good quality FE models of MEMS devices by replicating the traditional meshing approach.

Recent work in FEA of MEMS has used a mixed rigid/elastic formulation [1] that recognized that modeling proof masses as rigid elements improved computational efficiency. The automeshing tool described in this paper detects various MEMS features (like combs, springs and plate masses) from the layout and meshes them using a rules file. The algorithm is general and easily modified for any process and may be applied to improve the initial mesh generation of commercial MEMS FEA tools.

CMOS MICROMACHINING PROCESS

The meshing algorithm described in this paper has been developed for the high-aspect-ratio CMOS micromachining process developed at Carnegie Mellon University [2]. The process flow, shown in Figure 1, enables fabrication of micromachined structures in a standard 0.5μm three metal n-well CMOS process. The standard CMOS process is followed by two maskless dry etches to release the microstructures protected by the top-most metal layer. An anisotropic reactive ion etch (RIE) with CHF_3 and O_2 is first performed to etch away oxide not covered by any of the metal layers, resulting in high aspect ratio vertical sidewalls. The conditions for this etch are critical and have been studied in detail in reference [3]. This step is followed by an isotropic RIE (using SF_6 and O_2) to

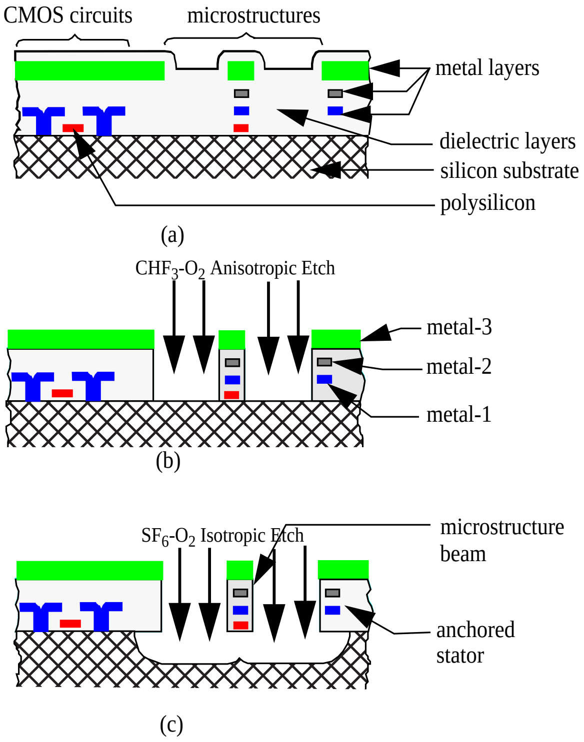

Figure 1: Schematic of the process for micromachined structures in standard CMOS.

remove the underlying silicon, thus releasing the microstructure. The advantage of dry etching is that it eliminates sticking problems associated with competing wet-etch release processes.

The microstructural layers can be designed with any of the metal layers as the etch mask, with their thickness being a function of the masking metal layer. The microstructural elements of the system are designed using the same design rules as the CMOS process. The automesher converts this layout directly into a FE model consisting of 20 node brick elements in the universal (UNV) file format compatible with many FEA tools.

3D CANONIZATION ALOGRITHM

The multilayer CMOS microstructure is described by a series of masks namely, Polysilicon, Metal 1, Metal 2, and Metal 3. The released structure can be represented as the logical OR of the physical metal layers, and delineates the overall geometry of the device. This logical layer is called the *structural* layer. The 3D canonical mesh representation of the structure is a brick mesh that has only one neighbor at each of its faces. The following algorithm can be used to create the 3D canonical mesh representation:

1. Read layer information from input CIF file (Figure 2a).
2. The *structural* layer is created by merging the metal layers, to obtain the geometry of the structure that is defined after etching. Feature detection of beams, masses, springs (meander, crab-leg, folded flexure) and comb fingers is accomplished from rectangles in this layer using algorithms in [5]. Every rectangle contained within the component is annotated as being one of the above.
3. Each CIF layer is represented by its 2D canonical form, which is made up of rectangles such that each rectangle has only one neighbor per edge. This can be easily achieved by extending the boundary edges into the interior of the layout area until it meets another boundary edge. Figure 2b is the canonical representation of the input layers [4].
4. The MEM layer is created by first copying the structural layer. Every rectangle in the MEM layer is further partitioned by each of the 2D canonized rectangles from each of the layers in Step 3. The MEM layer is illustrated in Figure 2c. It represents a surface mesh, that when extruded through all the layers present would yield a minimal mesh or the 3D canonical mesh representation of the structure, as shown Figure 2d. At this point we have the minimal 3D brick mesh required to model the device. This mesh is refined by rules described in a user-supplied rules file as described in the next section.
5. Once the mesh refinement process is completed, the finite element model is constructed from the MEM layer by extruding every rectangle through the structure thickness depending on the mask layer information. The dielectric layers of the CMOS micromachined beam are also extruded during this operation.

MESH REFINEMENT

The 3D canonical structural mesh is refined by rules supplied by the user, who defines the meshing rules for each type of component that can be detected by the detection algorithm. We define beams and plate masses as the basic elements for surface micromachined MEMS structures. Beams are released structures that are connected either at one or two ends to the rest of the structure or the anchor. Components like crab-leg springs, folded-flexure springs and comb drives can be decomposed into beam elements [5]. For each component the meshing rules are determined by the beam aspect ratio, which is the ratio of the beam length to width. For example a rules file may be defined as follows:

```
general
   beam aspect < 10 LW=100 Split=1
   beam aspect < 20 LW=4 Split=2
mass X=3 Y=3
comb
   beam aspect < 100 LW=50 Split=1
spring crab
   beam aspect < 5  LW=1  Split=1
   beam aspect < 10 LW=2  Split=1
spring foldedflexure
   beam aspect < 10 LW=10 Split=1
   beam aspect < 20 LW=20 Split=2
spring meander
   beam aspect < 4  LW=3  Split=2
   beam aspect < 7  LW=5  Split=2
```

The rules file describes the meshing rules for unrecognized structures (general), plate masses, crab-leg, folded-flexure and meander springs. Crab-leg springs that have beams with aspect ratio greater than 5 but less than 10 would be meshed such that the length to the width ratio of each finite

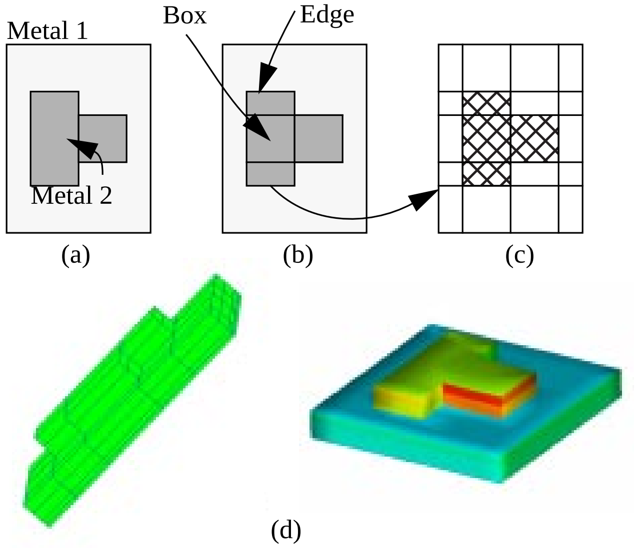

Figure 2: An illustration of the 3D canonization algorithm (a) CIF layout of metal 1 and metal 2 microstructure. (b) 2D canonical representation of the metal layers. (c) MEM layer created by splitting every rectangle in one layer with edges of the metal 1 and metal 2 layers. (d) The extruded mesh from the MEM layer.

element (LW) would be 2. “Split=1” defines the number of elements that mesh the beam uniformly across its width. Unrecognized components are treated as simple beams and their meshing rules are separately defined in component class *general*.

Mesh refinement is done by first partitioning the rectangles of the *structural* layer based on the beam mesh refinement rules for that component. The MEM layer is then partitioned with the edge of each rectangle in the modified *structural* layer. The final MEM layer is the surface mesh that is extruded to obtain the final mesh. The extrusion process can be modified to account for non-vertical sidewalls. In the final model, each finite element is a 20 node brick.

ILLUSTRATIVE EXAMPLES

The automatic mesh generator is used with different rules files depending on the analysis. For mechanical analysis the comb finger can be minimally meshed while the spring elements are finely meshed and vice versa for purely electrostatic analysis. To verify the goodness of the mesh, the solver can be run with a denser mesh by changing the rules file. This process can be continued until the desired accuracy is obtained.

The time to convert from a CIF layout to a UNV file is less than 2 minutes for structures with less than 2000 elements. This compares to several hours, if not days, for manual meshing of similarly complex multilayered structures.

Crab-Leg Resonator

The meshing of a crab-leg resonator is illustrated in Figure 3. The figure shows the layout of the resonator in standard CMOS using metal and poly layers and intermediate steps of the automeshing process. The component detection algorithm recognizes the crab-leg springs, mass, and comb fingers. Each component is meshed according to rules file defined earlier to generate the FE mesh. Modal analysis using MEMCAD [6] of this structure (3890 elements) yields the first resonant frequency at 49.96 kHz. When the LW of the crab leg was doubled (4120 elements) the resonant frequency was 49.83 kHz. The measured resonant frequency for this structure was 41.53 kHz.

Electrothermal Actuator

Simulation of curling due to residual stress is an important consideration in the design of devices in the CMOS micromachining process. The simulation process is demonstrated for an electrothermal actuator. The layout of the device with an integrated polysilicon heater is shown in Figure 4. The automatic mesher performance for various LW values of the beam element was evaluated by simulation. The meshed structure was evaluated using commercial MEMS FEA analysis tools [6][7]. The results are summarized in Table 1 and Figure 5. It is seen that the computation time is reduced by a factor of 40 compared to the uniform meshing case with an elemental area of 1 µm by 1 µm. This improvement in computation time arises because feature recognition identifies the comb fingers and plate masses which are minimally meshed for the thermal analysis. This meshing tool was used determine the optimal curl-matching layout for the comb fingers.

CONCLUSIONS

In this paper we have presented a prototype tool that speeds up the tedious process of meshing multilayer surface micromachined MEMS structures. The meshes generated are computationally more efficient than a uniform mesh with little loss in accuracy. Such tools enable iterative design of complicated MEMS structures for optimal design. This mesh generation algorithm can be used to replace the initial manual mesh in commercial MEMS simulation tools.

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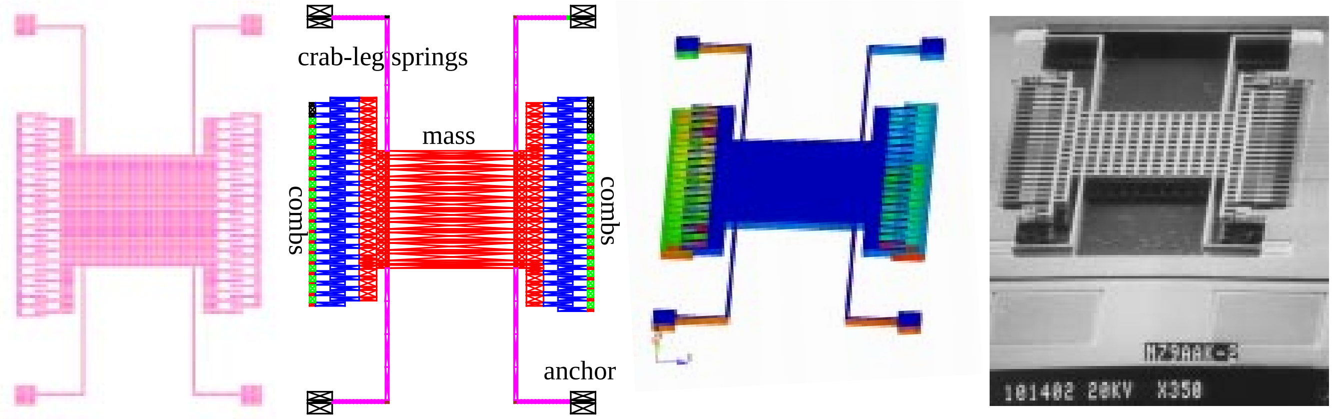

Figure 3: Illustrates the operations performed by the automatic meshing program. (a) Layout of a crab-leg resonator with microstructures defined in Metal 1, 2 and 3. (b) The final MEM layer after feature detection and mesh refinement. Mass, crab-legs, combs and beams components of the comb are detected. (c) The solid model of the resonator in MEMCAD[6]. (d) Scanning electron micrograph of the fabricated crab-leg resonator.

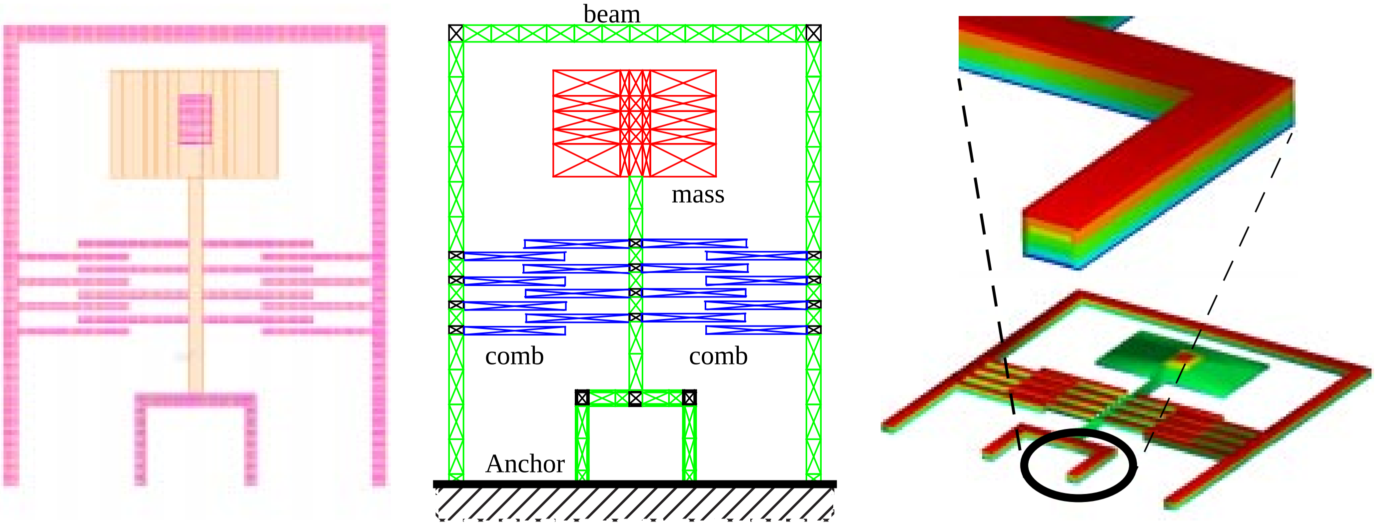

Figure 4: Illustrates the simulation of a electro-thermal simulation. (a) Layout of the actuator using the metal and the poly layer (b) MEM layer with feature detection based mesh refinement. The combs are meshed with an L/W ratio of 100 and the beams with a L/W ratio of 2. (c) The solid model of the actuator. Note the metal layers are not of the same width.

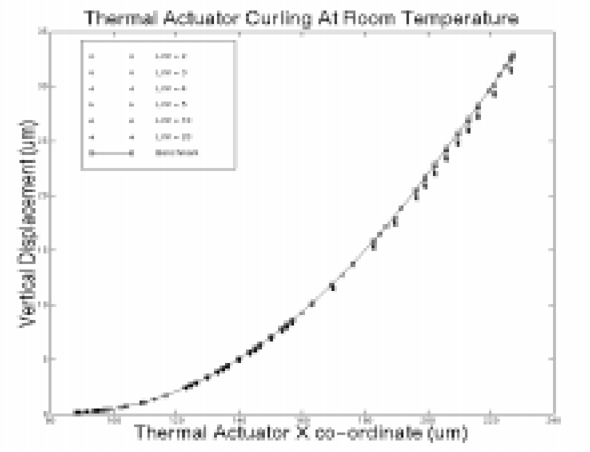

Figure 5: FEA of residual stress induced curling along the length of the electrothermal tip actuator at room temperature for different general LW values.

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Element L/W ratio	no. of Elements	Simulation Time (s)	z_{max} (µm)	% Relative Error
UNIFORM	6678	12856.6	32.66	0.00
2	2004	3817.4	32.39	0.83
3	1556	2202.4	32.24	1.28
4	1236	1963.2	31.40	3.85
5	1180	1160.2	31.72	2.87
10	860	869.4	31.54	3.43
20	724	306.06	31.27	4.26

Table 1: Comparison of thermal FEA of the tip actuator displacements z_{max} with different mesh densities. Comb and plate mass meshing is kept constant.

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