Function-Oriented Geometric Design Approach To Surface Micromachined MEMS

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ABSTRACT

Geometric modeling is an important aspect of MEMS design. It not only creates geometric model for visual evaluation, but also supplies input for device performance analysis. This paper focuses on developing a feature-based geometric design methodology that enables designers to create fabrication-ready 3D models of MEMS devices without concerning the mask layout. Compared with present geometric design routine, which builds 3D device model through simulating the fabrication process from the photolithography masks, the function-oriented geometric design method allows designers to establish 3D model by using a set of pre-defined volumetric primitives associated with geometric constraints. The fabrication information is derived from corresponding function-oriented data specified by designers. Hence, designers are released from the down-stream fabrication planning, and can focus on creative design. This research is the application of feature modeling and constraint-based design to the micro world.

Key Words: Surface Micromachined MEMS, 3D Geometric Design, Feature Modeling, Design by Feature

1 FUNCTION-ORIENTED PARADIGM

As we know, the microsystem is originally developed from the semiconductor industry. From the structural material, fabrication methods, to design paradigm, the microsystem inherits the characters of integrated circuits. Design a new device starts from figuring the masks. The design scheme is represented as a set of photolithograph masks. In this mode, the factors of the fabrication, rather than the function implementation, are the preferentially concerned topics. Therefore, the paradigm is fabrication-oriented. The 3D solid device model is generated after planning fabrication data. This paradigm, mainly concerning device fabrication-ability, makes the modeling procedure un-intuitive and cumbersome. Present MEMS geometric modeling approaches actually are simulation-based design verification tools, not design aid tools. Along with the development of microfabrication, especially the surface micromachining, more structural layers are involved, which make it possible that complex spatial structure can be made. However, under this situation, it is more and more difficult to handle function implementation and fabrication planning at the same time and by the same person. This difficulty imposes designer a heavy burden which may diverge them from creative contribution.

In view of the drawbacks of the fabrication-oriented design paradigm, an alternative scenario is expected to facilitate fundamental improvement on microsystems design. The concept of "structured design method" for microsystems [2, 3, 4] was proposed to "develop and integrate methodologies, tools, environments and technologies needed to be able to automate the rapid, efficient and accurate design and construction processes, artifacts and systems of artifacts". A key long-term objective is to develop a methodology that can be applied generally to mechanical and electromechanical systems. After several years of effort, although the situation has been greatly improved, this kind of demand still remains. Aiming to comprehensively solve the problems existing in designing surface micro-machined microsystems, the function-oriented design paradigm is proposed. The paradigm flow chart is shown in Figure 1. At the beginning phase of product development cycle, the 3D model can be built directly through the feature-based geometric modeler according to the designer's intents (desired functions). Following it, the 3D device model is visual evaluated and fed to the domain analysis tools to predict device performance before it is physical fabricated. Model modification need not refer to changing masks any more; instead, any adjustment of design can be completed directly on the 3D geometric model. The photolithograph mask is generated on the refined device model. This phase is moved from the upstream stage to downstream stage.

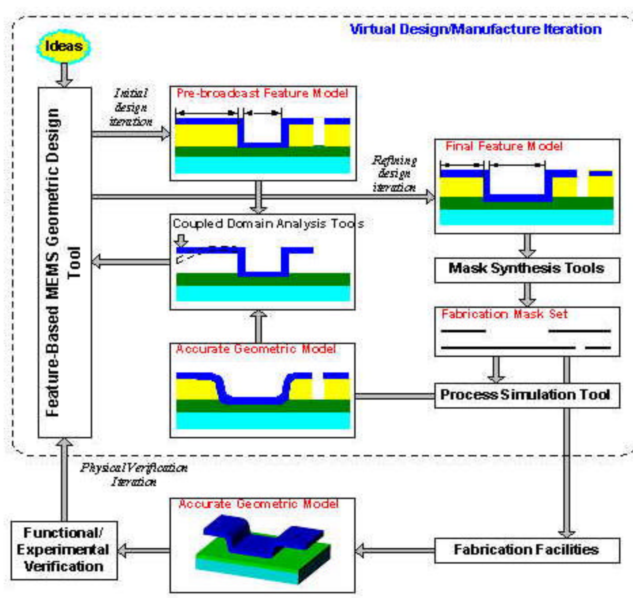

Figure 1: Function-Oriented Design Paradigm

In the function-oriented design paradigm, designers are allowed to directly manipulate and visualize the 3D model of the microdevice that they are working on, without detouring through the steps of mask layout and process simulation. Besides the precise geometric representation, the feature model of MEMS is compatible to carry comprehensive information that is valuable for most design activities in the whole product developing life circle. Finally, the mask synthesis tool generates masks from 3D device model. The two key points of implement this routine are *how to decouple the task of design and fabrication planning, and how to find the interrelation between them in order to automatically derive fabrication data from design information.*

2 DECOUPLING OF DESIGN AND FABRICATION PLANNING

Because the coupling of design and fabrication planning is the major reason leading current difficulties of modeling and maintaining the 3D MEMS device model [1], decoupling is the natural way to solve this problem. When designing a RF switch schematized in Figure 2, designer's concern is concentrated on some spatial structures which execute desired functions (such as the bending of the polysilicon beam, the dimple between two beams) and some geometric dimensions which may considerably influence the device performance (beam length *d1* and *d2*, width *d4*, gap distance *d3*, and dimple width *d5*). It will be intuitive and efficient for designer if the core component, polysilicon-1, can be separately and directly constructed without considering the etching operations on all involved layers.

It is assumed that a predefined fabrication process should be selected before a surface micromachined MEMS device is designed. Among the fabrication steps of surface micro machining, some (all kinds of deposit) are un-controllable for designer because the process parameters of deposit (type, material, thickness) are fixed when a standard fabrication process is selected to make the device. Designers have no authority to change them. On the contrary, some steps are controllable for designers since designers can specify the acting area of selective etching or doping, although some other process parameters cannot be modified by designers. Currently, the major task of MEMS geometric design is to specify the acting area of etching, the task of fabrication planning.

From the cross section of RF switch in Figure 2, the device geometry can be categorized into two folds. The first one is the geometry carved by high-aspect-ratio etching. For instance, the etching on the polysilicon-0 layer makes the square electrode. Apparently, as having a strong relation with fabrication, it is called fabrication-oriented (FAO) geometry. The other fold is the geometry generated when material is deposited on the previous etched layers. For instance, the bending and dimple on polysilicon-1 layer are formed by depositing material on the etched underneath layers. Sometimes, these types of shapes and their geometric parameters directly express design intents somehow. Hence, these shapes can be seen as function-oriented (FUO) geometry. These two forms are adopted to classify the task of design and fabrication from the view of geometry.

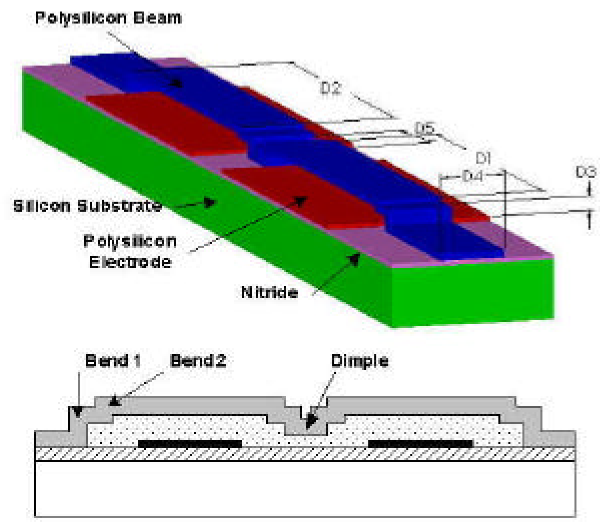

Figure 2: RF Switch (a), 3D model and constituent layers; (b), Cross-section and function-oriented geometry.

In previous research on feature modeling for MEMS [6, 7], two sets of features, design feature and fabrication feature , are defined to construct MEMS device model. Five general design features, including bend, protrusion, cut, anchor and transferring, are used to directly construct 3D device model. A feature instance is initialized by unambiguously specifying feature type, planar outline and depth value. Then, the volume of feature instance is merged into the original model to change device shape. The feature planar shape and location can be defined by imposing geometric constraints. The shape of most surface micromachined microdevices can be represented in the terms of these five design features and their combination. Two fabrication features are the two designer controllable fabrication steps, etching and doping. These features are used to represent fabrication operations.

The feature structure is diagramed in Figure 3. Design features are the interface between fabrication operations and designers. They are the engineering meaningful primitives by which designers construct device model according to desired function. Fabrication features are connected with fabrication process. As not transparent to designers, they are not explicitly specified. Actually, they are automatically derived from corresponding design features. Both the volumes of design feature and fabrication feature instances compose the MEMS feature model.

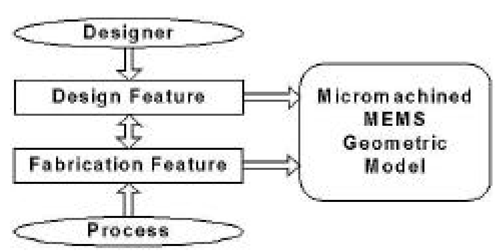

Figure 3: Bi-level Feature Structure

3 DESIGN FOR MANUFACTURING (DFM) FOR MEMS

The purpose of decoupling design and fabrication is to handle the fabrication planning automatically and systematically, rather than ignore the issue of fabrication in design phase. Manufacturability is one of the major factors evaluating design scheme. For surface micromachined MEMS, due to the restricted fabrication measures, arbitrary spatial shape cannot be made. This is the reason why present MEMS designers start a new device from figuring masks. Design for manufacturing (DFM), a key component of Current Engineering (CE), has been introduced into the MEMS system optimization [5]. In this research, DFM will be addressed to guarantee the manufacturability of a microdevice from the perspective of geometry.

Since MEMS devices are fabricated by the iterations of layer deposit and etching, tight contacts exist among the materials of each layer. Hence, the geometries carved by high-aspect-ratio etching in the lower layer must influence the shape of the upper layers. Based on this phenomenon, called geometric dependency, the fabrication feature can be derived from the inputted design feature. If a fabrication feature can be sought, the corresponding design feature is valid and can be attached on the object. Otherwise, it cannot be initialized and attached to the device model.

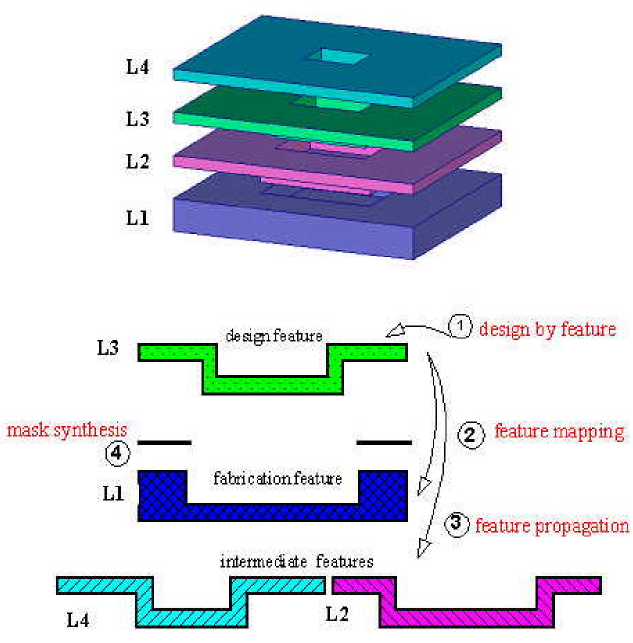

Figure 4: Feature Mapping and Feature Propagation

For the example schematized in Figure 4, the model consists of four structural layers which are labeled as *L1, L2, L3,* and *L4*, respectively. In the first step, a design feature "bend" is imposed on layer *L3*. The shape of layer *L3* is updated immediately by merging the feature instance into the original layer. Secondly, a fabrication feature acted on layer *L1* can be derived to achieve the "bend" shape because there is an etching acted on the layer *L1* according to the process. This deriving process is called feature mapping. Besides updating the layer *L3* and *L1*, all other involved constituent layers should also be updated, otherwise there will be volumetric interference among layers. Thirdly, two similar bend shapes should be initialized and attached on layer *L2* and *L4* respectively. This process is called feature propagation. Finally, the mask for the etching can be derived by extracting the planar outline of the fabrication feature attached on *L1*. In summary, the information transforms as the flowchart diagramed in figure 5. First, designers transfer intents into design features. Then, fabrication feature is derived through feature mapping. Some new design features may be generated through feature propagation. Finally, the fabrication feature is transferred to a photolithograph mask layout.

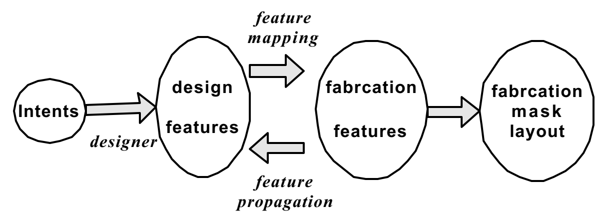

Figure 5: Information Transformation Flow

4 DEMO

Figure 6 shows the procedure applying the function-oriented geometric modeling method on RF switch design. Originally, there are four untouched constituent layers, *nitride*, *polysilicon-0 (PS0)*, *sacrificial oxide(SO)* and *poly-silicon-1 (PS1)*. In the first step, a "bend" feature is imposed on *PS1*. Its corresponding fabrication feature is the etching on *SO*. The bend forms the approximate shape of beam. Then, a "cut" is imposed on *PS0* to form the electrode. This feature will be propagated up to layer *SO* and *PS1* forming bend shape. In the third step, a bend feature, which forms the dimple in the middle position of the beam bottom, is attached on *PS1*. Its corresponding fabrication feature is also the etching on *SO*. But this time it is to-depth etching, not previous to-layer etching. In the fourth step, a cut feature is acted on *PS1* to control the beam width. Finally, wet etching solvent washes of the whole layer *SO*, then the component beam is released. The final 3D model is shown in figure 1.

This modeling procedure is totally different from that of the simulation-based modeling method [8]. It does not need mask as input. The modeling process is driven by the design intents. Designer can arbitrarily move their focus on the layers which they are interested with, then impose design feature on them. They need not worry about the manufacturability of the operations they make. The manufacturability has been checked during the process of feature mapping. This is a good design aid tool, rather than a design verification tool.

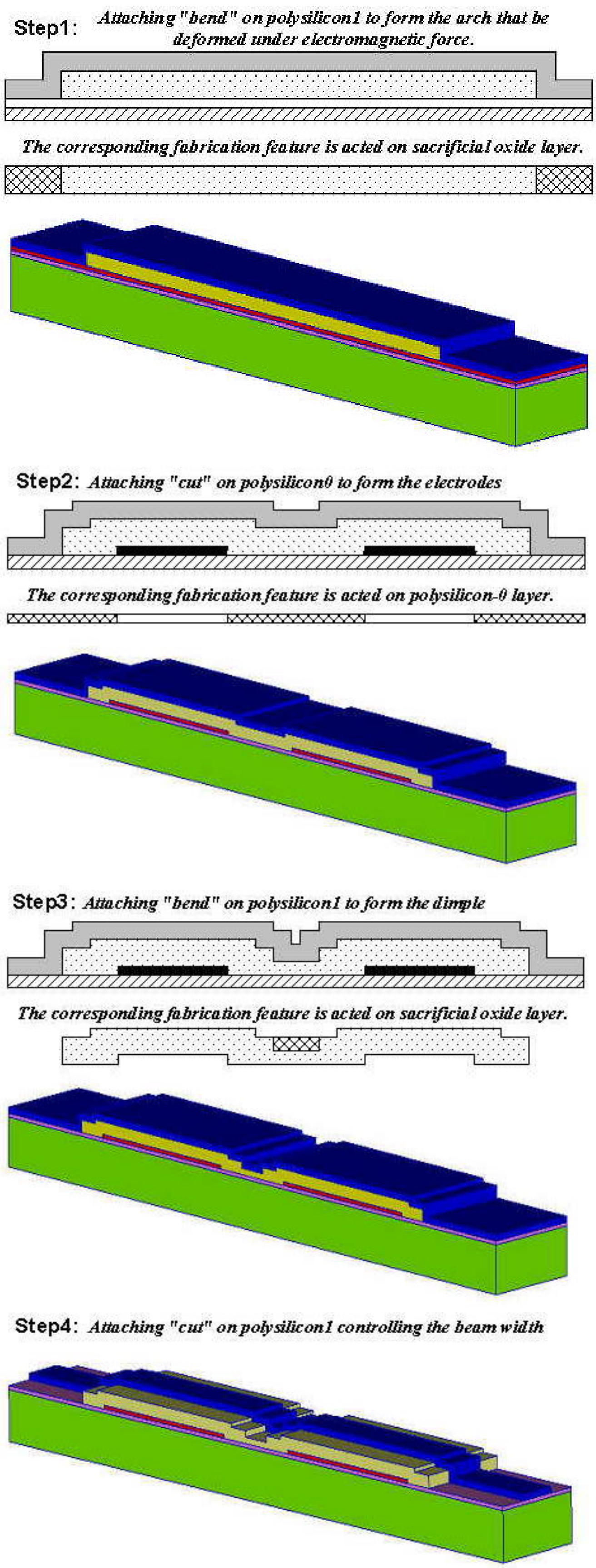

Figure 6: Design Process of RF Switch

5 CONCLUSION AND FUTURE WORK

In summary, the feature-based function-oriented geometric modeling approach greatly changes the picture of MEMS device geometric design. Under the support of function-oriented design tools, designers are allowed to concentrate on establishing suitable structure to implement desired functions. The fabrication data is automatically derived from design input. Finally, the mask set can be synthesized from derived. It is a practice of feature modeling technologies which are mature in macroworld on the domain of microdevice.

Work is continuing towards generalized feature representation, feature interference handling and process-independent modeling.

REFERENCE

[1] Antonsson, E., “Structured Design Methods for MEMS, Final Report”, *NSF MEMS Workshop, CalTech.,* 1995.

[2] Antonsson, E., “Microsystem Design Synthesis”, Chapter 5 in *Formal Engineering Design Synthesis*, Cambridge University Press, pp126-169, 2001.

[3] Fedder, G.K., “Structured Design of Integrated MEMS”, *Technical Digest of the 12th IEEE International Conference on MEMS’99,* Orlando, FL, January 1999.

[4] Senturia, S.D., “CAD Challenges for Microsensors, Microactuators, and Micro-systems”, *Proc. of IEEE,* Vol.86, No.8, pp. 1611-1626, August 1998.

[5] de Silva, M.G., “Design For Manufacturability for 3D MicroDevices”, *NSF Workshop on 3D Nanomanu-facturing: Partnering Industry,* Jan. 5-6, 2003, Birmingham, AL.

[6] Gao, F., Hong, Y. and Sarma, R., “Feature Model for Surface Micromachined MEMS”, 2003 ASME *DETC/CIE-48186,* September, 2003, Chicago, IL.

[7] Gao, F., and Sarma, R., “A Declarative Feature-Based Cross Sectional Design Tool for Surface Micromachined MEMS”, 2001 ASME DETC2001/CIE-21775, Sept. 2001. Pittsburgh, PA.

[8] Jorgensen, C.R. and Yarberry, V.R., “A 3D Geometry Modeler for the SUMMiT V MEMS Designer”, *Proc. of MSM 2001,* pp.594-597. Feb. 2001.