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3D-feature-based structure design for silicon fabrication of micro devices

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Abstract To make MEMS structure design in a more intuitive way, and to support the ‘‘function to 3D shape to mask’’ design flow, a 3D feature based structure design framework and its corresponding key enabling techniques are presented on the basis of inverse design processes and top-down design methodologies. Driven by space mapping among function and structure, the feature model and its parameters are restricted with the bond graph represented simulation model, which is constructed with functional components in simulation library at the system-level. Conforming design rules, the hierarchic feature information model is established and finally can be cascaded down to a group of 3D feature nodes, which are all silicon fabrication oriented and defined on the top of CSG/B-rep 3D solid models. Surrounding this feature information model, the 2D mask deducing and fabrication parameters extraction at the fabrication-level can be performed for manufacturability checking, design/fabrication conflict feedback and fabrication process sequence generation. Taking a micro gap-closing actuator as an example, the structure design process is demonstrated in terms of this 3D feature modeling methodology.

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1 Introduction

With the rapid development of fundamental theories of MEMS and the emergences of novel materials and fabricating technologies, more and more micro devices with complex 3D geometric structures can be fabricated. However, nearly all of structure design methods for micro devices are based on 2D-planar masks nowadays in order to meet the stringent fabricating requirements. According to these structure design methods, the 3D solid models of micro devices, which are used widly in functional design processes and device-level FEA simulations, can hardly be obtained without combined with fabricating technologies. Therefore, the designers must understand a great deal of additional fabrication knowledge so as to design the satisfied 3D solid models.

Actually, two limitations exist at least by adopting the 2D planar mask centered structure design methods for designing micro devices. First, the design flow can not be clearly separated into device design stage and fabrication stage, the structure design greatly depends on the laboratory experience, manufacturing process plan and manufacturing skills. Hence, structure designers at the device-level have to spend much time on fabricating technologies, which decentralize their attention on the structure design of micro devices. Second, 2D masks can not represent the 3D-models of micro devices in an intuitive way. In structure design processes, structure designers have to pay attention to combining 2D-masks with fabricating processes step by step to try to find the desired 3D shapes, which can perform the required functions exactly. It seems that 3D solid or feature modeling, which is now widely used in general mechanical design, can overcome the disadvantages mentioned above perfectly. Following MEMS top-down design flow, 3D-feature based structure design of micro devices can origin from a functional schema derived from the system-level design and simulation. 3D-feature nodes and their parameters required in structure design processes can be well defined to fit the characteristic of MEMS fabrication through feature mapping processes. Thus, designers at the device-level can pay less attention to the detailed fabrication and focus on creating 3D geometric models that satisfy the needs of functions, performance, structures and shapes. Through checking the manufacturability and deducing the fabricating process flow and masks, we can determine whether the given solution is available. On the basis of the above analysis, we mainly discuss some key issues on the 3D-feature-based micro structure design, the design framework, and corresponding enabling techniques in this paper.

As per arrangement of sections, Sect. 2 explains the reason why we do this research and gives a literature review. In Sect. 3, the framework for implementing the 3D feature based structure design methodology is introduced. As one of the most important contents in this paper, following in Sect. 4, several design functions like feature mapping from the system-level to the device-level, CSG/B-rep solid model data structure of the 3D-modeller and its corresponding modeling scene-graph for MEMS structure design, fabrication-oriented 3D-feature definition, feature-information model, feature-based structure design rules and how this design method supports the systematic mask synthesis are discussed. In order to demonstrate the concepts and methods mentioned in the above sections, a running example is described in Sect. 5. The correspondent running procedure is illustrated through executing a scene-graph-based 3D-feature modeling prototype tool developed with Java programming language in Java3D scene-graph. Finally, the interesting discussion concerning the problems we met during the research is presented and a conclusion is drawn in Sect. 6.

2 Motivation and literature review

There are two primary design flows for MEMS design, which are well known as bottom-up design flow and top-down design flow (Tamal 2003; Fedder 2000). The former is manufacturing-centered, which starts at a micro-fabrication process to confirm the manufacturability of a micro device without fully concerning with the function and performance demands of the design result. This design flow was adopted by some early MEMS CAD systems, such as MEMCAD (Senturia et al. 1992) at MIT. However, it causes that design results hardly satisfy the function and performance requirements, and designers have to act as laboratory researchers who master abundant MEMS fabricating technologies. On the contrary, the latter starts at the system-level and concerns with more function and performance requirements, so it makes designers pay less attention to fabricating technologies. M. S. McCorquodale (McCorquodale et al. 2003) compared these two design flows in detail, and described the advantages of top-down design flow. In the final report of ten-years perspective of MEMS design, the authors predicted that the desired approach of MEMS top-down design flow is exactly like "function-to-3D shape-to-mask" (Antonsson 1996).

In recent years, quite a few commercial and non-commercial MEMS design tools, such as Coventorware and IntelliSense (Finch et al. 2000; Gunar et al. 2001), have gradually adopted the top-down design methodology as their main design framework. As one of advantages of the top-down design flow, the system-level design process and device-level design process are separated clearly in the design flow. Through taking advantage of nodal design of actuators and sensors (NODAS) (Wong 2004; Vandemeer 1998) or black box (Gabbay 1998) design and simulation methods, designers at the system-level can design freely to meet the functional and performance requirements without concerning much with design processes at the device-level and the physical implementation at the fabrication-level. These researches are of great significance, but need to be further studied to meet the demand of design mapping from the schematic at the system-level to the 3D structure at the device-level.

It is obvious that design from 3D solid model directly, which is widely used in macro mechanical design, is an intuitive way to express the design intention and to meet the design requirement, especially in designing micro devices with complex structure. However, consulting the main stream structure design tools (Finch et al. 2000; Gunar et al. 2001), we can see that they are still using 2D planar masks centered design method. 2D masks are firstly designed by some VLSI mask design tools, such as L-Edit. Then, structure designers place their emphases on creating process simulations and 3D CAD models from masks and fabrication process data, which can be used to predict the physical behaviour of MEMS devices by FEA analysis (Jack 2001). The reason of using 2D planar masks centered structure design method is that it is a really hard work to deduce process sequence and to generate 2D fabrication masks from 3D geometric shapes. This procedure is also called as systematic mask synthesis. But fortunately, some researchers around the world has done much excellent work on this topic, Feng Gao et al. (2003) had made a useful research in this area by introducing the feature model to mask synthesis. Jianhua Li et al. (2005) developed a layered model to perform the mask synthesis according to MUMPS surface fabrication standard. Liu and Jiang (2006) put forward a two-layered mask synthesis model, which can not only deduce the fabricating process flow, but can also find some design conflicts. Robert W. Johnstone et al. (2005) summarized quite a few categories of fabricating compliant micro parameterized cells with functional and 3D structure parameters, and formally described these parameterized cells in SKILL interpreter language of cadence. All of these studies make it possible to perform a reverse design flow by deducing the 3D device shape models at the device-level to generate the process sequences and the fabrication 2D masks at the fabrication-level. Furthermore, it also necessary to do much work on constructing a 3D structure design framework and correspondent enabling technologies to perform an integrated ‘‘function to 3D shape to fabrication mask’’ design cycle.

To sum up, we think it is absolutely necessary and possible to apply the efficient top-down MEMS design methodology to follow the ‘‘function-to-3D shape-mask’’ design flow during the MEMS design process. It also means that the correspondent enabling technologies should be explored further in depth. Under this case, the feasible 3D structure design tool must be developed in order to meet the novel demands of current and potential applications.

3 Research framework

The 3D structures of MEMS are constructed to perform certain system functions. So we consider the 3D structure design process together with the system-level functional design and simulation process. From the perspective of viewing the system-level model of MEMS, the essential of MEMS can be considered as a physical system in coupled energy domains, which can output some certain physical quantities according to the input physical quantities. The function model of MEMS is represented with a physical simulation model which can be divided into sub-models and components in hierarchy architectures. Each sub-model might in coupled energy domain or single energy domain, and all of the sub-models and components are connected with energy quantities on the basis of the law of conservation of energy.

As shown in Fig. 1, the MEMS function model at the system-level is based on a 3D feature sub-model library. This library is expanded from the template library of the physical simulation components. The physical parameters of the simulation components are well defined to be able to mapping to the geometric parameters and material parameters of the correspondent sub-models of the 3D structure features at the device-level. So in this library of 3D feature sub-models, the mapping process of function/geometric features can be formalized by means of using the macro script language, and even the behaviours of micro device models constructed with the feature sub-models can also be fed back to the design models at the system-level in the same way.

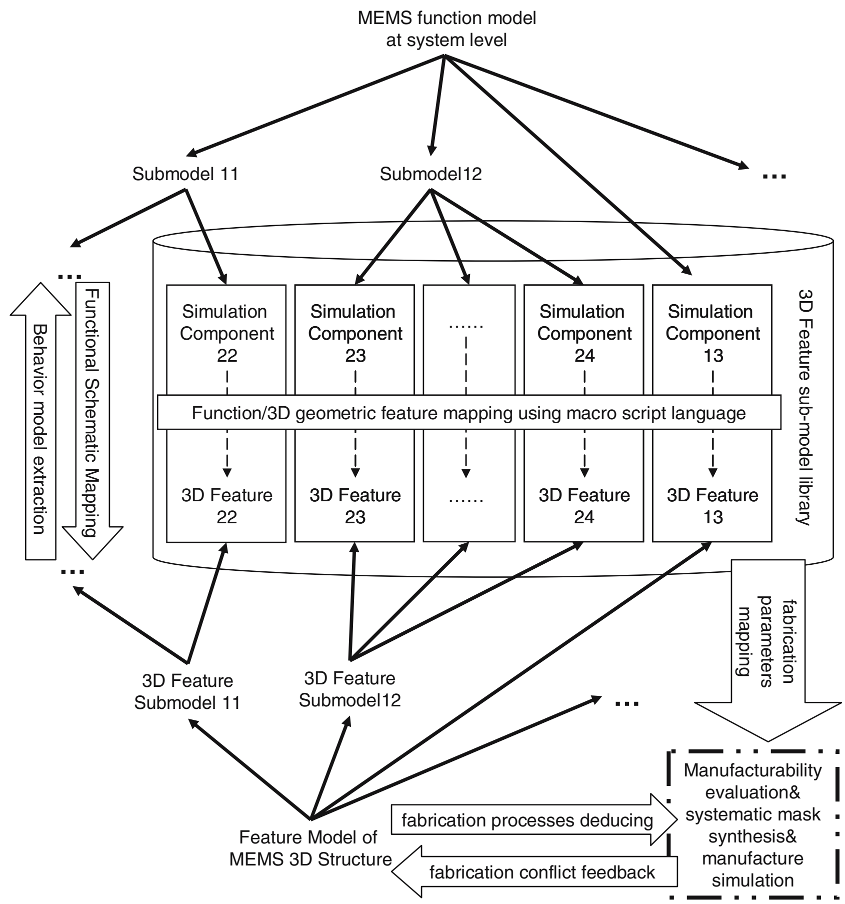
Since it is very important to check the manufacturability of the 3D feature information model constructed with the elements of the 3D feature sub-model library, all 3D features sub-models are built with the fundamental 3D feature nodes, which are all defined as the fabrication-oriented ones in Sect. 4.3.1. Some parameters of the 3D feature nodes are exactly derived from the fabricating parameters and material physical parameters. Moreover, a collection of design rules is also introduced to restrict the designers' behaviours in the 3D structure design process. Following these design rules, the 3D feature models of micro devices can be constructed well to reduce the conflicts between the design and fabrication processes. So it is convenient to obtain the fabricating parameters and 3D structure for the 2D mask geometric deduction from the 3D feature information model in the process of the systematic fabricating mask synthesis.

4 The key enabling technologies

4.1 Function representation and design at the system-level

There are several system-level design methods for MEMS design, such as NODAS (Vandemeer 1998) and black box analysis methodology (Gabbay 1998). Considering the ability to use bond graphs for realizing the coupled simulation of complex and heterogeneous MEMS, in this paper, we use the lumped bond graph system dynamical simulation models to represent the functional requirements of MEMS. The parameters of such lumped sub-models, which consist of the multiport field and junction structures of bond graphs, can be well designed to be mapped to the structure parameters at the device-level. A template library of

Fig. 1 The overall design architecture



simulation components is constructed, and shown in Fig. 2.

This template library contains two layers. The bottom layer is composed of the fundamental elements of the bond graphs. The upper layer is designed and implemented on the basis of the lumped sub-models which mainly consist of the multi-port field and junction structures of bond graphs. The physical parameters of the elements at the upper level library are well defined to be mapped to the structure parameters and material parameters of the 3D feature sub-models at the device-level.

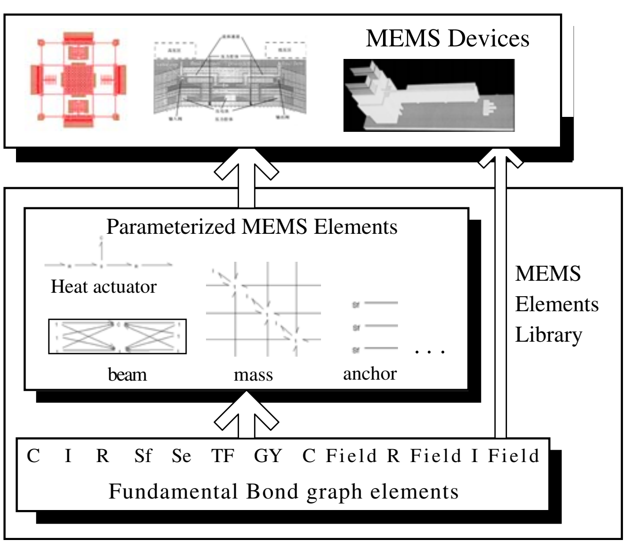


Fig. 2 Structure of simulation components template library **a** structure scheme **b** bond graph model

Take micro beam as an example, we can use the lumped bond graph model to build its micro simulation components. The correspondent process is just shown in Fig. 3.

The simulation parameters of the above micro beam are mapped to its structure parameters with the help of the matrix equation of multi-port field and junction structures of bond graphs in Eq. 1. Equation 2 transforms the displament from the local coordinate system of reference to the global coordinate system. Accoording to these equations, the mapping parameters of the micro beam from function to structure include the length, equivalent cross-sectional area, equivalent moment of inertia, and rotation angle in the global coordinate system.

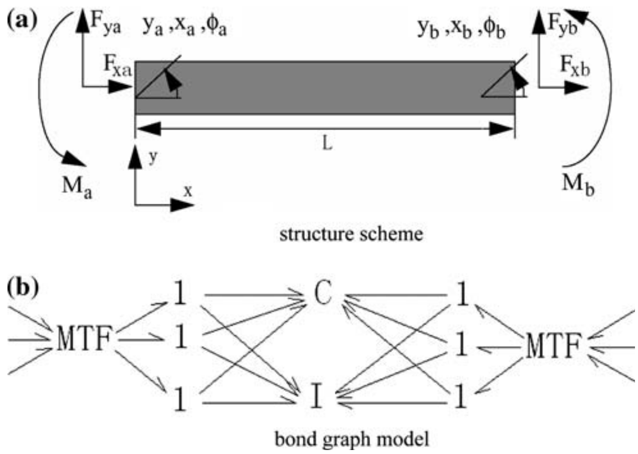


Fig. 3 Bond graph represented functional model of micro beam

$$\left.\begin{aligned} &M_M\cdot\ddot{q}_M+K_M\cdot q_M=F_M\\ &F_M=\left[F_{xa},F_{ya},M_{\phi a},F_{xb},F_{yb},M_{\phi b}\right]^{\mathrm{T}}\\ &q_M=\left[x_a,y_a,\phi_a,x_b,y_b,\phi_b\right]^{\mathrm{T}}\\ &M_M=\frac{\rho AL}{420}\begin{bmatrix}140&0&0&70&0&0\\0&156&22L&0&54&-13L\\0&22L&4L^2&0&13L&-3L^2\\70&0&0&140&0&0\\0&54&13L&0&156&-22L\\0&-13L&-3L^2&0&-22L&4L^2\end{bmatrix}\\ &K_M=\frac{EI}{L^3}\begin{bmatrix}AL^2/I&0&0&-AL^2/I&0&0\\0&12&6L&0&-12&-6L\\0&6L&4L^2&0&6L&2L^2\\-AL^2/I&0&0&AL^2/I&0&0\\0&-12&-6L&0&12&-6L\\0&6L&2L^2&0&-6L&4L^2\end{bmatrix}\end{aligned}\right\}\tag{1}$$

where ρ is the density of the micro beam, E is Young's modulus, A is the equivalent cross-sectional area, I is the equivalent moment of inertia.

$$\left.\begin{aligned} &M_M\cdot\ddot{q}_M+K_M\cdot q_M=F_M\cdot W_{\mathrm{L}}\\ &W_{\mathrm{L}}=\begin{bmatrix}\cos\Phi_{DC}&-\sin\Phi_{DC}&0&0&0&0\\\sin\Phi_{DC}&\cos\Phi_{DC}&0&0&0&0\\0&0&1&0&0&0\\0&0&0&\cos\Phi_{DC}&-\sin\Phi_{DC}&0\\0&0&0&\sin\Phi_{DC}&\cos\Phi_{DC}&0\\0&0&0&0&0&1\end{bmatrix}\end{aligned}\right\}\tag{2}$$

where W_{L} is the local rotation matrix, ϕ_{DC} is the rotation angle.

4.2 3D modeller for structure design of micro devices

4.2.1 Data structure of 3D models of micro devices

B-rep (Boundary representation) data structure is widely used in 3D mechanical structure design system, and it can be used conveniently for exchanging the data with the FEA software, such as ANSYS and Cadence, during the MEMS simulation process at the device-level. So in this paper we use a B-rep data structure (shown in Fig. 4) to represent the fundamental 3D model of micro devices.

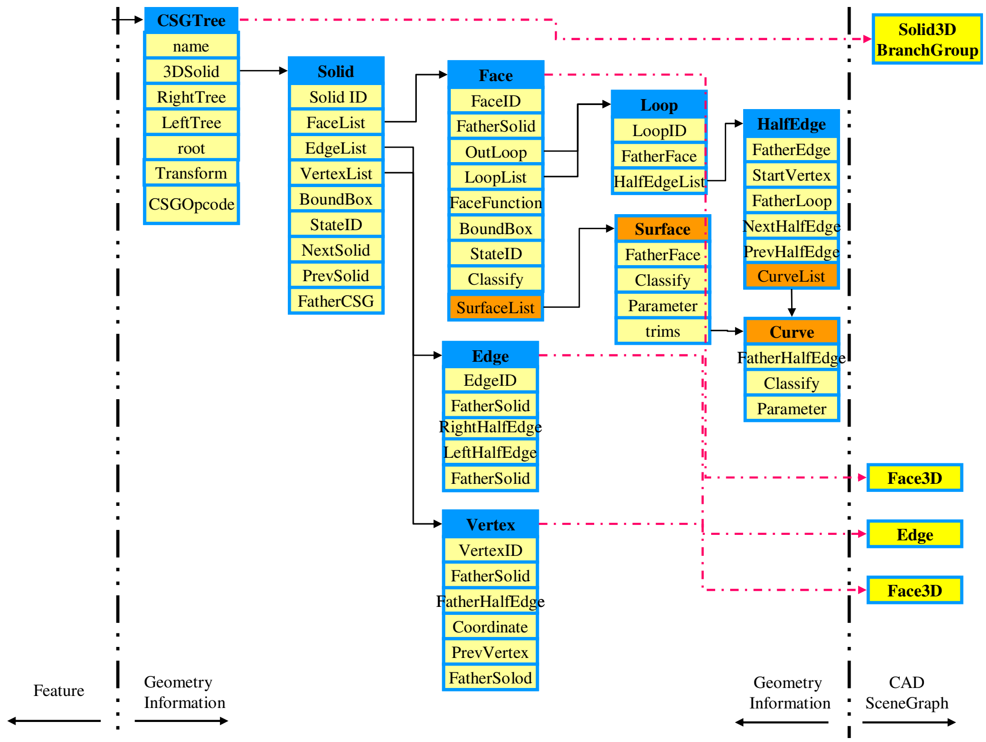
Due to a lack of fabricating abilities of MEMS, complicated geometric elements in MEMS structure design, e.g., freeform curve and surface, which are used widely in macro-mechanical design, can be hardly fabricated by utilizing today's fabricating technologies. So one of the simplest ways to construct the 3D-geometry fundamental elements is to take advantage of boolean binary tree of CSG (constructed solid geometry). Actually, CSG is a 3D modeling method using 3D solid boolean operations. The correspondent geometric model can be expressed as a binary-tree of some fundamental construct elements. Referring to the characteristics of micro devices, we defined four types of fundamental constructing elements, that is, cylinder, block, solid extrusion from the 2D planar mask, and 3D-geometry model of feature node.

Figure 5 shows an example of the CSG model of a micro device and its constructing process. In most cases, CSG binary tree constructed with the above four fundamental elements are sufficient for recording the structure design process of micro devices.

4.2.2 Scene-graph design of 3D model

Scene-graph uses tree structures for rendering the 3D-model and performing the man-machine interaction in a simple way. Figure 6 shows the scene-graph renders a structure of the 3D-model in detail. According to this figure, each face of the solid model is meshed to a triangular array called Face3D, and each edge and vertex are all mapped to the 3D rendering elements called Edge3D and Vertex3D, respectively. Therefore, all of the 3D elements of a solid model are put together in a local coordinate

Fig. 4 B-rep data structure of micro devices



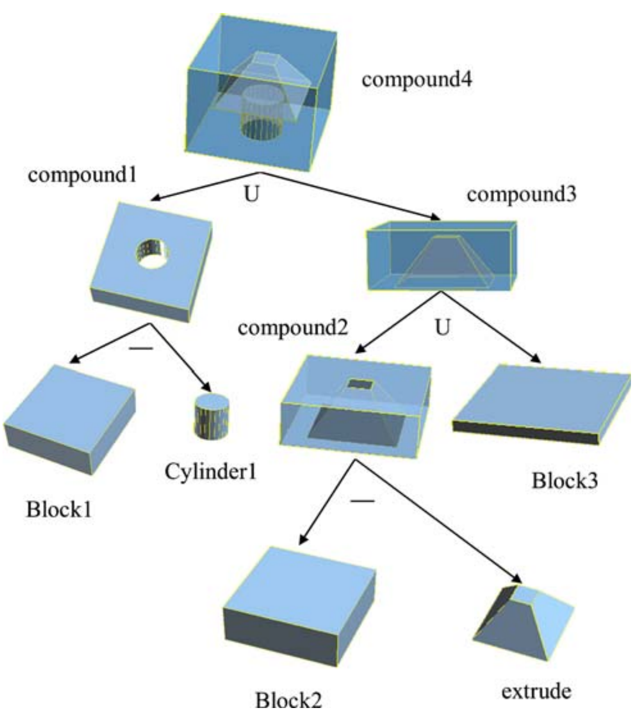


Fig. 5 CSG boolean design tree of micro devices

known as Solid3D. Designers can select, delete, add and modify the solid model through these 3D rendering elements.

4.2.3 Exchange of model and interface for device-level simulation

To get the behaviours of micro devices and feed back to the function design through evaluating their dynamic performance at the system-level, we need to use FEA simulation.

Before accomplishing a fabricating process planning of MEMS device under design, we can hardly get its 3D-model by using traditional design methods. But the execution of the FEA simulation depends on such a 3D-model. In the ''function-to-3D shape-to-fabrication'' design flow, however, the 3D model for simulation can be acquired directly. We used the IGES data exchange standard for the conversion of 3D models. Thus, the B-rep 3DSolid data structure in Sect. 4.2.1 can be easily exported to the correspondent IGES standard elements shown in Fig. 7.

4.3 Feature definition and design rules

4.3.1 Definition of 3D features

The CSG-represented 3D-model can be used conveniently in feature organization and solid construction. But purely CSG-represented micro devices can be hardly fabricated because of lacking the fabrication information. In order to solve this problem,

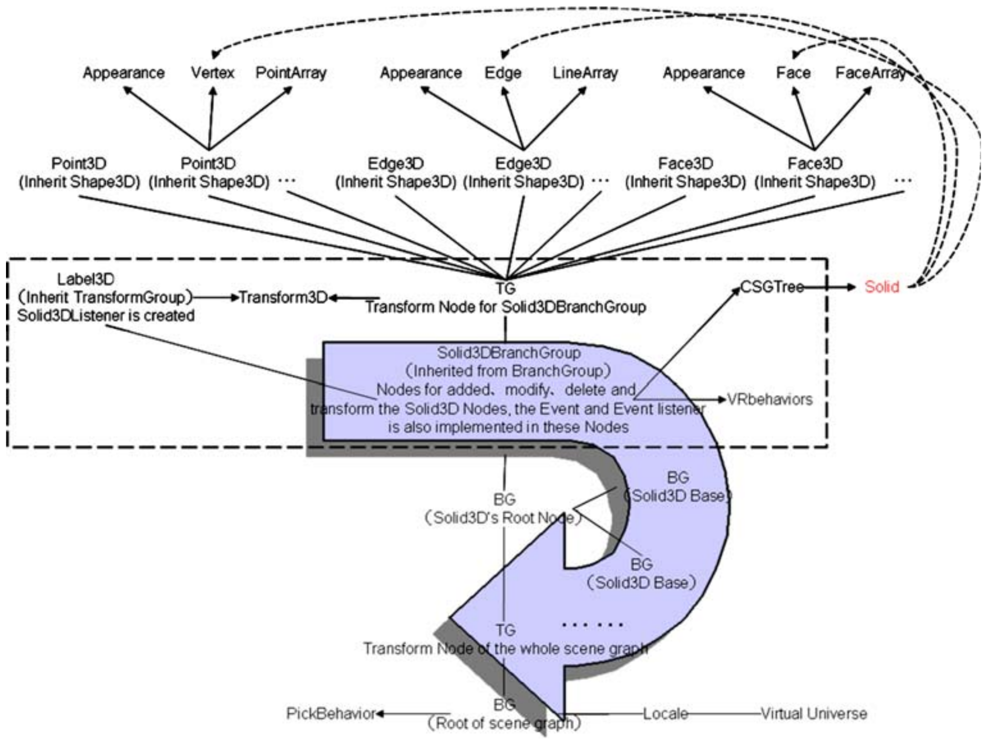


Fig. 6 Scene graph structure of 3D modeller

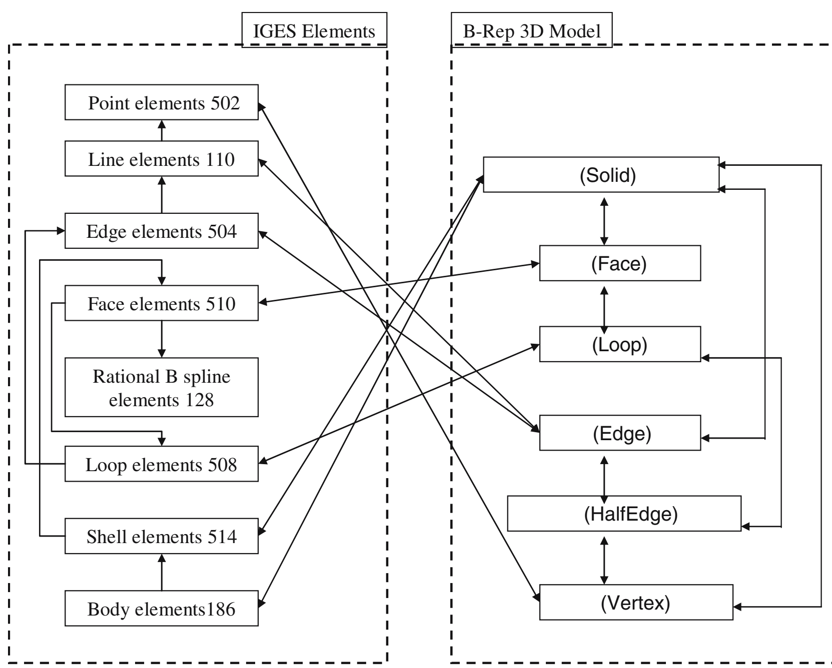


Fig. 7 Micro devices model conversion from 3D model to IGES elements

all 3D-features are defined as fabrication-oriented ones on the top of the correspondent CSG-model. It means that each defined feature is able to map to certain fabrication processes, its parameters also reflect the fabrication parameters, and its 3D geometric model is equal to the 3D-structure of the fabrication. So, in accordance with the fabrication technologies, such as isotropic-etching, deposition, anisotropic-etching, doping, and bonding, we will show several categories of 3D-features and their definitions below.

Substrate feature: This is the base of all features (Fig. 8a). It has only one structure parameter as the thickness (at *z* coordinate) of its 3D-solid, and its

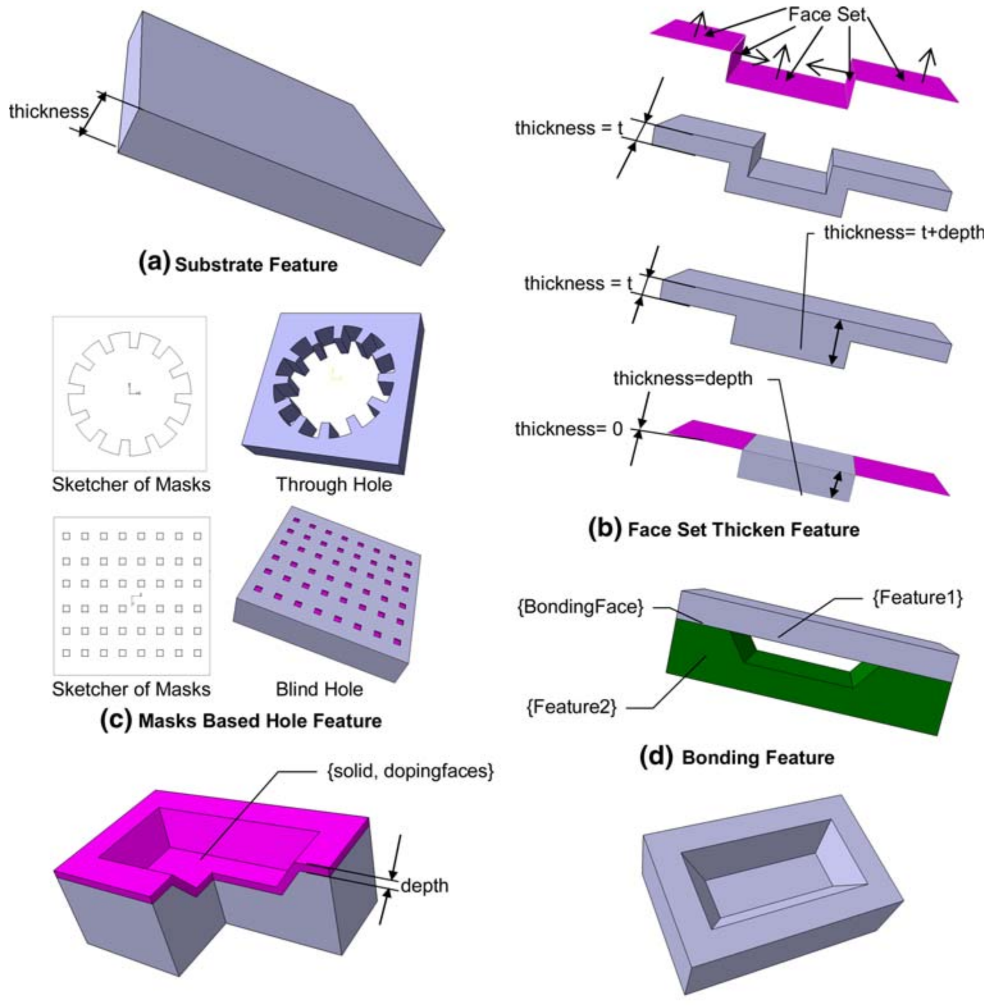


Fig. 8 Fabrication oriented feature nodes

dimension at both x and y coordinates both are all infinite. So we can define this feature as:

F_{sub}(thickness, materials)

Face-set thickness feature: With most surface silicon fabrication processes, deposition is a main method to generate geometric shapes, and those shapes are mostly ''shell''-like. In terms of using the ''face-set thickness feature'', we can build the geometric shapes of all depositing types, such as conformal (e.g., chemical vapor deposition), planar (e.g., electroplating and chemical mechanical polishing) and via (e.g., filling a paste and polishing to the top) as shown in Fig. 8b. Therefore, we define this feature like this:

$F_{fsthick}$({ (face, thickness)} , materials)

There, every face in the face set has its own thickness parameter to represent the above three types of depositions. In the conformal deposition cases, the thickness parameter of each face is conformed to be a certain value. In the planar deposition cases, the thickness parameters of bottom faces are equal to the thickness plus their depth to topper faces. In the via deposition cases, the thickness parameters of bottom faces are exactly equal to their depth while the thickness values of topper faces are zero.

Masks based hole feature: This feature reflects isotropic-etching fabrication technologies. It is constructed with planar masks which are represented with 2D-sketches and etching depth parameter of blind hole in non-through etching cases or non-depth parameter of through hole in through etching cases which are decided with ''isThrough'' parameter (Fig. 8c). Because of that, the isotropic-etching technologies can not only fabricate the structure layers which are designed directly with the features, but can also fabricate sacrificial layers which are deduced by systematic fabrication synthesis. So the etching solids are not limited to the shapes of features, and the common solid model can be used as the base etching shapes of this feature. So we can define this feature like this:

F_{hole}({ base - shape} , sketcher, depth, is Through)

Bonding feature: Wafer bonding fabrication technology is generally used to stick two shapes together. So, in order to construct this feature, two groups of feature shapes and their healing surfaces must be pointed out, and the corresponding definition of this feature is presented below (Fig. 8d).

F_{bond}({ feature1} , { feature2} , { Bonding Face})

Doping feature: The 3D-shapes of the doping area generated by doping technologies are similar to the shell feature in common mechanical feature design, and the remaining shapes after doping can be constructed by a CSG boolean subtract operation from the original 3D-shapes to the 3D-shapes of the doping area (Fig. 8e). The doping feature is this:

F_{dop}({ solid, dopingfaces} , depth)

Anisotropic etching feature: The anisotropic etching of crystalline silicon always results in curious fabrication shapes which depend much on crystallization direction, fabrication depth and fabrication materials (Liu and Zhu 2000). Its 3D shapes can be hardly modeled with common structure design method. So we define this feature below (Fig. 8f), and its 3D shape can be obtained with an anisotropic processing simulator through adopting the cellular automata method (Du 2004).

Fanitech (sketcher, depth, crystallization direction, materials)

According to the feature definition mentioned above, we can draw a conclusion that there are two types of feature parameters. One is 3D geometry parameter like the base face set of ‘‘face-set thickness’’ feature. This type of parameters can be gained with the CSG model. Another is used for fabrication, such as the material parameters and the thick parameter of ‘‘face-set thickness’’ feature. In the next section, the process of constructing a MEMS device using 3D-features defined in this section will be discussed.

4.3.2 Feature information model and its modeling rules

A feature information model organizes all features of a micro device to provide information and convenience for systematic mask synthesis. To construct the feature information model, all features defined in Sect. 4.3.1 are classified into main features and affiliate features. The feature information model of a micro device is organized hierarchically. In the top level, this feature information model of the micro device is made up of the main features and the feature information submodels which can be cascaded down to a large number of main features and affiliate features at the next level by means of classifying rules based on shapes and fabrication methods. Actually, the feature information sub-models are generally obtained with design space mapping from the system-level to the device-level. Affiliated features always adhere to the main features or some other geometric shapes. In fact, each feature has its own description in terms of shape, position, direction, and accessibility. At the same time, it can be mapped to certain fabrication methods based on the fabricating requirements of the micro device. For instance, all ‘‘mask-based hole features’’ may be mapped to different etching operations, but which kind of etching method is used just depends on how to select materials, precision conditions, layer affiliation with other shape features, etc.

Moreover, the feature information model is also a fundamental to form the fabrication sequence with which the 3D structures of the designed micro devices can be generated. For example, an affiliated feature ‘‘anisotropic-etching feature’’ attaching to the silicon ‘‘substrate feature’’ implies that this feature may be fabricated with bulk fabrication method first. And the shapes and parameters of this ‘‘anisotropic-etching feature’’ can also be obtained, depending on the correspondent crystallization direction used in fabrication. In order to reduce the design conflicts in the systematic fabrication reasoning and to accommodate to the fabrication condition, the feature information model needs to be properly built. Therefore, the design rules and design constraints of the feature-based structure design have been drawn up in the following.

Design rules 1: Structure design of a micro device must begin at a ‘‘substrate feature’’, and all features must be located at the front side or back side of this.

Design rules 2: For the main fabrication, the direction must always be perpendicular to the substrate upper plane in silicon-based MEMS fabrication. It means that the height direction of the modeling solids can be parallel with the normal vector of substrate upper plane, and if the rotation operation is needed to be performed in the modeling processes, these modeling solids can only rotate in this direction.

Design rules 3: All features are used to construct the 3D-shapes of structure layers, and the sacrificial layer must be deduced through the systematic fabrication reasoning.

Design rules 4: Due to lack of fabrication details, the resulting shapes of CSG-modeling can only be used for the construction of basic geometric elements of a feature, i.e. CSG-modeling process can construct the face-set of ‘‘face set thickness feature’’. It cannot be transferred to the fabrication deduction.

Design rules 5: All features are divided into main features and affiliate features. The main features include ‘‘substrate feature’’ and ‘‘face-set thickness feature’’. They are relatively independent of each other, and other features have to be affiliated to them. Only the main features can add material to form the structure model of a micro device under design. The affiliate features consist of ‘‘masks-based hole feature’’, ‘‘doping feature’’, ‘‘anisotropic-etching feature’’ and ‘‘bonding feature’’, and must be affiliated to some other 3D-shapes. The affiliate features often take out material from the structure model of a micro device under design or two micro components bonded together.

4.4 3D-structure design flow

4.4.1 Feature mapping from function to structure

The 3D-structure design flow is based on top-down methodology, and its main working logic is from the functional conceptual and system-level design to the 3D-feature represented structure design and finally to systematic fabrication deducing. There are two key conjunctions, which are how to map the conceptual and system-level design result (in this paper, the system-level design result is a dynamical simulation model represented by a bond graph model) to the device-level 3D-structure design process, and how to construct a feature information model to support systematic fabrication deductions.

To perform the function/3D-feature mapping operations, a macro script language is introduced. The syntax of this macro script language is similar to java script language. In the paper, we have used bean shell (http://www.beanshell.org) script language parser to handle the function/3D-feature mapping processes. Figure 9 shows the macro script for the micro beam function/3D-feature mapping and behaviour extraction from the device-level to the system-level.

As shown in Fig. 9, the mapping script can be divided into three parts. The first part is used to define the 3D-feature information sub-model of the micro components; the second part describes the bond graph represented function model; the last part mainly concentrates on how to convert the simulation parameters of function elements to the geometric and material parameters of 3D-features, and the reverse processes for extracting the behaviours of the micro device are also included in this part.

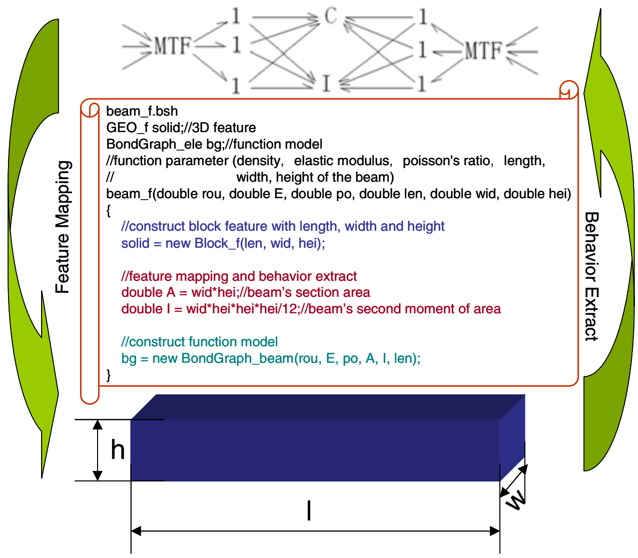


Fig. 9 An example of feature mapping from system-level to device-level

4.4.2 Systematic fabrication deducing supported 3D structure design

The purpose of using manufacturability evaluation and fabrication analysis feedback from the systematic fabrication deducing at the fabrication-level is to make 3D feature based structure design of micro device acceptable. Thus, the feature information model of the micro device must be organized to support the systematic fabrication deducing. In order to illustrate how to use the feature information model defined in Sect. 4.3 to create the geometric model of a micro-device with the design rules, and how to support the systematic fabrication deducing by using the feature information model, we just present an example about constructing the feature model of a kind of temperature sensor from its structure schema gained from the functional design at the conceptual-level in Fig. 10. This feature model also implicitly demonstrates the modeling process of this sensor referring to selecting feasible features and combining them together. Here, the structure diagram obtained from the conceptual design is presented on the top of Fig. 10. According to the hierarchical feature classification, as shown on the bottom of Fig. 10, the features which are selected to represent the temperature sensor can be put into a kind of multi-branch

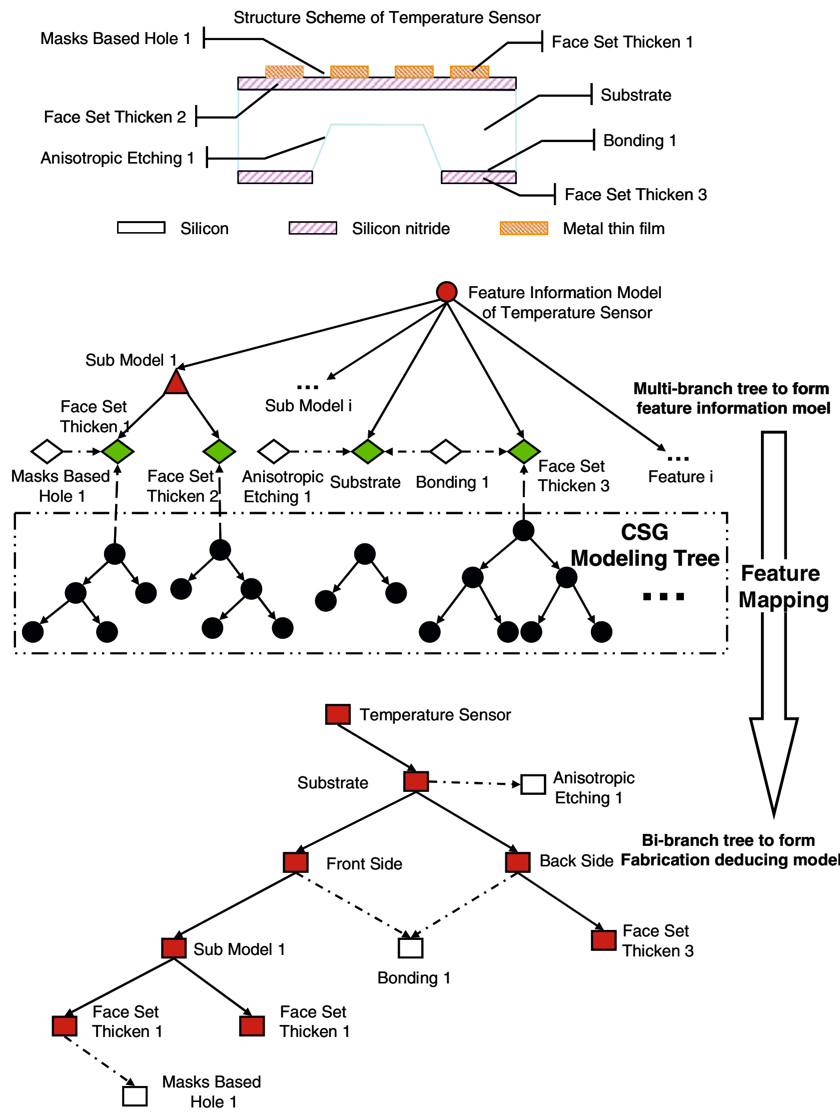


Fig. 10 Feature information model for design mapping

feature tree model. Each feature layer in this tree model of the sensor deals with either/both the cross section feature or/and upper the 2D layout feature. For example, the feature of ''face set thicken 3''is connected with the substrate with the affiliate feature ''bonding 1''. This ''face set thicken 3'', whose material is SiN and the thickness is 1 μm consists of a rectangle cross section feature and a rectangle upper 2D layout feature, and also attaches an affiliated feature named ''masks based hole 1''. Moreover, the substrate layer is constructed with a rectangle upper 2D layout feature and an affiliated blind-hole feature is panelled on this substrate. In this way, the topological structure of the layers is constructed with features. For convenient computer processing, the multi-branch feature tree model of the sensor needs to be transformed to the correspondent binary-branch feature tree model. As to the geometric information of this sensor, it should be put in referring to the correspondent shape dimensions and position parameters of selected feature. In addition, the fabrication information related to the selected features must be also determined based on the fabrication requirements of the sensor.

5 Case studies

On the basis of analyzing the design framework and its key enabling techniques for 3D feature based structure design of micro devices, this paper presents and builds a prototype of 3D feature modeler for MEMS structure design. This 3D-feature modeller is developed with Java programming language, and the 3D-device model can be manipulated and rendered in Java3D scene-graph. A snapshot of this software prototype is shown in Fig. 11.

According to the structure design framework and the key enabling techniques mentioned above, an example to illustrate 3D feature represented structure design procedure is presented.

Following the top-down design flow, the feature modeling process is demonstrated in Fig. 12. All modules of this MEMS system-level simulation platform and device-level modeling tools are written in Java programming language and the 3D design scene-graph is constructed on the top of Java3D.

The micro device in this example is a micro gap-closing actuator, which was a standard test micro device in SUGAR (Bai et al. 2001). The design flow can be described as below. First of all, the bond graph diagram represented functional model is built according to the design conceptual (see Fig. 12a, b), and function oriented feature library is used during the function model constructing. If some elements do not appear in the function oriented library, macro script must be down to subscribe those types of elements. So the final model can also be described by macro script language. And then the functional model will be simulated and optimized to satisfy the design conditions (in Fig. 12c). This process is called the system-level design. In this example, the optimized parameters of the system-level model are presented in Table 1 (Liu et al. 2005).

Functional nodes, which make-up of the system-level models, are combined tightly with the geometric features. The structure model can be easily constructed

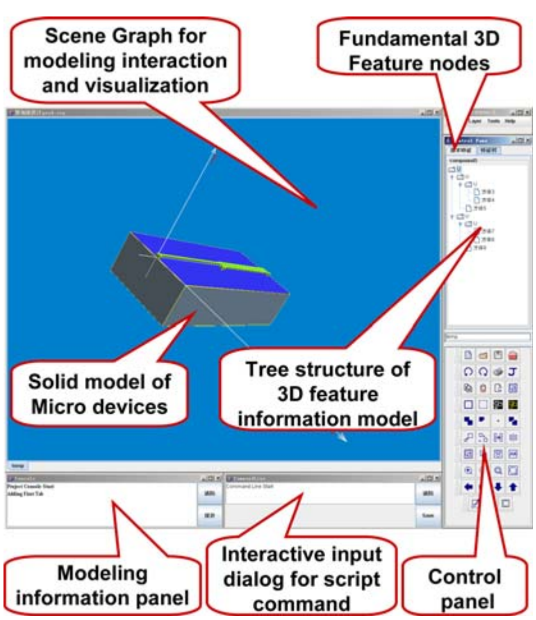


Fig. 11 A snapshot of 3D feature modeler

in terms of mapping the system-level functional nodes to the device-level structure features(see Fig. 12d). The dynamic performance of this macro device can also be simulated by FEA software or some other simulation methods through the 3D model exporting to the IGES format files. If there are design problems and conflicts in modeling or simulation result, the behaviours of the device-level can be extracted to the macro script so as to adjust the system-level models or parameters. After several cycles of design iterations, at last, the final design result can be obtained and delivered to the fabrication process.

However, it should be declared that the redesign process and stochastic node insertion described above have not illustrated explicitly in this example. In a complex design case, actually, the design process should strictly obey the properly design chain to reduce design iteration and shorten developing time.

6 Conclusions

In this paper, we present a kind of 3D-feature-based structure design framework for micro devices to perform MEMS top-down design method which deals with ‘‘function-to-3D shape-to-mask’’ design flow, and verify its feasibility through developing and running the correspondent software prototype. The characteristics of this work include three aspects:

- Lumped multiport field and junction structures of bond graphs are used as the output of the conceptual function design so as to perform the feature mapping from the conceptual function model to the 3D feature sub-model of micro-components through macro script language
- CSG boolean design tree and B-rep 3D solid data structure are introduced in 3D modeling processing, solid model representation and data exchange for the device-level FEA simulation
- Fabrication oriented feature nodes are defined and classified. Obeying the fabrication-oriented design rules, the hierarchical 3D-feature information model, which is used in systematic mask synthesis and manufacturability checking, is constructed with those feature nodes.

Future work will concentrate on the following aspects:

- Develop the collaborative design environment and study the concurrent design mechanism so that the cooperation of conceptual and system-level designers, structure designers and fabrication researchers can be carried out

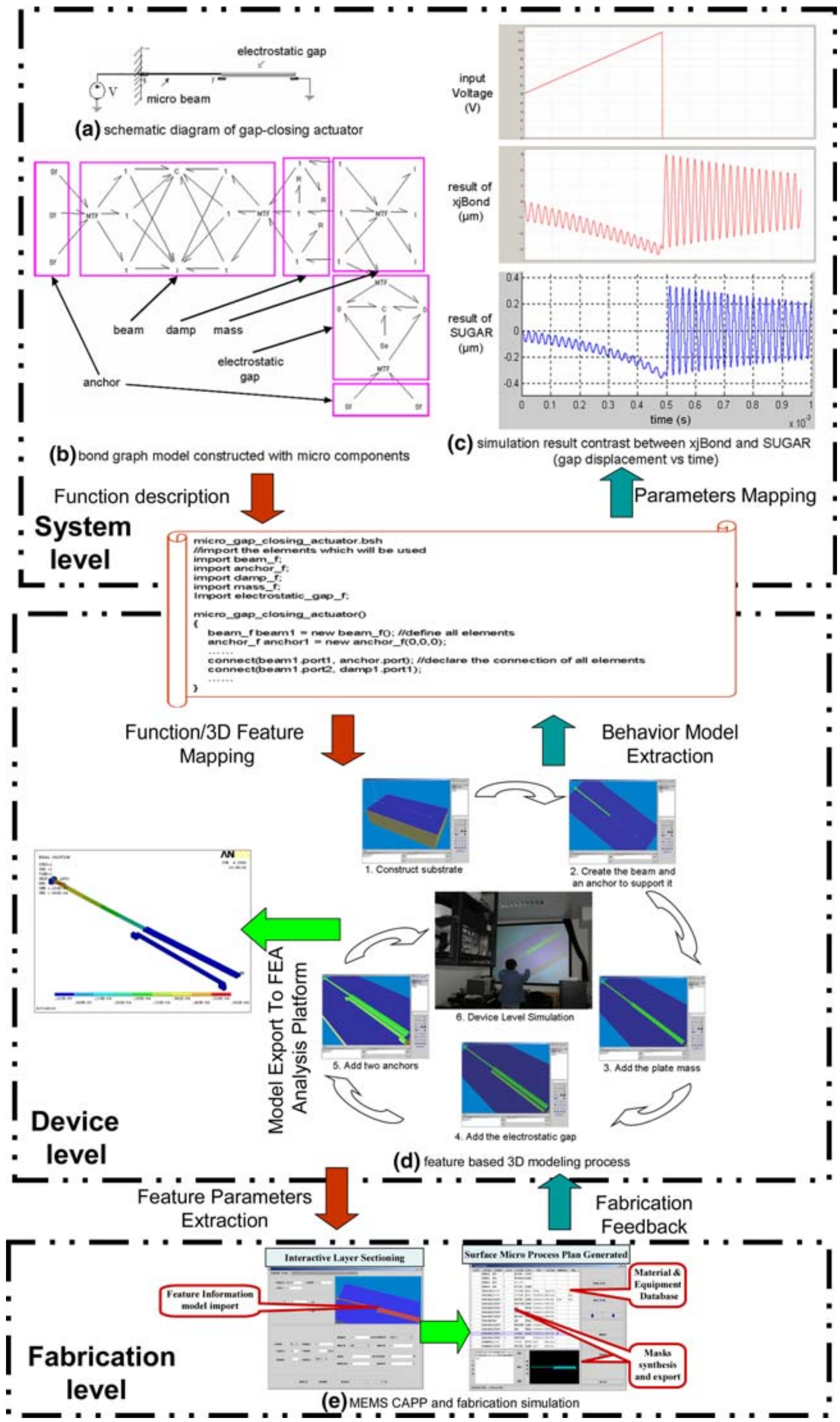


Fig. 12 A running example and corresponding working flow

Table 1 Physical parameters and optimized structure parameters of micro gap-closing actuator

Structure parameters (μm)	Optimized value	Physical parameters	Value
Length of beam	100	Density kg/m^3	2,330
Width of beam	2	Poisson's ratio	0.22
Thickness of beam	2	Young's modulus GPa	1.69
Length of electro-static gap	100	Damping coefficient μN(m/s)$^{-1}$	0.015
Width of electro-static gap	2	Dielectric constant pF/m	8.85
Thickness of electro-static gap	5		

- Study on persistent naming mechanisms of micro feature nodes and 2D/3D-feature constraints solving so as to make the design modification more convenient for redesign processes
- Integrate schematic analysis at the system-level, structure design at the device-level and mask deduction at the fabrication-level together so as to fit the framework of the feature information model more tightly.

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References

Antonsson EK (1996) Structured design methods for MEMS final report. California Institute of Technology, USA

Bai Z, Bindel D, Clark J (2001) New numerical techniques and tools in SUGAR for 3D MEMS simulation. In: Technical proceedings of the 2001 international conference on modeling and simulation of microsystems, Orlando 1:31–34

Du HX (2004) Bulk micromachining of silicon physics simulation. Master thesis, Xi'an Jiaotong University, Xi'an

Fedder GK (2000) Top-down design of MEMS. In: Proceedings of the international conference on modeling and simulation of microsystems (MSM 2000) (27–29 March, 2000)

Finch N, Marchetti J, Fujita H, Gouy JP (2000) CAD modeling of scratch drive actuation, Design, modeling, and simulation in microelectronics 4228:83–89

Gabbay LD (1998) Computer aided macromodeling for MEMS, Thesis of Ph.D., MIT, USA

Gao F, Hong YS, Sarma R (2003) Feature model for surface micro-machined MEMS. In: Proceedings of ASME design engineering technical conferences, Chicago

Gunar L, Arthur M, Issam L (2001) Top-down design flow for MOEMS Proc SPIE 4408:126–137

Jack WJ (2001) Microelectromechanical systems (MEMS): fabrication, design and applications Smart Mater Struct 10:1115–1134

Johnstone RW, Shimizu T, Parameswaran M (2005) Symbolic finite element analysis for parametric studies. In: Technical proceedings of the 2005 NSTI nanotechnology conference and trade show 3:585–588

Li JH, Gao SM, Liu YS (2005) Feature-based process layer modeling for surface micromachined MEMS. J Micro Mech Micro Eng 15(3):620–635

Liu Z, Jiang PY (2006) Systematic method for generating manufacturing process flow of micro devices based on feature technology. In: International conference on frontiers of design and manufacturing, Guangzhou

Liu C, Zhu ZJ (2000) Micromachining process simulation using a continuous cellular automata method. J Microelectromech Syst 9(2):252–261

Liu Y, Jiang PY, Liu Z (2005) Dynamic system modeling and simulation using bond-graph-based micro-components library for microelectromechanical systems. J Xi'an Jiaotong University 39(7):744–748

McCorquodale MS, et al (2003) A top-down microsystems design methodology and associated challenges. In: Proceedings of the design, automation and test in Europe conference and exhibition, Berlin 1:292–296

Senturia SD, Harris RM, Johnson BP, Kim S, Shulman MA, White JK (1992) A computer-aided design system for microelectromechanical systems. IEEE/ASME J Microelectromech Syst 1:3–13

Tamal M (2003) MEMS design and verification, test conference, proceedings. ITC 2003 Int 1:681–690

Vandemeer JE (1998) Nodal design of actuators and sensors, Technical Report. Carnegie Mellon University, Pittsburgh

Wong G (2004) Behavioral modeling and simulation of MEMS electrostatic and thermomechanical effects, Thesis of M.S., Carnegie Mellon University, Pittsburgh