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Mask synthesis and verification based on geometric model for surface micro-machined MEMS*

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Abstract: Traditional MEMS (microelectromechanical system) design methodology is not a structured method and has become an obstacle for MEMS creative design. In this paper, a novel method of mask synthesis and verification for surface micro-machined MEMS is proposed, which is based on the geometric model of a MEMS device. The emphasis is focused on synthesizing the masks at the basis of the layer model generated from the geometric model of the MEMS device. The method is comprised of several steps: the correction of the layer model, the generation of initial masks and final masks including multi-layer etch masks, and mask simulation. Finally some test results are given.

Key words: MEMS, CAD, Geometric model, Layer model, Mask synthesis, Surface micromachining
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INTRODUCTION

When designers develop microelectromechanical system (MEMS) devices with the traditional approach, they should devise the mask-layouts and fabrication process instead of the function and shape of the MEMS device. The geometric model of the MEMS device is then derived based on the simulated fabrication according to the devised mask layout and the process. This is analogous to generating a geometric model from the NC tool paths in the macro world. Obviously it is unintuitive and very difficult for the designers, especially when the structure of the MEMS device is complicated. Recently researchers start to investigate the structured design methods for MEMS, aiming at separating the design of MEMS from its process planning and fabrication (Antonsson, 1996). For the design of MEMS devices, a feature-based design method was proposed in Gao (2004). However, the research in this area is in its infancy and need to be further studied.

A new schema for the design and fabrication of MEMS devices was proposed as shown in Fig.1, aiming at enabling designers to concentrate on creative design activity without considering the tedious fabrication process. In the schema, the traditional CAD systems can be used to design the shape of the MEMS device instead of professional MEMS CAD systems. And remarkably, the process models of the MEMS device including mask-layouts and fabrication process can be generated based on the devised geometric model through mask and process synthesis. Thus, mask and process synthesis as well as mask verification is the key step in the schema.

Mask and process synthesis refers to automatically generate appropriate mask layouts and fabrication process description from the geometric model. However in the traditional approach, the mask layouts are given directly by the designer. Antonsson (1996) proposed a function-to-shape-to-mask process focused on bulk micromachining. An algebraic approach was presented for automatically generating masks given the geometric model of a MEMS device and the process sequence in refining the initial design (Ananthakrishnan *et al.*, 2003). In their approach, the geometric problem of mask synthesis is reduced to a system of linear equations. However, their solution

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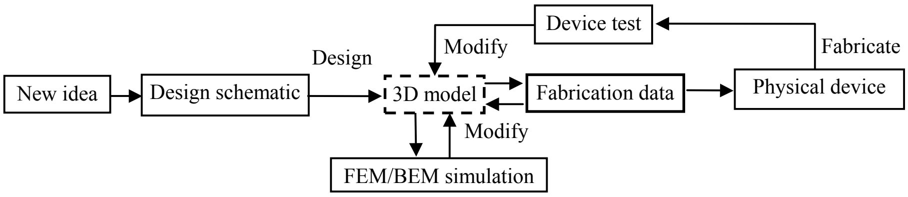

Fig.1 A new schema for MEMS device design

did not involve the property of materials, and is limited to volume modelling. In the feature-based design method (Gao, 2004), the mask layouts are generated from the fabrication features mapped from the design features. But, with this method, the design is still focused on layers of a MEMS device and there is need to develop a specific design tool.

In the proposed schema, a novel method of mask synthesis and verification for widely-used surface micro-machined MEMS is proposed whose overview is shown in Fig.2. In this method, the geometric model of the MEMS devices is preprocessed to automatically get the layer model that includes all the process layers involved in the fabrication of a MEMS device (Li *et al.*, 2005). After that, the mask and process synthesis based on the geometric model is reduced to that based on the layer model. In consequence, the process of mask synthesis and verification can be outlined into four steps: the correction of the layer model, generation of the initial masks and process sequence, generation of the final masks and process sequence including multi-layer etch, and simulation of the masks and process sequence. Here there is no any information about initial masks and process description. Especially, the current method is limited to the MUMPs (Koester *et al.*, 2002). In MUMPs, multi-layer etch is exactly based on the material property, i.e. it is etch-to-material etch which etches through more than one layer having the same material property until a different material is reached.

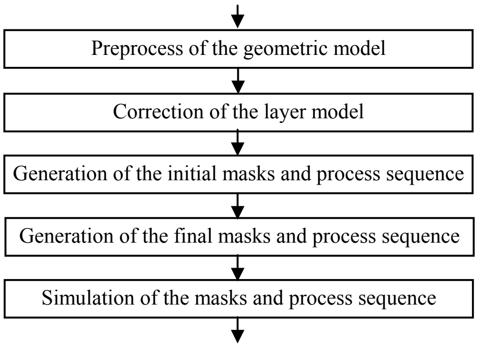

Fig.2 A schematic overview of the proposed method

The first step, the correction of the layer model, is to accurately express the influence of etch-to-material etch in layer model, and then to evaluate the manufacturability of the layer model.

Generally, for an etch-to-material etch which etches two layers L_1 and L_2, the layer between L_1 and L_2 should not appear in the etching area. However, the sacrificial layers that are completely generated in layer modelling may occupy the etching area of some etch-to-material etch. So the influence of etch-to-material etch should be accurately expressed through correcting the layer model. Analyses of the characteristics of sacrificial layers and etch-to-material etch show two specific properties that can be used as the criteria for correcting the layer model:

(a) The contact area of the two structural layers (called L_1 and L_2) between which there is a sacrificial layer (called L_3) should not overlap any solid of L_3, and the area where the L_1 need to be supported and the area the L_2 need to be protected should overlap or be overlapped by a sacrificial layer.

(b) There is a hint between the solid model and the corresponding layer model for the etch-to-material etch, i.e., one vertical face in the solid model corresponding with some faces in the layer model. And the projection of the specific face on the MBF (the top face of the substrate of a MEMS device) is called the dividing line. As shown in Fig.3, the face F_1 and face F_2, as well as the edge E_1, are the hints of

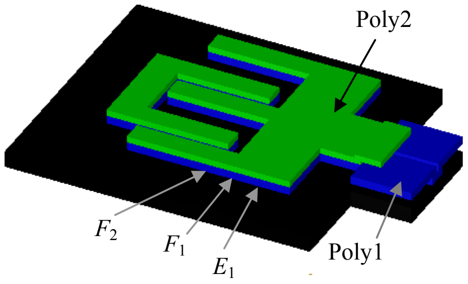

Fig.3 The hint of etch-to-material etch

one etch-to-material etch which etch both Poly1 and Poly2.

Based on the above properties, the correction of the layer model is described and divided into three steps for the three layers: (1) If the boundary on one sub etching area consists of all dividing lines, it is a multi-etching area; (2) If the boundary on one sub etching area involves some dividing lines, keep or delete the specific area in the above property (a), and the remaining part is a multi-etching area; (3) All the multi-etching areas are removed from the sacrificial layer.

It is noticeable that the layer model should be corrected once the sacrificial layers are created.

After the layer model is corrected, it must be evaluated to avoid manufacturability problems. The manufacturability of layer model involves the release of sacrificial material, the contact of all layers and the manufacturability of etching, etc. If there is any manufacturability problem, some redesign suggestions are generated based on evaluation results and the interference solid which records the evaluation information, and presented for the designer to refine the initial design.

The second step is to generate the initial masks and process sequence that are based on the layers in the layer model without manufacturability problems. Specially, the masks are created from the solids of the layers, and the process sequence is based on the layer sequence of the layer model, which is comprised of a list of process items including the type of the operation, the height, material, etc. In addition, each layer in this study is regarded as one deposit operation, an etch-to-layer etch and/or the combination of several etch-to-depth etches. Obviously the deposit operation needs no mask. The mask of the etch-to-layer etch is directly generated through projecting the solid of the layer onto the MBF. The masks of the etch-to-depth etch are generated by the following three steps: (1) Get the etching body; (2) Project the etching body onto the MBF to generate the etching area; (3) Perform a Boolean subtract on the depositing region and the generated etching area.

All the process items of the process sequence are created according to the type of operation.

In this step, the etch-to-material mask and process item is not considered. And it is noticeable that not all etch-to-layer etches created in this step are exactly the wanted etch-to-layer etches, and among them, some may not be single-layer etches. Therefore the masks and process sequence should be refined to include multi-layer etch mask based on the initial masks and process sequence.

For the etch-to-material etch, it can be seen that there is a specific property: supposing there are three layers L_1, L_2, L_3, and L_1 has the same material property as L_3, if there is an etch-to-material etch which etches both L_1 and L_3, the following cases must appear: (1) Intersection area I of the etching areas (the complement of the mask) of L_1 and L_2. A sub area F_1 of I is equal to a sub area F_2 of the etching area of L_3. Here, F_1 and F_2 are created in one etch-to-material etch; (2) A sub area F_1 of I is less than a sub area F_2 of the etching area of L_3. Here, F_1 and F_2 are created in one etch-to-material etch, but L_3 is more etched than L_1; (3) The other cases do not reflect any etch-to-material etches.

Based on the above analyses, an algorithm is developed to generate multi-layer etches masks and the final masks and process sequence through the Boolean operation of the etch-to-layer masks and etching areas. The process is illustrated with an example shown in Fig.4, where (a)~(c) are three initial masks for three different layers, and the etching area of Poly2 and the intersection of the etching areas of Poly1 and Ox2 are respectively shown in (d) and (e). And the final mask of Poly1 is shown in (f) while the process item related to Poly2 etching is changed an 'etch-to-material' type of etch.

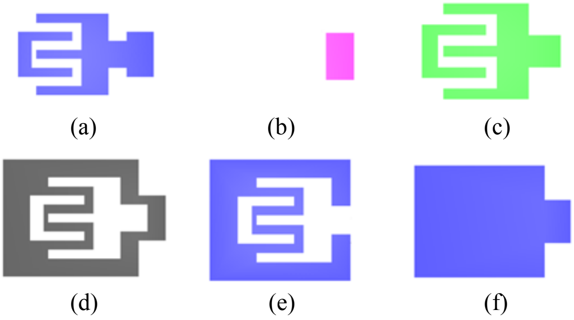

Fig.4 The generation of the final mask: (a) Initial mask of Poly1; (b) Initial mask of Ox2; (c) Initial mask of Poly2; (d) Etching area of Poly2; (e) Intersection of the etching areas of Poly1 and Ox2; (f) The final mask of Poly1

Once the final masks and process sequence are created, the process sequence is output to a process descript file which can be further used to conduct mask verification.

Mask verification is used to verify the accuracy of the created masks and process sequence. Essentially, mask verification is a simulation process of the mask generation based on the fabrication sequence. And the simulation result is provided to the designer to determine whether the generated masks are correct or not. Different from other works (Koppelman, 1989; Osterberg and Senturia, 1995; Dixit *et al.*, 1997), the emphases of the mask verification here is to test whether the etch-to-material and etch-to-layer is operated successfully based on the material property.

An algorithm is also developed for mask verification. The input of the algorithm is the process descript file and masks. When conducting mask verification, an intermediate model is maintained for depositing operation and two potential etched solids of two different materials are maintained for etch operation. For each layer, the solid is created based on the intermediate model and then the solid and the potential etched solids are "etched" by the etch operations. The result of the simulation is a process layer model for comparison with the layer model generated from the geometric model.

The algorithms were implemented with Microsoft Visual C++ and the geometric engine ACIS 6.0 and tested respectively. A micro actuator shown in Fig.5 is used as a test example. The solid model of the micro actuator is shown in Fig.5a, and the initial layer model and corrected layer model are respectively in Fig.5b and Fig.5c. The created masks are shown in Fig.5d. The simulation results before release and after release are respectively shown in Fig.5e and Fig.5f.

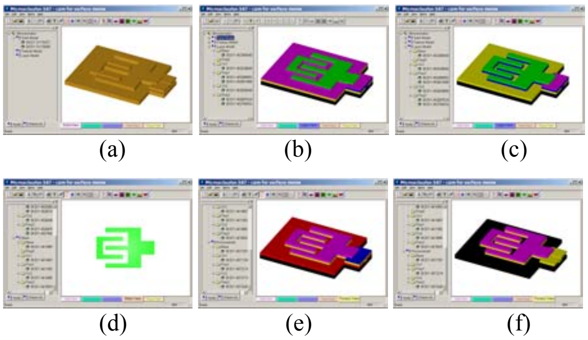
(a) (b) (c)
(d) (e) (f)

Fig.5 Mask synthesis and verification of a micro actuator: (a) Solid model; (b) Initial layer model; (c) Corrected layer model; (d) Masks; (e) Simulating result (before release); (f) Simulating result (after release)

In summary, we have introduced a systematic method for mask synthesis and verification based on the geometric model for surface micro-machined MEMS. The main contribution of the paper is that the masks can be generated directly from the geometric model and the fabrication data can be output straightforwardly. In addition, compared with other methods for mask synthesis, the multi-layer etches based on material property are also considered. In future work, the method will be enhanced in robustness, and the schema together with the method will be extended to more surface micro-machined processes, even for other MEMS processes.

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