A New, Topology Driven Method for Automatic Mask Generation from Three-Dimensional Models

R. Schiek* and R. Schmidt**

Sandia National Laboratory, Computational Sciences Department,
P.O. Box 5800, Albuquerque, New Mexico, 87185-0316, USA,
*rlschie@sandia.gov, **rcschmi@sandia.gov

ABSTRACT

Given a three-dimensional model of an object, the algorithm presented in this work derives the two-dimensional mask set required to manufacture the object in a surface micromachining process. Currently, designing a surface micromachined MEMS device requires the creation of a process dependent mask set describing how various layers of material are used to construct the device. This work describes an algorithm that infers from the horizontal, cross-sectional topology of a three-dimensional model, the masks required to fabricate the device. Such inferred masks are general in nature and are fitted to a specific production process if data describing the process's mask requirements are available; data for Sandia's SUMMiT V process is used in the current work. This work allows a MEMS designer to focus on creation of a three-dimensional model of their device rather than the masks required by different production processes.

Keywords: automatic mask generation, MEMS design, geometric modeling, topology, SUMMiT V

1 DESIGN PROBLEMS IN SURFACE MICROMACHINING

Designing a device for production by silicon micromachining is quite different from macro-scale mechanical design. In the macro-scale it is often sufficient for a designer to create a 3D model of their device, which a design program could then translate into the tool paths needed to produce it. For a silicon micromachined device, the designer must create a set of process specific masks needed to fabricate the device. Creating such masks is the equivalent of requiring the macro-scale designer to design the tools needed to fabricate their product as well as the product itself. Because masks are dependent on the process in which they are used and can have complex interactions within a production system, creation of the masks is a significant challenge to innovative device design and the manufacture of a device on multiple processes. Thus it is necessary and desirable to develop a method to translate a designers 3D model of a product directly into the masks needed to produce their product.

Earlier efforts on this problem have leveraged existing technology in process simulators, i.e. programs which when supplied with a mask set for a given process can simulate fabrication from those masks. Typically, this approach uses a trial mask set to produce a 3D object that is then compared to the desired object. Differences between the two objects are used to alter the trial mask set and then the process is repeated until a mask set is found which correctly produces the desired part. [1,2] Being computationally intensive, this approach has yet to produce masks for complex, multi-layer surface micromachined devices. Another approach starts from a 3D model that is annotated with data which describes when in the process each section of it will be made and from each annotated section a mask is derived. [3] More recently progress has been made on a geometric approach where a 3D model is interrogated for features that can be made via surface micromachining, and a mask set is derived for these features [4]. While promising, such an approach cannot produce masks for specific processes nor handle isotropic etching processes such as wet etches.

2 SURFACE MICROMACHINING

Motivation for an alternative approach can be found in consideration of the process steps typical of surface micromachining. For example, to produce the simple part shown in figure 1a, two layers of deposited material and two masks are used. First, a layer of silicon dioxide is deposited (silicon dioxide is commonly used as a supporting material since it can easily be removed at the end of the process) and a mask is used to define the region of silicon dioxide to be retained as shown in figure 1b. Unmasked silicon dioxide is etched away resulting in the structure shown in figure 1c once the mask is removed. Next, a layer of polysilicon is deposited. As before, a mask is used to define the region of polysilicon to retain during the next etch; see figure 1d. Etching the extraneous polysilicon and removing the mask produces the part shown in figure 1e. Finally, removal of the sacrificial silicon via chemical dissolution reveals the final, desired part as depicted in figure 1f.

Considering the production of this simple device, one can identify two, horizontal cross-sections in the 3D object which directly correlate to the masks used to manufacture the device. First, the narrow cross section of the post relates to the mask used to etch the sacrificial oxide. Second, the cross section of the larger top directly correlates to the mask used to produce the top section.

Therefore, if important cross sections can be identified in a 3D model, then these cross sections can be used to create masks to manufacture the device.

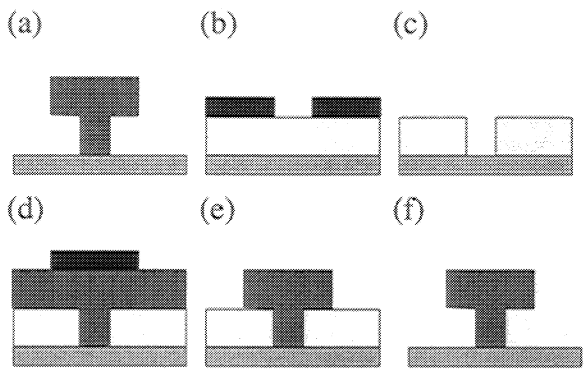

Figure 1: Surface Micromachining of a simple part. (a) Target polysilicon part on a silicon substrate. (b) A sacrificial oxide layer is deposited and a mask is placed on the oxide surface. (c) The oxide is etched and the mask removed. (d) Polysilicon is deposited and a mask placed on it. (e) Extraneous polysilicon is removed and the mask is removed. (f) The sacrificial silicon oxide is removed leaving the part.

3 TOPOLOGY IN SURFACED MICROMACHINED DEVICES

Whereas inferring the masks needed to fabricate the simple part shown in figure 1 is straightforward, a more analytical approach is required for complex devices. In analyzing the cross sections of a 3D model, three aspects are critical: topology, equivalency and area.

First, the cross sectional topology describes the connectivity or relationship between various cross sections. For the part shown in figure 1, the cross section of the top section remains constant until it connects to the cross section of the bottom post; the post then connects to the silicon substrate. Thus, if the cross section of the top section is represented by "A" and the cross section of the lower section is represented by "B" then the topology of this object is simply A is connected to B which connects to the ground (A $\rightarrow$ B $\rightarrow$ ground). The structure, A $\rightarrow$ B $\rightarrow$ ground, is hereafter referred to as a *topology tree*, or *topology graph* and A and B are considered *nodes* on that tree or graph.

The second important criterion is equivalency. The cross section representing the top section of the part in figure 1 could be taken at any position along the vertical axis within that top section. All cross sections within the top section of this part are identical and equivalent because the intersection and union of any pair of cross sections yields the same cross section.

The final important criterion with which to characterize a cross section is its area; which can also be used to infer some mask requirements. Given topology, equivalency and area, one can infer masks by a process described in the next section.

3.1 Relating topology to mask design

Once a description of a 3D model has been rendered into a topology tree, the masks needed to construct the device can be assembled. First, the cross sectional topology tree must be free of neighboring masks that are equivalent. Such cross sections are redundant and their omission from the topology simplifies the analysis. The identification of masks from a topology tree proceeds based on a given cross section's area and its topological neighbors' area. If A, B and C are topologically connected cross sections in the tree A $\rightarrow$ B $\rightarrow$ C and the notation area[A] denotes the area of cross section then the following heuristics can be used to categorize topology tree nodes:

Relationship	Node category
area[A] > area[B] < area[C]	B is a local minimum
area[A] < area[B] > area[C]	B is a local maximum
area[A] > area[B] and area[C] = 0	B is an ending minimum
area[A] < area[B] and area[C] = 0	B is an ending maximum
area[A] < area[B] < area[C] or area[A] > area[B] > area[C]	B is a connection

Table 1: Categorizing cross sections.

After categorizing the nodes, several inferences can be made. First, all local minima can be considered boundaries between successive structural layers in a multilayer process. For example, if two different depositions of polysilicon are used in a given process, then the local minima in a structure tend to occur where holes are needed in the intervening sacrificial oxide layer to connect the two polysilicon layers. This is not an absolute rule as one could always laminate two structural layers; such a design aspect will be captured later in this analysis. Lamination aside, local minima typically connect different deposition layers.

Next, the locations of all the local minima within a topology tree can be identified and recorded. These locations signify boundaries between different depositions in the manufacturing process. In a deposition zone, i.e. in the region between two deposition boundaries, the local maximum corresponds to the polysilicon mask used for this object.

Additionally, a deposition zone can contain an ending minimum or maximum. Such features uniquely identify special process masks used to produce *dimples* and *undercuts* respectively. Dimples are small protrusions of polysilicon typically under a large flat surface that do not connect to the surface below them. Dimples prevent adjacent surface adhesion by keeping such surfaces apart during release. Undercuts are used for rotating joints like pin joints and hubs for gears. These require an isotropic etching step but are topologically distinct, and thus easy to locate. Identification of ending minima or maxima in a topology tree leads directly to the identification of dimple and pin joint masks respectively.

3.2 Process influences

Identifying masks only from a topology tree will produce a very generalized mask set, not one fit for a specific process. The next step is to reconcile the set of candidate masks generated from the topology tree analysis with the mask requirements of a given process.

A surface micromachining manufacturing process will typically have a fixed order in which layers are deposited and fixed thicknesses on each layer. As such, the process will expect masks in a predetermined sequence. This process sequence is compared to the sequence of masks in the candidate mask set derived earlier. Certain mathematically allowed operations can be performed on the candidate masks to fit them to a specific process sequence. Specifically, masks can be inverted if say a dark field mask is required where a light field one was generated, i.e. the etching sense of the mask can be inverted. Candidate masks for layers that are thicker than the layers in the specific process can be split with an additional, identical sacrificial oxide mask placed in between the split mask allowing one to handle the problem of laminated layers mentioned earlier. Finally, the ordering of the candidate masks can be rearranged if the underlying product will be the same when the relocated mask is applied later in the process. This allows for specific material masks (such as a doped polysilicon) to be moved from their topological placement in the candidate mask set to a more pragmatic location in the process mask set.

Adjustments to the candidate masks can be done with a stepwise optimization sequence. If the optimization process fails to fit the masks to the given process, then the desired part cannot be fabricated in the given process. In such a case this algorithm can identify the topological feature which causes the problem and communicate it to the designer.

4 AUTOMATIC MASK GENERATION

The analysis described in the previous section forms the basis of the following algorithm, which successfully infers 2D mask sets from complex 3D models. Aspects of the algorithm that have not yet been discussed concern largely logistical points. For example, a given 3D model will have many non-intersecting bodies. It is efficent to work on one body at a time, so initially the model is divided into its non-intersecting components. Compensation for this division occurs later when the mask sets are summed. This summation is usually straightforward as the non-intersecting bodies typically have non-overlapping masks. Finally, a simplification of the topology tree is conducted where redundant nodes are joined, a process where by nodes that topologically connect the same nodes are combined to one node. Given a 3D model, the algorithm is:

1. Disassemble the model into all non-intersecting bodies.
2. For each body
    a. Generate a topology tree.
    b. Categorize the node of the tree.
    c. Combine redundant nodes.
    c. Locate deposition boundaries.
3. For each deposition domain (area between boundaries)
    a. Locate masks
    b. Save masks in candidate mask set
4. Sum all candidate masks
5. Reconcile masks with the target process.

It is significant to note that specific process details do not enter the algorithm until the final step. Allowing most of the algorithm to operate independently of process details keeps the algorithm flexible to process changes.

4.1 Algorithm Implementation

The algorithm was implemented in a C++ program called *faethm* using the ACIS geometric modeling library version 8.0 (http://www.spatial.com) for import and manipulation of the 3D models. Models were both manually generated and provided by Sandia's SUMMiT V 3D Modeler [5].

4.2 An Example

As an example, *faethm* will be demonstrated using the part shown in figure 2.

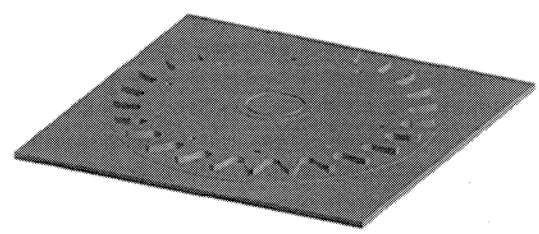

Figure 2: Gear and hub on silicon substrate.

The gear and hub represent two non-intersecting bodies. Thus, two topology trees will be generated for this device. The topology trees for the gear and the hub are shown in figures 3a and 3b respectively. Next to each node is a number representing the relative area of that node, or in the case of node E the area of each node labeled E.

Once the nodes of the gear's topology tree have been categorized, one determines that nodes B and D are local maxima, node C a local minimum and E nodes are dimples. The nodes labeled E are also redundant in that they all start from the same location, node D, and end after that. Therefore, all nodes E are consolidated into one node. A candidate mask set for the gear consists of two polysilicon masks (B & D), one sacrificial oxide mask (C) and one dimple mask (E).

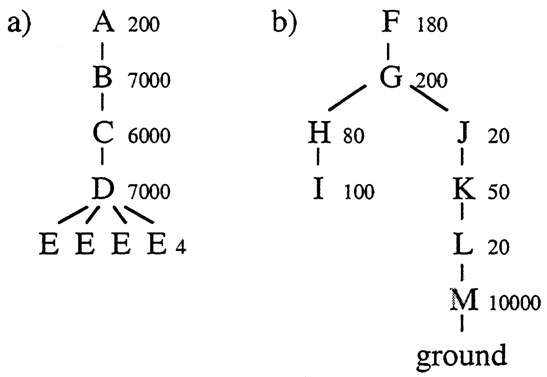

Figure 3: Topology trees for (a) the gear and (b) the hub.

The topology tree for the hub is branched, and the branching is not redundant so one cannot collapse it to an unbranched tree. Analyzing the nodes, one can determine that nodes G, K and M are local maxima, nodes J & L are local minima and node I is an undercut. Thus, to create a hub one will need three polysilicon masks (G, K & M), two sacrificial oxide masks (J & L) and one pin joint mask (I).

Summing the candidate mask sets for the gear and hub produces the mask set listed in table 2 along with their relative material layer thicknesses and heights.

Mask	Material Thickness	Top Height
Poly (B, G)	1.5	7.5
Sac Ox LF (H)	0.3	6.0
Sac Ox (J)	0.3	6.0
Pin Joint (H)	n/a	6.0
Poly (D, K)	1.0	5.7
Sac Ox (L)	2.0	4.7
Dimple (E)	1.5	4.7
Poly (M)	0.3	2.7

Table 3: Candidate mask set. Note the second and third masks from the top are light field and dark field masks and thus cannot be added directly.

Reconciling the mask set listed in table 2 with SUMMiT V mask requirements necessitates two alterations. Combining the second and third masks occurs first by taking the inverse of the light field mask (Sac Ox LF) and adding it to the following Sac Ox mask. Second, the Poly (D, K) mask is redundant as its outline is the same as Poly (B, G) and SUMMiT V mask specifications allow Poly (D, K) to be dropped. After those two alterations, the candidate mask set meets the requirements for SUMMiT V. The final mask set is shown in figure 4.

5 CONCLUSIONS

The algorithm presented here and coded in the *faethm* program is capable of generating accurate mask sets for complex 3D devices. By focusing on a model's topology first, this work can identify masks for anisotropic and isotropic (dry and wet) etching processes. *Faethm* is targeted for the SUMMiT V process, but the flexible nature of the algorithm allows for easy adaptation to other process.

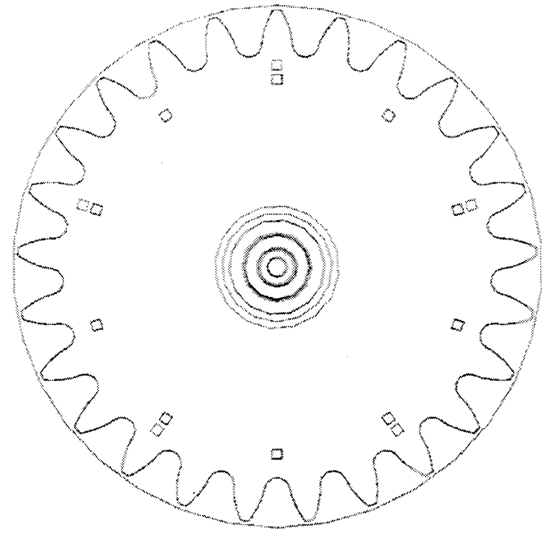

Figure 4: Final mask set for the gear and hub device.

6 ACKNOWLEDGEMENTS

The authors would like to thank Sandia National Laboratories and the Department of Energy for supporting this work. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

REFERENCES

[1] L. Ma & E. Antonsson, "Automated Mask-Layout and Process Systhesis for MEMS," Modeling and Simulation of Microsystems 2000, pp. 20–23, 2000.

[2] L. Ma & E. Antonsson, "Robust Mask-Layout Synthesis for MEMS," Modeling and Simulation of Microsystems 2001, pp. 128–131, 2001.

[3] V. Venkataraman, R. Sarma & S. Ananthasuresh, "Part to Art: Basis for a Systematic Geometric Design Tool for Surface Micromachined MEMS" Proceedings of the ASME Design Engineering Technical Conferences 2000, pp. 1–14, 2000.

[4] S. Cho, K. Lee & T. Kim, "Development of a geometry-based process planning system for surface micromachining," Int. Journal of Production Research, vol. 40, no. 5, pp. 1275–1293, 2002.

[5] C. Jorgensen & V. Yarberry, "A 3D Geometry Modeler for the SUMMiT V MEMS Designer," Modeling and Simulation of Microsystems 2001, pp. 594–597, 2001.