Automated Solid Model Extraction for MEMS Visualization

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ABSTRACT

A software tool has been developed to enable the rapid generation of solid models for MEMS structures. The automated 3-dimensional model extraction (3DMX) software, together with a description of a MEMS process, is capable of generating a solid model of a micromachined structure directly from its mask layout. The ability to automatically generate solid models of MEMS devices provides an effective path towards 3-dimensional visualization and design rule checking. The 3DMX software, which has been developed in C++ for code portability and extensibility, is applicable to a wide range of typical MEMS device features, including conformal and planar surfaces, vias, etch holes, planarizing layers, and bonded layers. The utility of the software is demonstrated for a variety of MEMS applications. The software algorithms are described, and ongoing development directions are discussed, including application to coupled-field modeling for MEMS transducers.

Keywords: visualization, 3-dimensional, modeling, process emulation

INTRODUCTION

The need for 3-dimensional modeling and visualization of MEMS transducers is becoming increasingly evident. Employing device visualization as part of an overall design strategy can provide important information to the MEMS designer, including identification of obscure layout errors, information on potential stress concentrations and failure modes, and other details which cannot be readily determined by design rule checking of the 2-dimensional mask layout. Performing 3-dimensional visualization of a device during the design process has the potential to reduce cost and development time for transducer fabrication. Traditionally, MEMS visualization has not been an integral part of the design process, since manual generation of accurate 3-dimensional models is labor intensive and time consuming. Automatic generation of accurate solid models is a necessary step towards the use of device visualization as a mainstream MEMS design tool.

SOLID MODELING FOR MEMS

The traditional design paradigm for MEMS systems involves an iterative design-fabricate-verify process which is time consuming, expensive, and does not allow meaningful design optimization to occur. A number of software tools have been introduced or are currently in development which specifically address these issues. The role of 3DMX in an overall MEMS CAD design environment is depicted in the flowchart of Figure 1. Starting with a set of functional design goals, a preliminary mask layout of the MEMS device is generated, either through analytical modeling of the device followed by manual mask layout, or through a layout synthesis process [10]. In traditional MEMS design, a 2-dimensional design rule check is performed on the mask layout, either by visual inspection or software evaluation, followed by device fabrication. After fabrication, the device is tested for functional verification, design errors are corrected in the layout, and the fabrication process is repeated as needed.

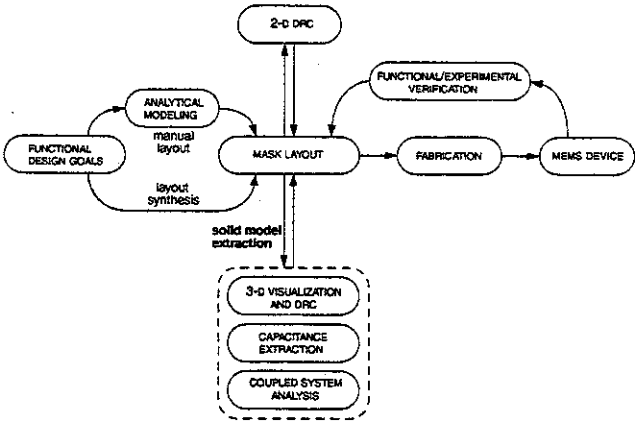

Figure 1. MEMS Design process employing solid model extraction.

By adding solid model extraction to the layout process, much of the iterative design optimization, which presently resides in the expensive and time consuming fabrication and functional verification loop, may be off-loaded to the pre-fabrication mask verification process. The solid model representation of the MEMS device may be used for 3-dimensional visualization and design rule checking, parameter extraction, or coupled-field simulation of the system.

3DMX FEATURES

While small aspect ratios and Manhattan geometries are generally the rule for integrated circuits, MEMS devices

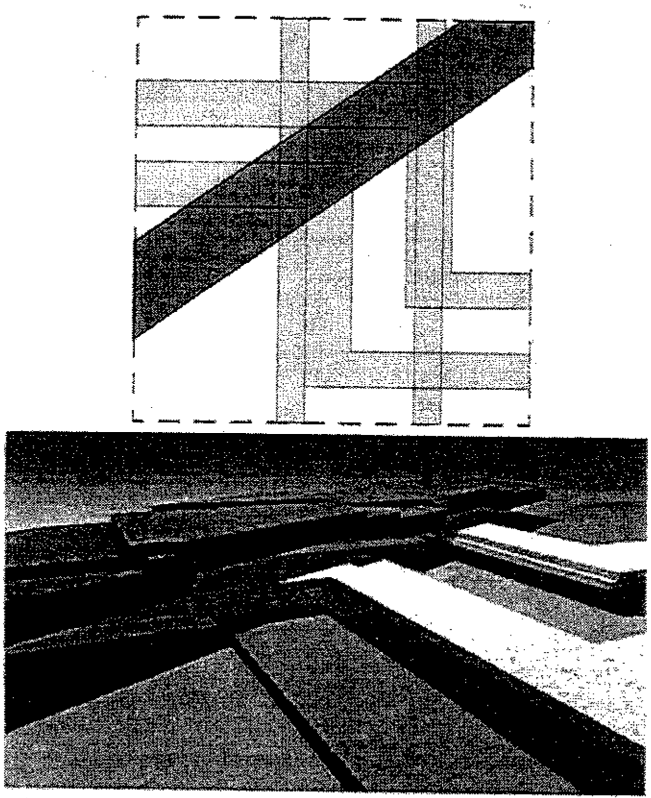

Figure 2. Layout and generated topography of a 3-layer interconnect structure.

often exhibit a large range of aspect ratios, together with non-manhattan in-plane geometries. The automatic generation of realistic models of MEMS devices requires software flexible enough to represent a wide variety of structures. The 3DMX software is capable of generating solid models for devices with arbitrary aspect ratios, non-manhattan geometries, conformal and planar topography, planarizing layers, bonded layers, vias, and etch holes. Both light and dark field layers are supported. These capabilities allow for the simulation of a wide variety of MEMS structures. For example, the three-layer interconnect structure depicted in Figure 2 contains a non-manhattan upper trace. The conformal deposition of this trace over the two lower traces results in a complex surface topography which would be difficult to predict without the aid of automated model extraction software.

A number of software systems applicable to MEMS solid model extraction have been developed in recent years. Several software packages developed for IC interconnect modeling, such as the popular TMA Layout [21], have demonstrated the generation of planar topography and non-conformal extrusions of the CAD layout. Recent work by Elliott on automated capacitance extraction for IC designs [3,4] has resulted in the successful 3DTOP software. 3DTOP is capable of emulating conformal depositions, but is focused on IC design rather than MEMS modeling. Physics-based modeling software such as SAMPLE-3D [16,19] work by Hsiau [6], and hybrid approaches which combine physics-based and geometric-based modeling such as OPUS/3D [18], have proven capable of generating highly detailed 3-dimensional meshes using complex deposition and etching rules. However, the computational requirements of such software precludes their use for rapid modeling of large MEMS systems. A number of packages such as OYSTER [8], IntelliCAD [5,11], 3D µV [9], and MEMCAD [15,17] have proven highly successful at automated solid model generation, including the ability to produce fully conformal 3-dimensional models. Currently, however, several of these packages provide restricted process emulation, while others are tied to underlying solid modeling engines and graphics libraries which limit their portability.

The 3DMX software features solid model extraction capabilities for a wide range of MEMS fabrication technologies. To maximize portability across a variety of hardware platforms, 3DMX has been written entirely in self-contained C++. This approach eliminates the need for an underlying commercial solid modeling engine or graphics library for operation of the software. The combination of the flexible modeling capabilities and portability of 3DMX differentiates it from other solid modeling extraction tools.

3DMX ALGORITHMS

The emulation of a particular process requires a mask layout, which defines the 2-dimensional geometry of each layer in the device, as well as a detailed description of the process used to fabricate each of the layers. The 3DMX software first converts the various geometric elements in the mask layout file, such as boxes, wires, and polygons, into an internally-defined polygon data structure. Although curves are not directly supported, non-manhattan polygons which approximate curves are allowed. The software manipulates the polygons from each layer to construct the solid model of the fabricated structure, with rules and constraints dictated by a user-defined process description. The resulting solid model is then exported for visualization using a rendering package of the user's choice.

The mask layout which describes the planar geometries of the layers in the device are defined in the input CAD file. The software is capable of reading several standard CAD file formats. Currently supported input file formats are CIF, KIC, GDSII, and DXF, and currently supported solid model output formats are 3DMF and POVRay.

Process Description

In addition to a CAD file containing the mask layout, the designer must provide information about the attributes of each layer in the CAD file. The set of attributes for all layers specifies the *process description* for the device. The process description defines the sequence of processing steps used to fabricate the microdevice, as well as the specific nature of

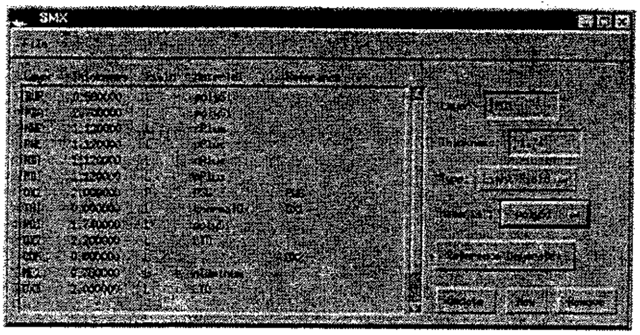

Figure 3. 3DMX process description interface

each step. The user interface for creating the process description is shown in Figure 3. Through this interface, the designer may specify characteristics including layer thickness, mask polarity, layer type (conformal, bonded, or planarizing), and material type.

The material type dictates the deposition properties for each layer to which the material type is assigned. Currently, this parameter is used to specify the amount of sidewall coverage for a given material. In an physical MEMS fabrication process, the amount of sidewall coverage depends on the particular process step being performed. For example, sidewall coverage during an evaporation step may be negligible, while a CVD deposition may provide excellent conformality over steps. This process-dependent parameter is simulated in 3DMX by taking into account a user-definable percentage of sidewall coverage for each material. A database containing sidewall coverage values is accessible through the 3DMX interface, allowing the user to modify sidewall coverage parameters for specific materials and process steps.

Solid Model Extraction

At the heart of the 3DMX software is the solid model extraction function. The extraction software first performs a union operation on the 2-dimensional objects in each layer in order to determine the minimal set of polygons which can be used to describe the layout. Each layer is then manipulated in sequence to simulate the deposition and etching process. A height map (z-map) of the surface is maintained during the simulation to represent the top-level surface topography. If the current layer is defined by the user to correspond to a conformal deposition, it is compared against the z-map to determine all polygon intersections. This operation is performed using a polygon clipping algorithm similar to that described by Schutte [20]. When a polygon on the current layer intersects a polygon in the z-map, the sides of the z-map polygon are expanded to simulate sidewall coverage, and the intersections are recomputed. Areas of the upper polygon which intersect the expanded z-map polygon are placed atop the original z-map polygon with a user-specified thickness, while those areas which do no intersect are checked for intersections with other polygons on the z-map.

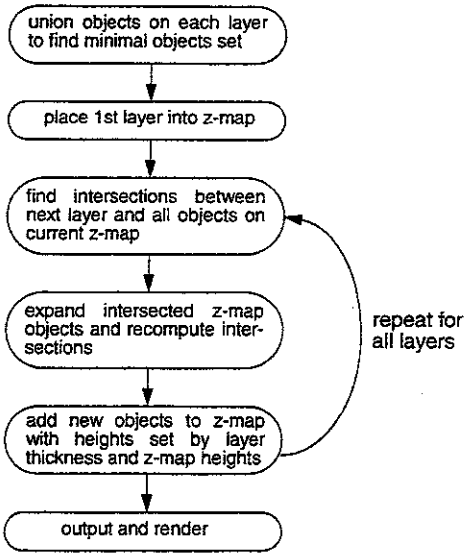

Figure 4. Simplified 3DMX software flowchart

After processing a layer in this manner, the z-map is updated and the next layer is processed. Once all layers have been sequentially processed, polyhedral elements conforming to each layer's topography are output in the final solid model for rendering and visualization. A simplified block diagram of this process is shown in Figure 4.

For the special cases of planarizing and bonded layers, the software constrains either the top height (in the case of a planarizing layer) or both top and bottom heights (in the case of a bonded layer) to be constant for the entire layer to simulate the physical nature of each fabrication step. Etching steps are also handled as a special case. Etch geometries are subtracted from their respective etched layers before those layers are checked for intersections with the z-map in the process described in Figure 4. This approach allows dark field mask patterns to be included in the input CAD file, so that via and etch hole geometries may be defined as separate masking steps in the fabrication process.

MEMS APPLICATIONS

The 3DMX software algorithms provide a geometry-based, rather than physics-based, approach to solid model extraction. As such, the accuracy of the resulting models is not equivalent to that achievable using physics-based software such as SAMPLE-3D. However, by allowing sufficiently detailed processing rules, 3DMX can provide fast generation of solid models with sufficient accuracy to describe complex MEMS structures produced by a wide variety of fabrication techniques.

Recent interest in CAD development within the MEMS community has been targeted on monolithically integrated or minimally assembled structures conducive to mass fabri-

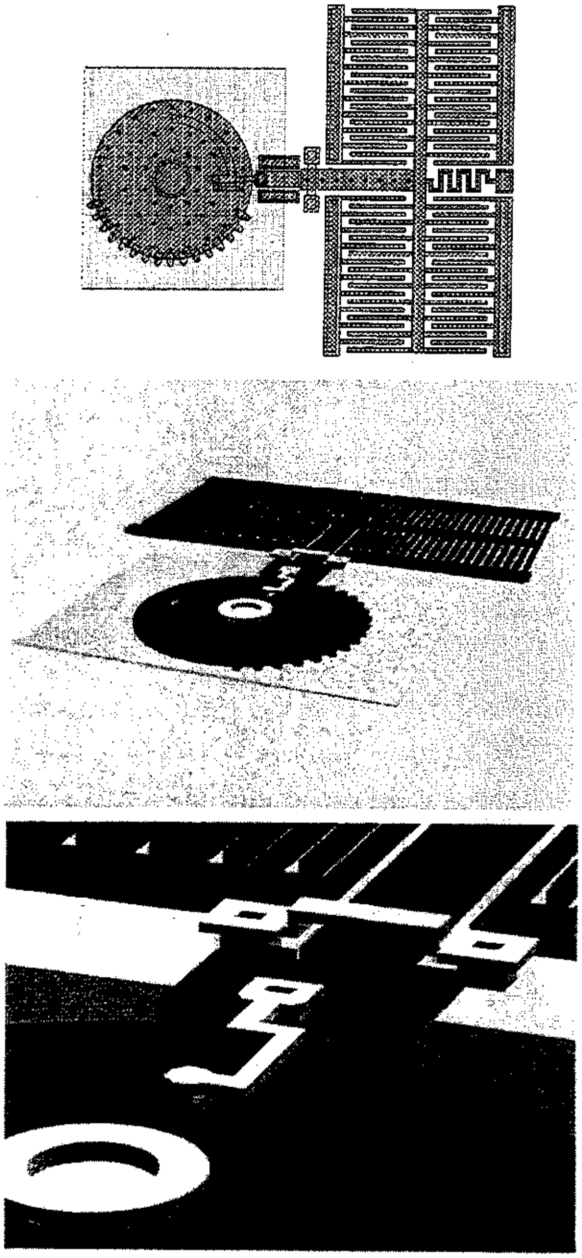

Figure 5. Mask layout, extracted solid model, and close-up view of a surface-micromachined mechanism.

cation, such as surface-micromachined mechanisms, transducers with integrated sensing and control electronics, and microfluidic systems. Examples of solid model extraction applied to each of these cases are discussed in the following.

Surface Micromachining

Three-dimensional visualization provides a design tool which compliments traditional 2-dimensional design rule checking. As surface micromachined devices become more complex, 3-dimensional visualization becomes increasingly useful as a design tool. For example, Sandia's SUMMiT process is capable of producing complicated micromechanisms by employing 3 structural polysilicon layers, in addition to a polysilicon ground layer [2]. In structures produced in such a process, the aggregate effect of overlapping non-planar layers on the overall device geometry is difficult to visualize without model extraction. To illustrate this point, consider the extracted solid model of a micromechanism designed in a simple 2-layer polysilicon process as shown in Figure 5. The 3-dimensional features of the device are readily apparent from the extracted solid model, while the original mask layout provides few clues about the non-planar device geometry.

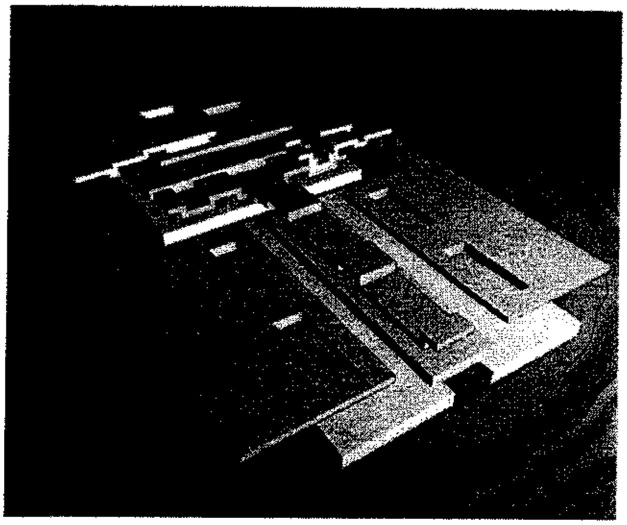

Figure 6. Solid model of the input stage of a charge amplifier.

Integrated MEMS

Micromachined transducers integrated with on-chip electronics are an important aspect of MEMS technology. The modeling of 3-dimensional topography in electronics is important in its own right for accurate parameter extraction [1,4,7]. As well, topography of the electronics can directly effect the geometry of overlying MEMS structures in certain integrated microsystems. For example, the resonant-gate FET device [14] consists of a cantilever beam suspended over the channel region of a MOS device in lieu of a fixed polysilicon gate. This MEMS device has a mechanical element (a cantilever beam) with geometry that is directly effected by the underlying MOS structure.

The topography of a typical CMOS process may be readily modeled using 3DMX. Figure 6 displays the extracted solid model for the input stage of a charge amplifier produced in a typical CMOS process. In this figure, all intermediate dielectrics removed to reveal the underlying layers. By employing physically-meaningful parameters for the process description, fairly accurate models of the CMOS structure may be achieved.

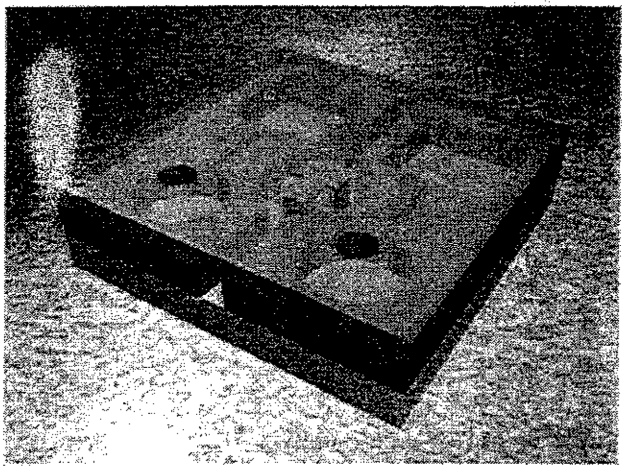

Figure 7. Microfluidic system with one-way valve.

Microfluidic Systems

The 3DMX software supports model extraction for MEMS designs which employ bonded wafers. One application which makes use of this feature is the modeling of microfluidic systems fabricated by wafer bonding techniques. The solid model extracted from a microfluidic device with an integrated one-way valve is shown in Figure 7. This particular fabrication process employs an SOI substrate machined by deep reactive-ion etching (DRIE), and a bonded top wafer planarized via chemical-mechanical polishing (CMP) with two fluid access ports etched by DRIE. The top bonded wafer has been rendered partially transparent to allow the underlying details to be visible.

FUTURE DIRECTIONS

The 3DMX software is currently able to emulate limited characteristics of typical microfabrication steps, and output a 3-dimensional solid model of the resulting structure for visualization. While these capabilities are useful for a number of applications, there are two areas in which 3DMX is currently deficient. Specifically, the software would benefit from (1) improvements in process emulation and supported fabrication steps, and (2) integration of the software with FEM or BEM analysis tools for coupled-field device simulation.

Improvements in the process emulation are needed to better approximate the actual MEMS structures. One limitation of the current software is the lack of support for non-vertical sidewalls. Rounded corners, another typical feature in many microfabricated devices, are also not directly supported, although they may be approximated by discretizing the curves. Expanding the range of fabrication steps which can be emulated by the software must also be addressed. In particular, the ability to model chemical-mechanical polishing (CMP) of wafer surfaces is absent, although support for planarizing layers provides a limited mechanism for approximating true CMP steps. Future developments in 3DMX will be directed at improving these process emulation capabilities.

Coupled-field analysis tools for the simulation of microstructures is another an area of strong interest. Due to its C++ code base and freedom from an underlying solid modeling engine, 3DMX is well suited for integration with portable coupled-field software tools. In this role, 3DMX would automatically generate the solid models required for the simulation of mixed-domain MEMS devices.

CONCLUSION

We have developed the 3DMX solid model extraction software for automating the process of solid model generation for MEMS devices. The software has been successfully applied to the modeling and 3-dimensional visualization of a variety of MEMS structures, including surface micromachined mechanisms, integrated CMOS electronics, and microfluidic systems. The extensive MEMS process emulation capabilities, together with the portability of the software, make 3DMX a highly flexible visualization tool for MEMS designers.

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