Visualizing Dynamic Etching in MEMS VR-CAD Tool

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ABSTRACT

In this paper we introduce our virtual etching as part of MAGDA a CAD system for Micro Electro Mechanical Systems (MEMS). Virtual prototyping visualizations require fast algorithms for visualization that are suitable for interactive design. Modern MEMS simulators do not offer dynamic visualizations for etching. Etching progress is time dependent, typically calculated with Finite Element Analysis, which has too slow a calculation time, hence is not suitable for interactive design. Etching progress is important in MEMS with small dimensions, where Silicon technology must be used, with its repeated cycles of deposition and lithography/etching until the desired structure is formed. While etching performance is well known from the Integrated Circuit processing, it is not so predictable in MEMS because the shapes are more complex. Underetching is not desired in IC technology, but it is crucial in shaping MEMS structures. We use a Marker/String method for the progressive mesh as a faster method suitable for interactive design. The method is not known much for etching; but used in other applications. We have found a way of overcoming swallowtail conditions that appear on corners. We are also able to simulate underetching. In this paper we demonstrate the progress of etching using a circular lithography mask calculated in 2D then rotated, and a square mask calculated in 3D. In both cases we are able to simulate underetching. The method can be extended into larger material removal CAD visualizations. In this way we made a step towards filling a long existing need in virtual prototyping.

Keywords

Scientific Visualization, VR-CAD tools, MEMS, Etching

1. INTRODUCTION

CAD tools have had an enormous impact in the design of any engineering product. When CAD tools are joined with virtual reality visualizations they provide invaluable visual feedback at the time of design. With improvements in computer speed and in computer graphics this has made drastic changes to the CAD design packages that are available. However, no matter how fast the hardware is, the problem of fast models for interactive design has not yet been overcome, and will always be a bottleneck.

The problem arises because for dynamic CAD visualizations typically two phases are required. One phase involves preparation of the visualization as a sequence of frames, that is for example where the 3D change in the material being etched is calculated, followed by its rendering for a 2D screen. The other phase consists in playing the animated video clip. Together they are a lengthy process and unsuitable for interactive design.

Scientific visualizations including multi-dimensional multivariate visualizations have now been around for several decades, e.g. environmental maps of pluviosity. In our research, we go a step further, trying to display results of predictive calculations dynamically on the very design visualizations of the structures they represent thus adding to the information content they can offer. In particular we aim for fast models that are suitable for interactive CAD design. In this paper we present the dynamic process of etching. Our environment is in Micro-

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Electro-Mechanical systems (MEMS) CAD development.

The introduction of CAD packages was a critical step in the widespread development of Integrated Circuits (IC) and reduction of the design and prototyping phase [Kar97]. There is a demand for CAD tools to aid in the development of MEMS devices. The typical evolution of CAD tools is that they emerge from applied research when particular devices were developed at different times, coming from specialized applications, rather than from specific design of the CAD tool. The result is a concoction of un-coupled and even incompatible pieces of software that are united under the umbrella of a "workbench". In such environments, computer crashes are common, leading to frustration and loss of time.

A rather small number of MEMS design software environments are available on the market. Perhaps the more widely advertised are ANSYS [ANS05] a multiphysics solver, Coventor [Cov05], Intellisense [Int05], and Femlab [Fem05] offering user-friendly Finite Element Analysis (FEA) environments and data mapped graphic results.

Other packages appear as a collection of tools at times limited to very specific applications [Rez97]. Their application potential may be restricted to modifications of existing library designs [Dew01]. They appear as by-products from code written for the design of a specific project [Lev98] or may be difficult to use [CFD]. Few have facilities for determining the MEMS manufacturing parameters as their primary purpose [MEM]. The availability of virtual reality in this area is very limited indeed.

To address the shortage of MEMS specific design tools, we have initiated ***M****EMS* ***A****nimated* ***G****raphic* ***D****esign Aid* (MAGDA) for virtual prototyping, with a strong emphasis on visualizations. It embodies Computer-Aided Design (CAD) tools for modeling and simulating the functioning of MEMS in virtual reality and to provide visualizations of their behavior and performance as multi-parameter functions. It is intended to overcome some shortages in some of the large and popular CAD tools, by complementing, rather than replacing already existing MEMS software.

Its application niche is the exploration for determining the MEMS manufacturing dimensions and aids in confining them. The functioning of a mechanical device depends on its geometry and dimensions; consequently they have also an effect on the reliability through their design, choice of materials and wear out. We pay special attention to the effects of geometries on the functioning of the MEMS. With these effects in mind, we aim for a robust design.

In an innovative way, MAGDA combines visualizations to display both the geometries of the device as it is being designed, and animated functioning, an attribute that is in part affected by those geometries [Sit03, Li05]. One important feature that makes MAGDA different from other CAD software is that we use transparency in most of our visualizations, to be able to observe structures that are hidden otherwise. Our method is particularly suitable for the upcoming 3D Imaging and Holography displays

The paper is organized in the following way: Section 2 provides a brief overview of what makes MEMS different and their fabrication. This is followed by section 3 where we explain about etching and ways of modeling etching. In section 4 we explain our adaptation of the Marker/String method specifically for etching, and in section 5 we present our two experimental application cases and discussion. Finally section 6 brings the conclusions, with suggestions for future work.

2. MEMS BACKGROUND

MEMS are minute devices that are in widespread use, for example in airbag triggers and inkjet print heads, optical, medical, and many other applications. With ever increasing new applications in the R&D phase, the MEMS industry is strong and growing, in particular in the medical and optical applications. This in turn requires adequate development tools with sophisticated modeling and simulation software to reduce the lengthy prototyping and optimization period.

By their very nature MEMS devices are microscopic and therefore difficult to observe. In the macroscopic world of our daily experience inertia and gravity dominate the motion of objects. In contrast, in the microscopic domain of MEMS adhesion and friction are the dominant forces. Therefore MEMS designers cannot use their intuition on how things behave. Because of the different dominant forces, MEMS cannot simply be downscaled counterparts of larger mechanical machines, requiring innovative designs and arrangements of their components, whose effects are often not fully understood.

MEMS have emerged from the Integrated Circuit (IC) manufacture, which has revolutionized the world and started just a few decades ago. They are produced hundreds of thousands at one time on a Silicon wafer, a disc of silicon 5 to 30 cm in diameter, and less than a millimeter thick. In a sequence of alternating depositing layers of material, which are then specifically patterned (lithography) by removing parts of the material in specific patterns so that the desired structures emerge. Examples of the kinds of material that are deposited or grown in layers are typically materials involving silicon or silicon oxides, but also metals. Due to the relatively recent MEMS industry, this often requires a lengthy and expensive cycle of trial and error. Silicon technology allows the construction of MEMS devices with a few micrometers (µm) in size, and whose structures are in the submicron range. In these processes etching is a fundamental processing step.

Another technique for producing a MEMS or parts of it is by producing a negative mould of the desired structure and the positive structure is then cast in metal or polymer (LIGA). The parts are then assembled into the micro system together with the regulating micro-circuitry. These devices are about two or more millimeters in size.

There are many more processing methods in a variety of sophistication and complexity, but for our purpose is not necessary to go deeper into the subject, for the interested reader a variety of introductory books are available, for example [Fat97], [Lys01].

3. ETCHING AND ITS MODELLING

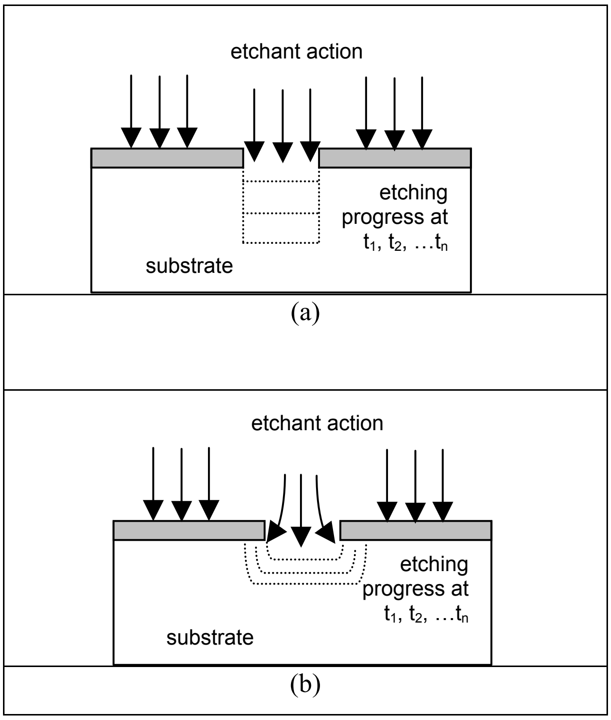
Etching is the removal of material by mechanical or chemical methods. There are two types of etching isotropic and anisotropic. In isotropic etching the material removal occurs in all directions equally, while anisotropic etching occurs at different rates in different crystalline directions. It is fast in one direction, and slow, almost negligible or none in another direction, thus making it suitable for selective etching and straight walls.

Typically in anisotropic etching the crystalline orientation of the material to be etched is exploited and used in conjunction with masks and the technology for specific desired results, for example a V-grove for optical MEMS. Anisotropic etching is the preferred technique in integrated circuit manufacturing, where straight lines are common, as it can be controlled to very fine precision.

Dry etching is anisotropic, where the material removal is done by electrochemical or mechanical means such as Reactive Ion Etching, Plasma Etching, Sputtering, a.o. Wet etching is usually an isotropic process, where a mask is applied to obtain the desired shape, and with enough time, this mask can be underetched.

Isotropic etching cannot be so easily controlled, as the result depends much on the purity and age of all materials involved (including the masking material). However, in MEMS, with its variety of shapes and larger dimensions, isotropic wet etching is often preferred.

As a progressive material removal, etching can be modeled with Finite Element Analysis (FEA). FEA calculations are known to be slow and hence not very suitable for interactive VR visualizations. Simulations using the latest software package releases run on a common PC range from about 10 minutes for fast and simple calculations, to almost an hour for a moderately complex model. Much depends on the meshing and required refinements.



(a)

(b)

Figure 1 Different types of etching: (a) anisotropic etching progresses in one direction only; and (b) isotropic etching progresses in all directions equally.

Another problem is that sometimes the calculations of the given case do not converge. This is perhaps why etching simulation models have not been seen much in MEMS CAD. Coventor [Cov05] has only recently announced its etching module, but it is for anisotropic etching only. Anisotropic etching is bounded by flat planes, hence easier to model.

In isotropic etching however, the main difficulty is in determining a parametric model for the curved surfaces, as their curvature changes throughout the process. This is difficult because the shape of the set of surfaces (or curves if in 2D) has to be determined specifically for the materials involved (substrate and etchant) and for each and every shape of mask. A general equation cannot be derived for all the variety of possible shapes of the structures in MEMS. An important work on etching has been prepared by Elwenspoek and Jansen [Elw98]. In general, MEMS structures require a variety and complexity of shapes, and the time and etching rate based on the chemical reactions are the sole options for controlling the etching progress. The usage of recipes for etching is common practice in clean rooms, hence, etching rates for different materials and etchants are well known and documented.

Underetching is the type of progress when portions of the substrate are etched out although they are masked. Underetching occurs from sideward etching excavating underneath the mask, as isotropic etching progresses. While underetching is normally undesired, it is important for MEMS in freeing mobile structures such as springs and gears. This has to be carefully controlled. Too much underetch and the structure to be freed is lost, too little underetch and the structure does not come free.

4. THE MARKER/STRING METHOD

In our endeavor to produce fast visualizations we need a model that is fast in calculation and capable of addressing complex structures, for example a set of combs, a spiral or any other shape. Amongst a range of approaches we have chosen to adapt the Marker/string method [Ada95] to our etching requirements. This method has been successfully applied in growth and solidifications in a slightly different way than for etching. One of the weaknesses in this method is that in sharp pointed structures (e.g. in the case of a complex mask shape), a swallow-tail condition can occur from the overlap. We have found a way to overcome this for the purpose of modeling etching. In this paper we focus on isotropic etching only, with its curved surfaces.

We can summarize our modeling approach applied for isotropic etching with the following points.

- *Surface.* The shape of any surface is characterized by vectors perpendicular to it. In the case of etching we have to find the vectors that are perpendicular to the surface (bowl) while it is being etched.
- *Grid.* We assume that the etchant is in contact with that surface. We set a grid and step size on the area that is not covered by the mask on the initially flat surface.
- *Direction.* We set a time step and initiate the process by selecting a point. We perform the cross product of the vectors that define the chosen point and its adjacent point on the grid. The resulting vector is perpendicular to the etched surface (with a small error which depends on the stepsize).
- *Progress.* We move to the next point in the grid, and then layer by layer. We repeat performing the cross products. The magnitude of the resulting vector is the vectorial sum of the vector at the current point, plus the new vector resulting from the cross product, with magnitude “etching rate”.
- *Horizontal component.* In the moment when the etching profile passes below the lower edge of the mask, and in each new row, we introduce a horizontal vector of magnitude etching rate on either side. This is legitimate under the assumption that etching occurs equally in all directions, floor or wall. The horizontal vectors, together with the vertical vectors result in vectors at different angles, and give rise to the rounded corners of the etched bowl- shape. The side vector also initiates and governs the progress of the underetching process.

Validation

The application of this method in the way we are doing is valid, because at any time step we progress by an etching rate unit. At any one time the resulting vectors are perpendicular to the new surface profile.

To avoid swallow-tails on mask corners, we have performed a rotation. In this way we have preserved the etching rate. We can do this for isotropic etching, but it would not be valid for material deposition as proposed in [Ada95].

At this time we have treated all directions equally. We have not yet dealt with the crystalline orientation, which can affect slightly the etching rate in the case of isotropic etching, such that it is different in one direction from another. This can be resolved by applying the appropriate etching rate magnitude to the vectors in the model, that is, using a variety of etching rates. This would be the generalization of the method for both, iso-, and anisotropic etching.

5. EXPERIMENTS AND DISCUSSION

To test this method, we have applied the method to (a) a circular mask, and (b) to a square mask. Both cases require different treatment. For both cases we have calculated the wire mesh with the Marker/String method as adapted in the previous section, and then rendered the mesh. In both cases we are using Si and Silicon etchant in the proportion (126 HNO_3 : 60 H_2O : 5 NH_4F) for our simulations. We are simulating a 10 μm thick mask, with an opening with 45μm radius for the round mask; and 90×90 μm opening for the square mask.

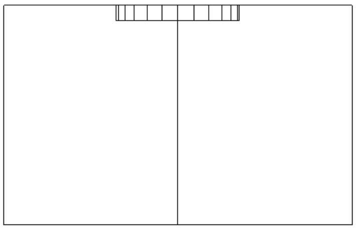
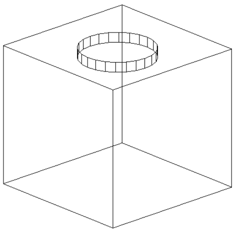
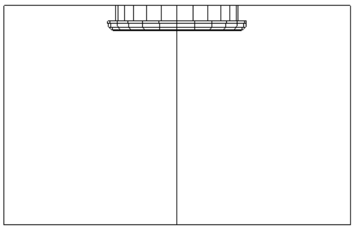
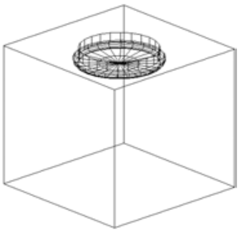
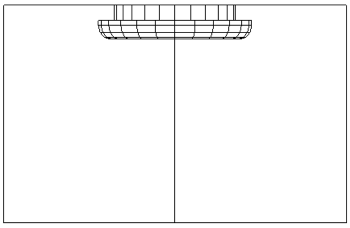
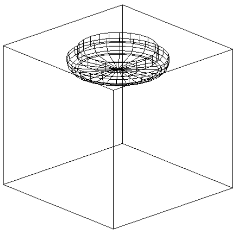
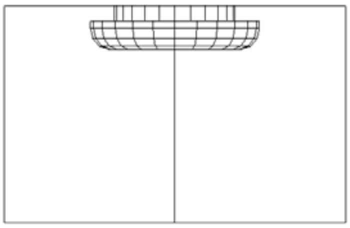
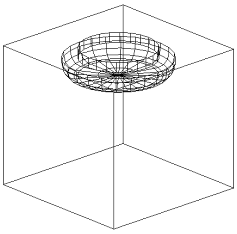
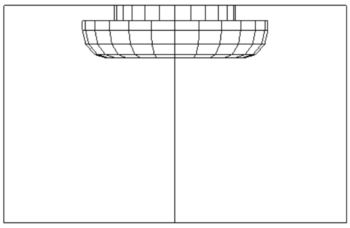
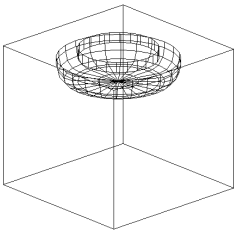
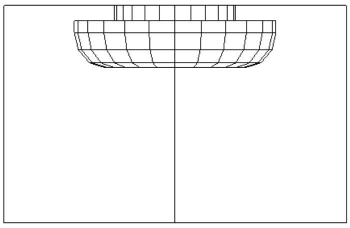
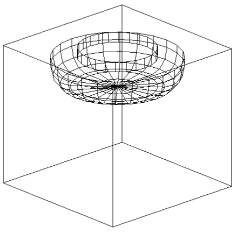
Round mask	***View: 2D***	***View: 3D***
Etch through mask time 0 -66.67 min		
Underetch at 106.67 min		
Underetch at 146.67 min		
Underetch at 186.67 min		
Underetch at 226.67 min		
Underetch at 266.67 min		

Figure 2 Progress of the etching surface at different time steps for the case of a 45 μm radius round mask opening

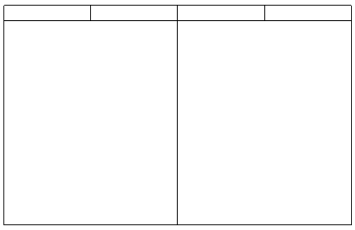
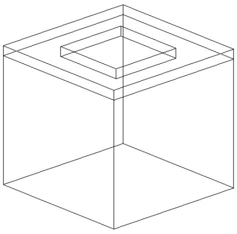
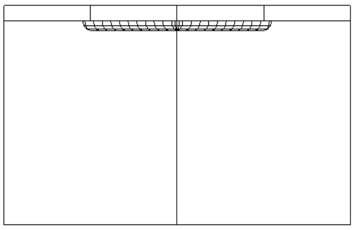
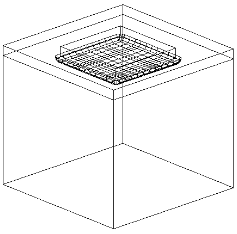
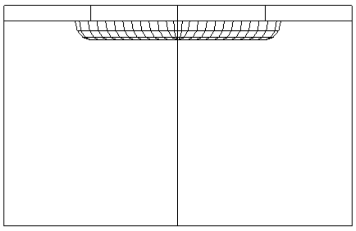
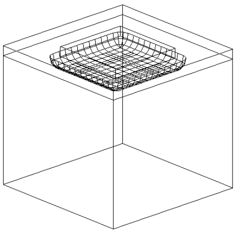
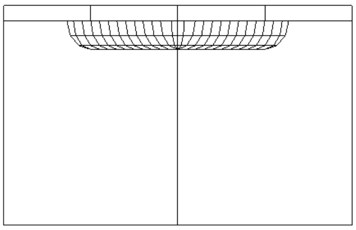
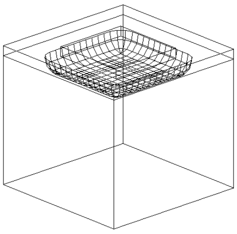
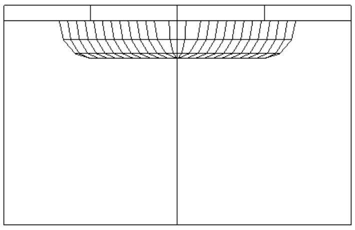
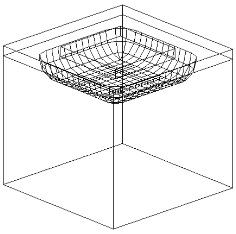
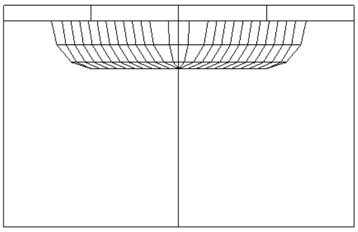
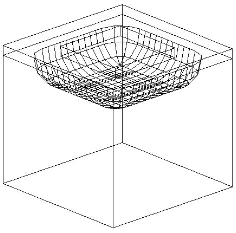
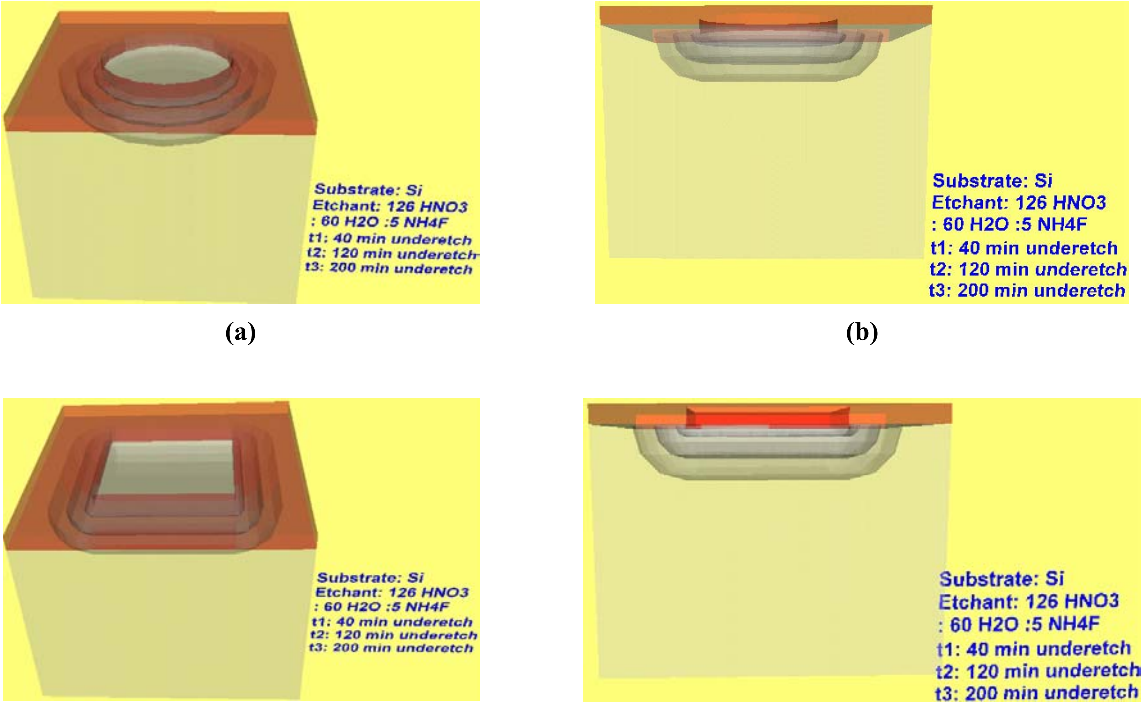
Round mask	***View: 2D***	***View: 3D***
Etch through mask time 0 -66.67 min		
Underetch at 106.67 min		
Underetch at 146.67 min		
Underetch at 186.67 min		
Underetch at 226.67 min		
Underetch at 266.67 min		

Figure 3 Progress of the etching surface at different time steps for the case of a 90×90 μm square mask opening

The calculations for the round mask are carried out in 2D. The resulting profile is then rotated stepping at an angle of 22.5°. The square mask is calculated in 3D for one quadrant, and then mirrored for the other quadrants. The progress of the etched surface is shown in the sequence of the wire frames in Figure 2 for the round mask, and Figure 3 for the square mask respectively. For the rendering we have chosen transparency, following our main philosophy in MAGDA. This is to allow better observation of structures that may be hidden by other structures, in this case the progress of the etched surface. Figure 4 shows the progress as rendered images at three different time steps.

In general we have found that our Marker/String adaptation works well for our purposes. The calculations are fast, results are obtained within seconds to simulate the progress of etching in a dynamic way for the wire-mesh. We have found that the underetched profile works satisfactory for both types of mask. However, for pointed corners a different etching rate must be used. This may slow down the process somewhat because at those corners the region for steeper etching has to follow a specific contour, merging later with the normal etching process, that is, changing continuously. Such a region is repetitively regular in the case of - for example - the pegs of a comb, but is different when irregular shapes are masked. High diversity together with high complexity in the shape of mask, will inevitably delay somewhat the calculation process.

The Marker/string method as we are using it, is affected by the error that is given by the assumption that distances between two points of the grid are straight, even when they are on a curved surface. This error is relatively small. It can be minimized with a smaller grid step at critical places such as corners and sharp edges. There is the inevitable trade off between accuracy and calculation time. However, for the purpose of visualizations this error is negligible and fades away in the visual representation by the resolution size of the pixels. Given that the method for calculating the wire-mesh is so fast, it is anticipated that this will not be a major problem. A systematic analysis of the optimal error minimization and grid size is envisaged for the future.



(a) **(b)**

(c) **(d)**

Figure 4 Rendered images of the etched surface with (a) round, and (b) square mask showing progress a three different time intervals

6. CONCLUSION

In this paper we have presented an adaptation of the Marker/String method to model isotropic etching, Our aim is to produce fast models that are suitable for interactive CAD for Micro Electro Mechanical Systems (MEMS). Our interest is for isotropic etching to cover the variety of shapes that appear in MEMS, but the method can be applied as well for anisotropic etching. We have demonstrated the model with two application cases, one for a round mask, and one for a square mask. In both cases, fast calculations and satisfactory results were obtained. Future work is aimed at using the level set approach for further speeding up the models and allow for more sophisticated structural complexity.

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