Virtual Etching and Transparency Aiding in MEMS Design

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Abstract—With increase in the MEMS applications in new fields and devices, along with increased complexity, the MEMS industry strives for a reduction in time between the conception of an idea and its prototype implementation. To facilitate this, there is an increasing demand for MEMS CAD tools. Not many MEMS-CAD tools are available, and of those very few are capable of simulating the etching process. Those who do, have limitations. This paper presents a different, simpler approach to modelling the etching process with transparent VR animations that are truthful in time scale and material removal. This work is part of an ongoing project towards a MEMS Virtual Reality MEMS CAD tool that models, simulates and provides behavior characteristics and VR visualization for MEMS devices. In this paper, the visual simulation of the etching process for a CAD tool is presented and demonstrated by examples.

Index Terms—CAD, MEMS, Etching, Virtual Reality, and Modelling

I. INTRODUCTION

This paper presents the VR modelling of etching application of Information Technology for the development of Computer Aided Design (CAD) tool for Micro-Electro Mechanical systems (MEMS). MEMS are the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through the utilization of micro-fabrication technology. MEMS are physically small, approximately 10 μm. They are typically fabricated using the same technology as in integrated circuits fabrication, from which they have emerged. Despite their rather recent appearance about two decades ago, MEMS device variety and application is rapidly increasing. It ranges from IT peripherals, automobiles and medical devices to household devices and telecommunications [1]. The advantages of the small sized MEMS technology include low cost, high production, small size, low energy consumption, robustness, high functionality and possible bio-compatibility [1].

The increase in new application fields of MEMS devices, in conjunction with increased intricacy in structures, the MEMS industry strives for a reduction in time between the conception of an idea and its model implementation. There is an increasing demand for MEMS CAD tools. A few MEMS-CAD tools are available, and of those very few are capable to simulate the etching process. Those CAD tools who do have etch simulations, have limitations. This paper presents a different, simpler approach to modelling the etching process with VR animations that are truthful in time scale and material removal. This work is part of an ongoing project towards a MEMS Virtual Reality MEMS CAD tool that model, simulates and provides behavior characteristics and VR visualization for MEMS devices [2]. In this paper, the visual simulation of the etching process for a CAD tool is presented and demonstrated by examples.

The purpose of modeling is to mimic a phenomenon or part of it in a controlled environment, with the intention to study/observe its behavior. Typically, the reason for doing this is a cheaper and faster replication of the phenomenon. The ultimate goal is prediction, and if possible the control of the system to be simulated. Therefore, the prediction must be as close as possible to the reality. Simulation generates an artificial history for the system under study (in time), so that one can draw conclusions or inferences for the operating characteristics of the real system. Simulating designs are valuable in fabrication and the use of CAD tool can reduce the cost as well as time between conception and prototype. With CAD tools designs can be improved for better performance[3].

There are few MEMS CAD etch simulation tools available, not all have an etching simulation facility. Some of MEMS CAD tools are university of Michigan’s CAEMEMS, MIT’s MEMCAD, Caltech’s SEGS simulator, IntelliSense’s IntelliSuite and University of Illinois’s ACES. Though these simulation tools help to simulate the etching process, they lack in dynamic three-dimensional visualization of the etching process. It is not always easy to imagine the resulting non-regular shape as it emerges after etching, by looking a 2-D flat outline of the etching mask. Many of the CAD tools emerged as a by-product from specific research and are suitable for specific classes of MEMS devices only. Typically, the commercial tools available may not be sufficiently generic in nature especially for simulating the etching process precisely.
in 3D and visualizations in time scale.

To overcome the specialization limitations of other CAD tools, in our work we have focused on the etching rate to generate the visualizations on a truthful time scale. In this way, our methods offer more generality and a wider application range.

The organization of this paper is as follows: Section 2 gives a brief overview of the MEMS fabrication methods and analyzes the requirements for the etching visualization. Section 3 describes the methodology used and provides examples of the visualization. This is followed by a discussion of the pro’s and con’s in section 4, and the Conclusions in section 5.

II. ANALYSIS

Our goal is to produce 3-D animations of the etching on a truthful time scale. To determine the requirements for these visualizations, we have to first look at where and how etching fits into the MEMS processing.

The MEMS fabrication process is a complex process involving hundreds of distinct processing steps. There are three main processes for MEMS manufacturing. They are by bulk micromachining, surface micromachining and LIGA [4]. Micromachining is a process in which material deposition in thin layers alternates repeatedly with the selective etching. Bulk Micromachining structures the MEMS devices by etching deeply into the silicon wafer. Surface micromachining is the fabrication of micromechanical structures by deposition and etching of thin structural and sacrificial film that mainly serves to give temporary support while a free standing structure, e.g. a cantilever, is being built [4]. The sacrificial layer is removed later. LIGA is a combination of X-ray lithography, electroforming and molding. In this paper, we focus on surface and bulk micromachining, both of which rely on etching for structuring the MEMS mechanical components. Etching is the process of selectively removing the material from the surface with the help of reactants or energy beams. There are several etching techniques and they produce different results in different directions. Depending on the end-result two methods exists: isotropic and anisotropic.

Etching is isotropic if it occurs equally in any direction. Anisotropic etches faster in one direction (vertical) than another (horizontal) does. Typically the shape of the removed material is curved or bowl shaped in isotropic etching, while it has straight, or slanted but straight walls in the case of anisotropic etching. Figure 1 shows the diagrams for isotropic and anisotropic etching. The choice for etching method, depends the on the application and the desired shape of the structure being built

The Selectivity and directional properties play an important role in Micro-structural etching [5]. A mask layer is usually applied where material removal (etching) is not required.

Depending on the etchant used, we distinguish between wet etching and dry etching. Wet etching is a process in which material is removed by immersing the wafer in a liquid bath of the chemical etchant. The actual chemical conditions for the etching depends on the layer being etched. Dry etching is a process in which material is removed with dry chemical etchants. Dry etching may be an alternative to wet etching especially for deep anisotropic etching of polymer or silicon. It provides better etch rate and profile control using dry etchant (plasma, reactive ions or reactants in vacuum).

There are various factors, which affect etching in the MEMS, with desired or undesired results

2. Time of etching [6]
3. Dopant type and concentration [6],[7]
4. Atomic configuration [8]
5. Crystal Orientation [7],[8]
6. Temperature [10]
7. Surface misalignment [6]
8. Surface Stress effects [7]
9. Concentration of etching solution (in wet etching) [10]

The time of etching is crucial, because etching goes on – in most cases – until it is willfully stopped. Small variations on the size of the material being etched, such as overetching and underetching, can have drastic if not fatal consequences for the proper functioning of the MEMS. High precision of the structures is paramount. Therefore, it is necessary at the time of design to determine the timing very accurately to achieve the desired results.

For the purpose of producing animated visualizations of the etching in MEMS, the computational methodology is based on the etch rate and the time.

Because etch rates depend on various factors, these factors were studied for the purpose of creating a database of etch rates depending on the etchants and wafer and the material under etch. This is a huge task and not necessary novel, due to the many types of etchants and etching conditions. However, for our purpose and in order to accomplish the goals of our VR CAD tool we need to build in at least part of the conditions where one or another etching process is suitable. To get a systematic overview we have produced an expanded version of tables of the different etching process, based on work of Modou [12]. An example of a small portion of such a table is shown in Table 1.
### III. METHODOLOGY AND VISUALIZATIONS

The purpose of this project was to make possible the dynamic three-dimensional visualisation of the etching process. We have chosen the etch rate and discrete time intervals for displaying the progress of the etching. We have found that there is no point, in trying to simulate the progress of etching in an (almost) continuous time, because the timing of the calculations would be forbidding and slow down the visualization beyond its fitness for use.

From the information on the tables discussed in the previous section a query tree was developed, based on factors affecting the performance of etch rate.

The Etch visualisation CAD tool is based on the conceptual algorithm, which is given below in Flow Chart 1.

Flow Chart 1: The conceptual algorithm.

The algorithm prompts for input of material to be etched, material thickness, crystalline orientation. Next, the user is prompted to choose a possibly suitable etching process and etchant from the database. The etch rates are determined from the database depending on the selection of material, process and the etchant. The user is prompted to input an approximate duration for etching and number of stages for etch display; it calculates display time for each interval as integer value. With etch rate, time, and process and mask description the depth of etching along with etching profile is calculated. The visualisation of etching process is then displayed as a progress updated in discrete time intervals. A size-scale is displayed next to the image. A user can then observe and refine the time interval until both the correct size of the shape and its corresponding time is obtained, with acceptable accuracy. For new materials their etch rate can be added to the database and the database can be updated according to the needs of the user.

Virtual Reality Modeling Language (VRML) was chosen as the modeling language for visualization of the MEMS etching process. VRML is popular, widespread, with the flexibility to be incorporated into Matlab. The other reasons for choosing the VRML include interactive visualisation in real time, and the fact that other visualisation components developed by Griffith University Modelling and Simulation group are implemented in VRML [13].

Transparency is used in the visualization method as this gives an insight into the etching process. Transparency also helps to know the effect of etching into the wafer and the etched mask itself. The different stages of the etching process are presented at different time frames, and remain visible as the simulation time progresses. This systematic approach of virtual visualisation was chosen in order to show the dynamic progress of etching, and to be able to fine tune the timing for a desired result of the size of the structure to be etched. One of the most important advantages of virtual prototyping is the possibility to visually experience and to verify certain functions of the model before real calculations are performed. However, this is independent of the etching visualization. The idea of interactivity gives the advantage of studying the effect of size of the structures on the performance of the MEMS.

Several application examples follow to illustrate the etching visualizations.

Our first example is anisotropic wet etching. This was chosen because it is a widely used technique of etching in MEMS [13]. The etchant, materials under etch and time intervals are chosen. Etch rate is looked up in the database.

The etch wafer in the application example is silicon and the layer under etch or the material under etching is single crystalline silicon with <100> orientation. The contour of mask is chosen as to be of same size as material under etching with a square exposed area.

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon (bulk)</td>
<td>Wafer</td>
</tr>
<tr>
<td>Silicon &lt;100&gt;</td>
<td>Material under Etch</td>
</tr>
<tr>
<td>Potassium Hydroxide (KOH)</td>
<td>Etchant</td>
</tr>
</tbody>
</table>

Table 2: Information of materials and etchant used in anisotropic wet etching example.

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**Table 1: Example of etch rate tabulation and etchants applicability for anisotropic wet etching [12].**

<table>
<thead>
<tr>
<th>Etchant</th>
<th>Etch rate (µm)</th>
<th>Etch ratio (100/111)</th>
<th>Mask Material</th>
<th>Etch conditions</th>
<th>Remarks/Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>KOH</td>
<td>1.4</td>
<td>400</td>
<td>Photo resist, Si₃N₄, SiO₂</td>
<td>Diluted, added with isopropyl alcohol, temperature 85 °C</td>
<td>Etch oxides fast, Lots of H₂ bubbles, Etch ratio is 600 for (110/111)</td>
</tr>
<tr>
<td>EDP</td>
<td>1.25</td>
<td>35</td>
<td>Si₃N₄, SiO₂, Ta, Au, Cr, Ag, Cu</td>
<td>Pyrazine additive 115 °C</td>
<td>Ages fast, few H₂ bubbles, silicates may precipitate and O₂ must be excluded and it is toxic in nature</td>
</tr>
<tr>
<td>TMAH</td>
<td>1.0</td>
<td>12.5-50</td>
<td>Si₃N₄, SiO₂</td>
<td>Water added and temperature is 90 °C</td>
<td>Easy to handle and smooth surface finish</td>
</tr>
<tr>
<td>N₂H₄</td>
<td>3.0</td>
<td>10</td>
<td>SiO₂</td>
<td>Isopropyl alcohol as additive and water as diluant and temperature of 115 °C</td>
<td>Toxic, explosive 50 % water is added to decrease these effects, May not etch Al</td>
</tr>
</tbody>
</table>

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**Table 2: Information of materials and etchant used in anisotropic wet etching.**

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Etchant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon (bulk)</td>
<td>Wafer</td>
</tr>
<tr>
<td>Silicon &lt;100&gt;</td>
<td>Material under Etch</td>
</tr>
<tr>
<td>Potassium Hydroxide (KOH)</td>
<td>Etchant</td>
</tr>
</tbody>
</table>
The etch rate is looked up in the database for the Potassium Hydroxide in Silicon <100>, which is 1.4 µm/min. The total time for the application example is taken as 120 seconds. Thus dividing, the etching progress is shown after the interval of 30 seconds each.

For the visualisation purposes, the different parts of the structures in examples are scaled.

One unit in VRML screen = 1 µm.

<table>
<thead>
<tr>
<th>PART NAME</th>
<th>Size (x, y, z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wafer</td>
<td>7 µm, 1µm, 5 µm</td>
</tr>
<tr>
<td>Material under Etch</td>
<td>7 µm, 3µm, 5 µm</td>
</tr>
<tr>
<td>Exposed area (Square)</td>
<td>3 µm, 0.0 µm, 3µm</td>
</tr>
<tr>
<td>Contour of Mask</td>
<td>7 µm, 0.1 µm, 5 µm</td>
</tr>
</tbody>
</table>

Table 3: Size description of the parts and their sizes for the anisotropic wet etching example.

The color scheme adopted in the examples is cyan colour stands for the wafer, greyish blue stand for the material under etch and the maroon color is the mask.

Etching progress is shown in the light yellowish color. The material index is shown on the left-hand side of the screen and the etchants are shown on the right side. In the right side, there is a start and stop button, which are used to start the visualization animation for the etching process.

The etch product and the etched shapes are determined by various factors including the etchant being used, the contour of the mask and the material under etch, orientation of the material under etch and the process of etching. In this example as the etchant is wet etchant and the material under etch is single crystal silicon with <100> orientation. The contour of the mask is a square, the etch product is a V- groove in the direction of the 100 orientation (according to Madou [12]).

Figures 2- 6 show the sequence of the visual simulation example of anisotropic wet etching.

Figure 2: Initial visualization of an anisotropic wet etching process. The wafer, the material layer under etch and the contour of mask are shown in the figure. The material index is on the left-hand side of the screen and etchant and the etch rate along with start and stop button are on right side.

Figure 3: The visualization of etching after 30 seconds time lapse. The geometry in this case is a V-grove as the material under etching is Silicon <100> and the contour of the mask is square.

Figure 4: The visualisation of etching after the 60 seconds time lapse. The 60 seconds is arrived after two stages of display update, hence the two different layers of etching progress can be seen in the figure.

Figure 5: The etching progress after 90 seconds from the start of etching. This figure shows the three stages of the visualisation. Update of etching progress is visible because of a 30-sec step for display update.

Figure 6: The etch results after the time lapse of 120 seconds. The etching is shown from the front side and it shows the progress of etching. The four layers can be seen in the figure, which shows how the etching is progressing. The front side gives a clear view of the progress in <100> direction as it is v–groove.
Figure 7: The visualisation from a different angle. It gives 3D sides view of the progress of etching.

Our second example is dry etching on the surface. This was chosen to show the applicability of surface micromachining and dry etching. The etch wafer in the application example is silicon oxide and the layer under etch is Stoic Nitride. The contour of mask in this case is a rectangular strip on top of material to be etched. The etch rate is looked up in the database for HF vapor in Stoic Nitride, which is 10 Å/min. The total time for the application example is 8 min. Thus after dividing, etching progress is shown after the interval of 2 minutes each.

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon Oxide</td>
<td>Wafer</td>
</tr>
<tr>
<td>Stoic Nitride</td>
<td>Material under Etch</td>
</tr>
<tr>
<td>HF Vapor</td>
<td>Etchant</td>
</tr>
</tbody>
</table>

Table 4: Information of materials and etchant used in dry etching example.

<table>
<thead>
<tr>
<th>PART NAME</th>
<th>Size (x, y, z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wafer</td>
<td>7 µm, 1µm, 5 µm</td>
</tr>
<tr>
<td>Material under Etch</td>
<td>7 µm, 3µm, 5 µm</td>
</tr>
<tr>
<td>Contour of Mask</td>
<td>1 µm, 0.1 µm, 5µm</td>
</tr>
</tbody>
</table>

Table 5: Size description of the parts and their sizes for the dry etching example.

Figure 8-12 shows the sequence of the visual simulation of dry etching. The etch product produced in this case is an inverted T-section on the surface.

Figure 8: The initial visualisation of dry etching process. The wafer, the material layer under etch and the contour of mask are shown in the figure.

Figure 9: The visualisation of etching at surface after 2 minutes lapse from start of etching. The etching is anisotropic in nature.

Figure 10: The visualisation of dry etching process after 4 minutes time lapse. The progress of etching is in vertical direction.

Figure 11: The visualisation of dry etching after 6 minutes time lapse. The 6 minutes are arrived after three stages of display update.

Figure 12: The visualisation from a different view after 8 minutes time lapse. The structure produced after etching is an inverted T-section on the surface.

The interactivity and animation gives the greater possibility to the user to look at the etching progress and its shape and development over time. It gives the freedom to stop the etching at any stage, and re-set the display step for refinement, or simply analyze the etching progress and its effect on the layer being etched.
The animated, interactive, simulated visualisation of etching helps in gaining visual and quantitative information about the etch progress. Transparency is an added feature that helps in determining the correct etching time or to analyze the effect of under etching or over etching.

IV. RESULTS AND DISCUSSION

We have provided a solution for the simulation of etching in MEMS, with a 3D animated display, that is updated dynamically at discrete amounts of time. The CAD application is interactive and the user can rotate the component and see it from various angles. It provides dynamic visualisation. The time for etching is user controlled and the process is shown in steps to show the progress of etching, and by refinement, allowing a precise determination of the etching time.

The material index and the etchant information including the etch rate are shown. The process can be started or stopped by mouse-clicking the start button. The display of the etching profiles is updated using analytical calculations.

Appearance: The material under etch is visualised in colour with transparency. This is done to visualise the etching progress, as the purpose of this tool is to show etching within the 3D structure.

Interactive steering: This feature allows interactively changing the simulation parameters and immediately seeing the effect of this change through the new data.

Dynamic animations: It starts with the click of button and stops with a click. Between the two the display is updated in discrete time intervals, whose step can be iteratively reduced (or enlarged) for refinement.

The 3D visualization gives a distinctive strength to the CAD approach when compared to others. The method can be used to predict etch products in a minimum amount of time compared to the relatively long duration of etching process. The approach is generalized. This means that a user will be able to choose a variety of materials, processes and the etchants from the large database.

The algorithm devised provides visualizations in scaled truthful time. The etching profile accuracy is maintained by calculating the profile from etch rate and time. Etching can be viewed with rotating, zooming, cross-section modeling and other 3D functions. This 3D tool can be incorporated with Matlab, which makes it compatible with other modules that are part of the MEMS-VR CAD tool.

The user can edit the database to correct parameters or add new materials through the database hierarchy. The database includes etch rate for a large number of etchants and materials to be etched. Both isotropic and anisotropic wet etching process characteristics have been included in the CAD tool approach.

In its current version, the CAD etching profile in the case of isotropic wet etching is not yet sufficiently realistic as is would appear in practice with rounded corners. To implement this will require further refinements of the displayed images. This will be done by using advanced mathematical techniques such as splines. Further research needs to be done in of the simulations of undercutting surfaces and other complex shapes. With the expansion of MEMS applications, there is demand and opportunity for an etching simulation facility as part of MEMS CAD tools. Available tools for simulation have limited applicability and lack a 3D visualization of the etching process simulation. Our CAD tool provides applicability in a generic modular way for large number of etchants and etching techniques.

V. CONCLUSION

A procedure for the etch simulation visualization in 3D has been presented in this paper. The requirements for the MEMS Etch simulation and visualisation were analyzed. A conceptual algorithm was developed for the CAD tool. A sample of the database for the various etchants and etch materials was shown. The combined design approach of modelling, simulation and visualisation, applied in the CAD tool reduces the time required for prototyping.

A prototype of visualization for the anisotropic wet etching has been thoroughly investigated. The appearance, interactivity and dynamic animations and other features were observed from the analysis of the application example. The CAD tool based on visual modelling allows efficient MEMS etching visualization. Future work needs to be focused to visualisation of under etching corner cutting and the roundness in the case of isotropic etching and complex anisotropic etching.

REFERENCES