Visualizing Reliability in MEMS VR-CAD Tool

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ABSTRACT

Visualizations are a crucial component in CAD systems, typically displaying design layout or physical behavior. In this paper we introduce in an innovative way visualizations, that combine both, the display of physical dimension and abstract concepts. These types of visualizations are part of MAGDA a CAD system for Micro Electro Mechanical Systems (MEMS). In MAGDA we display the geometries of the device as it is being designed, and the resulting reliability, an attribute that is in part, affected by those geometries. The reliability visualizations are a powerful contribution to working faster towards a robust design, reducing the trial and error phase in the design.

Keywords

Scientific Visualization, VR-CAD tools, MEMS, Reliability

1. INTRODUCTION

Since the proliferation of CAD tools, visualizations have gained importance. They provide invaluable visual feedback at the time of design, regardless whether it is for civil engineering or electronic circuit design-layout. Typically we find in a CAD system a graphics user interface and a simulation facility, both supported by sets of toolboxes. Traditionally the results of the simulations are displayed as characteristics of the product in design. In Engineering they are displayed as plots and curves. Scientific visualizations including multi-dimensional multivariate visualizations have now been around for several decades, e.g. environmental maps of pluviosity. In our research, we are going a step further, trying to display results of predictive calculations on the very design visualizations of the structures they represent thus adding to the information content they can offer. Our environment is in Micro-Electro-Mechanical systems (MEMS) CAD development.

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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, a strong growth is predicted for the MEMS industry. 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. To the contrary, 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 be simply downscaled counterparts of larger mechanical machines, requiring innovative designs and arrangements of their components, whose effects are often not fully understood.

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 of 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 small number of MEMS design software environments are available on the market. 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], [Cov01] or may be difficult to use [CFD]. They appear as a collection of tools [ANS], at times limited to very specific applications [Rez97]. Few have facilities for determining the MEMS manufacturing parameters as their primary purpose, and if so, they can be very expensive [MEM]. The availability of virtual reality in this area is very limited indeed [InteS].

To address the shortage of MEMS design tools, we have initiated MEMS Animated Graphic Design 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. With these effects in mind, and the importance of a robust design, we have included reliability estimations in our MEMS design package.

In an innovative way, MAGDA combines visualizations to display both, physical dimension and abstract concepts. We display the geometries of the device as it is being designed, the animated functioning, and the resulting reliability, an attribute that is in part, affected by those geometries. An example is shown towards the end of this paper. The reliability visualizations contribute to working faster towards a robust design by shortening the move from trial and error to an informed design decision.

MEMS are complex devices, and estimating their reliability is also complex. We are not aware of any publications that include reliability visualizations. The purpose of this paper is to explain how we go about this type of visualizations in MAGDA.

Visualizations are a crucial component in CAD systems, typically displaying design layout or physical behavior. In this paper we introduce in an innovative way visualizations, that combine both, the display of physical dimension and abstract concepts. These types of visualizations are part of MAGDA a CAD system for Micro Electro Mechanical Systems (MEMS). In MAGDA we display the geometries of the device as it is being designed, and the resulting reliability, an attribute that is in part, affected by those geometries. The reliability visualizations are a powerful contribution to working faster towards a robust design, reducing the trial and error phase in the design.

The paper is organized in the following way: Section 2 provides a mini-tutorial to MEMS fabrication and the design affecting the MEMS reliability. This mini-tutorial is confined to those parts in MEMS design that are relevant for understanding this paper. This is followed by section 3 where the complex reliability modeling for MEMS is presented. Section 4 presents the MAGDA reliability visualization with an application example and discussions. Finally section 5 brings the conclusions, with suggestions for future work.

2. MEMS FUNDAMENTALS

MEMS are microscopic. Their size ranges from that of a grain of pollen, or the thickness of a human hair to a few millimeters. To understand the design of MEMS we have to look first at the way they are manufactured.

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 its material in specific patterns so that the desired structures emerge. Examples of the kind of materials that are deposited or grown in layers are typically materials involving silicon or silicon oxides, but also metals.

The properties of those layers of material can selectively be modified by diffusion or implant of ions (e.g. Boron) to achieve specific electrical characteristics, e.g. conducting or non-conducting. The deposition and patterning includes a number of processing steps such as masking and etching or sputtering and ion implants. Typically this involves about 200 or more processing steps.

Another technique for producing 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. In this way very small devices can be made, for instance, pumps with miniature valves and flexing membranes of silicon, with just one or two millimeters in diameter.

While much of the patterning is well controlled in current process technology, the design and placing of the components, and their dimensions depends on the engineer's choice. Due to the relatively recent MEMS industry, this require often a lengthy and expensive cycle of trial and error.

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

MEMS are designed as sensors e.g. thermal, magnetic, optic; and actuators, such as valves, pumps, etc. The possible structures and components in MEMS are vast. They range from simple membranes and cantilevers, to complex gears and combs, and optical arrays. Some of the parts are moving, flicking, bending at a rates of up to 500 Hz, some respond to human interaction, while other equally important structures or rigid, e.g. mirrors in optical switching devices used in communications.

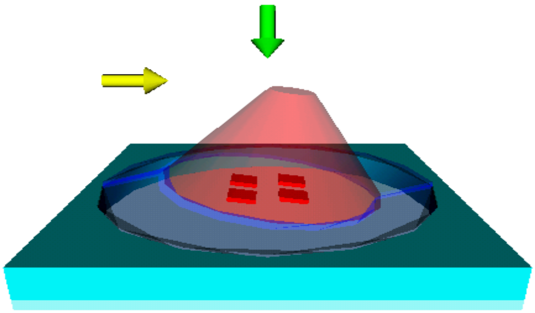
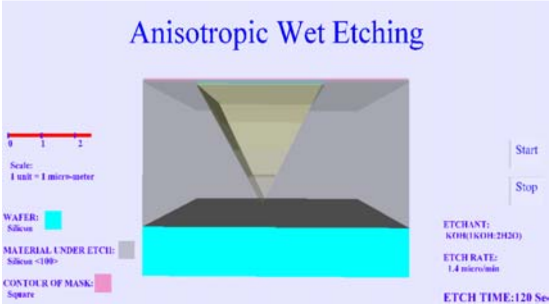


Figure 1 Example of animated MAGDA visualization of a tactile sensor

As an example Figure 1 shows as an animated MAGDA visualization a tactile sensor, using transparency to show the internal structures. [Li01]. This sensor was designed and implemented by Chu e.a. [Chu96]. The transparency of our images is a substantial advantage compared to the few visualizations in other MEMS CAD tools. The image shows one of the possible positions of the mesa, as a force, represented by a color-changing arrow, is applied (by mouse click on a button in the window) either vertically or as shear force [May02]. The magnitude of the force is set by pop-up dialogue box. The membrane underneath the mesa bends while the mesa tilts down or just deepens into the elastic membrane. However, this is not yet visible on this image.

Deformation calculations are normally done using finite element analysis, which are lengthy and unacceptably slow for visualizations that require quick results. Research is underway for simplified modeling and calculations of flexibility and plasticity for MAGDA visualizations. Nevertheless this example demonstrates understandably enough that the movable parts may be subject to deterioration by wear and tear with a limited lifespan. Here is where reliability comes into play.

The life span and performance of a MEMS does depend on the geometries and device dimensions, for example a thin membrane continuously flexing may not last as long as a thicker one, but the thicker one can affect the performance e.g. reduced sensitivity in this sensor, or in the throughput of fluid through a valve. Therefore in MEMS design a compromise needs to be reached, between the geometries of the device, the device performance, and the desired size of the MEMS, constraint by its final installation conditions.



Scale:
1 unit = 1 micro-meter

WAFER: 🟦
Silicon

MATERIAL UNDER ETCH: ⬜
Silicon <100>

CONTOUR OF MASK: 🟪
Square

ETCHANT:
KOH(1KOH:2H2O)

ETCH RATE:
1.4 micro/min

ETCH TIME:120 Se

Figure 2 MAGDA virtual etching of a v-groove showing the progress in 30-second intervals.

If the design is not robust, small manufacturing fluctuations such as the duration of etching lead to drastic changes in the device geometries, and consequent alterations in the performance of the device.

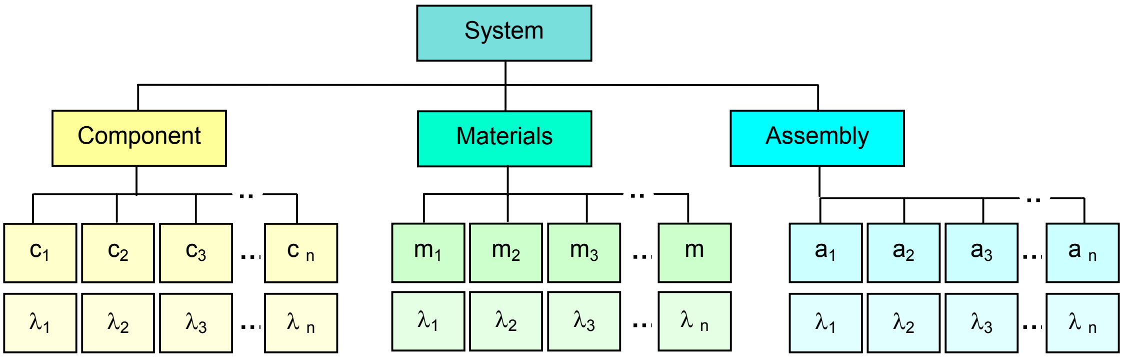


Figure 3 Hierarchical structure of proposed MEMS Reliability model

How critical this can be is illustrated with the example in figure 2 showing a MAGDA image for virtual etching [Jha02].

Again, transparency gives an advantage to see the progress in scaled time. The visualization shows the depth of the v-groove reached at different times in 30 seconds interval. One can see on the image that a mere 30 seconds make almost 1 µm difference in depth of the groove. This could be 10% or more of the size of the MEMS. In this case the inclination of the etching plane is determined by the crystalline orientation of the Silicon.

3. MEMS COMPLEX RELIABILITY MODELLING

MEMS reliability assessments are complex. Conventional predictions based on accelerated testing (burn in) cannot be applied, as it is usual done in IC. In MEMS quality sampling, it would not pick out the defective ones, on the other hand, the materials and glues employed may not be heat tolerant, such as resins and polymers; and finally, being mechanical devices, they will fail after a functional life time due to wear and tear. Models for reliability predictions such as used in IC do not hold.

Reliability modeling normally focuses on system performance as a function of component's performance, as either working (or idle), or failing. This is expressed as a probability of component failure or duration (time) of service as time between failures (TBF).

This model has the weakness that the components based approach alone is not sufficient as an indicator for reliability predictions. There are many other things in a MEMS product that can go wrong.

Our model considers the reliability looking at the components, the materials, and the assembly as potential reliability detractors. The design of a component affects its reliability. Non-robust design is susceptible to manufacturing fluctuations and the risk of reduced functional life by physical or chemical deterioration. The materials from which the components are made of can act as reliability detractors by physical/chemical changes such as change in composition (oxidation), corrosion, ageing, wear and tear. This is usually calculated using a Weibull distribution [Hen92], where the failure rate decreases (infant mortality) or increases with time (wear out), but then it does not look at the individual components or structural complexity. Therefore, we have incorporated into our model the effect of assembly of the devices from their components considering the interface between components. This includes the faults that arise from faulty assembly, or wrong, defective parts if they affect the interface. This consideration in our modeling holds, regardless whether the parts are assembled at the time of the production (eg. on a silicon wafer), or assembled after producing components separately eg. microassembly following LIGA processing.

It is clear that not all these factors will have equally strong impacts on the reliability, some will have more influence and some less, and somewhere the line must be drawn with regard to what needs to go into the model and what is negligible.

In our model, we break down the device in a hierarchical way, into components and subcomponents and so on. Each has its own probability of failure, or a distribution of it, if time dependant. Reliability values are calculated at the lowest possible levels. A clear distinction is made between the different failure rates, i.e. the early failure "infant mortalities" failures, the stable state failures and the age related failures from wearout or corrosion. Early failures often are due to gross defects which remain inactive during testing, but are triggered when in use for some time, e.g. the melting of a reduced width (over etched) interconnect line [Dim00].

For the purpose of our example we take the simple case considering the components in series. This is valid because at this time we are not considering redundant or "back-up" components. For a MEMS with *n* components, the reliability R_s is then

$$R_s = \prod_{i=1}^{n} R_i \qquad (1)$$

If we apply this to the sensor that we have shown in Figure 1, we can write

$$R_{system} = R_{elastom} \times R_{membr} \times \dots$$
$$R_{wirebond} \times R_{gap} \times R_{electrode} \qquad (2)$$

where component reliabilities correspond to different structures in the sensor respectively. In this case the elastomer, membrane, the bonding of the wire, the gap between the mesa and the piezoelectric contact, and the electrode in the sensor. It should be noted that for the sake of simplicity, we have used a rather reduced set of structures in our example. The membrane can break at the very early stage of microassembly, but it also can wear out and break very late in the MEMS lifetime. We have the elastomer (not shown in figure Figure 1) surrounding the mesa that can come off if it is not properly adhering. There is the wire bond that can melt open on a defectuous narrow place in early infancy, and on the other hand there is the gap distance that progressively decreases as the membrane fatigues and does not bounce back.

Each of the components reliabilities has its own parameters following either an exponential or a Weibull distribution. If developed further this becomes rather complex as we are dealing in general with the development of the n-variate case of the Weibull distribution. It is not the purpose of *this* paper to go into further details of the mathematical modeling, or the ways of calculating the different reliabilities. The example is sufficient to show how this can be visually exploited for the benefit of the MEMS designer. It suffices to say that each component's term is composed of up to three reliability distributions, for the design (geometries), for the materials, and for the interface.

4. APPLICATION EXAMPLE AND DISCUSSION

We wish to calculate the reliabilities for each component. Because they have different failure modes, they are modeled either with the exponential or the Weibull distribution, or both, depending on whether their components, materials or assembly is time dependent or not. Table 1 gives an overview of which reliability distribution was used in the calculation.

fault	*Model used*		*MTTF order of magnitude*
	Exp	*Weib*	
membrane strain defect (assembly)		✓	10^0
Elastomer adhesion defects		✓	10^1
gap distance problems		✓	
Elastomer thickness	✓		10^2
Membrane thickness	✓		
interface wire bonding	✓		
electrode size problems	✓		10^3
Membrane wearout		✓	10^4

Table 1Components and structures used in the reliability example (color coded fields)

In theory we have to calculate three reliabilities for each component. However, in practice it is not possible to do it exhaustively as the complete information might not always be available. In our example not all the three reliabilities were calculated for each component of the sensor, but only those that are relevant in our example. For example the elastomer as a material does not deteriorate, but its thickness does affect the contact with the electrodes.

In preparation for the reliability visualization we have then grouped the reliabilities according to their expected life span, their mean time to failure, and color-coded them. We have grouped the reliabilities in orders of magnitude. This gives a color scale mapping to a logarithmic scale. If the mean time to failures (MTBF) were closer to each other, a linear scale would suffice.

We can now apply this color-coding to the visualization of the MEMS. We use the same geometry visualization as it emerges from the design desk, but this time we use the reliability colors on the structure or parts of the structure where we have calculated its reliability. All other structures are left grey. In cases where there would be overlap of colors, for example membrane strain and membrane wear out, we assign the lower reliability color to the visualization, as one would in a worst-case scenario.

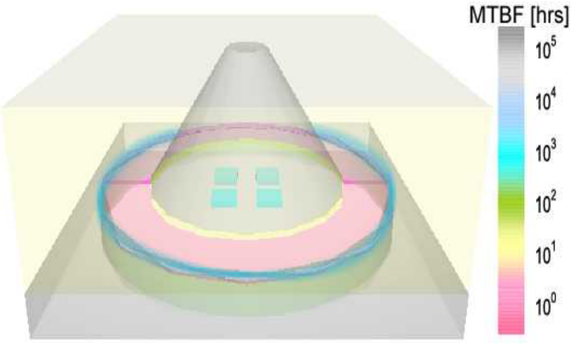


Figure 4 Reliability visualization of the sensor using color mapping

Figure 4 shows the reliability visualization. In this image the colors are mapped to the reliability of the structures, according to the scale on the right side [Nie97]. We can see that the membrane constitutes a large reliability detractor by its pink color. This corresponds to the high risk of breaking the membrane at the time of assembly. The membrane's wearout is represented as the cloudy rim (blue) at the intersection of the membrane and the depression (gap) where it sits on. One can also see that the elastomere and the gap distance are following in reliability risk. The elastomer adhesion is shown throughout the whole elastomer (surrounding the mesa cone) and it is attached to the mesa on a breakable yellow rim. The correct size of the four electrodes (aqua-blue) is crucial for the correct sensitivity to the sensor. The decreasing gap distance is shown as green on the sides of the depression well.

What this visualization shows at one glance whether reliability is good or not. Because this method is being automated and built into MAGDA, it is possible to see whether MEMS device that an engineer is about to design, will be sufficiently reliable or not.

One might argue that the mere color mapping is nothing new. However, it is new if we consider that we are visualizing reliability information, and we are doing this in view of the complexity of design and the tedious and costly phase of trial and error that is typical in MEMS design. In this light one can understand the importance of this type of visualization.

If the reliability visualization yields a graph that is high in red colors, then one can see immediately that there is a high reliability risk that may, or may not be improved by changing the design or the material, depending on the purpose of the MEMS. It is then a matter of going back to the drawing board for revisions of the MEMS geometry or its materials. For example, if by making a slightly thicker membrane such that the reliability color changes from red to yellow, one can decide whether this still yields an acceptable performance i.e. the sensor's sensitivity is sufficient for its purpose. Otherwise, one can simply accept it, at the risk of a lower reliability.

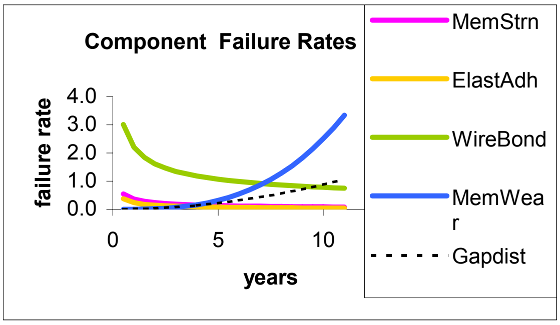


Figure 5 Failure rate distributions for the sensor case components, materials and assembly

In MAGDA a database provides material information such as materials resilience to stress, and fatigue to deformation for the materials that are used in MEMS fabrication. It also contains and specific probabilities to failure, based on design conditions and failure modes. More failure modes can be added progressively to the database. Figure 5 shows the failure rate distributions for each of the five of the components or structures used in our example. A sixth parameter, the electrode size has a constant probability of failure and is not shown on this plot because it would hide the lower curves.

When we are calculating the reliability normally we obtain a single value that represents the mean value of the device breaking down. In time dependent reliability calculations we look at the distribution. As expected the reliability distribution for the example given does follow a Weibull distribution, by doing conventional statistical methods such as plotting on a log scale [Ban89]. This is important at the time of testing, where the Weibull shape parameter is applied to decide on accept or reject on the sample population [His02]. At this time we have not yet found a meaningful way to visually represent the device reliability in time other than running through a sequence of frames, displaying the change in colors. However, at this time it is not implemented in MAGDA.

5. CONCLUSION

In this paper we have shown a powerful application of scientific visualization color mapping that can be applied to provide useful reliability information that aids in the design of MEMS. We have proposed a complex model for reliability predictions, based on the component's design, its materials and its assembly to support the visualization in a systematic way. Because MEMS are usually complex devices with many components whose geometries and materials have an impact on the reliability, it allows the designer to reduce drastically the trial and error design phase and move quicker to a robust design.

At this time, we can only use the Mean Time to Failure for the predictive assessment, because otherwise it would make its color mapping ambiguous. Future work is aimed at faster computations to show animations of the changing reliability color mapping in time.

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