Opto-mechanical Modeling for Fabrication of MEMS Micro-Mirrors

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ABSTRACT

Micro-mirror arrays are currently being developed by a number of companies for optical switching. To bring these products to the market quickly, a rapid development cycle is needed, leaving little time for multiple fabrication runs. CAD tools for MEMS can reduce the number of fabrication iterations run by allowing prototyping to occur within the virtual environment. Here, many models can be tested quickly and the design can be optimized prior to initial fabrication.

Modeling of micro-mirrors requires unique simulation capabilities beyond those required for traditional MEMS devices. In many cases, the device alone has unique features which require that CAD tools offer additional capabilities beyond typical electro-mechanical analysis. Second, the entire array must be studied, both from a fabrication and optical perspective. The output of a MEMS software CAD tool is input into an optical ray-tracing program to provide optical system performance of the total MEMS micro-mirror and provide non-sequential ray-tracing of a micro-mirror array.

This paper will present a method for rapidly developing MEMS micro-mirrors by utilizing CAD tools currently available. Design begins with a mask layout which leads to analysis of one mirror. These results are then used to model a complete array.

Keywords: MEMS, micro-mirror, simulation, CAD, non-sequential ray-tracing

1. INTRODUCTION

IntelliSense's CAD for MEMS tool, IntelliSuite™, focuses on device level simulation, while providing links to system level design tools. By providing accurate device level results, IntelliSuite generates accurate system level results with fewer design iterations.

To model a micro-mirror, a number of simulation elements must be brought together. First, accurate process simulation can generate the stresses in the material layers, and thereby the curvature of the mirror's surface. Second, the means of actuation, typically electrostatic, piezoelectric, or electromagnetic, should be studied. Third, many mirrors require contact analysis as they "snap" into position. Finally, more complex structures have been created which require single or multiple assembly steps to create the final device.

Once a device model is created, it can be activated, and the resulting mirror deformations, angles, and stability can be input directly into an optical ray-trace program[1]. The performance of either single mirrors or an entire array of mirrors can be modeled. Non-sequential ray-tracing allows the modeler to visualize spots created by multiple mirrors, thus the optical cross-talk can be observed.

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[1] Zemax (Focus Software, Tucson, AZ)

2. PARAMETERS MODELED

IntelliSuite's process simulation module enables the user to build custom process flows from a database of standard included process steps or from user-input proprietary process steps. Two-dimensional masks define the XY-dimensions of the structure, while the material thicknesses determine the z-dimensions. From the process data and mask set, IntelliSuite automatically generates a three-dimensional model for analysis.

The MEMS micro-mirror is initially modeled in its pre-activated configuration. This is derived from the fabrication process. When the structural model is complete, the actuation voltage(s) and/or current(s) can be applied to study the steady state or dynamic response. These dynamic changes will affect the mirror angle and stability. If the mirror is improperly designed (too thin), this could also have a significant effect on the mirror flatness. All of these parameters can be used as inputs into the optical system design software to model the overall system performance. They can also be used to model optical cross-talk (if any) between the outputs from the mirrors.

3. MASK LAYOUT

The mask layout is the first step in modeling the micro-mirror. The mask shown in Figure 1 was created in IntelliSuite Mask Editor. The output from this mask editor is compatible with other mask editors and standard mask formats such as DXF, GDS-II, and CIF. This particular mirror is a NASA Goddard Space Flight Center mirror that will be used in a space satellite adaptive optical system[2].

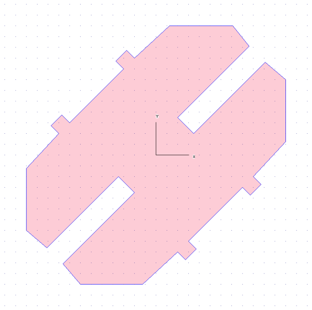
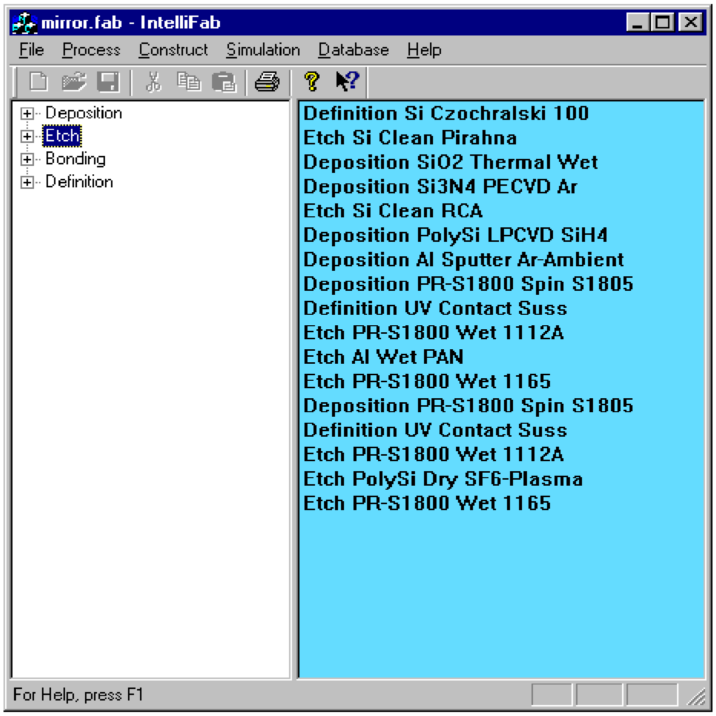


Figure 1 Mask for micro-mirror top surface

4. PROCESS TABLE

The process model output from IntelliSuite is used to create the device. This relates to the etching and deposition of materials on areas defined by the photolithography. Some materials actually change their physical characteristics due to some processes and this needs to be taken into account during the modeling stage. From the process model, a 3D finite element model is generated. The device can later be fabricated using the documentation generated by the process model.



Definition Si Czochralski 100
Etch Si Clean Pirahna
Deposition SiO2 Thermal Wet
Deposition Si3N4 PECVD Ar
Etch Si Clean RCA
Deposition PolySi LPCVD SiH4
Deposition Al Sputter Ar-Ambient
Deposition PR-S1800 Spin S1805
Definition UV Contact Suss
Etch PR-S1800 Wet 1112A
Etch Al Wet PAN
Etch PR-S1800 Wet 1165
Deposition PR-S1800 Spin S1805
Definition UV Contact Suss
Etch PR-S1800 Wet 1112A
Etch PolySi Dry SF6-Plasma
Etch PR-S1800 Wet 1165

Figure 2 Process flow for mirror fabrication

5. PROCESS VISULIZATION

The finished model of the mirror is generated from the process table. This visualization allows the effects of process variations to be studied. This is useful to immediately see how the structure changes as a result of changes in the process flow and mask layout. This virtual prototyping allows the device to be visualized without a fabrication run which saves time and resources.

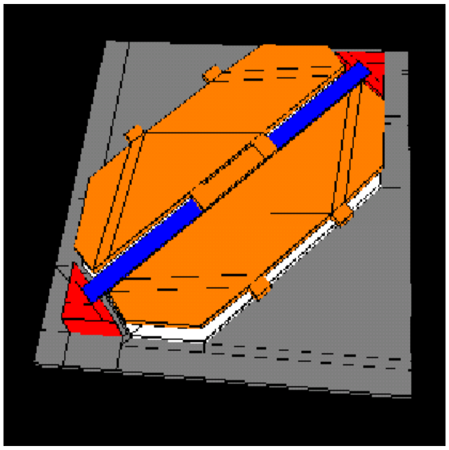


Figure 3 Visualization for the mirror process

6. SOLID MODEL

At this point in an electro-mechanical simulation, two meshes are generated. One is the mechanical mesh, for studying the stresses and deformations in the mechanical part; the other is the electrostatic mesh. The electrostatic mesh is a boundary element mesh used to generate the capacitance matrix, charge density distribution, and electrostatic pressures. The user has the ability to independently define both meshes in areas of interest. For the mechanical mesh, higher resolution is desirable in areas of high stress or deformation. For the electrostatic mesh, higher resolution is desirable in regions where the charge density is expected to be higher.

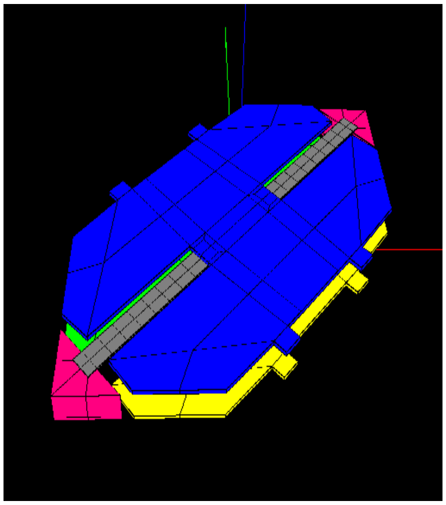


Figure 4 Final solid model of micro-mirror

7. ANALYSIS PARAMETERS

During the electro-mechanical analysis stage, boundary conditions and voltage loads are applied to the device. In the case of the example shown, a 28 V differential voltage is applied between the mirror (which is set to ground) and one of the electrodes. This is shown in Figure 5. To tilt the mirror in the opposite direction, the mirror remains at ground potential and the electrode with voltage gets grounded while the opposite electrode has voltage applied to it. By alternating the voltage on these electrodes, the mirror can be made to scan.

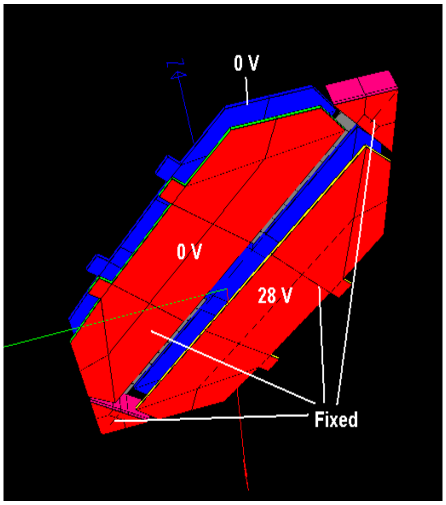


Figure 5 Voltages are applied to the micro-mirror and support structures are anchored

8. SIMULATION RESULTS

The relevant results generated by the MEMS electro-mechanical model are: displacement, rotation, stress, capacitance matrix, electrostatic pressures, natural frequencies and mode shapes, pull-in voltages, transient response, and deformed geometry. Figure 6 shows the magnified (5X) view with a static deformation resulting from the 28 V differential. If the mirror is not designed properly, it could collapse on itself so the simulation modeling saves hundreds of hours in designing test structures.

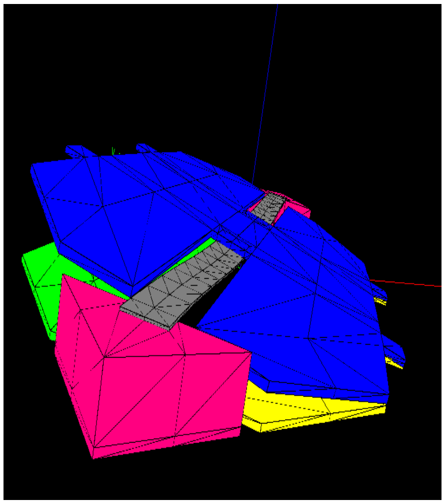


Figure 6 Tilted mirror model showing the bending of the support structures

9. ELECTRO-MECHANICAL MODEL OUTPUT SERVES AS INPUT FOR OPTICAL MODEL

The parameters from the IntelliSuite model that are used as inputs to the optical model are: 3D surface profile (polynomial fit to the surface curvatures), maximum mirror angle, jitter angle associated with mirror stability, and surface material (which effects reflectivity).

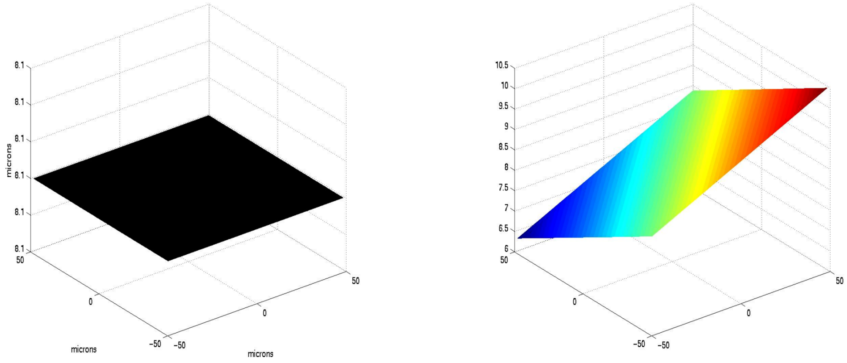


Figure 7 Un-tilted vs. tilted mirror surface plots which are based on outputs from IntelliSuite

A number of inputs are added to the ray-trace model to complete the data input. These include number of mirrors in X and Y, mirror width in X and Y, index of refraction before and after the mirror, operation wavelengths and possibly test wavelengths, rotation angle about Z, surface profile, reflection characteristics, and angle about X and Y.

10. EFFECT OF MIRROR DEFORMATION ON FAR FIELD PATTTERN

Single crystal silicon wafers are polished but still have certain degrees of curvature associated with them, albeit the radius of curvature is very large (2.5-7 meters)[2]. But even with this large radius of curvature, there is some effect on the optical performance. Although this example mirror was originally designed for a satellite adaptive optics application, it will be applied to a telecommunication application for this modeling example.

In this case, laser diode energy is collimated with a GRIN collimator and then travels 8 mm to a micro-mirror. The mirror then deflects the energy at a 30 degree angle (optical) to another GRIN lens receiver which collects the light and focuses it onto another fiber (see Figure 8). One could envision that multiple output GRIN lenses with fibers attached to them could be placed about an 8 mm radius around the mirror center of rotation to switch the input light to multiple outputs. Although this is a limited application in that the mirror has only one axis of rotation, it can illustrate the effect of how the mirror radius of curvature changes the optical throughput into an 8 micron diameter fiber.

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[2] Measured with a Zygo® interferometer and a Polytech PI® vibrometer

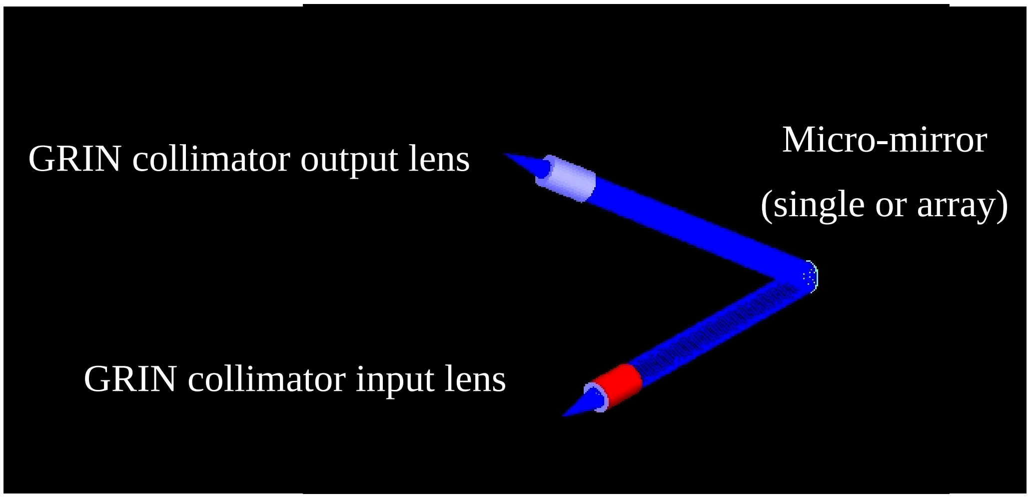


Figure 8 Optical layout: A laser diode source illuminates into a GRIN lens collimator that directs light off a micro-mirror to a GRIN lens receiver which focuses light onto a fiber

Using the optical set up of Figure 8, the mirror radius of curvature was varied up to infinity to see the effect of the throughput on an 8 micron fiber at the focal point of the output GRIN lens. The results of these variations are shown in Figure 9.

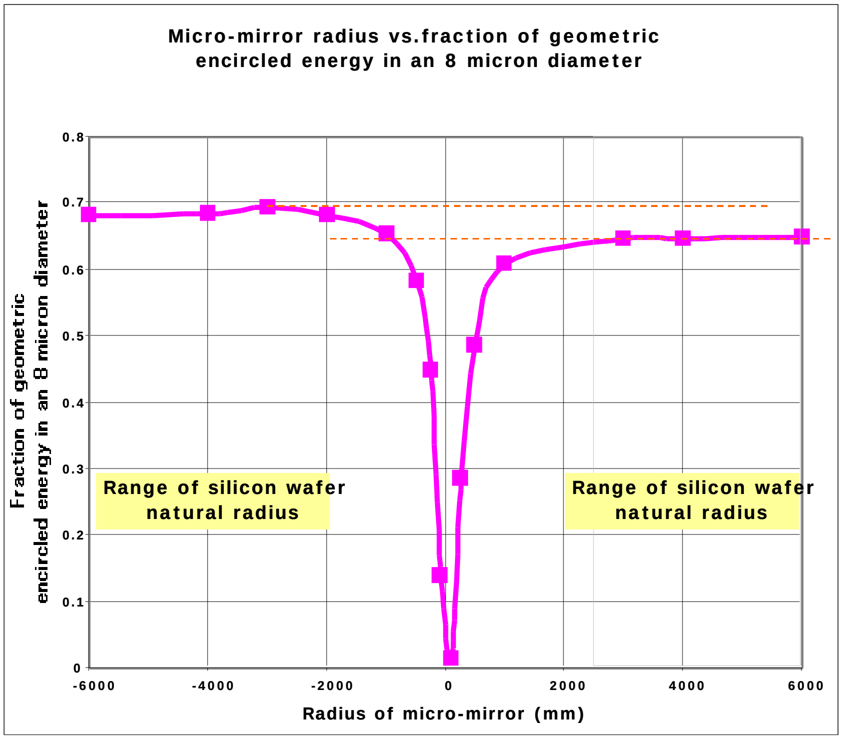
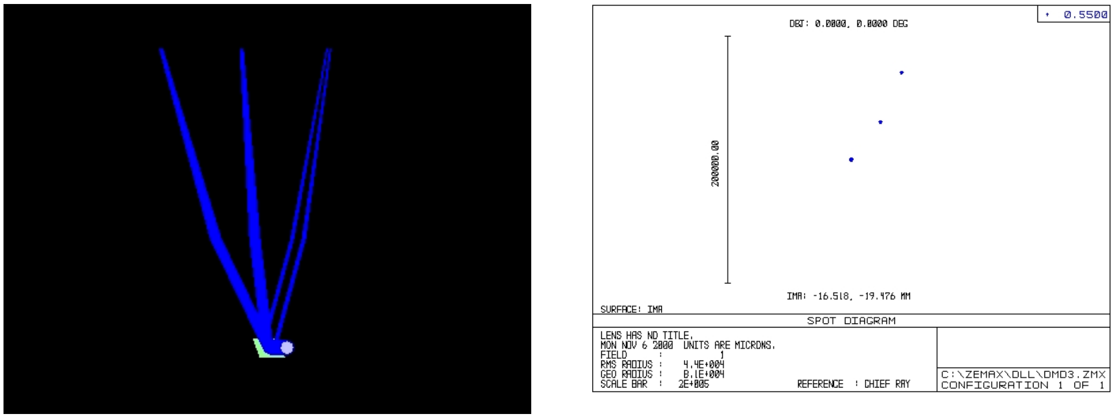


Figure 9 Effect of silicon wafer curvature on optical throughput of light reflected off a MEMS micro-mirror through a GRIN lens and into an 8 micron diameter fiber

The shorter the radius of curvature of the wafer, the more the light spreads out and the less that makes it through the 8 micron diameter fiber at the output GRIN lens focal plane. The shaded area indicates the range of radii of curvature of several silicon wafers. Note that the optical throughput actually changes by as much as 5% (for this example) when the radius is changed from positive to negative. When the curvature becomes very large in the positive or negative directions (towards infinity, i.e.: flat mirror), the throughput approaches the same value.

11. IMAGE FROM AN ARRAY OF MIRRORS

An array of mirrors can be modeled in ZEMAX to examine the scatter between channels. An example of this is shown in Figure 10. In this case, a 3x3 array of mirrors is modeled (9 mirrors) and the reflected energy from these mirrors is focused down onto 3 points. The point of this is that non-sequential ray tracing can now provide a powerful tool for the MEMS opto-mechanical modeler.



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LENS HAS NO TITLE.
MON NOV 6 2000  UNITS ARE MICRONS.
FIELD      :          1
RMS RADIUS :    4.4E+004
GEO RADIUS :    8.1E+004
SCALE BAR  :   2E+005               REFERENCE  : CHIEF RAY
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CONFIGURATION 1 OF 1
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(a)

(b)

Figure 10 (a) Non-sequential micro-mirror array model of a 3 x 3 array of micro-mirrors focusing onto 3 spots. (b) Picture of the focal plane showing the spatial arrangement of the three optical spots

12. CONCLUSION

Mirror deformation due to wafer flatness and electro-static pull can be modeled in InteliSense's IntelliSuite software and input into Focus Software's Zemax program to predict the final reflected beam quality. The measured radius on polished silicon wafers of 2.5 - 6 m should be taken into account in the final optical design. By simulating an accurately fabricated device, along with the system behavior, software modeling of MEMS devices can dramatically reduce time and cost to market.

13. REFERENCES

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2. Zemax Optical Design Program User's Guide