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**229196**

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# piezoVolume

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**Grant Agreement No.:**

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Duration: 3 years

# D2.5
# PiezoMEMS design tutorial

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## Abstract

The following document presents a training manual on CoventorWare Modeling of an Energy Harvester in section 1.Tthe sane device is used as a training example for MEMS+ in section 2. Both sections are material for HandsOn. The Section 3 is the SEMulator3D tutorial which is made of slides and Live exercises.


## Public introduction[1]

[1] According to Deliverables list in Annex I, all restricted (RE) deliverables will contain an introduction that will be made public through the project WEBsite

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# 1 PZT ENERGY HARVESTER DESIGN IN COVENTORWARE

## 1.1 Introduction

As wireless sensor nodes become smaller, their energy supply is a limiting factor for further miniaturization as integration density is limited by the space requirements of the energy storage system. MEMS based vibration energy harvesters, such as the one shown in this example, are becoming a key enabler for further miniaturization and deployment of energy autonomous sensor nodes. Among existing methods, piezoelectric harvesting is the more studied thanks to its promising results.

The device is made with the SINTEF MoveMEMS design kit. It is based on a PZT stacked on a SOI wafer. A description of the MoveMEMS process is also given in the *Using CoventorWare* manual, starting on page U4-24.

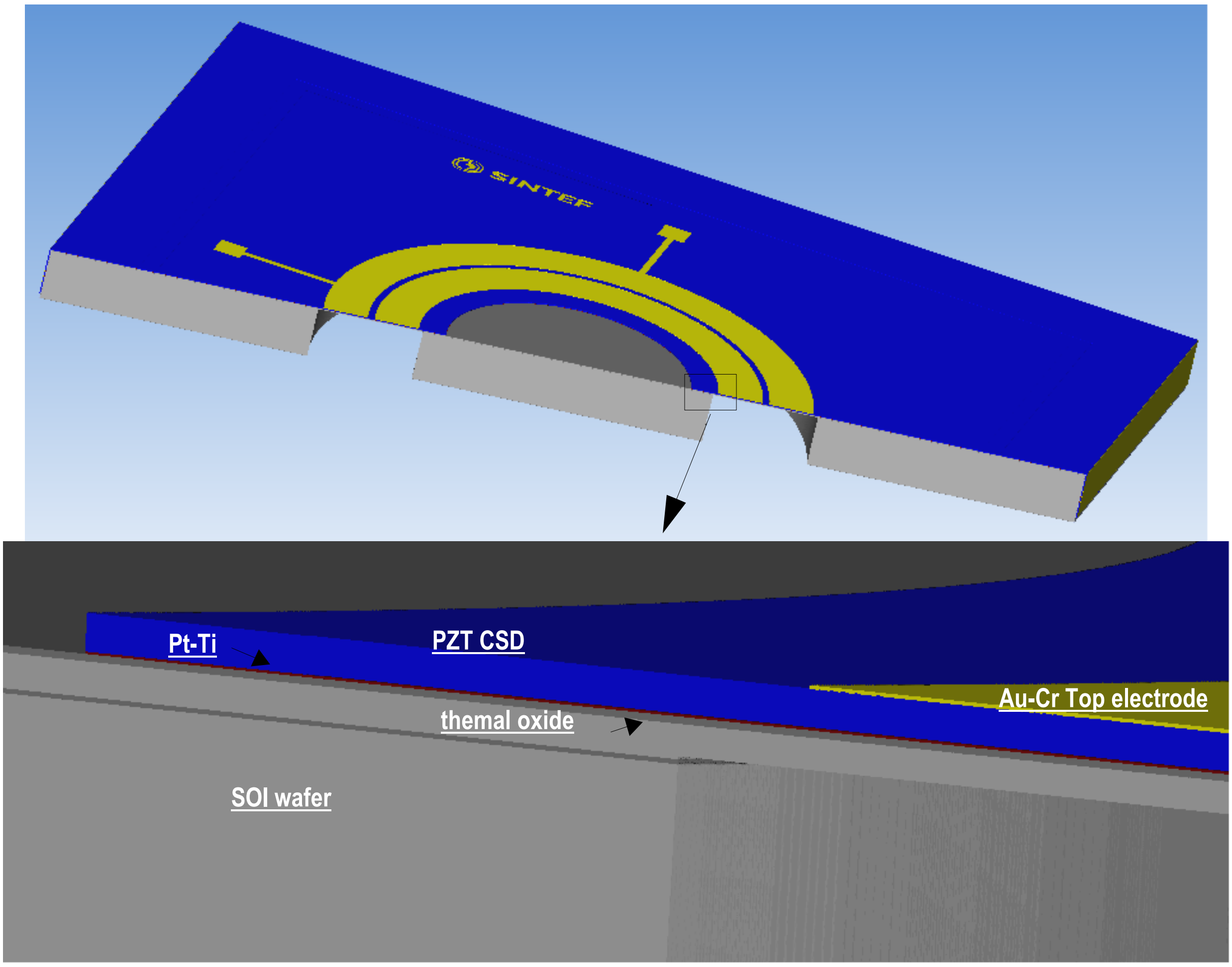
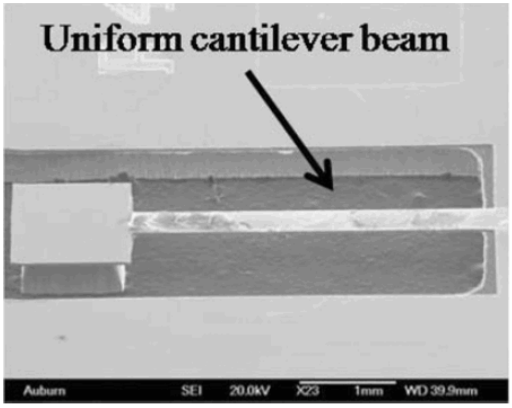



Figure 1.0 Process description

### 1.1.1 PZT cantilever with Si Proof mass

The piezoelectric cantilever consists of a multilayered film of $SiO_2$/ Pt/ PZT/Au deposited on a silicon beam of nearly 8 microns of thickness. The silicon substrate is used to make a proof mass to improve sensing of environmental vibration or movement by decreasing resonant frequency.

The device is similar to the one published by Shen et al (D. Shen, J.-H. Park, J. Ajitsaria, S.-Y. Choe, H.C. Wikle III, D.-J. Kim "The design, fabrication and evaluation of a (see picture below)). The process is also based on PZT on SOI, yet the thicknesses are different so this exercise is made with other dimensions and results are not compared.




Auburn University device (Ref 1)

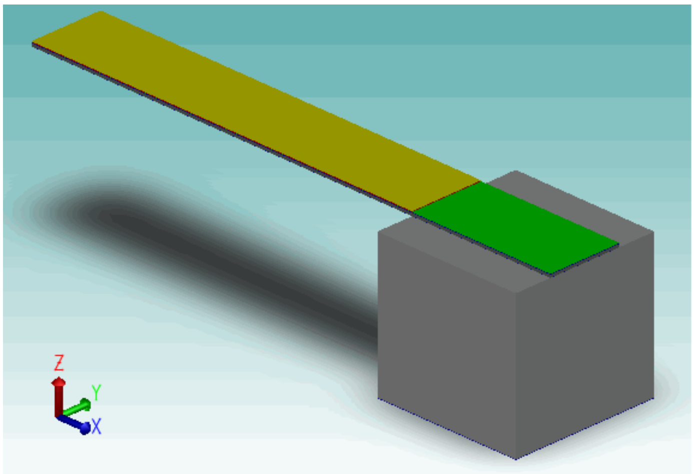



Figure 1.1 Cantilever and proof mass

### 1.1.2 Tutorial Overview

This tutorial is organized into three exercises, which demonstrate various techniques:

Exercise 1: Technology setup

- how to start a project
- how to add material to a Material Property Database
- how to create a suitable process

Exercise 2: 3D modelling

- how to draw a layout
- how to create the 3D MEMS
- how to mesh it
-

Exercise 3: Simulations in Analyser

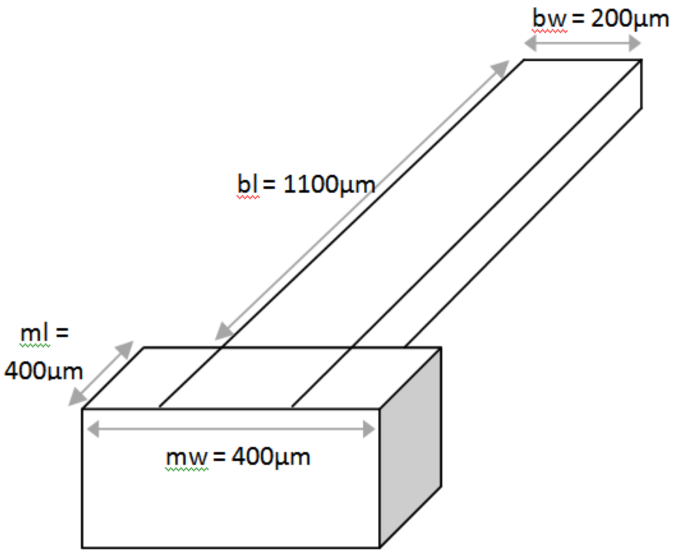
- how to run a piezoelectric modal analysis
- how to run an harmonic with load

## 1.2 Technology setup

In this section you will start a CoventorWare project and get familiar with its environment. You will then review the default Material Property Database and add the necessary materials. Finally you'll create a process file.

### 1.2.1 Preparation

The first design step is to define dimensions of the geometry. As can be seen in

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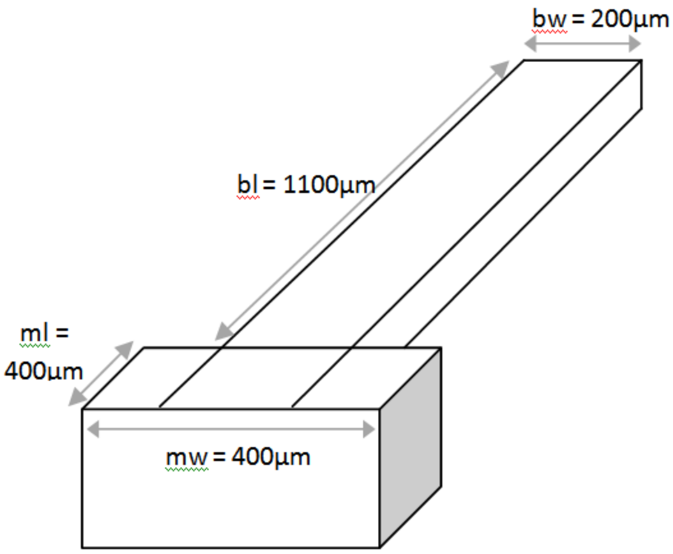



Figure 1.2 Cantilever dimensions

### 1.2.2 Initialization

During this initialization process, you will create a working project directory. This directory will contain all the files created in the tutorial, a project database for tutorial models, simulation results, and a settings file that saves window settings.

| Tasks | Clues & Comments |
|---|---|
| Start CoventorWare and load the tutorial called *SINTEF_energy_harvester*. | Find the *import tutorial* icon.<br>In the Project Browser, a default Settings file appears on the Settings file line. This settings file stores the combination of files as you put them in the function manager. |

### 1.2.3 Load and update a Material Database

| **Tasks** | **Clues & Comments** |
|---|---|
| Go in the project directory and copy paste sintef_initial.mpd. Name the copy *sintef_tutorial.mpd* | • MPD has automatic load and save. To create new files you must copy/paste one first.<br>• Default MPD file mpd1.mpd is in Shared folder in your work directory. |
| Load the *sintef_tutorial.mpd*. | Browse to the project folder |
| Add Au-Cr, PZT-CSD and Pt-Ti with following properties. | See Au-Cr properties 4, 5. |

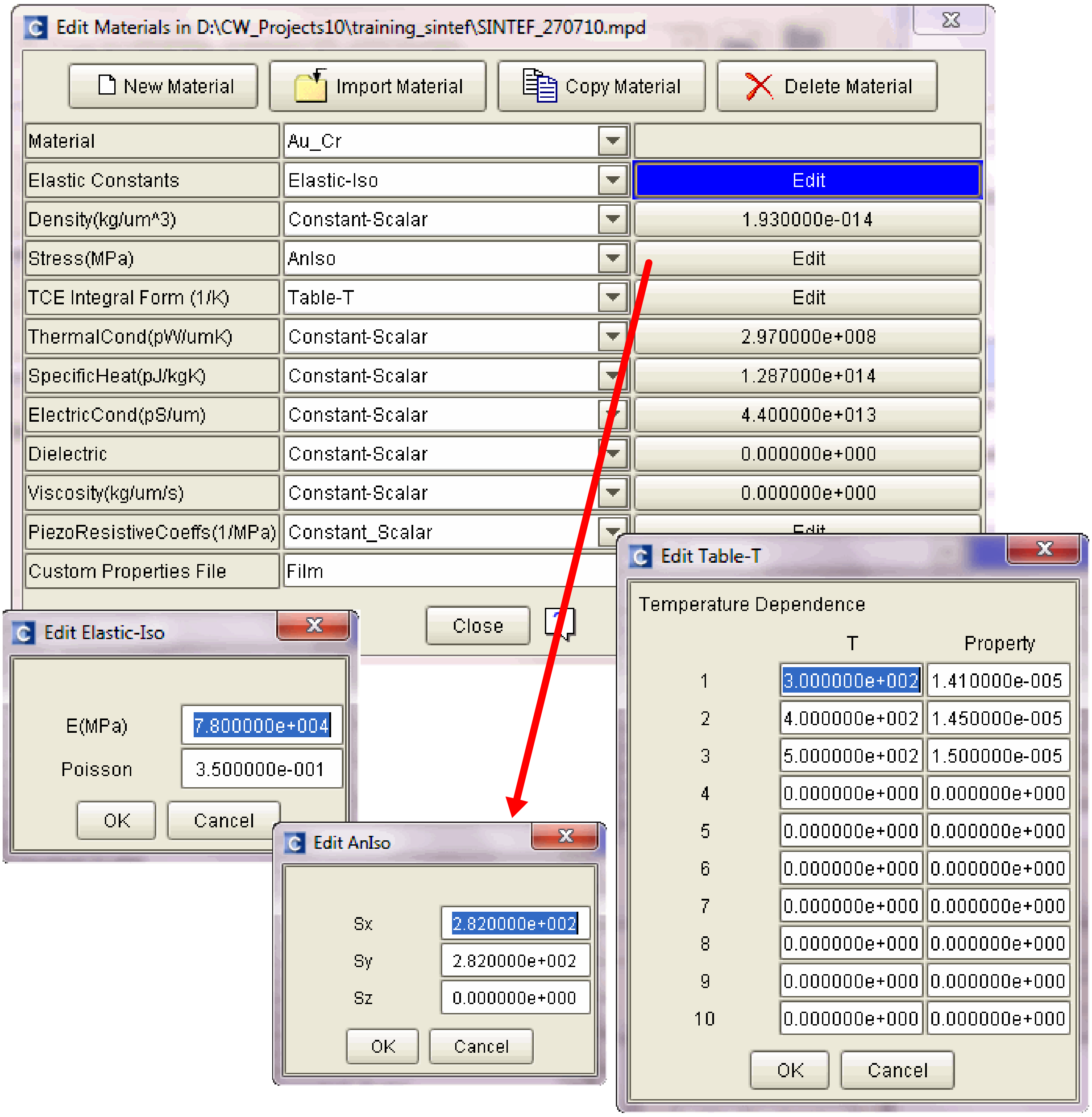



Figure 1.3 Au-Cr properties

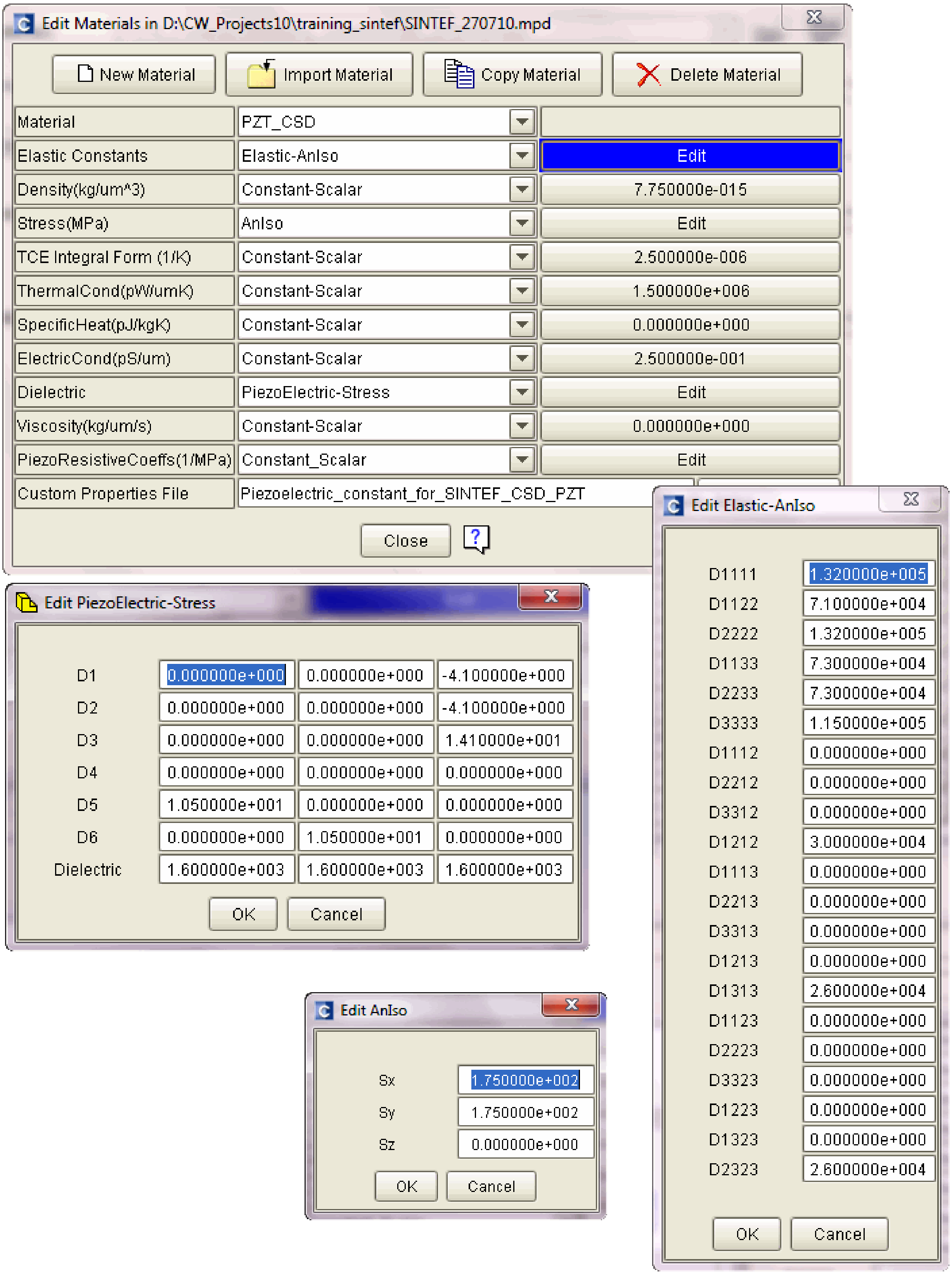



Figure 1.4 PZT properties

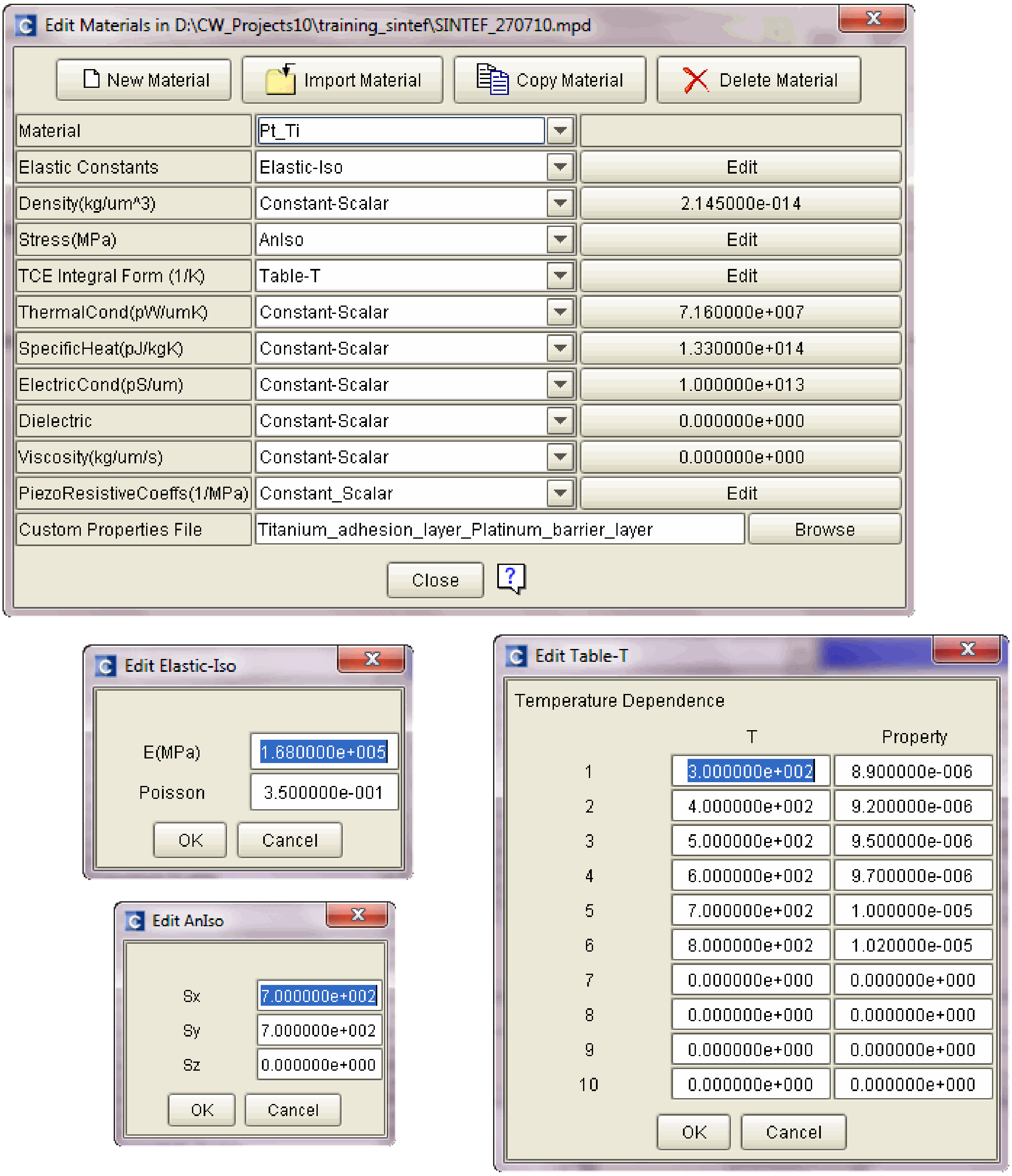



Figure 1.5 Pt-Ti Properties

**Additional Resources**

For more information on Material Properties Database see Using Coventorware Manual section 2.

### 1.2.4 Create a process

Once the materials are available in your Material Property Database you need to use or create a process description. Here we'll update a process with new steps.

| Tasks | Clues & Comments |
|---|---|
| 1. Load the process *sintef_initial* shown in [table below] and save it as *sintef_tutorial.proc* | **Exercise 1:** Pay attention if the step is a deposit or etch. You have the choice for etch type. |

| Number | Step Name | Layer Name | Material Name |
|---|---|---|---|
| 0 | Substrate | Substrate_Wafer | SILICON_100 |
| 1 | Silicon-On-Insulator (SOI) | | |
| 1.1 | Thermal Oxidation | Buried_Oxide | SiO2 |
| 1.2 | Grow Crystal Silicon | Si_Handle | SILICON_100 |
| 2 | Wet Oxidation | Oxide_layer | SiO2 |
| 3 | Oxide Etch Backside | | |
| 4 | *Oxide Etch Frontside* | | |
| 5 | Sputtering Bottom Electrode | Bottom_electrode | Pt_Ti |
| 6 | PZT Chemical Solution Deposition | PZT_piezoelectric | PZT_CSD |
| 7 | Metal Deposition | Top_electrode | Au_Cr |
| 8 | Top electrode Patterning | | |
| 9 | PZT Patterning | | |
| 10 | Bottom Electrode Patterning | | |
| 11 | Backsidet Etch | | |
| 12 | RIE Release Etch | | |

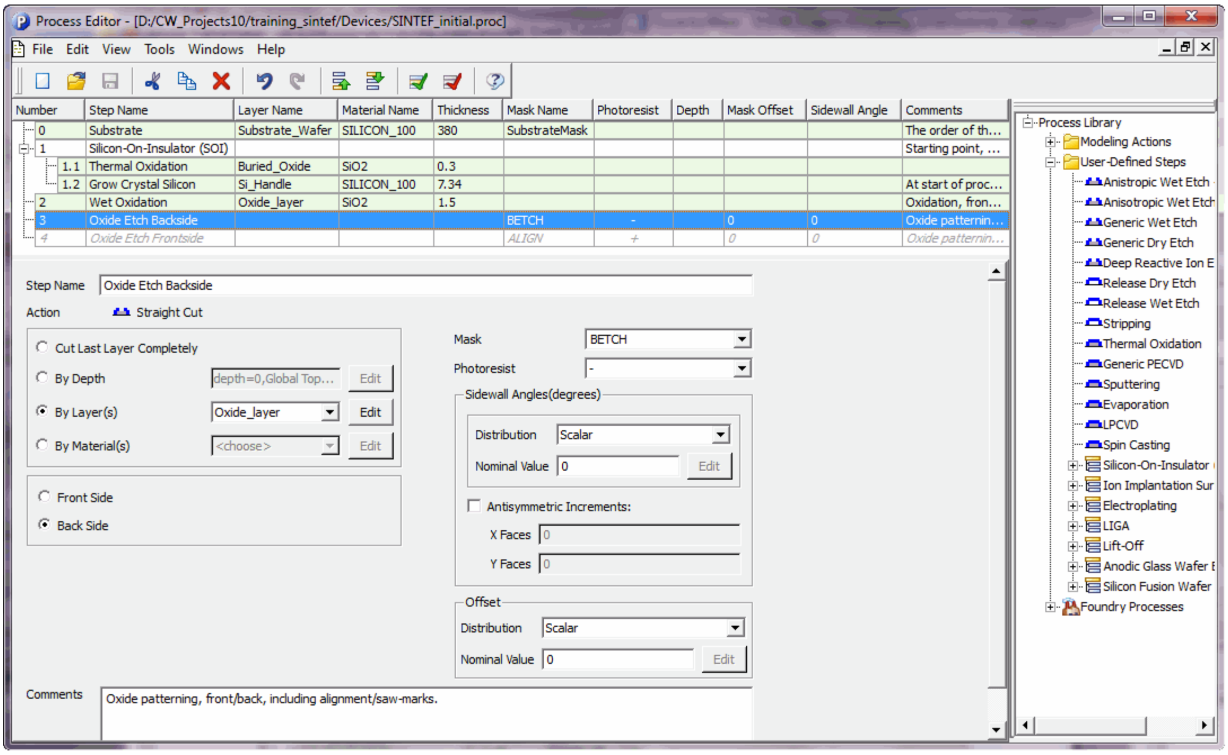



Figure 1.6 Initial process

| Tasks | Clues & Comments |
|---|---|
| **2.** Add the 3 deposit steps as shown below to make the piezoelectric stack. | Just note the thicknesses |

| Number | Step Name | Layer Name | Material Name | Thickness | Mask Name | Photoresist | Depth | Mask Offset | Sidewall Angle |
|---|---|---|---|---|---|---|---|---|---|
| 0 | Substrate | Substrate_Wafer | SILICON_100 | 380 | SubstrateMask | | | | |
| 1 | Silicon-On-Insulator (SOI) | | | | | | | | |
| 1.1 | Thermal Oxidation | Buried_Oxide | SiO2 | 0.3 | | | | | |
| 1.2 | Grow Crystal Silicon | Si_Handle | SILICON_100 | 7.34 | | | | | |
| 2 | Wet Oxidation | Oxide_layer | SiO2 | 1.5 | | | | | |
| 3 | Oxide Etch Backside | | | | BETCH | - | | 0 | 0 |
| *4* | *Oxide Etch Frontside* | | | | *ALIGN* | *+* | | *0* | *0* |
| 5 | Sputtering Bottom Electrode | Bottom_electrode | Pt_Ti | 0.12 | | | | | |
| 6 | PZT Chemical Solution Deposition | PZT_piezoelectric | PZT_CSD | 2 | | | | | |
| 7 | Metal Deposition | Top_electrode | Au_Cr | 0.2 | | | | | |

Figure 1.7 Deposit steps over oxidized SOI wafer

| Tasks | Clues & Comments |
|---|---|
| **1.** Add the etch steps for the top electrode, PZT, bottom electrode and the backside and frontside etch | On the backside etch you will etch the silicon substrate.<br>**b.** On the front side, you need to etch 3 layers: oxide_layer, buried_oxide and Si_handle. |
| **2.** Save the process. | The validation will be made by creating the 3D model. |

| Number | Step Name | Layer Name | Material Name | Thickness | Mask Name | Photoresist | Depth | Mask Offset | Sidewall Angle |
|---|---|---|---|---|---|---|---|---|---|
| 0 | Substrate | Substrate_Wafer | SILICON_100 | 380 | SubstrateMask | | | | |
| 1 | Silicon-On-Insulator (SOI) | | | | | | | | |
| 1.1 | Thermal Oxidation | Buried_Oxide | SiO2 | 0.3 | | | | | |
| 1.2 | Grow Crystal Silicon | Si_Handle | SILICON_100 | 7.34 | | | | | |
| 2 | Wet Oxidation | Oxide_layer | SiO2 | 1.5 | | | | | |
| 3 | Oxide Etch Backside | | | | BETCH | - | | 0 | 0 |
| *4* | *Oxide Etch Frontside* | | | | *ALIGN* | *+* | | *0* | *0* |
| 5 | Sputtering Bottom Electrode | Bottom_electrode | Pt_Ti | 0.12 | | | | | |
| 6 | PZT Chemical Solution Deposition | PZT_piezoelectric | PZT_CSD | 2 | | | | | |
| 7 | Metal Deposition | Top_electrode | Au_Cr | 0.2 | | | | | |
| 8 | Top electrode Patterning | | | | TOPEL | + | | 0 | 0 |
| 9 | PZT Patterning | | | | NOPIE | - | | 0 | 0 |
| 10 | Bottom Electrode Patterning | | | | BOTEL | - | | 0 | 0 |
| 11 | Backsidet Etch | | | | BETCH | - | | 0 | 0 |
| 12 | RIE Release Etch | | | | FETCH | - | | 0 | 0 |

Figure 1.8 Final Process

Now you are done with the technology which is the basis of all CoventorWare project. You are ready to start building your device.

### 1.2.5 Building the 3D model

This exercise will guide you through the creation of your MEMS device in 3D. It explains how to draw a layout using the process you have chosen, then build the 3D solid, mesh it and finally name the relevant patches.

### *1.2.5.1 Layout Editor*

The layout Editor will start with the layer names defined in the process.

| **Tasks** | **Clues & Comments** |
|---|---|
| **1.** Open the Layout Editor and review the layer parameters using the layer browser | We will use only some layers of the SINTEF process.<br>As defined in the process, ALIGN is ignored. |
| **2.** Change the necessary Dark/light option in layers | Dark or Light will define if the shape is preserved or etch |

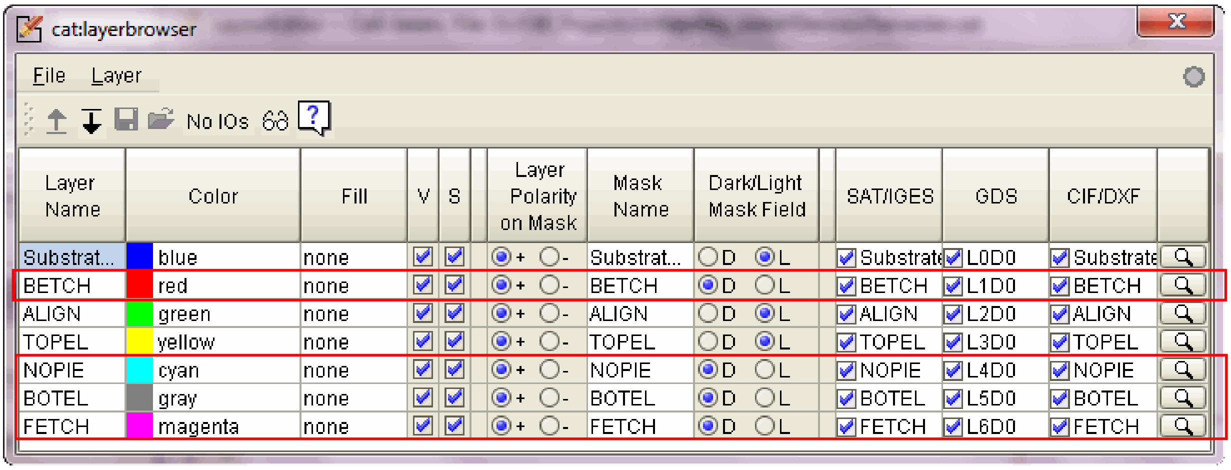



Figure 1.9 SINTEF process Final layer brower

| Tasks | Clues & Comments |
|---|---|
| 3. Select the NOPIE layer and create a rectangle of 200um in y and 1100um in x.<br>4. Select the FETCH layer and create a rectangle of 200um in y and 1500um in x.<br>5. Select BETCH and create a square of 400um side, and look<br><br><br>for its relative position. | Use the arrow in the current layer menu<br>b. Use the rectangle tool on the left toolbar and draw or enter points.<br>c. Use Modify > object to change the rectangle corners positions. |
| 6. Copy and paste the NOPIE rectangle into the TOPEL layer.<br>7. Copy and paste the FETCH rectangle into the BOTEL layer. | Use edit> paste to layer once the object selected. Place it and then correct its position or define its center while in the paste to layer menu |
| 8. Save the library as Energy_harvester and the cell as cantilever | The library is the .cat file storing the cells. One cell is just defined here but a hierarchy of cells can be created using the reference cell function. |

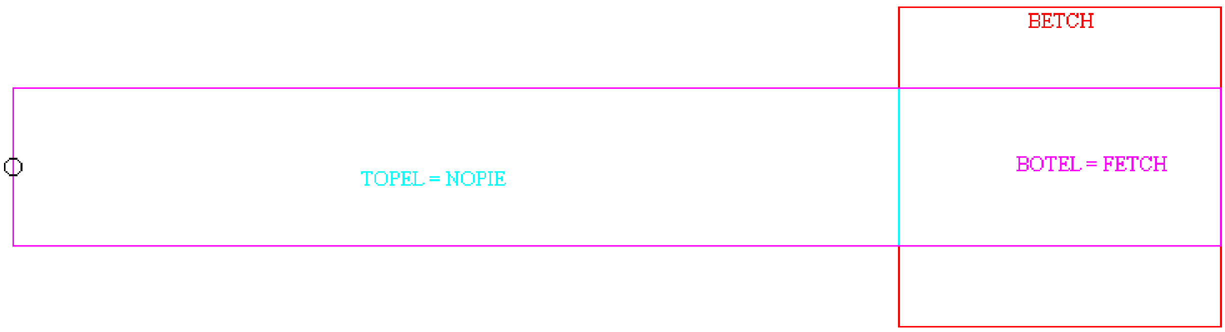
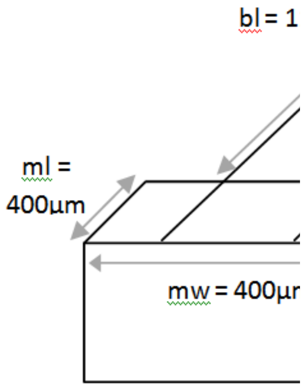



Figure 1.10 Energy Harvester Layout

### 1.2.5.2 Build the 3D model

Once the layout and process established and saved, the next step is to build, manipulate and check the 3D solid.

| **Tasks** | **Clues & Comments** |
|---|---|
| **1.** Create the solid and check it. | Just click the build 3D icon and save it as harvester.<br>**b.** For checking different viewing tools can be used |
| **2.** Correct either the process or layout if some errors appear. | See   as a reference.<br>**b.** In the drop-down arrow next build 3D icon choose the **rebuild** option to recreate the 3d solid from the modified process and/or layout. |

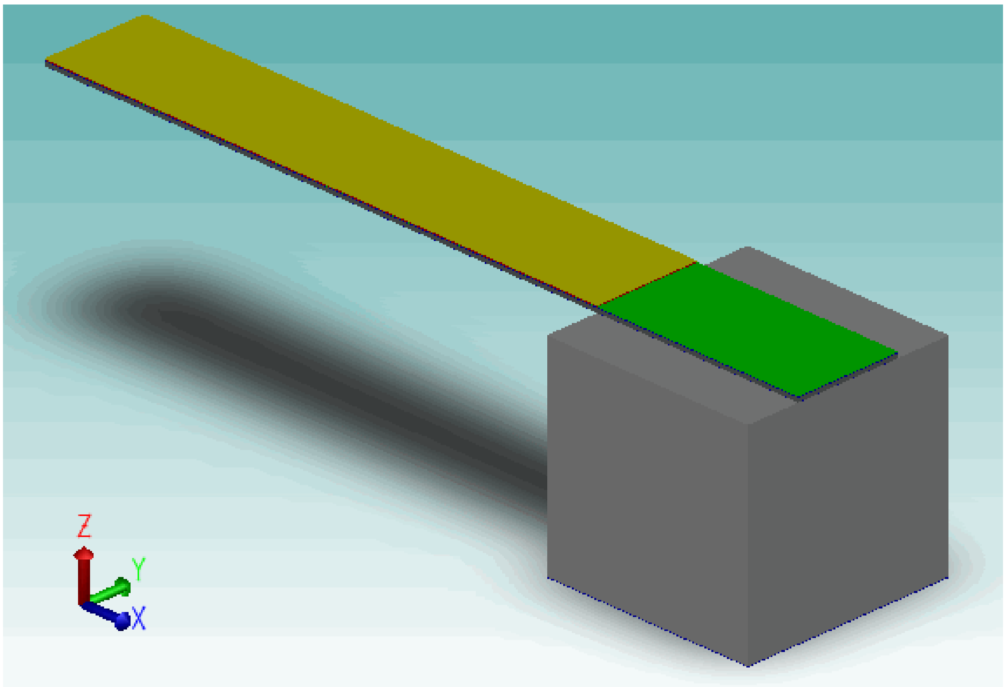



Figure 1.11 3D model of the energy harvester

### 1.2.6 Meshing

To run analyses into Analyser, a mesh is of course required and also patch (surface) names. We'll do this right now.

| Tasks | Clues & Comments |
|---|---|
| **1.** Add all the layers in the mesh model | Only one region should be created |
| **2.** Name the patches at fixed beam end as *anchor.* | Use the zoom and rotating tools to be sure to select all the patches. You should have 6.<br>**b.** Right click and find **set name** function |
| **3.** Name the patches of the piezoelectric layer corresponding to the electrodes as *topel* for the Au-Cr electrode and *botel* for the Pt-Ti electrode | Hide all layers except PZT to have a better viewing/selecting |
| **4.** Mesh with parabolic Manhattan bricks of 50 microns size in x and y and 0.3 in z. Define a maximum of 4 elements in the thickness. | Right click and find mesher settings<br>**b.** Look in Advanced options |
| **5.** Save it as *harvester_meshed*. | |

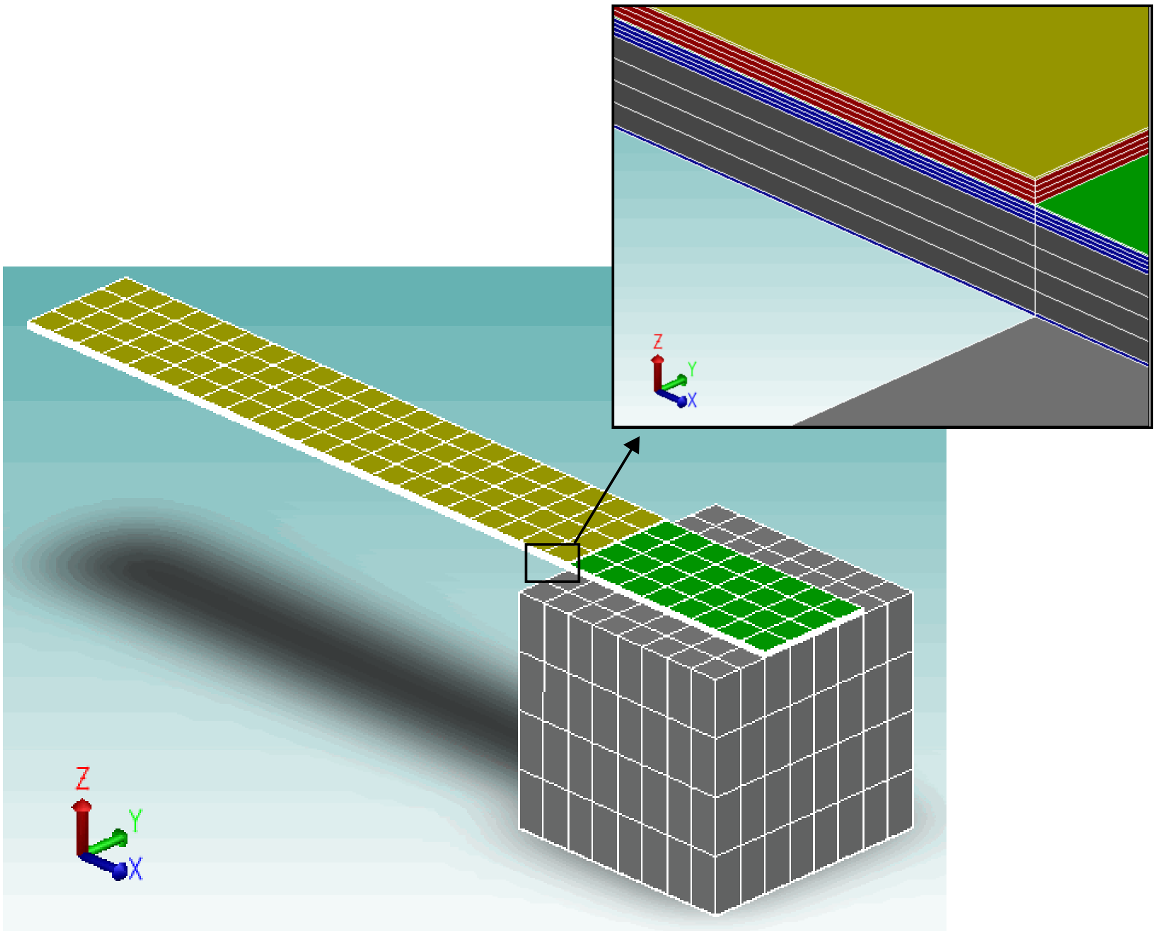



Figure 1.12 Meshed Energy Harvester

## 1.3 Simulations in Analyser

A piezo harvester acts like a battery (capacitive power source).

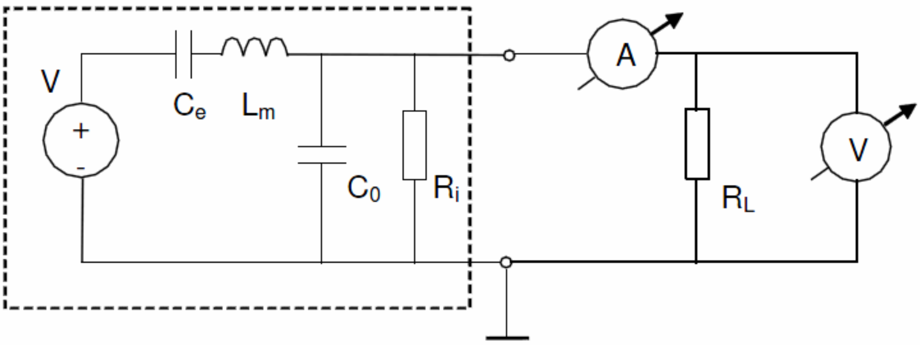



Figure 1.13: Equivalent circuit for piezo energy harvester

Figure 1.13 shows an equivalent circuit for a piezo harvester. In closed circuit (CC) conditions (i.e. when Rload = 0), the piezoelectric layer generates a charge only and no voltage is generated across the electrodes. In open circuit conditions the piezoelectric layer outputs a voltage without any charge. Both these *ideal* conditions can be simulated with Coventor's MemMech PZE solver.

To simulate CC the potentials on the electrodes are set to be equal, e.g 0V. MemMech will solve for the charge on each electrode generated by the reverse piezo electric effect. To simulate OC one electrode is set to *TiePotential*, the other to a potential, e.g. 0V. MemMech will solve for the unknown potential on the electrode that has the *TiePotential* specified and charge for the electrode that has potential specified.

Note, the MemMech PZE solver must have either a charge or voltage specified on each electrode. To simulate OC conditions one might therefore specify zero charge on each electrode. However, CoventorWare does not have the BC option to specify charge in the GUI. However, if no charge (or voltage) is specified, the solver assumes 0 total charge. So you can specify a zero charge indirectly by *not* setting a voltage boundary condition on an electrode.
Note also that, the surfaces of the piezoelectric layer are covered with a conducting (metal) layer to allow electrical connection. This electrical layer also enforces an equipotential over the underlying surface of the piezo. To enforce this condition in the MemMech PZE solver, use the tie potential boundary condition to constrain a constant voltage over the electrode.

### 1.3.1 Running a mechanical analysis

| **Tasks** | **Clues & Comments** |
|---|---|
| **1.** Open Analyser and run a mechanical modal analysis on the harvester model with the settings described on Figure 1.14 | This analysis does not include piezoelectric effect. |

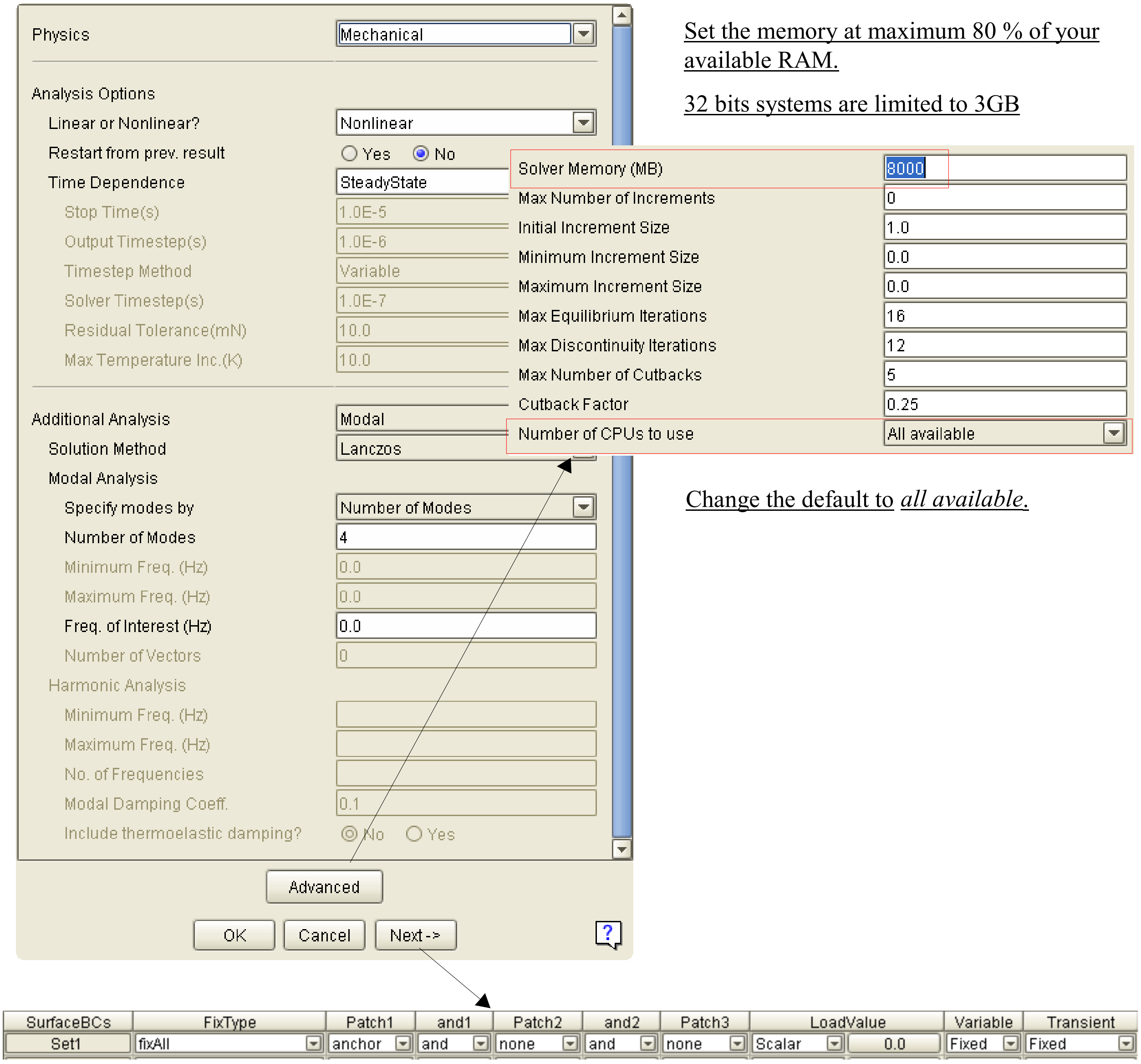


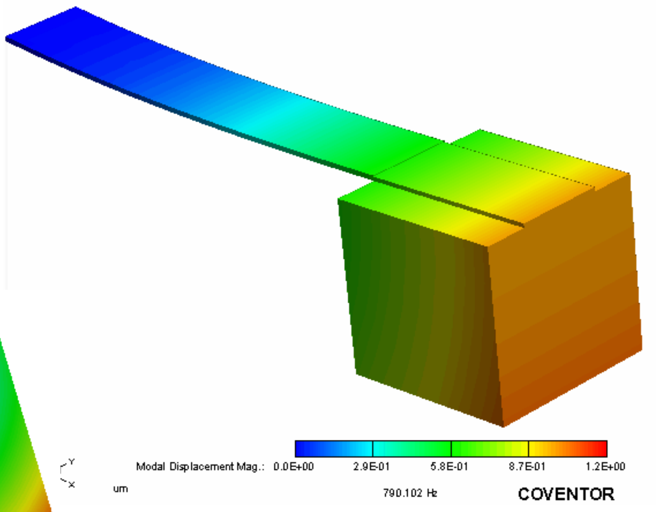

Figure 1.14 Mechanical modal analysis

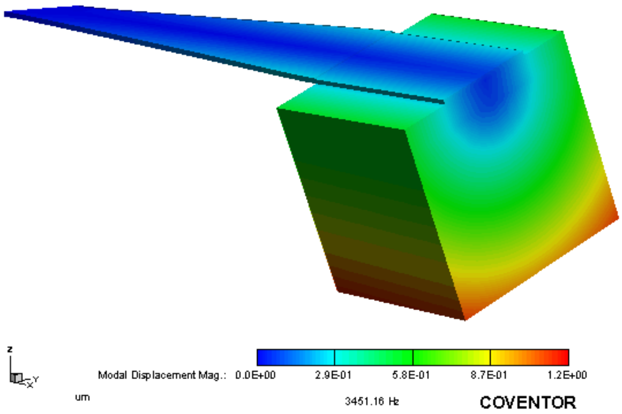
| **Tasks** | **Clues & Comments** |
|---|---|
| **2.** Look at 3D results and note the frequencies and mode shapes. (see Figure 1.15) | The piezoelctric effect is ignored in a mechanical analysis. These modes are purely mechanical. |
| **3.** In the Tables choose mechdomain. Look at the maximum displacement. | This 91 um displacement in z is due to residual stress. |

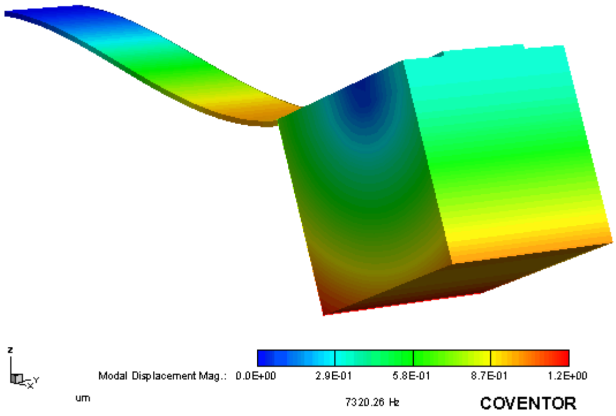
modeDomain

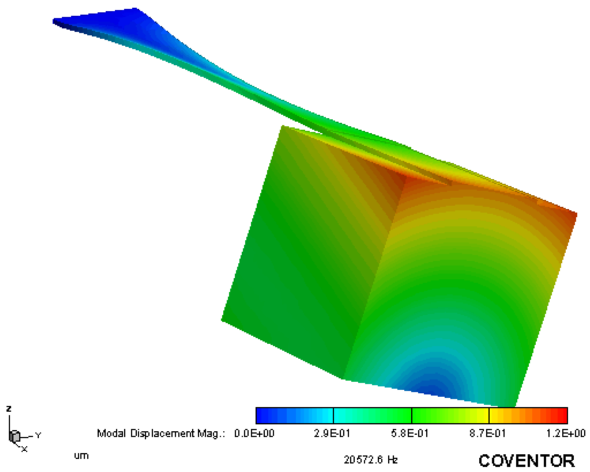
| | Frequency | Generalized Mass | Damping |
|---|---|---|---|
| 1 | 7.901016E02 | 9.890393E-08 | 0 |
| 2 | 3.451159E03 | 5.776458E-08 | 0 |
| 3 | 7.320258E03 | 6.12896E-08 | 0 |
| 4 | 2.057264E04 | 4.205255E-08 | 0 |

OK




mechDomain

| | Maximum | Minimum |
|---|---|---|
| Node Displacement | 9.746744E01 | 0 |
| Node X Displacement | 3.478031E01 | -3.744859E00 |
| Node Y Displacement | 5.320879E-02 | -5.320879E-02 |
| Node Z Displacement | 9.169676E01 | -1.203778E-32 |

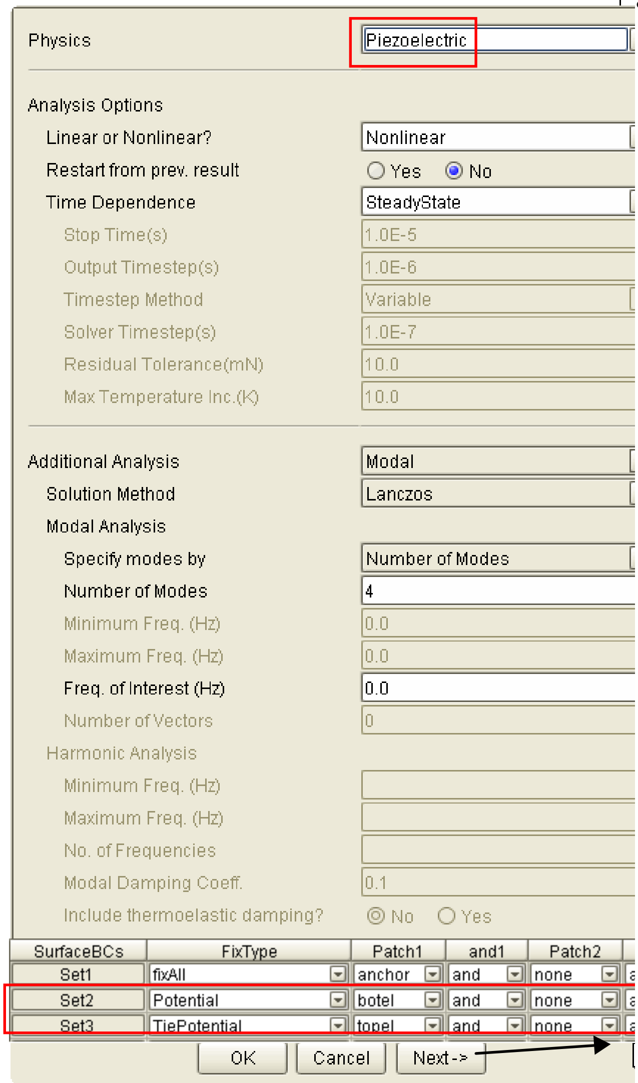
OK

Figure 1.15 Mechanical Resonant modes

## 1.3.2 Running a piezoelectric modal analysis

<table>
<tr><th>Tasks</th><th>Clues & Comments</th></tr>
<tr><td>

1. Run an open circuit piezoelectric modal analysis the settings described on




.

</td><td>This piezoelectric BCs simulate sensing behavior where the top electrode gets a voltage thanks to applied stress</td></tr>
<tr><td>

2. Look at results and note the new frequencies and max displacement.
3. Run a query to get the voltage on topel.

</td><td>

The frequency shift is due to piezoelectric effect. The residual stress impact differs and the displacement is only 86 um.

b. Note the piezo bricks have only 20 nodes instead of the 27 node of standard parabolic bricks. So results are inherently slightly different. A mesh convergence study is needed to validate them.

</td></tr>
</table>

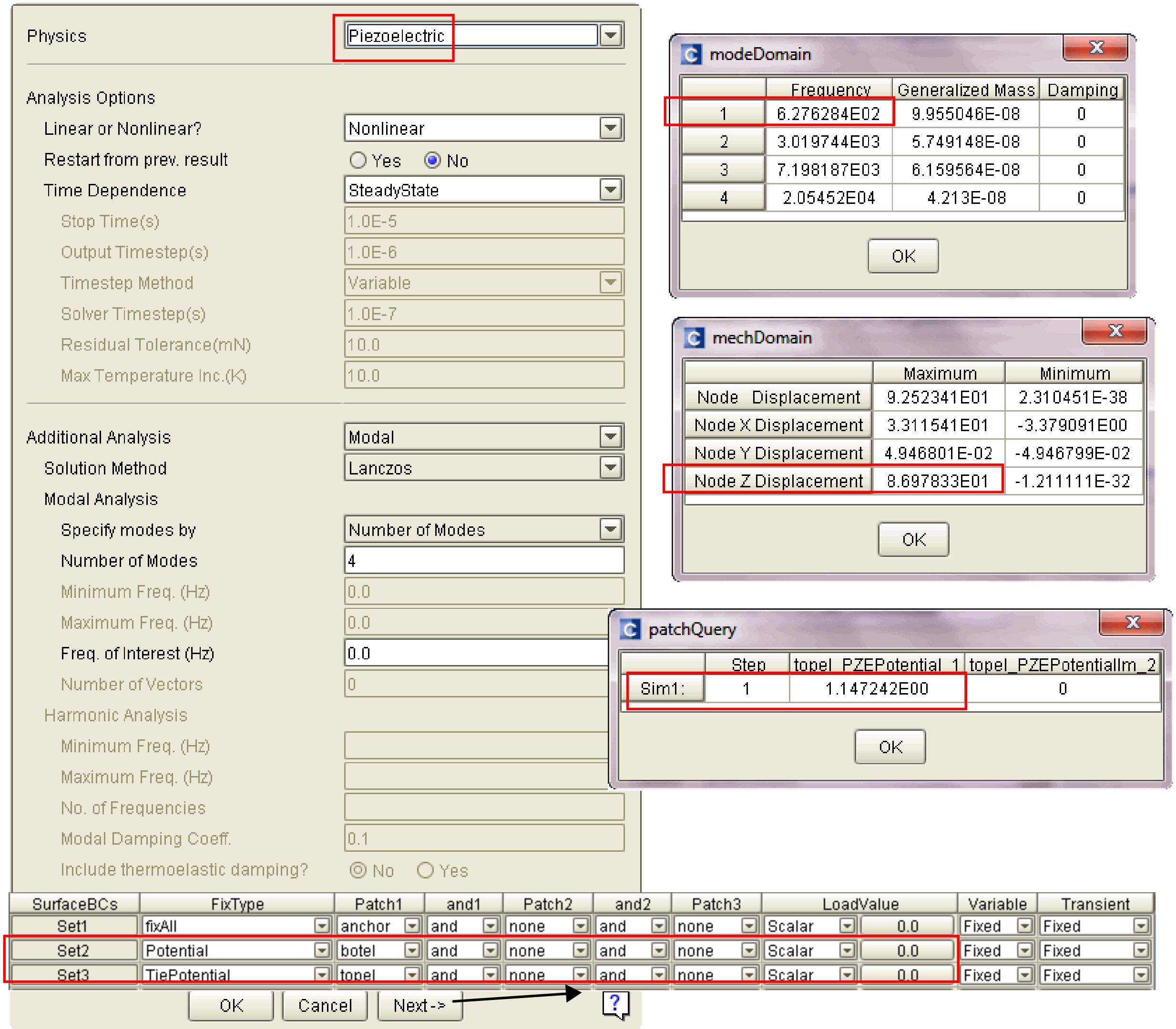



Figure 1.16 Piezoelectric modal analysis settings and results

### 1.3.3 Running an harmonic with resistive load

| Tasks | Clues & Comments |
|---|---|
| 1. Run a piezoelectric harmonic analysis around the first mode of the open state with 1G acceleration on Z and a resistive load of 100k ohms with the settings described on Harmonic analysi. | The acceleration is an harmonic BC. Keep surface settings.<br>b. Go in circuit elements to set a resistor between the 2 electrodes. |

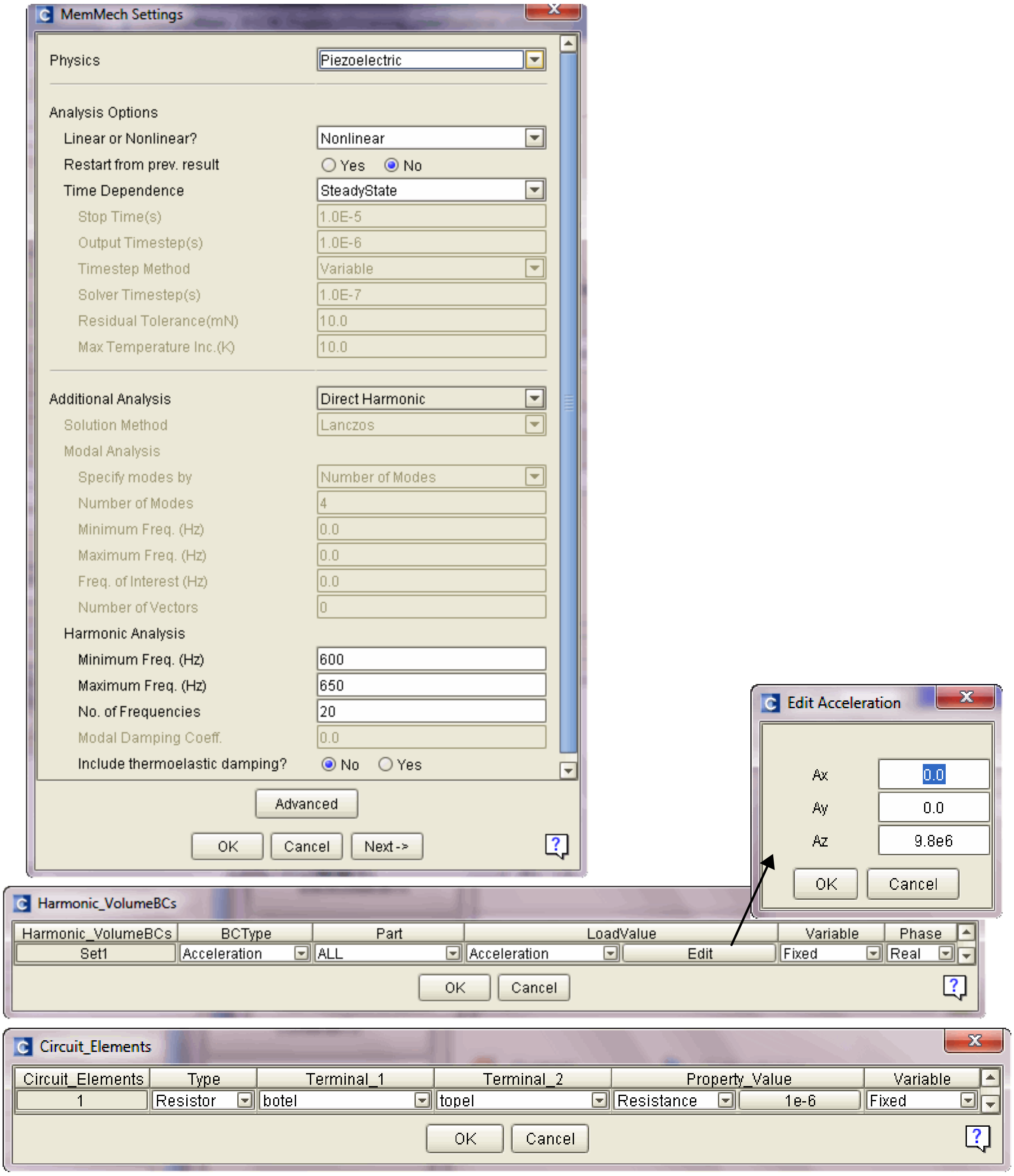



Figure 1.17 Harmonic analysis with circuit element resistor settings

| **Tasks** | **Clues & Comments** |
|---|---|
| **2.** Look at results plots for displacement and power. | The resistor plays a damping role in the analysis. |

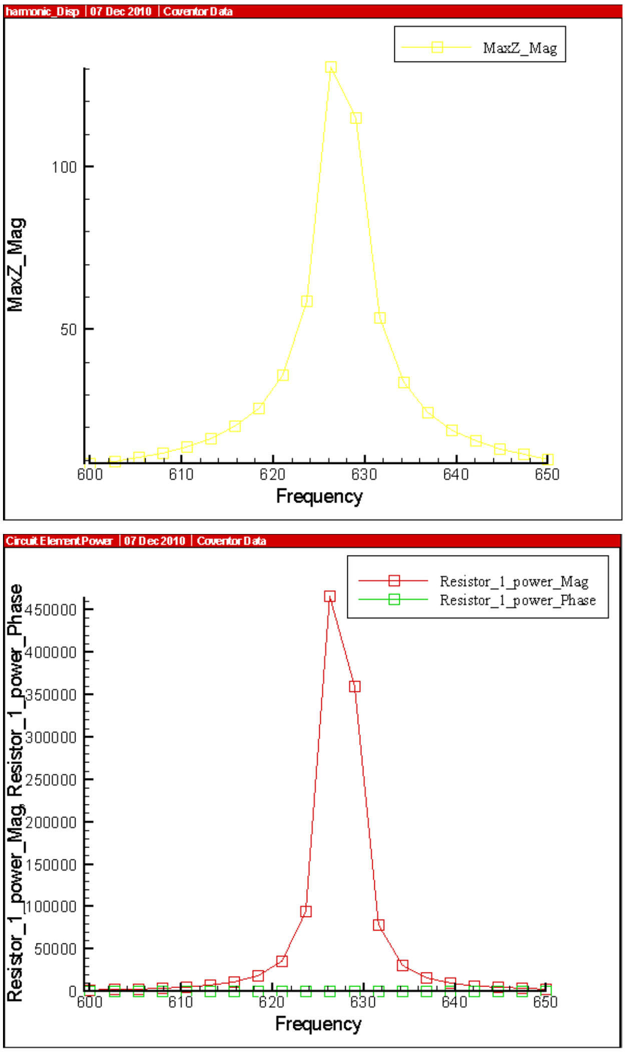



Figure 1.18 Harmonic Analysis Results

*1.3.3.1 References*


1. D. Shen, J.-H. Park, J. Ajitsaria, S.-Y. Choe, H.C. Wikle III, D.-J. Kim "The design, fabrication and evaluation of a MEMS PZT cantilever with an integrated proof mass for vibration energy harvesting", *J. of Micromechanical and Microengineering*, vol.18, April 2008
2. To find documentation please go to: Start > All Programs > Coventor > CoventorWare2010 >Documentation or browse to ...\Coventor\CoventorWare2010\docs

# 2 PZT ENERGY HARVESTER DESIGN IN MEMS+

## 2.1 Introduction

As wireless sensor nodes become smaller, their energy supply is a limiting factor for further miniaturization as integration density is limited by the space requirements of the energy storage system. MEMS based vibration energy harvesters, such as the one shown in this example, are becoming a key enabler for further miniaturization and deployment of energy autonomous sensor nodes. Among existing methods, piezoelectric harvesting is the more studied thanks to its promising results.

The device is made with the SINTEF MoveMEMS design kit. It is based on a PZT stacked on a SOI wafer. A description of the MoveMEMS process is also given in the *Using CoventorWare* manual, starting on page U4-24.

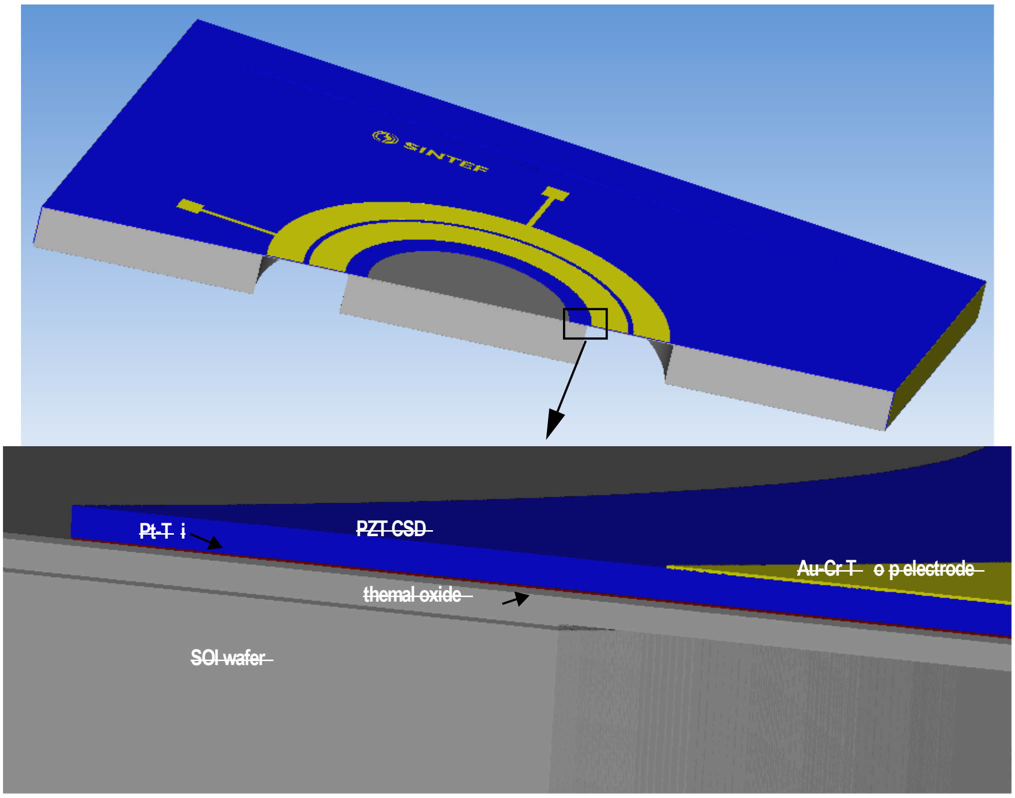
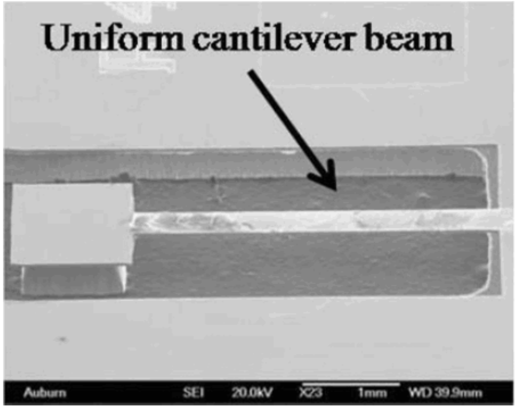



Figure 2.1 Process description

### 2.1.1 PZT cantilever with Si Proof mass

The piezoelectric cantilever consists of a multilayered film of SiO2/ Pt/ PZT/Au deposited on a silicon beam of nearly 8 microns of thickness. The silicon substrate is used to make a proof mass to improve sensing of environmental vibra ions or movements by decreasing resonant frequency. The device is similar to the one published by Shen et al (D. Shen, J.-H. Park, J. Ajitsaria, S.-Y. Choe, H.C. Wikle III, D.-J. Kim "The design, fabrication and evaluation of a (see picture below)). The process is also based on PZT on SOI, yet the thicknesses are different so this exercise is made with other dimensions and results are not be compared.




~~Auburn University device (Ref 1)~~

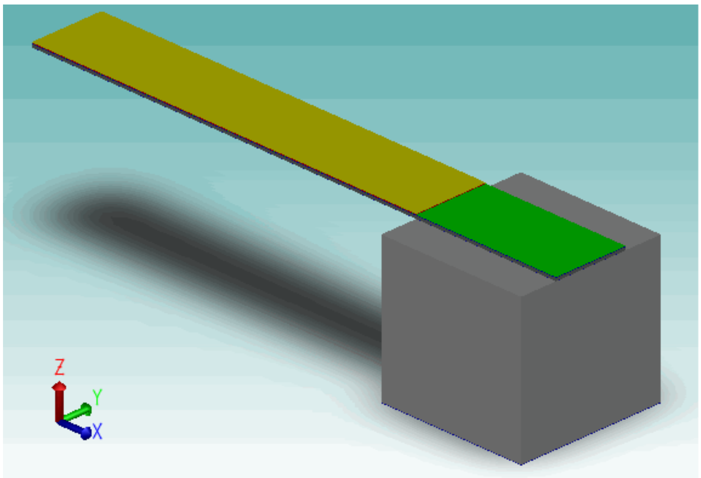



Figure 2.2 Cantilever and proof mass

### 2.1.2 Tutorial Overview

This tutorial is organized into three exercises, which demonstrate various techniques:

Exercise 1: Technology setup
- how to start a project
- how to use a design kit

Exercise 2: Design in Innovator
- how to parameterize dimensions
- how to create the 3D MEMS with components
- how to connect components
- how to apply Boundary Conditions

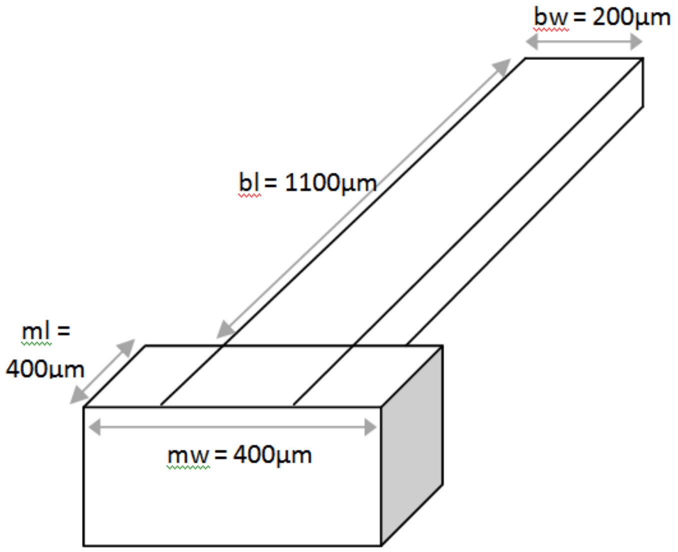
Exercise 3: Simulations in Cadence
- how to run a piezoelectric modal analysis

## 2.2 Technology setup

In this section you will start a MEMS+ project and use The SINTEF MoveMEMS design kit.

### 2.2.1 Preparation

The first design step is to define dimensions of the geometry. As can be seen in

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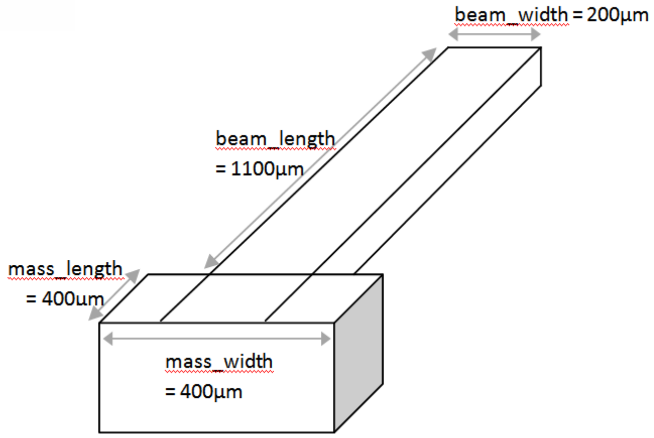


Figure 2.3 Cantilever dimensions

## 2.3 3D Device Creation Guidelines

The Section 6 of the *MEMS+ User Guide and Reference* has a description for each component used in this tutorial.

### 2.3.1 Initialization

The MEMS+ interface offers access to all its modules through a single console. They include the Material Database, the Process Editor, Innovator, and Scene3D (this one appears when opening simulation results). See

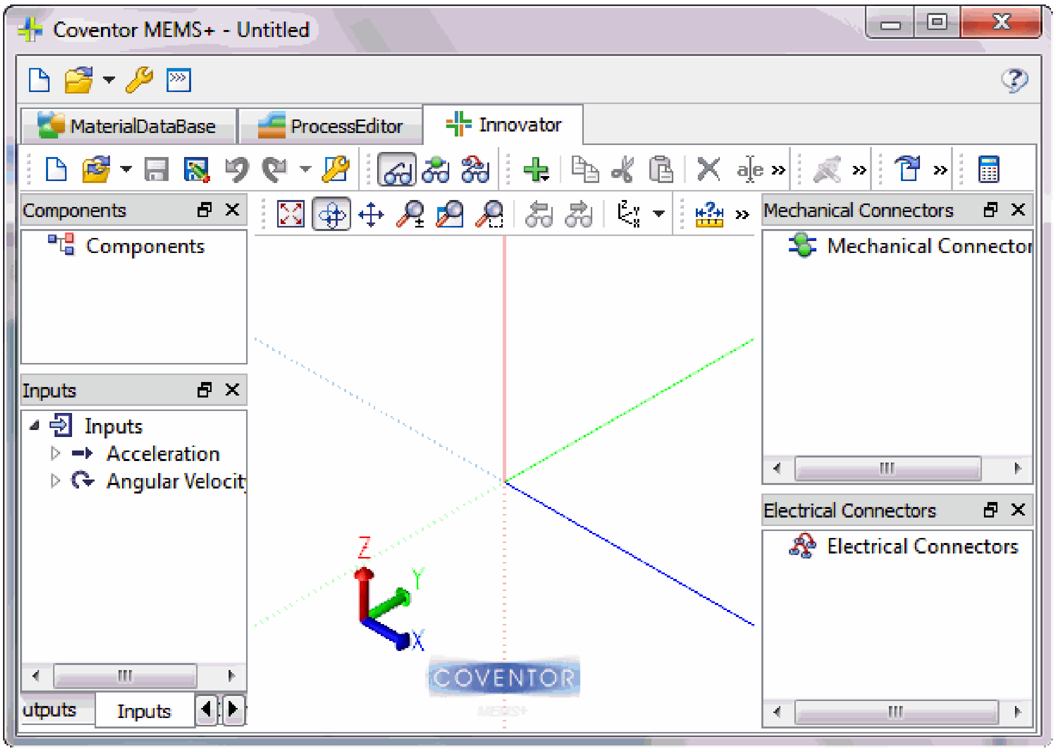


Figure 2.4 MEMS+ environment

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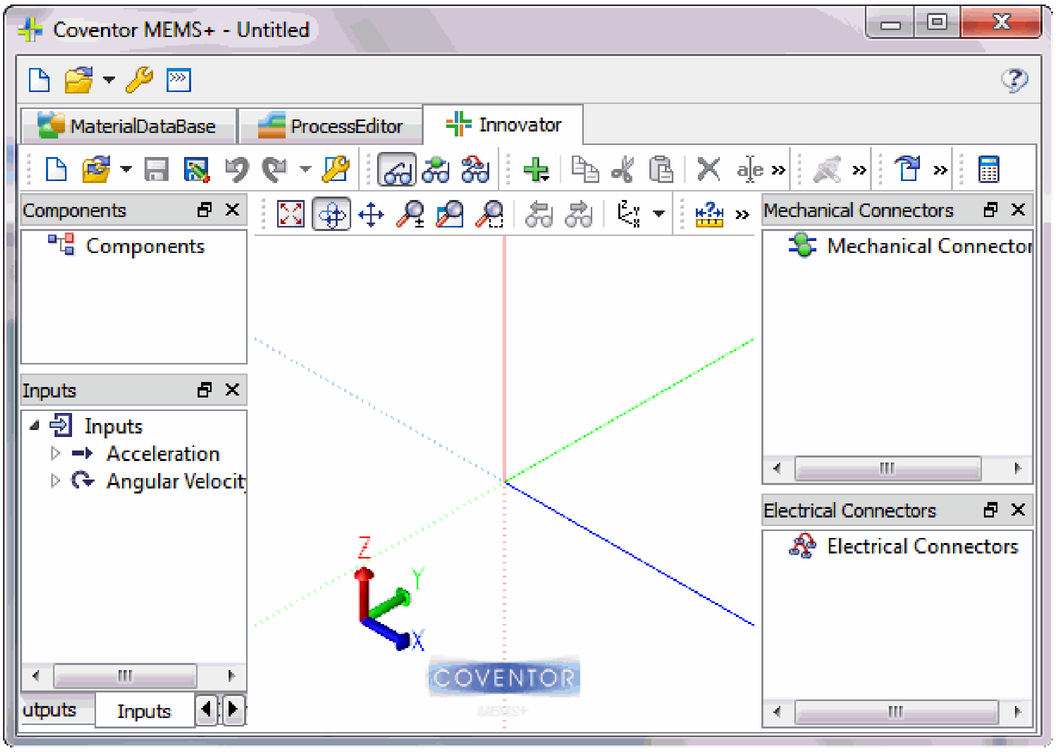
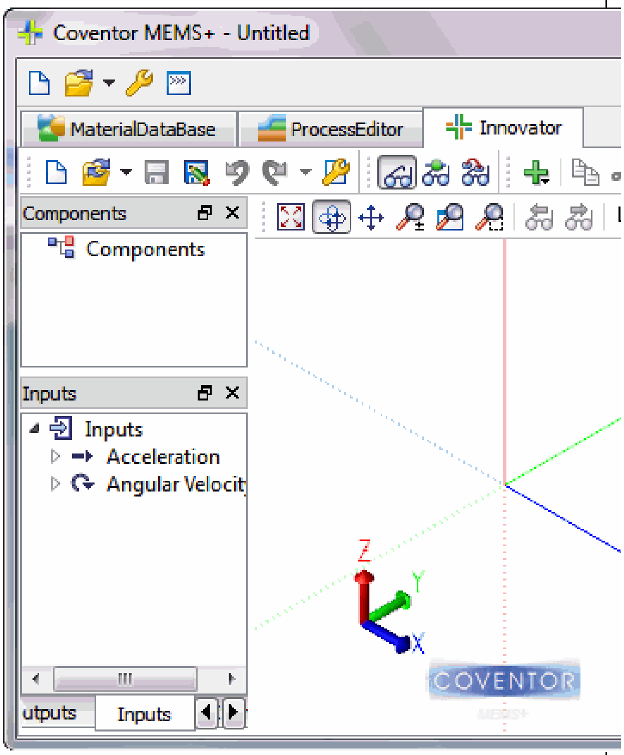



Figure 2.4 MEMS+ environment

| Tasks | Clues & Comments |
|---|---|
| 1. Start MEMS+.<br>2. Explore the interface, change options and move menus to create the environment as seen in<br><br><br>2. Figure 2.4 MEMS+ environment<br>2. . | You can select the subwindows and displace them by dragging anywhere. |

## 2.3.2 Modules

### *2.3.2.1 Material Database*

The first step in creating a design is to enter the material properties associated with the fabrication process in the Material Database, which stores materials and their properties in a *.mmdb* file. In the Process Editor, the user associates the process with the material database file, and the material list stored in that file becomes available in the individual steps of the process. In turn, the material properties of the selected materials are taken into account in the device simulation. The user can create a material database or can select and modify an existing database.

### *2.3.2.2 Process Editor*

The second step in creating a design is to use the Process Editor to create a description of the sequence of steps involved in the fabrication process. The user creates the sequence by selecting prototype steps from the Item Library. Each step has parameters that must be specified. For example, for deposit steps the user must specify the material to be deposited and the deposit thickness. For etch steps, the user must specify a mask and an etch operation by layer, material, or depth. In Innovator, the user selects this process file so that individual components can be assigned to the process deposit layer(s).

#### *2.3.2.3 Innovator*

Innovator allows users to assemble their MEMS device using a library of parametric components. As components are added, the user sets the dimension and layer information. Each component has a rich set of parameters that can be incorporated in a P-cell implementation. The component then appears on the canvas as the user defined it. Any mistakes in dimensions or orientation are immediately apparent to the user. When the model is complete, the user can export a layout in GDS or a solid model in SAT format or import the MEMS model into a Cadence Virtuoso P-cell or a schematic.

#### *2.3.2.4 Scene3D*

Scene3D allows users to import and visualize results from Cadence Virtuoso. This module is only accessible then a result file is selected. Users will be able to visualize DC, DC sweep, AC, and transient results with Scene3D. In Cadence, when the user creates a schematic using a MEMS+ symbol, and then simulates that schematic, Cadence produces results files with the same name as the Innovator schematic used to produce the MEMS+ symbol. Those result files can then be opened in Scene3D.

## 2.4 Use a design Kit

When MEMS+ is first launched, the Innovator tab is active. All MEMS+ components require a valid Material Database and process file as input. In the next steps you will load the SINTEF Material Database (.mmpd file) and MoveMEMS process flow (.proc file). The 3-D schematic file is dependent on the material database and process files, so if you select a 3-D schematic file, MEMS+ automatically loads the material database and process file used to create that schematic. Clicking on either the Material Database or Process Editor tabs will display the associated files.

| **Tasks** | **Clues & Comments** |
|---|---|
| 1. Click on the Material Database tab and load the SINTEF_MPD.mmdb. | a. Use the “replace” icon from the menu bar<br>b. The SINTEF_MPD.mmdb is stored here: *C:\Coventor\MEMS+1.0\Examples* |
| 2. Review properties and check they are the same as shown in next pages. | a. In the Material Properties sub-window make the *Expression* column appear by right-clicking on top bar. |

Once the materials are available in your Material Property Database you need to use or create a process description. Here we’ll load MoveMEMS process.

| **Tasks** | **Clues & Comments** |
|---|---|
| 1. Load the process *MoveMEMS.proc* shown in Figure 2.5.<br>2. Review the steps. | a. |

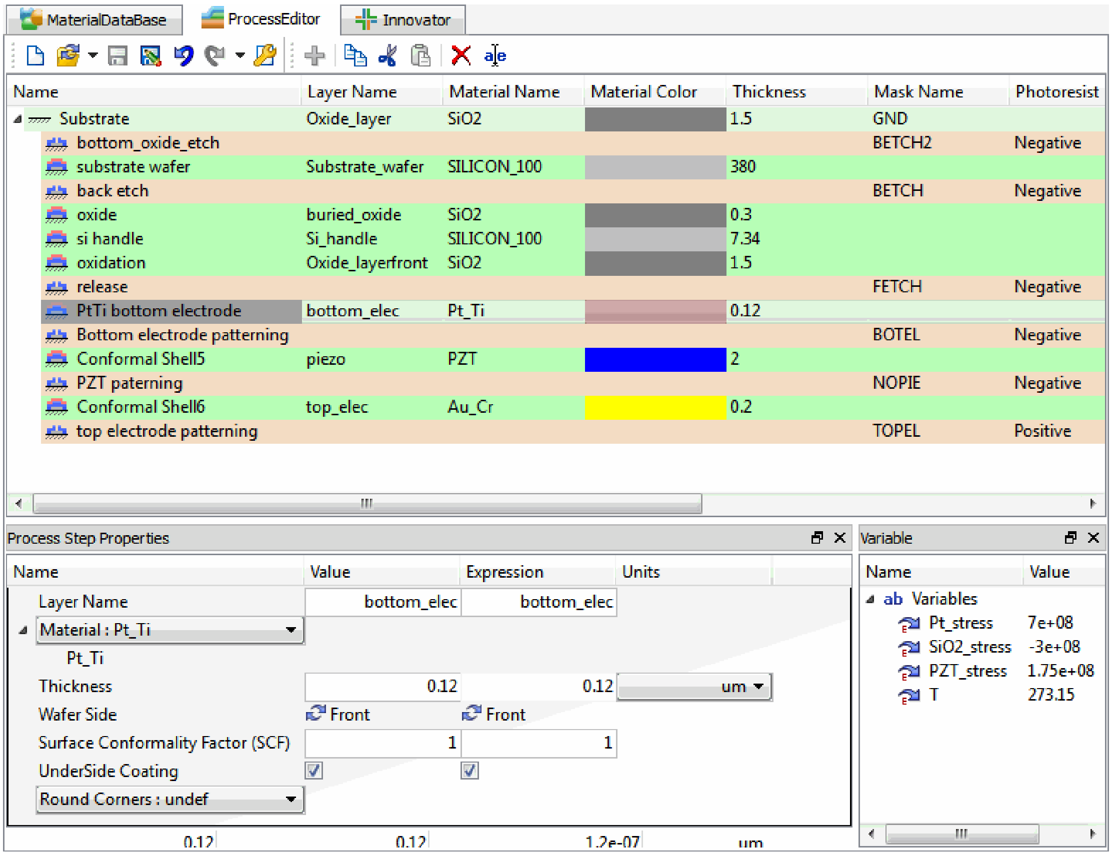



Figure 2.6 MoveMEMS process as described in MEMS+

Now you are done with the technology which is the basis of all MEMS+ project. You are ready to build your device.

## 2.5 Design in Innovator

This exercise will guide you through the creation of your MEMS device in 3D. It explains how to build the geometry from the MEMS component library, create mechanically and electrical connections, and expose variables of interest so that they can be changed in the simulator.

### 2.5.1 Let's parameterize!

In MEMS+ you can define variables in the variable table. Variables names can be created as unique names or share a common group name.

| Tasks | Clues & Comments |
|---|---|
| 1. In the innovator tab, Save the model as *Harvester* | |
| 2. Add the variables to the model as shown in<br><br>2. Figure 2.7 Var below. | a. Right click on Variables and add a group or a variable as needed.<br>Some limits can also be added for each variable. This allows you to integrate some design rules directly in the 3D Schematic<br>You can also define logical statement like *If...then...else*. It is written with the syntax: *if(a<=b,c,d)* |
| 3. Expose beam and mass groups to enable their direct use in the simulator. | When opening the MEMS+ device properties you'll be able to change the exposed parameters. |

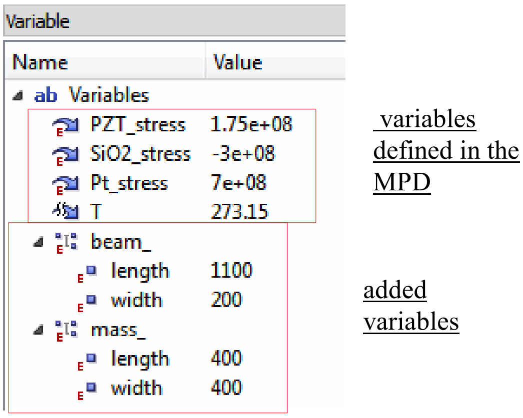



Figure 2.7 Variables

### 2.5.2 Create the 3D model

In this section you will use one rigid plate component to create the mass and one flexible plate to model the piezoelectric beam.

| Tasks | Clues & Comments |
|---|---|
| 1. Open the help and browse to the components properties | a. Review the parameters of each component while adding them for better understanding. |
| 2. Add one rectangular plate standing for the beam and name it PiezoBeam. | a. Right click on *Components* and select Add<br>ⓘ The plate is flexible and the number of mechanical connectors (18) is given by orders in x and y. |
| 3. Add a piezo layer and name the 2 added electrode connectors top and a bottom. | a. Again just right click on plate.....the piezo is recognized as PZT automatically<br>b. Use electrical viewing mode to identify E1 and E2. |

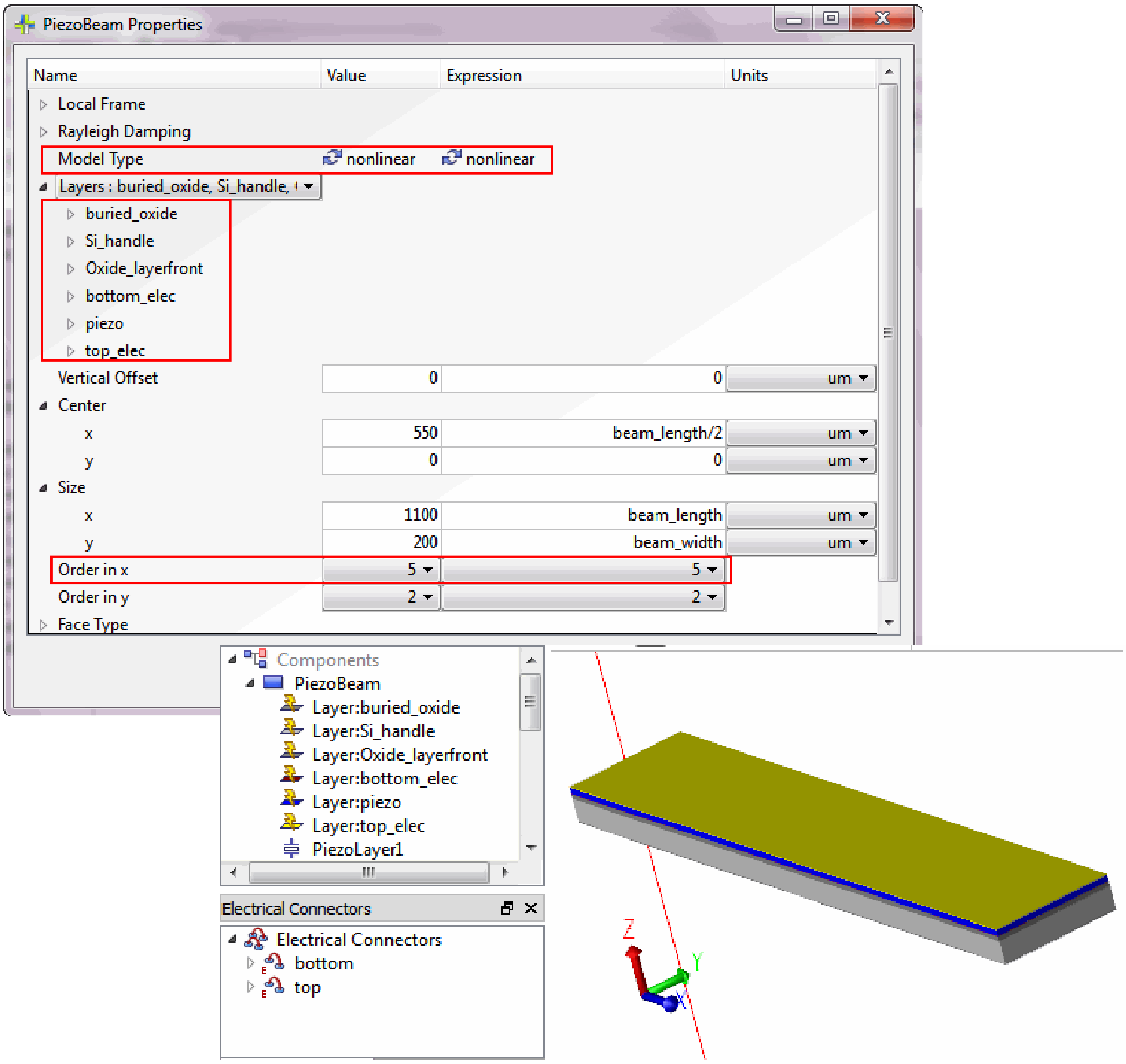


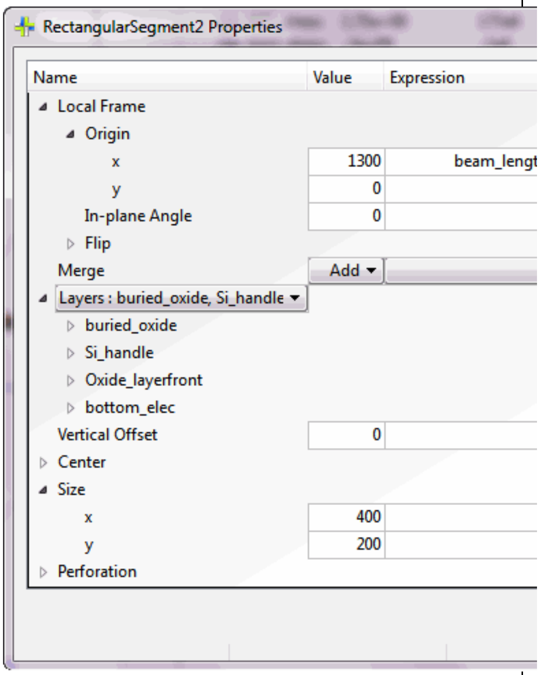

Figure 2.8 Beam properties

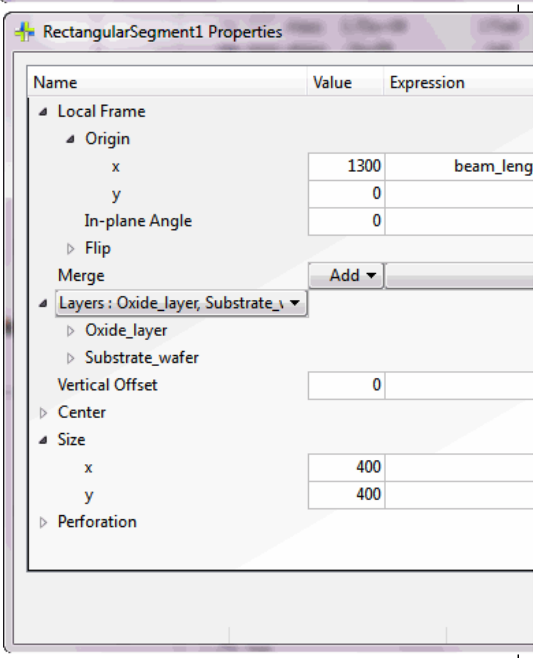
<table>
<tr><th>Tasks</th><th>Clues & Comments</th></tr>
<tr><td>

**4.** Add one rigid plate composed of two rectangular segments and name it Mass.

</td><td>

**a.** Use the properties of




**a.** Figure 2.9 Mas.

**b.** The layers are given in the picture below for both segments.

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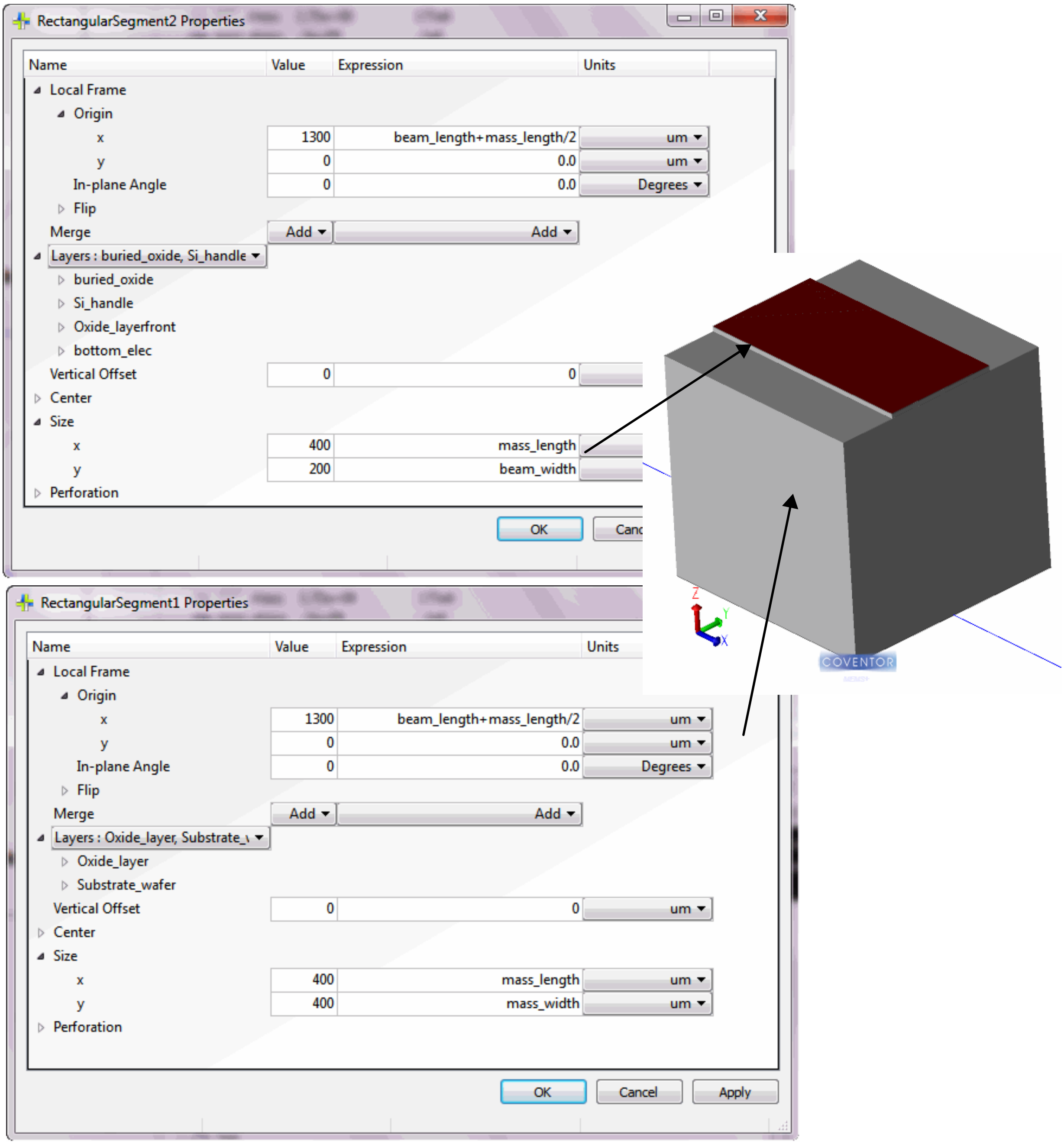



Figure 2.9 Mass two segments properties

### 2.5.3 Mechanical connection

| **Tasks** | **Clues & Comments** |
|---|---|
| **1.** Connect the mechanical connectors of the plates together. | **a.** Use the Mechanical Connector viewing mode.<br>**b.** Use the Autoconnect and place the point at beam end |
| **2.** Fix the beams end that act as anchor. | **a.** Use the *fix* icon. The connectors become yellow when selected and grey once fixed. |

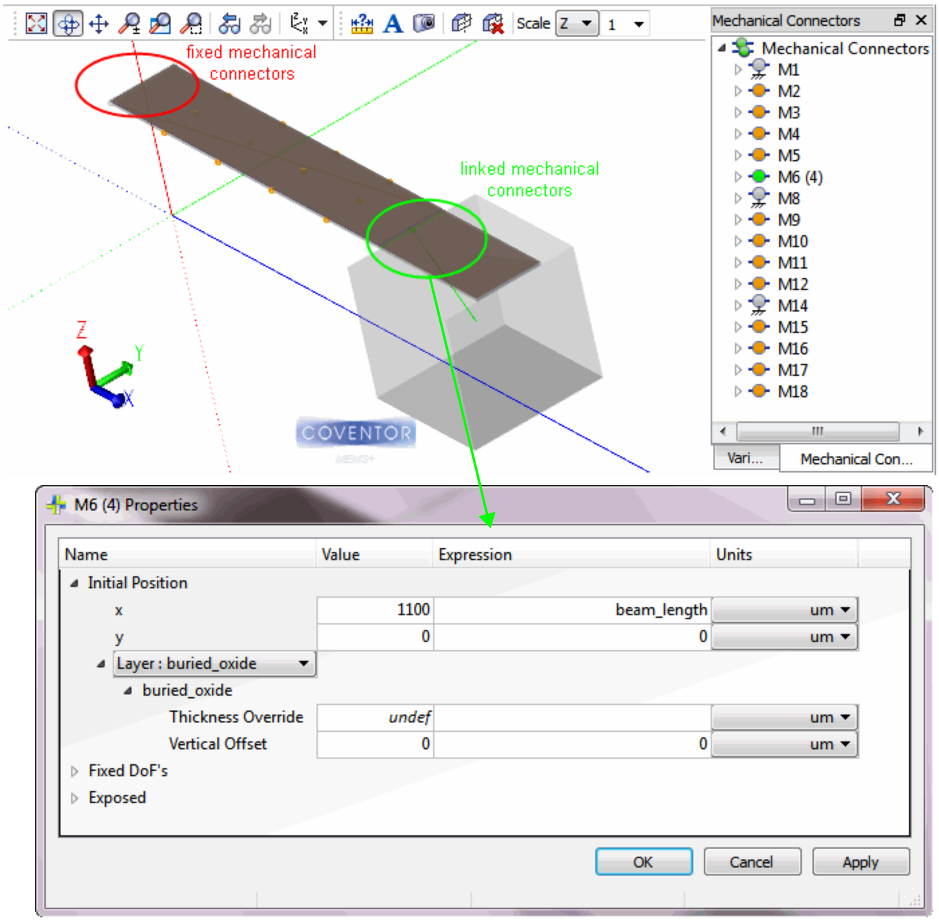



Figure 2.10 Mechanical connection

### 2.5.4 Expose all needed information

| Tasks | Clues & Comments |
|---|---|
| **1.** Expose the Inputs : acceleration and angular velocity | These will be input in Cadence environment to excite all DOF for the modal analysis. |
| **2.** Expose the electrodes | These will become pins in the simulator so that the device can be driven or sensed. |

You have finished the design. The device should match that shown below on

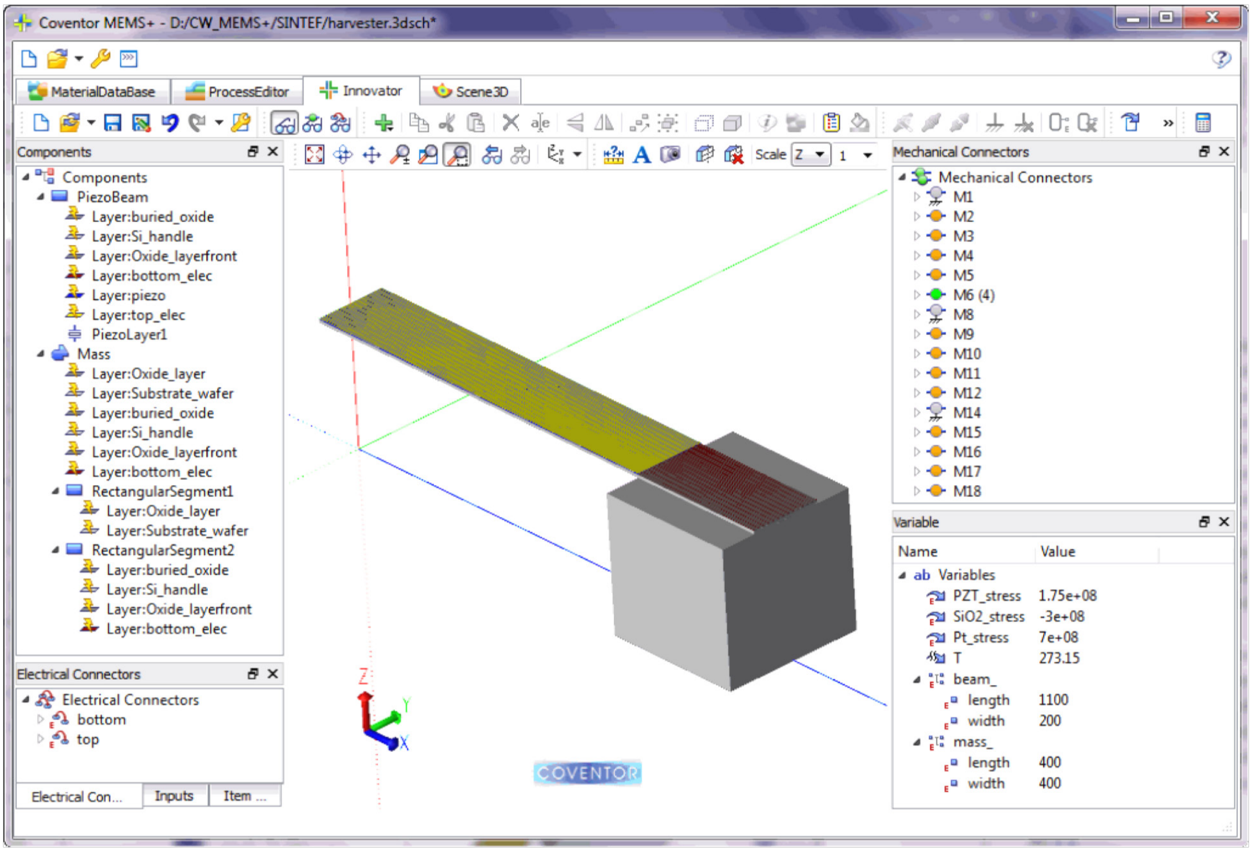



Figure 2.11 Final Device.

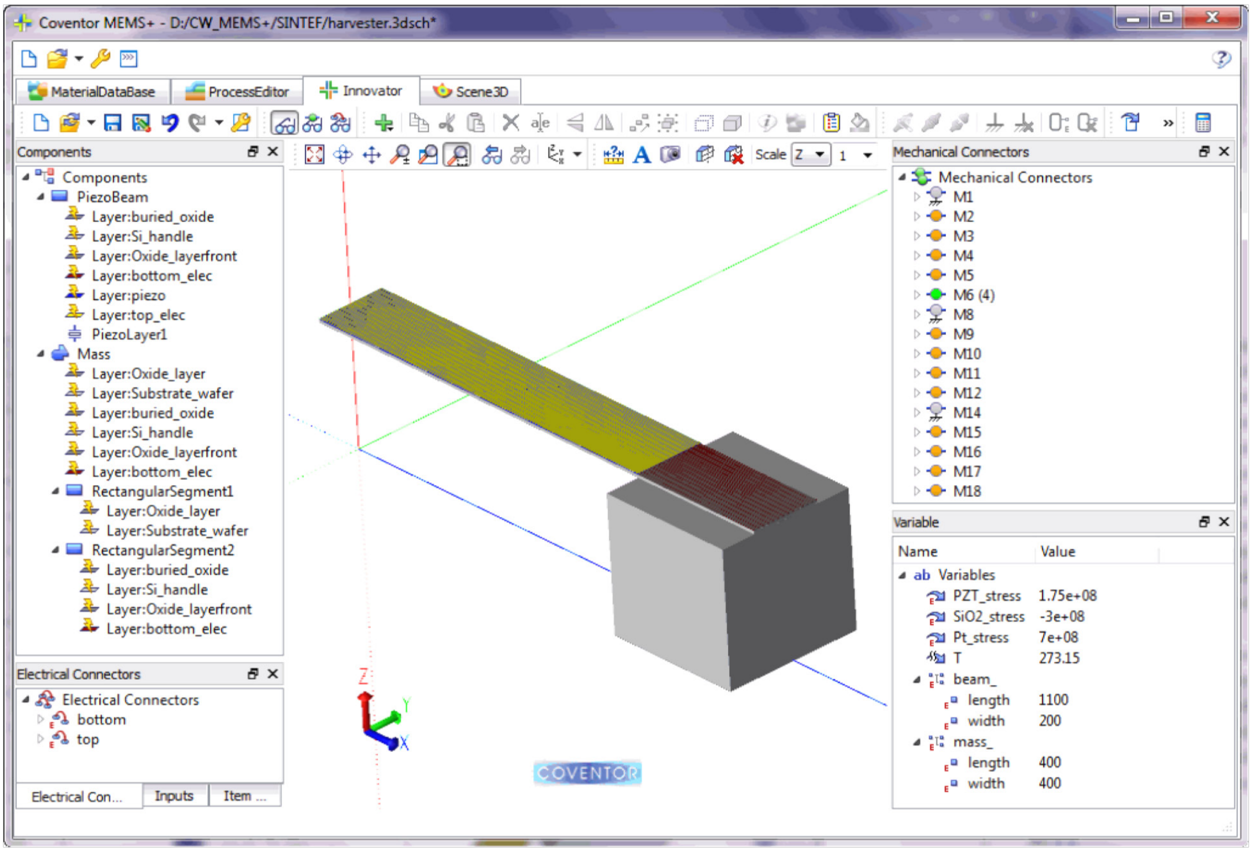


Figure 2.11 Final Device

## 2.6 Simulations in Cadence

This section demonstrates how to import a MEMS+ model into Cadence Virtuoso and then run an AC, DC, and transient analysis on a schematic which includes that model. It is not intended to be a detailed tutorial on how to use Cadence Virtuoso; for details on how to use the Cadence Virtuoso interface, see the Cadence Virtuoso online documentation.
This section of the tutorial assumes that you have Cadence Virtuoso installed and configured to run with MEMS+, and that you are familiar with Cadence Virtuoso.

#### *2.6.1.1 Additional Ressources*

For more information on configuring Cadence for MEMS+ see Section 3 of the *MEMS+ Installation.*

### 2.6.2 Creating the Schematic

In this section we will cover the Cadence Library Manager,
Schematic: MEMS+ schematic Import. Creation, parts library, wiring,
Layout: Cadence tech file, display resources, GDS import/export, shape creation, hierarchy references, Pcells, LSW manipulation, F3 key, ruler, world view (and other tools).

#### *2.6.2.1 MEMS+ import into Cadence*

The first step to simulating a MEMS+ model in Cadence is to import it into the Cadence Virtuoso environment.

| Tasks | Clues & Comments |
|---|---|
| 1. Start Cadence Virtuoso, and open the Library Manager. | a. At our Paris office, we have created a bash shell which set up the environment for MEMS+ and launch Virtuoso. Just type ***cadence610*** in a terminal.<br>b. Once opened, select *Tools > Library Manager*. |
| 2. Import the technology from MEMS+ using command *Create Tutorial Tech library from process* and name it *MoveMEMS* | a. Use the MEMS+ menu in the library manager<br>b. In the dialog that opens, specify a technology library name and browse to the *MoveMEMS* process file. |
| 3. Import the *harvester* MEMS+ model into the technology library you have just created. | a. Select the technology library and go in *MEMS+ > Import Innovator 3D Schematic*.<br>b. Make sure the Layout and Model options are selected |

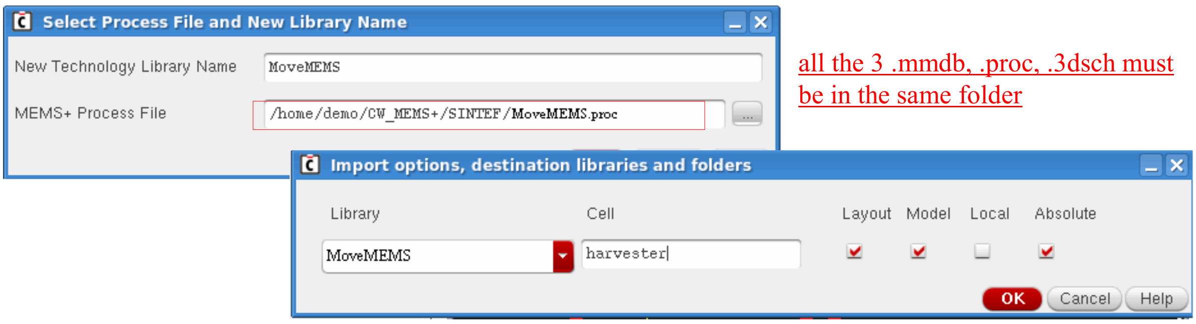



Figure 2.12 Import the process and device

| Tasks | Clues & Comments |
|---|---|
| 1. Open the layout, select one suspension arm and open its properties. | Note the layers in the LSW are taken from the process description; see **Error! Reference source not found.**. |
| 2. Open the symbol and check all exposed connectors are set as pins then open its properties. | a. Note that the symbol has 8 pins: the 6 mechanical inputs and the 2 electrical pins; see **Error! Reference source not found.**.<br>b. Edit > Properties > CellView |

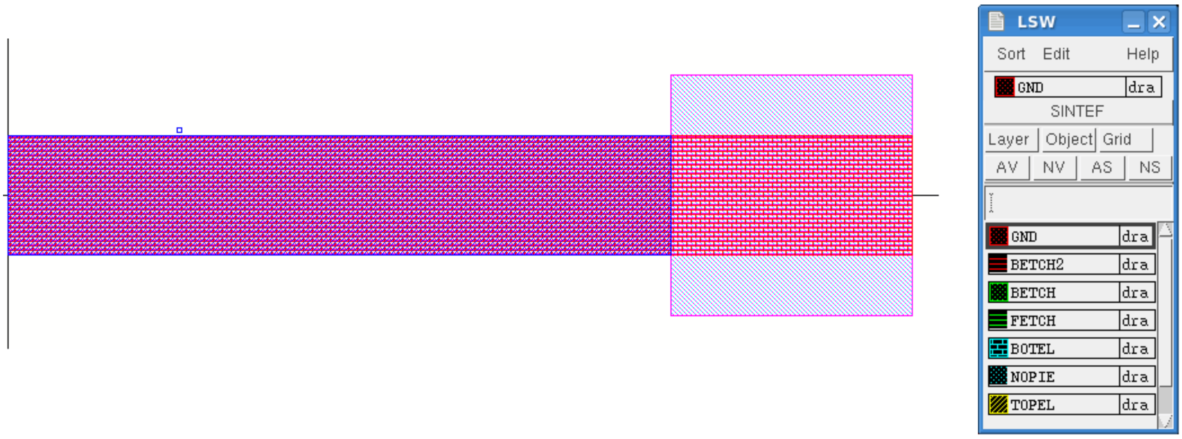



Figure 2.13 Harvester Layout

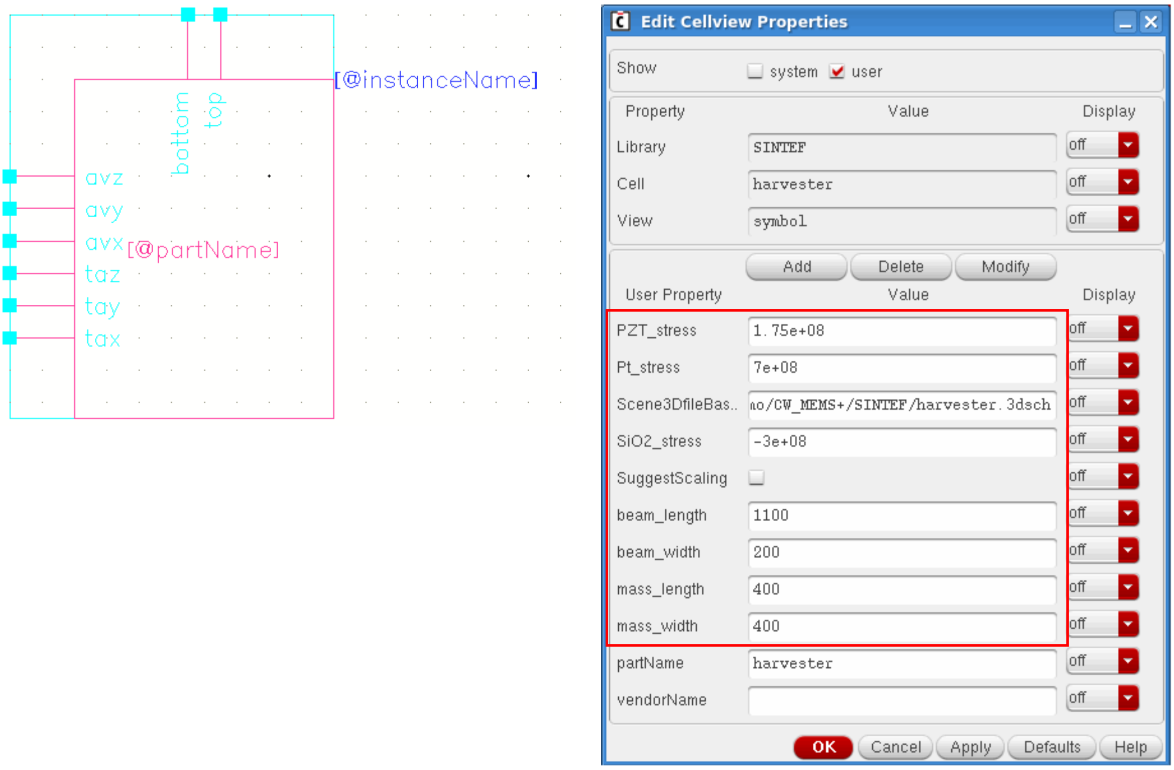



Figure 2.14 Harvester symbol

### 2.6.2.2 *Basic schematic creation*

We'll start to study the MEMS only by adding sources on the harvester pins.

| **Tasks** | **Clues & Comments** |
|---|---|
| **1.** Create a new cell named *harvester_testbench* with the schematic of **Error! Reference source not found.** using *vdc* voltage source, resistor *res* and *gnd* for the ground. | **a.** Work in the *MoveMEMS* library<br>**b.** Copy paste vdc source and just change its cell name for gnd and you'll have the updated component as they are all in the same library. |
| **2.** Set the voltage on the DC electric pin to 0. | No actuation and closed state modelling. |
| **3.** Check and Save and correct possible errors. | Read the virtuoso log CDS.log for hints and ask for help |

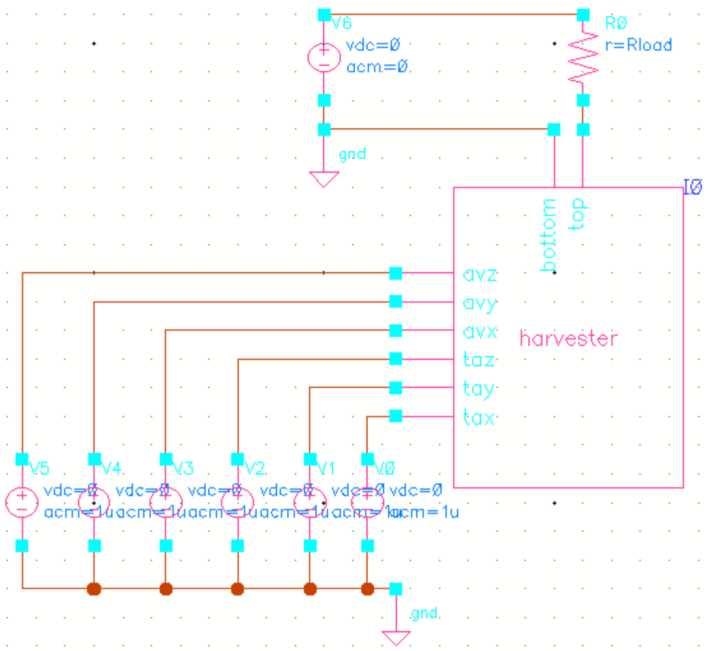
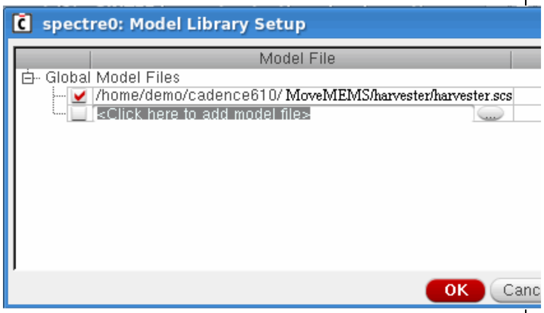



Figure 2.15 Test schematic for Harvester component

## 2.7 Simulations

| **Tasks** | **Clues & Comments** |
|---|---|
| **1.** Turn on the sources on the accelerations and angular velocities for the AC modal analysis. | Set the acmag of vdc sources to a non-zero value...1uV is fine. Keep the acphase and vdc to 0 for all |
| **2.** Launch the simulator ADE L. | |
| **3.** Go in Setup > Model Libraries and browse to the *varactor_mems.scs* file (see | This is to indicate the location of the MEMS+ device to Cadence simulator so it can netlist the complete schematic. |




**3.** Figure 2.16 Lin).

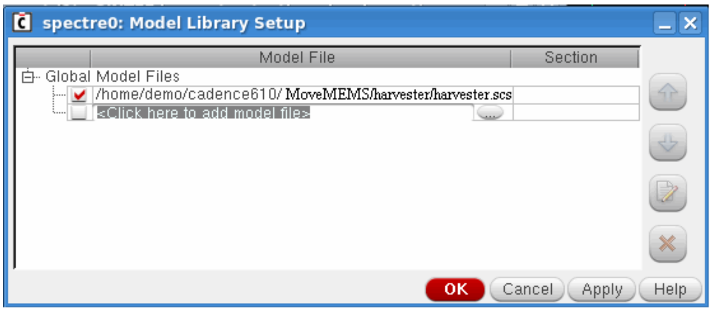



Figure 2.16 Link Cadence to MEMS+ model

### 2.7.1 Modal analysis

| Tasks | Clues & Comments |
|---|---|
| 1. Set an AC analysis from 100 to 10k with 10k number of steps in a linear mode. | Check you get the same line as in Figure 2.17 . |
| 2. Set the gmin value to 0 : In the ADE window, select *Simulation* > *Options* >*Analog*. In the Simulator Options dialog that opens, click on the *Algorithm* tab and Set the gmin value to *0*. | The gmin parameter controls the creation of additional conductances across each and every nonlinear device of the netlist. Its purpose is to facilitate the convergence of the solver. However, on typical MEMS devices, the default alue of 1e-12 is high enough to significantly affect the precision of a simulation with a MEMS+ model. It is best to run simulation involving MEMS+ devices with gmin set to zero. However, if you need gmin to be set to have the simulator converge, please verify its effect on the MEMS device. |
| 3. Set the Rload to 1T (1 teraohm) | |
| 4. Save this session as a CellView and name it *ac*. | so you'll keep your settings |
| 5. Start the simulation and check results are the one in<br>5. Figure 2.17 . | |
| 6. Browse results once the analysis is done to find signals inside a component. In this case open ac-ac and open instance I0 (MEMS reference in virtuoso) | a. Go in Tools > Results Browser and double click ac_ac then I0<br>➊ Note the instance number I0 and the connector number M6 may be different in your case. |

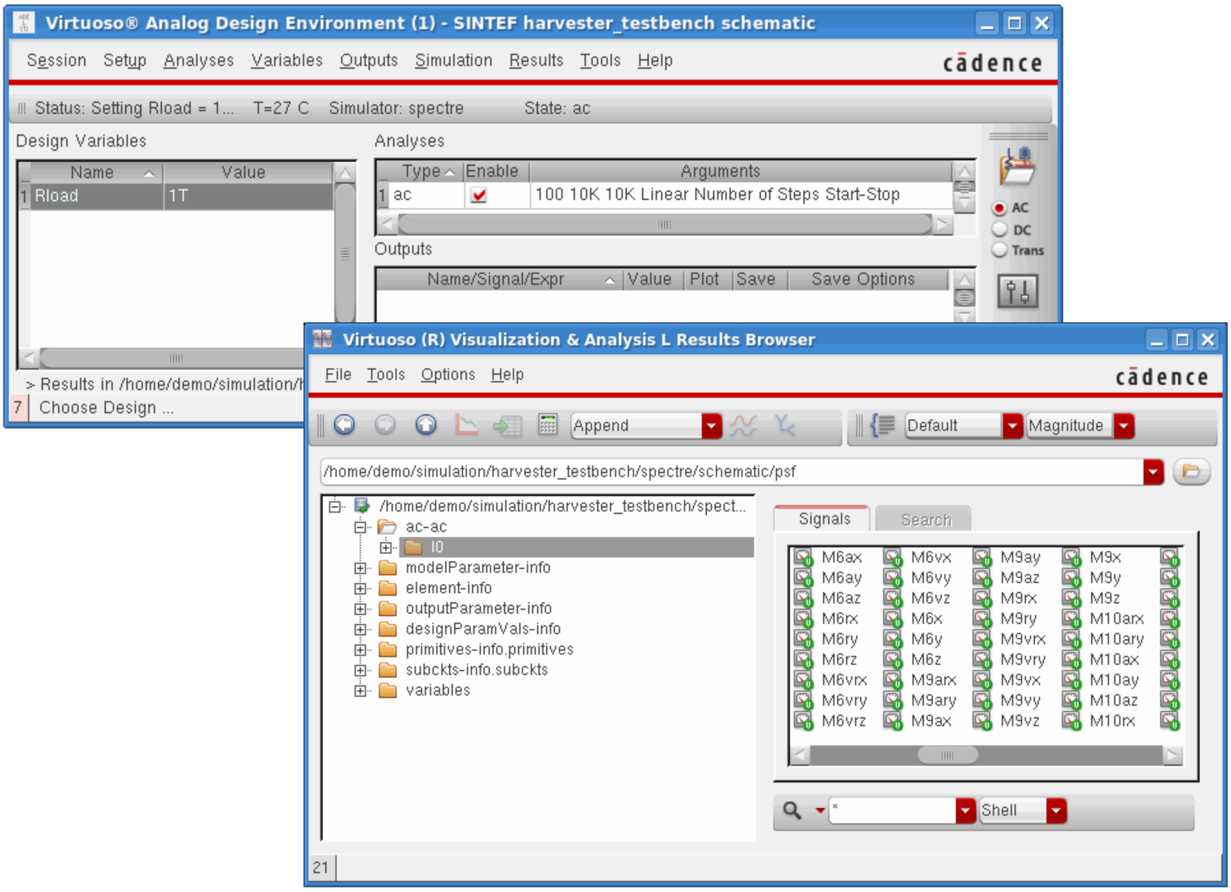



Figure 2.17 AC analysis

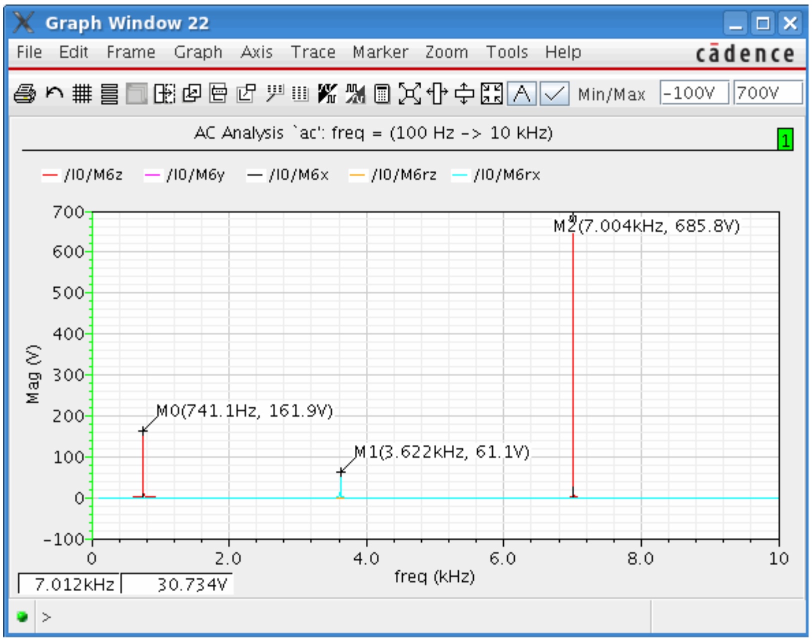



Figure 2.18 AC signals plot

| **Tasks** | **Clues & Comments** |
|---|---|
| **7.** Back into MEMS+ open DC results into Scene3D | Use open icon and choose the file with the name extended by .dc. |
| **8.** Measure the maximum displacement at device tip | |
| **9.** Open AC results into Scene3D. | Same with .ac |
| **10.** Use the graph tool to place the view at the peak frequencies and animate the 2 resonant modes found. | **a.** To add signals select the part in the component tree and drag it in the new graph<br>**b.** Right click to use *Move progress bar here* and *Add data label.*<br>**c.** Exaggerate displacements and increase the scales for a better viewing. |

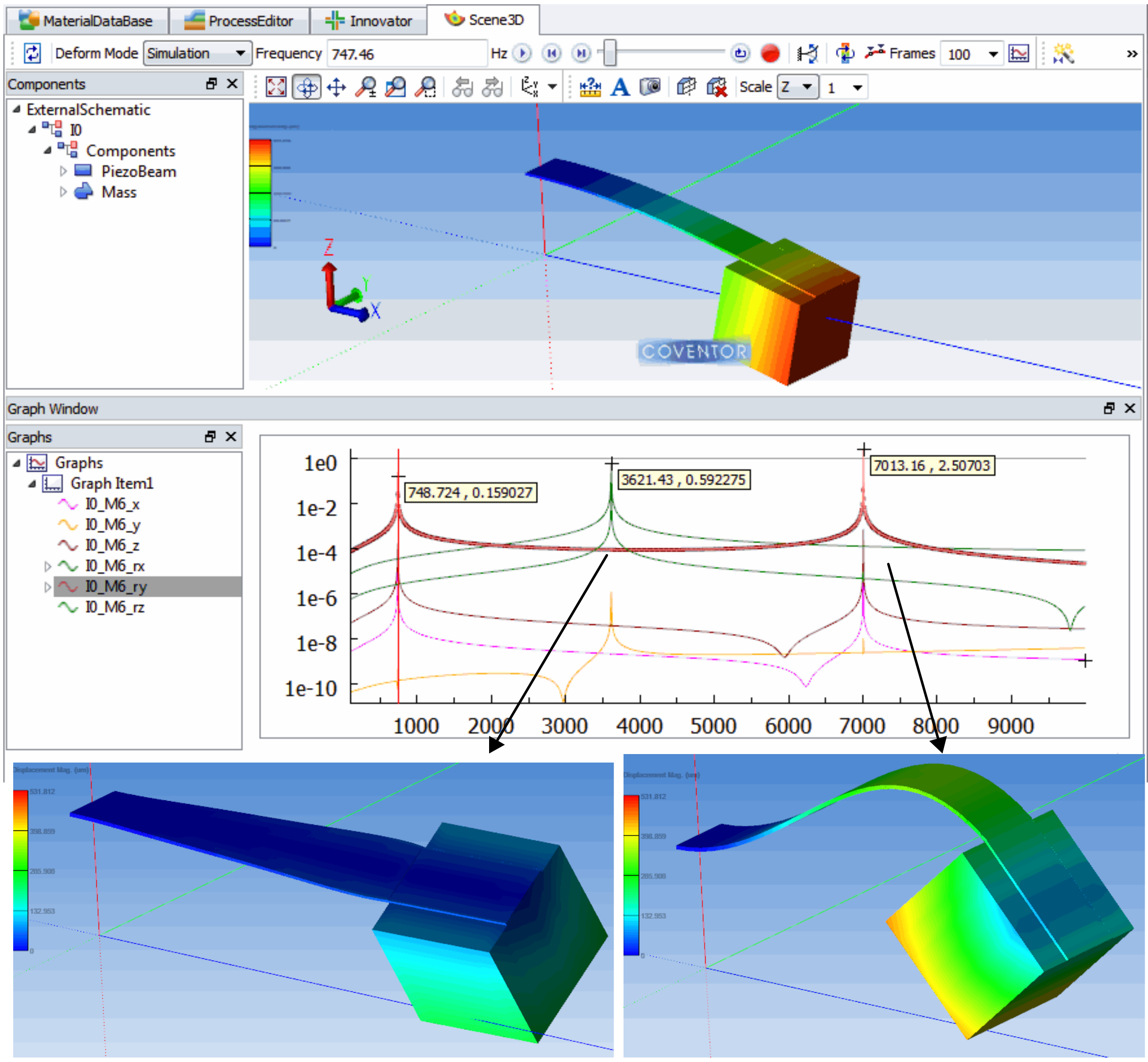
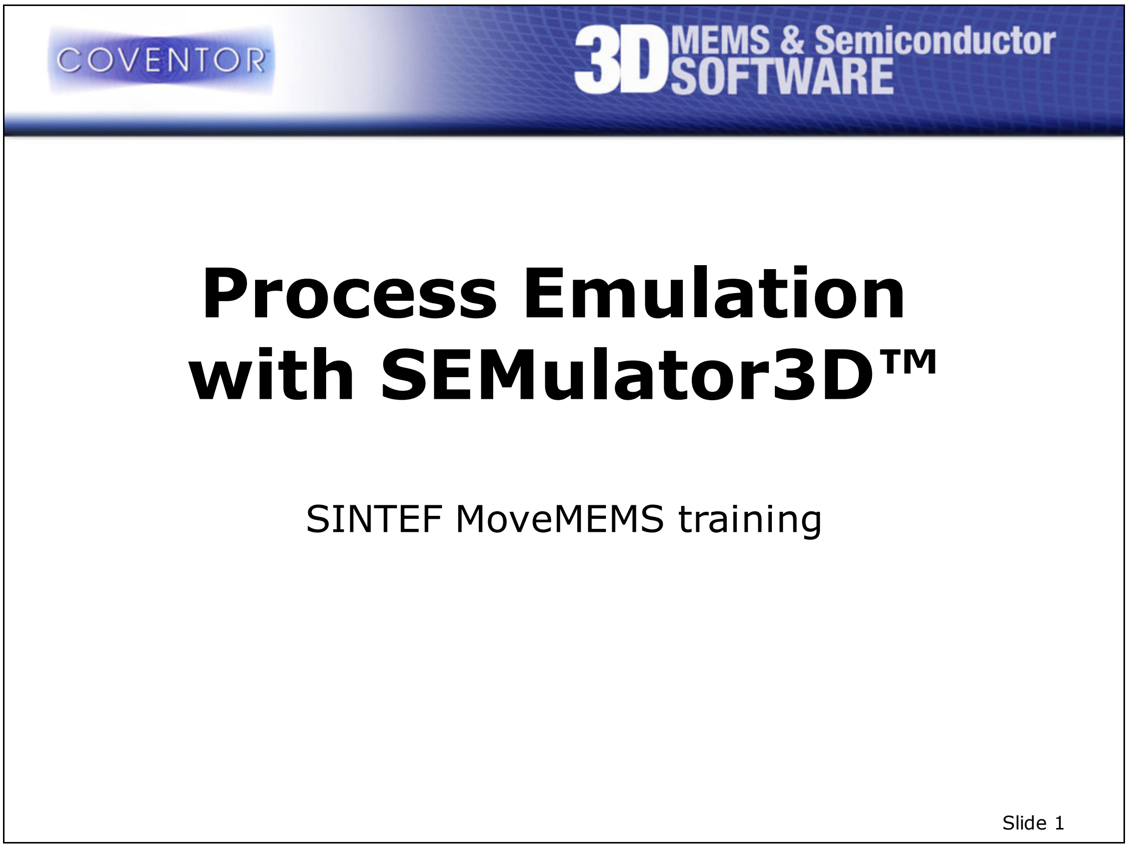
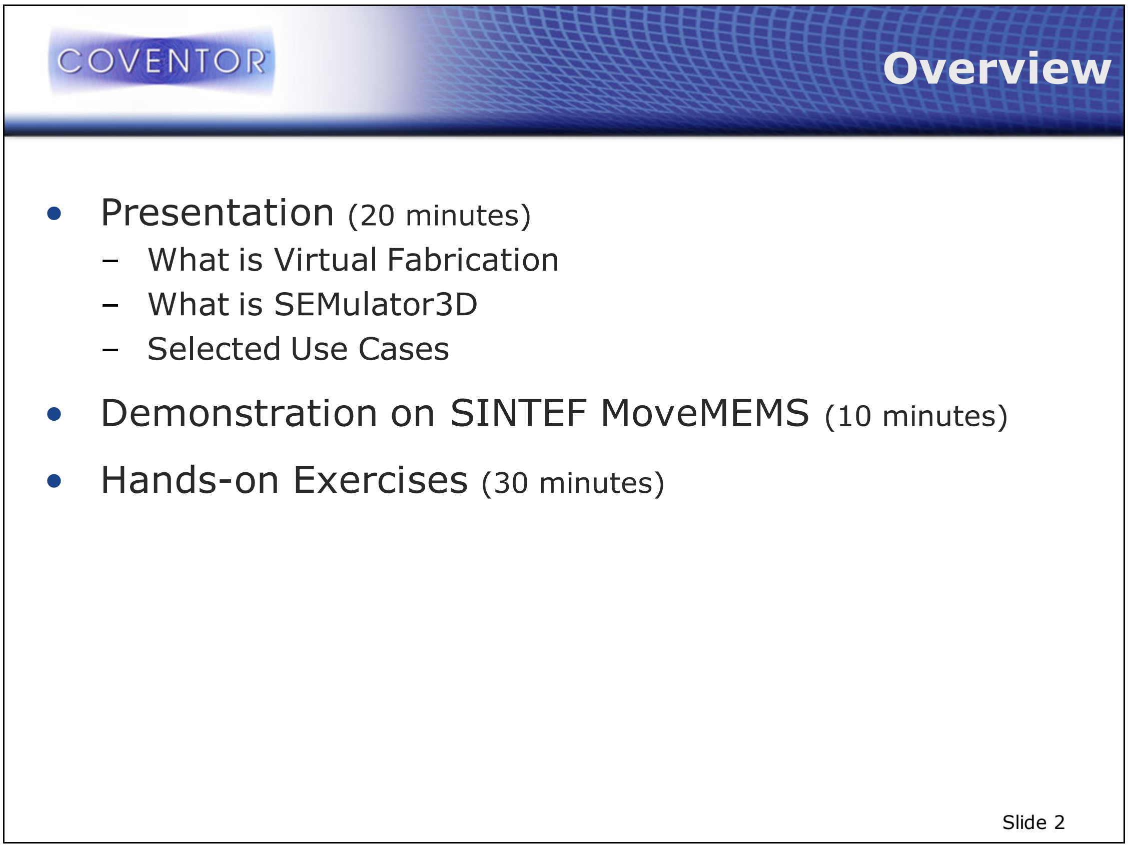
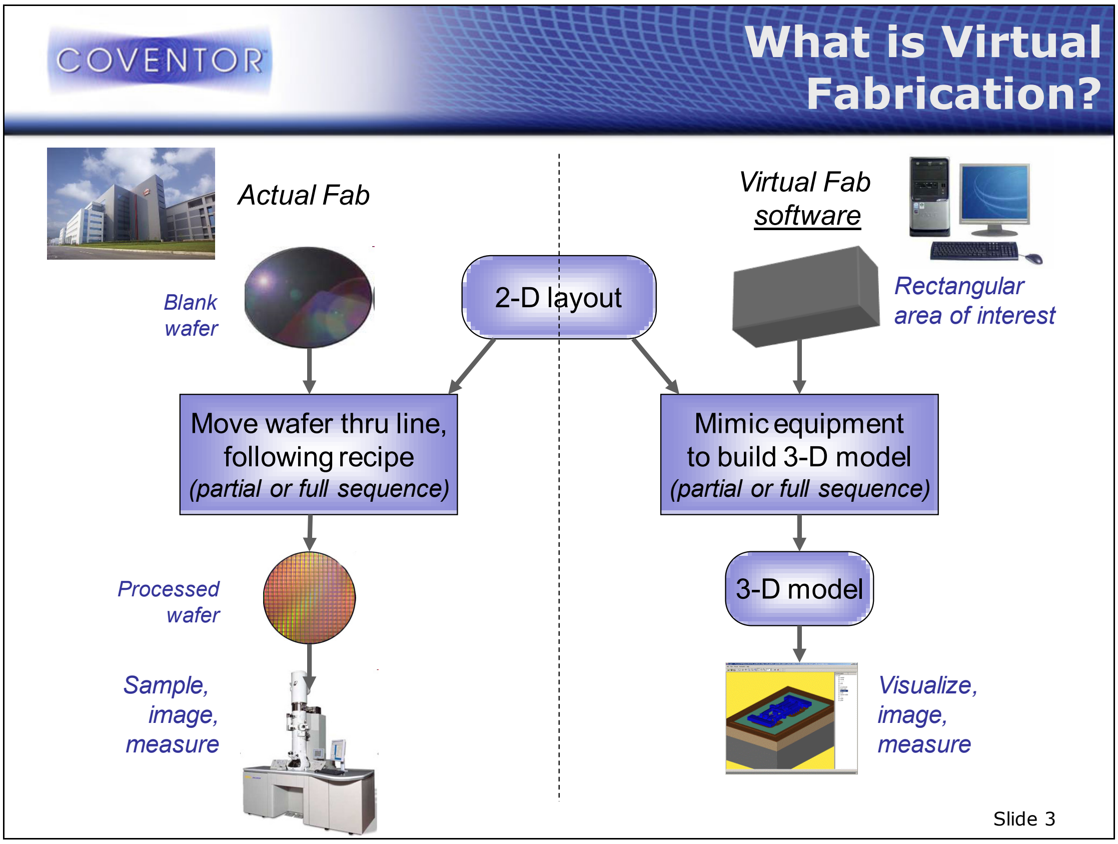


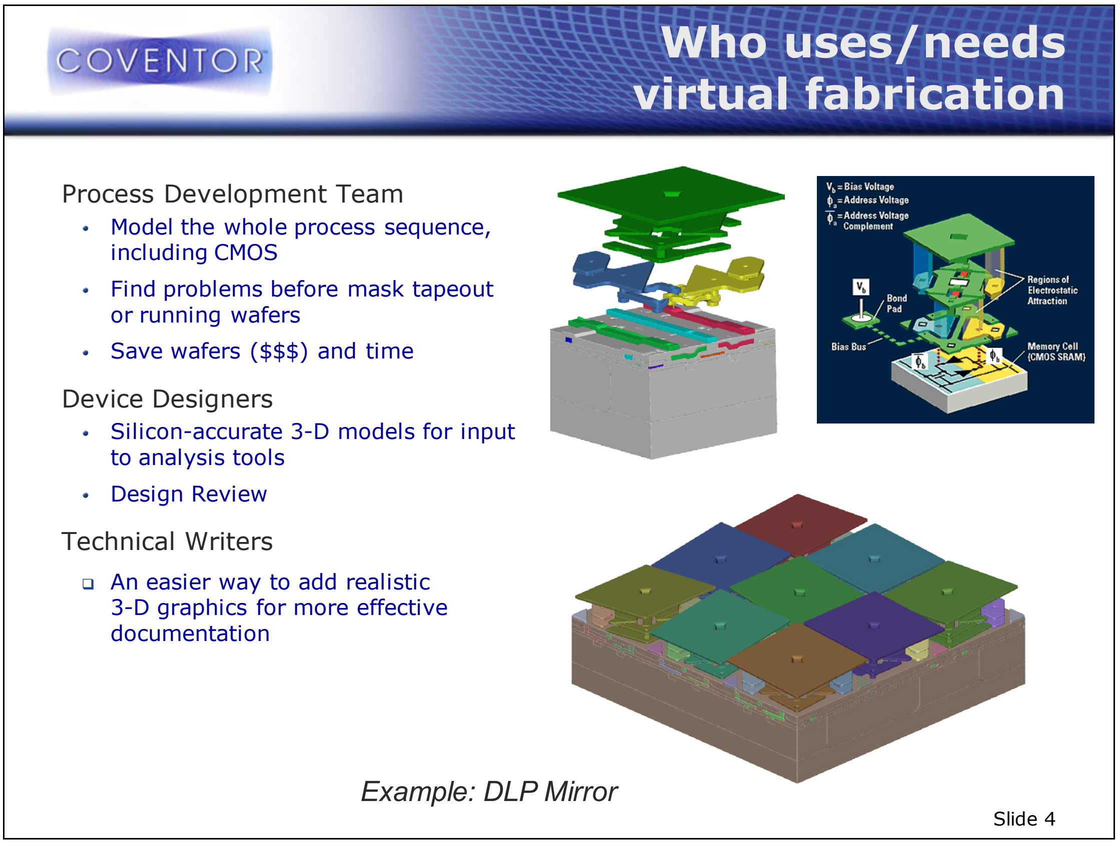

Figure 2.19 Resonant modes in z and rx/ry

# 3 USING SINTEF MOVEMEMS DESIGN KIT INTO SEMULATOR3D




COVENTOR
What is Virtual Fabrication?
Actual Fab
Virtual Fab software
Blank wafer
2-D layout
Rectangular area of interest
Move wafer thru line, following recipe (partial or full sequence)
Mimic equipment to build 3-D model (partial or full sequence)
Processed wafer
3-D model
Sample, image, measure
Visualize, image, measure
Slide 3

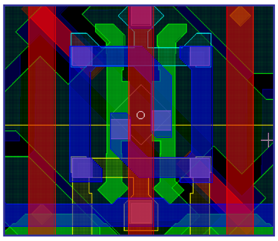

COVENTOR
Who uses/needs virtual fabrication
Process Development Team
• Model the whole process sequence, including CMOS
• Find problems before mask tapeout or running wafers
• Save wafers ($$$) and time
Device Designers
• Silicon-accurate 3-D models for input to analysis tools
• Design Review
Technical Writers
❑ An easier way to add realistic 3-D graphics for more effective documentation
Bond Pad
Bias Bus
Regions of Electrostatic Attraction
Memory Cell (CMOS SRAM)
Example: DLP Mirror
Slide 4

COVENTOR

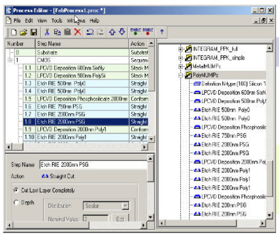
## What is SEMulator3D

*A modeling tool used by leading MEMS and semiconductor fabs*

GDSII Layout



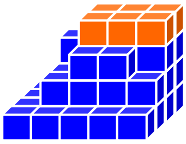
Process Description



*Customizable to <u>any</u> process technology*

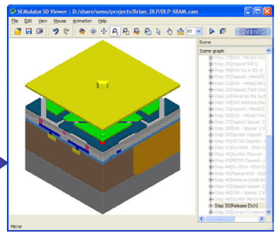
3D Modeling Engine

*builds voxel models by applying a sequence of primitive operations*

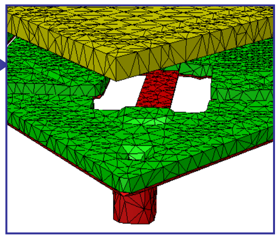


*Voxels are 3D pixels*

Visualization



Simulation Mesh



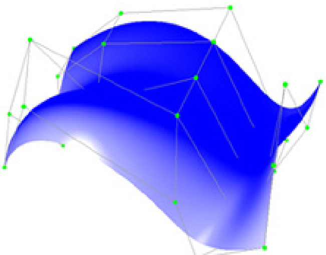
Slide 5

COVENTOR

## Alternative 3D Modeling Approaches

**Solid Modeling** – *Analog*

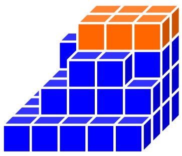
- Exemplified by Pro/E, SolidWorks, Solid Edge, CATIA, etc.
- Surfaces are modeled with mathematical shapes (planes, cylinders, spheres, NURBS…)



*NURBS surface*

**Voxel Modeling** – *Digital*

- Exemplified by SEMulator3D and medical image processing
- Volume is filled with uniformly sized cubic *voxels* ≅ 3D pixels



*Section of a voxel model*

Advantages of SEMulator3D voxel models for semiconductor applications

<u>Fidelity</u> – faithful to real process technology

<u>Robustness</u> – modeling operations do not fail

<u>Scalability</u> – modest CPU and memory req's; (model build from transistor to to wafer-level)

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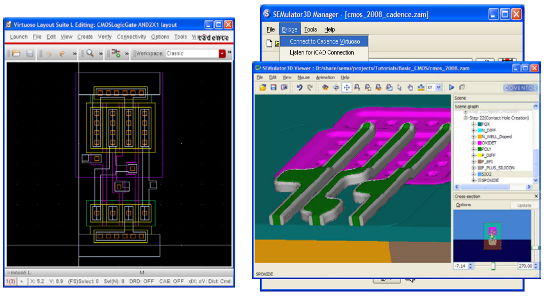
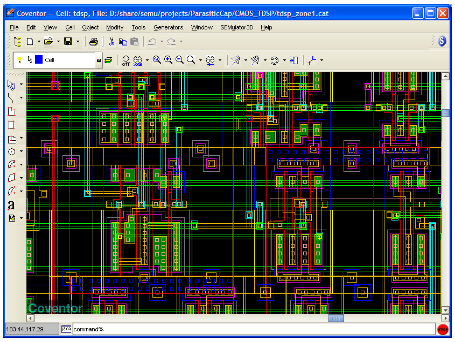
## Start with 2-D layout

Import GDSII data from any source
- GDSII files
- Cadence Virtuoso Bridge
- Knights/Magma Camelot Bridge

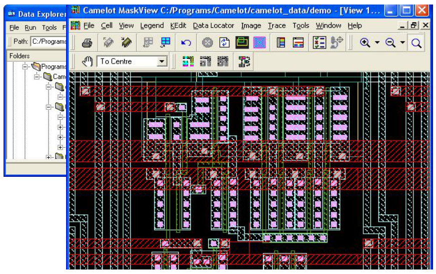
or create your own with the included SEMulator3D layout tool.



Cadence Virtuoso Bridge



SEMulator3D Layout Editor



Magma Camelot Bridge
*(formerly Knights Technology)*

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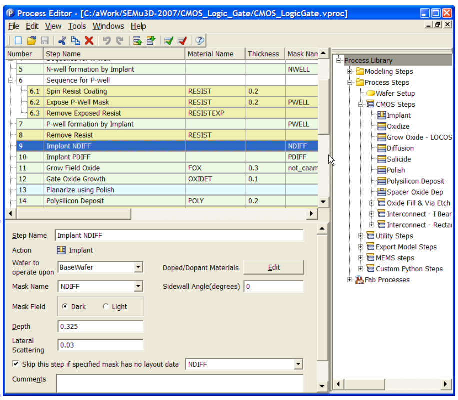
## Add the 3rd dimension…

*Process Editor*

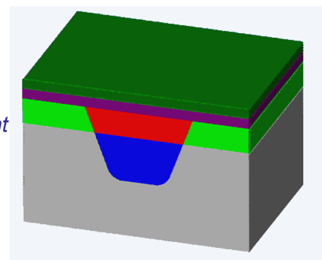
*Process Sequence*



*Parameters of Selected Step*

*Step Library*
- *Modeling Primitives*
- *Standard Steps*
  - *CMOS Steps*
- *Fab Processes*

*Implant*



Users can…
- Select a pre-defined, generic process stack
- Create a custom process stack using steps from the library
- Calibrate steps with data from cross-section measurements
- Create custom steps with Python scripting
- Import a process stack from an Excel spreadsheet or other data formats (*e.g.* XML) via Python

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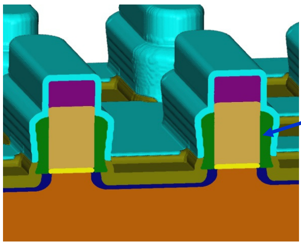
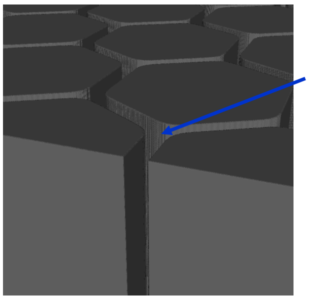
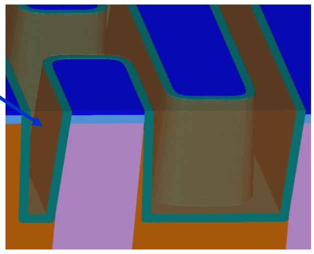
## SEMulator3D Library of Standard Process Steps

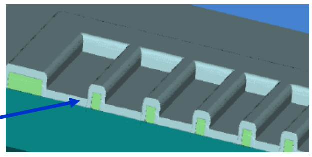


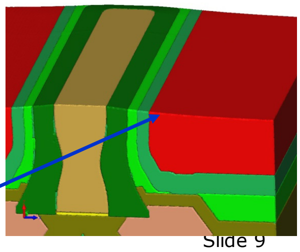


*MEMS/CMOS process steps*

- **Shallow Trench Isolation**
- **Implant, Extension Implant**
- **Spacer Formation**
- **Lithography**
- **Oxidation**
- **Diffusion**
- **CVD (many types)**
- **(D)RIE Etch**
- **Isotropic (wet) etching**
- **Lift-Off**
- **Sputtering, Evaporation**
- **CMP**







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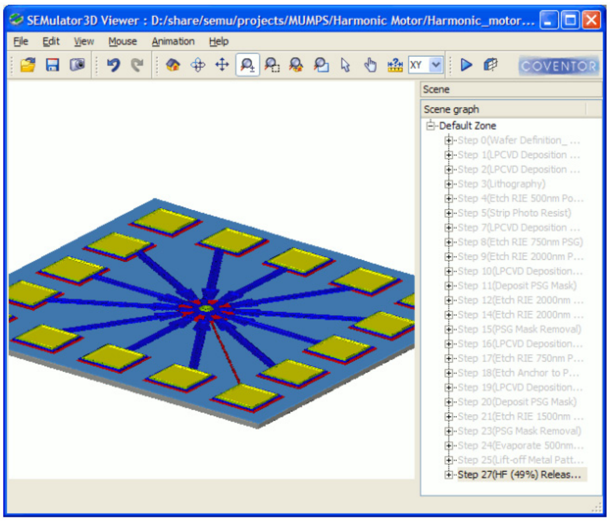
## Powerful 3D Visualization

*With the SEMulator3D Visualizer, you can*




- Interact with a 3-D view
- Create and animate dimensionally accurate cross sections
- Color by material or by electrical connectivity
- Hide/show materials or electrical nets
- Take measurements
- Exaggerate scale in x,y or z
- Capture 3-D images
- Animate the fabrication steps

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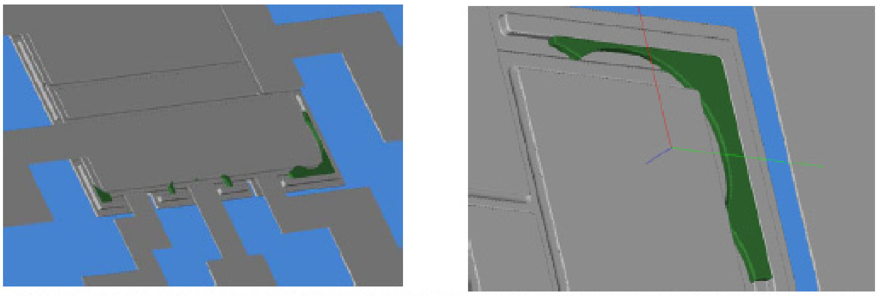
## Use Case – Design review

“We have now established a strict submission procedure within Baolab for all the foundry runs, and one imperative step is to simulate the whole die micromachining process using SEMulator3D and to visualize the 3D result using the mechanical coloring scheme, and this must be included in the final report.”



**Green indicates Oxide not removed despite non-violation of design rules**

baolab MICROSYSTEMS

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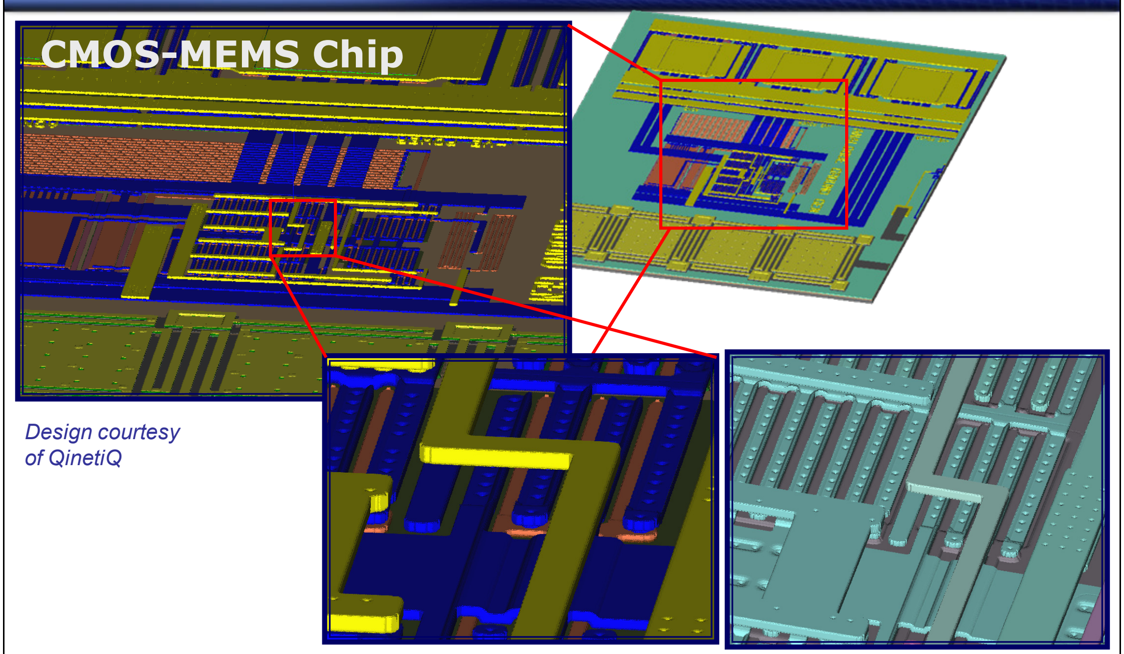
## Use Case - Connectivity Check




*Design courtesy of QinetiQ*

**Colored by material** **Colored by electrical connection**

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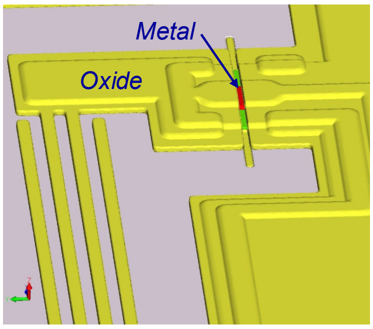
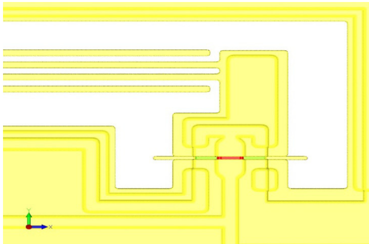
## Use Case - 3D design check

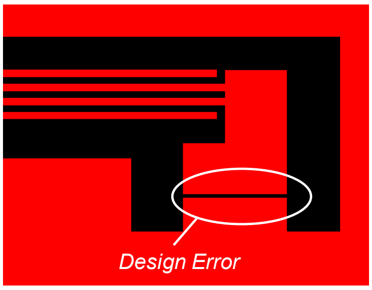
Example: A design error that was caught before mask tape-out (XFAB)




*Visual inspection of SEMulator3D model showed isolation trench structure would have been improperly exposed to subsequent DRIE*



*Top view of SEMulator3D model*




*DRIE Oxide Mask*

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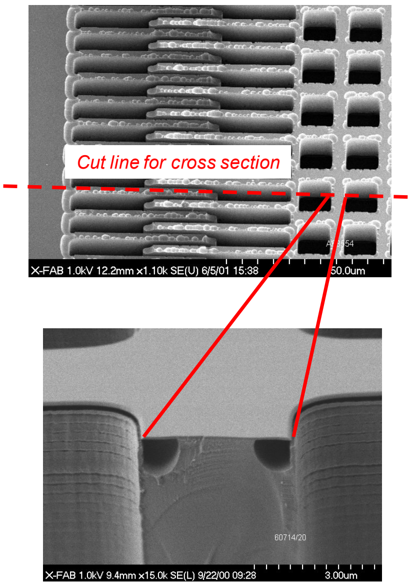
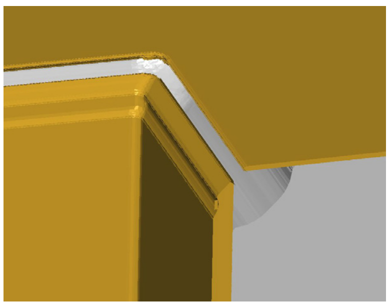
## Use Case - Process Development

During development of X-FAB's technology, undesired pockets formed in mechanical layer during release etch




Detailed 3-D process model of the protective oxide layer confirmed the hypothesis about the process failure:

*The release etch for the movable parts was etching through thin spots in the protective oxide layer*



*3-D Model*

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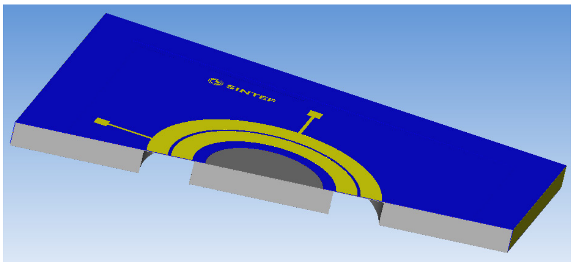
## Process Documentation and Training

The Traditional Way – Static 2D Cross Sections

- **Created in a drawing program or PPT**
- **Not to scale; not scalable**
- **Manual => High effort to reproduce the graphics**

The New Way – Interactive 3D Views

- **Created with SEMulator3D**
- **To scale, supports interactive measurements**
- **Quickly and automatically re-generate for new design & processes and variations**
- **Automatically generate ppt-slides**
- **New free viewer (2011 version)**

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## Beyond MEMS Processes…

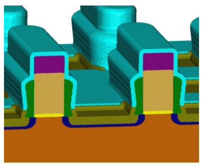
SEMulator3D applies to semiconductor processes as well

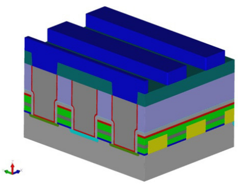
CMOS Logic
- FEOL and BEOL
- Digital and Analog/Mixed Signal
- Advanced processing nodes (22 and 15 n
- Current processing nodes (45 nm and larg

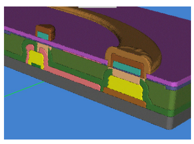
Memory
- Advanced 6T DRAM cells
- Advanced flash memory cells

CCD Image Sensors

Hard Disk Read/Write Heads







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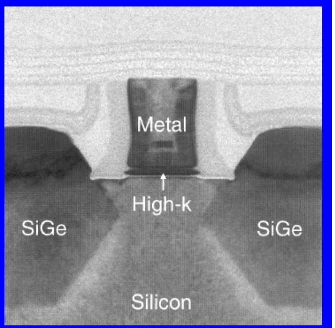
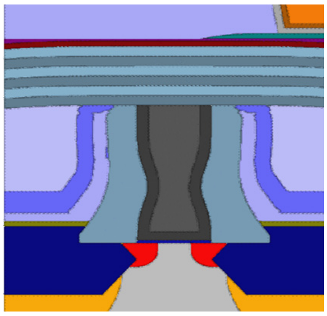
## CMOS Logic Example: Intel 45 nm Process

### Transistor Features

- **35 nm min. gate length**
- **160 nm contacted gate pitch**
- **1.0 nm EOT Hi-K**
- **Dual workfunction metal gate electrodes**
- **3RD generation of strained silicon**




*Presented at the IEDM2007 conference by K. Misty from Intel:* **A 45nm Logic Technology with High-k + Metal Gate Transistors, Strained Silicon, 9 Cu Interconnect Layers, 193nm Dry Patterning, and 100% Pb-free Packaging**



*SEMulator3D cross section*

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## Scalability – model large area of interconnect on a desktop PC

Proprietary Voxel Modeling Technology

- Compression – enables the storage of hundreds of billions of voxels(!)
- Acceleration – dramatically reduces model build times.
- Visualization – advanced techniques allow interactive manipulation of huge 3D models.

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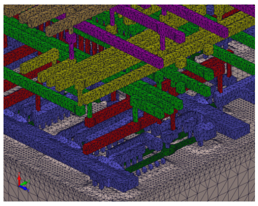
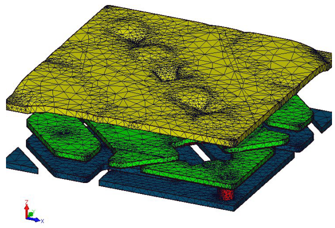
## Introducing SEMulator3D 2011

Many improvements and new features will be included:

**Parallel Model Builds**
**A portable 3D model format and new 3D Viewer**
**New meshing capabilities**
**Automatic model re-build**
**Several new steps in the Process Editor**





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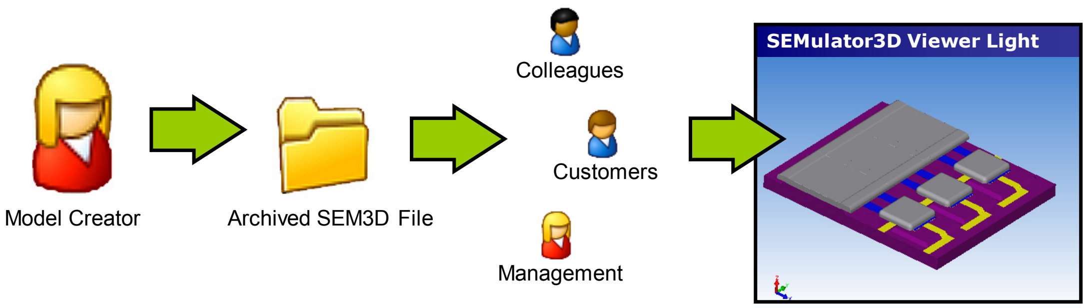
## SEMulator3D Viewer "Light"

- SEMulator3D is an excellent content creation tool.
- A "Light" version of the Viewer will allow anybody to view SEMulator3D models.
- Distribute 3D content to other people.
- Think of it like the Adobe PDF Reader.

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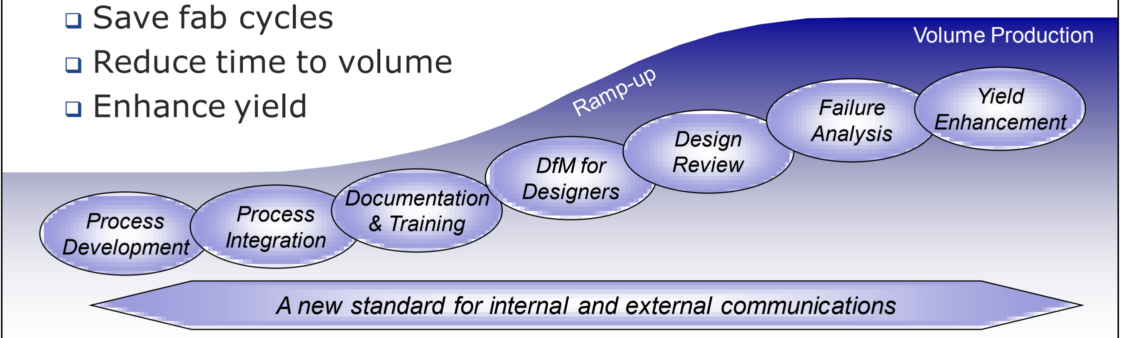
## SEMulator3D Summary

A unique tool for semiconductor/MEMS manufacturers and their customers…

- Accelerate process development
- Save test wafers
- Save fab cycles
- Reduce time to volume
- Enhance yield

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## Overview

- Presentation (20 minutes)
  - What is Virtual Fabrication
  - What is SEMulator3D
  - Selected Use Cases
- Demonstration on SINTEF MoveMEMS (10 minutes)
- Hands-on Exercises (30 minutes)

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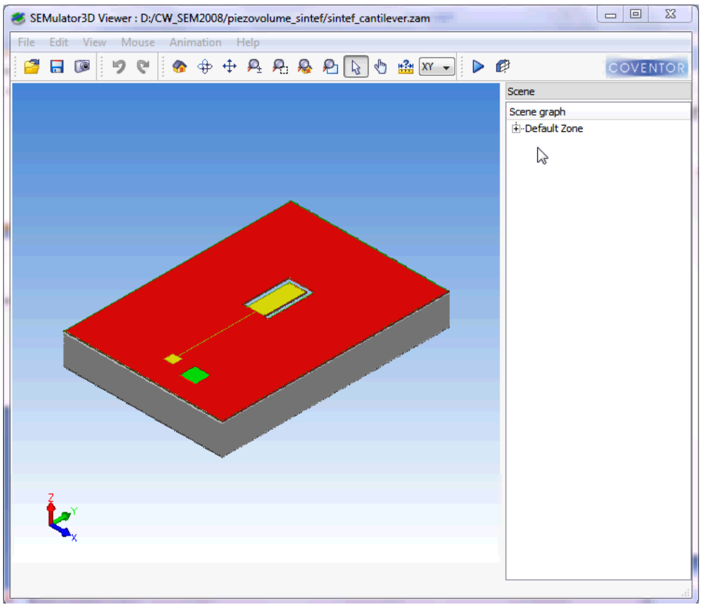
## Demo SINTEF MoveMEMS

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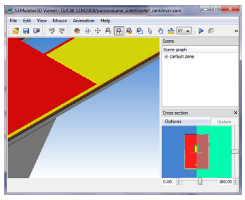
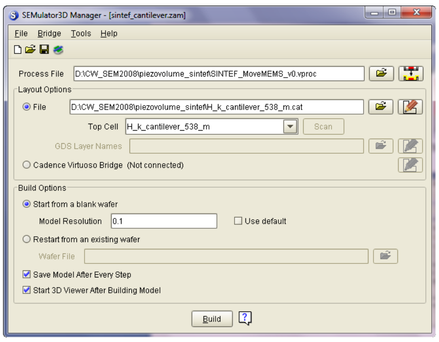
## Hands-on Exercises (1)

### Exercise 1



1. Open "SEMUlator3D Manager"
2. Load and open MoveMEMS process file
   - "SINTEF_MoveMEMS_v0.vproc"
3. Adjust process file to SINTEF material properties (via File->Properties)
   - "SINTEF.vmpd"
4. Specify layout (cantilever) and the topcell
   - "H_k_cantilever_538_m.cat r.cat"
5. Build model with 0.1 resolution
6. Explore 3D viewer
7. Review process step-by-step
   - Use ↑ ↓ of keyboard
8. Use x-section
9. Find and investigate x-section of
   - Back etch cavity
   - Anchors

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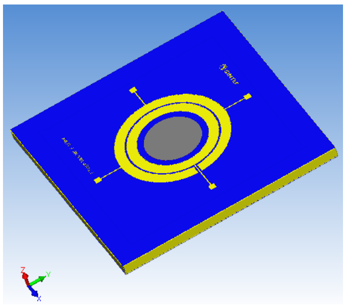
## Hands-on Exercises (2)

**Exercise 2 -** build model for the Mirror layout

1. Open layout and review
2. Change for a DRIE back etch instead of KOH
3. Build model with higher resolution (0.01)
4. Change the visibility of substrate to hide it
5. Make a process step animation movie



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## Hands-on Exercises (3)

**Exercise 3 –** Mesh the Mirror

1. Use GET tool to select only the Mirror device for emulation
2. Add a Volume Mesh to the process to create a unv format
3. Build model 0.1 resolution
4. Enable Mesh viewing in Zsplat

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