Created in COMSOL Multiphysics 6.1

Normal Modes of a Biased Resonator — 3D Geometry from a GDS-File

Introduction

When modeling a MEMS or semiconductor device with complex 3D structure, the geometry buildup can be time consuming, tedious, and error-prone. Buildup can require numerous primitive shapes in an assembly that does not correspond to how such a device would be fabricated, i.e. through sequence of processes that deposit and pattern the distinct materials one layer at a time. This tutorial demonstrates how, with the ECAD Import, and Design Modules, we can emulate semiconductor fabrication processes to build 3D geometry more efficiently and in a way that reflects actual semiconductor or MEMS fabrication.

This tutorial recreates from a GDS file the device structure modeled in the Stationary Analysis of a Biased Resonator — 3D using operations available in the ECAD Import, and Design Modules. The original model was created from 15 rectangles specified by 60 parameters. In contrast, this tutorial builds the geometry layer-by-layer and requires only 7 parameters with 6 of them for specifying thicknesses of the layers. This greatly simplifies future optimization studies.

After the geometry model is completed, the tutorial solves for the eigenmodes of the structure which can be compared to the results in the Normal Modes of a Biased Resonator — 3D.

Model Definition

The following is an outline of the steps that you can use to emulate basic MEMS or semiconductor fabrication processes using geometry operations. For the detailed instructions see the Modeling Instructions section.

DEPOSITION OF A LAYER OF MATERIAL OVER A FLAT SURFACE

To create the geometry for a layer deposited over a flat surface, use an Import operation. Depending on the mask in GDS file, the resulting layer could be patterned or unpatterned.

During the import the layer is extruded according to the specified thickness and elevation values. The substrate layer imported in this way is shown in Figure 1.

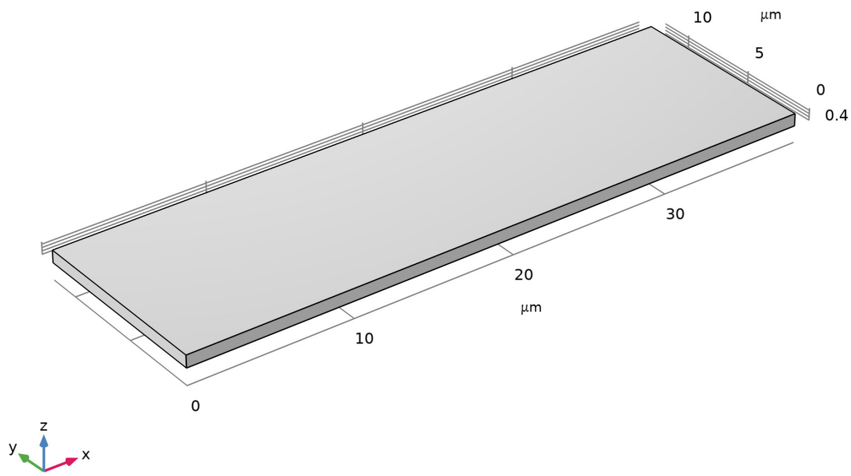


Figure 1: First layer: substrate.

The unpatterned nitride layer, imported as the second layer in the structure is shown Figure 2.

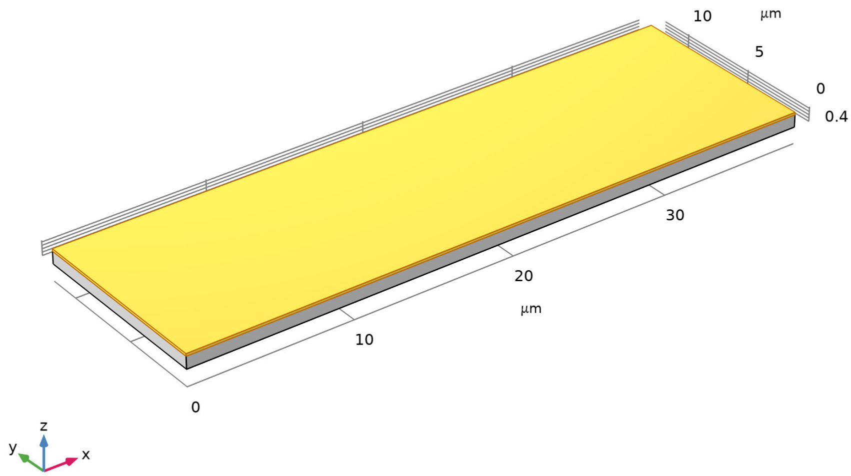


Figure 2: Second layer: nitride.

DEPOSITION AND PATTERNING OF A LAYER OF MATERIAL OVER A FLAT SURFACE

When a patterned layer is deposited over a flat surface, and the GDS file contains the mask for the layer when using positive photoresist, the imported layer can be directly extruded by the Import operation. The import then replicates the sequence of processes that include material deposition, photoresist coating and exposure, etching of the material, and the photoresist stripping. In the model, this is illustrated by importing layer 3 that corresponds to the polysilicon base, shown in Figure 3.

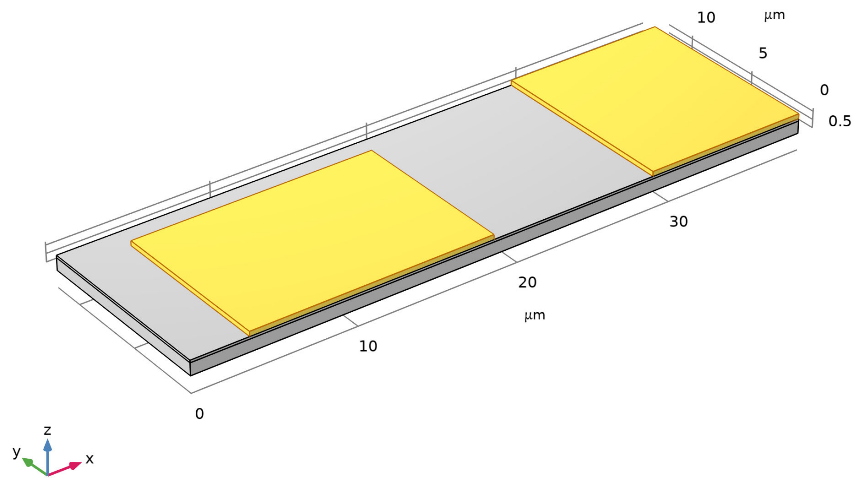


Figure 3: Third layer: the polysilicon base.

CONFORMAL DEPOSITION OF A LAYER OF MATERIAL OVER NON-FLAT SURFACE

Two layers in this structure are deposited over a non-flat surface: the sacrificial layer and the polysilicon layer for the beam. You can follow the same workflow for creating both layers. The following is an overview for how to create the sacrificial layer which covers the patterned polysilicon base and the exposed parts of the nitride layer. This layer is thus to be created over a non-flat surface, so the import operation cannot be used to extrude the layer mask in one step. Instead, a sequence of geometry operations, including Offset Faces and Difference, is first used to emulate the deposition of the material. The result of these operations is shown in Figure 4.

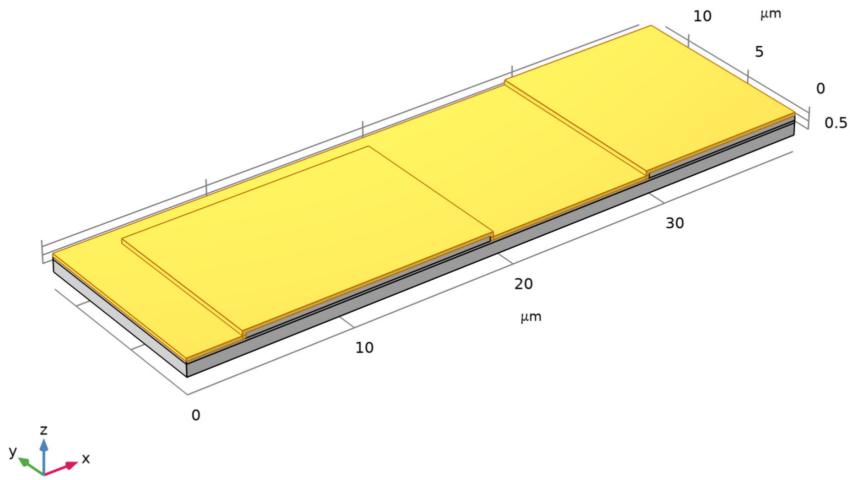


Figure 4: The fourth sacrificial layer. This layer is conformal to the underlying polysilicon base.

COATING AND PATTERNING OF VIRTUAL PHOTORESIST

The patterning of the conformal sacrificial layer can be done in two steps. First, create a virtual photoresist by importing the mask. This is equivalent to photoresist coating and lithographic patterning, as shown in Figure 5. In the subsequent step, use the Intersection operation to transfer the pattern of virtual photoresist to the target layer. The virtual photoresist layer must penetrate the entire depth of the target layer, so this determines the elevation and thickness of the imported mask layer.

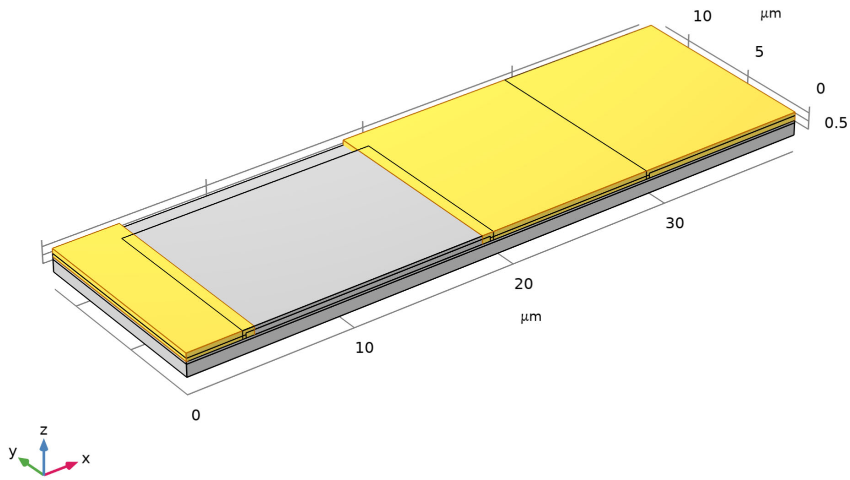


Figure 5: Patterned virtual photoresist layer.

PATTERNING OF A LAYER OF MATERIAL OVER NON-FLAT SURFACE

By using the Intersection operation, you can transfer the photoresist pattern to the target sacrificial layer. This step is equivalent to an etch process followed by a photoresist strip. What remains is the patterned sacrificial layer, as seen in Figure 6.

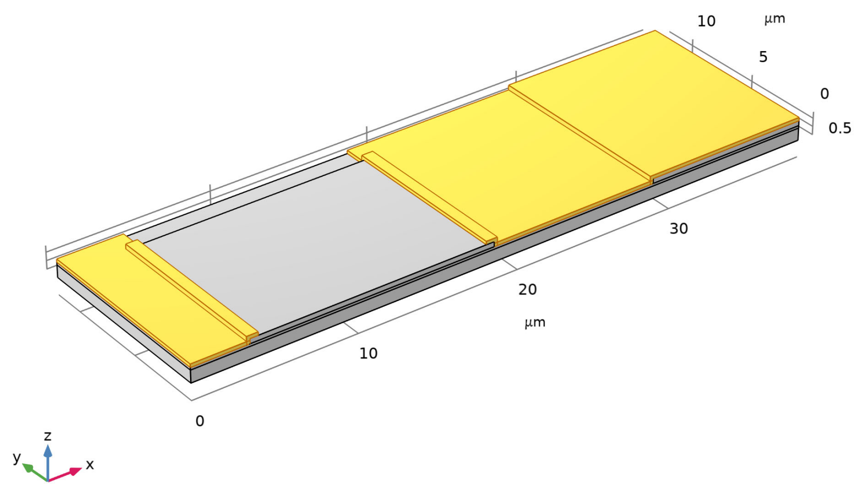


Figure 6: Patterned sacrificial layer.

To obtain the patterned polysilicon beam deposited over the sacrificial layer and the exposed faces of the polysilicon base and nitride layers, follow the same steps as when creating the sacrificial layer. The result is shown in Figure 7.

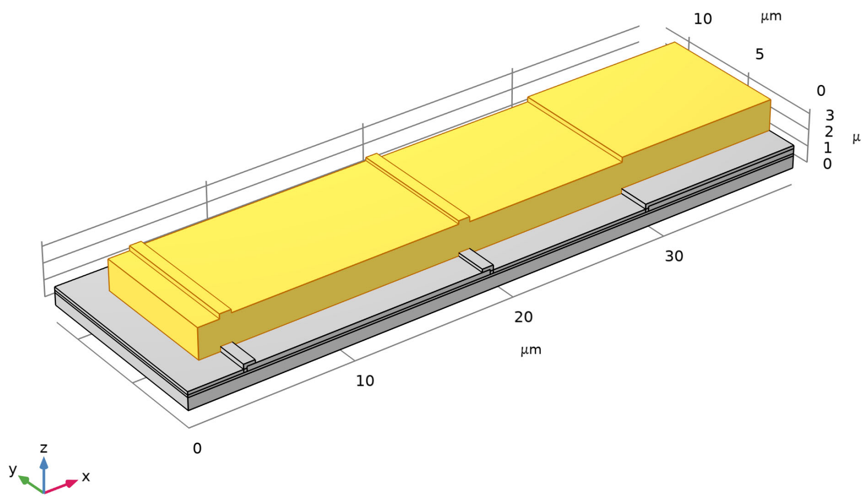


Figure 7: Patterned polysilicon beam.

REMOVAL OF A LAYER OF MATERIAL

To remove the sacrificial layer seen in Figure 8 use the Delete Entities operation. This step is equivalent to an isotropic etch process for releasing the structure. The completed half structure is shown in Figure 9.

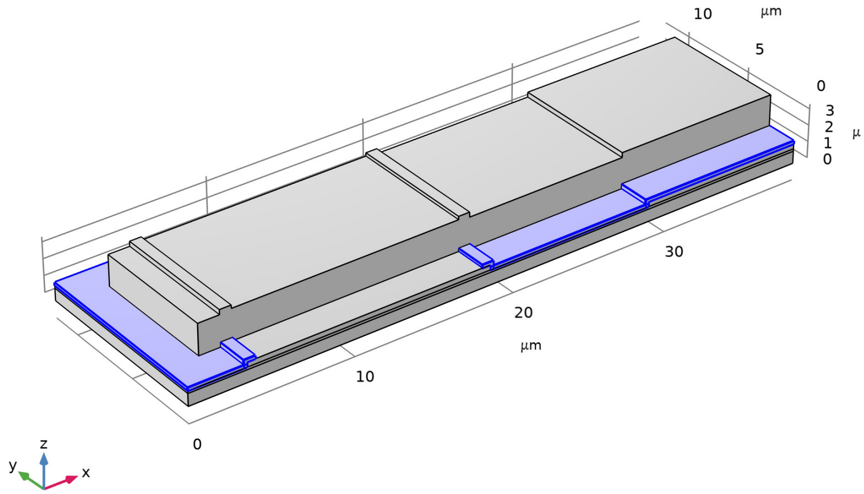


Figure 8: The sacrificial layer under the polysilicon beam is selected for removal.

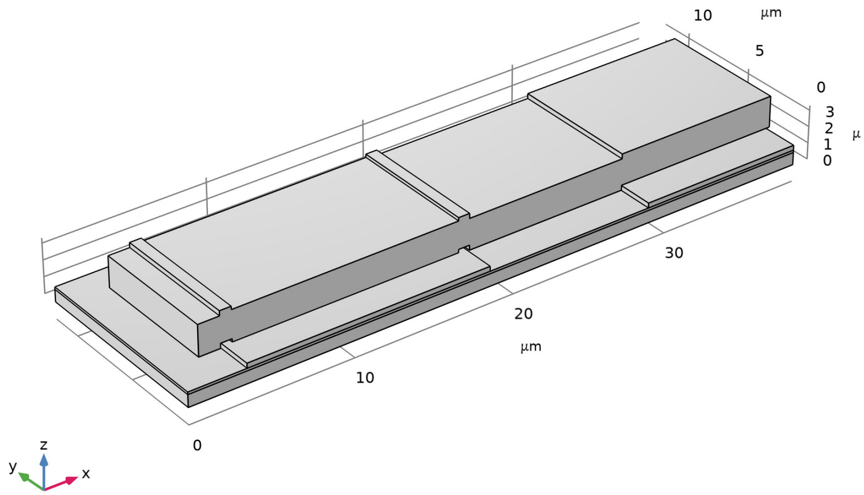


Figure 9: Completed half of the geometry.

For this tutorial it is not enough to model half of the geometry using symmetry boundary conditions, because doing so excludes all the antisymmetric vibrational modes. The geometry is therefore mirrored prior to performing the eigenfrequency analysis.

Results and Discussion

Figure 10, Figure 11, and Figure 12 show the normal modes of the device, together with the eigenfrequencies, in the unbiased state. The lowest three normal modes are symmetric and anti-symmetric bending modes and a torsional mode. These results are similar to those in Normal Modes of a Biased Resonator — 3D.

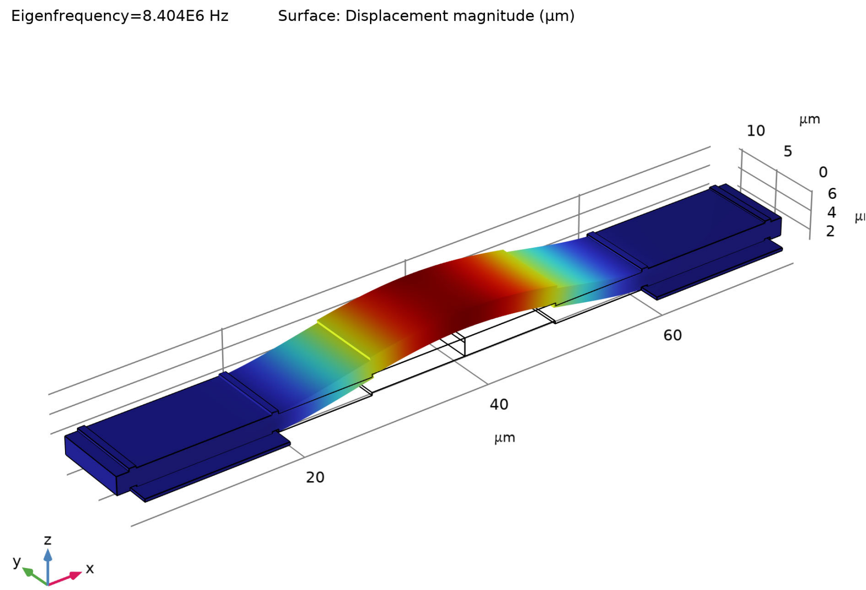


Figure 10: Symmetric bending mode, f_0 = 8.4 MHz.

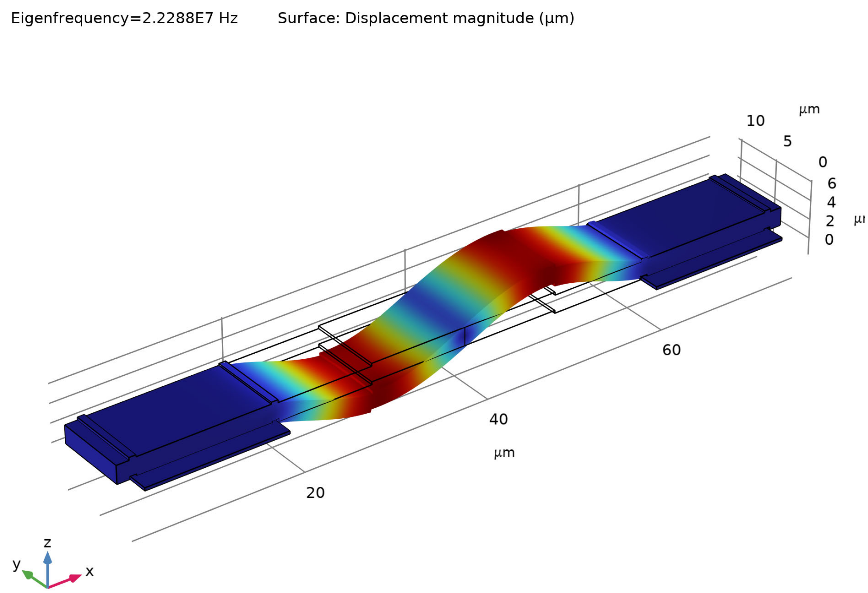


Figure 11: Anti-symmetric bending mode, f_0 = 22.3 MHz.

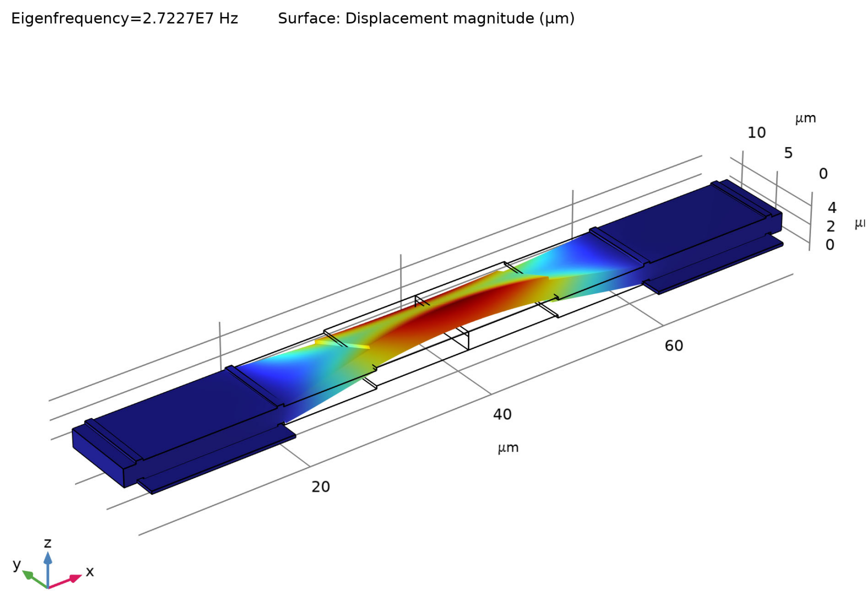


Figure 12: Torsional mode, f_0 = 27.2 MHz.

Application Library path: `MEMS_Module/Actuators/biased_resonator_3d_ecad_design`

Modeling Instructions

Create a 3D model with a Solid Mechanics interface.

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, click **3D**.

2 In the **Select Physics** tree, select **Structural Mechanics>Solid Mechanics (solid)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **General Studies>Eigenfrequency**.

6 Click **Done**.

GLOBAL DEFINITIONS

Enter the parameters used for creating the geometry.

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

2 In the **Settings** window for **Parameters**, locate the **Parameters** section.

3 In the table, enter the following settings:

Name	Expression	Value	Description
t_sub	0.75[um]	7.5E-7 m	Thickness of substrate
t_nitride	0.15[um]	1.5E-7 m	Thickness of nitride layer
t_base	0.3[um]	3E-7 m	Thickness of polysilicon base layer
t_sl	0.2[um]	2E-7 m	Thickness of sacrificial layer
t_poly	1.9[um]	1.9E-6 m	Thickness of polysilicon layer
w_box	38.9[um]	3.89E-5 m	Width of box

GEOMETRY 1

While it is possible to import all layers at the same time, it is easier to view the resulting 3D geometry if you import and build the layers one at a time.

1 In the **Model Builder** window, expand the **Component 1 (comp1)>Geometry 1** node, then click **Geometry 1**.

2 In the **Settings** window for **Geometry**, locate the **Units** section.

3 From the **Length unit** list, choose **µm**.

In addition to the ECAD Import Module functionality, the Offset Faces operation, which is part of the Design Module, is used to create the geometry. Make sure that the CAD kernel is used.

4 Locate the **Advanced** section. From the **Geometry representation** list, choose **CAD kernel**.

Import 1 = L1, Substrate

Start with importing the substrate.

1 In the **Home** toolbar, click **Import**.

2 In the **Settings** window for **Import**, type `Import 1 = L1, Substrate` in the **Label** text field.

3 Locate the **Import** section. Click **Browse**.

4 Browse to the model's Application Libraries folder and double-click the file `biased_resonator_3d_ecad_design_layout.gds`.

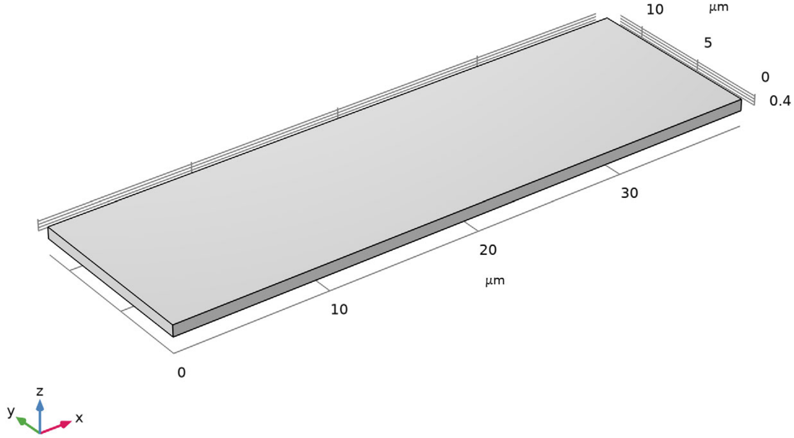
5 Find the **Layers to import** subsection. Select the **Manual control of elevations** check box.

6 In the table, enter the following settings:

Name	Type	Thickness (µm)	Elevation (µm)	Import
LAYER1	Metal	t_sub	0	√
LAYER2	Metal	0	0	
LAYER3	Metal	0	0	
LAYER4	Metal	0	0	
LAYER5	Metal	0	0	

7 Locate the **Selections of Resulting Entities** section. Clear the **Layer selections** check box.

8 Click **Build Selected**.



Import 2 = L2, Deposit Nitride Layer

Continue with creating the nitride layer. The easiest is to duplicate the previous import, then edit the settings for importing Layer 2 from the file.

1 Right-click **Import 1 = L1, Substrate** and choose **Duplicate**.

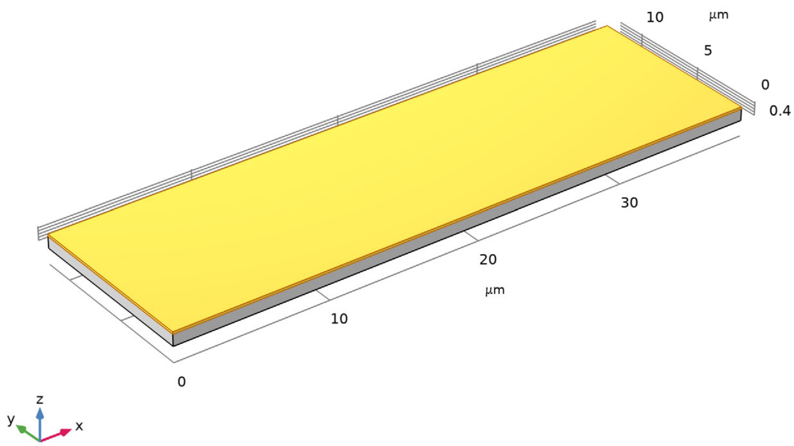
2 In the **Settings** window for **Import**, type `Import 2 = L2, Deposit Nitride Layer` in the **Label** text field.

3 Locate the **Import** section. Find the **Layers to import** subsection. In the table, enter the following settings:

Name	Type	Thickness (µm)	Elevation (µm)	Import
LAYER1	Metal	t_sub	0	
LAYER2	Metal	t_nitride	t_sub	√

4 Click **Build Selected**.

5 Click **Highlight Result**, for a better visualization of the result from the import.



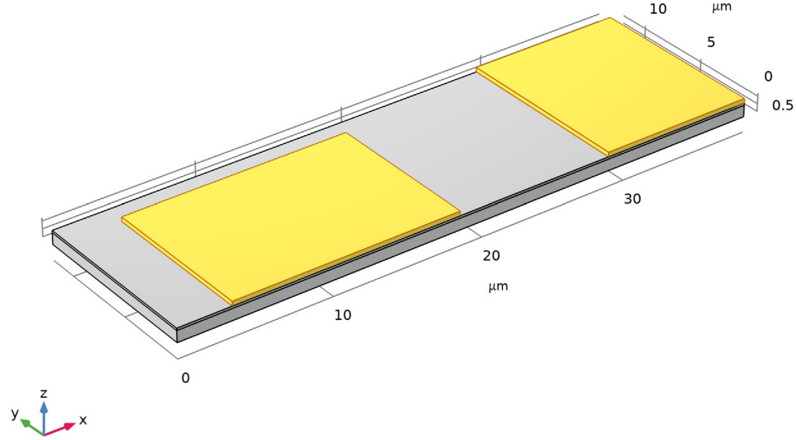
Import 3 = L3, Deposit and Pattern Polysilicon Base Layer

Next, create the polysilicon base layer. The mask for this is Layer 3 in the GDS file. This is a patterned layer, but as it is deposited over a flat surface, you can import and extrude it in one step, just as the previous two layers.

1 Right-click **Import 2 = L2, Deposit Nitride Layer** and choose **Duplicate**.
2 In the **Settings** window for **Import**, type `Import 3 = L3, Deposit and Pattern Polysilicon Base Layer` in the **Label** text field.
3 Locate the **Import** section. Find the **Layers to import** subsection. In the table, enter the following settings:

Name	Type	Thickness (µm)	Elevation (µm)	Import
LAYER2	Metal	t_nitride	t_sub	
LAYER3	Metal	t_base	t_sub+t_nitride	√

4 Click **Build Selected**.



Offset Faces 1 = Deposit Sacrificial Layer

Continue with creating the sacrificial layer, which is deposited over the polysilicon base, as well as the exposed nitride layer. Before importing the mask for the sacrificial layer, emulate its deposition by using the Offset Faces operation to offset in the normal direction the top faces of the nitride and polysilicon layers, and the exposed vertical faces of the polysilicon islands.

1 In the **Geometry** toolbar, click **Editing** and choose **Offset Faces**.

2 On the object **imp3**, select Boundaries 1, 4–7, and 10 only.

3 On the object **imp2**, select Boundary 4 only.

4 In the **Settings** window for **Offset Faces**, locate the **Faces** section.

5 Select the **Keep input objects** check box.

6 Locate the **Offset** section. In the **Distance** text field, type `t_sl`.

7 In the **Label** text field, type `Offset Faces 1 = Deposit Sacrificial Layer`.

8 Click **Build Selected**.

Offsetting the faces created larger copies of the nitride and polysilicon objects, while also keeping the original objects for these layers, since the **Keep input objects** check box is selected. To obtain only the sacrificial layer as one object, use a Difference operation to remove the objects for the nitride and polysilicon layers from the objects resulting from the offset.

Difference 1 = Deposit Sacrificial Layer

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Difference**.

2 In the **Settings** window for **Difference**, type `Difference 1 = Deposit Sacrificial Layer` in the **Label** text field.

3 Select the objects **off1(1)** and **off1(2)** only.

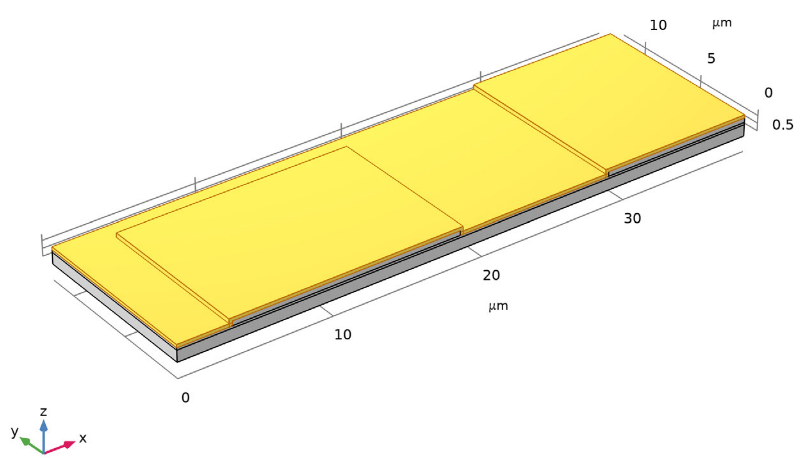
4 Locate the **Difference** section. Find the **Objects to subtract** subsection. Click to select the **Activate Selection** toggle button.

5 Select the objects **imp2** and **imp3** only.

6 Select the **Keep objects to subtract** check box.

7 Clear the **Keep interior boundaries** check box.

8 Click **Build Selected**.



Next, import the mask for the sacrificial layer, which is Layer 4 in the GDS file.

Import 4 = L4, Pattern Sacrificial Layer

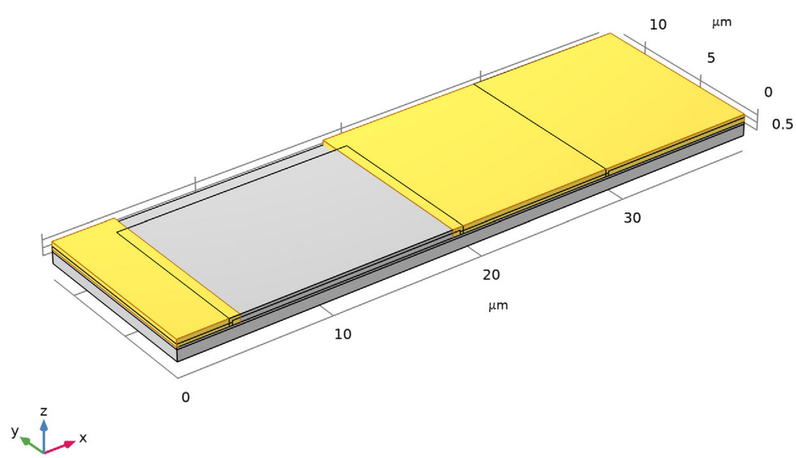
1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** right-click **Import 3 = L3, Deposit and Pattern Polysilicon Base Layer (imp3)** and choose **Duplicate**.

2 In the **Settings** window for **Import**, type `Import 4 = L4, Pattern Sacrificial Layer` in the **Label** text field.

3 Locate the **Import** section. Find the **Layers to import** subsection. In the table, enter the following settings:

Name	Type	Thickness (µm)	Elevation (µm)	Import
LAYER3	Metal	t_base	t_sub+t_nitride	
LAYER4	Metal	t_base+t_sl	t_sub+t_nitride	√

4 Click **Build Selected**.



Intersection 1 = L4, Pattern Sacrificial Layer

To create the patterned sacrificial layer, intersect the extruded mask layer, resulting from **Import 4**, with the sacrificial layer that resulted from the **Difference 1** operation. This step emulates the sacrificial layer etch followed by a photoresist strip.

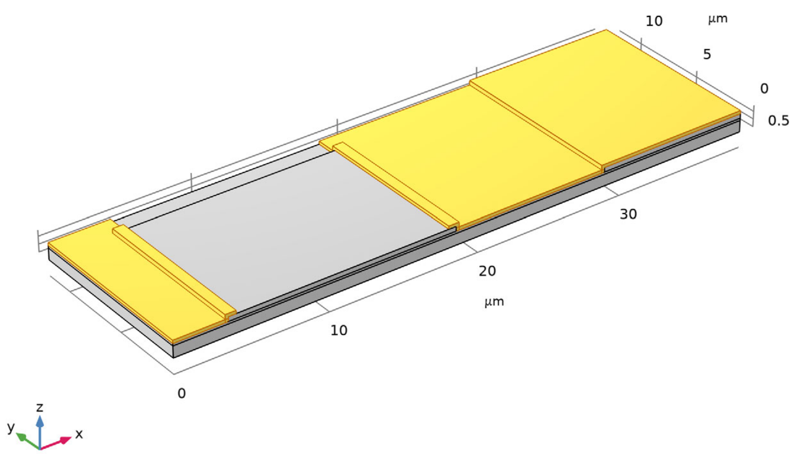
1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Intersection**.

2 In the **Settings** window for **Intersection**, type `Intersection 1 = L4, Pattern Sacrificial Layer` in the **Label** text field.

3 Select the objects **dif1** and **imp4** only.

4 Locate the **Intersection** section. Clear the **Keep interior boundaries** check box.

5 Click **Build Selected**.



The layer for the polysilicon beam is patterned and deposited over the sacrificial layer, and the exposed faces of the polysilicon base and nitride layers. To create this layer apply the same steps as when creating the sacrificial layer. Continue with offsetting the top faces of the sacrificial, polysilicon base and nitride layers.

Offset Faces 2 = Deposit Polysilicon Layer

1 In the **Geometry** toolbar, click **Editing** and choose **Offset Faces**.

2 In the **Settings** window for **Offset Faces**, type `Offset Faces 2 = Deposit Polysilicon Layer` in the **Label** text field.

3 On the object **imp2**, select Boundary 4 only.

4 On the object **imp3**, select Boundary 4 only.

5 On the object **int1**, select Boundaries 4, 9, 18, 22, and 31 only.

6 Locate the **Offset** section. In the **Distance** text field, type `t_poly`.

7 Locate the **Faces** section. Select the **Keep input objects** check box.

8 Click **Build Selected**.

Difference 2 = Deposit Polysilicon Layer

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Difference**.

2 In the **Settings** window for **Difference**, type `Difference 2 = Deposit Polysilicon Layer` in the **Label** text field.

3 Select the objects **off2(1)**, **off2(2)**, and **off2(3)** only.

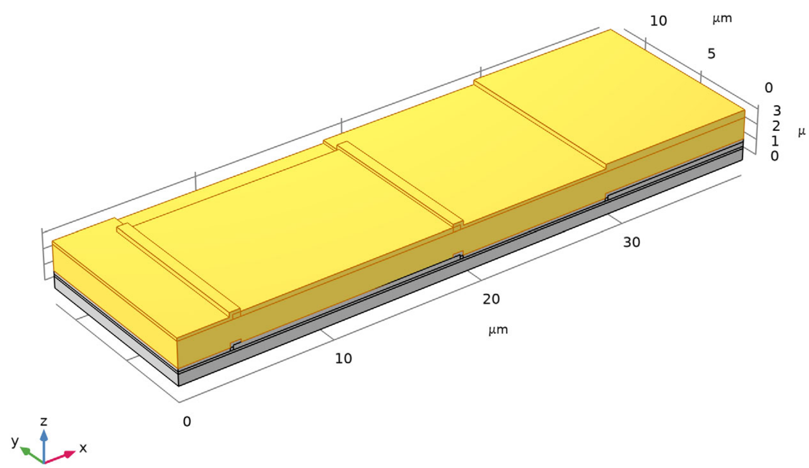
4 Locate the **Difference** section. Find the **Objects to subtract** subsection. Click to select the **Activate Selection** toggle button.

5 Select the objects **int1**, **imp2**, and **imp3** only.

6 Select the **Keep objects to subtract** check box.

7 Clear the **Keep interior boundaries** check box.

8 Click **Build Selected**.



Import 5 = L5, Pattern Polysilicon Layer

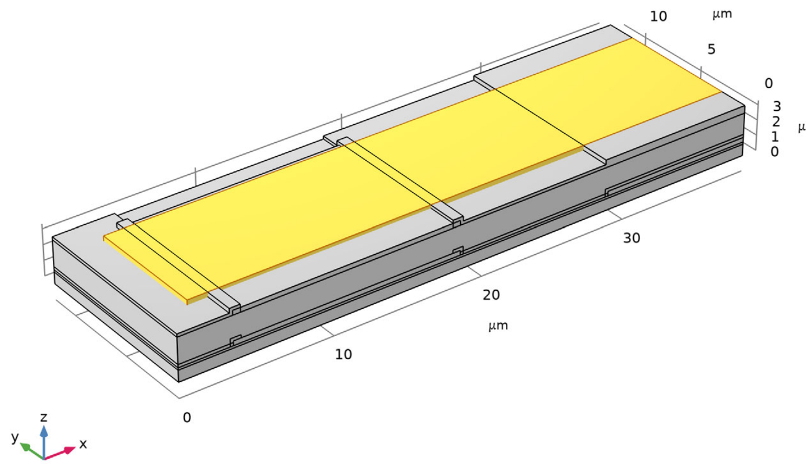
1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** right-click **Import 4 = L4, Pattern Sacrificial Layer (imp4)** and choose **Duplicate**.

2 In the **Settings** window for **Import**, type `Import 5 = L5, Pattern Polysilicon Layer` in the **Label** text field.

3 Locate the **Import** section. Find the **Layers to import** subsection. In the table, enter the following settings:

Name	Type	Thickness (µm)	Elevation (µm)	Import
LAYER4	Metal	`t_base+t_sl`	`t_sub+t_nitride`	
LAYER5	Metal	`t_base+t_sl+t_poly`	`t_sub+t_nitride`	√

4 Click **Build Selected**.



Intersection 2 = Pattern Polysilicon Layer

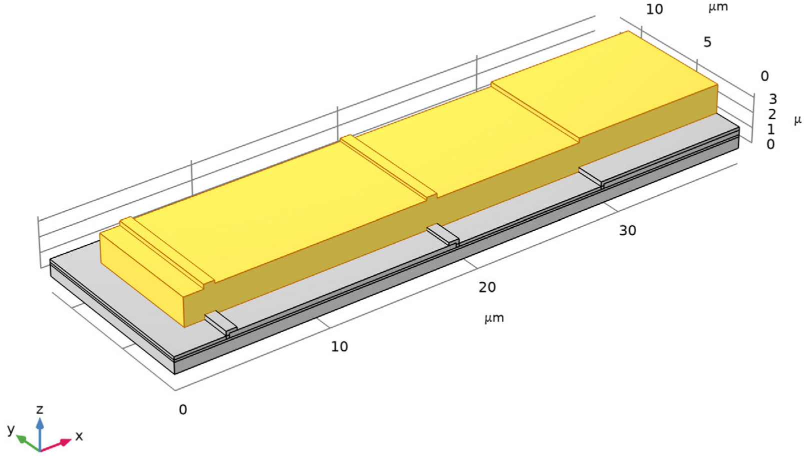
1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Intersection**.

2 In the **Settings** window for **Intersection**, type `Intersection 2 = Pattern Polysilicon Layer` in the **Label** text field.

3 Select the objects **dif2** and **imp5** only.

4 Locate the **Intersection** section. Clear the **Keep interior boundaries** check box.

5 Click **Build Selected**.



To obtain the final geometry, delete the object for the sacrificial layer. This step emulates an isotropic oxide etch to release the polysilicon beam.

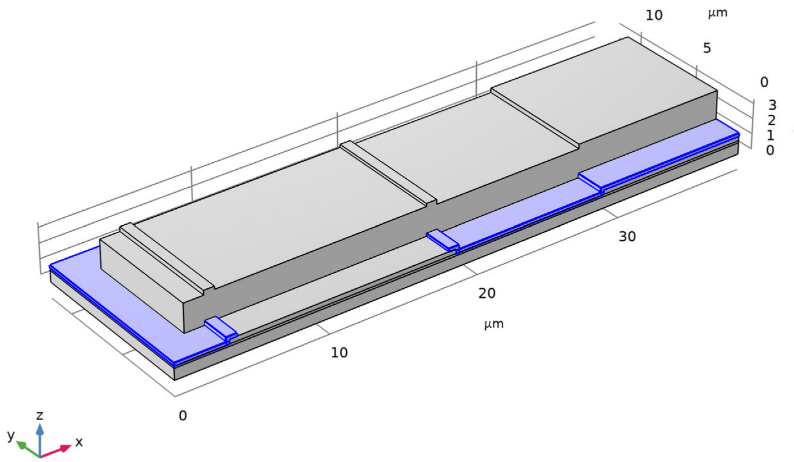
Delete Entities 1 (del1)

1 In the **Model Builder** window, right-click **Geometry 1** and choose **Delete Entities**.

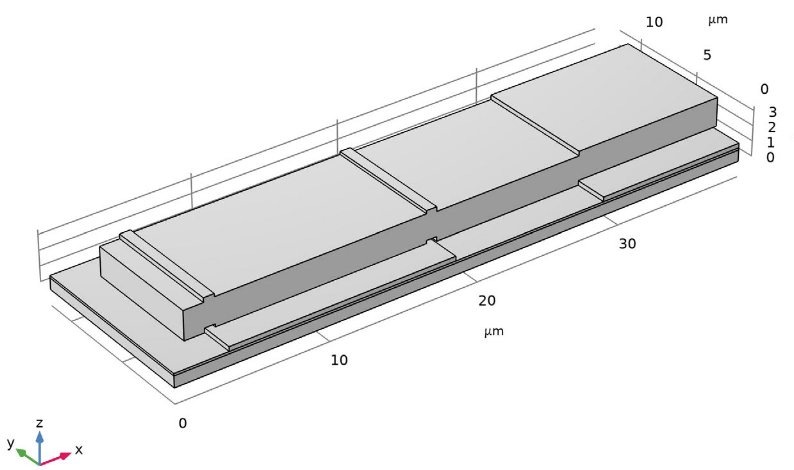
2 In the **Settings** window for **Delete Entities**, locate the **Entities or Objects to Delete** section.

3 From the **Geometric entity level** list, choose **Object**.

4 Select the object **int1** only.



5 Click **Build Selected**.



Define named selections for the layers.

Explicit Selection 1 = Polysilicon Beam

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 On the object **imp3**, select Domain 1 only.

3 On the object **int2**, select Domain 1 only.

4 In the **Settings** window for **Explicit Selection**, type `Explicit Selection 1 = Polysilicon Beam` in the **Label** text field.

5 Click **Build Selected**.

Explicit Selection 2 = Bottom Electrode

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 On the object **imp3**, select Domain 2 only.

3 In the **Settings** window for **Explicit Selection**, type `Explicit Selection 2 = Bottom Electrode` in the **Label** text field.

4 Click **Build Selected**.

Explicit Selection 3 = Nitride

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Explicit Selection 3 = Nitride` in the **Label** text field.

3 On the object **imp2**, select Domain 1 only.

4 Click **Build Selected**.

Explicit Selection 4 = Substrate

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Explicit Selection 4 = Substrate` in the **Label** text field.

3 On the object **imp1**, select Domain 1 only.

4 Click **Build Selected**.

Finally, mirror the geometry so that asymmetric eigenmodes can be calculated.

Mirror 1 (mir1)

1 In the **Geometry** toolbar, click **Transforms** and choose **Mirror**.

2 Click in the **Graphics** window and then press Ctrl+A to select all objects.

3 In the **Settings** window for **Mirror**, locate the **Point on Plane of Reflection** section.

4 In the **x** text field, type `w_box`.

5 Locate the **Normal Vector to Plane of Reflection** section. In the **x** text field, type `1`.

6 In the **z** text field, type `0`.

7 Locate the **Input** section. Select the **Keep input objects** check box.

8 Click **Build Selected**.

ADD MATERIAL

1 In the **Home** toolbar, click **Add Material** to open the **Add Material** window.

2 Go to the **Add Material** window.

3 In the tree, select **MEMS>Semiconductors>Si - Polycrystalline silicon**.

4 Click **Add to Component** in the window toolbar.

5 In the tree, select **MEMS>Insulators>Si3N4 - Silicon nitride**.

6 Click **Add to Component** in the window toolbar.

7 In the tree, select **MEMS>Insulators>SiO2 - Silicon oxide**.

8 Click **Add to Component** in the window toolbar.

9 In the **Home** toolbar, click **Add Material** to close the **Add Material** window.

MATERIALS

Si3N4 - Silicon nitride (mat2)

1 In the **Model Builder** window, under **Component 1 (comp1)>Materials** click **Si3N4 - Silicon nitride (mat2)**.

2 In the **Settings** window for **Material**, locate the **Geometric Entity Selection** section.

3 From the **Selection** list, choose **Explicit Selection 3 = Nitride**.

SiO2 - Silicon oxide (mat3)

1 In the **Model Builder** window, click **SiO2 - Silicon oxide (mat3)**.

2 In the **Settings** window for **Material**, locate the **Geometric Entity Selection** section.

3 From the **Selection** list, choose **Explicit Selection 4 = Substrate**.

SOLID MECHANICS (SOLID)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Solid Mechanics (solid)**.

2 Select Domains 3, 4, 7, 9, and 10 only.

3 In the **Settings** window for **Solid Mechanics**, locate the **Domain Selection** section.

4 From the **Selection** list, choose **Explicit Selection 1 = Polysilicon Beam**.

Fixed Constraint 1

1 In the **Physics** toolbar, click **Domains** and choose **Fixed Constraint**.

2 Select Domains 4 and 10 only.

MESH 1

In the **Model Builder** window, under **Component 1 (comp1)** right-click **Mesh 1** and choose **Build All**.

STUDY 1

Step 1: Eigenfrequency

1 In the **Model Builder** window, under **Study 1** click **Step 1: Eigenfrequency**.

2 In the **Settings** window for **Eigenfrequency**, locate the **Study Settings** section.

3 Select the **Desired number of eigenfrequencies** check box. In the associated text field, type 3.

4 In the **Home** toolbar, click **Compute**.

RESULTS

Mode Shape (solid)

In the **Model Builder** window, expand the **Results>Mode Shape (solid)** node.

Surface 1

1 In the **Model Builder** window, expand the **Results>Mode Shape (solid)>Surface 1** node, then click **Surface 1**.

2 In the **Settings** window for **Surface**, locate the **Coloring and Style** section.

3 Click **Change Color Table**.

4 In the **Color Table** dialog box, select **Rainbow>Rainbow** in the tree.

5 Click **OK**.

6 Click the **Zoom Extents** button in the **Graphics** toolbar.

7 In the **Settings** window for **Surface**, click **Plot Next**.

8 Click **Plot Next**.