Created in COMSOL Multiphysics 6.2

Disc Resonator Anchor Losses

Introduction

Electromechanical resonators and filters are widely used in signal processing and communications applications. Over the past decade significant progress has been made in miniaturizing these systems using microfabrication technologies. In many of these applications it is important to produce resonators with high quality factors. Several mechanisms limit the obtainable quality factors of MEMS resonators including thermoelastic damping (for flexural modes), material losses (the fundamental limiting factor on the obtainable quality factor), and anchor losses. Anchor losses occur when the vibration of the structure and its supporting anchors excites acoustic waves propagating in the substrate. These waves are radiated away from the resonator resulting in a loss of mechanical energy, or damping. In many cases anchor damping can represent the limiting loss mechanism that determines the resonator quality factor. Modifications in the anchor design can significantly effect the coupling of the resonant mode to the substrate, so numerical simulations of anchor damping can be a useful tool to employ as part of the resonator design process.

This model shows how to determine the anchor damping limited resonator quality factor of a diamond disc resonator, using a PML to absorb the waves propagating in the substrate. It is based on the work presented in Ref. 1 and Ref. 2.

Model Definition

Figure 1 shows a slice through the structure on a plane with an edge parallel to the line of axial symmetry. The critical components of the device are highlighted. The resonator is attached to the substrate by a polysilicon stem. The disc (polycrystalline diamond) and stem (polysilicon) are made from different materials so that there is an impedance mismatch between the materials. This mismatch is designed to suppress energy transfer to the substrate, enhancing the quality factor of the device Ref. 1. A hemispherical section of the substrate is modeled and the waves propagating away from the anchor are absorbed by a perfectly matched layer (PML), which is applied to a layer at the edge of the substrate. The outer surface of the PML is fixed.

Since the fundamental model has axial symmetry, the device is modeled using a 2D axisymmetric geometry.

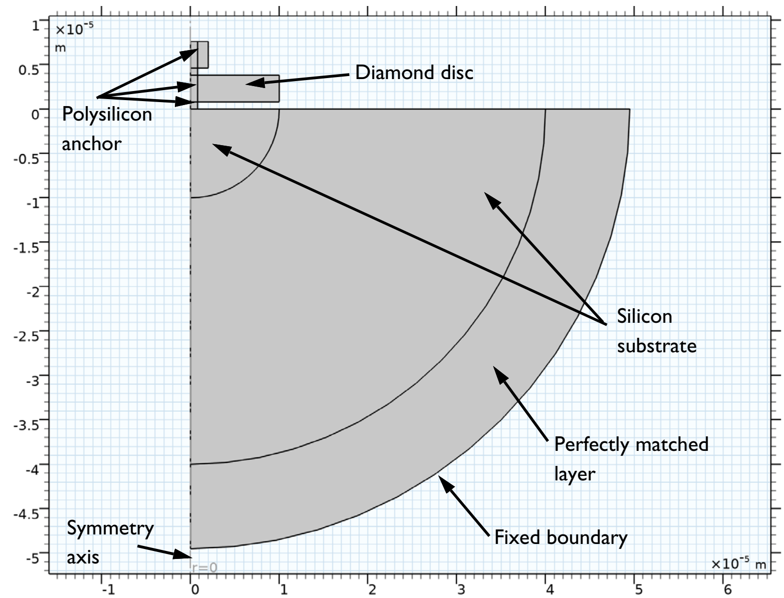

Figure 1: Axisymmetric model geometry, with key parts of the structure highlighted.

Results and Discussion

Figure 2 shows the resonator displacement in the fundamental mode of the resonator, which occurs at a frequency of 537 MHz. This compares reasonably well with the experimentally measured value of the resonant frequency, which was 546 MHz. Figure 3 shows a 3 dimensional rendering of the displacement, with a color scale chosen to emphasize the waves propagating in the substrate. The energy transmitted by these waves is responsible for the anchor losses. The effect of the PML is also apparent in this figure, and it seems that the waves are absorbed well by the PML in this model.

The quality factor of the resonator is related to the ratio of the real and imaginary parts of the eigenvalue of the mode. In this case the computed quality factor is 22,000, which is a similar magnitude to the quality factor measured in vacuum of approximately 17,500 (Ref. 1). This indicates that anchor damping is likely to be the dominant loss mechanism for devices designed in this manner.

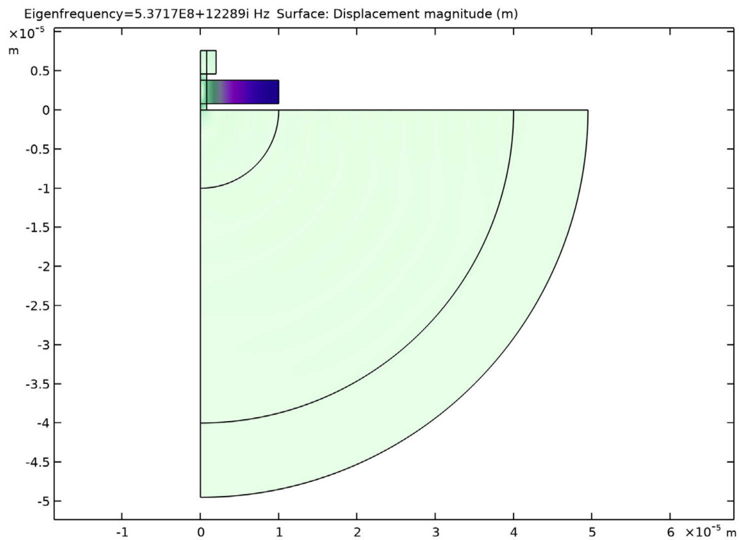

Figure 2: Section through the axisymmetric vibration mode of the disc showing the displacement of the structure. The disc undergoes uniform extension along the radial direction.

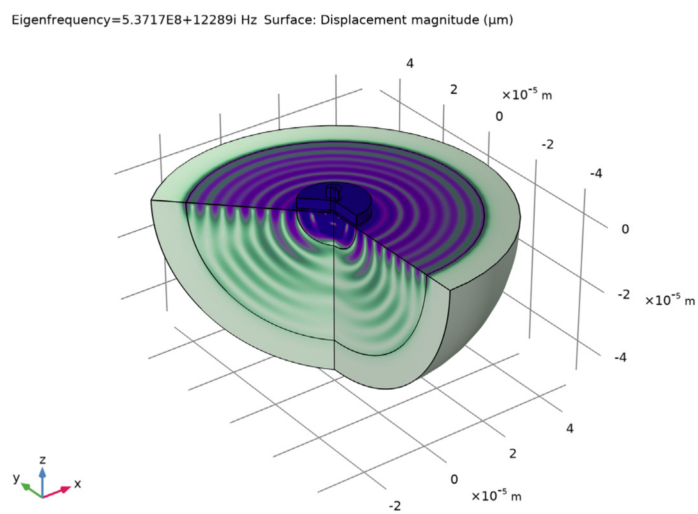

Figure 3: Total displacement of the structure as a whole with a color scale chosen to emphasize the waves propagating in the substrate.

References

1. J. Wang, J.E. Butler, T. Feygelson, and C. T.-C. Nguyen, "1.51-GHz nanochrystalline diamond micromechanical disk resonator with material-mismatched isolating support," *Proceedings of the 17th International IEEE Microelectromechanical Systems Conference*, pp. 641–644, Maastricht, 2004.

2. P. Steeneken "Parameter Extraction and Support-Loss in MEMS Resonators", *COMSOL Conference 2007*, Grenoble. (Available at: https://www.comsol.com/paper/download/43866/Steeneken_pres.pdf and https://arxiv.org/ftp/arxiv/papers/1304/1304.7953.pdf.)

Application Library path: `MEMS_Module/Actuators/disc_resonator_anchor_losses`

Modeling Instructions

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

NEW

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

MODEL WIZARD

1 In the **Model Wizard** window, click **2D Axisymmetric**.

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

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
R_d	10[um]	1E-5 m	Disc radius
H_d	3[um]	3E-6 m	Disc height
H_p	0.8[um]	8E-7 m	Post height
R_p	0.8[um]	8E-7 m	Post radius
R_s	40[um]	4E-5 m	Substrate section radius
t_PML	wl	9.5E-6 m	PML thickness
wl	9.5[um]	9.5E-6 m	Wavelength of acoustic waves

GEOMETRY 1

Rectangle 1 (r1)

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

2 Right-click **Geometry 1** and choose **Rectangle**.

3 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

4 In the **Width** text field, type `R_d`.

5 In the **Height** text field, type `H_d`.

6 Locate the **Position** section. In the **z** text field, type `H_p`.

Rectangle 2 (r2)

1 In the **Geometry** toolbar, click **Rectangle**.

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Width** text field, type `R_p`.

4 In the **Height** text field, type `2*H_d+2*H_p`.

Rectangle 3 (r3)

1 In the **Geometry** toolbar, click **Rectangle**.

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Width** text field, type `2.5*R_p`.

4 In the **Height** text field, type `H_d`.

5 Locate the **Position** section. In the **z** text field, type `H_d+2*H_p`.

Circle 1 (c1)

1 In the **Geometry** toolbar, click **Circle**.

2 In the **Settings** window for **Circle**, locate the **Size and Shape** section.

3 In the **Radius** text field, type `R_s+t_PML`.

4 In the **Sector angle** text field, type `90`.

5 Locate the **Rotation Angle** section. In the **Rotation** text field, type `270`.

6 Click to expand the **Layers** section. In the table, enter the following settings:

Layer name	Thickness (m)
`Layer 1`	`t_PML`
`Layer 2`	`R_s+-R_d`

7 Click **Build Selected**.

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

DEFINITIONS

Perfectly Matched Layer 1 (pml1)

1 In the **Definitions** toolbar, click **Perfectly Matched Layer**.

2 Select Domain 1 only.

MATERIALS

Silicon Substrate

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Blank Material**.

2 In the **Settings** window for **Material**, type `Silicon Substrate` in the **Label** text field.

3 Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Young's modulus	E	`130[GPa]`	Pa	Young's modulus and Poisson's ratio
Poisson's ratio	nu	`0.28`	1	Young's modulus and Poisson's ratio
Density	rho	`2230[kg/m^3]`	kg/m³	Basic

Polysilicon

1 Right-click **Materials** and choose **Blank Material**.

2 In the **Settings** window for **Material**, type `Polysilicon` in the **Label** text field.

3 Select Domains 4–7 and 9 only.

4 Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Young's modulus	E	`150[GPa]`	Pa	Young's modulus and Poisson's ratio
Poisson's ratio	nu	`0.22`	1	Young's modulus and Poisson's ratio
Density	rho	`2330[kg/m^3]`	kg/m³	Basic

Diamond

1 Right-click **Materials** and choose **Blank Material**.

2 In the **Settings** window for **Material**, type `Diamond` in the **Label** text field.

3 Select Domain 8 only.

4 Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Young's modulus	E	`1061[GPa]`	Pa	Young's modulus and Poisson's ratio
Poisson's ratio	nu	`0.12`	1	Young's modulus and Poisson's ratio
Density	rho	`3440[kg/m^3]`	kg/m³	Basic

SOLID MECHANICS (SOLID)

Fixed Constraint 1

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Solid Mechanics (solid)** and choose **Fixed Constraint**.

2 Select Boundary 26 only.

MESH 1

Mapped 1

1 In the **Mesh** toolbar, click **Mapped**.

2 In the **Settings** window for **Mapped**, locate the **Domain Selection** section.

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

4 Select Domains 1 and 4–9 only.

Distribution 1

1 Right-click **Mapped 1** and choose **Distribution**.

2 Select Boundary 25 only.

3 In the **Settings** window for **Distribution**, locate the **Distribution** section.

4 In the **Number of elements** text field, type `8`.

Distribution 2

1 In the **Model Builder** window, right-click **Mapped 1** and choose **Distribution**.

2 Select Boundaries 5, 12, and 13 only.

3 In the **Settings** window for **Distribution**, locate the **Distribution** section.

4 In the **Number of elements** text field, type `4`.

Free Triangular 1

In the **Mesh** toolbar, click **Free Triangular**.

Size

1 In the **Model Builder** window, click **Size**.

2 In the **Settings** window for **Size**, locate the **Element Size** section.

3 From the **Predefined** list, choose **Extremely fine**.

4 Click **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 `1`.

4 In the **Search for eigenfrequencies around shift** text field, type `5e8`.

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

RESULTS

Mode Shape (solid)

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

Deformation

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

2 In the **Settings** window for **Deformation**, locate the **Scale** section.

3 Select the **Scale factor** check box. In the associated text field, type `1E-7`.

4 In the **Mode Shape (solid)** toolbar, click **Plot**.

Compare the resulting plot with that in Figure 2.

Mode Shape, 3D (solid)

In the **Model Builder** window, expand the **Results>Mode Shape, 3D (solid)** node.

Deformation

1 In the **Model Builder** window, expand the **Results>Mode Shape, 3D (solid)>Surface 1** node.

2 Right-click **Deformation** and choose **Disable**.

Surface 1

1 In the **Model Builder** window, click **Surface 1**.

2 In the **Settings** window for **Surface**, locate the **Expression** section.

3 From the **Unit** list, choose **µm**.

4 Click to expand the **Range** section. Select the **Manual color range** check box.

5 In the **Maximum** text field, type `6e-7`.

6 In the **Mode Shape, 3D (solid)** toolbar, click **Plot**.

Compare the resulting plot with that in Figure 3.

Global Evaluation 1

1 In the **Results** toolbar, click **Global Evaluation**.

2 In the **Settings** window for **Global Evaluation**, locate the **Expressions** section.

3 In the table, enter the following settings:

Expression	Unit	Description
`imag(-lambda)/(2*abs(real(lambda)))`		

4 Click **Evaluate**.