Modeling of a silicon piezoresistive pressure sensor

This example illustrates the use of a piezoresistive material model to simulate a silicon piezoresistive pressure sensor.

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Products: Abaqus/Standard

Application description

The model shown in Figure 1 represents a simplified piezoresistive membrane-chip pressure sensor. It consists of a silicon piezoresistive membrane chip bonded with glass and then glued to a base. Four p-doped piezoresistors (labeled R1, R2, R3, and R4 in Figure 2) are placed on top of the membrane and arranged to form a Wheatstone bridge circuit as shown in Figure 2.

A constant current is applied to the circuit. Without any applied pressure, the resistances of the four resistors are the same, and the output voltage between nodes 1 and 2 is zero. When a uniform pressure is applied on the top surface, the resistances of the four resistors change with the applied pressure. The stress state in resistors R1 and R4 is different from the stress state in resistors R2 and R3. Therefore, the resistances of R1/R4 and R2/R3 change differently with the applied pressure. The output voltage between nodes 1 and 2 can be measured for different values of the applied pressure.

Geometry

The four piezoresistors are placed 0.396 mm from the center of the membrane, as shown in Figure 3. They are aligned with the [1 1 0] direction, which represents the direction cosines of the longitudinal resistor direction and the crystal axis. The size of the piezoresistors $l_0 \times w_0$ is 90 μm × 25 μm, and the thickness h_0 is 0.3086 μm, as shown in Figure 3 and Figure 4. The height of the base is 2 mm, and the diameter is 4 mm. Table 1 provides a summary of the other model dimensions.

Abaqus modeling approaches and simulation techniques

The four piezoresistors are meshed using coupled thermal-electrical-structural elements Q3D8R, while all the other region of the model are meshed using C3D8R elements. To model the Wheatstone bridge circuit, each pair of adjacent resistors is connected to a reference node virtually by uniformly coupling the electrical potential of the nodes on the end surfaces of the resistors to that of the reference node. A total of four reference nodes are introduced, corresponding to nodes 1, 2, 3, and 4 in Figure 2

Analysis types

A fully coupled thermal-electrical-structural analysis is performed.

Mesh design

The silicon is partitioned into two parts: the silicon membrane top and the silicon support. These two parts are meshed separately. The glass and the base are also meshed separately. All the parts are connected by tie constraints.

Materials

The orthotropic elasticity properties (see Table 2) for the silicon material were obtained from Hopcroft, Nix, and Kenny (2010). Table 3 lists the piezoresistive coefficients for the p-doped silicon (Kumar and Pant, 2014). The initial resistivity of the four piezoresistors is 0.3 Ωmm. The thermal properties of silicon are summarized in Table 4.

The Young’s modulus and Poisson’s ratio of the glass is assumed to be 6.28×10^7 KPa and 0.2, respectively. The Young’s modulus and Poisson’s ratio of the base material is assumed to 1.38×10^8 KPa and 0.317, respectively.

Boundary conditions

All the bottom nodes of the base are fixed. The temperature of all the resistors is set to be 25°C. The electrical potential of node 4 is constrained to be 0 mV.

Loads

A uniform pressure 1000 KPa is applied on the top of the silicon membrane. The electrical loading is a steady 1mA current over the duration of the step. This loading is applied as a distributed current density on the surfaces of R2 and R4 that are coupled to reference node 3.

Acknowledgements

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Results and discussion

Figure 5 shows the output voltage across nodes 1 and 2 versus the applied pressure. The figure shows an essentially linear relationship between the applied pressure and the output voltage. The maximum deflection at the center of membrane is very small compared to the membrane thickness. At such small deformations, the solution changes linearly with the applied pressure. Figure 6 and Figure 7 show the contours of the electrical potential field and the von Mises stress field, respectively, in the four resistors. The stresses in resistors R1 and R3 are different, and this difference leads to the differences in the electrical potential in these two resistors. Similar observations can be made regarding the fields in resistors R2 and R4.

Input files

Silicon_PR_Pressure_Sensor.inp

Input file for the example.

References

Kumar, S.S., and B. D. Pant, "Design Principles and Considerations for the 'Ideal' Silicon Piezoresistive Pressure Sensor: a Focused Review," Microsystem Technologies, vol. 20, no. 7, pp. 1213–1247, July 2014.

Hopcroft, M. A. , W. D. Nix, and T. W. Kenny, "What is the Young's Modulus of Silicon?," Journal of Microelectromechanical Systems, vol. 19, no. 2, pp. 229-238, April 2010.

Tables

Table 1. Geometry of the model.

Piezoresistor	l_0	90 μm
	w_0	25 μm
	h_0	0.3086 μm
Membrane	L1	0.912 mm
	W1	0.912 mm
	t	50.4 μm
Silicon	L	2 mm
	W	2 mm
	H1	0.36 mm
	θ	54.7°
Glass	L	2 mm
	W	2 mm

	H2	0.96 mm
Position	p	0.396 mm

Table 2. Orthotropic elasticity properties of silicon (modulus unit: 10^7 KPa).

E_1	E_2	E_3	ν_{12}	ν_{13}	ν_{23}	G_{12}	G_{13}	G_{23}
13.0	13.0	13.0	0.28	0.28	0.28	7.96	7.96	7.96

Table 3. Piezoresistive coefficients for p-doped silicon (unit: 10^{-12} Pa^{-1}).

Π_{1111}	Π_{1122}	Π_{2222}	Π_{1133}	Π_{2233}	Π_{3333}	Π_{1212}	Π_{1313}	Π_{2323}
66.0	-11.0	66.0	-11.0	-11.0	66.0	690.5	690.5	690.5

Table 4. Thermal properties of silicon.

Specific heat	Thermal conductivity	Thermal expansion	Density
7.94×10^8 μJ/Kg/°C	1.24×10^5 μW/mm/°C	2.46×10^{-6} $°C^{-1}$	2.33×10^{-6} Kg/mm^3

Figures

Figure 1. Half cut view of the model.

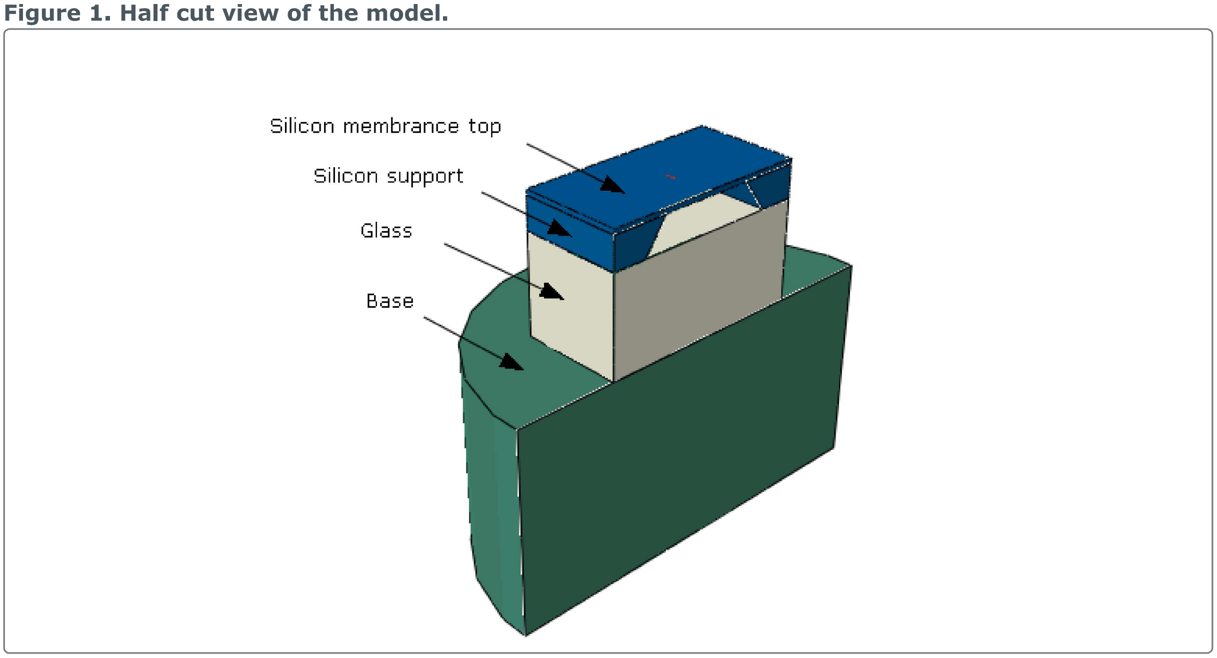


Figure 2. Wheatstone bridge circuit.

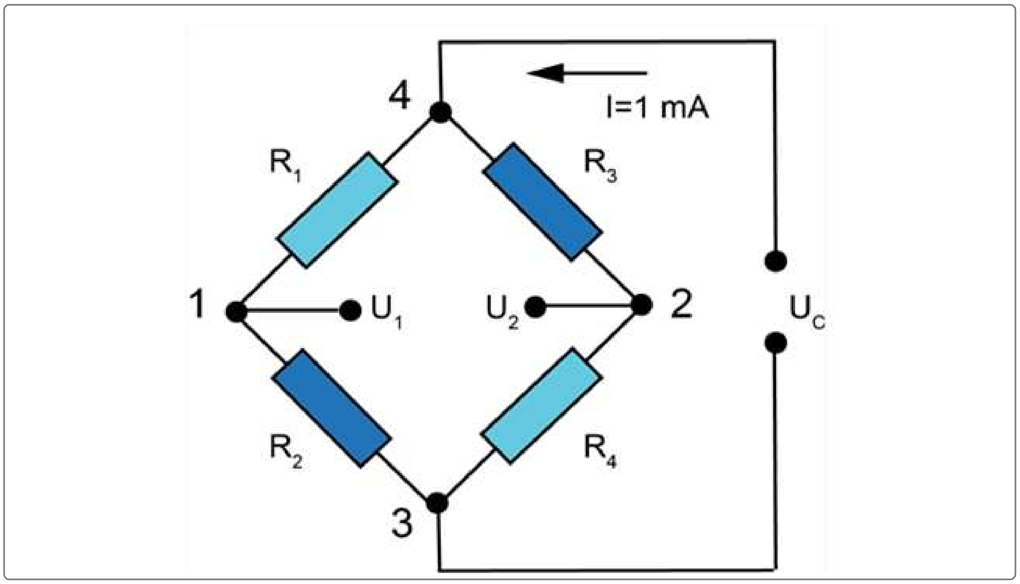


Figure 3. Top view of the model.

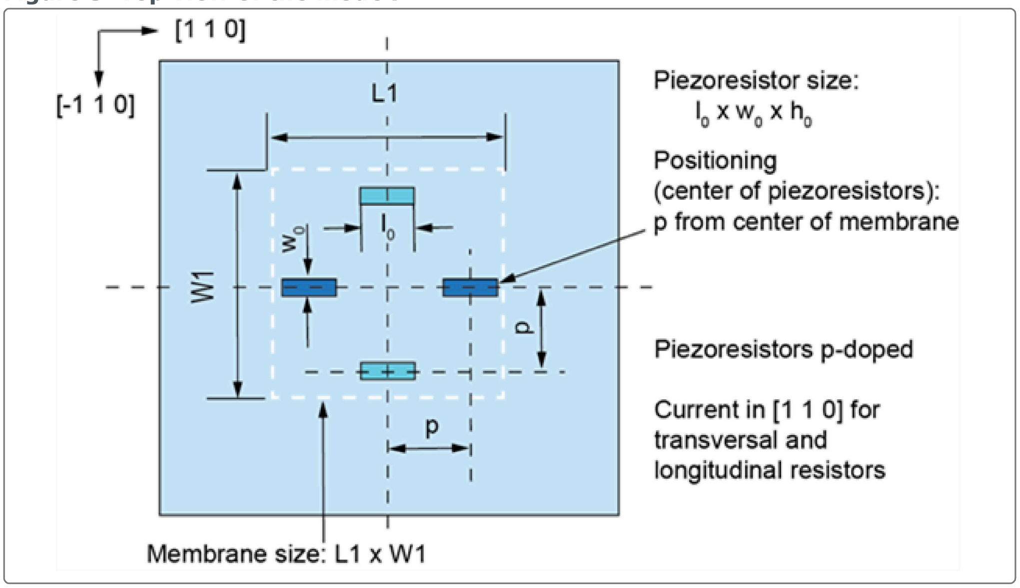


Figure 4. Cut view of the silicon and glass part.

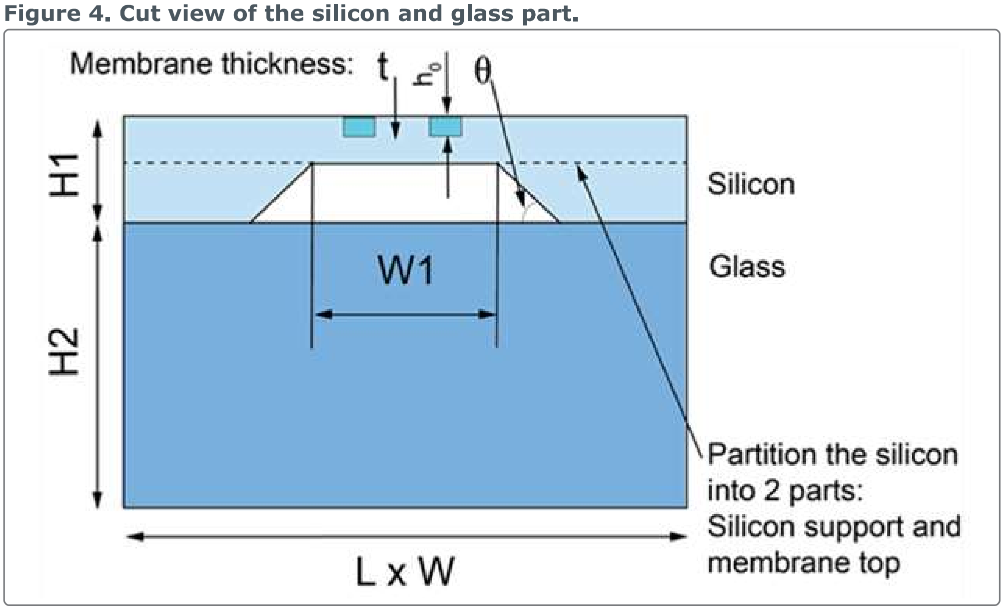


Figure 5. Output voltage vs the applied pressure.

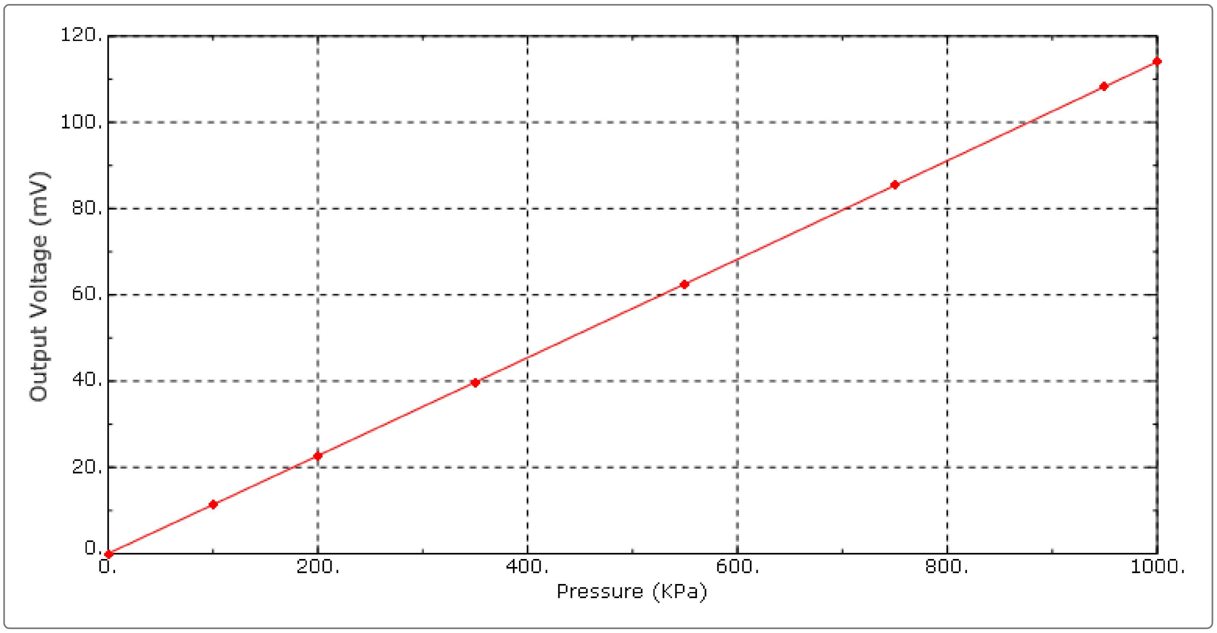


Figure 6. Electrical potential contour of the four piezoresistors.

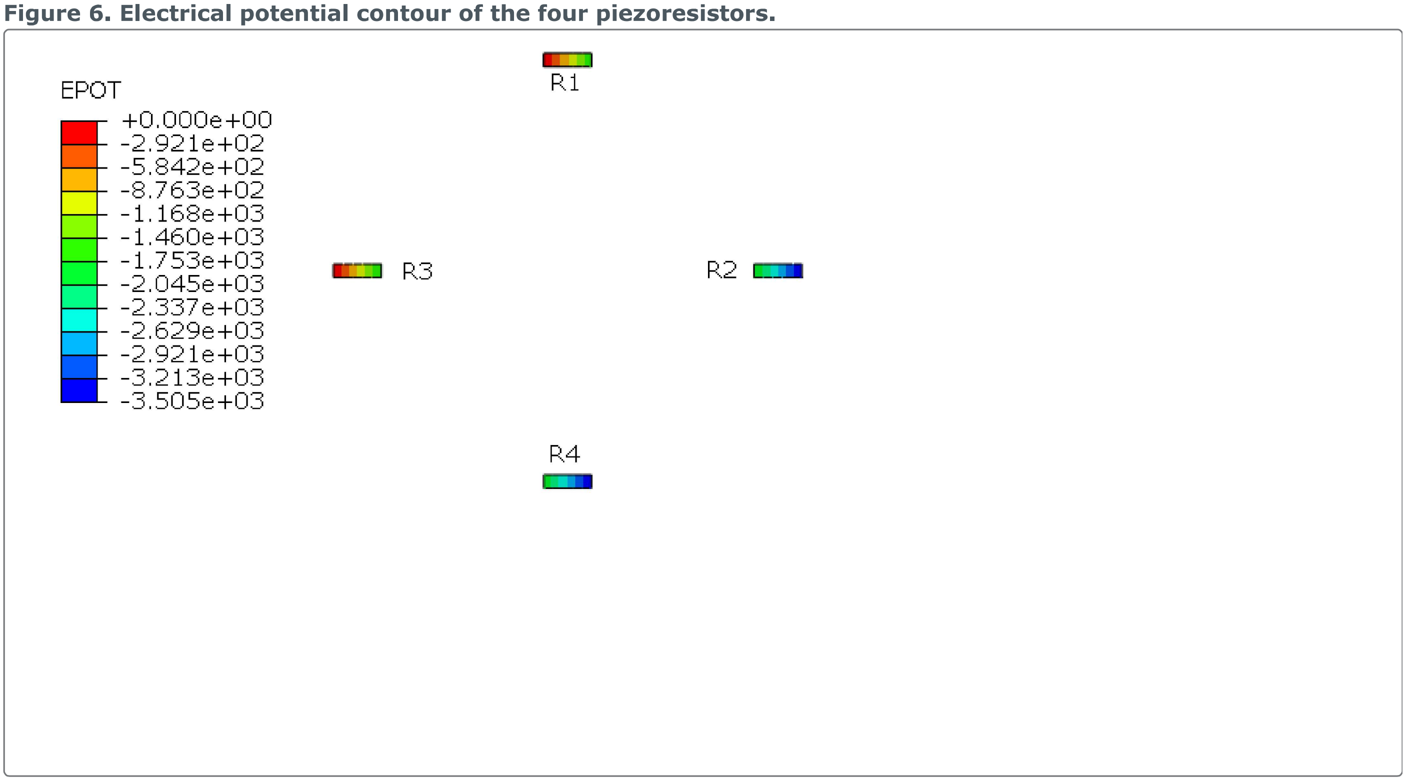
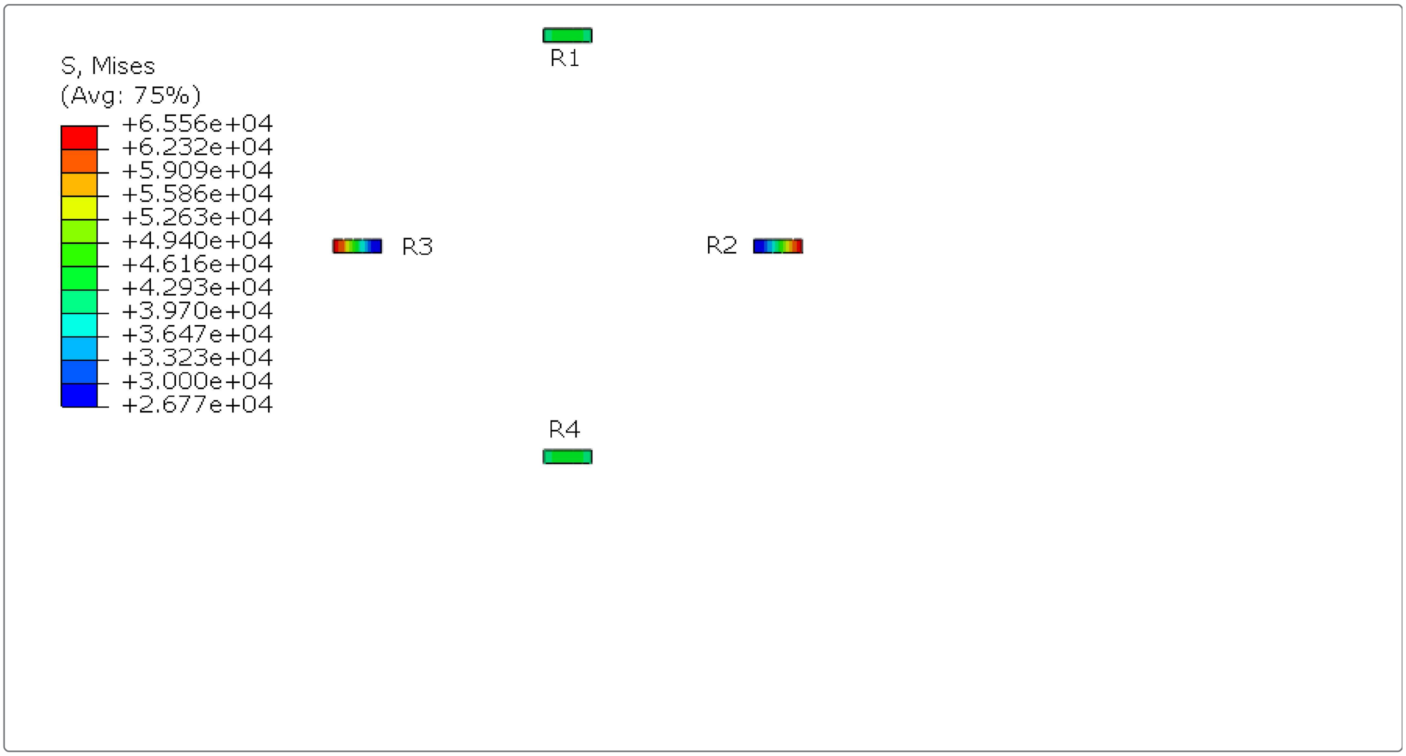


Figure 7. Von Mises stress contour of the four piezoresistors.


S, Mises
(Avg: 75%)
+6.556e+04
+6.232e+04
+5.909e+04
+5.586e+04
+5.263e+04
+4.940e+04
+4.616e+04
+4.293e+04
+3.970e+04
+3.647e+04
+3.323e+04
+3.000e+04
+2.677e+04
R1
R3
R2
R4