Analysis of Mechanical Sensitivity of MEMS Pressure Diaphragm for Contact Formation

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Abstract

This paper presents a novel design of MEMS Pressure diaphragm for enhanced mechanical sensitivity and contact formation analysis between the diaphragm and a suspended rigid structure under atmospheric load. The combination of different thicknesses of polyimide and metal materials in the diaphragm provides unique design that serves two purposes of increasing sensitivity by the polyimide and holding of the encapsulated pressure by the metal. The contact formation is established between the diaphragm and the suspended rigid structure and the differences between mechanical sensitivities are compared with individual sensitivities of diaphragm and the suspended rigid structure design. The proposed structure is modeled and studied using COMSOL Multiphysics® simulation software.

Keywords: MEMS Pressure Diaphragm, Mechanical Sensitivity, Contact Formation

1. Introduction

Micro-Electro-Mechanical Systems or MEMS are micrometer size miniature devices that combine electrical and mechanical components. They are widely used in diverse applications. To mention a few, MEMS devices are used as sensors and actuators in Automobile, Consumer Electronics, Aerospace and many more. Because of their compact size and extremely light weight, the art of miniaturization has reached a new level with increasing complexity in design. Also, they have potential of providing significant cost reduction due to batch fabrication. MEMS Pressure sensors work on principle of mechanical bending of thin diaphragm under applied load over a diaphragm area. The diaphragm design is most critical for designing any pressure sensor devices and therefore, its sensitivity is crucial to efficiency of the sensor. The sensitivity is defined as the increase in the deflection of diaphragm as a result of increase in pressure acting on the diaphragm. Single diaphragm under atmospheric pressure becomes stiff upon deflection. To avoid, stiffening effect, the unique design introduced here provides a diaphragm and a rigid structure for use with a MEMS transducer. Several techniques using corrugations have been used earlier to improve the mechanical sensitivities using Polycrystalline Silicon [1] and Silicon Nitride as the base diaphragm materials [2]. Although these researches achieved high mechanical sensitivities but the extra fabrication processes significantly increased the production cost. On the other hand, polymer materials are elastic and can withstand greater mechanical strain than silicon and are not as brittle. Usually Polyimide (Polymer) degrades when subjected to higher temperatures. This limits post processing steps to low temperatures [3]. It also provides higher sensitivity as it has very low Young`s modulus (2.5GPa) compared to Polycrystalline Silicon (160GPa) and Silicon Nitride (250GPa). The thin metal layer on top of polyimide holds the atmospheric pressure and doesn`t allow it to leak.

The mechanical sensitivity upon a contact formation between the diaphragm and suspended rigid structure is also analyzed when pressure loads are acting. The sensitivity changes significantly depending on the contact area.

2. Theory

Figure1 shows the MEMS transducer which includes diaphragm that consists of a thin first layer formed of metal and has thickness of few hundred nanometers. The second layer is polyimide and is thicker than the first layer. The rigid structure is of Polycrystalline silicon material with thick boss suspended using high compliant springs for high mechanical sensitivity. The diaphragm lies below the suspended rigid structure. The encapsulation of the diaphragm and suspended rigid structure under atmospheric load is shown in the figure.

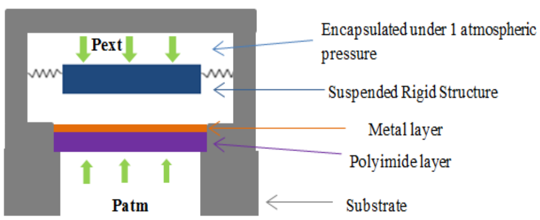

Figure 1. Diaphragm and Suspended Rigid Structure for MEMS transducer

2.1 Diaphragm Sensitivity without contact formation

The first situation is analyzed with the pressure loads, atmospheric, Patm (acting over 100% radius) and external load, Pext (acting over 90% radius) acting on the diaphragm from opposite ends. We have assumed external load is directly acting on the diaphragm and doesn`t involve any suspended rigid structure as shown in Figure2.

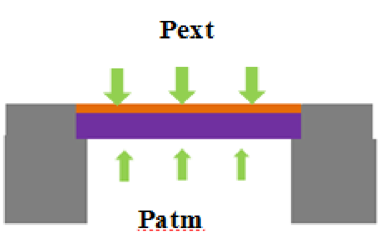

Figure 2. Distributed boundary loads acting on the diaphragm, Pext here is assumed due to load by rigid structure

2.2 Diaphragm Sensitivity with contact formation between Diaphragm and Suspended Rigid structure

This analysis is done with realistic non-linear contact simulations where diaphragm and rigid structure boundaries form contacts under applied loads as shown in figure1. To achieve maximum mechanical sensitivity, the rigid structure is designed such that the boss is suspended with a long spring that itself has a high sensitivity of over 6nm/Pa. The metal side of the diaphragm and the suspended rigid structure are encapsulated under 1 atmospheric pressure or approximately 100kPa.

The design parameters are defined in the Table 1.

Table 1. Design Parameters

Parameters	Value
Diaphragm material	Polyimide and Metal
Diaphragm Radius	250 µm
Diaphragm (Polyimide) thickness	2 µm
Diaphragm (Metal) thickness	200 nm
Rigid Structure or Boss Radius	225 µm
Rigid Structure or Boss Thickness	10 µm
Thin suspension Radius	>250 µm
Suspension thickness	1 µm
Patm, Pext	100 kPa

3. Model and Simulation

In order to validate the design and results, Finite Element Method implemented in the COMSOL Multiphysics® simulation software has been used to calculate the mechanical sensitivity in the Structural Mechanics module. The mechanical sensitivity can be expressed as

$$S_m = \frac{dw}{dP} \tag{1.1}$$

where w is the deflection of the diaphragm and P is the pressure acting on the diaphragm. In terms of initial stress and area the mechanical sensitivity is approximately given by [4],

$$S_m = \frac{A}{8\pi\sigma h_d} \tag{1.2}$$

where A, σ, and hd are the diaphragm`s area, tension stress and thickness, respectively. Thus selscting the diaphragm material to obtain lower initial stress will offer higher mechanical sensitivity. Also more thinner diaphragm have higher sensitivity.

A 2D axisymmetric model is implemented for both the cases mentioned above. Figure 3 shows the first case where there is diaphragm consisting of polyimide at bottom and metal layer at top. The diaphragm is constrained near the edge at 250[um]. Pext is acting only over 90% area of the diaphragm, i.e. till 225[um] from top and Patm is acting over the whole area from bottom.

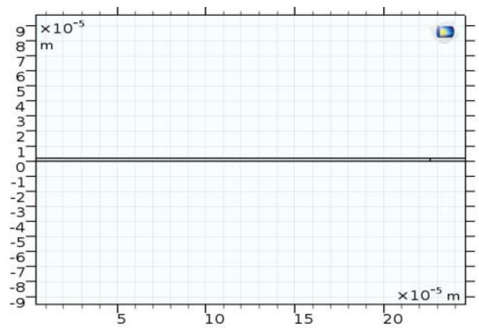

Figure 3. Simulation set up for case 2.1

A 2D axisymmetric model is also used for second case as simulation setup. The diaphragm is kept on a substrate and the rigid boss structure is suspended using a thin spring or suspension system placed on the substrate edge. The gap between the two structures is maintained at 5 µm.

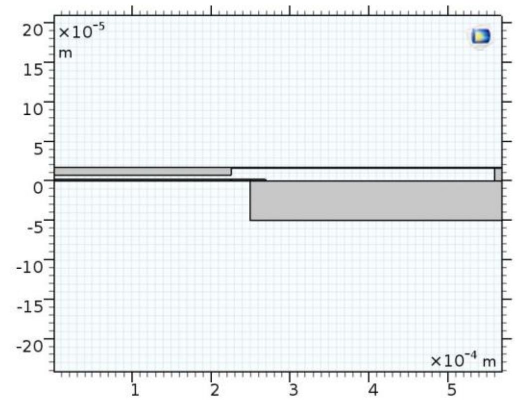

Figure 4. Simulation set up for case 2.2

The COMSOL Multiphysics® simulation software helped solving the non-linear problem using Newton Raphson iterative technique. This method converges if the initial estimate for the solution is close. Otherwise it may converge very slowly or even diverge. The strategy used here is to apply the loads gradually so that the solution from the previous load can be used as a trial estimate in the next round of iterations, keeping the initial estimate close to the solution. This technique is also known as load ramping.

The two contact algorithms that the COMSOL Multiphysics® Simulation software offers are Augmented Lagrangian and Penalty method. The Penalty method is computationally cheaper that means it has faster computation time whereas the Augmented Lagrangian method is more robust but computationally expensive.

Mesh refinement is done for source and destination boundaries as shown in figure 5. Figure 6 is a zoomed view of the mesh near the axisymmetric boundary. It is recommended to mesh the destination surface at least twice finer compared to the source mesh. The polyimide and the metal layer here is chosen as destination and the suspended rigid boss structure is chosen as source boundary.

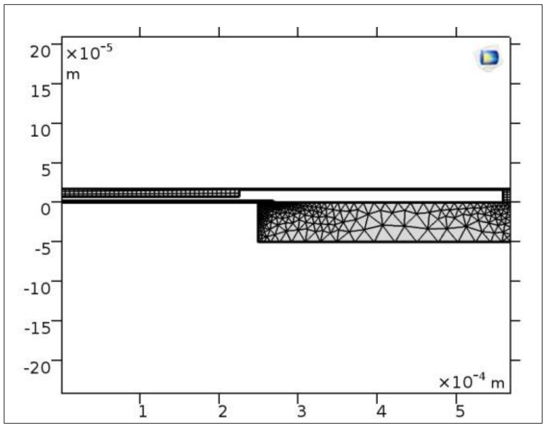

Figure 5. Mesh refinement for the design of case 2.2

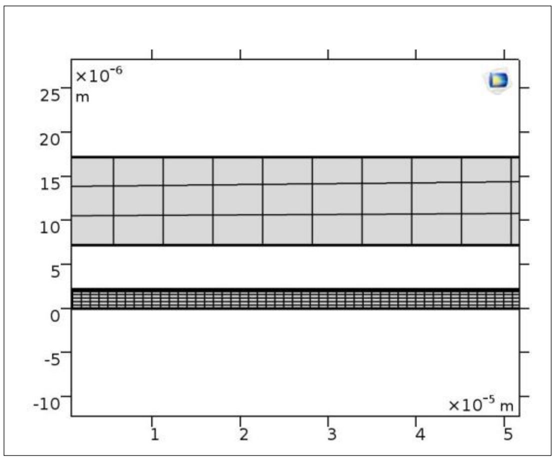

Figure 6. Zoomed in mesh view for source and destination surfaces

4. Experimental Results

The mechanical sensitivity and maximum stress for the first case without contacts is analyzed using different materials and choosing different initial stress values as shown in Table 2.

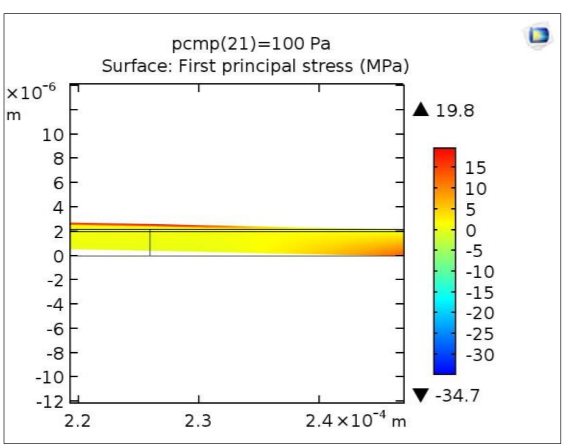

Figure 7. First Principal stress distribution on the polyimide layer near the fixed constraint and distributed stress on the top metal layer

Table 2. Values and Results

Rad	Mat	td	Initial Stress	Sm	Max. Stress
250 [um]	PS	2.2 [um]	100 [MPa]	0.06 [nm/Pa]	125 [MPa]
250 [um]	PS	2.2 [um]	1 [MPa]	0.38 [nm/Pa]	33 [MPa]
250 [um]	PI	2.2 [um]	1 [MPa]	3.2 [nm/Pa]	27.4 [MPa]
250 [um]	PI +M	2 [um]+ 0.2[um]	1 [MPa]	2.4 [nm/Pa]	19.8 [MPa]

Rad: Diaphragm Radius, Mat: Material, td: Diaphragm thickness, PS: Polycrystalline Silicon, PI: Polyimide, M: Metal, Sm: Mechanical Sensitivity

Figure 8 shows the variation of mechanical sensitivity with polyimide and metal thickness. As expected, the thinner the diaphragm, the higher mechanical sensitivity or Compliance (Cm) it has.

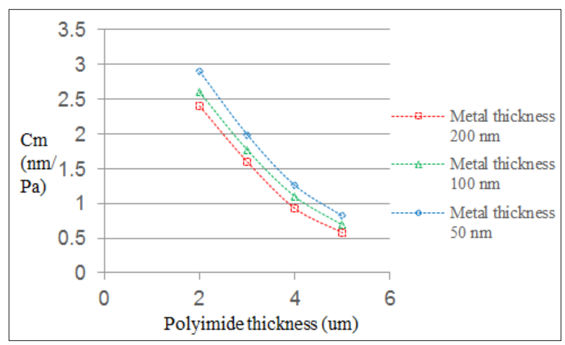

Figure 8. Variation of compliance, Cm with polyimide and metal thickness

The after simulation images for the contact formation case is shown in figure 9. The observation has been made for the situation when suspended rigid boss structure makes 80% and 90% of the contact area respectively and the sensitivity is measured when both the structures moves in unison after coming in contact.

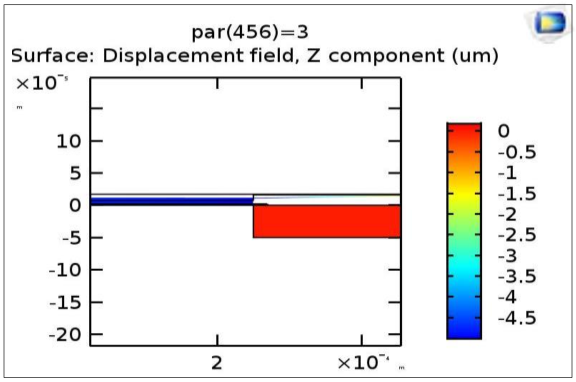

Figure 9.Contact formation between diaphragm and suspended rigid structure a) z-surface displacement profile for 90% contact radius

The mechanical sensitivities obtained for the two cases are shown in table 3 and its variation with contact radius is plotted in figure 10.

Table 3. Sensitivity variation with Contact Radius

Dia. Mat.	Rigid structure Mat.	Initial Stress	td	Contact Rad.	Sm
PI	PS	1 [MPa]	2.2 [um]	200 [um] (80%)	0.2 [nm/Pa]
PI	PS	1 [MPa]	2.2 [um]	225 [um] (90%)	0.04 [nm/Pa]
PI+ M	PS	1 [MPa]	2.2 [um]	240 [um] (96%)	0.01 [nm/Pa]

Dia.Mat.: Diaphragm Material, td: diaphragm thickness, Rad.: Radius, Sm: Mechanical Sensitivity, PI: Polyimide, PS: Polycrystalline Silicon, M: Metal

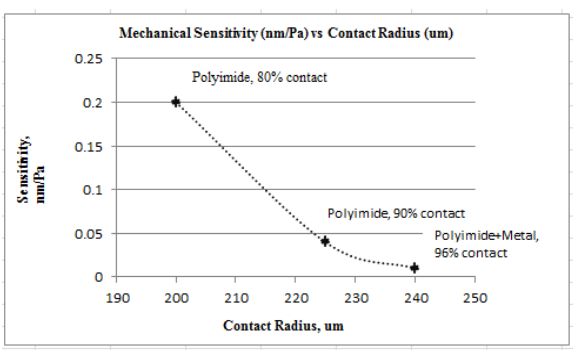

Figure 10. Variation of Contact Radius with Mechanical Sensitivity for different material combination

5. Conclusions

To reduce stiffness of the diaphragm, the atmospheric pressure exerted on the second layer of polyimide generates concentrated stresses while exposing the rigid first metal layer to distributed stresses. The combination of polyimide and metal layer gives six times higher mechanical sensitivity than Polycrystalline Silicon diaphragm of same specification as obtained in table 2.

From the contact simulation, we expect the sensitivity to be calculated as a parallel combination of individual sensitivities of diaphragm and the suspended rigid structure. The diaphragm mechanical sensitivity with Polyimide and metal layers, obtained was 2.4 nm/Pa as shown in table 2 and the suspended rigid structure sensitivity was 6 nm/Pa as designed for high sensitivity and its geometry can be further adjusted to satisfy contact area situation. So, one would expect the overall sensitivity of this parallel combination to be approximately 2 nm/Pa.

However, the results in table 3 show to be just 0.01 nm/Pa which is two orders of magnitude less. The reason for significant difference between the two cases 2.1 and 2.2 respectively, can be pointed to the behavior of contact parts moving as a thick structure unit after contact establishment and hence the drop in sensitivity. Also, the sensitivity drops as contact area is increased.

6. References

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