Mechanical Behavior Simulation of MEMS-based Cantilever Beam Using COMSOL Multiphysics

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Abstract. This paper presents the studies of mechanical behavior of MEMS cantilever beam made of poly-silicon material, using the coupling of three application modes (plane strain, electrostatics and the moving mesh) of COMSOL Multi-physics software. The cantilevers playing a key role in Micro Electro-Mechanical Systems (MEMS) devices (switches, resonators, etc) working under potential shock. This is why they require actuation under predetermined conditions, such as electrostatic force or inertial force. In this paper, we present mechanical behavior of a cantilever actuated by an electrostatic force. In addition to the simplification of calculations, the weight of the cantilever was not taken into account. Different parameters like beam displacement, electrostatics force and stress over the beam have been calculated by finite element method after having defining the geometry, the material of the cantilever model (fixed at one of ends but is free to move otherwise) and his operational space.

Keywords: Simulation, COMSOL, Cantilever beam, Electrostatics force, MEMS.
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INTRODUCTION

MEMS are fabricated by microelectronics manufacturing techniques. They are coupled devices since they consist of small scale electrical and mechanical components for specific purpose. The mechanical behavior of MEMS is in general coupled with the electrical behavior. Membranes, bridges and cantilevers are the basic's mechanical structures of MEMS. Their typical dimension varies from a few micrometers to a few millimeters. A structure having a cantilever configuration is a basic element of most MEMS actuators and sensors such as switches, capacitive pressure sensors, accelerometers, filters, resonators and many others [1]. The major advantages are their versatility and fabrication steps simplicity. The interest in cantilevers has driven investigations from various aspect including static and dynamic performances under certain influences such as potential fields. The electrostatic actuation is commonly used in MEMS devices, where pull-in voltage represents a topic of high interest in the study of micro-beams such as suspended cantilevers.

In MEMS, the shock due to electrical actuation can cause failures inducing large deflection of cantilevers, which may lead to device failure. Therefore, the concern of designers is to investigate how to prevent such problems. For this purpose, several

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analytical and numerical methods of modeling were used as a design tool for understanding the mechanical behavior of microstructures. These can be classified into experimental works, to identify the failure mode under electrical constraint; in the other hand, theoretical works try to predict through model and simulation the response of microstructures during shock. Among the experimental works, Béliveau et al. [2] tested commercial accelerometers under shock loads. Brown et al. exposed MEMS sensors, commercial accelerometers, and pressure sensors to high shock load in harsh environments [3]. Tanner et al. [4] tested MEMS micro-engines with comb-drive actuators against shock pulses of various time durations and amplitudes. Li and Shemansky [5] conducted experimental drop tests of MEMS accelerometers. Sheey et al. [6] investigated experimentally the response of cantilever micro-beams to high-g mechanical shock. Kimberley et al. [7] conducted several tests on RF MEMS switches under various ranges of mechanical shock.

In addition, other investigations have been also presented in the modeling of MEMS devices and structures. Several works have been based on finite-element models (FEM), for example Cunningham et al. [8], Wagner et al. [9], etc. Other researchers modeled the shock problem of MEMS using mass-spring-damper models, such asSrikar and Senturia [10]. Also, a number of studies accounted for the flexibility of microstructures and treated them as distributed parameters systems in analytical models including the works of Tas et al. [11], etc. Younis et al. have developed analytical and computational techniques to investigate shock in MEMS. In [12–17] the response of microstructures under the combined effects of mechanical shock and electrostatic forces has been investigated theoretically and experimentally.

In this paper, we present the mechanical behavior simulation of MEMS based cantilever beam made of poly-silicon; which is the most common structural materials used for a large variety of MEMS applications. In this simulation we have used COMSOL MULTIPHYSICS through the couplings of three modes:

- The plane strain and electrostatics (ES) modes from MEMS module.
- Moving mesh (ALE) from COMSOL module.

The main objective of this study is to acquire MEMS devices design ability in terms of design rules and multidisciplinary approach in order to build reliable micro-system.

From the literature we have to note that different shape of cantilevers is used as shown in figure 1; mostly they have a characteristic length around 0.5 mm, thickness ranging from 3 to 8 µm and electrode gaps nearby 10 µm [18], the figure 1.c is our type structure in this work.

(a) (b) (c)

FIGURE 1. Different types of micro-cantilevers used in MEMS devices.

A commonly used principle to drive MEMS devices is electrostatic actuation. It is based on the electrostatic force between elements with a different applied voltage. Electrostatic actuators consist of two electrodes movable one and fixed. When the actuation voltage is applied the gap between electrode decrease generally. All electrostatic actuators use electrostatic attraction force driven by Coulomb's law. Usually actuator operate at lower voltage (< 10V in many cases) and show the jump phenomenon, which occurs at a critical voltage (known as pull-in voltage) occurring mechanical contact between suspended structure an substrate or the pull down electrode [19].

DESIGN PARAMETERS (MODEL DEFINITION)

The model consists of 2D cantilever with length $l_{electrode}$ fixed at one end; the structure is suspended over a stationary pull-down electrode (is fixed by L_x lateral distance of cantilever anchoring point) by g_0 gap. Which is subjected to a driving voltage V_{in}, resulted in a position dependent deflection Y(x). Figure 2 shows the cross-section of the proposed geometry model in 2D.

The used model is coupling three modes of application. The plane strain and electrostatics (ES) application modes from MEMS module and the moving mesh (ALE) application mode from COMSOL MULTIPHYSICS. The work hypothesis is based on thin film elastic isotropic cantilever under large deformation mode; according to our assumption related to 2D study the masse of the cantilevers is reduced to linear one.

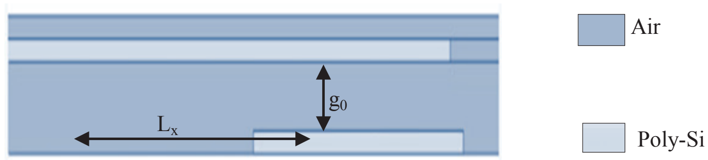

FIGURE 2. Geometry of the studied model.

The cantilever made of poly-silicon is initially at rest in its under-formed configuration. In the COMSOL model, the environment around the micro-cantilever is air which is electrically insulated. The table 1. below shows the mechanical characteristics of the cantilevers.

TABLE 1. Dimension and material properties of cantilever beam and pull-down electrode

Description and symbol	Value	Unit
Length, $l_{cantilever}$	350	µm
Length, $l_{electrode}$	160	µm
Thikness, $t_{cantilever}$	5	µm
Thikness, $t_{electrode}$	5	µm
Gap, g_0	15	µm
Lateral distance, L_x	200	µm
Young's modulus, E	190	GPa
Density, ρ	2300	Kg/m^3
Poisson's ratio, v	0.273	-
Relative permittivity, ε_r	4.5	-

We note that constant (ε_r) is the relative dielectric of the material covering the bottom electrode and the surface micro machined of cantilever; where the thickness is around 100 nm. The iterative calculations in obtaining pull-in voltage come from coupling of mechanical and electrical behavior. The beam bending configuration depends on the applied load (electrostatic force, Van der Waals force, Casimir force and the gravitational weight) witch change the distance or the gap between the cantilever beam and the actuation electrode. In this case, the gap is large (around micrometers) where the Casimir and Van der Waals forces are null.

Boundary Conditions

In the ideal case, the conditions at the imposed borders must reproduce the real environment containing the structure during its operation. The cantilever beam has its deformations and its displacements blocked at the points of anchoring, the fixed electrode is defined as fixed constraint as shown in the figure 2. In addition, this cantilever is free to move vertically. Therefore, when a voltage is applied between the cantilever and lower electrode, the electrostatic attractive force is generated and causes the motion of the structure.

Meshed Geometry

The moving mesh (ALE) application mode evaluates the displacement of the cantilever beam as a function of applied potential. As the micro-cantilever bends, the geometry of the air changes. We note that the default mesh displacement feature constrains all the remaining boundaries to have zero displacement. In addition, the Lagrangian method is used where the mesh movement follows the cantilever motion (Figure 3).

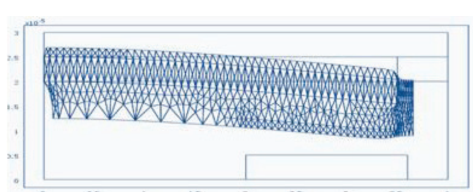

FIGURE 3. Meshed geometry.

SIMULATION RESULTS

The cantilever length is 350 µm. Therefore it is prudent to include the weight of cantilevers in aim to chuck the effect of the weight force on displacement. As shown in figure 4, we observe the tip deflection due to gravitational force, which is about 1.507 Å. Therefore, the weight of the cantilever was not taken into account for the further study.

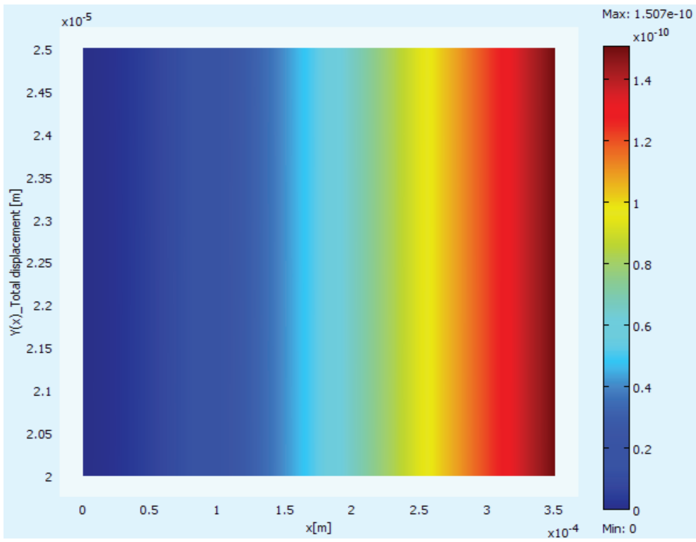

FIGURE 4. Deflection of cantilever beam due to gravitational loading.

For the next step of our work we involve the study of cantilever displacement as function to voltage as shown in figure 5. The V_{in} parameters vary from $1V$ to $4V$.

We note that there are positive feedback exits between the electrostatic forces and cantilever displacement. Therefore, the electrostatic forces induce bending of beam to grounded electrode. We observed that the voltage range can be divided in two regions, less than 4 V the displacement of MEMS device react in stable mode, however, when voltage is higher than 4 V the MEMS device becomes unstable, due to the overcoming of the stress forces comparing to electrostatic forces, which cause gap collapsing. This critical voltage in called the pull-in voltage (At applied voltage lower than the pull-in voltage, the beam stays in equilibrium position where the tress forces balance the electrostatic forces).

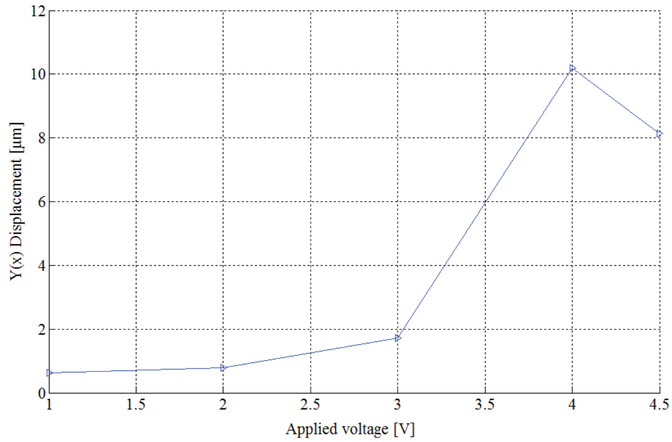

FIGURE 5. Cantilever displacement calculated.

Regarding to the quality of mesh grid we obtained the profile of deformation of the cantilever. Embedding point is characterized by a null deflection whatever the time and the loose, at the lead point of cantilever correspond to the maximum deflection (equal to 10.196 µm).

The deformed shape of the cantilever along the edge for several applied potential values between 1V and 4V applied considering homogenous material is shown in figure 6. Additionally, the potential field and deformation at the cantilever beam's equilibrium position for an applied potential of 4*V*. The solution ceases to converge just before the beam touches the pull-down electrode. Figure 6 shows the potential field and deformation at the cantilever beam's equilibrium position for 4V applied voltage.

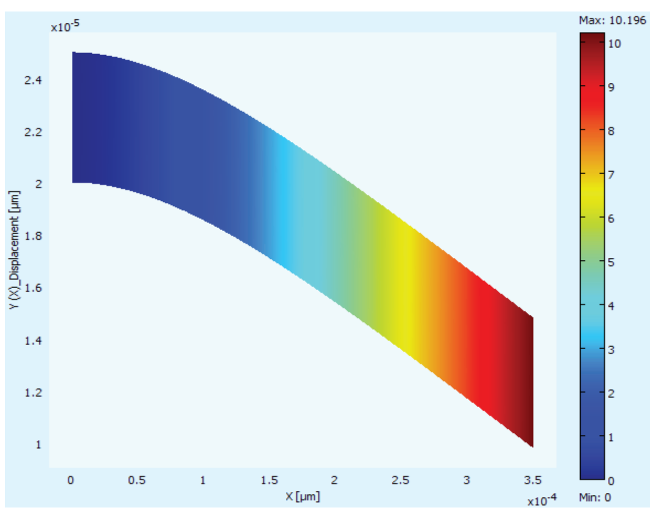

FIGURE 6. Deformation at the cantilever beam's at equilibrium position for an applied potential of 4V.

Also, figure 7 shows below the Von Mises stress behavior of cantilever beam's at equilibrium position for an applied voltage about 4V. Stress concentrations occur at the application of the applied voltage and at the anchored part of the beam. In addition, the minimum tress occurs at the suspended beam. Tensile and compressive stresses of the cantilever beam (2D) occur respectively at the top and bottom surfaces of the beam. Between the areas of tensile and compressive stresses, there is a neutral fiber which is not deformed.

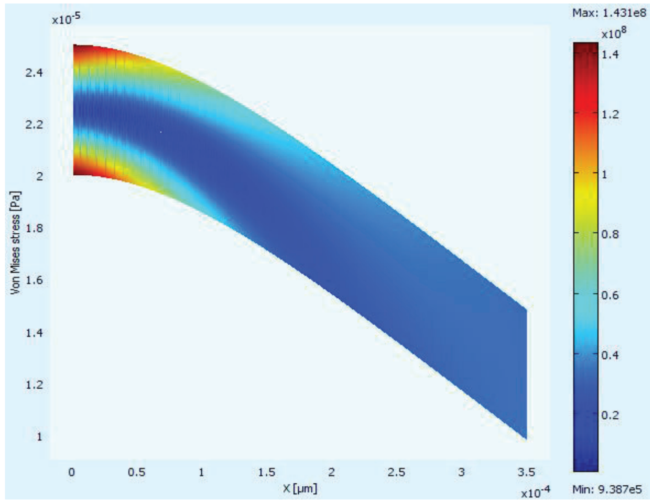

FIGURE 7. Von Mises stress behavior of cantilever.

CONCLUSION

In this paper, the electrostatic actuation was involved for cantilever beams and bottom electrode made of poly-silicon. We have identified the different types of cantilever, and then we studied the beam having the simple geometry (used generally in the switches) and relative dimensions to MEMS devices manufactured in clean-rooms. We noted that the good result requires to configuring (size and location) of the actuation electrode. In addition, for each application mode, we have taken into account the control of imposed conditions at boundaries.

We have concluded through the calculation of linear weight density force regarding to cantilevers structure; that weight does not influence the cantilever displacement. Therefore, in this case the attractive force is resumed to electrostatic force. Where the maximum displacement (at suspended end) is 10.196 μm, at 4V applied voltage.

In this work we have used the moving mesh application of COMSOL Mutli-physics in aim to predict more specifically the real mechanical behavior of cantilevers. Moreover, a series of static simulation was carried out using the developed COMSOL Mutli-physics model in order to determine values of pull-in voltage for cantilever beam, additionally the dimensions and position of actuation electrode was considered. This method is not limited to cantilever structure; this analysis can also be done in other models of MEMS devices.

Finally, we consider the modeling and simulation of cantilever beam in 3D. Moreover, we will take into account the time and other factors such as temperature, variation of materials, etc.

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