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The Effect of the Electrode Position on the Dynamic Behavior of an Electrostatically Actuated Microcantilever

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Abstract: Electrostatic actuators have major role in many MEMS devices, e.g. sensors, actuators. The amount of applied voltage to an electrostatic micro-actuator has a direct impact on the amplitude of deflection throughout the cantilever. This research aims to study the effect of the electrode length and the applied voltage on the amplitude of deflection of the micro-cantilever. Also, the resonant frequency for the cantilever was computed for full length and compared with simulation results. Finite element method, ANSYS was used as a simulation tool.

Keywords: Electrode size, finite element analysis, cantilever.

1. Introduction

MEMS resonators are the key players in most of the MEMS sensors and actuators. Electrostatic actuation is the most commonly used method of actuation compared to other alternative methods (e.g. electrothermal and piezoelectric), and this is mainly due to the low power consumption and ability to very high resonance frequencies [1], [2]. Electrode layers are used to apply electrostatic voltage to the actuated resonators. For the cantilever resonator a top layer of electrode is deposited. The electrode characteristics (geometrical dimensions and elastic parameters) influence the performance of the resonating structure [3]. On the other hand, the deposited electrode material might have undesirable mechanical and electronic properties compared to the resonator device. Reducing the electrode length will reduce their effect but at the same time this will affect the active area for electrostatic actuation which may require high voltage to be applied. The effect of reshaping the metal electrode as well as of changing its thickness, on the functionality of the resonators, has been investigated in the literature [4], [5], [6] [7]. This work aims to investigate the effect of the electrode length on the amplitude of deflection of the electrostatically actuated microcantilever.

2. The model of the electrostatic actuator

The electrostatic actuator consists of four main parts: silicon base layer (200*2*20 µm), silicon dioxide isolator layer (50*3*20 µm), silicon actuator layer (200*2*20 µm), and copper pad layer (200*2*20µm). The actuator was modelled in finite element software (ANSYS v.15) as shown in in *Fig. 1*. The properties of the materials used are presented in *Table.1*.

Table.1: Material properties

Material	Elastic module E	Poisson's ratio PR	Density $\boldsymbol{D}$	Thermal expansion coefficient $\boldsymbol{\alpha}$	Thermal conductivity $\boldsymbol{k}$	Resistivity $\boldsymbol{R}$
	MPa		$\boldsymbol{kg/m^3}$	$\mathbf{1}/K$	$\boldsymbol{W}/mK$	Ωm
Si	$185 \cdot 10^3$	0.28	$2.3 \cdot 10^3$	$2.33 \cdot 10^{-6}$	157	$6.4 \cdot 10^2$
SiO_2	$73 \cdot 10^3$	0.23	$2.27 \cdot 10^3$	$0.5 \cdot 10^{-6}$	1.4	$10 \cdot 10^8$
Cu	$110 \cdot 10^3$	0.34	$8.9 \cdot 10^3$	$16.56 \cdot 10^{-6}$	393	$1.72 \cdot 10^{-8}$

Size of element: smart sizing, number of elements=4, element type: soild227, pick under size control: global.

From *Fig. 1.c* it can be observed, that the electrostatic force is distributed over the geometry, and the base layer is fixed, while the actuator layer can move due to the actuation force.

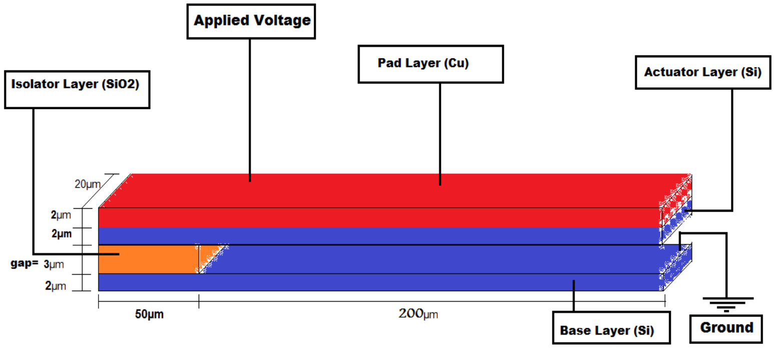

Figure 1.a: The geometry of the electrostatic microcantilever.

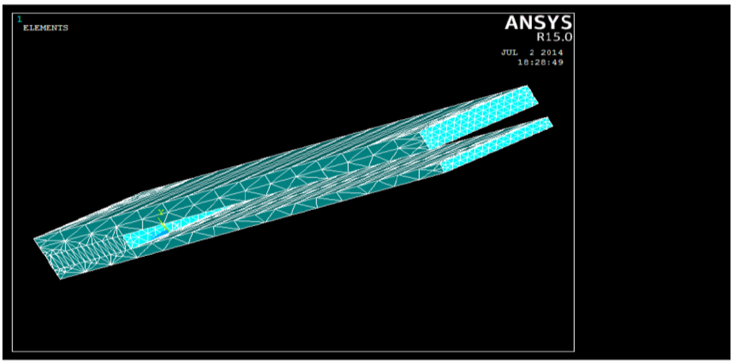

Figure 1.b: Finite element model with mesh.

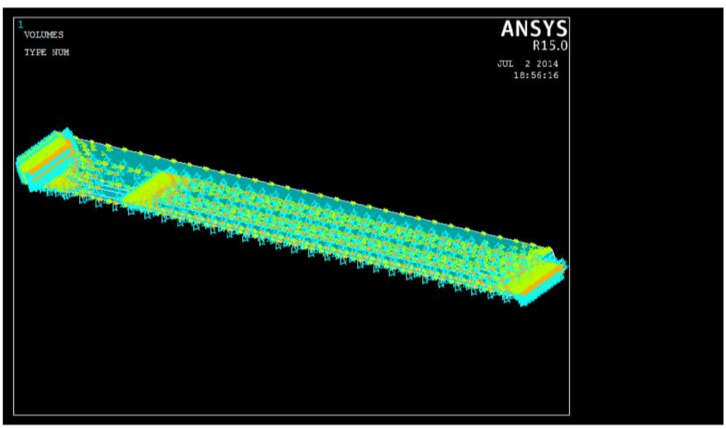

Figure 1.c: The geometry with the loading scheme.

To verify the ANSYS model, we calculated the resonance frequency and compared it with the value obtained from simulation as follows.

Firstly, we found the position of the neutral axis Δ from the equilibrium conditions by

$$\Delta = \frac{E_1 b^2{}_1 - E_2 b^2{}_2}{2(E_1 b_1 + E_2 b_2)} = 0.254\mu m \tag{1}$$

where E_1 and E_2 are the Young's moduli of the actuator layer and pad layer respectively. b_1 and b_2 are the thicknesses of the actuator layer and pad layer respectively as shown in *Fig 2*.

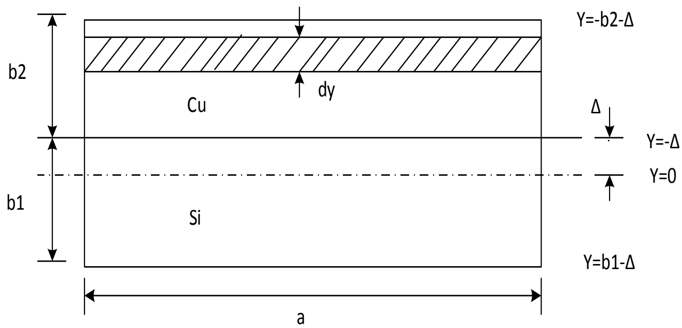

Figure 2: Microcantilever cross-section.

Subsequently, we computed the bending stiffness of the cross-section by substituting (1) in (2):

$$k = \frac{a}{3}\left[E_1(b^3{}_1 - 3b^2{}_1\Delta + 3b_1\Delta^2) + E_2(b^3{}_2 - 3b^2{}_2\Delta + 3b_2\Delta^2)\right] = 14971\times10^{-12}\,N.\mathrm{m}^2, \tag{2}$$

where a is the width of the actuator layer and of the pad layer.

Thirdly, we obtained the equivalent Young's modulus (which is valid for a homogenous cross section with identical size, that leads to the same bending stiffness) by substituting the results from (2) in (3):

$$E_{eq} = \frac{k}{y_z} = 140GPa, \tag{3}$$

where $y_z = a(2\mathrm{b})^3/12$.

Then, we calculated the mean mass density of the cross-section from the equality of the unit-length masses as $A\cdot\rho_{eq} = A_1\cdot\rho_1 + A_2\cdot\rho_2$, as shown below:

$$\rho_{eq} = \frac{\rho_1 b_1 + \rho_2 b_2}{b_1 + b_2} = 5600 kg / m^3 \quad (4)$$

where ρ_1 and ρ_2 are the densities of the actuator layer and of the pad layer respectively.

Finally, we obtained the resonance frequency of the cross-section by substituting the results from (3) and (4) in (5):

$$f = 0.1616 \frac{t}{l^2} \sqrt{\frac{E_{eq}}{\rho_{eq}}} = 80.8 kHz \quad (5)$$

where t is the thickness of thee cross-section, and l is the length of the cantilever.

The calculated value of the resonance frequency (80.8 kHz) is close to the value obtained by ANSYS (78.12 kHz) in *Fig. 3*. This error stems from the consequence of the approximations in the numerical methods of the eigenvalue computation using FEM.

2. Results and discussion

A voltage of 54 mV was applied to the electrode layer (when the electrode covered 100% of the actuator layer) and the maximum deflection of the cantilever was measured as shown in *Fig. 4*. Later on, the electrode length was varied and the corresponding maximum deflection was obtained. The DMX value shown the *Fig. 4* is the maximum displacement of the tip of the cantilever (about 3 μm).

The applied voltage was then varied from 0 to 200 mV, while reducing the size (length) of the electrode layer from 100% (when it fully covers the actuator layer) to 10% of the actuator layer. The results are shown in *Fig. 5*. Although some of the maximum deflection values exceed the electrostatic gap value (which indicates that the actuator will hit the base layer), it is acceptable since it is not meant to mimic a real case. Alternatively, we can consider the values of deflection that are below 3 μm or even below the pull in gap. If the geometry of the model is modified, a larger gap can be specified, and we could still obtain same relations about the effect of the electrode length. In addition, the resonance frequency of the cross-section is obtained analytically by (5) and by ANSYS as in *Fig. 3*. The errors between the calculated frequency and frequency obtained from ANSYS could be related to the meshing errors.

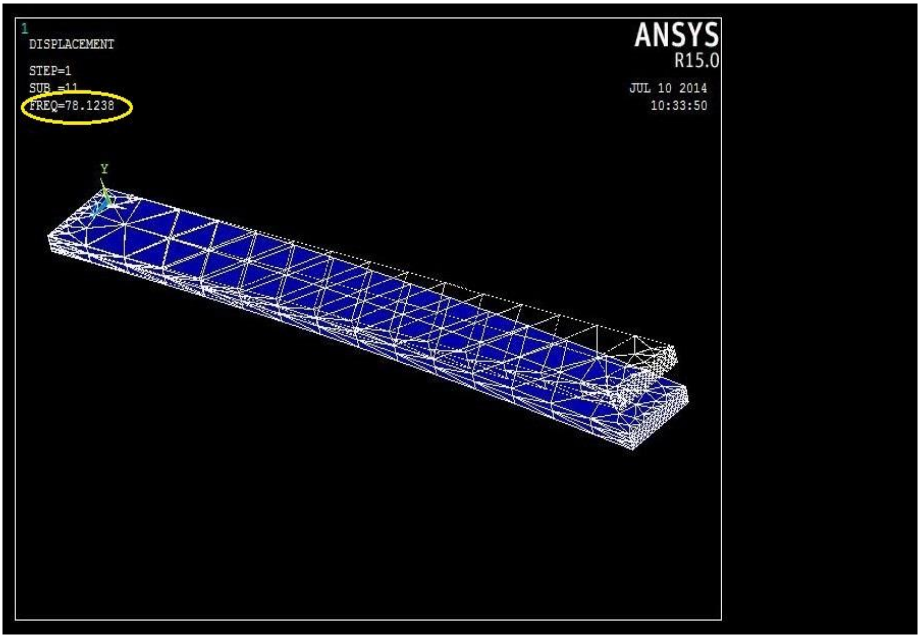

Figure 3: The first eigenmode with the highlighted resonant frequency of the cantilever.

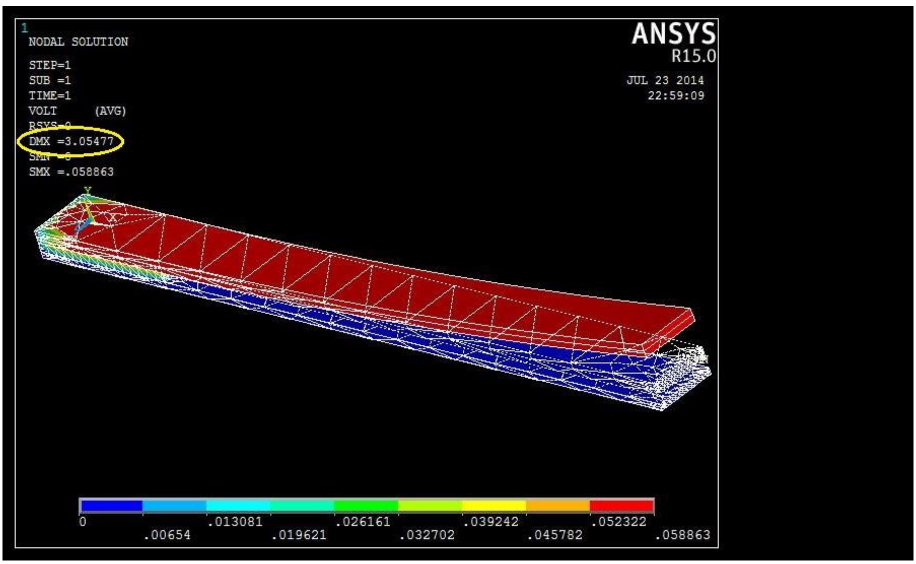

Figure 4: The electrical potential and the amplitude of deflection under applied voltage (54 mV) for 100% coverage of actuator layer.

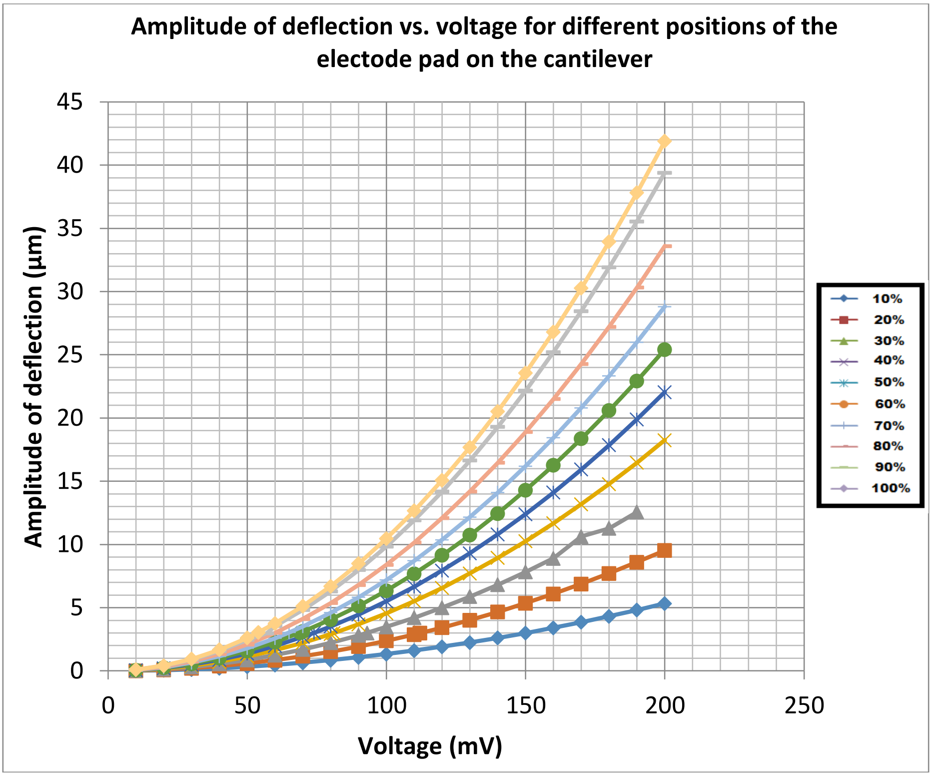

Figure 5: The amplitude of deflection vs. voltage for different positions of the electrode pad on the cantilever.

Conclusion

The effect of the electrode’s geometrical dimensions (length) on the performance of the resonating structure was investigated. For comparison, the resonant frequency of the cantilever cross section is obtained analytically and by simulation in the case of the entirely covered cantilever. Sizing the electrode length affects the amplitude of the deflection and the voltage necessary to achieve a certain deflection level. The results show that the amplitude of deflection may decrease significantly as a result of reducing the size of the electrode. For example, at 200 mV, reducing the electrode length to one tenth reduces the amplitude of deflection almost eight times.

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