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Thermal Analysis of Electrostatic Micro Actuator

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Abstract

Electrostatic actuators have major role in many MEMS devices, e.g. sensors, actuators, RF-MEMS. The amount of applied voltage to an electrostatic actuator has a direct impact on temperature distribution throughout the actuator, which affects the resonant frequency of the actuator. This paper aims to study the temperature distribution in a micro-cantilever at different applied voltages. Finite element method, ANSYS, was used as a simulation tool.

Keywords: Micro cantilever, temperature, Electrostatic, Finite element

I. Introduction

Electrostatic actuation is widely adopted in MEMS devices among other methods of actuation (e.g. electro thermal, piezoelectric,…etc.). In some cases, it is necessary to increase the applied voltage that causes the electrostatic actuation. For example, to avoid stiction of the vibrating structure while having sound level of actuation, one might increase the air gap (the insulation layer) which require increasing the applied voltage [1]. Also, to achieve higher amplitude of actuation, it is necessary to increase the applied voltage [2].

One of the problems associated with increasing the applied voltage is the joule heating effect [3]. An increase in the temperature of electrostatically actuated MEMS device can greatly affect the performance of the device. This heating side effect will result in different problems such as, generating thermal stresses [4], straining the microstructure, and even changing the mechanical properties of the vibrating structure material which result in changing the expected resonance frequency of the device [5]. There are number of powerful software which can be used to model MEMS devices, e.g. ABAQUS [6], COMSOL [7], and ANSYS [8]. The aim of this work is to monitor the impact of electrostatic actuation voltage on mechanical behaviour of a micro cantilever using ANSYS software. This mechanical behaviour includes; strain amplitude of actuation, as well as the temperature distribution as a result of the applied voltage.

II. Actuator Design

The Electrostatic actuator device consists of four main parts; base layer, isolator layer, actuator layer, and pad layer. The base was silicon .The Isolator layer is located between base and actuator layers was made of silicon dioxide (SiO_2) with a thickness of 270µm. The Actuator material is with a length of 814 µm, 2 µm thick, and 500 µm width. The Pad layer was placed at the top of the actuator and it is made of material with high electrical conductivity (copper) with dimensions similar to the actuator. Figure.1 shows the layout of the device as modelled in ANSYS while Table.1 presents the mechanical properties of the materials used.

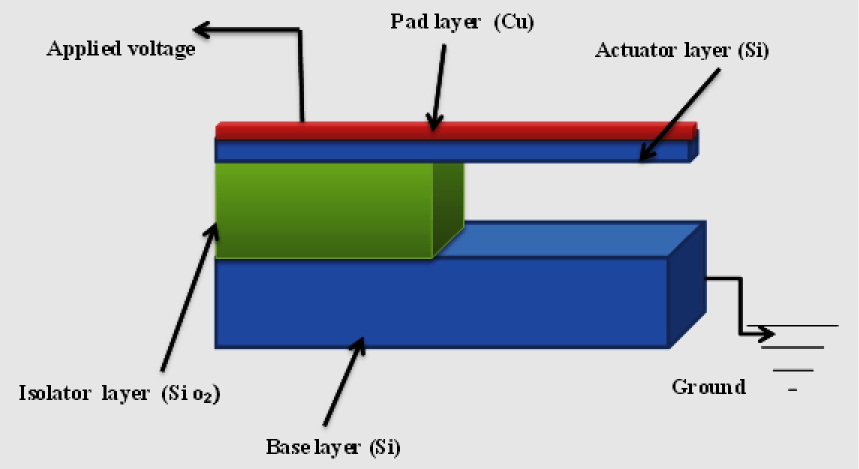

Figure 1: Layout of the electrostatic actuator

Table 1: Mechanical properties of the materials used in the device [9]

property **material**	**Elastic modules (E), Gpa**	**Poison ratio(υ)**	**Density($_\rho$), Kg/m^3**	**Thermal conductivity(k), W/m.^{0}C**	**Thermal expansion coefficient(α), 1/^{0}C**	**Resistivity (R), Ωm**	**Thermal convection (h),w/m^2 ^{0}C**	**Specific Heat J/kg ^{0}C**
SI	185	0.28	2300	157	2.33e-6	6400	10	385
SIO2	73	0.23	2270	1.4	.5e-6	1e20	5	0
CU	110	0.34	8900	393	16.56e-6	1.72e-8	15	712

III. Modelling and Simulation:

The structure was modelled with ANSYS using solid 98 element type. Coupled thermal-electrical analysis was carried out. Each part of the structure was meshed separately (attributed mesh) as shown in Figure.2. Boundary conditions as well as electrical, thermal and structural loads were applied. A voltage was applied between the pad and the base layer while the structure was allowed to dissipate heat through convection. Static and modal analysis were carried out. the model was verified by working out the natural frequency and comparing it with one obtained from ANSYS model. The natural frequency was calculated as using the following equation;

$$f = 0.16 * \sqrt{\frac{E\,t^2}{\rho\,l^4}} \tag{1}$$

Where f is natural frequency, E is elasticity modulus, ρ is the density,t is the thickness, and l is the length of the actuator. The values used in the above equation for the Young's modulus and density are the equivalent ones. This is due to the fact that the vibrating part consists of two materials (silicon and copper). The equivalent Young's modulus and equivalent density were found to be $137.966 \times 10^9 N/m^2$ and $5600 kg/m^3$ respectively.

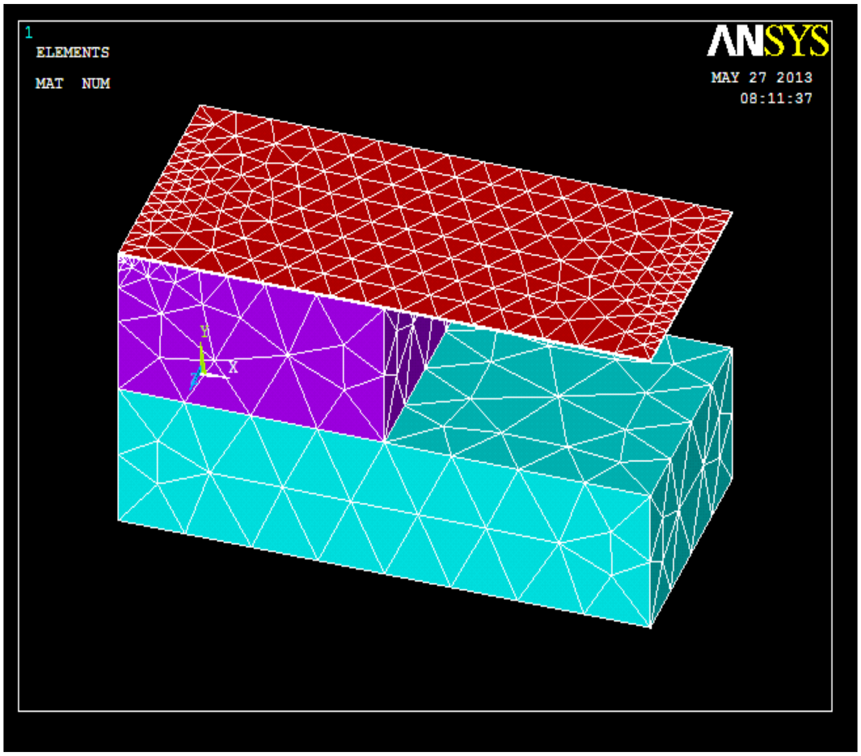

Figure 2: Meshing using solid 98 element type

The calculated natural frequency (10.8 kHz) agrees with value obtained from ANSYS (10.2 kHz) with about 6% error. This error is due to approximation in the formulas used to calculate the equivalent Young's modulus, equivalent density, and the natural frequency. Another verification of the model was carried out by plotting the electrical potential throughout the structure as shown in Figure.3. A 15V was applied to the top copper layer while the bottom silicon layer was grounded. This voltage will be used later to actuate the device electrostatically.

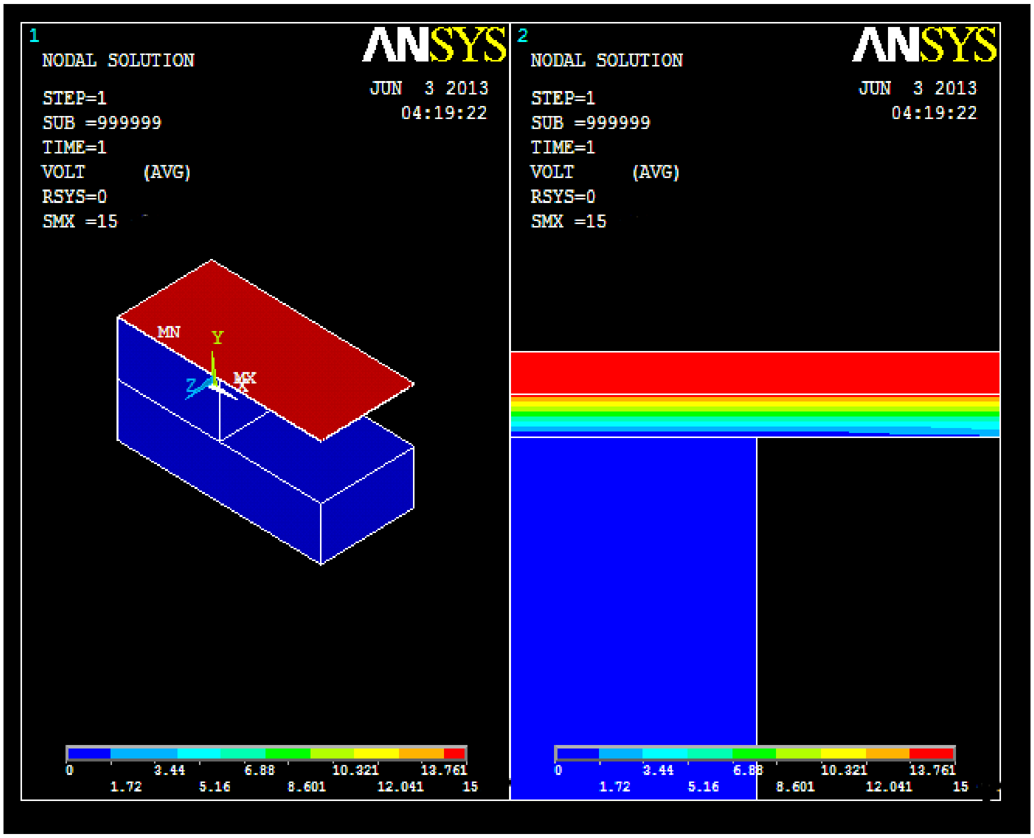

Figure 3: Electrical potential distribution when applied voltage is 15 Volts.

It is noticed from Figure.3 that the maximum voltage potential is concentrated on the pad layer which has the highest electrical conductivity (copper electrode), However the amount of electricity decreases gradually in throughout the silicon semiconductor layer and it is zero in isolator layer as well as at the grounded bottom silicon layer

IV. Results and Discussion

A potential voltage (15 volts) was applied to the pad layer while the base layer was grounded to generate the required electrostatic force for actuation. Meanwhile the heating effect the applied voltage was monitored. Figure.3 shows the temperature distribution when the applied voltage was 15V.

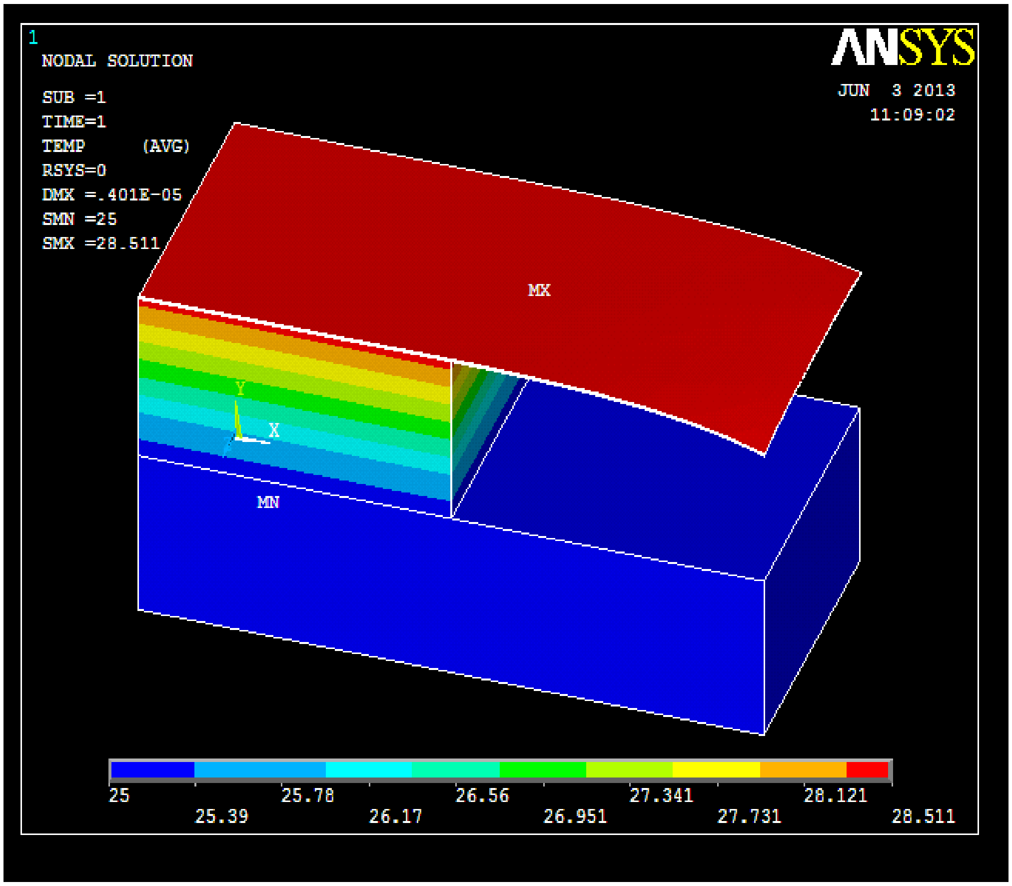

Figure 3: Thermal distribution at 15 V applied voltage.

It is clear that the amount of heat generated from applied voltage has a maximum value (3.511 ˚c above ambient temperature25˚c) in pad layer, which has direct contact with heat source. The heat flows to the isolator by conduction and therefore the temperature decreases gradually through isolator layer. Meanwhile, the heat is dissipated by convection through surfaces of the structure until it reaches ambient temperature25 ˚c in the base layer. The same test was carried out at different voltages (from 1 volts to 20 volts) and the change in temperature, strains, and the amplitude of deflection were calculated as shown in Table.2

Table 2: The effect of applied voltage on temperature, deflection, and strain

Voltage (volte)	**Maximum temp** (˚c)	**ΔT (˚c)**	**Amplitude (μm)**	**Strain in direct(X)*e-3**	**Total strain (X,Y,Z)*e-3**
1	25.016	0.016	3.51	0.550	0.586
2	25.062	0.062	3.52	0.551	0.587
3	25.140	0.140	3.53	0.553	0.589
4	25.250	0.250	3.55	0.555	0.591
5	25.390	0.390	3.57	0.558	0.594
6	25.562	0.562	3.59	0.562	0.598
7	25.765	0.765	3.62	0.566	0.603
8	25.999	0.999	3.65	0.571	0.609
9	26.264	1.264	3.69	0.577	0.615
10	26.560	1.560	3.73	0.584	0.621
11	26.888	1.888	3.78	0.591	0.629
12	27.247	2.247	3.83	0.599	0.637
13	27.637	2.637	3.89	0.607	0.646
14	28.058	3.058	3.95	0.617	0.656
15	28.511	3.511	4.01	0.627	0.667
16	28.995	3.995	4.08	0.637	0.678

17	29.510	4.510	4.15	0.648	0.690
18	30.056	5.056	4.23	0.660	0.702
19	30.633	5.633	4.31	0.673	0.716
20	31.242	6.242	4.40	0.686	0.730

When the values obtained in Table.2 were plotted against the applied voltage, it was noticed that the temperature of the actuator increases with the applied voltage. It was also noticed that the amplitude of actuation for the cantilever also increases with the applied voltage due to the increase in the generated electrostatic force. When the x-direction and total strains were plotted, the total strain reduces along the cantilever. This distribution was due to the fact that part of the applied electric energy is converted into mechanical energy (actuation) while in the fixed part it is merely converted to heat that causes larger strain. Since the cantilever length was much larger than the width, the dominant part of the total strain occurs in the x-direction (alng the length of the cantilever)

Conclusion

The effect of temperature generated from electrostatic actuation was investigated on a micro actuator. This study applied an FEM to work out the temperature effect on strain and amplitude of actuation. The study was carried out using ANSYS software. It was found that the effect of increasing the applied electrostatic voltage is very minor at low voltages but it needs to be considered at high voltages.

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