Analysis of a Monometallic Two Arm Horizontal Thermal Actuator for MEMS

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Abstract **This paper presents Finite Element Analysis of a horizontal monometallic thermal actuator for MEMS application with three different materials namely Single Crystal Silicon, Poly-Silicon and Titanium. It is aimed to predict the suitability of the three materials for the actuator. Using the software COMSOL™ Multiphysics 3.5, deflection, stress and temperature analyses are carried out, for a range of applied voltages within 8V. Two sets of boundary conditions are considered in this work. In the first case all the boundary conditions are set as having conductive heat flux and in the second case the micro air gap between the two arms of the actuator is considered as an insulating layer. By employing these two cases, a comparison study is presented. It is seen that Titanium and Single Crystal Silicon has high temperature generation and less deflection respectively for the range of applied voltages, but for moderate deflection and temperature generation Poly-Silicon is better than the other two.**

Keywords- MEMS, monometallic, thermal actuator, FEA, COMSOL Multiphysics

I. INTRODUCTION

MEMS is an acronym for Micro-Electro-Mechanical-System. The greatest promise of MEMS lies in the ability to produce mechanical motion on a small scale [1]. This feature helps in greatly reducing size, power consumption and cost without compromising accuracy. Thermal Actuator is an important component used in MEMS applications. It works on several principles such as thermal pneumatic, shape memory alloy (SMA) effect, bimetal effect, mechanical thermal expansion etc. The thermal pneumatic micro actuator uses thermal expansion of a gas or liquid or the phase change between liquid and gas to create the actuation. In some alloys, shape memory alloy effect occurs due to reversible thermal mechanical transformation of the atomic structure of metal at a certain temperature. In bimetallic actuators, due to the difference in thermal expansion coefficients of two metals, the layered strip gets deflected. Mechanical thermal actuators are based on the asymmetrical thermal expansion of a microstructure with two arms made of same conductive material, but different heating power and hence different thermal expansion [2]. This results in a longitudinal expansion when a current passes through them. The thermal actuator used in this approach has been previously modeled using Poly Silicon [3]. In this actuator temperature difference between the hot and the cold arm is determined by only the difference of their width. In another type of actuator, this temperature difference is further increased by extending the aluminum leads far onto the cold arms, thus keeping the power dissipation on the cold arms to a minimum [4]. Since thermal expansion leads to deflection of the microstructure, therefore proper modelling of heat transfer through the surfaces of the actuator is very important. The accurate and practical modelling of the heat transfer phenomenon can fairly predict the effect on the actuator movement and stability. In this paper three materials, Single Crystal Silicon, Poly Silicon and Titanium are used to compare the results.

II. PRINCIPLE AND DESIGN

A two arm horizontal thermal micro actuator [5] is selected for design and simulation. It consists of two arms of the same material connected at one end of which one is of smaller cross section. The electrical resistance of the thinner arm is higher than that of the thicker arm. When an electric current passes through the thin and the thick arms, the heat generated in the thin arm is much more than that of the thick arm such that the temperature of the thin arm is much higher than the thick arm. Since the cold and hot arms are made of the same material and same thermal expansion coefficient, the temperature difference causes the hot arm to expand more than the cold arm. As the non connected ends are kept fixed, the result is the deflection of the actuator. The basic geometry of the micro-actuator is shown in Fig.1.

The analyses are carried out for deflection of the actuator, the maximum temperature generated in the actuator and the stress developed for different applied voltages. In this analysis three materials namely Titanium (Ti), Single Crystal Silicon (SCS), Poly-Silicon (Poly-Si) are incorporated. These three materials show variations within the chosen applied voltage range. Single Crystal Si and Poly-Si are semiconductor materials while Titanium is a metal. Both Single Crystal Si and Poly-Si are brittle and Ti is a ductile metal. Therefore it is obvious that their performance will vary.

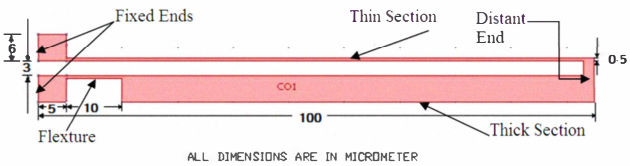

Figure 1. Basic model of the actuator

The consideration of the boundary condition is also an important aspect in the analysis because the analysis is done in the micro level. In micro scale analysis correlations cannot be used in the same way as in macro scale system. These correlations are based on the value of Rayleigh number.

III. ANALYSIS METHODOLOGY

Two cases have been considered when the analyses are carried out. They differ in provided boundary conditions to the thermal actuator faces as explained in detail below. The software used for these analyses is COMSOL™ Multiphysics, which is a Finite Element Analysis (FEA) tool for analysis of multiphysics environment. There is an MEMS module incorporated in the software especially for design and simulation of MEMS systems.

A. *Case-I*

In macro-scale system, the value of convective heat transfer coefficient '*h*' may be approximated using free convection correlations based on Rayleigh number. However, these correlations are not valid for this micro-scale system where Rayleigh number is of the order of 10^{-3} to 10^{-2}. This minuscule Rayleigh number suggest that most of the energy loss that takes place from the actuator is strictly through conduction into the surrounding air, although it will be termed as convection so as not to be confused with the conduction in the actuator [5].

Heat dissipation through radiation to ambient can be neglected in comparison with heat losses through conduction to the substrate which is considered as a heat sink. At high input voltage, the radiation heat becomes significant because of the high temperature induced by the Joule's heating but in this analysis not more than 8 V is used.

In Case I all faces are given conductive heat flux boundary condition. The properties of the materials used are according to the data given in the software itself.

B. *Case-II*

In this case, the small air gap present in the thermal actuator is treated as an insulating layer because this gap is very small i.e. 3 μm where air will be trapped with almost zero velocity and thus will act as an insulating layer. Thus the boundary conditions on the three faces surrounding this layer are given as thermal insulation in this analysis. Other assumptions are kept same as in the case-I.

IV. RESULTS AND DISCUSSIONS

A. *Case-I*

The data for the deflection, temperature generated and stress developed in the actuator are collected within the voltage range from 0.5 V - 8 V. The three materials show different variations within this applied voltage range. A discussion for the suitability of the materials on the basis of results obtained is presented.

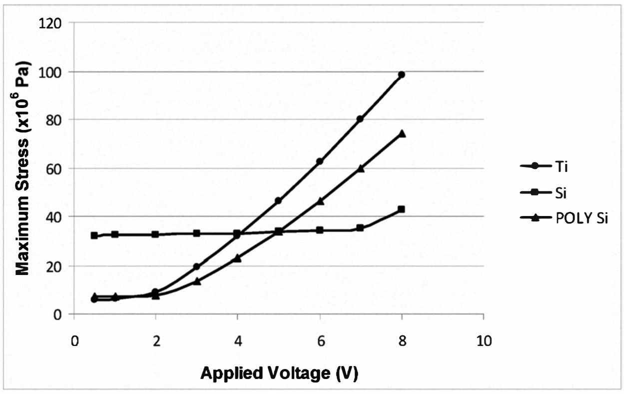

Figure 2. Plot between Applied Voltage & Maximum Stress

1) The fracture strength for Poly-Silicon is between 1.2-3 GPa. In this analysis the maximum stress for Poly-Si is found to be 74.19 MPa at 8 volt. In case of Single Crystal Silicon (SCS) the maximum stress at 8 volt is found to be 42.55 MPa and the fracture strength for SCS is in the range 0.26 – 26.4 GPa. For Titanium, the maximum stress is 98.26 MPa at 8 volt and failure occurs when the stress value reach 0.64 to 0.78 GPa. So there is no chance of failure of the three materials. The comparison of stress is plotted graphically in Fig. 2 and representative stress distribution in the actuator is shown in Fig. 3.

2) For the same applied voltage, Titanium gives maximum deflection out of three materials at each and every voltage. At the applied voltage of 8 V, the deflection for the materials Ti, Si and Poly-Si are 1792 nm, 256.1 nm and 376.4 nm respectively. The comparison of deflections is shown graphically in Fig. 4 and Fig. 5 displays the deflection pattern.

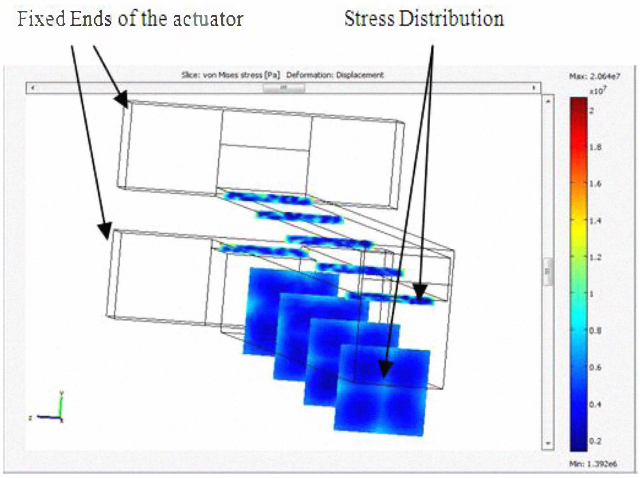

Figure 3. Slice View of Stress Distribution in the actuator

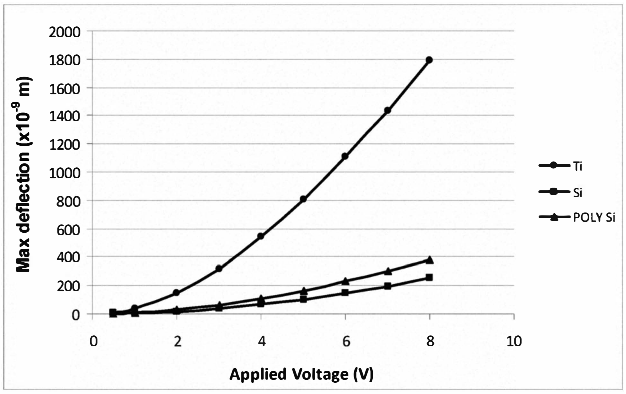

Figure 4. Plot between Applied Voltage & Maximum deflection

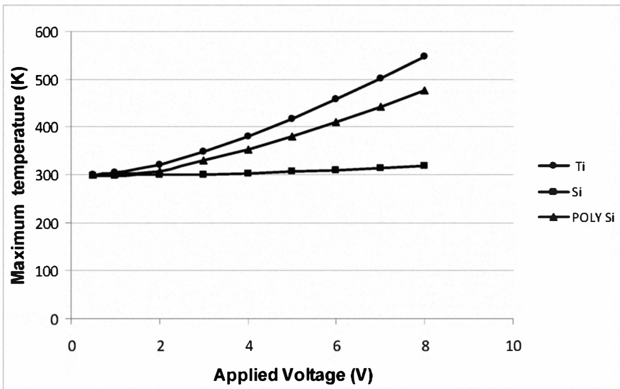

Figure 6. Plot between Applied Voltage & Maximum Temperature

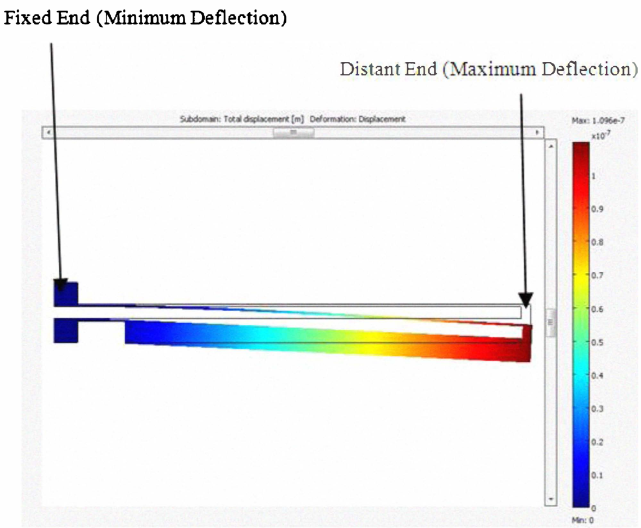

Figure 5. Deflection of the actuator

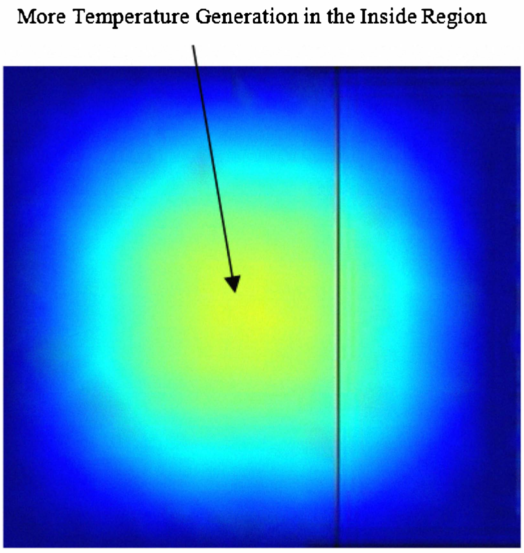

Figure 7. Slice View of Temperature Distribution in Thick Arm

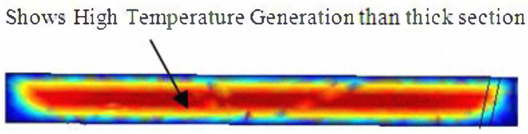

Figure 8. Slice View of Temperature Distribution in Thin Arm

3) From the temperature point of view, Ti achieves the maximum temperature. The increase in temperature is not significant in case of Si and so it is preferable if the system does not allow high temperature. The comparison of temperature is plotted graphically in Fig. 6. Fig. 7 and Fig. 8 refer to the temperature distribution in the thick and the thin arm respectively.

4) For Si more voltage is required to be supplied in order to get the same deflection as produced by Ti and Poly-Si. So this is in contrast to economy and cost.

5) The melting point of Titanium is 1660ºC. Therefore this material allows the adoption of high voltage accompanied by increase in temperature. Only requirement is that the system should permit high temperature. By using this material same deflection as produced by the other two materials can be achieved at a much lower applied voltage.

B. Case II

In this case of analysis the readings for the same parameters (deflection, temperature & stress) are taken for the aforementioned three materials. The following observations in comparison to Case I are noticed.

The temperature corresponding to each voltage for the three materials is found to be more than that in Case I. This increase in temperature is not a limiting condition on the basis of melting point of the material. Therefore, if the system permits, this is feasible. The graphical representation of temperatures for Case II is shown in Fig. 9. Also a comparison of temperatures for the two cases is provided in Table I.

TABLE I. COMPARISON OF TEMPERATURES

Material	Temperature Range: Case I (K)	Temperature Range: Case II (K)
Poly- Si	302.00- 409.93	313.37- 616.99
SCS	298.34- 309.79	299.36- 341.76
Ti (up to 5V)	304.07- 417.10	321.37- 644.44

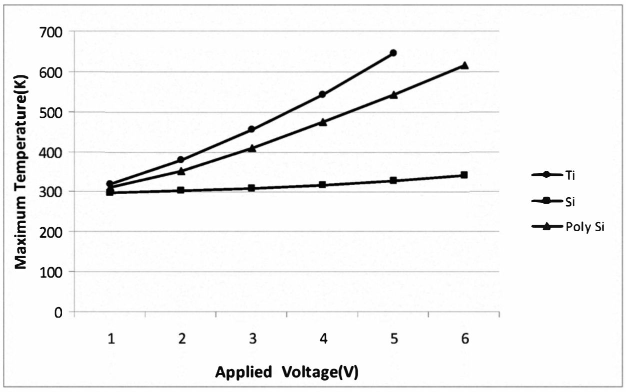

Figure 9. Plot between Applied Voltage & Maximum Temperature

As the temperature generated in the actuator is more, so it is obvious that more heat will be produced in the actuator which in turn increases the deflection. The increases in deflections as observed in the three materials are summarized in comparison with Case I in Table II for the voltage range 1V - 6 V.

TABLE II. COMPARISON OF DEFLECTIONS

Material	Deflection Range: Case I(nm)	Deflection Range: Case II(nm)
Poly- Si	7.56-228.70	31.62-785.30
SCS	9.69- 146.30	20.02-605.70
Ti(up to 5V)	38.13- 805.80	160.30- 2698.00

This increase in deflection is very much prominent in case of Ti. The graphical representation for deflections in Case II is shown in Fig. 10.

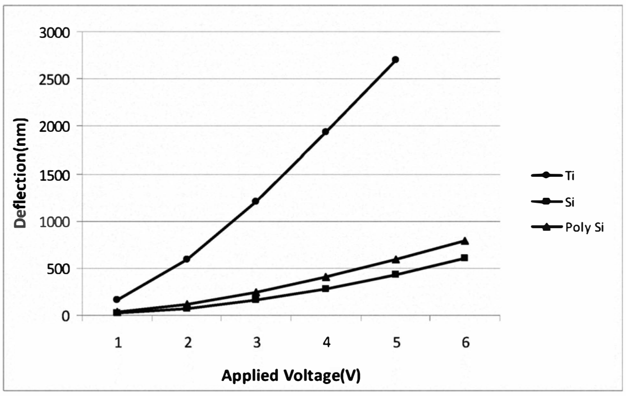

Figure 10. Plot between Applied Voltage & Maximum deflection

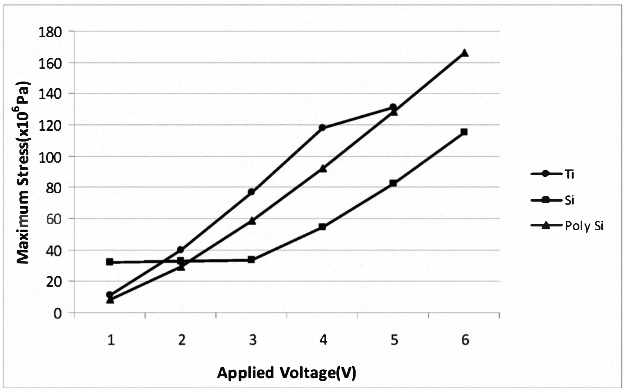

Figure 11. Plot between Applied Voltage & maximum Stress

TABLE III. COMPARISON OF STRESSES.

Material	Stress Range: Case I(MPa)	Stress Range: Case II(MPa)
Poly- Si	7.36- 46.28	8.12- 166.30
SCS	32.14- 34.13	32.21- 115.00
Ti(up to 5V)	6.09- 46.44	11.38- 131.10

The stresses developed in this method are also found to be greater than that in Case I. But this does not create any difficulty, since the values are less than the failure limit of the materials in each case. A comparison with Case I is tabulated in Table III. The graphical representation for maximum stresses in the second case is shown in Fig. 11.

V. CONCLUSIONS

This study predicts the behavior of the three materials namely Single Crystal Silicon, Poly-Silicon and Titanium for the micro thermal actuator used in MEMS. Titanium comes out to be a suitable material for achieving higher deflection at a lower applied voltage compared to the other two materials. But it is accompanied by more increase in temperature. If there is a limitation to the allowable temperature of a system, then the best suitable material is Single Crystal Silicon. For moderate temperature generation and deflection, Poly-Silicon is suitable.

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