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COMPARATIVE STUDY OF DIFFERENT MICRO-THERMAL ACTUATORS FOR MEMS APPLICATION

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This paper presents a comparative study of three micro-thermal actuators which differ in their construction & material being used. Model-I is the basic model and Model-II and Model-III are developed with a view to achieve improved performance over Model-I. The main objective of this analysis is to achieve greater deflection from the considered actuator models under a range of applied voltages. Apart from deflection analysis, analyses for temperature distribution and stress developed in the actuator models are also carried out for feasibility study. The materials under consideration are Poly Silicon, Single Crystal Silicon and Titanium. The software used for modeling and simulation is Comsol Multiphysics.

Keywords: Micro-thermal actuator; MEMS; Comsol.

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1. Introduction

The acronym MEMS stands for Micro-Electro-Mechanical-System. It is also known as Microsystem Technology in Europe and as Micromachines in Japan. These systems integrate sensing, actuation, computation, control, communication and power. The most intriguing characteristic of MEMS is micro-scale mechanical movement which helps in reducing size, power consumption and cost as well as improving accuracy.[1] An actuator in MEMS is used for gaining controlled movements by using electrical or magnetic energy. It works on several principles such as thermal, pneumatic, shape memory alloy (SMA) effect, bimetal effect, mechanical thermal expansion etc. 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. Corntois and Bright[2] have concluded that electro-thermal actuators made of polycrystalline silicon (poly-silicon) are capable of large deflections and high forces in a current/voltage regime that is compatible with standard integrated circuit electronics. Individual thermal actuators typically operate at 2V to 9V, and 1mA to 5mA. Two arm thermal actuators, which are also known as thermal bimorph actuators, in arrays have been used in self-assembly designs[3], and for actuation of micro-mirrors[4]. Huang and Lee[5] have developed and implemented an analytical model to predict the thermal and deflection response of the actuator. The model assumes conduction through polysilicon and air as the major mode of heat transfer and radiation being active only at high input powers. Enikov and Lazarov[6] have described the development of thermal micro-actuators on printed circuit boards i.e. PCB-integrated metallic thermal micro-actuators. They have found that in comparison to silicon devices, metallic thermal micro-actuators have a larger thermal expansion coefficient and can thus undergo larger deformations for a given temperature difference. Alternatively, since the power required for keeping the switch closed is dependent on the heat dissipation to the surroundings, for a given stroke, the metal actuator will operate at a lower temperature resulting in lower steady-state power consumption. Improvements in power consumption can also be achieved by modifying the nature of the underlying substrate.

MEMS devices require very sophisticated machineries and approach for fabrication. The fabrication processes consist of layer by layer deposition of material or etching. Since without a nearly perfect design these modes of manufacturing become quite difficult, proper design and simulation to test an article's usability is very important before-hand to manufacturing. An error free and feasible design is of utmost importance in MEMS fabrication.

2. Principle and Design

The actuator taken for basic analysis, i.e. Model-I, is a two arm horizontal U shaped thermal actuator as shown in Fig.1. The principle and the basic design are explained as follows.

This system utilizes two beams of contrasting size made of the same material and joined together mechanically. A current is passed through the entire system and travels from one fixed end or anchor to the other. In case of the thin arm, the resistance to current flow is much greater than the thick arm and so the temperature rise in thin arm is more than that in thick arm. Thus, when a current flows through the actuator the expansion in the thin arm is more than that in the thick arm due to variation in cross section and which results in the deflection of the actuator.

Model-II is also a two arm horizontal U-shaped thermal actuator constructed by varying the length of the arms and keeping their cross-sections same. Basic geometry of Model-II is shown in Fig.2. This is also monometallic in construction. In this case the resistances offered by the two arms differ due to change in length. A current is passed through the entire structure from anchor to anchor, heating the longer arm while leaving the short arm relatively cooler. Large thermal stresses will develop in the longer arm as it tries to expand due to increase in temperature, and the differential stress between the arms will cause the entire system to deflect vertically downward.

The three materials incorporated for the analyses of these models are namely Poly-Silicon (Poly-Si), Single Crystal Silicon (Si) and Titanium (Ti). Poly-Si and Si are semi conductor materials while Ti is a metal. Si and Poly-Si are widely used materials in MEMS applications. Some metals like Ni, Cu, Au, Co and Ti and their alloys are also used in MEMS devices as structural materials. Ti is ductile, has higher coefficient of thermal expansion and higher yield strength. Hence it can be used for sensing and actuation. So, Ti has been selected along with Si and poly-Si to compare its performances with the Si and poly-Si. The properties of the materials used are taken from the material properties database of the software used.

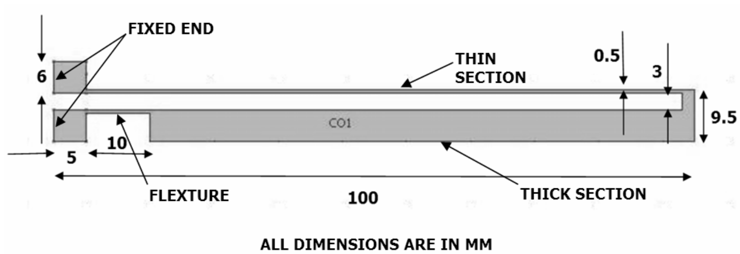

Fig.1. Basic geometry of Model-I & III

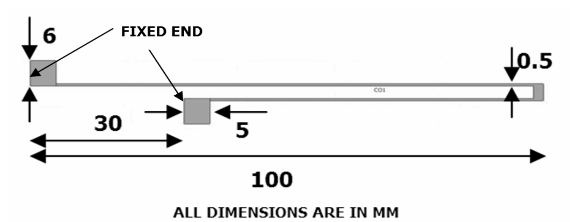

Fig.2. Basic geometry of Model-II

Model-III employs two materials simultaneously for its construction. Ti is provided in the thin arm and Poly-Si is provided in the thick arm. Since, the upper thin arm is under tension and lower thick are is under compression. In geometry, this is similar to Model-I. The actuators with the presented design can be used as the limbs for micro grippers, actuating links for deflection of capacitor plates in tunable capacitors etc.

A comparison of these three models in terms of their deflection, temperature and stress distribution is presented in this paper. The modeling, simulation and analysis have been carried out using the software called Comsol Multiphysics.

3. Problem Formulation

3.1. *Assumptions*

The following assumptions are considered while carrying out the analysis.

(i) The actuator is operated at steady state.
(ii) All the materials are homogeneous and isotropic.
(iii) Non deformed temperature of the materials is 25ºC (298 K).
(iv) 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.[7]
(v) 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 and heat losses through air to the substrate due to convection.[7]
(vi) At high input voltage, the radiation heat becomes significant because of the high temperature induced by the Joule's heating. Since the voltage range of analysis is 1V to 8V, radiation heat transfer can be neglected.
(vii) The inner faces of the small gap between the two arms of the actuators constitute a static air gap acting as an insulating layer.

3.2. *Boundary Conditions*

This work comprises of three energy domains - electrical, thermal and structural. The boundary conditions for the coupled electric–thermal– elastic analysis are as follows:

Electric field: A potential difference (V) is applied across the fixed ends of both the arms of the microactuator.

Thermal field: Air surrounding the microactuator is assumed to be at 25 ºC. As all surfaces of the microactuator are in contact with surrounding air, the problem is modeled as conduction problem. Hence, a temperature of 25ºC is assumed to be maintained on each surface. Heat dissipation by convection and radiation is neglected. In order to realize the assumptions in the simulation environment of Comsol Multiphysics, all the outer faces of the actuator models are given conductive heat flux boundary conditions and the inner faces are kept thermally insulated.

Structural field: One end of the device is considered to be fixed without any displacement as it lies on the substrate, while the other end is made free for deflection. The stress is developed due to the bending of the structure. It should remain within the maximum allowable limit for the material. This limits the maximum deflection of the cantilever and hence the maximum voltage applied on the device. In this analysis, Von Mises stress is calculated.

4. Analysis Methodology

Taking into account all the above assumptions and boundary conditions during analysis, a comparison of Model-I, Model-II and Model-III is carried out on the basis of the maximum deflection attained by the actuator, the temperature generated, and the maximum stress developed in the actuator. At each and every step of the analysis, temperature and stress values are compared with the permissible limit for the respective material. The concern objective of the analysis is to achieve possible higher deflection so that generated temperature and developed stress lie within the permissible limit.

The type of elements chosen is tetrahedral elements, which are the default elements given by the software. These elements are suitable for dividing the 3-dimensional geometry even with curved surfaces and edges. The default mesh by the software is chosen for each model. The Model-I and Model-III are geometrically same. In these models the number of tetrahedral elements is 23082. In case of the Model-II, the number of tetrahedral elements is 21389.

5. Results and Discussions

In this study three different models of thermal actuators are considered. Model-I is the basic model where the preliminary analyses are carried out. The independent variables that have been considered for this analysis are the variation in length, cross section and material. Analysis is carried out for deflection, temperature generated and stress developed by the actuator. The main concern of the analysis is to achieve more deflection at a low applied voltage. Attention is also provided to the developed stress and maximum temperature generated in the actuator so that these parameters remain in the permissible limit. The data for maximum deflection, temperature and stress developed are taken between 1V to 8V. It is observed that the generated temperatures and stresses fall within the permissible limit. The temperature should be below the melting point of the material being used. Also stress is examined by comparing it with failure limit. The following observations are made after analysis.

The deflection patterns for Model-I and Model-II are shown in Fig.3 and Fig.4 respectively. The deflection given by the Model-II is much less than that given by Model-I. This is true for all the aforementioned three materials. The comparison of deflections in Model-II using Poly-Si with Model-I using the same material corresponding to the range of voltages is shown in Fig.5. In Model-I, at the same applied voltage, Ti gives maximum deflection out of three materials at each and every voltage. This is seen in the Fig.6. In case of temperature, Ti achieves the maximum temperature. The increase in temperature is not significant in case of Si. Temperature plot of Model-I can be seen in Fig.7. The stress values lie within the permissible limit and this can be observed in Fig.8 for the three materials in Model-I.

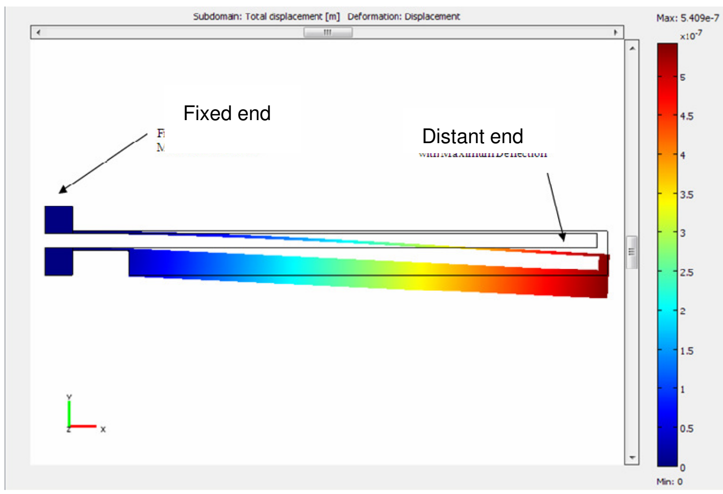

Fig.3. Deflection of Model-I

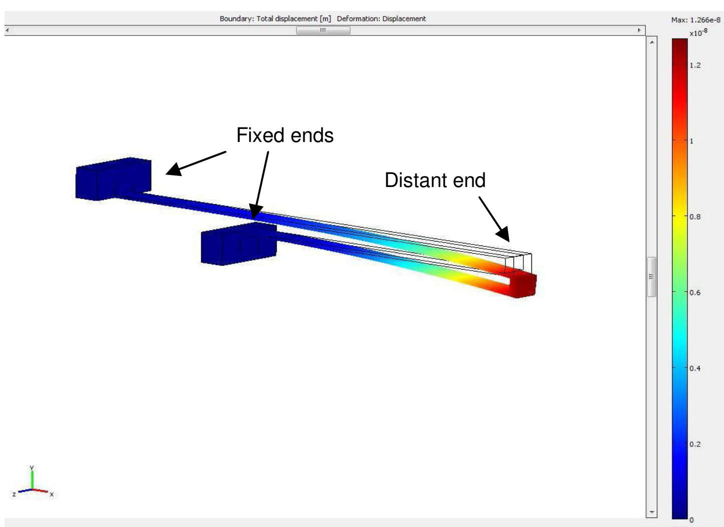

Fig.4. Deflection of Model-II

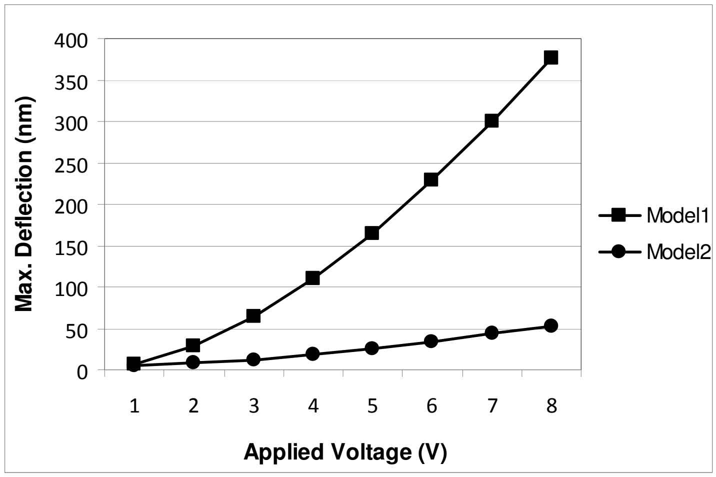

Fig.5. Comparison of deflections in Model-II using Poly-Si with Model-I using the same material

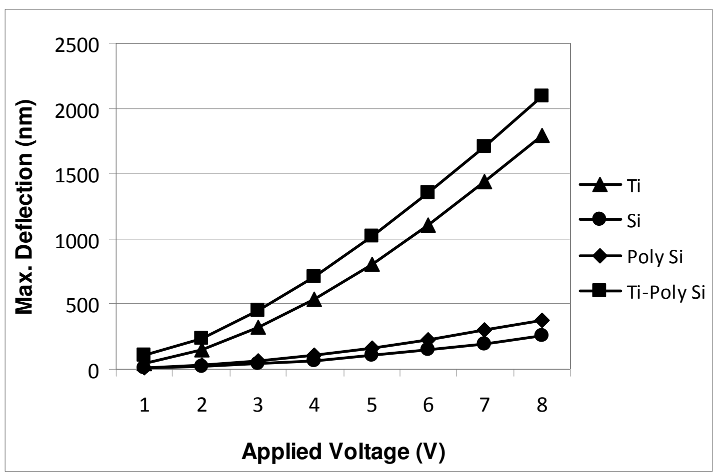

Fig.6. Comparison of deflection for Model-III (Ti-Poly Si) with Model-I (Ti, Si, Poly-Si)

Model-III shows a very good performance in terms of deflection for the applied voltage range of 1V to 8V. The thin arm uses Ti and the thick arm uses Poly-Si. The two arms are of the same length. By incorporating these two materials it is observed that the deflection increases at a much faster rate. Moreover, the rise in temperature and stress developed fall within the limit. So, this actuator can be used for getting higher deflections. The plot in Fig.6 shows its comparison with Model-I (using Ti, Si and Poly

Si) for deflection. But there is a limitation to the applied voltage and this must be kept below 8V. In this range, the temperature generated in the actuator falls within the safe zone. The comparison of Model-I and Model-III in terms of temperatures and stresses can also be observed in the two plots shown in Fig.7 and Fig.8. Figure7 shows that the temperature generated for the specific range of voltage for Model-III with Ti-Poly Si and Model-I with Ti are almost same. Again from Fig.8, Model-I with Ti, Poly Si and Si have lower stress generation as compared to Model-III (with Ti Poly Si). Therefore Model-III has a disadvantage regarding higher stress generation.

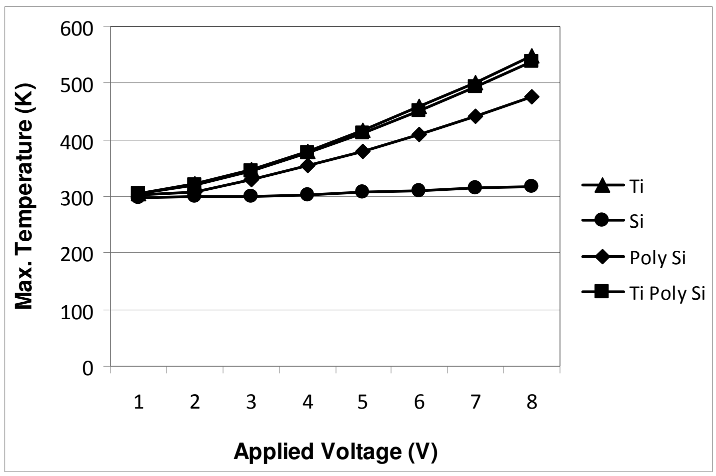

Fig.7. Comparison of temperatures for Model-III (Ti-Poly Si) with Model-I (Ti, Si, Poly-Si)

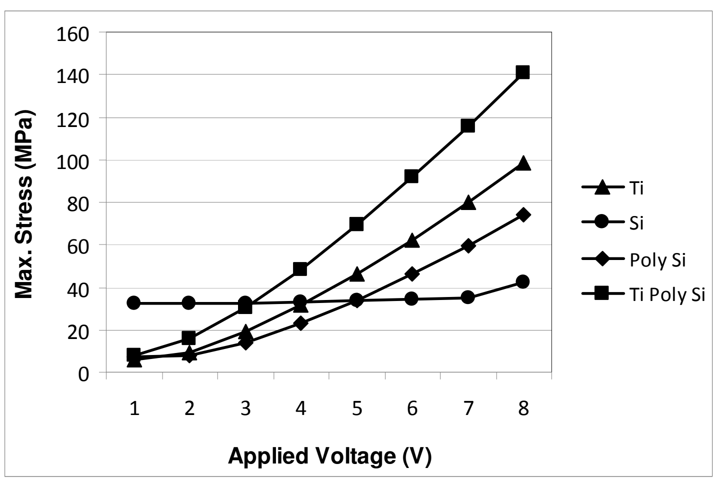

Fig.8. Comparison of stresses for Model-III (Ti-Poly Si) with Model-I (Ti, Si, Poly-Si)

6. Conclusions

The following conclusions are derived after carrying out above analyses.

- For Model-I, in order to achieve higher deflection at low applied voltage, out of the three materials i.e. Poly-Si, Si and Ti, the best suitable one is Ti. But it is accompanied by more increase in temperature. If there is a limitation to the allowable temperature of a system, the best suitable material is Si as it shows a very low change in temperature compared to the other two. For moderate temperature and deflection, out of these three materials Poly Si is recommended.
- Model-II does not satisfy the basic need i.e. higher deflection in comparison to the Model-I. Instead it provides much lower deflection as compared to Model-I.
- Model-III shows higher deflection than Model-I within the applied voltage range of 1V to 8V. But due to more stress development there is a limitation to the applied voltage. Below 8V, Model-III is the best suitable one for achieving greater deflections.
- The temperature attained in Model-III lies within the safe zone for the materials and if the system, of which Model-III is a part, allows this much of increase in temperature; no difficulty arises for using this Model-III below the applied voltage of 8V.

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