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Design, Analysis and Comparison of Multilayer Electro Thermal Micro Actuators for MEMS Application

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Abstract

This paper presents the design, analysis and comparison of two different types of multilayer electro thermal actuators for MEMS application, consisting of Titanium (Ti), Silicon Dioxide (SiO_2) and Poly-Silicon (poly-Si). Deflection, temperature and force analyses have been carried out for a range of applied voltages within 5V using the software *CoventorWare*. The types of actuators designed and analyzed in this work are solid cantilever actuator and slotted U-beam type cantilever actuator. At first, the solid cantilever actuator has been analyzed by applying a potential difference across the ends of Ti layer for different thickness of the actuator. Then the slotted cantilever of U-beam type has been analyzed by applying a potential difference across the fixed ends of the Ti layer. Comparison between solid and U-beam type actuators has been made. It has been observed that the deflection of the actuator decreases with increase in the thickness of each layer. However the temperature and the force at the fixed end increases. On comparing the results of the solid and the U-beam it has been observed that even though the deflection of the U-beam is less than that of the solid beam the temperature and the force at the fixed end in case of U-beam is also very much lesser which increases the controlling limit of the device in terms of applied voltage. Thus it has been found that selection of U-beam type slotted cantilever is preferable over the solid cantilever.

Key words: MEMS, Micro, Actuator, Electro thermal

1. Introduction

MEMS has been identified as one of the most anticipating and assuring technologies for the 21st Century. This has the potential to dramatically affect all of our lives and the way we live. It is already on its way to revolutionize both industrial and consumer products by combining silicon-based microelectronics with micromachining technology.

Sensors and actuators are the integral parts of any MEMS devices. Sensors detect the variations in signals and measure these, while actuators perform the required actions. Among the different types of actuators electro-thermal actuators are one of the most effective types as they can deliver a high specific work (force–displacement product per volume) compared to other types of microactuators. Burns and Bright (1997) compared single and double hot arm thermally-driven actuator designs, and demonstrated various devices constructed with the new thermal actuator design. Chiao and Lin (2000) studied the self-buckling behaviour of micro machined beams under resistive heating. This model consisted of both electro-thermal and thermo-elastic actuators. These actuators were analyzed for beam-shape poly-Si microstructures that were fabricated by a standard surface micromachining process. Chen *et al.* (2003) designed and fabricated a novel bi-directional out-of-plane electro-thermal actuator. The specialty of this actuator is that it can move in two directions unlike the bi-metal and hot-cold arm thermal actuator. Wu and Xie (2008) have undergone the study of a large vertical displacement electro-thermal bimorph micro actuator with almost no lateral shift. They used a unique three-bimorph actuation mechanism to achieve lateral shift free (LSF) piston motion. Tod and Xie (2008) have reported a simple electrothermomechanical lumped element model (ETM-LEM) that describes the behaviour of an electro thermal bimorph actuator. They integrated an electrothermal LEM of a heater with a thermo mechanical LEM of a bimorph actuator to develop the ETM-LEM.

In this paper, an attempt has been made to analyze multilayer electrothermal actuators using *CoventorWare* software package.

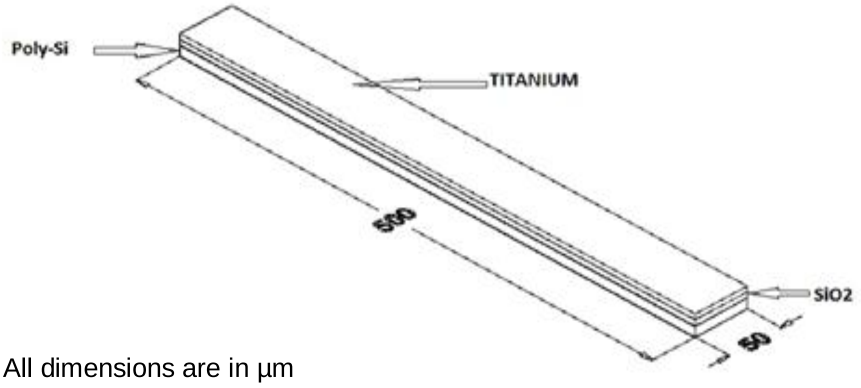
2. Detailed Objective

The main objective of this paper is to design and analyze multilayer electrothermal microactuators of various shapes using *CoventorWare* software package. The detailed objectives are as follows.

- To design and analyze a model of 3-layer electrothermal actuator of solid rectangular type.
- To design and analyze a model of 3-layer electrothermal actuator of slotted U-beam type.
- Types of analyses to be done:
    a. Displacement analysis of the nodes.
    b. Temperature analysis of the nodes.
    c. Nodal Force analysis.
- To compare the Solid and U-beam type actuators.

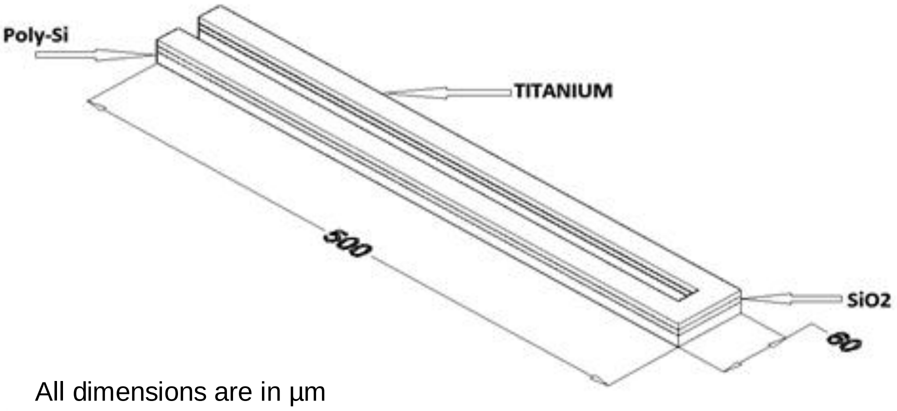
3. Work Definition and Methodology

Two types of cantilever actuators have been designed and analyzed, each of which consists of three layers of materials *viz*. Titanium (Ti), Silicon Dioxide (SiO_2) and Poly-Silicon (poly-Si) of different thicknesses as shown in Fig. 1 and Fig. 2.



All dimensions are in µm

Fig 1: Solid Cantilever actuator having three layers.



All dimensions are in µm

Fig 2: Slotted U-beam type cantilever having three layers.

The major reasons for selecting these three materials are availability of their fabrication techniques and adequate information about their properties. The top layer is of Ti, the middle layer is of SiO_2 and the bottom layer is of poly-Si. The Ti layer is selected because it is having higher coefficient of thermal expansion (CTE). The poly-Si layer is selected because it has a high value of Young's modulus, while the SiO_2 layer acts as an insulator. The higher value of Young's modulus of poly-Si helps in better tip deflection of the beam. The heat dissipation into the surrounding of the device is assumed to take place by conduction as in microstructure the Rayleigh's number is very small. The thicknesses of Ti, SiO_2 and poly-Si layers are varied in the range of 1µm to 3µm in order to get the design having best performance. The following assumptions are made in these analyses.

- The device is operated at steady state.
- The materials are assumed to be homogeneous and isotropic.
- The device is operated at a surrounding temperature of 298K.

There are four basic steps to be performed in the analysis using the software. These are given below in brief.

a. **Modelling:** The 3-D modelling of the design has been done using designer tools of *CoventorWare*.
b. **Mesh Generation:** Meshing of the design is done using Manhattan Bricks in the mesher settings.
c. **Boundary Condition:**
    - Electric Potential
        - Solid Beam: A potential difference is applied across the free and fixed ends of the Ti layer assuming the other outer surfaces to be electrically insulated.
        - U-shaped Beam: A potential difference is applied across the fixed ends of the Ti layer.
    - Geometrical Constraint: One end of the beam is kept fixed while the other end is kept free like a cantilever.
    - Temperature: The surface temperature of the beam is considered to be 298K.
d. **Solution:** Finally the model has been solved by using Electro Thermo Mechanical Module of the analyzer.

The equations used in evaluating the results are as follows:

$$V = \rho \frac{L}{A} \tag{1}$$

$$H = \frac{V^2}{R} t \tag{2}$$

$$F_r = EI \tag{3}$$

$$F \propto \frac{1}{F_r} \tag{4}$$

Where V is the voltage applied

ρ is the resistivity of the material

L is the length

A is the cross sectional area of the material layer

H is the heat produced due to Joule Heating

R is the resistance

t is the time for which voltage is applied

F_r is the flexural rigidity

E is the Young's modulus of elasticity

I is the moment of inertia of the beam

F is the flexibility

4. Results and Analysis

When voltage is applied the temperature rises because of Joule heating and as a result linear expansion of Ti layer takes place. Due to the insulating effect of SiO_2 layer, Joule heating is not transmitted to the poly-Si layer and hence no linear expansion is there. As a result of the two effects, deflection of the cantilever beam occurs at the tip. This deflection increases the stress on the cantilever.

The U-beam design has added advantage over the solid cantilever actuator in the following manners.

- The voltage is applied across the two fixed ends; this is much easier than applying voltage between fixed and free ends.
- The slot cut in the middle or the U-shape reduces the mass of the actuator to some extent.

The performance of the actuator depends on the tip deflection and hence the cantilever beam is analyzed for the deflection, temperature and force by varying the thickness of each layer and applied voltage.

i. *Deflection Analysis*:

For the deflection analysis in both the types of cantilevers, first the thickness of the Ti layer is varied keeping the thickness of the other two layers constant and then varying the applied voltage in a gradual manner. Same procedure is followed for varying the thickness of the SiO_2 layer and poly-Si layer. Deflections of both solid and U-beam type cantilevers throughout the length at 1V are shown in Fig. 3 and Fig. 4 respectively.

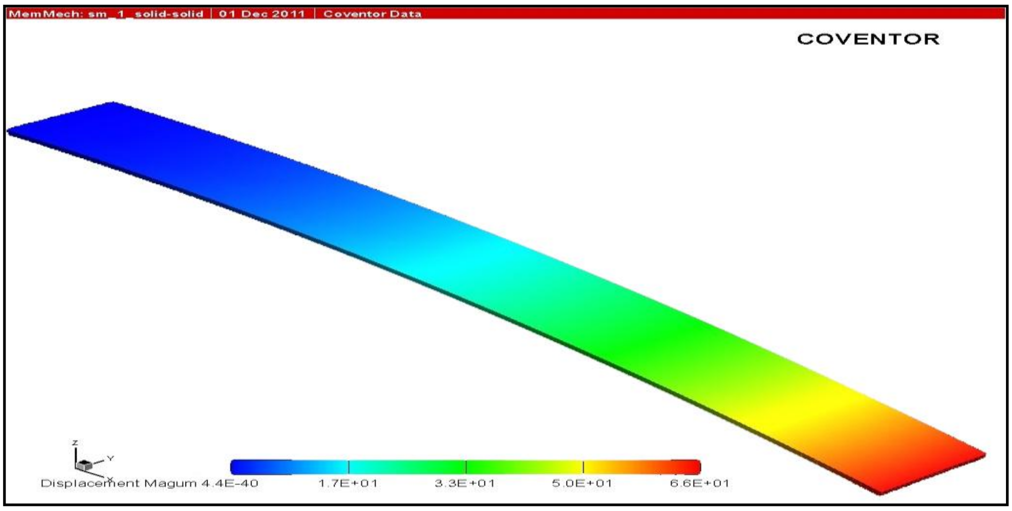


Fig 3: Deflection of solid beam at 1V having thickness Ti=1µm, SiO_2=1µm, poly-Si=2µm

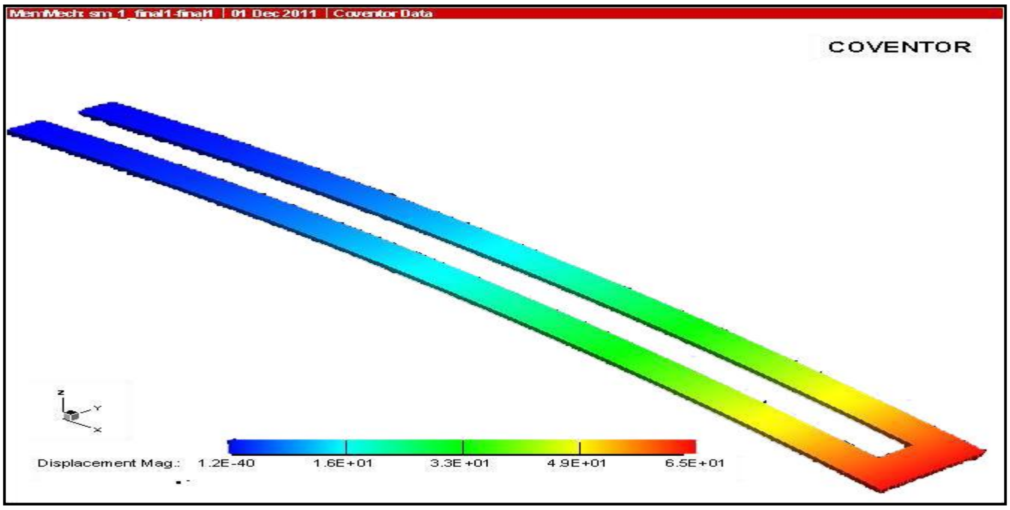


Fig 4: Deflection of U-beam at 1V having thickness Ti=1µm, SiO_2=1µm, poly-Si=2µm

All the observations for variation of Ti layer for both solid and U-beam type cantilevers are summarized in the plot shown in Fig. 5 and Fig. 6 respectively. It is observed that when the thickness of the Ti layer increases the deflection of the device decreases. As the thickness increases, the cross sectional area increases which decreases the resistance and hence the Joule heating increases. As a result, the linear expansion of the Ti layer increases but increase in thickness increases the moment of inertia. The increase in moment of inertia increases the flexural rigidity which thereby decreases the flexibility of the beam as per Eq. 3 and Eq. 4. Hence the tip deflection of the beam decreases.

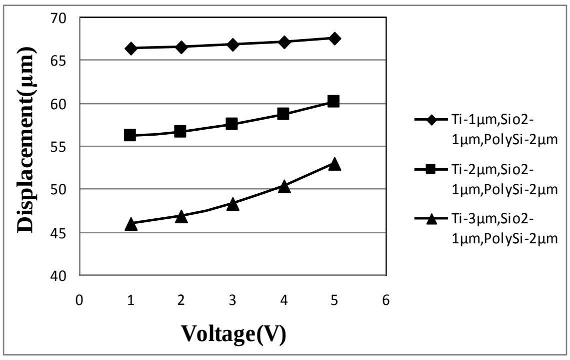


Fig 5: Tip deflection of solid beam at different thickness of Ti layer

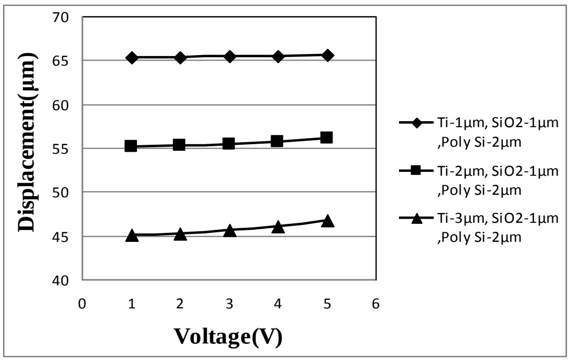


Fig 6: Tip deflection of U-beam at different thickness of Ti layer

Similarly when the thickness of both poly-Si and SiO_2 layers increases for both the cantilevers, deflection in the device decreases. Increase in the thickness of the poly-Si and SiO_2 layer increases the moment of inertia of the beam which increases the flexural rigidity of the structure. As a result the flexibility of the beam decreases which reduces the tip deflection of the beam.

ii. *Temperature Analysis*:

Temperature analysis is done by varying the thickness of each layer of both the cantilever beams along with the voltage. The variation of temperature with the variation of thickness of the Ti layer for both the beams is shown in the Fig. 7 and Fig. 8. With the increase in the Ti layer the temperature increases due to the increase in the Joule heating. The increase in cross sectional area, decreases the resistance, increases the Joule heating which in turn increases the temperature. The maximum temperature attained at 5V in case of solid beam is 350.6 K and for slotted U-beam type beam it is 330.57K.

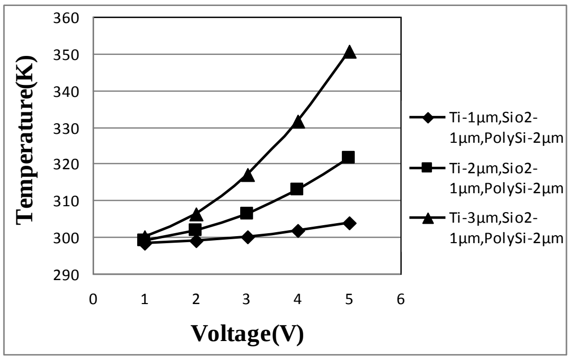


Fig 7: Maximum temperature of solid beam varying Ti layer thickness

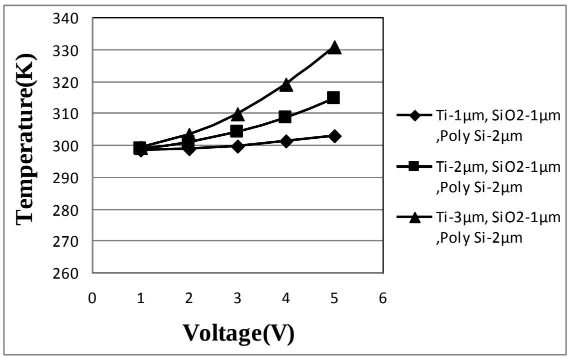


Fig 8: Maximum temperature of U-beam with with varying Ti layer thickness

With the variation of the thickness of the SiO_2 layer and poly-Si layer there is no change in the temperature of the beam. It is so because the insulator (SiO_2) which prevents the transfer of heat from the Ti layer to the poly-Si layer.

iii. *Force Analysis at the Fixed End*:

Force analysis is done by varying the thickness of each layer of the device along with the voltage. As the device is a cantilever structure, force is the maximum at the fixed end of the device. The variations of force at the fixed end of the device with the variation of the thickness of the Ti layer for both solid and U-beam type cantilevers are shown in the Fig. 9 and Fig. 10 respectively. With the increase in the thickness of the Ti layer force at the fixed end of the device increases. It is due to the increase in the temperature of the device. Moreover the increase in the moment of inertia of the device increases the bending moment which increases the force at the fixed end.

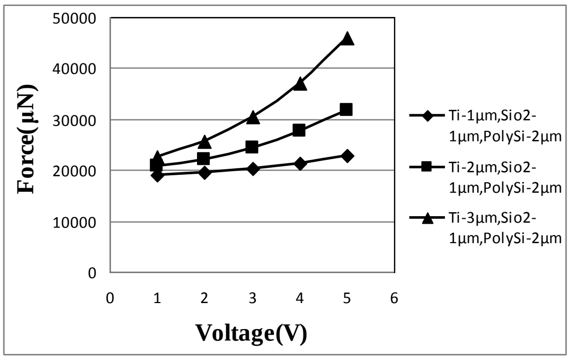


Fig 9: Force at the fixed end of solid beam with varying Ti-layer thickness

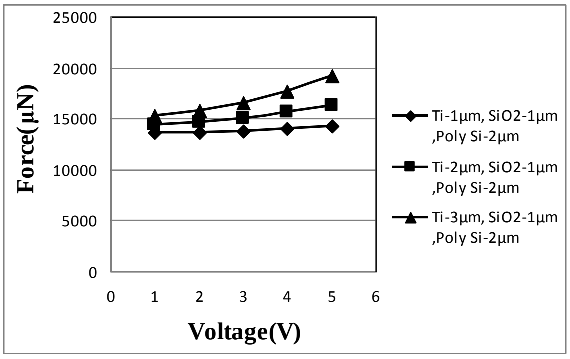


Fig 10: Force at the fixed end of U-beam with varying Ti-layer thickness

Similarly increase in the thickness of SiO_2 and poly-Si layers increases the force at the fixed end which is because of the increase in the moment of inertia. The increase in the moment of inertia results in increase in the bending moment and hence force at the fixed end for both the cantilevers.

5. Comparison between Solid and U-beam Actuators

From the analyses done for the solid and the U-beam cantilever it has been found that as the applied voltage increases the Joule heating increases. The heating effect increases the tip deflection, temperature and the stress at the fixed end for both the solid and U-beam actuators. This increase in the stress value at the fixed end reduces the controlling limit in terms of applied voltage. Comparing the solid and the U-beam, the deflection for the U-beam is found to be less than that of the solid beam. In case of the slotted cantilever device the length of the electric current path is more and cross sectional area of the current path is less compared to the solid cantilever device. This results in the increase in resistance due to which Joule heating effect decreases. Moreover there is increase in the heat dissipation area of the slotted cantilever which reduces the temperature of the device. Because of this temperature reduction controlling limit of the slotted cantilever increases significantly.

6. Conclusions

From the above analyses the best results for each actuator have been shown in a tabular form and are compared.

Geometry	Deflection(μm)	Temperature(°C)	Force(μN)
Solid beam	67.5069	303.84	22796.0
U beam	65.5915	302.81	14228.5

Table 1. Results for each actuator for an applied voltage of 5V and thickness Ti-1μm,

SiO_2-1µm and poly-Si-2µm

From the Table 1 it has been found that the deflection and temperature for both the beams are almost same with minor variations but the force at the fixed end decreases drastically for the U-beam compared to the solid beam. Hence it can be concluded that:

- The controlling limit of the U-beam is higher than solid beam in terms of the applied voltage and hence a voltage greater than 5V can be applied.
- U-beam is the better design out of the two designs that have been analyzed.

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