Analysis of a Chevron Beam Thermal Actuator

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Abstract. Thermal MEMS (Micro-Electro-Mechanical Systems) actuators and sensors have a wide range of applications. The chevron type thermal actuators comparatively show superior performance over other existing electrostatic and thermal actuators. This paper describes the design and analysis of chevron type thermal actuator. Here standard design of Chevron type thermal actuator is considered which comprises of proof mass at center and array of six beams of a uniform cross section of 3x3 microns and an initial angle of 5°. The thermal actuator was designed and analyzed using analytical and finite element method and the results were compared. The model was also analyzed for initial angles of 2.5° and 7.5°, and the results were compared with FEA model. The cross section of the beam was varied and the finite element analysis of all three models was compared to suggest the best suitable thermal actuator structure.

1. Introduction

In last two decades, a wide variety of magnetic, electrostatic and electro-thermal microelectromechanical systems (MEMS) actuators, have been investigated [1]. Electro-thermal actuators in Microelectromechanical systems consist of an important class of MEMS actuators which has tremendous potential in micro-actuation applications. A significant amount of research efforts have been attracted by electrothermal actuators due to its compact geometry and also relatively large displacement in perpendicular and parallel direction to the substrate, compared to other type of actuators.

MEMS devices have a lot of applications in all fields [1]. MEMS accelerometers are used in automobiles for airbag deployment and electronic stability control. MEMS Gyroscopes are used in automobiles, helicopters, planes for detecting roll, pitch and yaw angles. Inkjet printers use thermal bubble ejection to deposit ink on paper. MEMS have a number of uses in bio-medical which includes biochips for detection of hazardous chemical and biological agents, and Lab-on-Chip biosensors and chemo-sensors. MEMS thermal sensors and actuators are used in space exploration field for temperature measurement and control.

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Guckel [2] developed nickel based bimorph thermal actuator which has been fabricated using LIGA process. He observed large displacement at a thermally induced tip. First order mathematical model for thermal actuator via analytical technique was also further proposed by him. Design and modeling of bimorph thermal actuators have been well developed since then [3]. The main principle behind these thermal actuators is to achieve displacement in a microstructure by thermal expansion, which depends upon cross section area, a coefficient of thermal expansion and temperature gradient. Heating of bimorph actuator can be done by ohmic heating that is by passing current through the structure. Depending upon the heating, temperature of structure increases, which will produce a proportionate amount of thermal deflection in the actuator. But deflection in bimorph actuator produces a lot of stress in the cantilever beam, which reduces the range over which bimorph actuator can be used. Force produced for actuation by single polysilicon bimorph thermal actuators can only produce a small force, typically < 10 μN.

Michael J. Sinclair [4] proposed a chevron beam for the temperature measurement. Here an array of beams is packed close together and connected to a third arm to create a movement. It requires more area compare to bimorph thermal actuator but it produces more force for actuation compared to bimorph.

Silicon is one of the most commonly used materials for the production of MEMS devices. The Coefficient of thermal expansion is one of the important property while considering a thermal actuation. For silicon, a coefficient of thermal expansion is not constant throughout its working condition. C. A. Sweson [5] recommended the different values for the coefficient of thermal expansion of silicon. He also suggested analytical equation to represent the expansivity of silicon from 90K to 850K. It increases as working temperature of material increases. Hence a change in dimension per unit rise in temperature of a working condition will be different at different working temperature. It means a change in dimension of silicon material from 100°C to 150°C will be different as compared to change in dimension from 500°C to 550°C.

Analysis of these Silicon based MEMS devices can be done using an analytical model as well as finite element method. Here, in this paper, we designed a chevron type of a thermal actuator. We analyzed this design using FEM to obtain the dimensions for the beam. Also, we compared these FEM results with an analytical model developed for this design, which depends upon design dimension and silicon material properties. We compared the results obtained by changing the initial angle values and cross section in the chevron model to observe its effect on the deflection.

2. Methodology

Chevron beam thermal actuator is basically an array of silicon beams arranged in pairs, and having a predefined initial angle. When these beams are heated, they expand and tend to buckle. The actuator is heated by Joule effect by passing current through the structure. The pre-bent angle (α) present in the beams makes the buckled beam move in the vertical direction as shown in the figure (2).

A central beam or proof mass is attached for allowing the coupling of the beams for a uniform movement and to transmit forces. The amount of movement of the proof mass depends on the angle (α) and the length of the beam. Deformation in the beam can be calculated by using equation (1)

\[
d = \frac{\left | l^2 + 2l' l - l^2 \cos^2(\alpha) \right |}{l} \sin(\alpha)
\]

Where \( l' \) is the elongation in single beam due to thermal expansion, and can be calculated as,

\[
l' = l \times (\text{Coefficient of thermal expansion of material}) \times (\text{Change in temperature})
\]

Here elongation in beam due to thermal expansion will be different for different temperature because the coefficient of thermal expansion of silicon increases as temperature increases that we can observe from equation (6).

As per the requirement, expected deflection in overall actuator will be different for different applications. In this paper, we assumed that expected deflection in a beam, when the temperature increases from room temperature (room temperature assumed to be 22°C) to 500°C is 4 μm. So first we
calculated the coefficient of thermal expansion of silicon at 500°C using equation (6). Then using equation (1), (2) and value of a coefficient of thermal expansion at 500°C, we calculated the length of a beam, which is approximately equal to 200μm. While calculating a length of a beam we assumed an initial angle of the beam with horizontal (α) to be 5 degrees and expected deflection in actuator as 4μm with a uniform square cross section of 3μm of a beam. Based on these design specifications we made CAD model of an actuator as shown in figure (1).

This paper consists of evaluation and comparison of actuators having different cross sections of the beam like a uniform square, single tapered and double tapered. The beam with uniform square cross section has a side of 3μm. The single tapered beam has a cross-sectional area varying from 5μm x 3μm on one side to 3μm x 3μm on the other. The double tapered beam has a cross-sectional area varying from 5μm x 3μm on one side to 3μm x 3μm in the center and again to 5μm x 3μm on the other side. The initial angle of the beam (α) with respect horizontal is taken as 5 degrees. Later, we also compared results of an actuator for 3 different initial angle structures. The number of beams used in the actuator can vary depending on the force to be transmitted and the amount of heating required. In this paper number of beams used on each side of the proof mass is 3.

Any movement of the actuator perpendicular to the plane of the array of beams can be prevented by imposing restrictions on it. In this paper, the actuation is considered only in a single vertical direction.

3. Analytical Model

In this model, a length of each beam is 200μm, which is much larger than its cross section size. So the thermal expansion in the beam was considered as one-dimensional heat transfer. Also, deflection calculated analytically by considering the two-dimensional figure of a structure. Schematic diagram of a structure with all parameters is as shown in figure (2).

Here  
- l is a length of the single beam.
- l’ is an elongation of a single beam due to thermal expansion.
- α is an angle of a beam with a horizontal axis.
- d is a deflection in beam due to thermal expansion.
- L is original length of a beam.

Then we can write relation between L and l as,  \( l = L\cos(\alpha) \) and vertical distance as,  \( L\sin(\alpha) \) or  \( l \sin(\alpha)/\cos(\alpha) \).

So deflection in beam due to thermal expansion can be given by,
\[
\frac{1}{\cos(\alpha)} \left[ l^2 + l'^2\cos^2(\alpha) + 2ll'\cos(\alpha) - l'^2\cos^2(\alpha) \right]^{\frac{1}{2}} = \frac{l\sin(\alpha)}{\cos(\alpha)}
\]

(3)
As values of $\alpha$ and $l'$ are very small, so we can approximate the values of $l'^2$ as 0 and $\cos(\alpha)$ as 1. Therefore the final deflection equation in beam can be simplified as,

$$d = \left[l^2 + 2ll' - l^2 \cos^2(\alpha)\right]^{\frac{1}{2}} - l \sin(\alpha)$$  \hspace{1cm} (5)

Where $l'$ can be found as,

$$l' = L \times (\text{Coefficient of thermal expansion of material}) \times (\text{Change in temperature})$$

Here for this analysis of structure, we considered silicon material, as silicon is most commonly used material for MEMS. C. A. Sweson [5] suggest the analytical equation to represent the expansivity of silicon from 90 to 850K as following,

$$\theta = \alpha + A \frac{x^2 e^x}{(e^x - 1)^2} + B \frac{(y - 1)^2}{1 + by}$$  \hspace{1cm} (6)

Where $\theta = \text{coefficient of thermal expansion}$

$$a = -0.687 \times 10^{-6} K^{-1}$$

$$A = 5 \times 10^{-6} K^{-1}$$

$$B = 0.220 \times 10^{-6} K^{-1}$$

$$b = 0.316$$

$$x = \frac{T}{685}$$

$$y = \frac{395}{T}$$

$T = \text{Temperature in Kelvin}$

Figure (3) represents deflection in structure from equation (5) for temperature range from 50 to 500$^\circ$C (323 to 773 K)

![Analytical Model](image_url)
4. Finite Element Analysis

As like previous analysis model, here also deformation in actuator was calculated for different temperatures but by using finite element analysis (FEA). End bars of structures were considered fixed in boundary condition and temperature of an overall structure was increased from room temperature (considered as 22°C) to 500°C linearly. Meshing of a model was done and it is as shown in figure (4). Material considered for this analysis was Silicon and coefficient of thermal expansion values at different temperature were according to equation (6). Deflection in the structure was calculated at each 50°C interval. Also, stress in a model was checked for that. Deformation in chevron model is shown in figure (5).

Based on the stress distribution of the previous model, we can change the cross section of a beam of a model to achieve good stress distribution by maintaining deformation range. In the first model, a cross section of the beam was 3μm × 3μm which was constant throughout its structure. Later, we changed its cross section to 5μm × 3μm to 3μm × 3μm from the end bar till proof mass. In third model, we changed its cross section as 5μm × 3μm from end bars to 3μm × 3μm till mid of the beam and again to 5μm × 3μm till the proof mass. For all these three structures we performed same analysis by fixing end bars and varying an overall temperature of a structure from room temperature (considered as 22°C) to 500°C linearly. Same silicon material was considered for analysis of a structure and its coefficient of thermal expansion values was based on C. A. Sweson’s [5] equation (6). Deflection and stress values were calculated from these analyses at each 50°C temperature interval and compared those values with previous structure.

From the analytical model, we can observe that the deflection in the actuator depends on the initial angle of the beams. Hence if we change the initial angle, the displacement of the proof mass for same temperature rise will change. In this paper, in a first model, we considered initial angle as 5 degrees. Then in next two models, we changed the initial angle to 2.5 and 7.5 degrees. Analysis performed on these models is same as in the above paragraph. Deflection values were calculated for the analysis of these models and the results were compared.
5. Results and Discussion

As shown above, we analyzed chevron model by using an analytical method and by using Finite Element Method for square cross section area of a beam. We also compared those results as shown in the figure (6)

In the figure (6) we observe that at higher temperature there exists deviation in analytical model and FEA. This deviation happens because while deriving equation (5) we neglected $u^2$ term, which becomes significant at higher temperatures.

Then we performed finite element analysis for other two models by varying cross section of a beam under same boundary conditions and got a deflection of a structure at a different temperature. We compared deflection values of all three structures in figure (7).

In figure (7), we observed that deflection in a beam for different cross section area is almost same. As per the A. S. Usmani [6], based on a fundamental principle of the structural behavior of beam, under thermal effects change in cross section area has very less effect on the overall deflection range of a structure, when a length of a beam is much larger than its cross section size. Beam with less cross section area will have more deflection due to change in temperature in chevron model. So as per the finite element analysis also we observed that as we vary the cross section area deflection of a beam remains almost constant.
For the same structures, we calculated stress values at different temperatures for all three structures using FEA. Figure (8) shows the comparison between three structures for maximum stress values at different temperatures. It indicates that stress values for beams of different cross sections are approximately same for single tapered and double tapered model, while comparatively very less for uniform square cross section area according to FEA.

For also different initial angle models, we performed FEA and analytical model analysis and calculated displacement in the structure by using both the methods. The comparison between displacement values for different initial angle models by using analytical model is shown in figure (9) and by using FEA is shown in figure (10).

Figure (9) and Figure (10) shows that, by using both the analytical and FEA method, as the initial angle decreases, deflection in beam increases, which we can observe from equation (5).

Figure (11) shows the comparison of stress values for different initial angles of a structure. From the figure, we can see that as the initial angle decreases, maximum stress in structure increases.

6. Conclusion

From stress and deflection graphs, we conclude that beam with uniform square cross section area gives more working deflection range for same temperature variation with very little variation in maximum stress value. So beam with uniform cross section area will be more suitable to use for the given chevron model. And from models with different initial angles, we saw that even though a model with initial angle 2.5 degrees have maximum displacement range but stress developed inside that is maximum. So by considering both displacement and stress graphs, a model with 5 degrees as an initial angle should be preferred. Hence, the overall chevron model with 5° as an initial angle and with uniform cross section area of the beam was found to be a more suitable actuator for use.

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