Modeling and Analysis of Thermal Bimorph Using COMSOL

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Abstract: In this paper modeling and simulation results of a thermal bimorph is capable of producing increased displacement for increasing temperatures are presented. Thermal bimorphs are popular actuation technology in MEMS (Micro-Electro-Mechanical Systems). Bimorph actuators consist of two materials with different coefficients of thermal expansion. The main objective of this work is to investigate the deformation in bimorph actuator for varying temperatures. Deformation increases with increase in length of the actuator. Thus, temperature produces thermal strain and thermally induced deformation and this makes the microstructure into a thermal actuator.

Keywords: Thermal Bimorph, microactuator, thermal actuator.

1. Introduction

A bimorph actuator consists of two thin-film layers. Difference in the strains produced in the two layers causes a bimorph to curl, there by leading to actuation [1]. Understanding about the actuation of thermal bimorph actuated probe and investigation of physical phenomena by heat transfer is achieved using finite element analysis methods. Through virtual simulation, the author could predict deflections and temperature distribution [2]. The measurement of temperature and heat is widely practiced and can be achieved using many different principles. In this paper concentrated mainly on thermal bimorph sensors. Thermal bimetallic effect is a method used for sensing and actuation. This mechanism allows the temperature variation in microstructures to be exhibited as the transverse displacement of the mechanical beams. The thermal bimorph consists of two materials joined along their longitudinal axis serving as a single mechanical element. Often a thermal bimetallic actuator may consist of more than two layers of materials [3]. Curved bimorphs undergo combined out-of-plane bending and twisting upon actuation. The analysis procedure outlined in this paper may be extended to bimorphs of arbitrary shape by treating the in-plane radius of curvature, R as a function of the distance along the bimorph [3]. The large out-of-plane bending displacement and force generated by this actuator at a low driving voltage and a low actuation temperature are quite unique characteristics [4]. The presented actuator can find applications where a large vertical displacement is needed and it is fabricated to be small in size, lightweight and low in cost [5]. Bimaterial actuators consist of materials with different coefficients of thermal expansion and function similarly to a bimetallic thermostat [6]. In this paper SiC as a new material for the bottom layer of an electrothermal bimorph actuator is proposed and tested [7]. The actuator, based on a piezocantilever, combines the piezoelectric effect and the thermal bimorph principle [8]. The model agrees with experimental results within 15% for temperature distribution data and 10% for rotation angle versus voltage data for voltages less than 15 V. At higher voltages the experimental results deviate from the results predicted by the model [9]. Thermal bimorph is for the better understanding of relation between performance and design parameters [10].

2. Methodology

Principle of actuation is by increase in temperature heats the bimorph, as aluminum expands more beam bends and results in an angular displacement. A thermal bimorph beam is composed of two material films, with different Coefficients of thermal expansion CTE, bonded at an interface. Typically thermal bimorphs are made of one material with a low CTE, such as a dielectric like Polysilicon, and another material with a high CTE, such as metal like aluminum. When the temperature of the bimorph is raised, the high CTE material will expand more than the low CTE material. Since both materials are bonded together, stress develops in both material layers due to the bonded interface constraint.. The high CTE material exhibits a compressive stress because it is stretched below its equilibrium length, and the low CTE material exhibits a tensile stress because it is stretched past its equilibrium length. The stresses that developed upon an increase in temperature will cause the bimorph to curl towards the Coefficient of thermal expansion of aluminum with α_1=23e^{-6}[1/K] where, the Coefficient of thermal expansion of Polysilicon is α_2=2.33e^{-6}[1/K], low CTE material to minimize the internal energy stored by the stress. However thermal expansion co-efficient for most materials are very small hence amount of displacement would be small.

The temperature at which the bimorph materials are deposited, assuming no residual stress is present from processing conditions, both materials will be at their equilibrium lengths and the bimorph will be flat. The opposite effect happens when the temperature of a bimorph is lowered. The high CTE material will contract more than the low CTE material, and will develop tensile stress. The lower CTE material will be contracted to a length shorter than its equilibrium length and will develop compressive stress. When the temperature of a bimorph is lowered, the bimorph will bend towards the high CTE material to minimize the internal energy stored by the stress. The effects of an increase in temperature to the curl of a cantilevered bimorph are shown in Fig 1.

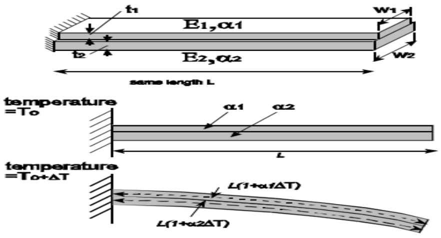

Figure 1 Thermal bimetallic bending ($\alpha_1 > \alpha_2$)

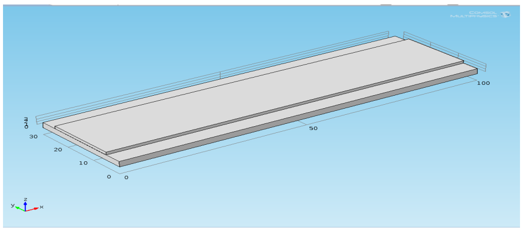

Figure 2 Geometry of thermal bimorphs actuator using comsol 4.2

3. COMSOL Implementation

The proposed structures is modeled and simulated in COMSOL 4.2 simulation software. MEMS module was used to design actuator. In Structural mechanics physics the Joule heating and thermal expansion is selected as physics in order to determine deformations and temperature for varying temp and provide the fixed constraint on one of the edge of thermal bimorph. The polysilicon and aluminum materials are used. In designing thermal bimetallic actuator consist of two metals used as the actuator material, the material properties of polysilicon are Young's modulus: 160[GPa], Density: 2320[kg/m^3], Poisson's ratio: 0.22, Coefficient of thermal expansion ($\alpha1$): 2.6*10^{-6}[1/K], Electrical conductivity: 5*10^4[S/m]. Similarly aluminum is having Young's modulus 70e^9 [Pa], density 2700[kg/m^3] and Poisson's ratio 0.33, where Polysilicon is having Young's modulus 169e^9[Pa], Density 2320[kg/m^3] and Poisson's ratio 0.22.

Comsol simulations were preformed on the thermal bimetallic actuator to investigate the effect of variations in the temperature Vs deformations.

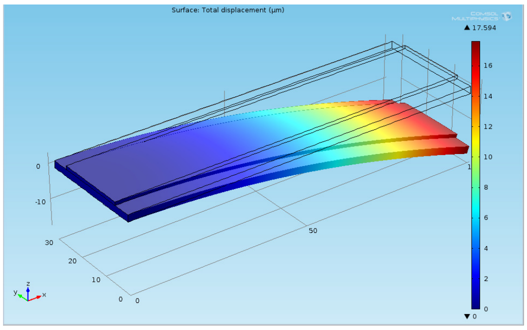

Figure 3 Total displacement is 17.594µm at 1000K and L=100µm ($\alpha2 > \alpha1$)

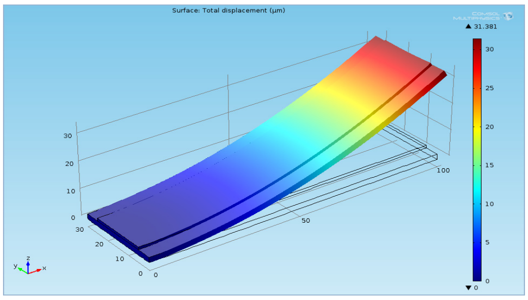

Figure 4 Total displacement is 31.381µm at T_o =1000K and L=100µm ($\alpha1 > \alpha2$).

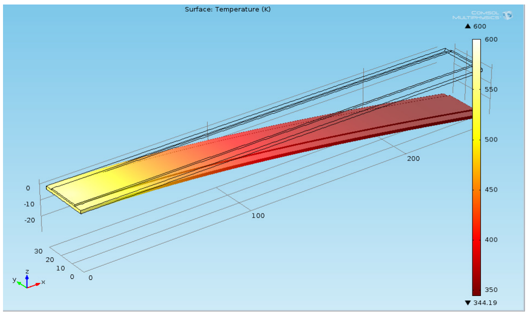

Figure 5 Temperature distribution of thermal bimorph ($\alpha2 > \alpha1$) at T_o =600K and L=250µm, resulting deformation is 29.861 µm.

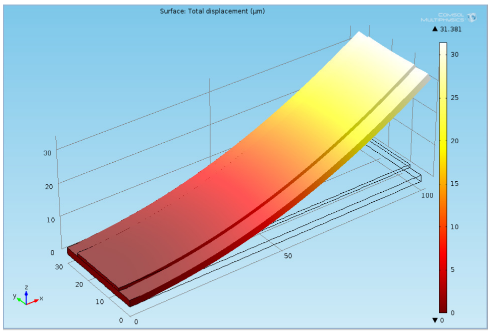

Figure 6 Temperature distribution of thermal bimorph ($\alpha1 > \alpha2$) at T_o =1000K and L=100 µm, resulting deformation is 31.38 µm.

In this work it is shown that by increasing the temperature from 300K to 2500K the deflection also increases from 0.1705µm to 54.93µm shown in Fig 3 and also in Fig 4. Initially in first case aluminum block is placed at bottom and polysilicon block is placed at top layer and observed that as two-layered materials are tightly joined at the interface, the beam curve down towards the aluminum as shown in Fig 5. In second case aluminum block is placed at top and polysilicon block is placed in bottom layer and observed that the beam curves up towards the aluminum as shown in Fig 6. Hence the beam bends in downward direction as CTE of top beam is more and when the CTE of bottom beam is more it bend in upward direction.

4. Thermal Bimorph

The Bimorph cantilever beam is made of two layers of same lengths. Composite beam with two layers, made of materials 1 and 2, having the same length (L) but different coefficients of thermal expansion (CTE) ($\alpha_1 > \alpha_2$) shown in Fig 1. The layer on top is made of aluminum, where as the layer on bottom is made of Polysilicon. The width of both layers is 20µm. In geometry length of the both segment is equal to 100µm as shown in Fig 2. The subscript refers to the material layer. Likewise, Young's modulus, width, and thickness of the two layers are denoted E_i, w_i, and t_i (i=1 or 2). ΔT is Uniform rise in temperature, the length of two sections changes equally. Because the two-layered materials are tightly joined at interface, the beam must curve towards the layer made of the material with lower CTE value. A transverse beam bending is therefore produced. The below equation is analyzed in order to calculate the displacement of a bimetallic beam. Initially values of radius of curvature for uniform change in temperature are determined. Radius of Curvature decreases with increase in ΔT.

$$\frac{1}{r}=\frac{6w_1w_2E_1E_2t_1t_2(t_1+t_2)(\alpha_1-\alpha_2)\Delta T}{(w_1E_1t_1{}^2)^2+(w_2E_2t_2{}^2)^2+2w_1w_2E_1E_2t_1t_2(2t_1{}^2+3t_1t_2+2t_2{}^2)}$$

Let beam curves under uniform change in temperature of ΔT, assume the shape of the section for an arc with length of the arc being L. The radius of curvature of the arc **r** can be calculated using this formula. Where w_1=20µm, w_2=30µm, t_1=1µm, t_2=2µm, E_1=70Gpa, E_2=169Gpa, $\alpha_1=23*10^{-6}$[1/K], $\alpha_2=2.33*10^{-6}$[1/K], let L=100µm, Where α is Co-efficient of thermal expansion. The arc is a section of a circle with radius of curvature being denoted r, spanning an arc angle θ. The value of θ is determined using values of length of the beam and determined radius of curvature as given in following equation

$$\theta = L / r$$

Once the radius of curvature is found, the vertical displacement of the free end of the beam can be determined by trigonometry. The vertical displacement at the free end of the cantilever is given in equation

$$d = r - r \cos \theta$$

If the overall bending angle is small, the magnitude of vertical displacement can be estimated by replacing cos θ with the first two terms in its Taylor series expansion given in equation below.

$$d = r - r\,(1-1/2\,\theta^2 + O\,(\theta^4) = ½\, r\, \theta^2$$

5. Result and discussion

The simulation results obtained in this work corresponds to their analytical models validating the conformity of the analysis using above expressions. Comparisons between Simulated and analytical values for displacement with L=100 µm shown in table 1and corresponding graph is shown in Fig 7. Now for a varying length L=100µm, 150µm, 200µm, 250µm deformations are determined and it is found to be increasing with increase in length of a beam shown in table 2 and corresponding graph representing temperature Vs displacement between the lengths L is varied from 100µm to 250µm shown in Fig 8, here one can say as length of bimorph increases deformation also increases.

Table 1 Comparison of simulated and analytical displacement with L=100 µm.

Temperature difference (K) ΔT	Displacement (µm)	
	Simulated	Analytical*
50	1.2445	1.5819
100	2.4891	3.0432
200	4.978	6.0800
500	12.4484	15.10385
1000	24.891	29.519

Table 2 Comparison of simulated displacement for varying length L=100 µm, 150 µm, 200 µm, 250 µm.

Temperature difference (K) ΔT	Simulated at L=100µm	Simulated at L=150µm	Simulated at L=200µm	Simulated at L=250µm
50	1.2445	2.345	3.565	4.866
100	2.4891	4.6904	7.1297	9.732
200	4.978	9.3804	14.259	19.463
500	12.4484	23.4514	35.657	48.657
1000	24.891	46.901	71.303	97.32

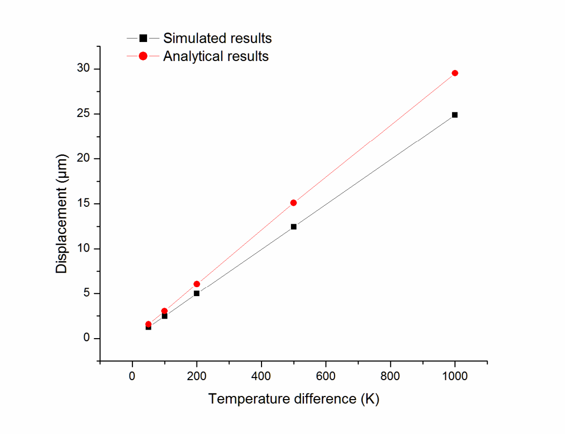

Figure 7 Plot showing Comparison of analytical and simulated results of Thermal Bimorph actuator, at L=100µm.

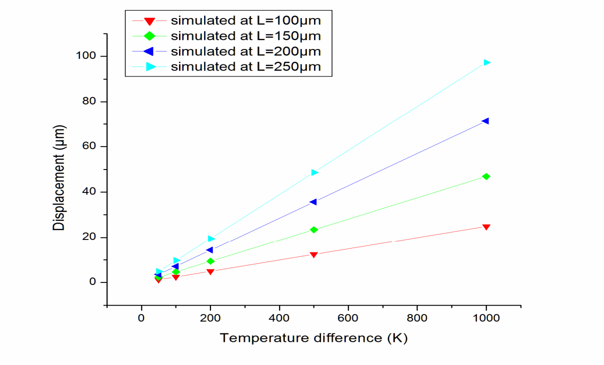

Figure 8 Plot showing increase in deformations for varying length

6. Conclusion

In this work coupled multiphysics simulation and study of the thermal behavior of a thermal bimorph is carried out using COMSOL 4.2. The simulation and analytical results are also compared. Their operating principle is based on differential thermal expansion induced by Joule heating and thermal expansion. Thermal bimorphs and other thermal actuators have been used in many applications, like micro grippers, micro-optical mirrors etc. In most cases open loop control is used due to difficulties in fabricating positioning sensors together with actuator.

7. References

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