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Thermally Controlled MEMS Switch

Prof. Gaurav R. Agrawal
Assistant Professor, Department of Electronics & Telecommunication Engg, Govindrao Wanjari College of Engineering & Technology, Nagpur.

Abstract: *This paper presents calculations, modelling and simulation of thermally controlled MEMS switch. The design is made up of a thermal bimorph. Thermal bimorphs are constructed using two materials with different thermal expansion coefficients. The deflection also depends on material properties such as thermal conductivity, Young's modulus and Poisson's ratio.*

The main objective of this work is to investigate the displacement of around 10µm on the free end of a cantilever structure for a resonance frequency of 1kHz and 4kHz with a drive-in voltage of less than 0.5V. Deformation or displacement also depends on the length of the resonant beams. The applied voltage and the flowing current generates heat in the material and due to different thermal coefficients a stress is generated which acts as a force to drive the free end leading to deformation of the structure, and making the microstructure to operate as a thermal actuator. The simulation is done using finite element modelling by the use of COMSOL Multiphysics environment. Analytical and simulated results are also compared in the report.

Two similar designs of bimorph are studied and modelled deploying different materials. Design 1 consists of Tungsten and Poly-Si whereas the design 2 has Gold and Nickel. Both designs give displacements of 10.2µm and 10.4µm with resonance at 3987.1Hz and 1014.7Hz respectively.

I. Introduction:

The measurement of temperature and heat is widely practiced and can be achievedusing many different principles. One being the use of a bimorph. A bimorph actuator consists of two thin-film layers having different coefficients of thermal expansion. When this actuator is subjected to temperature it causes the strain in the two layers resulting in a bimorph structure 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 simulation, one canjudge the deflections and temperature distribution over the beam [2].

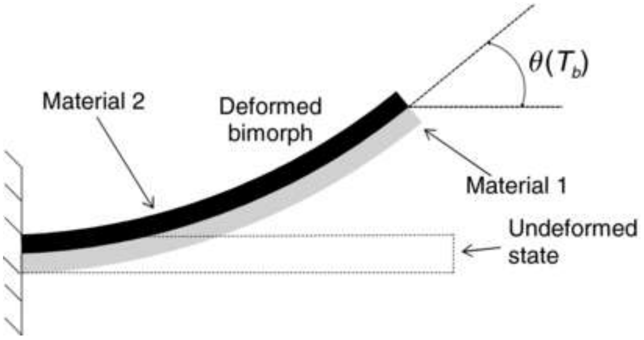


Fig. 1: Schematic of a Thermal bimorph [1]

Bimetallic strips can be used for sensing and actuation. This mechanism allows the temperature variation in microstructures to beexhibited as the 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 two layers of materials. [3]. One can even make a tri-morph or a quad-morph using three or four materials respectively. Depending on the type of materials used and their thermal coefficients, the bimorph may bend in either upward or downward direction.

Another variation in the structure can be made using curved bimorphs. These 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].

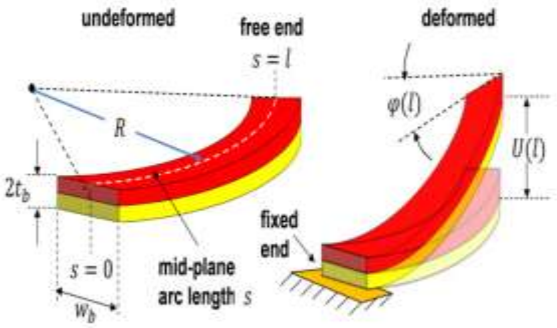


Fig. 2: A curved bimorph [3]

The large out-of-plane bending displacement and force generated by this actuator at a sufficiently smalldriving voltage and a low actuation temperatures are some of theunique characteristics [4]. Bimorphs can be deployed where a large vertical displacement is needed along with being a smaller device, lightweight and cheap [5].

The actuator presented in this report is optimized after understanding the resonant frequencies using different materials. The deflection or bending can be achieved by applying voltages adequate to have the anticipated magnitude. The required specifications for the design being the switch contact area to be 100µm x 100µm with a minimum vertical displacement of 10µm to have off state isolation. The drive voltage for this structure need not be more than 5V. This defines the device dimensions wherein a minimum of 100µm thick bottom layer is required for the operation of the switch. The proposed structure along with the base and contact pad may be shown as:

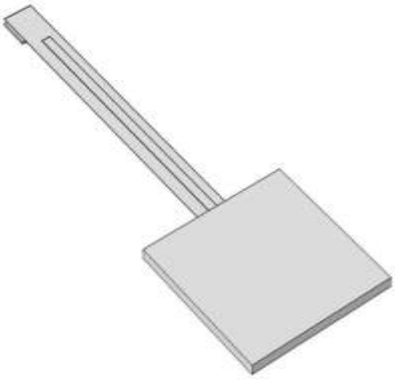


Fig. 3: Proposed design

Device Design:

The thermal bimorph is simulated in finite element software COMSOL which gives enough insight that one can comprehend the operation of the structure along with the device resonance. Different materials having different thermal and mechanical properties were studied for a fixed dimensions to have an understanding of resonance to proceed with the design. The length, width and thickness of bottom and top material were chosen to be 500µm/500µm, 100µm/30µm and 2µm/2µm respectively.

The selection of Gold to be the bottom layer and Nickel to be top layer results in the lowest resonance frequency. Hence, this combination can be used to have 1kHz design. Another combination was selected for 4kHz design in which Polysilicon was selected as bottom layer due to ease of fabrication in sacrificial micromachining process along with Tungsten as top layer. Tungsten is picked due to its lower resonance with polysilicon in bimorph and ease of fabrication.

The dimensions of proposed model of the two bimorph structures are shown in table 1.

	4 KHz design 1		**1 KHz design 2**	
	Bottom Layer (µm)	**Top Layer (µm)**	**Bottom Layer (µm)**	**Top Layer (µm)**
Material	Poly-Si	Tungsten	Gold	Nickel
Length	1000	850	1000	850
Thickness	1	1.5	2	0.75
Width	100	30	100	10

Table 1: Proposed models of thermal bimorph

The bottom and top layers have different lengths so as to have the desired resonant frequencies. Along with the length the width and thickness of the top material needs to be different. The mathematical model that gives deflection of the bimorph can be shown in equations 1,2 and 3 [7,8]. These equations hold true for equal lengths. But give good approximation for different lengths.

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

where w_1,E_1, t_1 and α_1 are width, Young's modulus, thickness and thermal expansion coefficient of top material, w_2, E_2, t_2 and α_2 are width, Young's modulus, thickness and thermal expansion coefficient of top material, δT is the temperature difference and r is the radius of the curvature forming an arc angle θ. The value of θ can be determined by using the length of the cantilever as shown by simple equation 2,

$$\theta = \frac{L}{r} \qquad (2)$$

The vertical displacement of the free end of cantilever can be found by the equation 3 [7,8].

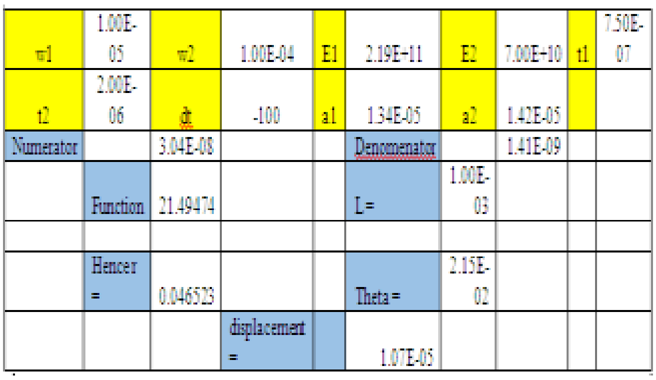
$$vertical\ displacement\ (d) = r - rCos(\theta) \qquad (3)$$

The calculations for the proposed design are as shown in Table 2.

Table 2: Mathematical Calculations of the proposed design

w1	3.00E-05	w2	1.00E-04	E1	4.11E+11	E2	1.60E+11	t1	1.50E-06
t2	1.00E-06	Dt	18	a1	4.50E-06	a2	2.60E-06		
Numerator		1.51807E-07			Denominator		7.54E-09		
	Function	20.14453958			L=	1.00E-03			
	Hence r=	0.049641244			Theta=	2.01E-02			
			displacement=		1.01E-05				

(a) Design 1: 4kHz design

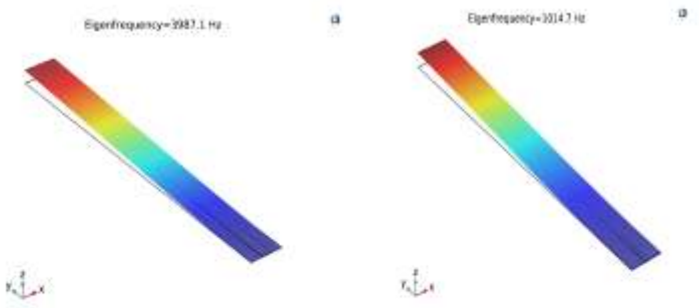


w1	1.00E-05	w2	1.00E-04	E1	2.19E+11	E2	7.00E+10	t1	7.50E-07
t2	2.00E-06	dt	-100	a1	1.34E-05	a2	1.42E-05		
Numerator		3.04E-08			Denomenator		1.41E-09		
	Function	21.49474			L=	1.00E-03			
	Hencer =	0.046523			Theta=	2.15E-02			
			displacement =		1.07E-05				

(b) Design 2 : 1kHz design

II. Results & Discussions:

As discussed in previous sections we have two designs operating at different frequencies. The "Joule Heating and Thermal Expansion" physics is used for simulation in COMSOL environment. The results of Eigen frequency study of these two designs are as shown in fig.4.

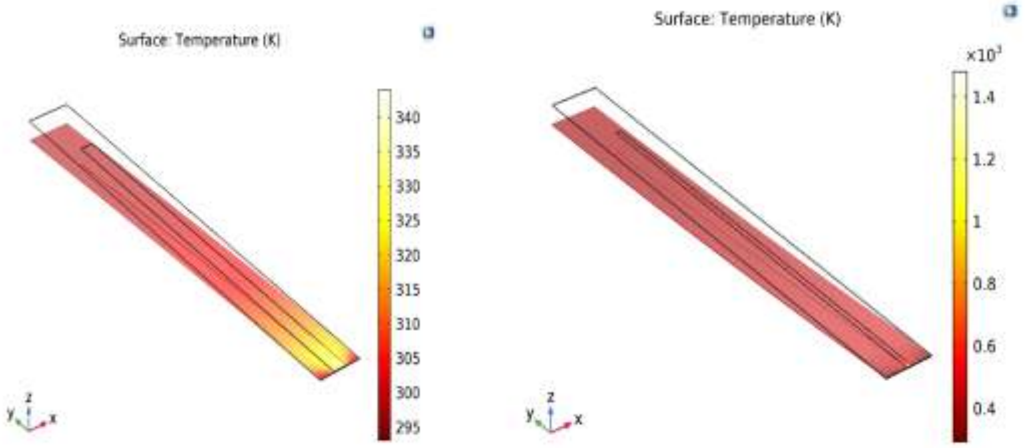


(a) Design 1 **(b) Design 2**

Fig. 4: Eigen frequencies of both designs

As can be seen from the Fig. 4 the natural frequencies of these structures are close to the actual target frequency. When a voltage is applied to these cantilever bimorphs at the fixed end such that upper layer is connected to +ve of supply and –ve connected to lower layer.

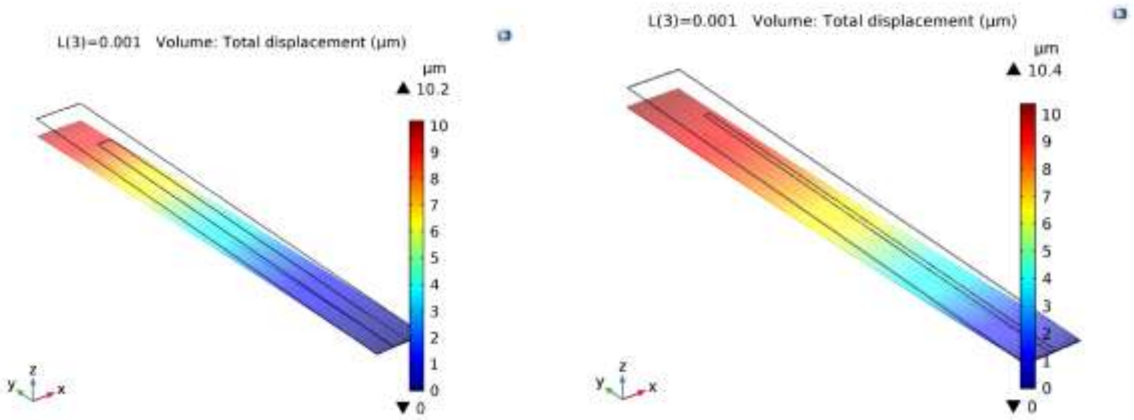
If the thermal distribution in both the designs is examined and can be seen in Fig 5. It is observed that the temperature difference across the length of the cantilever in both designs also differs. This is due to the different surface resistances of the materials used in the design.It can also be easily observed that in design 1the difference is ~45^{o}K whereasin design 2the difference is ~1000^{o}K. This difference is produced due to the different voltages applied to two designs leading to different currents flowing through them. To produce the required deflection, a higher voltage is required for design 2. The design 1 operates at 44mV whereas design 2 operates at 210mV. The applied voltages are much less than the design specifications.



(a) Design 1 **(b) Design 2**

Fig.5: Temperature variation in both designs

Another stationary study was performed on these devices to observe the effects of applied voltage and the variations in length on displacement. The lengths were swept in the range of 980-1010µm for both the designs. It can be observed from Fig. 6 that for the designed length of the structure the required displacement of ~10µm was obtained.



(a) Design 1 **(b) Design 2**

Fig.6: Displacement of both designs

It can be also be observed from fig. 6 that the displacement of the bimorphs is in downward direction. This is due to the different thermal expansion coefficients of the two materials. The top material has a higher value than the bottom material. This results in the top material to expand more than the bottom material, causing the structure to bend down.

III. Conclusion

In this report different parameters like displacement, frequency and the thermal study of bimorphs are discussed. It shows that the simulations and analytical values match when proper temperature gradients are applied. The Table 3 shows these values as a comparative study.

Table 3: Comparison of Analytical and simulated values

	Design 1 : 4kHz		**Design 2: 1kHz**	
	Analytical	**Simulated**	**Analytical**	**Simulated**
Displacement (μm)	10.7	10.2	10.1	10.4

When compared with other MEMS actuation method, it is found that the proposed actuator can worm at lower supply voltages, thereby useful in battery operated systems. It can also be observed that the design parameters such as the choice of material, physical dimensions and applied voltage are the key factors that govern the frequency and displacement of the structure.

Majorly this type of actuator finds applications in micro mirrors or structures that need to raise height at a lower voltage. This can also be used in low voltage switches.

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