A Stress-Induced Thermal actuator for Optical Purpose

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Abstract

We present a micromachined, stress-induced, thermal bimorph actuator for optical purpose. Piston motions of more than 3um are demonstrated by FEM simulation. Upon the release from the substrate, the actuators lift off the substrate due to a large built-in bending moment arising from the compressive residual stress in the poly-silicon layer and tensile residual stress in the metal layer. Large displacement and low operating voltage (<2V) are obtained simultaneously.

Introduction

The smart phase-only micro-mirror array is one of the promising MEMS devices that will lead to many applications such as optical beam steering, optical interferometer, etc. Large mirror deflections are required to modulate light. Mirrors that reply on a sacrificial layer to provide the gap for the electrostatic actuation are limited to a micron or less [1]. Thermal actuation as an alternative is capable of increasing the stroke. An example has been shown by Tuantranont *et al.* [2]. Another is presented in this paper.

Figure 1 is a schematic diagram of a segment of the actuator array. Upon release, the actuator is elevated above the surface of the substrate due to a built-in bending movement created by variation in residual stress through the thickness of the beam.

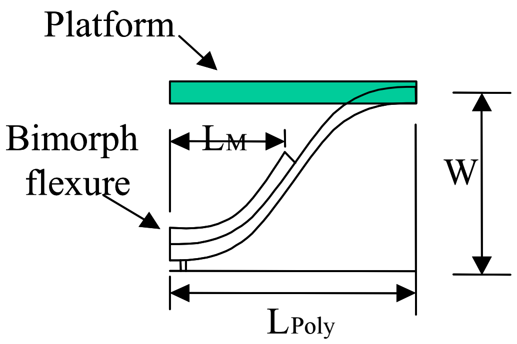

Figure 1. Actuator schematic

Mechanical Modeling

Bimorph flexures have been well studied. They have been mostly used as thermal actuator. Some researchers utilize the deflections of them due to residual stress. This work takes the advantage of both.

The previous publications [3, 4] have described bimetallic cantilever. Figure 2(a,b) shows the schematic of a bimorph cantilever. Figure 2(c) shows the residual stresses in the cantilever. Following the approach of Judy *et al.* [5], we obtain the radius of curvature of the pre-biased flexure in terms of residual stresses, moduli, dimensions and temperature:

$$\rho_{free-end}=\frac{\frac{2(EI)_{equiv}}{t_1+t_2}\left(\frac{1}{E_1t_1b_1}+\frac{1}{E_2t_2b_2}\right)+\frac{t_1+t_2}{2}}{\frac{\sigma_2}{E_2}-\frac{\sigma_1}{E_1}+(\alpha_1-\alpha_2)\Delta T} \qquad (1)$$

where

$$(EI)_{equiv}=\frac{(t_1^2b_1E_1)^2+(t_2^2b_2E_2)^2+2t_1t_2b_1b_2E_1E_2(2t_1^2+2t_2^2+3t_1t_2)}{12(t_1b_1E_1+t_2b_2E_2)} \qquad (2)$$

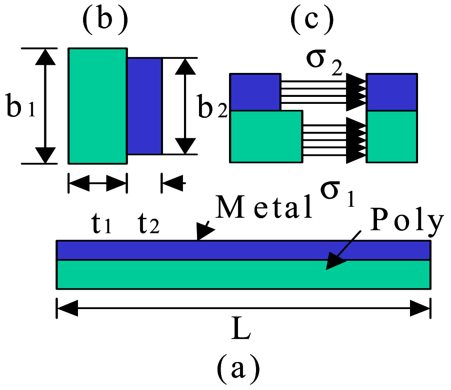

Figure 2. Bimorph Cantilever schematic (a) cross section view 1; (b) cross section view 2; (c) residual stresses distribution.

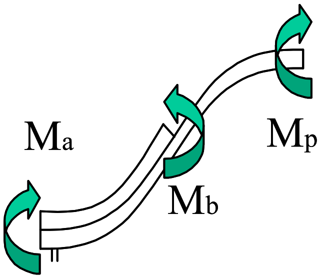

Figure 3. Side View of the bimorph flexure showing pertinent moments acting on the beam.

However, if this bimorph flexure is used in the actuator shown in Figure 1, the actuator will not lift off upon release. Helmbrecht *et al.* [6] proposed a way to analyze the bimorph flexure shown in Figure 1. Following the approach, Figure 3 is a schematic diagram of a flexure showing the pertinent moments acting on the beam. The beam is subjected to a moment from the anchor M_a, a moment from the bimorph M_b, and a moment from the attachment to the top plate at the end of beam M_p. Under equilibrium, moment balance must be hold. Using these moments values and the beam dimensions, the beam deflection can be derived from Euler beam theory [7] by carrying a nodal analysis [8].

Assuming the angle at the attachment to the top plate is zero, we obtained the deflection and angle along the bimorph flexure:

$$\theta(x)=\begin{cases} \dfrac{M_b-M_p}{(EI)_{equiv}}x & 0\le x\le l \\ (-\dfrac{M_p}{(EI)_{poly}})(x-l)+\dfrac{M_b-M_p}{(EI)_{equiv}}l & l\le x\le L \end{cases} \qquad (3)$$

$$w(x)=\begin{cases} \dfrac{1}{2}\dfrac{M_b-M_p}{(EI)_{equiv}}x^2 & 0\le x\le l \\ \dfrac{1}{2}(-\dfrac{M_p}{(EI)_{poly}})(x-l)^2+\dfrac{M_b-M_p}{(EI)_{equiv}}(lx-\dfrac{l^2}{2}) & l\le x\le L \end{cases} \qquad (4)$$

Where,

$l = L_{metal},\qquad L = L_{poly}$

$$M_p=\frac{1}{\rho_{free-end}}\cdot\frac{1}{\dfrac{l}{(EI)_{equiv}}+\dfrac{L-l}{(EI)_{poly}}}\cdot l \qquad (5)$$

$$M_b=\frac{(EI)_{equiv}}{\rho_{free-end}} \qquad (6)$$

The moment values can be determined by measuring test structures made in the same process run as the beams.

Finite-Element Simulation

The analytical modeling has the limitation because it doesn't consider the temperature distribution in the flexure and the calculated tip deflections assume that the angle of the tip of the bimorph flexure is zero. For the more detailed analysis, the finite element model has been performed to analyze the actuator static deflection by using ANSYS package. The modeling has three steps. (1) The static analysis for getting the deflection distributions resulting from the residual stress; (2) an electro-thermal analysis to obtain the temperature distribution from the electric input; (3) the thermo-mechanical analysis for getting the final deflection distribution resulting from the residual stress and thermal actuation from the electric current.

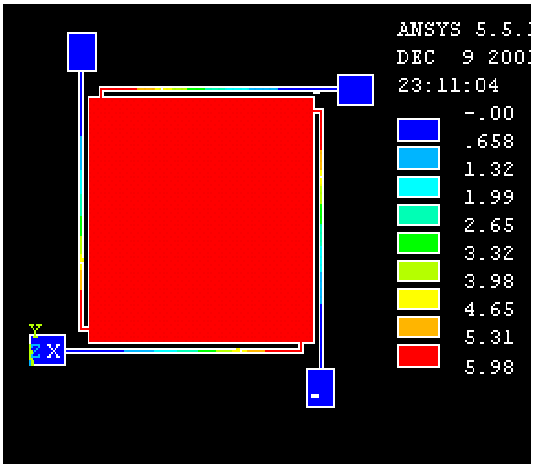

Figure 4. The FEM results of deflection distribution among the actuator resulting from the residual stresses.

- Residual Stress Induced Deflection

An assumption is made that the residual stresses in the polysilicon and metal are constant in each layer (no strain gradient). For the polysilicon layer the typical value in deposited polysilicon is -450Mpa (compressive) [9]. The residual stress in the metal layer is greatly dependent on process parameters such as the deposition temperature, metal layer thickness, substrate temperature. The value used in the modeling is 70Mpa (tensile). The more exact value will be determined by measuring test structures made in the same process run as the beams. Figure 4 shows the deflection distribution resulted from the residual stresses.

- Electro-thermal Analysis

We applied the input voltage onto the two anchors of the four anchors and grounded the rest of anchors. Heat transfer modes considered here were conduction to the substrate, natural convection to the air, and radiation. The room

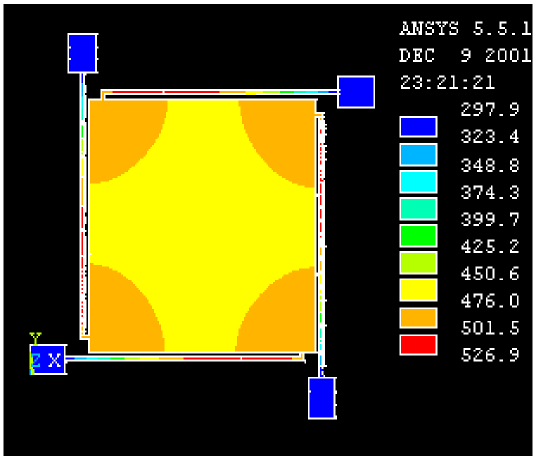

Figure 5. The FEM results of the temperature distribution among the actuator resulting from Joule heating (Input voltage=1.0V).

temperature was given to each four anchors. The natural heat convection coefficient was obtained using the temperature dependent thermal properties of the air and used for modeling the heat loss to the air from the actuator structure. The temperature distribution among the actuator from the FEM analysis is presented in the figure 5. To accurately model the temperature distribution, we used directly coupled method to perform electro-thermal analysis.

- **Thermo-mechanical Analysis**

In the thermo-mechanical analysis, the thermal response of a system significantly influence the response of the structural field but not vice-versa. Therefore after getting the temperature distribution from the electro-thermal analysis, we can use that result as loads for the following structural analysis. This analysis, using sequential method, can significantly reduce the computation time and avoid the convergence problem.

The final deflection distribution among the actuator from the ANSYS modeling is shown in figure 6. For the optical application as a mirror, we want the flat plate as flat as possible. The inverted parabola shape of the mirror plate was found in their previous research, where the four bimorph flexures are at the corners [8]. But our actuator plate is almost flat, since the polysilicon beams that connected the bimorph flexures with the plate act as torsional spring with low stiffness which make the plate flat.

The comparison of the deflections of the flexure tip between the FEM analysis and theoretical modeling is shown in figure 7. In theoretical

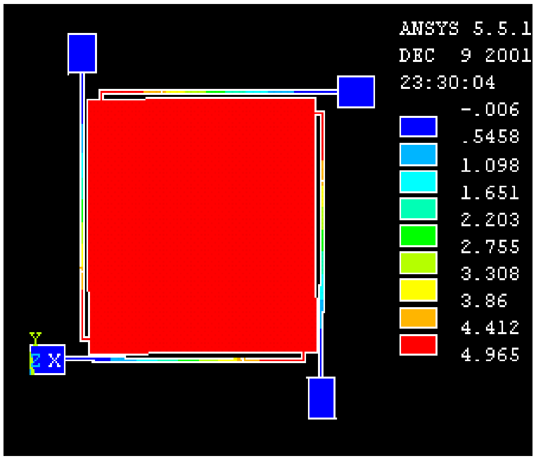

Figure 6. *The FEM results of the deflection distribution resulting from the thermal actuation after release (Input voltage =1.0V).*

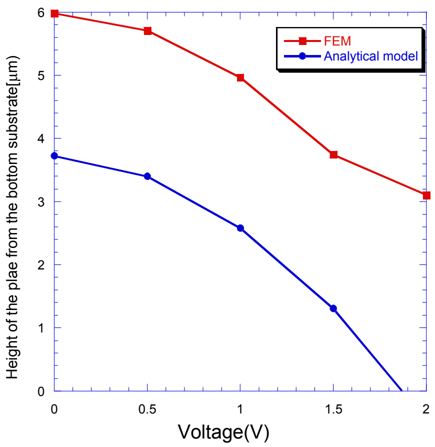

Figure 7. The comparison of the tip deflection obtained from theoretical modeling and FEM analysis.

modeling, we used the average temperature of the actuator obtained from the FEM electro-thermal analysis. A discrepancy was observed between theoretical modeling and FEM analysis. This might attributed to uneven temperature distribution, nonlinear deflection behaviors in the flexures and non-zero angle at the tip of the bimorph flexure.

Fabrication

The actuator array will be fabricated through the commercially available surface micromachining technology (Multi-User MEMS Process – MUMPS). The structure layers are going to be made with 1.5um-thick polysilicon (poly2). A 0.5um metal will be deposited on top of the structure layers. The PSG layer will be removed when the actuator is released.

When we design the test structures, we varied the ratio of metal length to polysilicon length and the length of the beam which connect the bimorph flexure with the top plate. So we can find the optimum ratio which will give us the largest displacement. Free end bimorph beams are used to measure the radius of curvature and determine the bimorph moment.

Experimental (need be done)

Conclusion

A residual stress induced, thermal actuator for optical purpose has been demonstrated. Finite element analysis as well as theoretical analysis have been performed to analyze the actuator. The theoretical model gives us a good first order approximation. A large stroke (3um) is obtained with a very low input voltage (2v).

Acknowledgement

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