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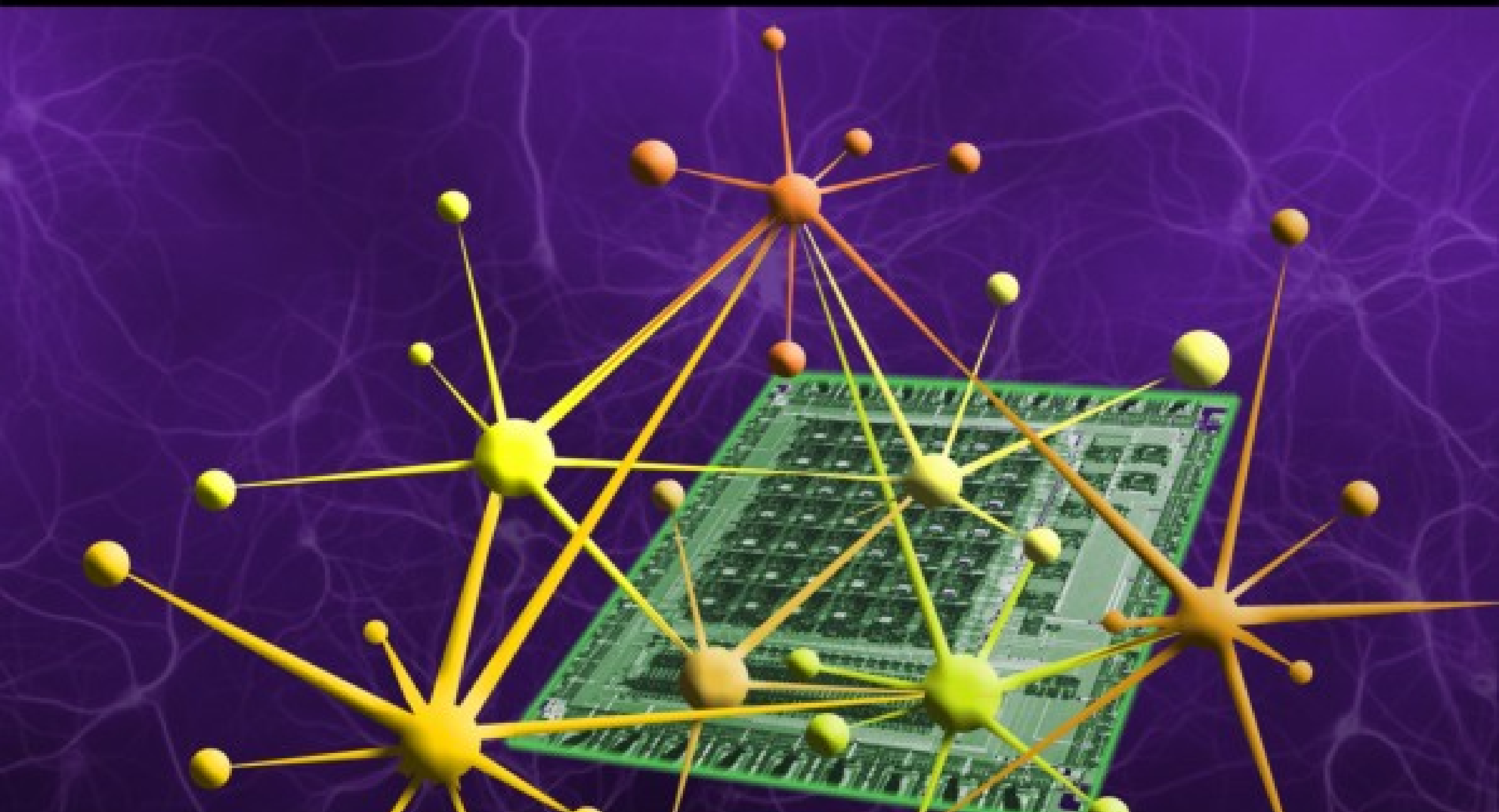

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Mechanical Behavior of a Thermal Micromirror Based on a Bimetallic Cantilever Beam

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Abstract: In this work mechanical behavior of a thermal micromirror based on a bimetallic cantilever microbeam was studied. The main target is to control the reflection of an incident ray in order to strick to a specific point. Tip slope of the bimetallic beam that is deflected due to temperature changes acts as an intermediary to relate the angle of the reflected ray and temperature changes. Governing equations to indicate the relation were derived and analytically solved. Required time of the system to the temperature changes was calculated. Detecting the position of the reflected ray is possible whereas deflection and consequently slope of the beam vary linearly with temperature. The proposed micromirror can be used as a thermal sensor whereas deflection varies linearly with temperature. *Copyright © 2007 IFSA.*

Keywords: MOEMS, Micro cantilever beam, Bimetal, Thermal, Micromirror

1. Introduction

Micro Electro Mechanical Systems (MEMS) is inherent in micron-sized mechanical devised that can sense, process and/or control the surrounding environment. Sensing capabilities derive from mechanical features measured in microns. Integrated optical systems have received considerable attention over the several years. MEMS technology makes it possible to fabricate micro optic systems with high performance and low cast. Optical MEMS can mean two things: microsystems for optics or microsystems with optics. Micro Opto Electro Mechanical Systems (MOEMS) fit in the first category and contain movable components that have an effect on an optical signal that is pointed at the surface on this optical component. It is a special class of MEMS that requires a different set of rules for operation as opposed to common sense in our normal macro world. On a micro-scale, intermolecular forces are so strong that the pages of a micro book cannot be separated. But such problems can be turned to our advantage if we learn how to use them. For example, the deformation of a beam anchored at one end is proportional to its mass. This means that comparing the deformation of a one millimeter long beam to one micron long beam, the microbeam appears much stiffer by having a deformation one billionth of the mini beam and only being a thousand times smaller.

Key components in micro-optic systems are micromirrors that have been shrunk down to the microscopic world. Their main application areas are projection display systems, pattern generators in mask less lithography systems, optical scanners, printers, optical spectroscopy, aberration correction, adaptive optical systems and switches and cross connectors in optical communication systems.

The micromirrors can operate in one-dimensional (1D) piston-mode and two-dimensional (2D) tilt-mode [1]. Micromirrors with multiple degrees of freedom (MDOF) have many applications which include optical displays, optical switches, and imaging systems. MDOF micromirrors have been demonstrated to have either strictly two rotational DOFs (2D) or both two rotational DOFs and one translational DOF (3D). Such types of micromirrors have been designed using electrostatic, electromagnetic, piezoelectric, and electrothermal actuation mechanisms. Based on their motion types, micromirrors can be classified into four categories: deformable, movable, piston, and torsional micromirrors.

Three different types of deformable mirrors such as Spatial Light Modulators (SLMs), based on device concepts like Viscoelastic Control Layer (VCL), Cantilever Beam Mirror (CBM) [2], have been developed [3]. Due to good dynamic response and small possibility of adhesion, the torsional micromirror [4] like torsional micromirrors with lateral actuators [5] has been widely used for applications requiring high speeds and large arrays. Some sample of piston mode are like tilting and piston-type micromirror [6, 7] and piston-like out-of-plane motion micromechanical structures [8], and at last micromirrors with flexure springs [9] can named as a sample for movable micromirrors.

In this article a novel deformable micromirror is proposed in which the temperature changes deform bimetallic cantilever microbeam and changes the slope of it. In other words the main aim is to find a relation between the tip slope of the deflected bimetallic beam and temperature changes. The calculated results for the beam were compared and it had compact conformity with the results of reference [2].

2. Model Description

The proposed model consists of a bimetallic cantilever microbeam, anchored at one end and free at the other end. Different expansion coefficient of two utilized metals causes the beam's flexure owing to temperature changes. Fig. 1 shows a schematic view of the undeflected and deflected microbeam due to temperature rise.

A relation between the temperature changes and the beam's slope is quested purpose in this work. The temperature of the bimetallic beam is controlled by application of a voltage. Due to micro scale of the bimetallic beam, the reaction of the system to the temperature changes is enough fast and consequently the response time of the proposed micromirror is enough small.

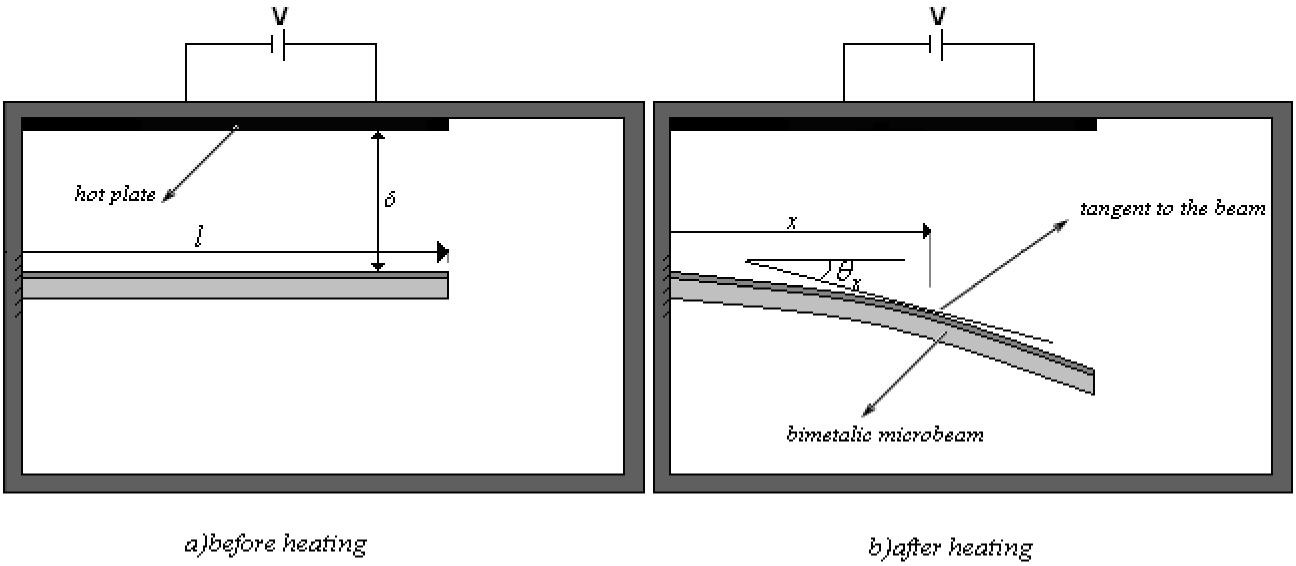

Fig. 1. Schematic of the thermal micromirror.

3. Mathematical Modeling

Fig. 2 shows an element of the bimetallic cantilever microbeam: *l*: length, *s*: thickness, *b:* width α: expansion coefficient, *A*: cross sectional area and *E* is Young's modulus. In the proposed model *h/l* is small enough that can be neglected the shear strain (Euler-Bernoulli beam theory) and total strain in *x* direction (ε_x) can be expressed as Eq. (2) [10]. The parameters of the upper layer of the beam are indicated by index 1 and of the lower one by index 2. *x* axis is coordinate along the length of the beam with origin at the anchored end and *z* axis is along the cross section that it's origin is at the neutral axis of the cross section.

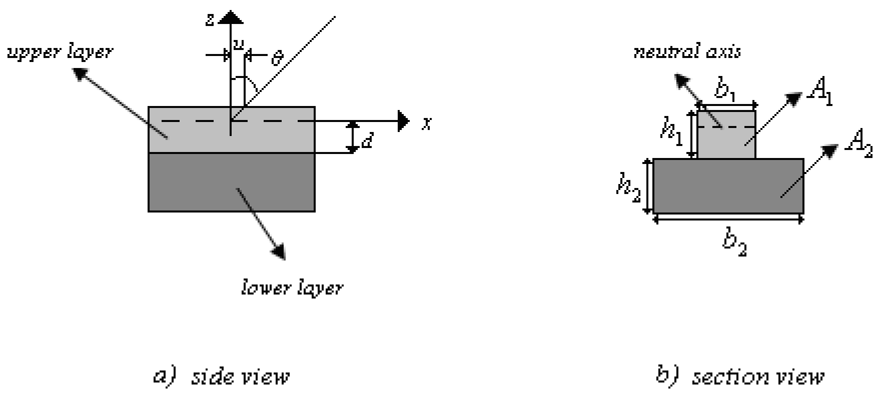

Fig. 2. An element of the bimetallic cantilever microbeam.

There are no external axial loads acting on the beam so:

$$\int_{A_1} \sigma \, dA + \int_{A_2} \sigma \, dA = 0 \tag{1}$$

Total strain (mechanical and thermal) can be achieved by geometrical calculation based on Euler-Bernoulli beam theory as:

$$\varepsilon_{total} = \varepsilon_m + \varepsilon_T = z\frac{d^2 w}{dx^2}, \tag{2}$$

where thermal strain is related to temperature rise respect to initial temperature:

$$\varepsilon_T = \alpha\,\Delta T \qquad \Delta T = T - T_0 \tag{3}$$

therefore:

$$\varepsilon_m = z\frac{d^2 w}{dx^2} - \alpha\Delta T \tag{4}$$

Using of Hook's law:

$$\sigma = \varepsilon_m . E = E\,z\frac{d^2 w}{dx^2} - E\alpha\Delta T \tag{5}$$

By substituting equations (5) in to equation (1):

$$nb_1\int_{-d}^{h_1-d} E_2 (z\frac{d^2 w}{dx^2} - \alpha_1\ \Delta T)dz + b_2\int_{-(d+h_2)}^{-d} E_2 (z\frac{d^2 w}{dx^2} - \alpha_2\ \Delta T)dz = 0\,, \tag{6}$$

where d is the distance from contact surface of two materials up to neutral axis and $n = \frac{E_1}{E_2}$

By integrating, the Eq. (6) is reduced to following form:

$$\frac{d^2 w}{dx^2}\left[\frac{nb_1h_1^2 - 2nh_1b_1d - 2b_2h_2d - b_2h_2^2}{2}\right] - (nb_1h_1\alpha_1 + b_2h_2\alpha_2)\ \Delta T = 0 \qquad , \tag{7}$$

when there are no external forces so the bending moment at cross section is zero:

$$M(x) = \int_A \sigma\, z dA = 0 \tag{8}$$

Composing Eq. (6) and (8):

$$nb_1\int_{-d}^{h_1-d} E_2 (z\frac{d^2 w}{dx^2} - \alpha_1\ \Delta T)zdz + b_2\int_{-(d+h_2)}^{-d} E_2 (z\frac{d^2 w}{dx^2} - \alpha_2\ \Delta T)zdz = 0 \tag{9}$$

Integrating of Eq. (9) results Eq. (10) as below:

$$\begin{gathered}\frac{d^2 w}{dx^2}\left[d^2(nb_1h_1 + b_2h_2) + d(b_2h_2^2 - nb_1h_1^2) + \frac{nb_1h_1^3 + b_2h_2^3}{3}\right] = \\ \Delta T\left[-d(nb_1h_1\alpha_1 + b_2h_2\alpha_2) + \frac{(n\alpha_1b_1h_1^2 - \alpha_2b_2h_2^2)}{2}\right]\end{gathered} \tag{10}$$

By calculating of d from equations (7) and substituting it in to equation (10):

$$\frac{d^2w}{dx^2} = \frac{6nb_1b_2h_1h_2(h_1+h_2)(\alpha_2-\alpha_1)}{n^2b_1^2h_1^4+b_2^2h_2^4+nb_1b_2h_1h_2(6h_1h_2+4h_1^2+4h_2^2)}\Delta T \tag{11}$$

Whereas the slope of the beam can expressed as:

$$\theta(x) = \frac{dw}{dx} = \int \frac{d^2w}{dx^2} + C \tag{12}$$

C is the constant of integration and can be evaluated from the known boundary condition of the slope at the fixed end:

$$\left.\frac{dw}{dx}\right|_{x=0} = 0 \longrightarrow C = 0$$

Finally the slope of the beam at a given x along its length can be calculated as below:

$$\theta(x) = \frac{dw}{dx} = \frac{6nb_1b_2h_1h_2(h_1+h_2)(\alpha_2-\alpha_1)\,x}{n^2b_1^2h_1^4+b_2^2h_2^4+nb_1b_2h_1h_2(6h_1h_2+4h_1^2+4h_2^2)}\Delta T \tag{13}$$

Therefore the microbeam's slope relates to the temperature changes. According to the law of geometrical optics, some parameters will be introduced such as the angle of an incident and its reflection ray. In this work, the main purpose is to detect the reflected ray to a desired position, as Fig. 3:

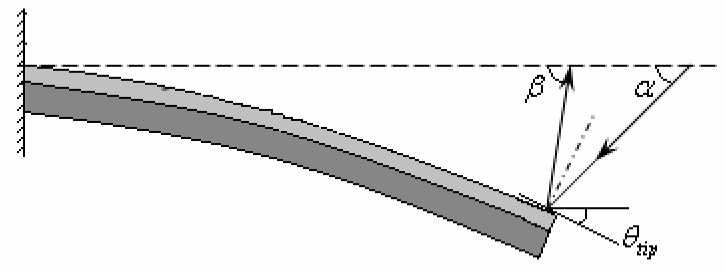

Fig. 3. The incident and reflected rays to the tip of the microbeam.

$$\theta_{tip} = \frac{\beta-\alpha}{2} \tag{14}$$

4. Response Time

Because of small physical size of the device, the Biot number is suitably less than 0.1 so it is closely approximated to neglect temperature gradient within the solids. The essence of the lumped capacitance method is the assumption that the temperature of the body is spatially uniform at any instant during the transient process. Considering the gas film is thin, no convection currents will be experienced and only pure conduction is observed. Balancing an overall energy on the solids:

$$\frac{T_p - T_1}{R_u} - \frac{T_1 - T_2}{R_1 + R_2} = \rho_1 c_1 V_1 \frac{dT_1}{dt} \quad \textit{(upper beam 1)} \tag{15}$$

$$\frac{T_p - T_2}{R_d} + \frac{T_1 - T_2}{R_1 + R_2} = \rho_2 c_2 V_2 \frac{dT_2}{dt} \quad \textit{(lower beam 2)}, \tag{16}$$

where:

$$R_1 = \frac{h_1/2}{k_1 S_1},\ R_1 = \frac{h_2/2}{k_2 S_2},$$

$$R_u = \frac{\delta}{k_{gas} S_1},\ R_d = \frac{\delta + h_1}{k_{gas}(S_2 - S_1)};\ S_1 = l \times b_1,\ S_2 = l \times b_2,$$

where ρ, *c* and *V* are the density, specific thermal capacity and the volume of the upper and lower beams, respectively, *k* is the thermal conductivity, T_p is the temperature of the hot plate, and *t* is the time variable. Temperature difference between two layers of the beam is because of the different conductivity coefficient and geometrical and physical properties of the layers. For convenience let

$$P_1 = \frac{1_1}{R_u \rho_1 c_1 V_1},\ P_2 = \frac{1}{R_u \rho_2 c_2 V_2}$$

$$F_1 = \frac{1}{(R_1 + R_2)(\rho_1 c_1 V_1)},\ F_2 = \frac{1}{(R_1 + R_2)(\rho_2 c_2 V_2)},$$

then

$$\frac{d}{dt}\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} -(P_1 + F_1) & F_1 \\ F_2 & -(P_2 + F_2) \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \end{bmatrix} + T_p \begin{bmatrix} P_1 \\ P_2 \end{bmatrix} \tag{17}$$

Solving the equations set by applying the initial conditions:

$$T_1 = T_2 = T_0 \quad at \quad t = 0$$

We get the final solution as:

$$\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = (T_0 - T_p)\left\{ \begin{bmatrix} I_1 & -I_2 \\ F_2 I_3 & -F_2 I_4 \end{bmatrix} \begin{bmatrix} e^{r_1 t} \\ e^{r_2 t} \end{bmatrix} + \begin{bmatrix} T_p \\ T_p + (1 - F_2)(I_3 - I_4) e^{-(P_2 + F_2)t} \end{bmatrix} \right\}, \tag{18}$$

where

$$r_1 = \frac{-(P_1 + P_2 + F_1 + F_2) + \sqrt{(P_1 + P_2 + F_1 + F_2)^2 - 4(P_1 P_2 + F_1 P_2 + P_1 F_2)}}{2}$$

$$r_2 = \frac{-(P_1 + P_2 + F_1 + F_2) - \sqrt{(P_1 + P_2 + F_1 + F_2)^2 - 4(P_1 P_2 + F_1 P_2 + P_1 F_2)}}{2}$$

$$I_1 = \frac{r_2}{r_2 - r_1},\ I_2 = \frac{r_1}{r_2 - r_1},\ I_3 = \frac{I_1}{P_2 + F_2 + r_1},\ I_4 = \frac{I_2}{P_2 + F_2 + r_2}.$$

5. Numerical Results and Discussion

The geometrical and physical properties of the bimetallic beam were listed in Table 1.

Table 1. The geometrical and physical properties of the bimetallic beam.

Design Variable	Value
$\alpha_1(Au)$	$14.3\times10^{-6}\quad k^{-1}$
$\alpha_2(Si)$	$2.6\times10^{-6}\quad k^{-1}$
h_1	$1.8\quad \mu m$
h_2	$4\quad \mu m$
b_1	$80\quad \mu m$
b_2	$100\quad \mu m$
l	$500\quad \mu m$
E_1	$80\quad GPa$
E_2	$122\quad GPa$
δ	$2\quad \mu m$

They are reference values for any where that no values are given. To have large and sensible deflection the expansion coefficient of two materials (Silicon and Gold) were considered with high different values. According to Eq. (13) the slope of the bimetallic cantilever microbeam increases linearly with temperature rise. The slope of this line can be defined as a new factor called sensitivity factor as bellow:

$$S.F=\frac{\Delta\theta}{\Delta T} \tag{19}$$

In order to verify the model, obtained results were compared with which has been done by reference [2]. Fig. 4 shows the variation of the tip slope versus temperature rise for different thicknesses. Fig. 5 declares that the increasing of total thickness while $h_2=2h_1$, reduces the sensitivity factor. Fig. 6. shows this trend for different selected materials.

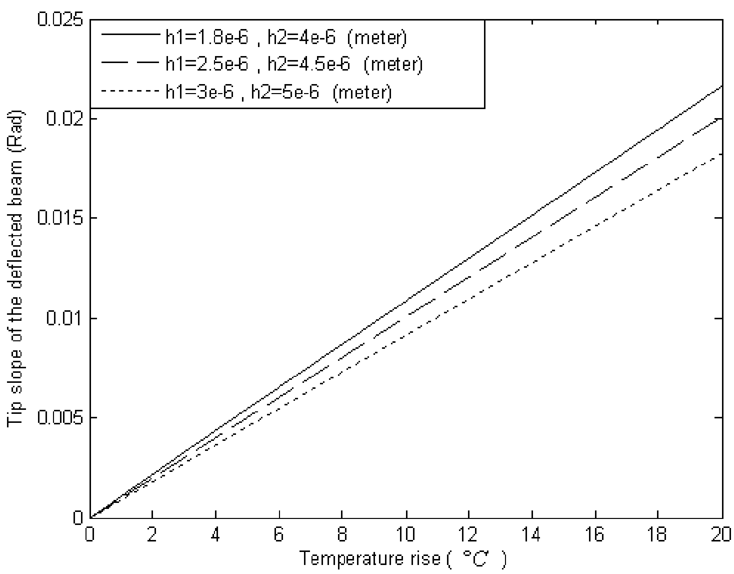

Fig. 4. The effect of the bimetallic microbeam's thickness on the tip slop of the bimetallic beam versus the temperature.

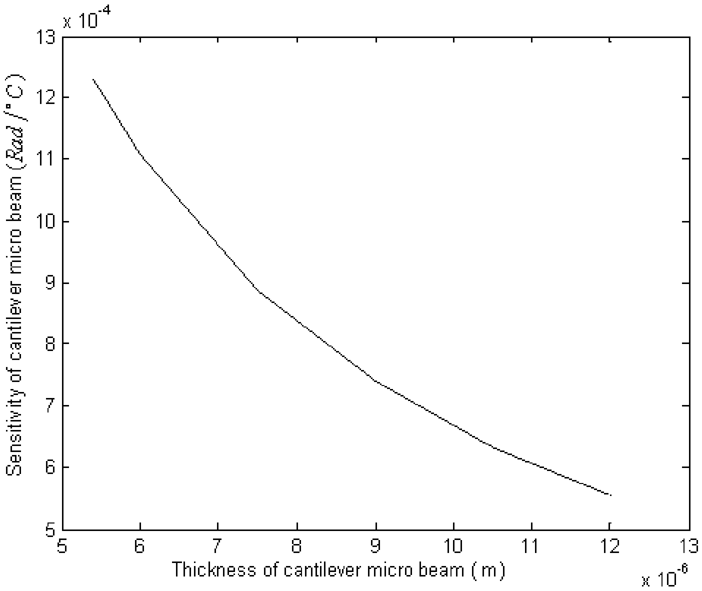

Fig. 5. Sensitivity factor versus variation of the beam's thickness.

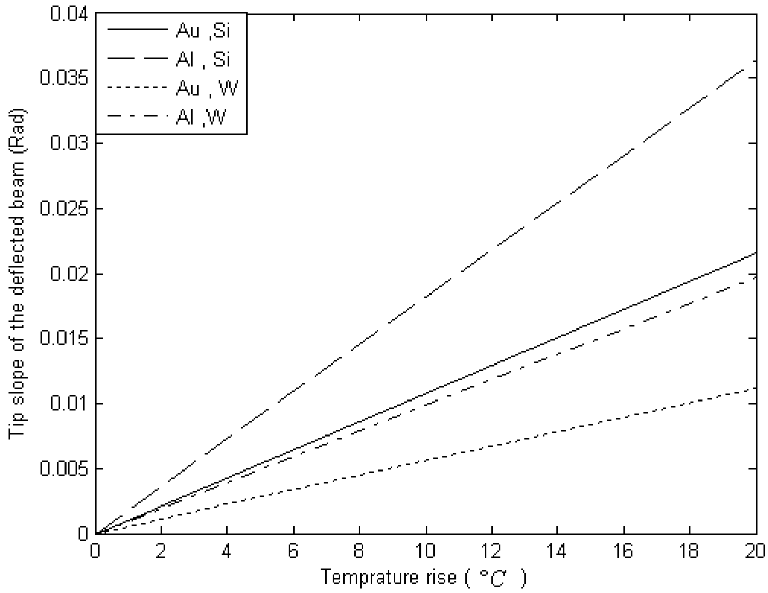

Fig. 6. The effect of the used materials for the bimetallic beam on the tip slop of the bimetallic beam versus temperature.

And finally Fig.7 shows the time for the layers of the microbeam to react and reach to the temperature of the hot plate while the initial temperature of the beam is 0 and the temperature of the hot plate is $20^\circ C$ .Smallness in size causes that two curves T_1/T_p and T_2/T_p seem coinciding but there is a so much unnoticeable difference between these two curves.

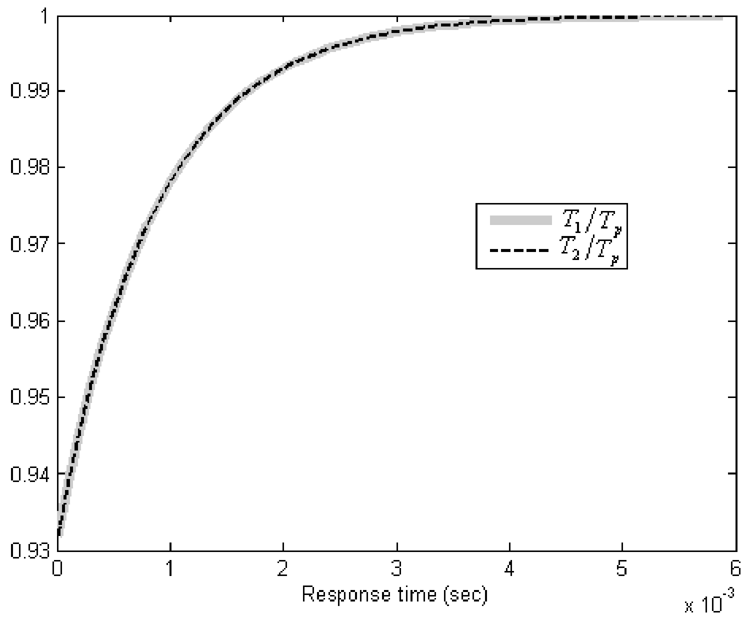

Fig. 7. Variation of temperature of the layers versus time.

6. Conclusion

In this paper:

- The governing equations of a novel micromirror based on deflection of a bimetallic cantilever beam were derived to obtain the tip slope of the anchored bimetallic beam versus temperature changes based on Euler-Bernoulli beam theory;
- The detecting point of the reflected ray by controlling of the temperature of the bimetallic beam was controlled;
- The proposed micromirror can be used as a thermal sensor whereas deflection varies linearly with temperature.
- It was showed that the thickness of the layers of the beam and successful selection of the materials of the bimetallic beam affect on the sensitivity of the device.
- Also it was showed that the response time of the thermal micromirror is considerably small.

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726- 5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually.

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