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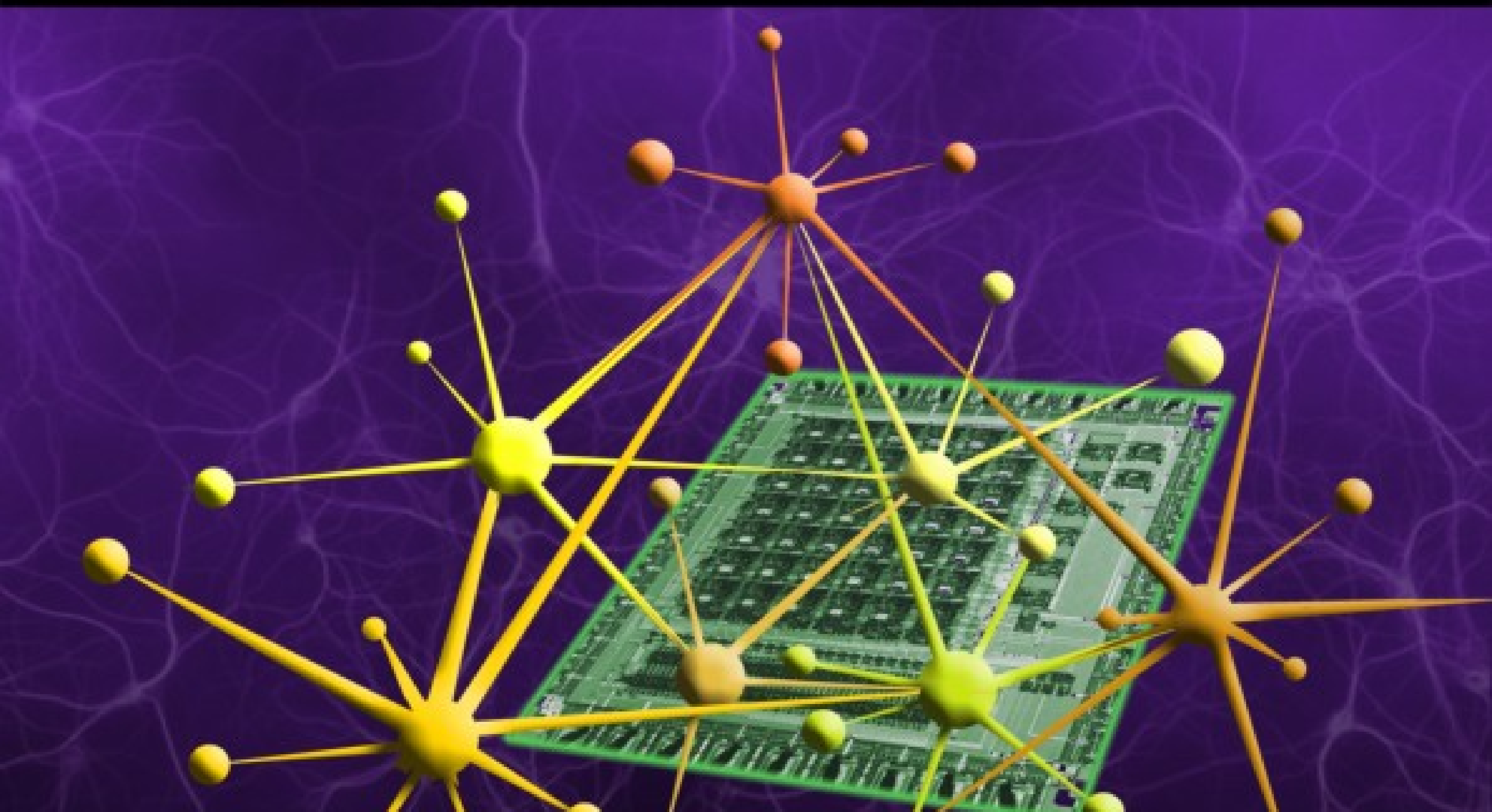

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MEMS Tunneling Micro Thermometer Based on Tip Deflection of Bimetallic Cantilever Beam

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Abstract: Micro-electro-mechanical (MEM) technology promises to significantly reduce the size, weight and cost of a variety of sensor systems. In this article has been described a highly sensitive novel type of thermometer based on deflection of a "bimetallic" microbeam. The proposed thermometer converts the thermal changes of a cantilevered bimetallic beam of submillimeter size into an electrical signal through tunneling-current modulation. The governing thermo-mechanical equation of a bimetallic cantilever beam has been derived and solved analytically. The obtained results show that the proposed tunneling micro thermometer is very sensitive to temperature changes due to exponential increasing of tunneling current but because of small gap between metallic electrodes, measurable range of temperature changes is small. *Copyright © 2007 IFSA.*

Keywords: Tunneling, Thermometer, Bimetallic Cantilever, MEMS

1. Introduction

Micro-electro-mechanical (MEM) sensors promise to provide low-cost alternatives to present micro-sensors for a variety of applications in automotive, telecommunication, military, and space systems. The ability to mass produce small sensors using fairly conventional IC manufacturing techniques has allowed the manufacturing costs to drop to below US$20/sensor for MEM-based accelerometers, thermometers, pressure sensors and etc.[1] The remarkable displacement sensitivity of the scanning tunneling microscope (STM) has inspired the development of a new class of sensors. These devices, called tunnel sensors, are based on electron tunneling displacement transducers [1]. For these transducers, displacement is measured by the change in tunnel current between two electrodes. Tunnel sensors have several attractive properties. The most important of these is a large sensitivity to very small changes in the separation between a pair of metallic electrodes. The current between the electrodes is governed by quantum mechanical tunneling and depends exponentially on the gap between the electrodes. Typically, the tunnel junction is biased at a few hundred millivolts and the gap is set to maintain a tunneling current of about 1 nA. This corresponds to a tunneling gap of about 1 nm. Several tunnel sensors have been built or proposed. In 1987, Niksch and Binnig [2] first proposed using a tunneling displacement transducer for measuring gravitational waves collected by whip or horn-shaped transformers. In the following year, in back-to-back publications, two prototypes for electron tunneling sensors were introduced, an accelerometer [3] and a magnetic-field sensor [4]. Other micromachined sensors based on tunneling transducers have also been reported. Kenny et al. [5, 6] demonstrated a miniature infrared detector that is similar to a golay cell except that a tunneling transducer is used to measure the deflection of the diaphragm that expands in response to the thermal expansion of a trapped gas. Other tunnel sensor concepts for magnetic field [7, 8], electric field, temperature [9], gravity, sound, pressure [10], strain, and chemical moiety have been proposed but not yet implemented. All of the micromachined tunnel sensors have resolutions at least equivalent to commercially available room temperature devices, but with significantly reduced volume, power, and potentially, cost.

In this paper has been described a novel micromachined tunneling thermal sensor. The device detects temperature by sensing changes in tunneling current due to tip deflection of a bimetallic microbeam. This sensor was designed with the objective of making a small, low power, high sensitivity sensor.

2. Tunnel Sensor Concept

The tunneling current, I_T is an exponential function of the gap distance, *w*, between the tunneling tip and the sensor structure,

$$I_T = V_b \exp(-\beta\sqrt{\varphi} w), \tag{1}$$

where V_b is the bias voltage applied between the tip and the conducting electrode, $\beta = 1.025 eV^{-0.5} / A^{\circ}$, and φ is the effective tunneling barrier height between the tip and structure. For vacuum tunneling, the energy barrier height is approximately equal to the electrode work function [11]. For a typical barrier height of 3 eV, the tunnel current increases by one order of magnitude for each decrease in electrode separation, *w*. In typical devices, one angstrom of displacement can produce a change in the tunneling current by a factor of two or three. However, at a convenient operating voltage (10 mv-1 v), the tunneling current varies from 0.2 to 10 nA which can be measurable and to be able to measure a tunneling current, the tip and structure must be spaced no more than 10nm apart.

3. Model Description

As it is shown in Fig. 1, a thermal sensor consists of a cantilever beam of submillimeter size made of two different materials as a bimetallic beam which can be bent because of different temperature expansion coefficient of selected materials, thereby when the operating temperature changed in system, the microbeam deflected. Thus due to its tip deflection, the magnitude of tunneling current between two electrode change which means the influence of temperature on the distance between the tunneling tip and the end of the cantilever beam which can be easily measured.

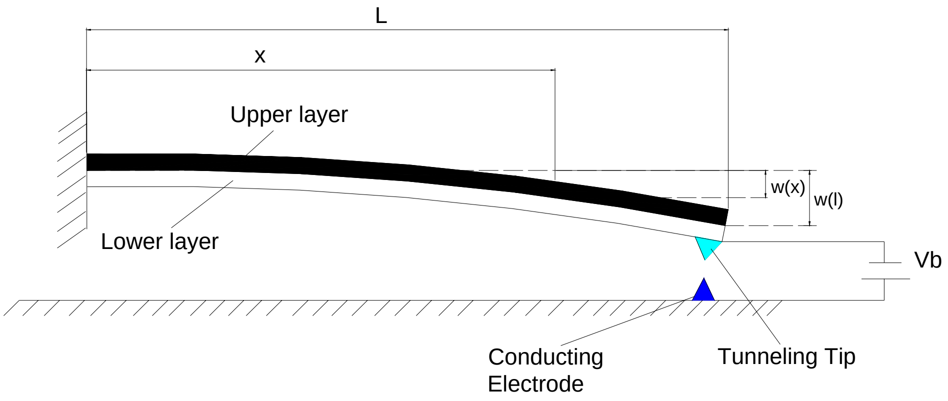

Fig.1. Schematic of a bimetallic cantilever thermometer.

4. Mathematical Modeling

Fig. 2 shows a schematic of a typical bimetallic cantilever microactuator and defines the geometry. The length of the two layers combined in the sandwich-like structure is assumed to be equal as this configuration provides the maximum force (holding all other parameters constant). All other dimensions and physical values may be different and are indicated by indices 1 for the lower beam and 2 for the other one, respectively. We assume $\alpha_2 > \alpha_1$, where α the thermal expansion coefficient is. The temperature distribution within the cantilever because of their small size is assumed to be uniform.

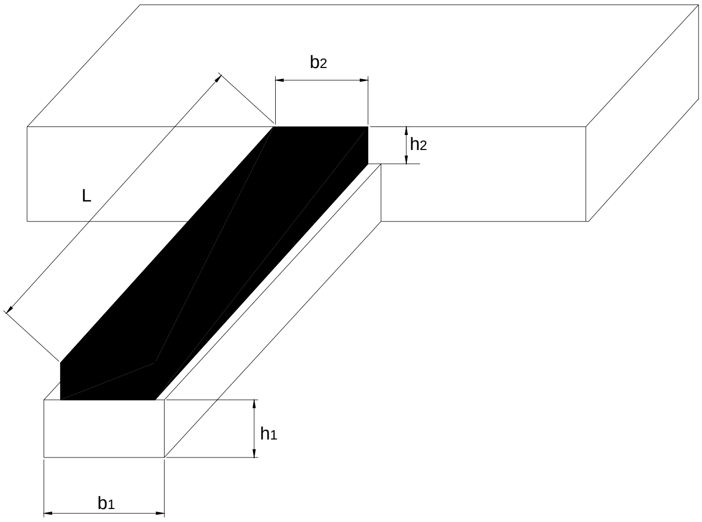

Fig.2. A schematic of a typical bimetallic cantilever micro actuator.

Fig. 3 shows an element of a bimetallic cantilever beam [12]. Assume a beam with length *l*, thickness *h*, width *b*, cross sectional area *A*, and isotropic with Young's modulus *E*. Suppose that *x* is the coordinate along the length of the beam with its origin at the left end, and *z* is the coordinate along the cross section with its origin at the neutral axis of cross section. *w*(*x*) is the deflection of the beam.

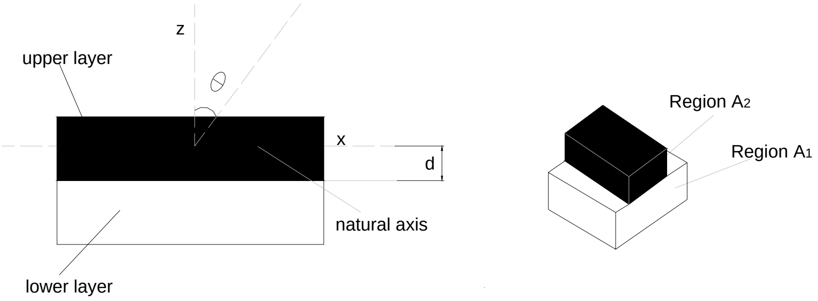

Fig. 3. An element of the bimetallic cantilever beam.

For selected microbeams, $\frac{h}{l}$ is usually small enough to neglect the shear deformation and using of strain definition [13], the total strain at the *x* direction at the given cross section and defined *z* based on Euler- Bernoulli beam theory can be written as:

$$\varepsilon_{tot} = z\frac{d^2w}{dx^2} \tag{2}$$

Total strain, is the sum of mechanical and thermal strains, thus:

$$\varepsilon_{tot} = \varepsilon_m + \varepsilon_T\,, \tag{3}$$

where:

$$\varepsilon_T = \alpha\Delta T\,, \tag{4}$$

with:

$$\Delta T = T - T_0\,, \tag{5}$$

where ΔT is the temperature rise which is to be measured respect to the initial temperature T_0. Substituting Eqs. (2) and (4) into Eq. (3), the following equation can be obtained:

$$\varepsilon_m = z\frac{d^2w}{dx^2} - \alpha\Delta T \tag{6}$$

Using of Hook’s low and Eq. (6), the relationship between the stress and the strain can be expressed as below:

$$\sigma = Ez\frac{d^2w}{dx^2} - E\alpha\Delta T \tag{7}$$

The axial force respect to the equilibrium condition along the *x*-axis is given as:

$$\int_{A_1}\sigma\; dA + \int_{A_2}\sigma\; dA = 0 \tag{8}$$

substituting the Eq. (7) into Eq. (8):

$$\int_{-h_1-d}^{-d} b_1 (E_1 z \frac{d^2 w}{dx^2} - E_1 \alpha_1 \Delta T) dz + \int_{-d}^{h_2-d} b_2 (E_2 z \frac{d^2 w}{dx^2} - E_2 \alpha_2 \Delta T) dz = 0 , \tag{9}$$

where *d* is distance of neutral axis from contact surface of two materials. By integrating, the Eq. (9) can be reduced to:

$$\frac{d^2 w}{dx^2}\left(d(-h_1 b_1 - n h_2 b_2) + \frac{n b_2 h_2^2 - b_1 h_1^2}{2} \right) - \Delta T (\alpha_1 b_1 h_1 + n \alpha_2 b_2 h_2) = 0 \quad , \tag{10}$$

where $n = \frac{E_2}{E_1}$. The bending moment *M(x)* at a given section is:

$$\int \sigma z dA = M(x) \tag{11}$$

As there is no acting external force on the cantilever beam so the bending moment is equal to zero:

$$M(x) = 0 \tag{12}$$

substituting Eq. (7) and Eq. (12) into Eq. (11):

$$\int_{-h_1-d}^{-d} b_1 (E_1 z^2 \frac{d^2 w}{dx^2} - E_1 \alpha_1 z \Delta T) dz + \int_{-d}^{h_2-d} b_2 (n E_1 z^2 \frac{d^2 w}{dx^2} - n E_1 \alpha_2 z \Delta T) dz = 0 . \tag{13}$$

By integrating of the Eq. (13), we have:

$$\begin{aligned} &\frac{d^2 w}{dx^2}\left[d^2 (b_1 h_1 + n b_2 h_2) + d(b_1 h_1^2 - n b_2 h_2^2) + \frac{(b_1 h_1^3 + n b_2 h_2^3)}{3} \right] + \\ &\Delta T \left[d\left(\alpha_1 b_1 h_1 + n \alpha_2 b_2 h_2\right) + \frac{\alpha_1 b_1 h_1^2 - n \alpha_2 b_2 h_2^2}{2} \right] = 0 \end{aligned} \tag{14}$$

Substituting value of *d* from Eq. (10) into Eq. (14) and simplify it, the final expression which indicates the relationship between deflections of the bimetallic cantilever and a given temperature changes can be written as follow:

$$w(x) = \frac{3 n b_1 b_2 h_1 h_2 (h_1 + h_2)(\alpha_1 - \alpha_2) \Delta T}{b_1^2 h_1^4 + n^2 b_2^2 h_2^4 + n b_1 b_2 h_1 h_2 (6 h_1 h_2 + 4 h_1^2 + 4 h_2^2)} x^2 \tag{15}$$

Finally, using of Eq. (15), and substituting the value of *w*(*x*) into Eq. (1) the expression for calculating the tunneling current with respect to temperature rising is derived as follow:

$$I_T = V_b \exp(-\alpha \sqrt{\varphi} \frac{3 n b_1 b_2 h_1 h_2 (h_1 + h_2)(\alpha_1 - \alpha_2) \Delta T}{b_1^2 h_1^4 + n^2 b_2^2 h_2^4 + n b_1 b_2 h_1 h_2 (6 h_1 h_2 + 4 h_1^2 + 4 h_2^2)} l^2) \tag{16}$$

Sensitivity of the sensor is a function of current changes through temperature which can be defined as bellow:

$$S = \frac{\Delta I}{\Delta T} \tag{17}$$

5. Calculated Results

First, to show the feasibility of our proposed model and obtained results, it is tried to compare the calculated results of microbeam deflection with the results of Ref. [14] .For this aim we should choose the same geometrical and material properties.

As the results declare there is no difference in results between this work and Ref [14]. But as we should have deflection no more than 10nm in order to establishment the tunneling current, so we have to change the geometrical and material properties in order to sense the current variation. The length and thickness of the cantilever are geometrical parameters that influence in wide range. Table 1 shows the geometrical and material properties of the proposed model. The values for $\Delta\alpha$ are limited by the amount of materials compatible with standard IC production steps and anisotropic etching techniques [15]. Fig. 4 shows the diagram of beam deflection at the various temperatures.

Table 1. Geometrical and material properties of the bimetallic cantilever thermometer.

Design variable	α_1(Si)	α_2(Pt)	E_1	E_2	b_1	b_2	h_1	h_2	L
Value	2.6×10^{-6} k^{-1}	8.9×10^{-6} k^{-1}	162×10^{9} Nm^{-2}	147×10^{9} Nm^{-2}	65 μm	20 μm	12 μm	1.8 μm	200 μm

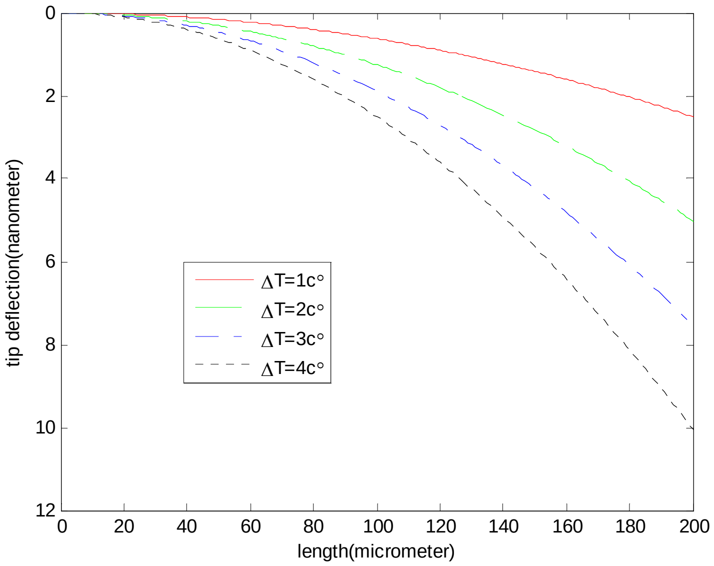

Fig. 4. Tip deflection versus length of the beam.

Due to the Eq. (15), as the temperature increases, the tip deflection of the micro beam increases too. Thus, the variable height of tunneling tip changes, which causes the tunneling current of the system changes. The changed current value can be used to evaluate the temperature rising of the desire environment. Fig. 5 shows the value of the tip deflection of the bimetallic cantilever beam at the different temperature raising.

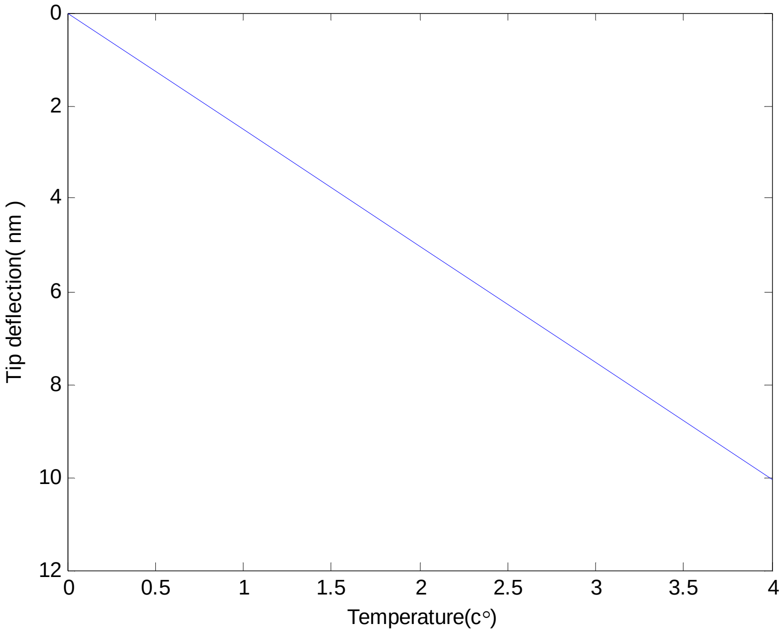

Fig. 5. Tip deflection versus the temperature raising.

Using of Eq. (16), the change of tunneling current in the proposed model due to the variation in the temperature can be easily found. Fig. 6 shows the value of the current due to the increasing of the temperature. As it is shown in Fig. 6 and Eq. (16) the value of the tunneling current changes is exponentially with respect to temperature raises.

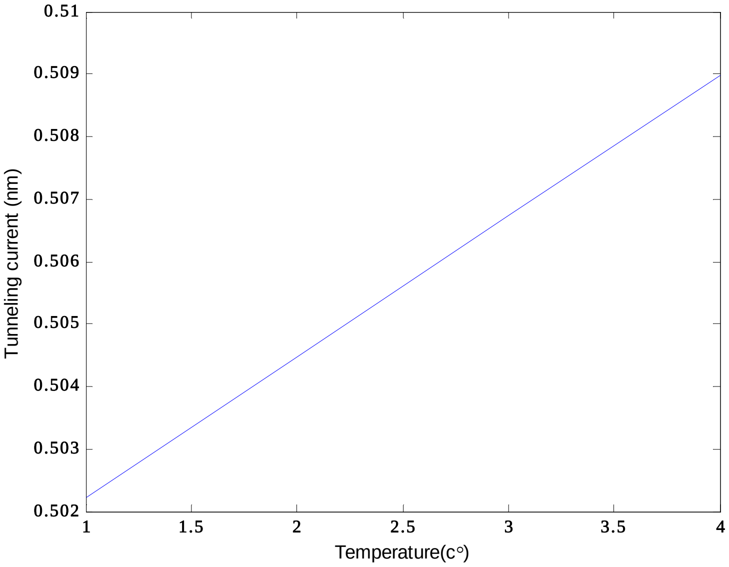

Fig. 6. Tunneling current versus temperature raising.

Using Eq. (17) sensitivity of the sensor versus the length of the beam is shown in Fig. 7 as which can be seen the sensitivity increases as the length of the beam grows.

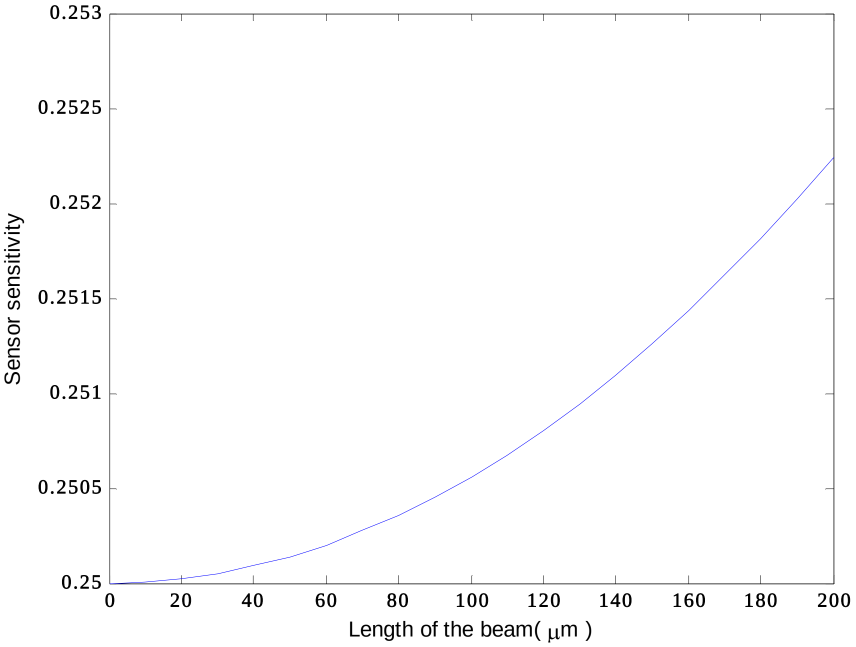

Fig.7. Sensitivity versus length of the beam.

6. Conclusion

A novel model of micromachined temperature sensor based on variation of tunneling current was designed. The governing thermo-mechanical equation of the model was derived and solved analytically. The calculated results showed that by increasing the temperature, the tunneling current grows exponentially, but as we have to limit the temperature variation in order to have small deflection, the relation between temperature and the tunneling current is approximately linear.

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Guide for Contributors

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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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