Design of MEMS based temperature Sensor for Contactless Measurement

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Abstract - The objective of this paper is to design a MEMS temperature sensor based on a cascade three-stage "bent- beam " structure . A suspended structure mechanically deforms in response to the change in ambient temperature , and then, a displacement is obtained; the structure is composed of three cascaded systems in order to enhance sensor sensitivity . The final conversion is made to an electrical signal that is obtained by using a capacitor having one electrode fixed to the substrate and one electrode embedded into the moving tip of the MEMS sensor. The readout of the unknown temperature is therefore remotely performed by coupling the variable MEMS capacitor to a fixed inductor to compose a resonant LC circuit, which is magnetically coupled to a reader circuit placed outside the environment where the measurement takes place. The temperature to be measured is therefore first converted into a displacement that, in turn, induces a change in a capacitor value; a variation in the resonant frequency of an LC circuit is finally observed through the remote readout circuit.

Keywords - Bent- beam structure s, contactless sensors, microelectromechanical systems (MEMS), temperature sensors.

1. INTRODUCTION

Several scenarios exist where a cabled connection between the primary sensor and the signal conditioning circuit is not allowed. Contactless measurement strategies can therefore be adopted to gather information from sensors used in hostile or inaccessible areas. The literature offers many examples and many application fields for remote and contactless sensors; examples are remote data acquisition from an autonomous sensor module based on an optical link [1], pressure sensors in microelectromechanical systems (MEMS) technology for high- temperature applications [2], contactless sensors for biomedical applications [3], and chemical sensors for high-temperature environments [4].

A particular situation could arise when the measurement environment is unsuitable for electronic circuitry due to high temperature s and the temperature itself is the quantity to be measured. Solutions to this problem are required not only in the area of process control but also in risk prevention and contingency management and whenever a sensor is required to be placed inside the environment. High- temperature rooms, industrial ovens, or, generally speaking, environments that are incompatible with either wire or active electronic parts are some examples.

A typical approach to the problem of remote temperature sensing relies on radiation-based thermometers; however, small low-cost devices that can easily be placed inside the measurement environment are of great interest.

From this perspective, MEMS technology allows suitable solutions providing different materials that are compatible with high- temperature environments and that allow for the implementation of contactless reading mechanisms.

Several designs and procedures for the fabrication and testing of micro fabricated mechanical temperature sensors have been presented in the literature [5], with a variety of architectures [6]. The common working principle is based on the structural deformation that appears as a consequence of a temperature increase.

In this paper, a novel contactless temperature sensor is developed. It is based on an array of V-shaped bent- beam structure s [7]. Similar structure s have been previously proposed in the literature mainly as in-plane thermal actuators [7]–[11] or strain sensors [12], [13]; here, the remote sensing of environment temperature is addressed.

The common working principle is based on the structural deformation that appears as consequence of a temperature increase. In this paper a novel contactless temperature sensor is developed. It is based on an array of V-shaped bent beam structure s. Cascade architecture has been designed in order to enhance the sensitivity of the sensor. A passive remote readout system, based on LC resonant architecture with varying capacitor, which produces a frequencyshiftasoutputhasbeenconceived.Thereforewires,contacts,activeelementsand power supplies within the sensor have been removed.

Cascade triple- beam architecture has been designed in order to enhance the sensitivity of the sensor. A passive remote readout system, based on an LC resonant with varying capacitor, which produces a frequency shift as output in response to the temperature change, has been conceived. Therefore, wires, active elements, and power supplies within the sensor have been removed. Some preliminary results on the sensor characterization have been previously reported by the authors in [14], while some results on a hybrid solution for the wireless sensor readout have been also presented in [15] where the MEMS sensor is used in a system including an external printed circuit board coil.

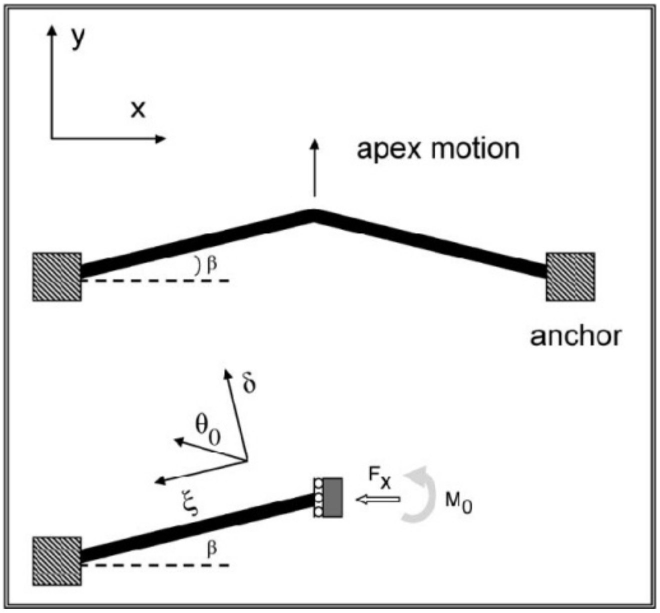

Fig. 1. structure and operation of a single-bent- beam sensor.

Here, both a more exhaustive characterization and a more accurate modeling of the MEMS device are presented.

The MEMS sensor has been designed so that the temperature induces a displacement of one conductive electrode (the tip of the cascaded triple bent beam) toward a fixed electrode, thus realizing a variable capacitor that is coupled with an embedded coil inductor [14]. This LC circuit will respond, when remotely interrogated, with a resonance frequency that is a function of the capacitance value which, in turn, depends on the temperature to be measured [15].

An accurate analytical model of the proposed device, together with the actual design realized with the Metal MUMPs technology [16], is presented in this paper. In particular, an accurate analysis of the non ideal characteristics of the MEMS sensor will be developed here, leading to a better comprehension of some unexpected behaviors. Finally, extensive simulation and experimental results, obtained by using the designed and fabricated prototype, will be reported to validate the approach discussed here.

2. SYSTEM MODEL

A reference bent- beam device is shown in Fig. 1. It is composed of a V-shaped beam anchored at the two ends. The thermal expansion of the structure induces a displacement of the central apex along the y-direction. Owing to its symmetry, this is the only possible direction of deformation for the device considered.

Because of the system symmetry, it is sufficient to analyze only one-half of the structure . In order to determine the free displacement, the beam can be considered as subjected to an equivalent force that causes the free expansion at the apex. Flexure symmetry is also useful to determine the boundary conditions. Displacements and rotations of the beam ends are constrained to be zero, except in the direction of the applied force, and the boundary conditions are determined by solving the equilibrium equations $\Sigma F = 0$, $\Sigma M = 0$, and $\Sigma T = 0$, where F , M , and Tare the forces, the moments, and the torques applied to the structure , respectively.

These boundary conditions are expressed in terms of the reaction forces, moments, and torsions at the end of the beam . Finally, Castiglione’s second theorem [17] states that the partial derivative of the strain energy U of a linear structure , with respect to a given load P , is equal to the displacement δ of the point where the load is applied. This theorem can be extended to the applied moments M and their corresponding angular displacements θ, resulting in

$$\delta = \frac{\partial U}{\partial P} \quad \theta = \frac{\partial U}{\partial M} \tag{1}$$

In applying Castiglione’s theorem, the strain energy must then be expressed as a function of the load. If, for example, a straight bar subjected to a number of common loads (axial force N , bending moment M , shearing force V , and torque T) is considered, the strain energy has the following form:

$$U = \int \frac{N^2}{2AE} dx + \int \frac{M^2}{2EI} dx + \int \frac{\alpha V^2}{2AG} dx + \int \frac{T^2}{2JG} dx \tag{2}$$

where A is the cross-sectional area, G and J are the torsion modulus and the torsion constant, respectively, the product EI is called the flexural rigidity of the beam , E is the Young’s modulus of elasticity, α is a coefficient depending on the cross sectional shape [18], and I is the bending moment of inertia.

By focusing on the subject of this paper, only the displacements resulting from bending are considered in the analysis, whereas deformations from shear, beam elongation, and shortening are neglected; the strain energy of the beam is found by integrating the strain energy density along the beam

$$U = \int_0^L \frac{M^2}{2EI} d\varepsilon \qquad (3)$$

The ξ-coordinate points along the beam axis, while L is the length of the beam . The angle at the fixed end of the beam θ0 is fixed at zero by the symmetry of the flexure. An external bending moment M0 constrains the angle in the analysis. The beam bending moment is

$$M = M_0 - F_y \varepsilon \qquad (4)$$

Whereξ is along the beam (x-axis) and Fy is along y.

A first invocation of Castigliano's second theorem gives a relation between the external moment and the load

$$\theta_0 = \frac{\partial U}{\partial M_0} = \frac{1}{EI}\int_0^L M \frac{\partial M}{2EI} d\varepsilon = \frac{1}{EI}\int_0^L (M_0 F_0 \varepsilon) d\varepsilon \qquad (5)$$

That, combined with the constraint θ0 = 0, gives M0 = FyL/2. The displacement along the y-direction δy can be obtained

$$\text{as } \delta_y = \frac{\partial U}{\partial P} = \frac{1}{EI}\int_0^L M \frac{\partial M}{\partial P} d\varepsilon = \frac{1}{EI}\int_0^L F_y \left(\frac{L}{2} - \varepsilon\right) d\varepsilon \qquad (6)$$

then

$$\delta_y = F_y \frac{L^3}{12EI} \qquad (7)$$

The last step is to derive the moment of inertia I = Izz= Ixx+Iyy, where

$$I_{xx} = \int_{-\frac{L}{2}}^{+\frac{L}{2}} \frac{A}{L} x^2 \sin^2(\beta) dx = \frac{AL^2}{12} \sin^2(\beta) \qquad (8)$$

$$I_{yy} = \int_0^L \frac{A}{L} \varepsilon^2 dy = \frac{AL^3}{3} \cos^2(\beta) = I_Z \cos^2(\beta) \qquad (9)$$

Finally

$$\delta_y = F_y \frac{L}{12E(I_{xx}+I_{yy})} = \frac{F_y L^3}{12EI_Z \cos^2(\beta) + AEL^2 \sin^2(\beta)} \qquad (10)$$

where $F_y = \alpha\ EA\ \Delta T \sin \beta$ is the *y*-component of the axial equivalent force related to the temperature change ΔT.

3. CASCADEBENT BEAM STRUCTURE S

The second actuator designed is hexa cascaded bent beam structure which is shown in Fig.2,threebent beam structure present in the first row, on the apex of the three beam s another two bent beam is present and finally on the apex of the two beam s the last bent beam structure present on the top.

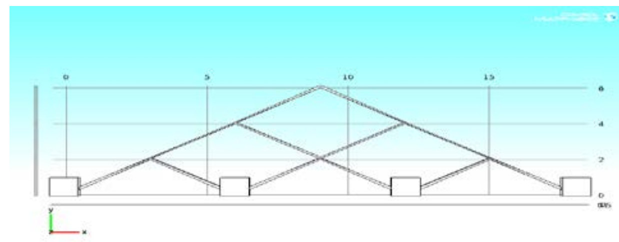

Fig.2 structure of hexa bent sensor

The second actuator designed is triple bent beam structure which is shown in Fig. 3thefixedends of the single bent beam structure is fixed on a separate apex of the another two bent beam, so it will have more sensitivity compared to the single bent beam actuator.

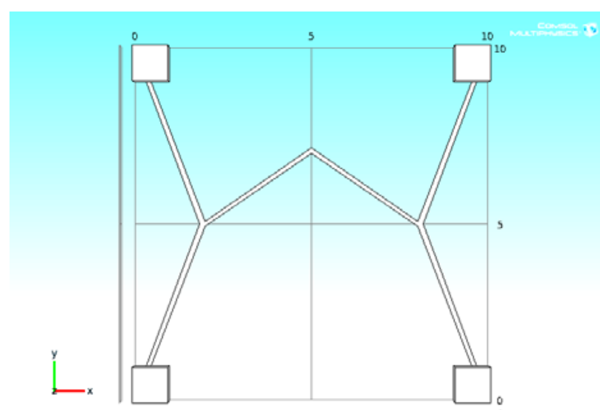

Fig.3 structure of triple bent sensor

4. SIMULATION/EXPERIMENTAL RESULTS

The thermal actuators designed are simulated using COMSOL multi physics software. temperature is given as input and the displacement is obtained as output. For all the three thermal actuator designed the output is presented in this section also the results are discussed.

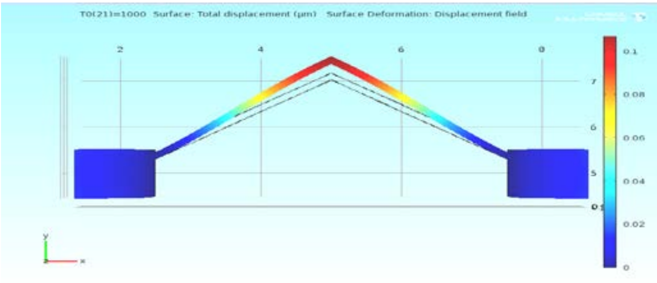

Fig.4Deformationofsingle bent beam

TheFig.4showsthedeformation of the single bent- beam structure deformation due to the applied temperature .The heat is applied throughout the single bent- beam structure using the joule heating and thermal expansion physics. The temperature is given using parametric sweep from 50K to 1000K at an interval of 50K and the corresponding displacement at the apex of the actuator is evaluated using point evaluation.

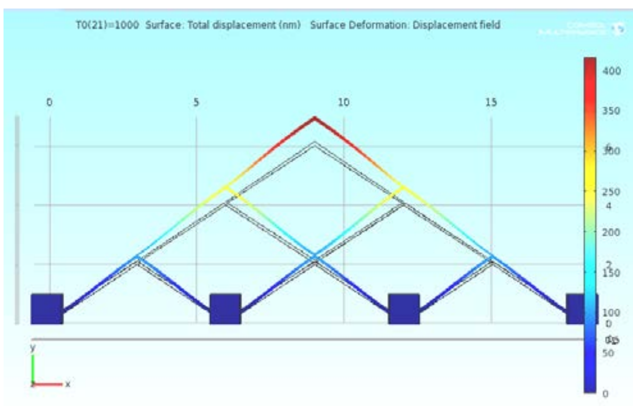

Fig. 5 Deformation of Hexabent beam

The F ig.5 shows the deformation of the hexabent- beam structure due to applied temperature. In single bent- beam structure theapexproducesadisplacementof0.1µmfor temperature of 1000K,forthissame temperature the hexabent- beam structure produces a displacement of 0.41µm. Therefore this hexabent- beam thermal actuator produces a displacement approximately four times higher than the single bent- beam structure.

The Fig.6 shows the deformation of the triple bent- beam structure due to applied temperature . The result is plotted between the temperature versus displacement and shown in Fig.4.6 and it is found the displacement is linear within crease in temperature. In triple bent- beam structure theapexproducesadisplacementof0.49µmfor temperature of 1000K; therefore this triple bent- beam thermal actuator produces a displacement approximately five times higher than the single bent- beam structure .

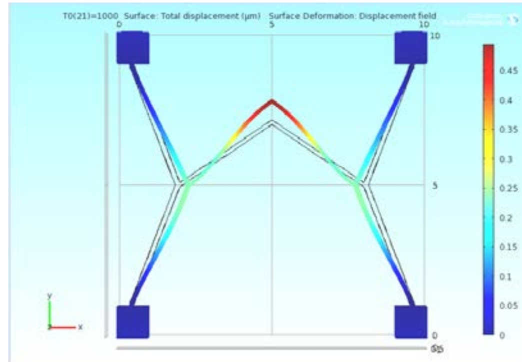

Fig. 6 Deformation of triple bent beam

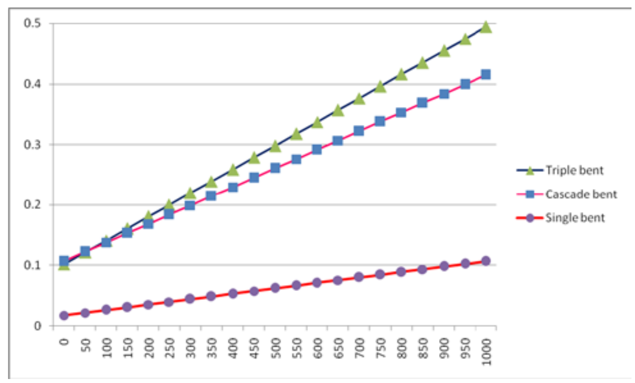

Fig. 7 Comparison of results

When comparing all the three thermal actuator designed triplebent- beam cascade structure gives the maximum displacement therefore the sensitivity of the sensor will be more in the case of the triple bent beam thermal actuator structure. Triple bent- beam thermal actuatorgives1.2timeshigherdisplacementthancascadebent- beam and five times higher displacement than single bent- beam .Since triple bent- beam structure has good sensitivity when compared to other two models for further design of the sensor triple bent- beam structure is used.

The design ofa thermal actuator for a novel temperature sensor for contactless measurements has been described in this paper. Three cascaded V-shaped bent- beam devices has been modeled and then designed. The experimental characterization of the device behavior has been performed in terms of displacement versus temperature change in all the three V-shaped bent- beam devices. Among the three devices designed triple bent- beam thermal actuator has the best sensitivity .

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5. CAPACITANCE CONVERSION

Capacitance is an electrical property which is created by applying an electrical charge to two conductive objects with a gap between them. A simple demonstration is two parallel conductive plates of the same profile with a gap between them and a charge applied to them. In this situation, the Capacitance can be expressed by the equation

$$C = \frac{K\varepsilon_0 D}{A} \quad (11)$$

Where*C* is the capacitance, k is the dielectric constant, ε_0 isthe permittivity of free space, *A* is the area of the plates, and*d* is the plate separation. A common approximation in capacitors is that the dielectric material fills the void betweenthe two conducting plates, which implies that the dielectric thickness, *D*, is equal to *d*, the plate separation.

The capacitance C is directly proportional to the Area of the plates A and inversely proportional to the distance between the plates d. Therefore change in capacitance can be obtained by changing the distance between the plates or changing the area of the plates by sliding one plate on another without touching it.

A capacitor is used to convert the displacement obtained by the triple bent- beam thermal actuator in to an electrical signal using variation in the distance between two plates Among the two plates one should be the fixed and another should be the movable. The movable end should be placed on the apex of the thermal actuator.

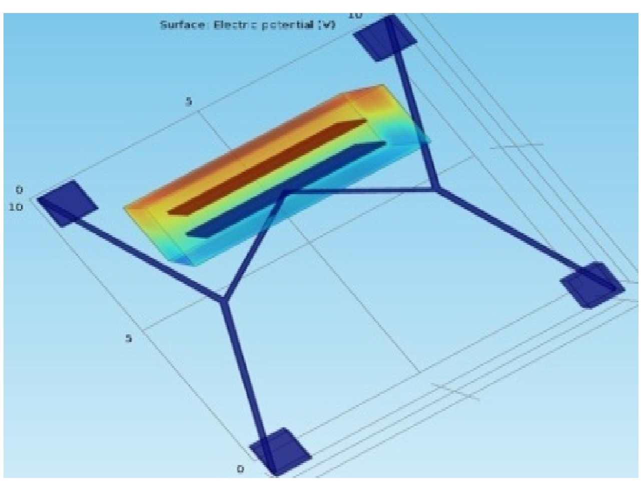

Fig. 8Change in capacitance using variation in distance

A capacitor is used to convert the displacement obtained by the triple bent- beam thermal actuator in to an electrical signal using variation in the Area between two plates by sliding the plates among the two plates one should be the fixed and another should be the movable. The movable end should be placed on the apex of the thermal actuator.

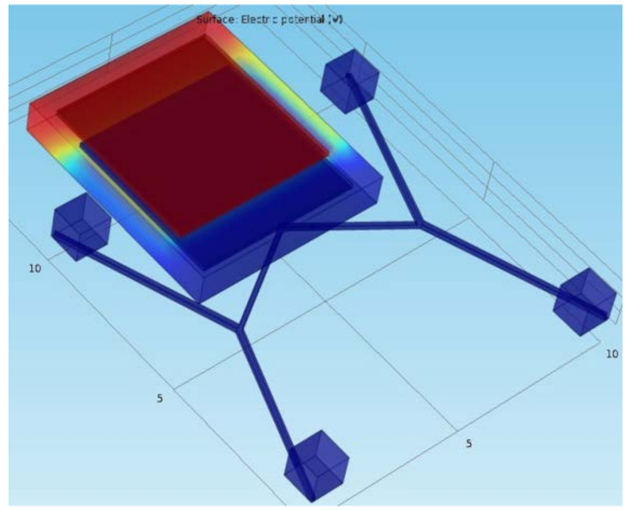

Fig. 9Change in capacitance using variation in Area

The interdigitated capacitor is an element for producing a capacitor-like, high pass characteristic using micro strip lines to convert the displacement in to an electrical signal using interdigitated (comb) capacitor. Among the two plates of the interdigitated capacitor one should be the fixed and another should be the movable. The movable end should be placed on the apex of the thermal actuator.

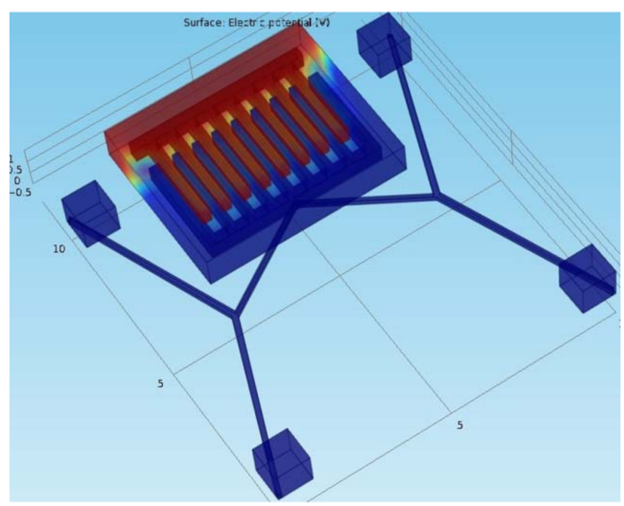

Fig. 10Change in capacitance using interdigitated capacitor

Sensitivity of the sensor is given by change in capacitance per Kelvin. sensitivity of the capacitor using distance variation is 1.259e-18 F/K, for capacitor using change in area is 0.217e-18 F/K and for interdigitated capacitor the sensity is 0.409e-18 F/K. Among the three types of capacitor designed capacitance variation using distance variation gives more sensitivity

6. CONCLUSION

The development of a novel temperature sensor for contactless measurements has been described in this paper. Cascaded V-shaped bent- beam devices have been modeled, both analytically and numerically, and then designed. To obtain variation in capacitance three different types of capacitor designed and find out the sensitivity .

The experimental characterization of the device behavior has been performed both in terms of displacement versus temperature change and in terms of capacitance variation versus temperature variation.

Great efforts have been devoted here to gain a better understanding of the device behavior. In fact, even if the whole device is represented by a linear model and the displacement is linear with temperature , the measured output capacitance was nonlinear. Finally, referring to contactless readout, the design of an integrated inductor has been presented in order to realize an *LC* resonator that can be coupled with a remote readout circuit to sense the resonance frequency shift in response to temperature variation.

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