Macromodeling Temperature-Dependent Curl in CMOS Micromachined Beams

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ABSTRACT

Temperature sensitive curling is commonly observed in MEMS structures fabricated using a standard CMOS process. In this paper, a macromodel for vertical and lateral curling effects is derived by extending thermal multimorph theory for cantilever beams. Stresses induced by temperature change are lumped to form equivalent force and moment sources at the two ends of a beam. The macromodel is added onto an existing mechanical beam model which is used to build and simulate MEMS in a schematic view. Strain in the polysilicon layer of the CMOS microstructure leads to piezoresistance. The macromodel implementation includes computation of strain. The deflections in the lateral and vertical directions from simulations using the macromodel match finite-element analyses to within 3% and match experimental measurements to within 15%.

Keywords: CMOS micromachining, thermal multimorph, lumped parameter simulation, NODAS

1 INTRODUCTION

CMOS-MEMS is a promising technology which allows tight integration of sensors and circuits [1]. Accelerometers and gyroscopes have been demonstrated in CMOS-MEMS [2][3]. CMOS microstructures are composed of a stack of metal, oxide and polysilicon layers. Therefore, vertical curling of the CMOS microstructure is unavoidable. Furthermore, mask misalignments among the metal layers can lead to lateral curling of beams. The presence of the polysilicon layer in the CMOS microstructure provides piezoresistive sensing capability. However, the lack of a multi-domain system-level simulation facility hampers its extensive use.

Integrated MEMS design involves complex systems of multiple beams, plates and anchors with electronics. Lumped parameter models for MEMS elements are needed in order to build a comprehensive design environment. NODAS is a schematic-based design methodology for MEMS [4]. It provides libraries of parameterized atomic-elements such as *beam*, *plate*, and electrostatic *gap*. A simulation capable of capturing curling effects will be immensely useful in designing CMOS-MEMS and in estimating the effects of process variations such as mask misalignment. The models presented in this paper are aimed at enhancing the NODAS elements, but can be used on any lumped parameter environment.

Vertical stress gradients in a cantilever beam arising due to the multi-layer nature of the CMOS microstructures have been analyzed previously using thermal multimorph theory [5][6][7]. The technique outlined is useful for calculating the curvature of cantilever beams. However, interconnected beams and the boundary conditions arising due to such interconnections, pose a more complicated problem.

In this paper we present a macromodel for 3D beam curling effects obtained by extending the analysis in [5]. This formulation is compatible with existing behavioral models for beams [4] and is capable of handling arbitrary boundary conditions. Using this macromodel the internal stresses in the different layers in the CMOS microstructure can be calculated. The stress in the polysilicon layer can be used to incorporate piezoresistive effects.

The analysis for deriving the macromodel is described in Section 2, the comparison with finite element analysis (FEA) in Section 3, experimental verification in Section 4 and conclusions in Section 5.

2 CURL MODELING

The analysis of curl with temperature for a multilayer structure has been obtained by extending Timoshenko's analysis of thermal bimorphs [5][6][7]. A multilayer cantilever structure is shown in Figure 1. Axial forces acting at the centroid of each layer lead to vertical and lateral bending moments. Each layer, i, has a thickness t_i, width w_i, area

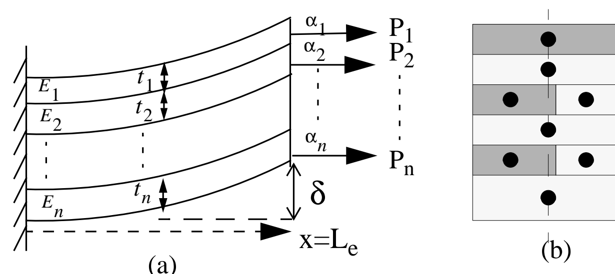

FIGURE 1. (a) Model of a CMOS cantilever beam composed of metal, dielectric and polysilicon layers. (b) Cross-section of an asymmetric multi-layer beam with dots representing the axial forces acting out of plane. Since the forces are asymmetrically located there is a resultant lateral bending moment in addition to the vertical bending moment

$A_i = w_i t_i$, coefficient of thermal expansion, α_i, and an effective Young's Modulus E_i. The out-of-plane curling due to residual stress gradient in the beam produces a tip deflection, δ. The material properties for each layer are assumed to be uniform throughout the layer and independent of temperature.

Let P_i represent the force in the ith layer due to the interfacial forces between adjacent layers. Since the forces P_i are produced by action-reaction pairs, they sum to zero. Let M_{yi} represent the moment about the y-axis in the ith layer produced by the interfacial forces.

$$\sum_{i=1}^{n} P_i = 0 \; ; \left(\sum_{i=1}^{n} M_{yi} \right) = -(Z^T \boldsymbol{P}) \tag{1}$$

where, $\boldsymbol{P}$ denotes the force column vector and $\boldsymbol{Z}$ is the moment arm vector measured from the neutral axis of the composite beam.

$$\boldsymbol{P} = \begin{bmatrix} P_1 \\ P_2 \\ \dots \\ P_n \end{bmatrix}, \quad Z = \begin{bmatrix} z_1 \\ z_2 \\ \dots \\ z_n \end{bmatrix} = \begin{bmatrix} \frac{t_1}{2} - z_0 \\ t_1 + \frac{t_2}{2} - z_0 \\ \dots \\ \sum_{i=1}^{n-1} t_i + \frac{t_n}{2} - z_0 \end{bmatrix} \tag{2}$$

where z_0 is the vertical distance of the neutral axis of bending from the top of the beam and z_i is the distance of the centroid of each layer from the neutral axis. Thickness of the beam is assumed be to much less than the radius of curvature (ρ), and the radius of curvature can be assumed to be the same for each layer.

$$\frac{1}{\rho} = \frac{M_{yi}}{E_i I_{yi}} \text{ or } M_{yi} = \frac{E_i I_{yi}}{\rho} \text{ where, } I_{yi} = \frac{1}{12} w_i t_i^3 \tag{3}$$

where I_{yi} is the moment of inertia of the ith layer having width w_i taken about the principal axis of the layer parallel to the y-axis. Let T_o represent the characteristic temperature of the beam when it is flat [5]. Equating axial strains at the interfaces between layers due to temperature change, $\Delta T = T - T_0$

$$\frac{P_{i+1}}{E_{i+1} A_{i+1}} - \frac{P_i}{E_i A_i} + \Delta T(\alpha_{i+1} - \alpha_i) - \frac{z_i - z_{i+1}}{\rho} = 0 \tag{4}$$

Observing the uniformity of the above equation in the subscript i, we get:

$$\frac{P_i}{E_i A_i} + \Delta T \alpha_i - \frac{z_i}{\rho} = C \tag{5}$$

where C is a uniform axial strain for all layers. Multiplying throughout by $E_i A_i z_i$, we get

$$P_i z_i + E_i A_i z_i \Delta T \alpha_i - \frac{E_i A_i z_i^2}{\rho} = C(E_i A_i z_i) \tag{6}$$

Summing up over all layers and using (1) and (3)

$$-\sum_i \frac{E_i}{\rho}(I_{yi} + A_i z_i^2) + \sum_i E_i A_i z_i \Delta T \alpha_i = C \sum_i E_i A_i z_i \tag{7}$$

Noting that the first term on the left hand side contains the parallel axis theorem for computing moments and that the right hand side reduces to zero, we obtain the total bending moment acting on the composite beam as:

$$M_y = \sum_i (z_i w_i t_i E_i \Delta T \alpha_i) \tag{8}$$

A similar analysis for the lateral moment yields:

$$M_z = \sum_i (y_i w_i t_i E_i \Delta T \alpha_i) \tag{9}$$

The total axial thermally induced force is given by:

$$F_x = \sum_i (w_i t_i E_i \Delta T \alpha_i) \tag{10}$$

Using superposition we can apply any additional force or moments at the ends of the beam and thus take care of arbitrary boundary conditions. Applying the force and the moments given in (8), (9), (10) at the ends of the beam will result in exactly the same displacement and rotation of the composite beam as that produced in each individual beam by the forces and moments produced by the interfacial forces between layers and the thermal stresses. The Norton equivalent model of the macromodel is shown in Figure 2.

In order to model the piezoresistive effect we need to calculate the strain in the polysilicon layer along the length of the beam. Using Euler-Bernoulli beam theory, it can be shown that the total change in resistance depends on the average strain along the length of the beam, which can be shown to be dependent only on the axial strain of the beam and the curvature at the center of the beam. The average lon-

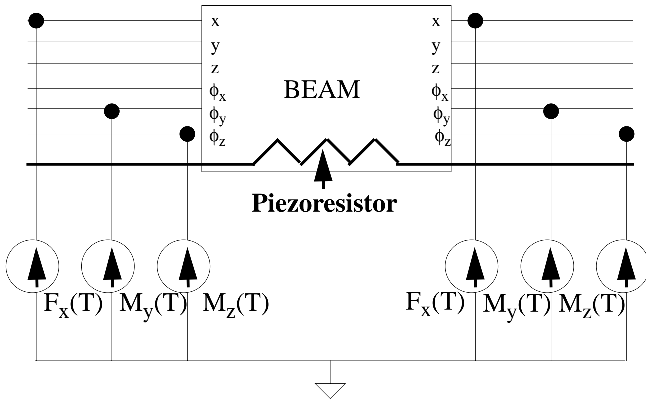

FIGURE 2. Norton equivalent of a beam macromodel with thermally induced lumped force and moment sources and an embedded piezoresistor. The beam has three translational pins, three rotational pins and one electrical pin at each port.

gitudinal strain in a layer which is at distance of (c_y, c_z) from the centroid of the composite beam is:

$$\varepsilon_l = \left(\frac{(x_1 - x_2)}{L} + \frac{(\phi_{y1} - \phi_{y2})c_z}{L} + \frac{(\phi_{z1} - \phi_{z2})c_y}{L}\right) \qquad (11)$$

where, $(x_1, \phi_{y1}, \phi_{z1})$ and $(x_2, \phi_{y2}, \phi_{z2})$ are the axial positions, vertical rotation and lateral rotation at the two terminals of the beam and L is the length of the beam. The resistivity change is related to the longitudinal strain in the layer through the piezoresistive coefficient, π_l as:

$$\frac{\Delta\rho}{\rho} = E_l \pi_l \varepsilon_l \qquad (12)$$

Transverse piezoresistance of polysilicon is much lower than longitudinal and has been omitted from the above equation.

3 FEA VERIFICATION

Thermomechanical FEA was done on a CMOS beam with 3 metal layers. The bottom two metal layers were deliberately misaligned as shown in Figure 3 (a) in order to produce lateral curling with temperature change. Figure 3(b) shows the comparison of tip deflections predicted by the macromodel and the FEA. The deflection is linear with temperature and the difference between the macromodel and the FEA is less than 3% for all temperatures.

In order to verify the generality of the model, seven different beam compositions were analyzed. Table I summarizes the comparison. The type of the beam refers to the composition with numbers denoting presence of the corresponding metal layer and P indicating presence of polysilicon layer. The beams were 100 µm long, the metal layers are 2.1 µm and the polysilicon is 1.2 µm wide. The temperature change was 100 K. The tip deflection values are in µm.

Type	321P	32P	31P	3P	21P	2P	1P
FEA	1.37	2.00	0.84	1.47	2.86	3.07	8.19
Model	1.36	1.98	0.82	1.44	2.81	3.03	8.06

Table I Vertical deflection (in µm) of tip in 100 µm: Macromodel vs. FEA

4 MEASUREMENTS

Measurements to characterize vertical and lateral curl in CMOS beams were made on beams with integrated heaters. An SEM of the test structure is shown in Figure 4. The structure has 3 main parts. A heated base with an integrated polysilicon heater embedded in the structure. A meandering

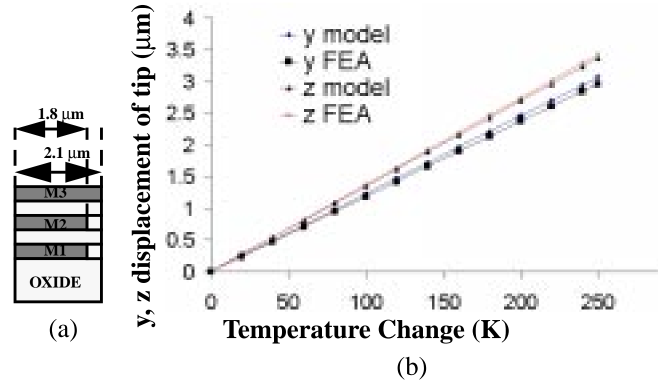

FIGURE 3. (a) Cross-section of beams. Metal3 is 2.1 µm wide and Metal2 and Metal1 layers are 1.8 µm wide and are offset by -0.15 µm from the center of the beam (b) Comparison of behavioral curl model with FEA for beam of length 100 µm. Difference is less than 3% for all temperatures.

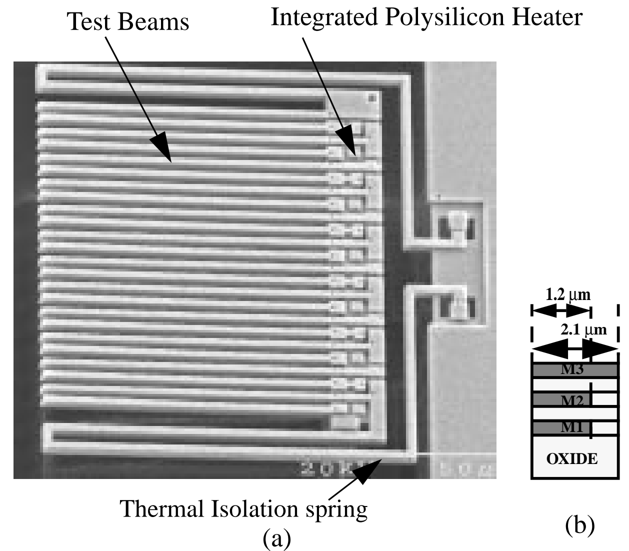

FIGURE 4. (a) SEM of the test structure used to characterize beam curling with temperature. It consists of alternating misaligned and symmetric beams (b) Cross-section of the measured beams (misaligned)

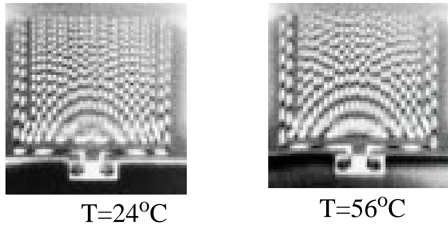

FIGURE 5. Interferometric images of the out-of-plane curl of the test structure at 24°C and 56°C. One fringe length corresponds to 245 nm displacement in the vertical direction

spring that thermally isolates the heated base from the substrate. The test beams are attached to the heated base. Ohmic heating is used to increase the temperature of the base. The temperature of the base and the beams is the same as thermal losses to the substrate are small due to the small device area. The device temperature was extracted from the resistance change in the polysilicon heater. The temperature characteristic of the polysilicon heater was characterized separately by measuring the resistance of the polysilicon heater while the device was placed in a temperature-controlled oven. The device temperature was measured using the temperature characteristic of threshold voltage of the N-well-substrate diode. Measurements with an infrared microscope were made to confirm the uniform temperature distribution.

A 10 Hz triangular heating pulse was applied to the heater. Beam deflections in the lateral direction and the beam curvature were measured using the MIT microvision system [8]. The temperature distribution is expected to reach its equilibrium value at every measurement as the thermal time constant of the structure is 6 ms. The beam out-of-plane curl measurements were confirmed by static interferometry images of the structure. The change in device shape with temperature is shown in Figure 5.

Comparison of the measured deflection vs. temperature with the macromodel is shown in Figure 6. A measured

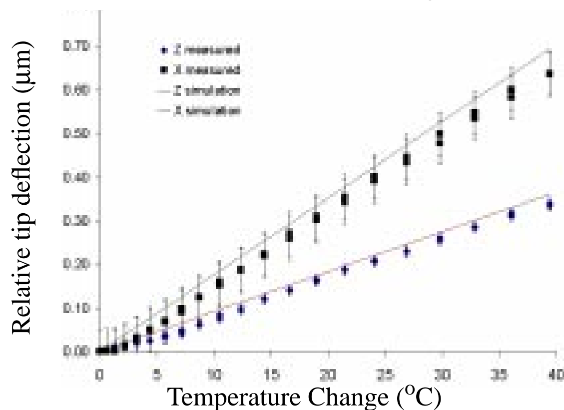

FIGURE 6. Comparison of relative tip deflection from measurements and macromodel showing a match to within 15%. 100 nm and 20 nm error bars are shown for the z and x deflections respectively.

0.15 μm overetch was incorporated in the deflection computation. The measured and the modeled deflections match to within 15% for large deflections. Possible sources of error include temperature calibration and microvision resolution.

5 CONCLUSIONS

A macromodel suitable for schematic-based simulation of thermally induced lateral and vertical curling in multi-layer CMOS sensors was derived using thermal multimorph theory. By interconnecting beams the curling characteristic of CMOS sensors can be simulated before design. Further, effects of manufacturing variation such as mask misalignment on sensor performance can now be studied in an integrated manner. The macromodel predicts deflections to within 3% of FEA and within 15% of measurements on test structures.

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