Postbuckling analysis of a thermally driven microbeam under realistic conditions

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Abstract. Thermal buckling behavior of line shape microactuators in a fully coupled field process is simulated. As a consequence of the miniaturizing, some effects belong to coupling of different physical fields appear, and some issues, which are minor at macroscopic scales, have to be taken into account. In order to have a robust design of these micro-systems, it is important to correctly analyze the coupling between electrical, thermal and mechanical fields. Regarding effect of more physical aspects and ignoring the simplifying statements, the calculated results are consistent more with reported experimental measurements in the literature. Recommended modifications not only improve the results to be consistent with experiments, but also play key roles for the development of MEMS actuators based on joule-heating effects such as Heatactuators and Hexsil tweezers. While the simulation of micro actuators mostly consist of coupled field analyses, the results prove the requirement of transferring more detailed outputs from one field to another one as inputs.

1. Introduction

A common actuation mechanism for microelectromechanical systems (MEMS) is joule-heating-induced thermal expansion. [1]-[5]. Ease of fabrication, quick and large movement and forces let them [6] have several applications in Microsystems. For example, they could be implemented to predict the magnitude of residual stress in thin film [7, 8 and 9]. Different bistable or multistable mechanisms of buckled beams have been applied for memory elements [7, 10], pumping mechanism [7, 11], and snapping microactuator [3]. All of these applications have used on/off property with buckling effect. The driving mechanisms of these microactuators could have three sources, electrostatic [6, 12, 13 and 14], magnetic [6, 13] and electrothermal forces [15]. The electrothermal actuation is simple and can be easily generated with a normal input power. These microactuators could exert translational [16], rotational [12, 13] or combined translational/rotational [6, 14] movements. By that means, microbeams provide the possibility to lift up the micro platforms vertically with minimum rotations [6]. In order to optimize or improve any of electro-thermally driven MEMS structures, a clear understanding of the responses should be achieved with a more accurate modeling [5]. Simulations starting from electrical impulse that provides the joule heating energy to the mechanical actuation are not accurate because of missing some important physical factors. A microstructure fabricated by the MCNC multi-user MEMS process (MUMPs) [15], is modeled because of the availability of experimental data for correlation with finite element. This coupled electro thermal and elastic model has been utilized in the simulation of a laterally driven clamped-clamped microbeam with 2-\( \mu \)m wide, 2-\( \mu \)m thick and 100-\( \mu \)m long.
During the process, electrical power makes the microstructures experience a temperature rise; therefore, thermal expansion tends to elongate the beam. Nevertheless, anchors prevent this elongation and produce high compressive stress; where as the overall stiffness of structure will decline. The compressive stresses in addition to imperfections are origins of buckling. Teh and Lin [17] have discussed the experimental results of this phenomenon in time domain. From physical point of view, this buckling scenario may be divided into two parts, electro-thermal and thermomechanical modeling. Previously, many empirical and analytical works have been done on the electro-thermal analysis. Lin and Chiao studied the electrothermal response of line shape microstructures analytically and solved thermal governing equations to offer the profile of temperature distribution as a function of passing current, which indicates the maximum temperature in the middle of the beam and minimum temperature (ambient temperature) at two ends.

Recently, similar works are considering more accurate models using FEA to have better predictions. For electromagnetic portion of the simulation, Mankame and Anthasuresh [18] have used a comprehensive thermal model to characterize an electro-thermal actuator. The model accounts for all modes of heat dissipation and the temperature dependence of thermo-physical and heat transfer properties over a wide range of temperature, i.e. 300-1500 K [18]. These models have been improved by Lott et al. [19] using finite element model to simulate this behavior with temperature dependent conductivity for polysilicon. The former works adequately discussed the electrothermal behavior of these actuators [20]. At second part, thermomechanical modeling, Majority of past efforts [21, 5, and 7] did not mention adequate physical factors and the simulations are under modifications. Chiao and Lin [5, 6] have studied the self-buckling of micromachined beams under resistive heating analytically considering nonlinear behavior and using FEM included temperature distribution through beam. They compared their simulation results with experimental results but the correlations were not satisfactory because of poor modeling technique [5]. Improvement of the correlations can be accomplished by modifying the model, which includes more physical factors. These physical features are discussed as follow.

2. Disparity of cross section from desired one because of fabrication process

Process variations may change the cross section of microbeams. For example, a trapezoidal, instead of a square shape may be the true cross section of the beam as the result of an imperfect reactive-ion-etching process [5, 7]. In addition, the width and thickness of the beams may also vary from different wafers or even different locations of the same wafer. Fig. 2 shows the probable cross section. This factor affects the performance of the micro beam. The simulation shows that it decreases the critical temperature about 1 K. Note that on one hand, this feature has negligible effect on the buckling
temperature, but on the other hand, it could destroy the mission of actuators by activating them in a non-predefined direction.

Figure 2. Deviation from ideal one of true cross section

3. Residual stress in micromachined beam produced during manufacturing process.
A passive residual strain of 6.4e-5 has been detected in microbeams via the MCNC MUMPs process [22]. The corresponding compressive residual stresses are 9.6 Mpa for polysilicon films with Young's modulus of 158 Gpa. It is reported [5] when compressive residual stress exists within a microbeam, the critical temperature to cause the buckling of microbeams decreases. Chiao and Lin [5] mentioned as an effective character but the amount of effect has not calculated yet within any analysis for MEMS devices. In this work, the prestressed nonlinear finite element simulation was developed to predict the changes in critical temperature and postbuckling behavior of microbeams. In this work, the prestressed nonlinear finite element simulation was developed to predict a drop of 23.4 $^\circ$K in buckling temperature. Fig.3 shows the comparison between postbuckling results of original model and prestressed one.

Figure 3. Central displacement of micro beam versus temperature illustrating the Influence of 9.6 Mpa residual stress in comparison with original model
4. Temperature distribution profile throughout the beam provided by electro-thermal analysis

Temperature distribution profile was estimated analytically by Lin and Chiao [20]. Fig. 4 illustrates the distribution of temperature along beam for an average temperature of 773.2 K.

![Temperature distribution over beam](image)

Figure 4. Temperature distribution over beam

The simplification of temperature distribution with average temperature does not affect the accuracy of results, as long as the properties are independent of temperature. It will be proved in the following that if material properties are assumed independent of temperature, the average temperature and the distributed temperature loading produce equal compressive force and have the same effect in postbuckling response of microbeams. As it is known, the origin of thermal buckling is anchors’ resistance to thermal expansion. Overall elongation of a beam under temperature loading is estimated by Eq. 6.

\[ \Delta l = \int E \alpha \Delta T \, dx \]  

(6)

If \( E \) and \( \alpha \) are assumed independent of temperature, Eq. 6 yields:

\[ \Delta l = E \alpha \int \Delta T \, dx \]  

(7)

On the other hand, if average temperature is taken into account, the elongation is as follows:

\[ \Delta l = E \alpha \Delta T_{avg} \, L \]  

(8)

Where, \( \Delta T_{avg} \) is the average temperature and defines as:

\[ \Delta T_{avg} = \frac{\int \Delta T \, dx}{L} \]  

(9)

Substituting Eq. 9 into Eq. 8 yields

\[ \Delta l = E \alpha \int \Delta T \, dx \]  

(10)

Eq. 10 and 7 are identical. Therefore, there is no difference between these two assumptions and so the simplification of temperature distribution with average temperature does not affect the accuracy of results, as long as the properties are independent of temperature. When simulation includes
temperature dependence of properties, temperature distribution plays an effective roll in the buckling predictions. Fig. 7 shows the influence of temperature distribution in comparison with original results when dependence of properties is considered.

5. Discussions
A number of modeling issues are considered and discussed in detail. Variation of cross section from true one, Residual stress and Temperature distribution profile are included in the model. The effect of each one is summarized in Table 1.

| Modification                              | Critical temp change                  |
|------------------------------------------|---------------------------------------|
| Deviation of cross section               | Below 1%                               |
| Residual stress                          | -3% if the residual stress is compressive |
| Temperature distribution profile         | No change                              |

Table 1. Influence of physical factors in buckling temperature

Finally, results of these modifications are compared with Lin and Chiao’s experiments [5] and previous analyses [1]. Lin and Chiao measured the buckling temperature around 673.2°K (3 mA) which is less than analytical prediction of 804.2°K (20% error). Table 1 illustrates that the modifications have improved the prediction of buckling temperature from 20% error to 16% over estimation in the smaller deflections when the beam starts to buckle.

6. Conclusion
Including several physical characteristic to increase the accuracy, thermal Postbuckling of microbeam is simulated using the nonlinear finite element simulation. The remaining distance to 673.2°K (experimental result) mainly belongs to temperature dependant properties, uncertainties in material properties, section dimensions and compliance of supports. This paper and previous works [2] show the major roll of realistic modeling in prediction of MEMS devices behavior, working with Joule heating in relatively high temperatures. As a result, it is concluding that establishing databases and standard testing systems for MEMS materials is essential for reliable operation of Microsystems. When both high stress and temperature change are involved, the reliability of MEMS devices may be affected. Several MEMS structures that may have great chance in encountering this problem includes thermally driven microactuators [3–5], anemometers [6], chemical sensors that operate at elevated temperature [7] and micro turbines [8]. Therefore, it is important to investigate the actual behavior of micro devices in the micro scale for reliable operation of these and other MEMS products. In addition, sophisticated modeling techniques in coupled field analysis of Microsystems should be set in motion. The complexity of boundary conditions and applied loads should be taken into account because of the interactions in coupled field analysis. According to the results of this work, the behavior of microstructures is more sensitive to physical features in micro scaled coupled field events. While, the measured data for properties, geometries and loading conditions have great uncertainties the stochastic simulations for Microsystems are necessary to predict their performance and reliability. Because the microactuators have several applications, their fatigue life assessment is also important to be estimated including all mentioned physical features. From manufacturing point of view, results presented here invest valuable discussion on the control of tolerances and cross section topologies as effective factors on the performance of micro systems. Further more, the effect of residual stresses on the critical temperature is calculated and it makes the future simulations consider it.
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