Multiphysics Coupling Analysis of MEMS Sandwich Structures

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Abstract

A new method of active natural frequency tuning has been demonstrated by employing residual stress variation resulting from temperature changing in the layers. A sandwich structure has been modeled and the thermal-electro-mechanical coupling is analyzed by the FEA-simulation tool, ANSYS. This kind of structures can be used for resonant sensors, frequency-selective MEMS etc.

Introduction

Microelectromechanical System (MEMS) is a rapidly growing technology with a broad range of commercial applications, mainly in sensors and actuators fields. Residual stress always exists in most microstructures fabricated by surface micromachining. Generally, it is harmful to the structure characteristics, but many microstructures are demonstrated to utilize residual stress (reference 1, 2). Also a sandwich structure is introduced here, which employs residual stress to vary the structure resonant frequencies. The most commonly used material is polysilicon, however silicon nitride film with high tensile residual stress is used as the main body of the structure here. Polysilicon film as the Joule heating layer to heat up the structure. So the polysilicon layer is very thin (0.1 μm), silicon nitride layer is much thicker (2.5 μm). The dominating stress value in silicon nitride is intrinsic (microstructural) stress, not the thermal stress, but the intrinsic stress are of complex physical origin and can not easily be expressed in terms of fundamental materials properties. And the stress is linearly temperature dependent over a wide temperature range, so the fictive thermal expansion coefficient of it must be calculated to introduce internal stress to ANSYS (reference 1). Process parameters must be well controlled, so polysilicon and silicon nitride layer characteristics in this sandwich structure are:

1) Residual stress in polysilicon layer is very small, so at room temperature, polysilicon layer internal stress is not to be introduced to ANSYS.
2) Residual stress in silicon nitride must be large, up to about 700 MPa, so the characteristic of the sandwich structure is vary with the temperature notably.

Thermal-structural model

The sandwich structure model is comprised of three layers. The middle layer is silicon nitride layer, as the main body layer, to achieve the frequency tuning characteristics as indicated. The top layer and the underside layer are polysilicon layers, as the Joule heating layers to heat up the middle layer. Polysilicon layers are very thin, that can reduce the affect to the whole structure, and the middle layer is thick more. As the residual stress in polysilicon is very small, so the internal stress doesn't need to be introduced to ANSYS, as free residual stress parts. Then the analysis is performed:

Firstly, built up the model and mesh it, apply the average temperature of the structure as thermal load to the silicon nitride layer with the fictive thermal expansion coefficient.

Secondly, perform a static analysis with the prestress flag on [PSTRES, ON], obtain the internal stress of the middle layer, then use a prestress modal analysis to calculate the frequencies and mode shapes of the prestressed sandwich structure with the prestress flag on [PSTRES,ON] too.

Lastly, increase the average temperature of sandwich structure step by step, one step is 10 centigrade. In each step, the prestressed modal analysis is performed to obtain the frequency variation with the increasing temperature.

Analysis Procedure and Results

First, the sandwich structure is analyzed as a 2D model, meshed with BEAM3 Element, with the room temperature as thermal load applied to it. As the BEAM can not model multilayer, the polysilicon layer is considered as a silicon nitride layer. Performing a prestressed modal analysis, obtain the results:

SET	TIME/FREQ	LOAD STEP	SUBSTEP	CUMULATIVE
1	0.35956E+07	1	1	1
2	0.85216E+07	1	2	2
3	0.15354E+08	1	3	3
4	0.24238E+08	1	4	4
5	0.35206E+08	1	5	5

Then a 3D model is analyzed with SOLID45 element, the polysilicon layer is considered as a silicon nitride layer too, the result are:

SET	TIME/FREQ	LOAD STEP	SUBSTEP	CUMULATIVE
1	0.36718E+07	1	1	1
2	0.54526E+07	1	2	2
3	0.86865E+07	1	3	3
4	0.11784E+08	1	4	4
5	0.15643E+08	1	5	5

Looking at the results, the first three "in-plane" modes (in the xy-plane) agree well.

When the 3D model is refined to be analyzed, the results are almost equal. It can be seen from the result, 3D model are more accurate. Therefore we perform a modal analysis with a 3D model in this paper. When considering the polysilicon layers, first modal frequency is 0.37482E+07. So although the polysilicon layer is a small structure in ANSYS, it cannot be omitted. In the micro bridge devices, we are interested in the first natural frequency, so only the first resonant frequency is obtained in other temperature conditions.

After the prestressed modal analysis is performed, the relationship of frequency variation and the temperature can be obtained (figure 1). Looking at the figure, the frequency is approximately linear temperature dependent over 20~500 centigrade temperature range. The linear curve is

$$\text{frequency} = -1.2947 \times 10^{3} * \text{temperature} + 3.7912 \times 10^{6}$$

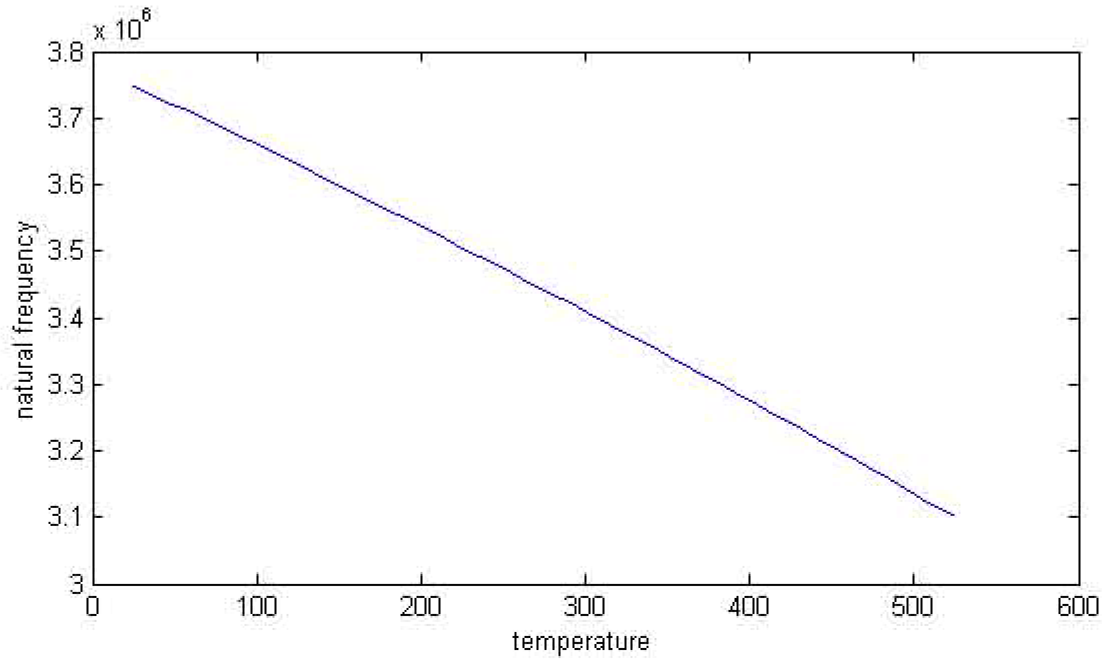

Figure 1 - Frequency changes of the structures with the average temperature

So, the sandwich's nature frequency approximately linearly decreases with the temperature increasing, 1.295 kHz frequency decrease corresponding to 1 centigrade temperature increasing. However, the following quadratic fitting curve is meeting the calculating results better, but the difference between them is small, and it is not convenient for calculating in practice also.

$$f = -0.2760t^2 - 1.1429 \times 10^3 t + 3.7763 \times 10^6$$

Where,

$f =$

natural frequency of the sandwich structure.

$t =$

average temperature of the sandwich structure.

This frequency variation property can be use to actively tune the resonant frequency of microbridge and frequency-selective MEMS (reference 3). Moreover, When the structure heats up resulting in a decrease in Young's modulus, this effect can also help to actively lower the natural frequency (reference 4, 5). This effect is not considered in the paper.

Thermal-electro-structural model

The thermal-electro-structural model is much more complicated than the thermal-structural model (figure 2), as we must consider the electrostatic drive parts and the electrostatic field in the air. But this sandwich structure can be regarded as 2D model to reduce the complexity, and the accuracy has been proved in many literatures.

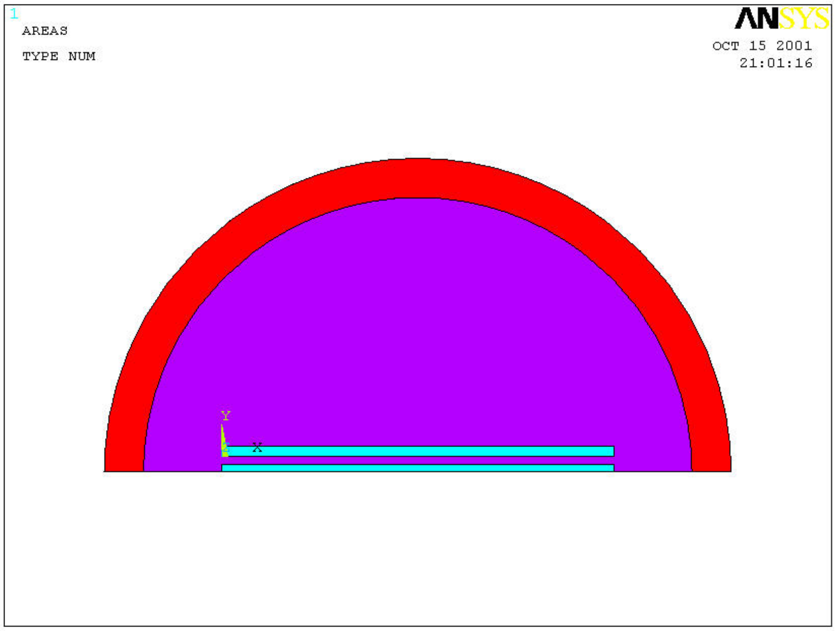

Figure 2 - Overall model plot of the thermal-electro-structure analysis

The 2D-sandwich structure is meshed with 2D structural solid element PLANE42, the air domain is meshed with 2D electrostatic solid element PLANE121, and the open boundary of air is meshed with 2D infinite solid element INIFIN110. one layer of INIFIN110 elements is used, and the exterior surface of this element is flagged using the INF option on the SF command.

Last, we apply displacement constraints to the structure, and voltage constraints on the electrostatic drive electrode part and the sandwich structure (figure 3).

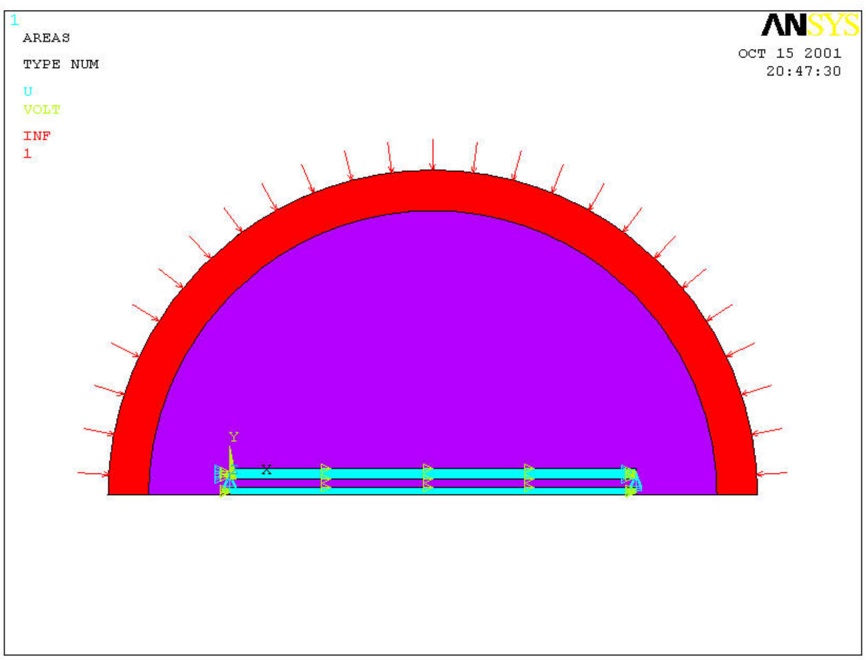

Figure 3 - Constraints plot of the thermal-electro-structure analysis

Analysis Procedure

A sequential coupled-field analysis is performed using the physics environments method. When the residual stress is introduced to ANSYS, it is found that the maximal displacement of the sandwich structure is equal to residual stress free sandwich structure, it is 0.0015 μm in this paper at 0 centigrade. So in the thermal-electro-structural analysis of the sandwich structure, the residual stress is not considered.

In analysis procedure, the average temperature of sandwich structure as thermal loads to the structure is increased step by step. In each step, the electrostatic-structural coupled field analysis is performed to obtain the maximal displacement of the sandwich structure.

Analysis Results & Discussion

As indicated, residual stress does not affect the structure displacement in electrostatic-structural analysis. And it is found that the displacement is increasing linearly with the temperature increasing (figure 4). The fitting curve is:

$$y = 3.7558 \times 10^{-6} t + 0.0015$$

where,

$y =$

maximal displacement of the sandwich structure.

$t =$

average temperature of the sandwich structure.

When the average temperature of the sandwich structure increases up to 500 centigrade from 20 centigrade, maximal displacement is obtained from 1.5760×10^{-3} μm to 3.3773×10^{-3} μm

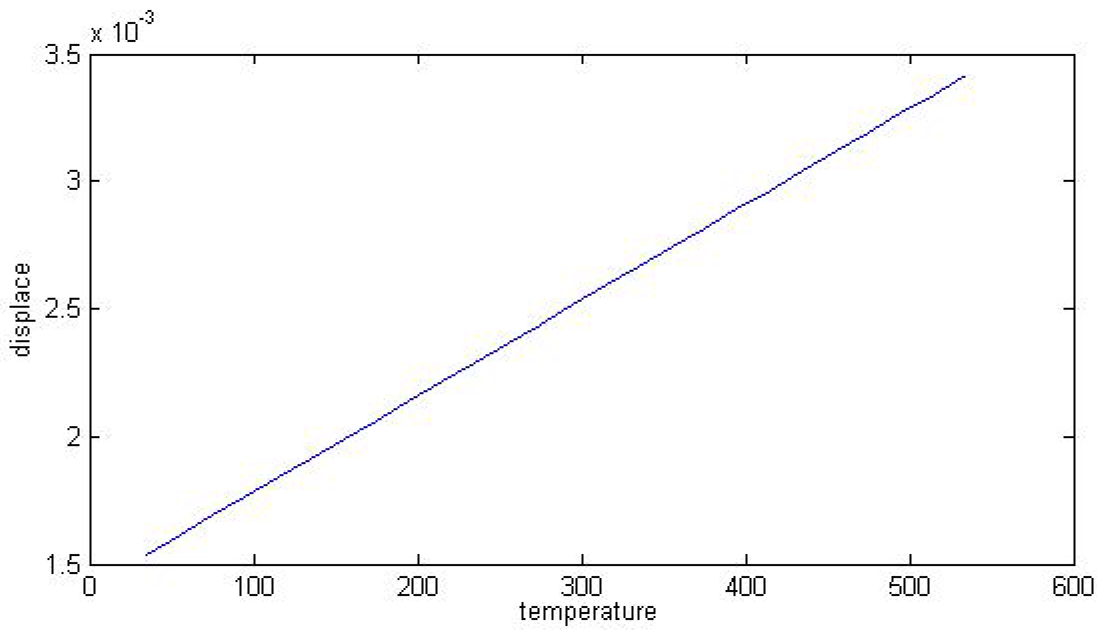

Figure 4- Displacement changes of thermal-electro-struture analysis

Conclusion

An active frequency tuning mechanism utilizing the residual stress in MEMS structure has been proposed. From computation, this method can adjust the natural frequency of the sandwich structure up to 1.295kHz with the 1 centigrade temperature variation. Both thermal-structure and thermal-electro-structure coupling models are analyzed in this paper. In many resonant MEMS devices, actively adjust the resonant frequency is important, this method can help to that devices design.

References

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