A Study on Alleviating Deformation of MEMS Structure and Prediction of Residual Stress in Surface Micromachining

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ABSTRACT

Recently, the acceptance of micro electromechanical systems (MEMS) technology is growing in various areas such as medical, optical, automobile and telecommunication. In realizing the needs in MEMS, techniques derived from mechanical engineering plays an essential role in the determination of geometric design variables and process parameters, experiments in fabrication and the elastic and plastic deformation, the fatigue fracture, durability estimation under operational conditions.

RF switch that shorts and opens a circuit of RF transmission line is a application that MEMS technique can contribute. During the fabrication process, the residual stress build up, which is caused by the thermal expansion coefficient mismatch between deposited materials, is unavoidable and leads to the deformation of structures. In order to cope with this problem, a finite element analysis was carried out to predict and optimize the residual stresses in a multi-layered structures and a new method to restrain deformation is proposed..

Keywords: MEMS, RF Switch, surface micromachining, residual stress, finite element method

1 INTRODUCTION

MEMS-based 3 dimensional structures can provide advantages like higher efficiency and performance to RF application [1-3]. MEMS fabrication process, however, has problem of initial deformation caused by residual stresses due to internal and external factors during the fabrication process [4]. This problem is realized not only right after the completion of fabrication process, but also during the post process like packaging and in-use conditions. Changing the process condition can manage the residual stress somewhat, however, the effects are highly limited, because the properties of deposited films are also changed [5].

In this study, finite element analysis approach of estimating residual stress is laid out. A new methodology to handling residual stress and resulting deformation of structure, which is purely dealing with geometric shapes and dimensions, is introduced and tested.

2 ANAYTICAL APPROACH

The feature of seesaw type RF MEMS switch what are used in this research is shown in Figure.1. The difference of stress gradient between two different layer materials causes this undesirable deformation of structure. To simulate deformation due to residue stress, finite element analysis model used residual stress values as initial stress conditions after experiment of cantilever.

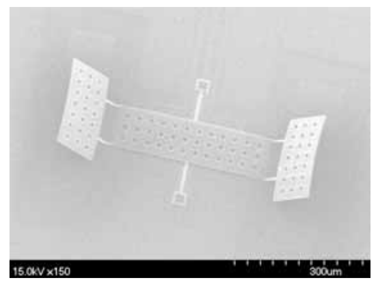


Figure 1: SEM of deformed structure in residual stresses

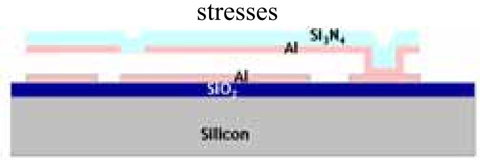
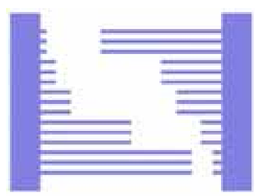
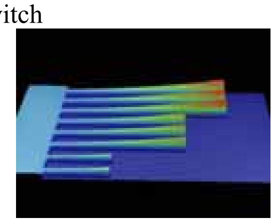


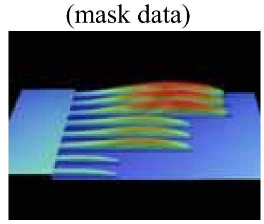
Figure 2: Cross-section view of RF MEMS Switch



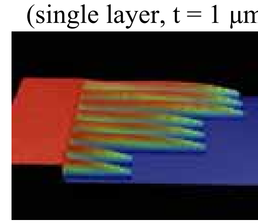
a) Stress test pattern (mask data)



b) SiNx cantilver (single layer, t = 1 μm)



c) Al-3%Ti cantilever (single layer, t = 0.5 μm)



d) SiNx/Al-3%Ti cantilever (double layer, t = 1.5 μm)

Figure 3: Optical profile of cantilever specimen

The specimen for measurement of stress gradient is made by following procedure. First, thin films of same thickness with structure layers are deposited on the sacrificial photo resistor coated on substrate. Then cantilever beam of different length, spaced with substrate, are made by photolithography followed by ashing process to release.

Radiuses of curvature are measured from initially deformed cantilevers in curved shape by WYKO optical profiler. Surface micro machined thin film structure is so compliant that mechanical contact profiler has difficult to measure accurately. The changing color represents the height of cantilever structure, shown in Figure 3(b-d). The radius of curvature from previous experiment can calculates bending moment from equation (1)

$$\frac{1}{R} = \frac{M}{EI} \tag{1}$$

R, M, E, I mean radius of curvature, bending moment, Young's modulus and Moment of Inertia respectively. Also, the maximum deformation in edge of cantilever is defined by equations from Euler's beam theory. Equation (2) is used for comparison between finite element analysis result and experimental results.

$$y_{\max} = \frac{ML^2}{2EI} = \frac{L^2}{2R} \tag{2}$$

In the mean time, Maximum stress values for initial stress gradient of finite element analysis model are calculated with equation (3).

$$\sigma_x = \frac{EI/R}{I} = \frac{\mathrm{E}}{\mathrm{R}} \tag{3}$$

So under the assumption that stress gradients of each internal element cause bending moment that deform the structure, each stress gradient are calculated from equation (3) and applied in finite element model.

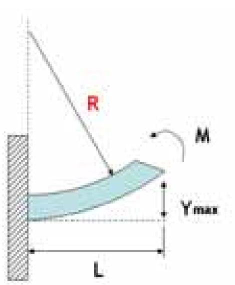


Figure 4: Bending of the cantilever beam due to the bending moment.

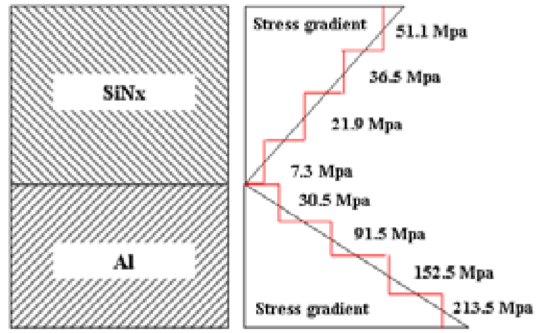


Figure 5: Modeling methodology and initial stress conditions of single and composite film

Figure 5 shows distribution of applied stress gradient, which is perpendicular with thin film, in finite element model as initial conditions. The simulation model has been verified for accuracy by the comparison of simulation result and experiment measurement in Figure 6.

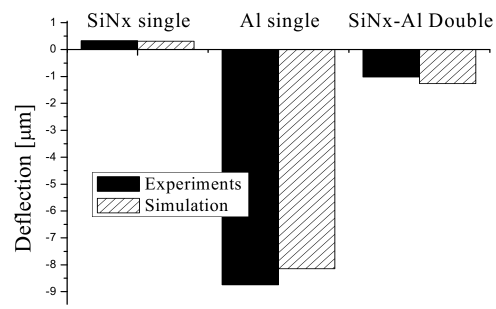


Figure 6: Comparison of experiment vs simulation results

3 UNIT CELL

To separate influence of entire structure shape, the unit cell is introduced to minimize structural deformation. As shown in figure 7, whole structure is assumed combination of simplified unit cells. Minimum deflection of whole structure can be achieved by unit cell minimization. This methodology can offer actuator designer maximum degree of freedom independent of whether other structure design factor.

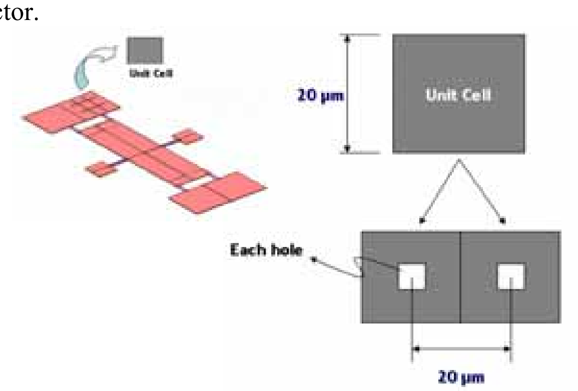
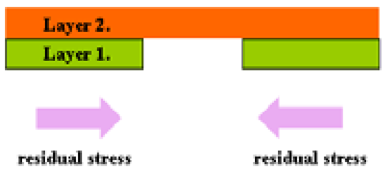


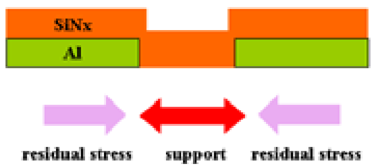
Figure 7: Introduction of unit cell

3.1 Realization of deposit phenomenon

Surface micromachining uses vapor deposit process, not like bulk micromachining, to pile materials sequentially. Double layer structure shown in figure 8(a) keeps original form when they are assembled from parts prepared separately. But patterned empty area of bottom layer is filled with top layer which confirms with bottom layer well. This characteristic is caused by thin film deposition process like sputtering like figure 8(b).



(a) General composition bonding



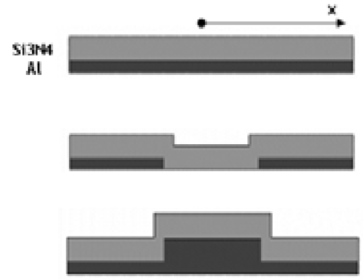
(b) Deposition process
Figure 8: Section view of unit cell

The restraint to equivalent bending moment of two composite layers is improved when filled material has higher strength than bottom material. The main concept of this research was that if empty space is patterned with particular shape, alleviation of deformation in piled thin film structure will be achieved efficiently. The deflection was obtained by simulation which used finite element model of deposition type unit cell and measured stress gradient along the thickness. Materials of lower and upper layers are aluminum and SiNx each. Young's modulus of SiNx is 3 times higher than Aluminum's. Maximum deformation of planar structure can be expressed by equation (4) for a line of curvature. Figure 13 shows that deflections are related with distance along the path and Type B has significantly small deformation. The phenomenon that center area is flatter than side in unit cell represents well effect of this research.

$$y_{\max} = \frac{L^2}{2R} \tag{4}$$

3.2 Deflection in different unit cell type.

Previous finite element model was used to obtain deformation of each deposit type A, B, C with measured stress gradient along the thickness. Materials of lower and upper layers are Aluminum and SiNx each. Young's modulus of SiNx is 3 times higher than Aluminum's. Maximum deformation of planar structure can be expressed by equation for a line of curvature.



(a) Type A
(Plain)

(b) Type B
(Embedded)

(c) Type C
(Rib)

Figure 9: Three types of unit cell structure(section)

Figure 10 shows that deflections are related with distance along the path and Type B has significantly small deformation. The phenomenon, that center area of unit cell is flatter than side, represents clear effect of this research.

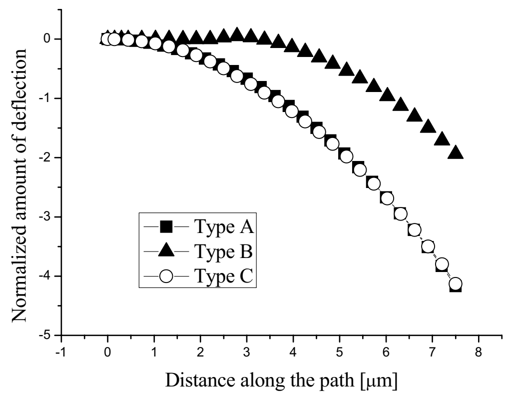
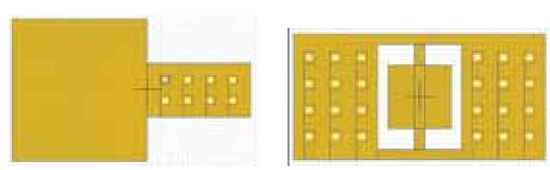


Figure 10: Amount of deflection for deposit types

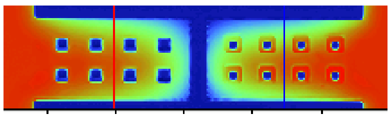
4 EXPERIMENTS

Two sets, shown in figure 11, of simple cantilever and seesaw structure are fabricated with two unit cell type A and B to verify the simulation experimentally. Single ended cantilever can have initial bending in start line of released film due to mean stress of film. Unlike cantilever, seesaw structure has same boundary condition with actual switch actuator. Radius of curvature is used for deformation of structure to compensate the deflection results. The relative deflection of embedded cell structure was compared with original structure to verify the effect of proposed structure.

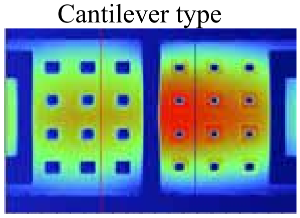


(a) Cantilever (b) Seesaw
Figure 11: Mask of Tested Structure

The simulation predicted 25% of reduction in deformation for new proposed structure over plain double layers, type A. The experiment, however, was resulted in even grater reduction of 35% depending on the geometry of type B test structure. Contour and profile shows the actual restraint effect in figure 12 and figure 13.

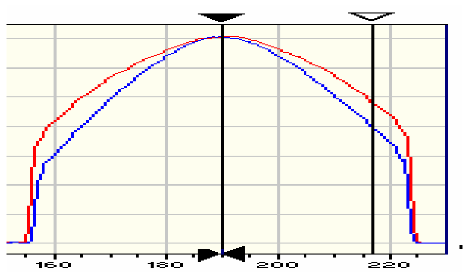


(a) New (b) Old
Cantilever type

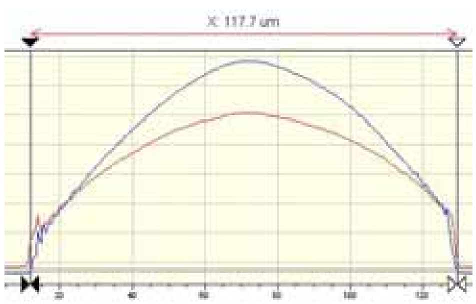


(c) New (d) Old
Seesaw type

Figure 12. Contour plot of test structure in height



(a) Cantilever test structure



(b) Seesaw test structure

Figure 13: Profile of experimental result

5 CONCLUSION

The deformation of multi-layered MEMS structure is inevitably caused by the residual stress generated during surface micromachining process. New embedded structure as well as processing sequence, which can be applied to general multi-layered MEMS structure, was proposed to alleviate this unwanted deformation. Even though the degree of restraint varies due to the ratio between horizontal and vertical dimensions, improvements were evidenced.

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