MEMS Test Structures for Residual Stress Measurements

Akshdeep Sharma [*, 1], Maninder Kaur[1], Dinesh Kumar[2] and Kamaljit Rangra*[1]
[1] Central Electronics Engineering Research Institute (CEERI), PILANI, [2] Kurukshetra University Kurukshetra, Haryana, India
*Corresponding author: Sensors and Nanotechnology Group, Central Electronics Engineering Research Institute (CEERI), Council of Scientific and Industrial Research (CSIR), Pilani, 333 031, Rajasthan, India.
akshdeepsharma@gmail.com , kjrangra@gmail.com

Abstract: A set of microstructures for in situ stress measurement is presented, based on a lancet principle having dedicated designs for the amplification of dimensional variation induced by internal stress of the materials. The presented technique has an advantage over the traditional rotating structures and wafer curvature measurements in terms of the simplified readout mechanism. The test structures are realized by surface micromachining techniques, adopting photoresist as a sacrificial layer and electroplated gold as a structural layer. COMSOL multiphysics simulations are adopted to analyze the behavior of gold structures under the influence of thermal variation using “thermal structural interaction” MEMS module. The residual stress is obtained in the range of 200±30MPa.

Keywords: MEMS, Test structure, residual stress, surface micromachining.

1. Introduction

In micro-electro-mechanical systems (MEMS) technology the residual stress of deposited layers induces strain in the structures and subsequent movement of their released parts. This displacement can be magnified to produce an indication of the internal stress of the film. Several layouts are available for direct measurements of the stress in deposited layers [1–5]. The aim of the test structures is to provide quick and reliable information which can become vital for optimizing residual stresses in micro-mechanical device fabrication.

Traditional array structures such as buckling beams offer a discrete means of measuring stress, but with some limitations: different structures are needed to measure tensile and compressive stress. The resolution is poor because of the discrete measurement. The array of structures increases the wafer area requirement.

Pointers are rotational type test structures which can measure both types of stresses and can be useful to measure the strain in structural layer. The displacement of pointer reflects the strain in the material. However, this displacement provides a limited range of 1µm/50MPa with reduced sensitivity [6].

The lancet layout offers a solution to all these limitations by providing a single structure for both tensile and compressive stress, with continuous readout and small wafer area encumbrance [5]. This work focuses on the possibility to magnify the lancet displacement by adopting geometrical amplification; tilted arms offer an interesting solution, being capable of providing a simple and direct amplification of strain. In order to address this problem a magnification device has been modeled and implemented. This structure allows larger displacement and consequently higher sensitivity.

2. Method, Theory and Layouts

Basic layout model of pointer structure depends on three major parts: tilted beam, driving bar and junction as shown in figure 1. In these structures the strain of structural layer (relative to substrate) is converted into a displacement that can either be measured by optical or electrical means. If, Young’s Modulus of the material is known, residual stress of structural membrane can be inferred. Two components are defined, one being the pointer and central anchor (junction), the other being the tilted beams part, which is the part that magnifies the displacement of the pointer. This displacement is used as an input for the junction structure. The junction component determines the force generated by the junction on the driving bar along the x axis, and this force is used as an input for the tilted beams model through which strain can be calculated.

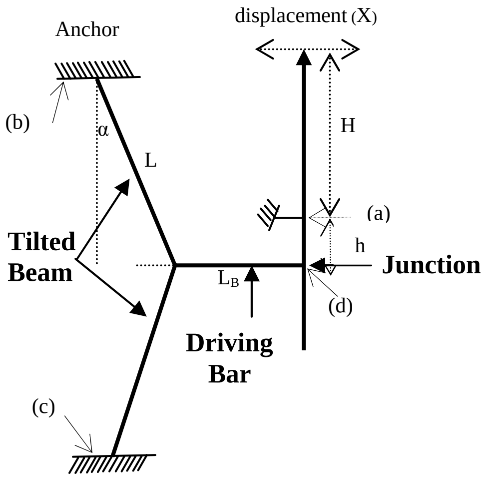

Figure 1 Conceptual schematic of the lancet.

2.2 Governing Equations

The geometrical variables of the model are shown in figure 1. The model calculates the planar strain of the structure with respect to the substrate, for a certain displacement of the pointer. The lancet is fixed at point (a), with length (H) and distance (h) between the anchor (a) and the junction (d). The tilted arms are fixed at points (b) and (c), with length (L), inclination (α) and they are connected with the lancet by a driving bar of length (L_B). When the structure is released, the residual stress induces strain in the tilted arms; this geometrical variation generates a force along the *x*-axis which leads to movement of the driving bar. The movement of the bar is amplified with respect to the tilted arm strain, the ideal relation between material strain and pointer displacement (X) for asymmetric model.

$$X = \frac{H}{h}\left\{\Delta L_B + (L+\Delta L)\,\mathrm{x}\sin\left[arccos\left(\frac{Lcos\alpha}{L+\Delta L}\right)\right] - Lsin\alpha\right\} \tag{1}$$

The symmetric lancet model is reported in figure 2. In this structure another tilted beam is added in other side of asymmetric structure. It improves the robustness and helps the pointer to move in longitudinal direction. The displacement produced by strain of the material is magnified twice as compared to the earlier structure. As a consequence of the lancet thickness ($2x$), for this geometry a different model is required. The displacement Δx remains the same as for the asymmetric model. Total displacement in symmetrical model is:

displacement = H sinα

$$= Hsin\left[\arcsin\left[\frac{x+\left\{\Delta L_B+(L+\Delta L)\times sin\left[arccos\left(\frac{Lcos\tau}{L+\Delta L}\right)\right]-Lsin\tau\right\}}{h/_{sin\beta}}\right]-\beta\right] \tag{2}$$

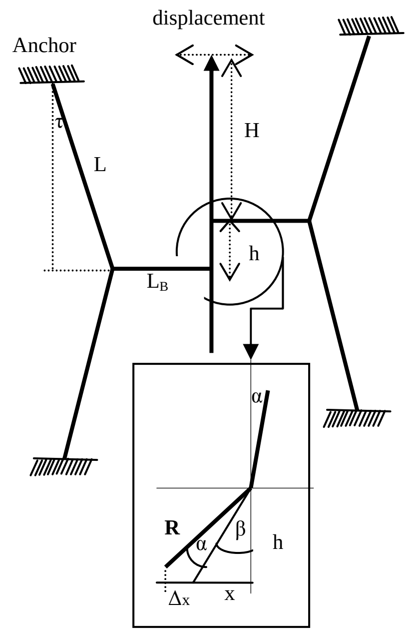

Figure 2 Conceptual schematic of the symmetric lancet with magnify image between anchor and junction

3. Device simulation

A set of simulations was dedicated to the analysis of the surface micromachining structures. The mechanical properties of electroplated gold as a structural layer were used to find out the thermal structural interaction. COMSOL MEMS module for thermal structural interaction was used to find out the stress,strain and displacement due to thermal expansion of material.

A complete set of finite element simulations was performed using COMSOL™ simulation software, in order to examine the stress distribution and identify the pointer displacement. Simulation for optimal tilt angle of 8^0 was opted from reference [5]. An image of the displaced asymmetrical pointer is shown in figure 3.

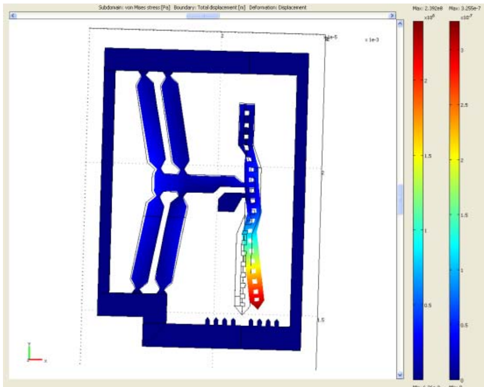

Figure 3 Simulated results of asymmetric pointer structure with single junction layout

For simulations anchors were fixed and rest of the released structure is free to move. The material properties of gold were used from MEMS material library (thermal conductivity k=317W/mK, density ρ =19300kg/m^3, heat capacity at constant pressure C_p=129J/kgK). Figure 4 shows the maximum stress 217MPa and corresponding displacement 0.9µm, when the structure is released at room temperature (25^{0}C).

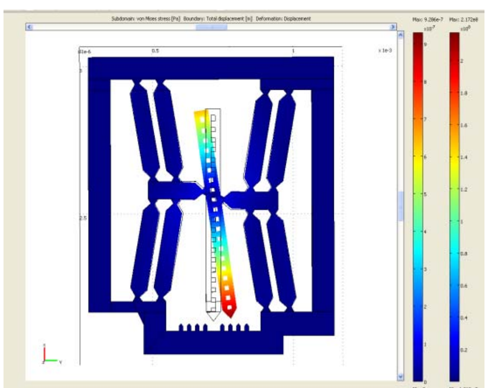

Figure 4 Simulated result of symmetric pointer structure with double junction layout

A major drawback in movement magnification is that the effective strength component is reduced, making it more difficult to compensate the non-ideality of the junctions. Therefore, a double arm set was implemented to grant a greater force to the driving bar and the lancet. Double arms are also important to reduce the degrees of freedom of the driving bar, constraining the movement to *x*-axis only.

The lancet in the asymmetric model was designed so that both the anchor and the junction lay on the longitudinal axis, generating a bent shape which helps avoid rotations along the *y* axis and improving robustness. The simulated displacements of asymmetrical and symmetrical lancet structures are shown in figure 5 and 6 respectively.

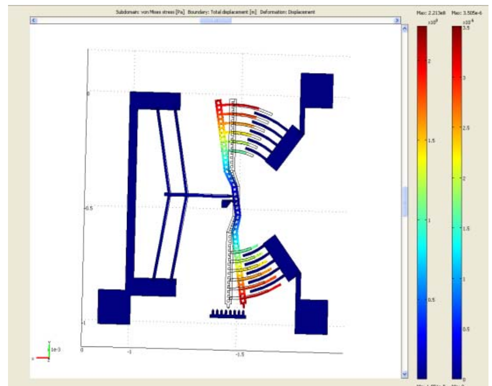

Figure 5 Simulated results of asymmetric lancet structure

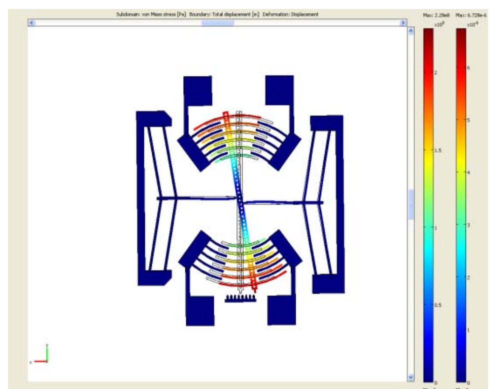

Figure 6 Simulated results of symmetric lancet structure

5. Fabrication

A set of structures were realized using surface micromachining techniques, on a 2″ diameter P-type <100> oriented silicon wafer. A thermal oxide was grown on the substrate, then a conventional positive tone photoresist was deposited and patterned as a sacrificial layer. After that, the wafer was deposited with a chromium adhesion layer and gold seed layer by sputtering technique. Then a second photoresist was deposited and patterned, to work as a mould for the electroplating structural layer 2 µm thick gold was plated by using a commercial sulfite bath solution. Wet etching methods were used to remove the photoresist mould and seed layer followed by a dry etching process to remove the sacrificial photoresist layer without generating stiction forces between membranes and the surface. The strain resulting from mismatch of TCE between the structural layer and the silicon substrate induces a stress. In general, stress induced by electroplated gold is in the range of 180-200 MPa [7]. A SEM image of the released symmetric lancet structure is reported in figure 7. A detailed lancet type pointer structure with additional vernier scale and comb drive capacitance for electrical readout of the displacement is also shown in figure 7 below:

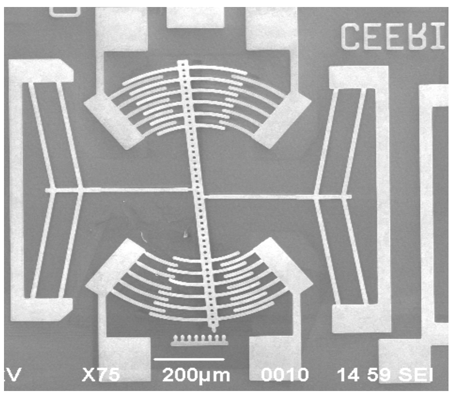

Figure 7 SEM image of symmetric lancet with electrical output readout

6. Results and Conclusions

The structures are asymmetric and symmetric with respect to anchor post. The simulation results of COMSOL for asymmetric pointer structures show maximum displacement and stress as 0.3 μm and 239 MPa, where as symmetric pointer structures show maximum displacement and stress as 0.9 μm and 217 MPa respectively. The structures with asymmetric and symmetric lancet type with electrical read out, shows a maximum displacement of 3.5 and 6.7 μm and maximum stress 221 and 228 MPa as shown in figures 5 and 6. It is observed that symmetric lancet structure produces magnified displacement of the pointer which is twice of the asymmetric one. The SEM micrograph of symmetric lancet fabricated structure is shown in figure 7.

A novel structure for in situ stress measurement was designed and fabricated with surface micromachining techniques. This structure allows the magnified optical read out of internal stress of a deposit layer, with increased resolution as compared to the previous pointer structures. Detailed analysis of FEM simulation was performed to examine the behavior of fabricated gold structures, taking into account the plastic regime of the material correlation between lancet displacement and internal stress was obtained, in a range of 200 ±30MPa.

7. Acknowledgements

The authors are thankful to all colleagues of Sensors and Nanotechnology Group; who helped in fabrication of the structures

8. References

1. B.P. van Drieenhuizen, J.F.L. Goosen, P.J. French, Comparison of techniques for measuring both compressive and tensile stress in thin films, Sens. Actuators A. 37/38, 756–765 (1993).
2. L. Elbrecht, U. Storm, R. Catanescu, Comparison of stress measurement techniques in surface micromachining, J. Micromech. Microeng. 7 , 151–154 (1997) .
3. B. Yogesh, K. Najafi, Gianchandani, Bent beam strain sensors, J. Microelectromech. Syst. 5 (1) , 52–58 (1996).
4. Q. He, Z.X. Luo, X.Y. Chen ,Comparison of residual stress measurement in thin films using surface micromachining method, Thin Solid Films 516, 5318–5323 (2008) .
5. A. Bagolini, B. Margesin, A. Faes, G. Turco, F. Giacomozzi, Novel test structures for stress diagnosis in micromechanics, Sensors and Actuators A 115, 494–500 (2004).
6. A. Bagolini, A. Faes, B.Margesin, Analytical model for magnified displacement Stress test structures,DTIP of MEMS & MOEMS, TIMA Labs/DTIP Montreux, Switzerland, 01-03 June (2005).
7. B. Margesin, A. Bagolini, V. Guarnieri, F. Giacomozzi, A. Faes, R. Pal, M. Decarli, Stress characterization of electroplated gold layers for low temperature surface micromachining. in: Proceedings of the DTIP 2003, France, 402–405, (2003).