FEM based Optimization of Microstructure Membranes

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Abstract: Membranes are the most fragile part of microstructures which can face ductile failure if the thickness of a membrane is not capable of handling the pressure exerted on it during fabrication. This work presents the method for optimizing thin membrane structures typically used in thermal applications such as micro-heaters and thermoelectric devices. Membrane width and thickness plays a major role in deciding its capability for handling stress. The work compares the different sized membranes to optimize the dimensions against the load exerted during lithography process for a thermoelectric device structure. Analysis is done for membrane widths ranging from 200µm to 600µm at a thickness level ranging from 10µm to 90µm. Value of applied load is taken as 80000N/m^2 as obtained from SUSS Micro-Tec Lithography process which exerts a pressure of 0.8bar on target structure. The wider membranes (~600µm) with less thickness (~30µm) are found highly stressed. For successful fabrication and operation of a device it is necessary that before moving to the fabrication stage, the proposed micro-structure device must be analyzed and optimized by structural modeling to avoid any kind of undesirable deformation or ductile failure.

Keywords: Membrane, Lithography, Ductile Failure

I. INTRODUCTION

Thin membranes play a major role in many microstructure applications such as temperature sensing microstructures, pressure sensing microstructures, ultrasonic devices and works related to measurement of small variations in ambient sources. Feasibility of such devices relies on mechanical properties such as load bearing strength, ductility, dynamic response etc. of the thin membranes of these microstructures. For successful operation of suspended and free to move microstructures it is necessary to consider the effect of residual stresses in the thin membranes. Internal mechanical stress not only leads to wrap displacing upward or touching down the substrate but also degrades performance of micro-system. Lynford O. Davis investigated the reasons that cause a membrane-based structure to bow. The reasons can be: (1) residual stress developed during the deposition, (2) the effect of atmospheric pressure on the membrane (constant ~0.1MPa), or (3) thermal stress contribution during deposition [1]. This paper investigates the stress and deformation created in membrane during lithography stage. Based on this investigation proper measures can be taken to reduce stress and unwanted deformation in membrane. Kuan H. Lu et al. has presented that stress are directional and can be minimized [2]. After fabrication surface profiler can be used to further investigate the deformation created on membrane [3].

In this work mechanical stresses due to suction load during lithography are evaluated for Silicon membrane by using FEM (finite element method) based tool COMSOL 3.3a. The tool assess the observed stress and deformation in terms of Von-Mises Stress and displacement in a freely suspended membrane by obtaining the values of Young's Modulus, Poisson's ratio, Thermal expansion coefficient and Density parameters of respective material from the tool library. The goal of this work is to investigate the influence of varying width and thickness of membrane on the stress and deformation resisting capabilities of microstructure so that optimized dimensions of membrane can be obtained. The simulation work ensures that the optimized dimensions will fortify the microstructure during fabrication process.

II. DEVICE DESIGN

A thin membrane microstructure has been designed which is typically used for thermoelectric applications. The thermoelectric devices are based on the concept of converting temperature difference across junctions of 2 different materials into a potential difference. Such application based devices includes a cavity portion over which the thin membranes are placed. This cavity portion reduces the conduction heat flow from hot to cold junction of a thermoelectric device to provide a low thermal gradient (rate of temperature change with distance) across the hot and cold junctions of the device. Maintaining a low thermal gradient provides a better temperature difference and this is the most desirable property in the thermoelectric devices.

The design of microstructure illustrated in this paper has 3 key features:

1. Periphery
2. Enclave
3. Membrane

Enclave is the enclosed substrate portion encapsulated by the outermost substrate i.e. Periphery/Edge. In a thermoelectric device junctions placed on enclave are provided heat and junctions placed on Periphery are kept at room temperature. The thin ring shaped membrane acts as a platform or a kind of bridge to link substrates of periphery and enclave.

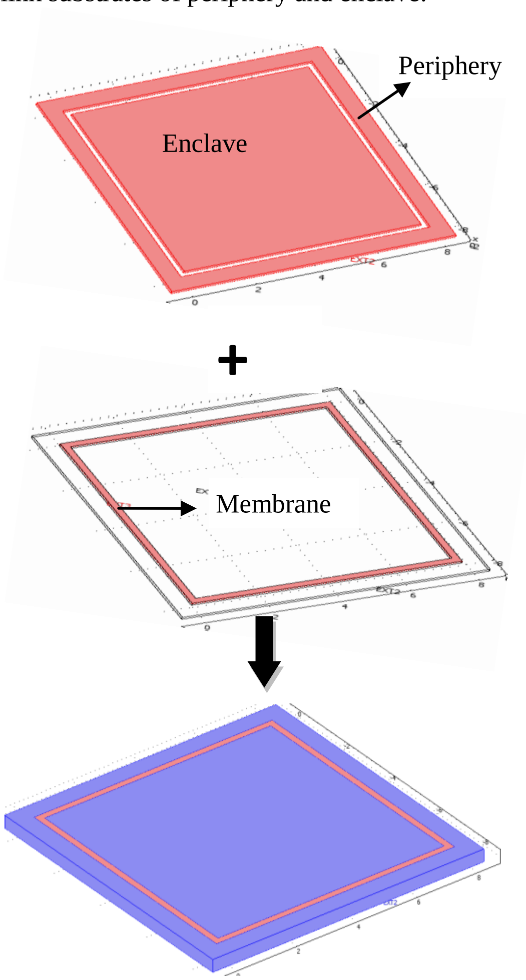


Fig 1: COMSOL structural representation of thin membrane microstructure design.

A membrane of less thickness and larger width is desirable from the point of view of a thermoelectric device as it gives a low thermal gradient. The thickness of periphery and enclave is as much as thickness of the wafer (~365µm). The thickness and width of membrane is optimized to satisfy the requirements of a thermoelectric device and making it feasible for the operation. The size of whole structure is taken as 9mm×9mm to allow the large range of variation in dimensions of the membrane for detail analyzing. To optimize the membrane size width is varied from 200 to 600µm with varying thickness from 10 to 90µm

III. Simulation Techniques

The static structural analysis is performed by using "Solid, Stress-Strain" option of "Structural Mechanics Module" in COMSOL 3.3a. It helps in understanding the displacements, stresses, and strains resulting in 3D objects under applied loads and constraints.

SUSS Micro Tec Lithography process exerts 0.8 bar pressure on Silicon microstructure that is equivalent to $80000 N/m^2$ load on the film. Membranes of various thickness and widths have been analyzed for the load applied perpendicularly to the plane of membrane.

A. Observation Parameters:

Our aim is to observe Von-Mises stress and deformation in Z-axis as deformation in X and Y-axis has negligible contribution to device failure.

a. Von-Mises Stress:

Von-Misses stress refers to a theory called the "Von-Misses Hencky criterion" for checking ductile failure. An elastic body that is subjected to a system of loads in 3 dimensions, a complex 3 dimensional system of stresses is developed. Von Mises criterion is a formula for calculating whether the stress combination at a given point will cause failure. If the value of "Von- Mises Stress" exceeds the yield stress (ultimate tensile strength) then the material is considered to be at the failure condition. Unit for Von-Mises stress parameter is in Pascal. A microstructure which develops a stress of 5×10^8dynes/cm^2 or above on applying a specified load is considered highly stressed for most applications.

b. Displacement:

Displacement indicates the amount of deformation observed in structure due to applied load. It can be calculated for a single node or for the whole layer of membrane. Its unit is in meters.

B. Finite Element Method:

The finite element method (FEM) is a numerical technique for finding approximate solutions of Partial

Differential Equations (PDE) and integral equations. Finite element method divides the target structure into small elements. In our work Lagrange's quadratic equation has been utilized to obtain unknown field quantities for each element. The size of these small elements defines the meshing size. Small elements are desirable to study detailed geometric properties and smaller the element size, greater is the accuracy level. So finer the meshing, more accurate is the result.

C. Subdomain Properties:

The material selected for optimizing structure is Silicon. Its mechanical properties are the known quantities which are feeded as input to calculate the unknown quantities in a system of equations of Matrix form for each node.

[Known quantities]= [known quantities] [unknown quantities]

Notations of parameters for Si in COMSOL 3.3a library:

E = Young's Modulus: 160×10^9Pascal or 160×10^{10}Dynes

V = Poisson's Ratio : 0.28

a = Thermal Expansion coefficient: 2.6×10^{-6}[1/K]

ρ = Density : 2329[kg/m^3]

D. Boundary Conditions:

Boundary conditions define the regions which are subjected to applied load which leads to internal stress and deformations in those areas. The specified load value is the suction load experienced by microstructure during lithography stage. Boundary conditions are given in terms of Loads and Constraints.

a. Loads and Constraints:

The bottom most layers of the 2 substrates of microstructure are considered as "fixed" constrained and no external load is applied to them. Whereas the whole top layer including membrane part is kept "free" to constraints and given a load of 80000N/m^2. Thus the membrane act as freely suspended thin film exposed to internal stresses due to applied load.

E. Meshing parameter:

The accuracy of results depends on number of nodes or elements and ultimately the meshing size. Fewer numbers of nodes are preferable from the point of view of computer resources. A compromise is made between required accuracy and computational resources for extremely thin membranes.

For the simplicity in simulation "Extremely coarse" meshing has been used for membranes of width 10µm thick, "Extra coarse" meshing has been used for membranes of width 20µm thick and "normal meshing" has been used for membranes having thickness 30µm and above.

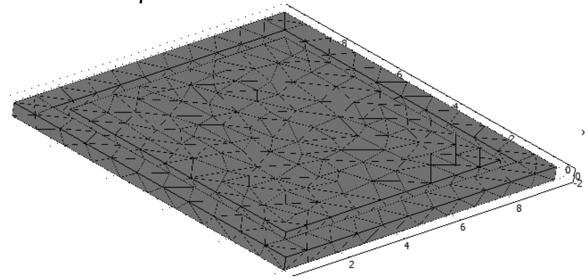


Fig 2: Meshing done to divide target structure in small elements.

IV. Results and Observations

As per concept of stress, the stress developed is inversely proportional to area under action keeping the load constant.

a. Observation for stress: For a fixed thickness, stress developed in broad membranes is more than the narrow ones. The output results also present one thing that 30µm thick and below membranes are highly stressed.

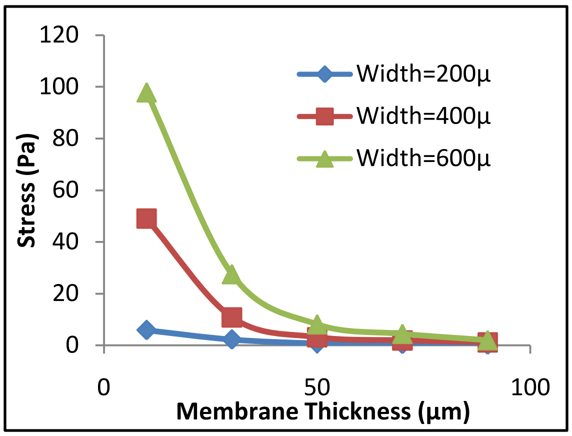
b. Observation for Deformation: For narrow films displacement in z-direction is smaller than the wider film which is expected.

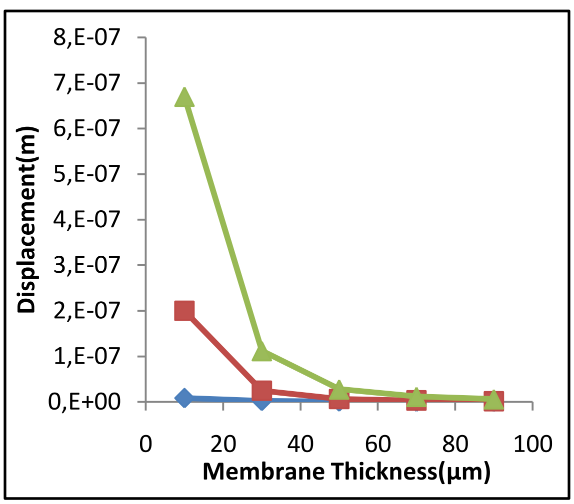
As the structure is typically designed for thermoelectric applications so the membranes having stress value above 5×10^7Pa or 5×10^8dynes/cm^2 are considered highly stressed film which can suffer ductile failure during fabrication process. The data obtained from simulation results shows that larger width of membrane can make it highly stressed membrane.

Table 1: Stress and deformation in membrane for varying widths at different range of thickness

Least stress is observed in 200µm wide membrane with thickness of 90µm. However it is also observed that for 200µm wide membranes stress level is tolerable for any range of thickness. At 600µm width, influence thickness level is effective. Membranes below 30µm are highly stressed and cannot be employed in microstructure. Thus a thick membrane can be used for applications needing wider membranes.

Comparison for different sizes of membrane is shown in Fig 3(a) and (b) by graph plot for varying widths at different thickness level. It is evident from the graphs that stress and deformation observed in wider membranes raises with reducing values of membrane thickness





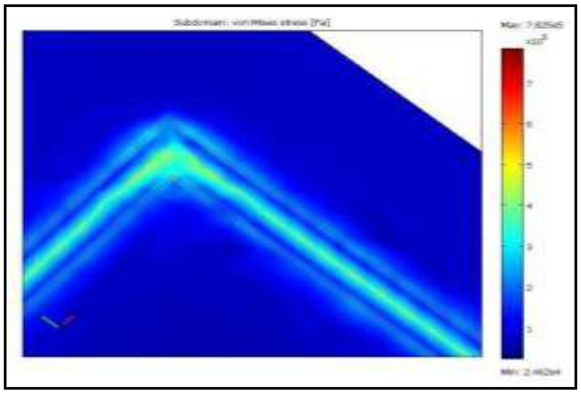
S. No	Membrane Thickness (µm)	Membrane width : 200µm		Membrane width: 400µm		Membrane width: 600um	
		Stress (Pa)	Displacement (z-direction) (m)	Stress (Pa)	Displacement (z-direction) (m)	Stress (Pa)	Displacement (z-direction) (m)
1.	**10**	$5.9e^{6}$	$8.5e^{-9}$	4.9e7	$2.0e^{-7}$	$9.8e^{7}$	$6.7e^{-7}$
2.	**30**	$2.2e^{6}$	$2.4e^{-9}$	$1.1e^{7}$	2.5[illegible]	[illegible]e^{7}	$1.12e^{-7}$
3.	**50**	$1.1e^{6}$	$1.01e^{-9}$	$3.1e^{6}$	$6.7e^{-9}$	$8.2e^{6}$	$2.78e^{-8}$
4.	**70**	$5.2e^{5}$	$6.2e^{-10}$	$1.86e^{6}$	$3.3e^{-9}$	$4.4e^{6}$	$1.16e^{-8}$
5.	**90**	$2.8e^{5}$	$4.45e^{-10}$	$1.2e^{5}$	$1.8e^{-9}$	$1.9e^{6}$	$6.3e^{-9}$

(a)

Fig 3: Comparison of differently sized membranes for observed (a) stress and (b) deformation.

Another observation outlined the most critical zones of a membrane. The stress and displacement created in membranes is larger on corners as compare to the edges. The images are simulated results for 200µm wide membrane of thickness 50µm[illegible]rners of a membrane various planes exists sim[illegible]usly. Thus the applied load acts on membrane through different planes at corners. This results in large influence of applied load on corner areas as compare to other areas. These portions make the membrane more fragile and delicate. Fig 4 gives a closer view of corner areas where large amount of stress and deformation are observed. Red colour marks the extremely stress or deformed portion and blue colour indicates least affected areas.

(b)



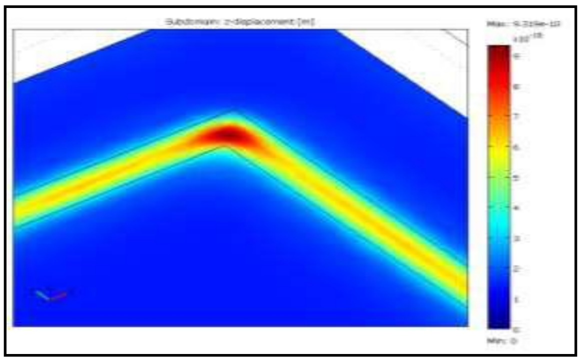


Fig 4: Simulated observation for resulting (a) stress and (b) deformation in membrane corners.

V. Conclusion:

The work presented in this paper is mainly focused on optimizing dimensions of membrane to make a reliable microstructure. Various sized membranes are compared to obtain the better one. For a thermoelectric device where larger width of membrane and smaller thickness is desirable for good performance, a compromise has to be done between dimensions to make the device feasible. Further to avoid high stress developed at corners or undesirable deformations at critical points various measures can be taken: To reduce stresses at corners supporting beams at corners needs to be applied depending on suitability of microstructure suitability. Moreover, applications where very thin membranes are required vertical supporting beams can be used at bottom of membrane to reduce stress. This study presented the method for optimization of the membrane dimensions which need to be considering while designing a microstructure.

Further work can be done to explore the induced thermal stresses during the high temperature fabrication processes for further optimization of thin membrane based microstructures. Various designs of membrane can be compared to investigate the most reliable structure.

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References:

[1]. Lynford O. Davis "*Investigation of residual and thermal stress on membrane-based MEMS devices*", University of South Florida, October 2009.

[2]. Kuan H. Lu, Xuefeng Zhang, Suk-Kyu Ryu, Rui Huang, and Paul S. Ho, "*Thermal Stresses Analysis of 3-D Interconnect*", Tenth International Workshop on Stress- Induced Phenomena in Metallization, Texas, AIP Conf. Proc. 1143, pp. 224-230, November 2008.

[3]. M W Denhoff, "*A measurement of Young's Modulus and residual stress in MEMS's bridges using a surface profiler*", Institute for Microstructural Sciences, National Research Council ,Ottawa, Canada, June 2003