Silicon Nitride Corrugated Membrane with High-Width-Aspect-Ratio for MEMS Microphones

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Abstract

This paper presents the corrugated membrane design with focus on the corrugation width to improve the acoustic sensitivity of the micromachined silicon MEMS microphones. In this work, the effect of residual stress is considered on the deflection and compliance of the silicon nitride diaphragm. Finite Element Modeling approach and analytical analyses have been carried out to optimize the acoustic sensitivity of the corrugated membrane. It is shown that for a given thickness, 1.1um and height 3.5um of corrugated membrane of diameter 1.4mm, the corrugation width can be optimized for varying number of corrugations to achieve high compliance or sensitivity. A very good agreement between the simulations and experimental results have been established for membrane with varying number of corrugations. Acoustic sensitivity as high as 7.75 nm/Pa can be achieved with 3 corrugations with residual stress of 220MPa in the silicon nitride film and high width-aspect-ratio of 60:1.

Keywords: Silicon MEMS Microphone, Corrugated Membrane, Acoustic Sensitivity, Acoustic Compliance, High-Width-Aspect ratio, Finite Element Modeling (FEM)

Introduction

Using Microelectromechanical systems (MEMS) technology, the silicon microphone has been vastly used nowadays in many commercial applications including smart phones, tablets, ear phones, IoT devices, automobiles etc. With the advantage of high sensitivity, lower noise floor and ease of fabrication and packaging for the capacitive transduction method, its performance is superior compared to piezoelectric or piezoresistive microphones [1].

The acoustic compliance (in meters per Pascal) of the membrane is defined by the ratio of center deflection to the applied sound pressure.

$$Acoustic\ Sensitivity = \frac{Center\ Deflection, m}{Sound\ Pressure, Pa}$$

The term acoustic compliance is often interchangeably used with acoustic sensitivity. Generally, the acoustic compliance of the microphone diaphragm is strongly determined by the initial stress in the thin film. Besides the initial stress, optimization of the geometry of the membrane is also essential to precisely control the membrane sensitivity. In general, thin films have been subjected to suffer from residual stress which can cause undesirable behavior like film buckling, diaphragm cracking and need for high actuation voltage [2]. Precisely controlling the initial stresses in the thin film within certain limits of the deposition process have been very challenging [3]. Geometrical approach in changing or optimizing the design will be an easier way to solve the initial stress issues. Corrugated membranes have been in use for a long time in the industry as they significantly reduce the initial stress in the center region of the membrane to provide improved acoustic sensitivity and linear range of operation compared to circular clamped membranes [4]. Acoustical compliance of the circular membrane can be approximately calculated using [5],

$$S(circular) \approx \frac{R^2}{8.t.\sigma_0} . (\frac{2.E.t^2}{(1-\vartheta^2).\sigma_0.R^2} + 1)^{-1}$$

where, R and t are the radius and thickness of the membrane. σ_0, E and ϑ are the intrinsic stress, modulus of elasticity and Poisson`s ratio of the membrane.

Numerous studies have been done before for the membranes with corrugations to establish compliance and initial stress relation considering non-linearity caused by large deflections of the membranes. For all these analyzes, corrugation depth and membrane thickness have been projected as the most important factors for the corrugated membrane design [6]. This paper explores the corrugation width to membrane thickness aspect ratio as an important design parameter to improve the acoustic sensitivity or compliance of the membrane.

Finite element modeling approach has been implemented to optimize the membrane performance using COMSOL Multiphysics® simulation software tool. The limitations of the analytical equations which have been used in the previous studies are also highlighted. The FEA results obtained seem to match very well with the experimental results.

Microphone Design

A schematic cross-sectional, not to scale, representation of the corrugated microphone design has been shown in the Fig. 1. The diaphragm is constructed of silicon nitride membrane with conductive thin polysilicon deposited on top for capacitance sensing. The back-plate is also constructed of silicon nitride with polysilicon electrode embedded to form other parallel plate of a capacitor. The back-plate is highly perforated to reduce squeeze-film and viscous damping due to the air gap between the diaphragm and back-plate and air flowing through the back-plate perforation walls. The trapezoidal geometry corrugation profile is constructed using etching the sacrificial oxide layer to form the trenches and depositing silicon nitride film. The corrugated membranes are fully constrained and hence are insensitive to the vertical stress gradients.

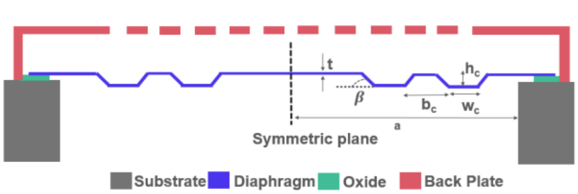


Fig. 1. Cross-section schematic representation of corrugated membrane MEMS microphone

Analytical Analysis and Finite Element Simulation

M. Fuldner *et al.*, derived advanced analytical equations for the corrugated membrane design using enhanced theory of circular membranes [7]

$$C_{corrugated} = C_{circular}\,(\sigma_0).$$
$$\left(1 + 6.\,sin\beta\,.\frac{{h_c}^2}{t^2}\,.\,N_c.\frac{w_c}{R - N_c.(w_c + b_c}\right)$$

where, w_c is the corrugation width, b_c is the width between two corrugations, N_c is the number of corrugations, β is the inclination angle of the corrugation wall from the bottom surface of the corrugation, h_c is the corrugation height, t is the membrane thickness and R is the radius of the corrugated membrane.

But the validation of the analytical equation was in excellent agreement only for the thin membranes whose thicknesses are less than 1um. The mechanical sensitivity obtained for the 4 corrugations with membrane diameter of 1mm, thickness of 0.2um, corrugation height of 0.6um and intrinsic stress 35MPa was approximately 12.5 nm/Pa as measured and ~12 nm/Pa as theoretical. For the thicker membranes (>1um), the presented analytical equation showed discrepancy with the numerically simulated value. The reason being, the analytical equation did not take into account the increased tangential bending stiffness of the corrugated membrane and predicted higher compliance which was highlighted in the paper.

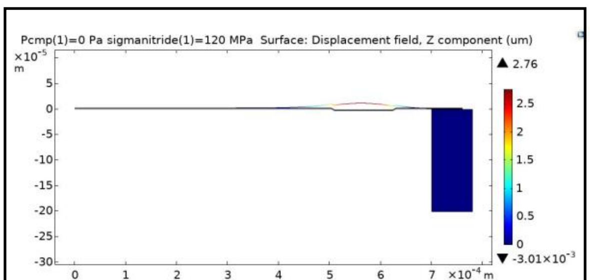
The finite element modeling comes handy in such situations where the analytical equations fail to include the mechanical effects such as stress and stiffness. For a specified values of parameters as shown in table 1, the acoustic sensitivities are obtained with variation in corrugation width and initial stresses in the silicon nitride film.

Table 1
Geometry and Material Properties

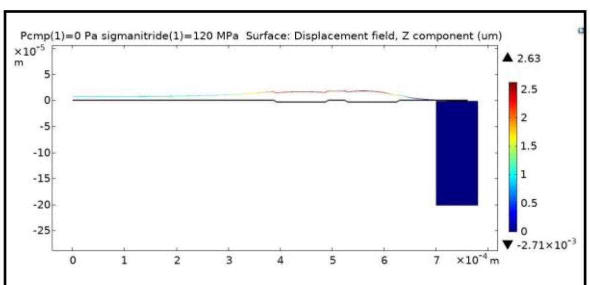
Parameters	Value
Diaphragm Radius, *a*	700 um
Diaphragm material	Silicon Nitride
Diaphragm Thickness, *t*	1.1um
Corrugation Height, h_c	3.5um
Number of Corrugations, N_c	1, 2 and 3
Wall angle, β	60º
Distance between two corrugations, b_c	30um

Distance from constrained region to first corrugation	70um
Sacrificial oxide thickness	1.5um
Sacrificial oxide initial stress	100 MPa (compressive)
Density (Silicon Nitride)	3100 [kg/m^3]
Young`s modulus (Silicon Nitride)	250e9 [Pa]
Poisson`s ratio (Silicon Nitride)	0.23
Density (Sacrificial Oxide)	2200 [kg/m^3]
Young`s modulus (Sacrificial Oxide)	70e9 [Pa]
Poisson`s ratio (Sacrificial Oxide)	0.17

The deflection profile of a 2D axisymmetric model for number of corrugations 1, 2 and 3 are shown in Fig. 2 with initial stress in the silicon nitride membrane being 120MPa. Each of the corrugations gets elongated as shown in zoomed view in orthographic projection in Fig. 3, thereby, reducing the initial stress in the center region of the membrane and making it more compliant to the sound pressure. The outermost corrugation nearest to the supported edge gets maximum elongation due to large moment generated by the lateral force acting on the membrane and the innermost corrugation shows minimum elongation.



(a)



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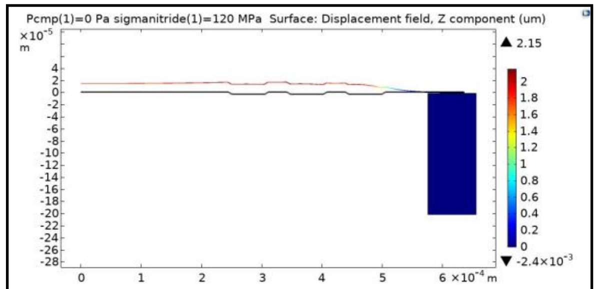

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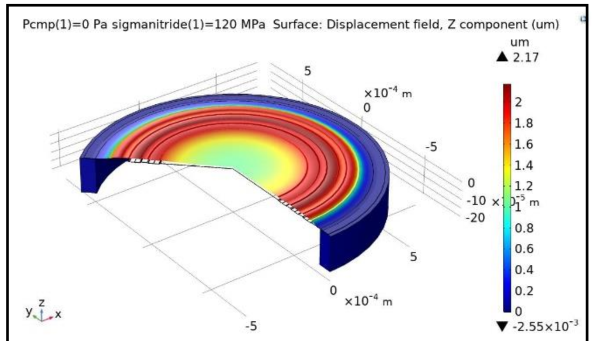

(d)

Fig. 2. Deflection profile of corrugated membrane with 120MPa of initial silicon nitride stress, (a) N_c=1 corrugation, (b) N_c=2 corrugations, (c) N_c=3 corrugations, (d) 3D cross-section view for N_c=3 corrugations

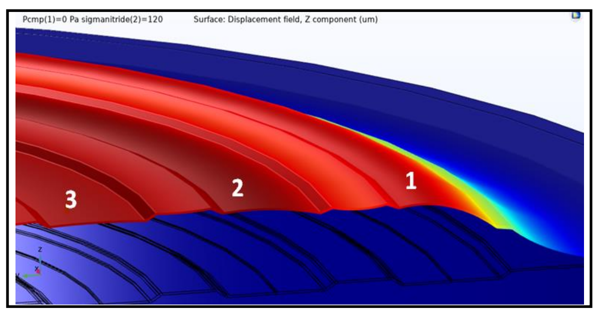

Fig. 3. Zoomed-in view to show elongation in corrugation width walls 1, 2 and 3 for membrane with N_c=3 corrugations

The center acoustic compliance, nm/Pa, for number of corrugations 1, 2 and 3 are plotted with respect to variation in initial stress of the silicon nitride film. It is assumed that the average deflection will be one half of the center deflection [8]. It is observed that the corrugation width, in addition to corrugation height and thickness, also has a strong design dependency in optimization of the acoustic compliance or sensitivity of the membrane.

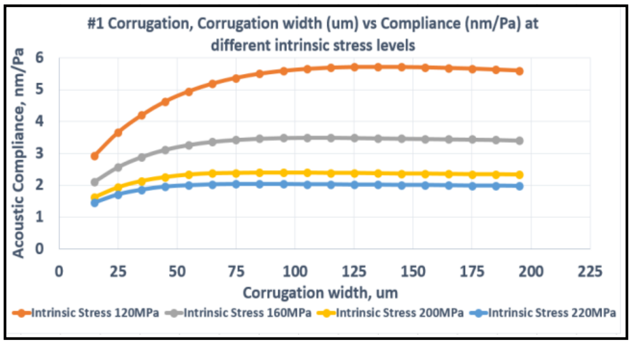

Fig. 4. Acoustic compliance vs Corrugation width for different initial stresses of silicon nitride, N$_c$=1 corrugation

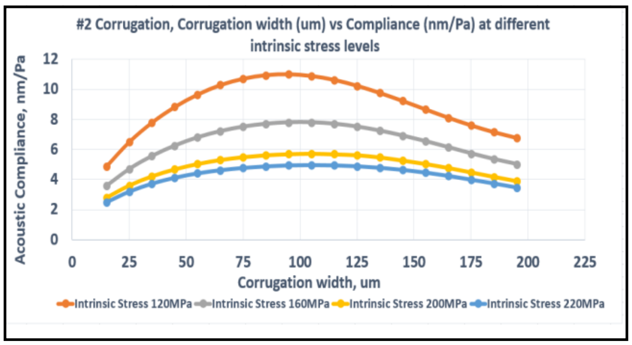

Fig. 5. Acoustic compliance vs Corrugation width for different initial stresses of silicon nitride, N$_c$=2 corrugations

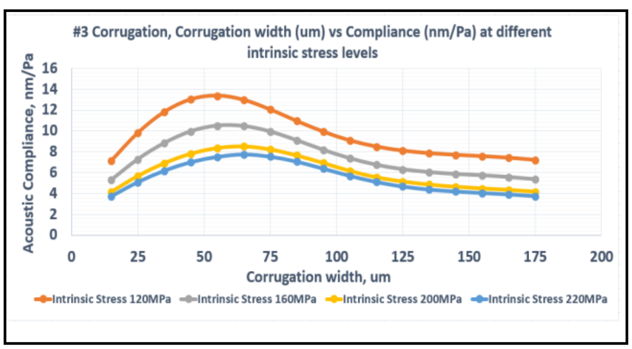

Fig. 6. Acoustic compliance vs Corrugation width for different initial stresses of silicon nitride, N$_c$=3 corrugations

Based on the simulated results, it is observed that for a given number of corrugations, there is a maxima for the acoustic compliance or sensitivity of the membrane which is governed by certain corrugation width and initial stress combination. As the corrugation width is further increased for a given number of corrugations, the acoustic compliance tends to show a declining trend in the performance which indicates that the corrugated membrane starts to get stiffened. The high-width-aspect ratio which is defined as the ratio of corrugation width over the membrane thickness to achieve maximum acoustic compliance.

This aspect ratio is 100:1, 85:1 and 50:1 for 1, 2 and 3 corrugations respectively with initial silicon nitride stress of 120MPa.

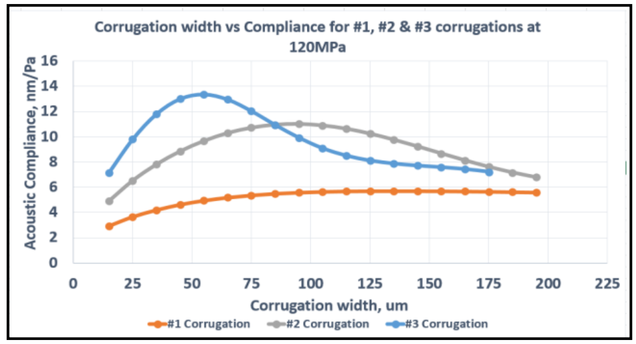

Fig. 7. Acoustic compliance vs Corrugation width for 120MPa of initial stresses of silicon nitride with N$_c$=1, 2 and 3 corrugations

Fig. 7 shows that the acoustic compliance as high as 5.7nm/Pa, 11nm/Pa and 13.4nm/Pa can be achieved with number of corrugations as 1, 2 and 3, respectively at 120MPa of initial stress of silicon nitride membrane. The following nth order polynomial functions have been derived for number of corrugations 1, 2 and 3 to achieve maximum acoustic compliance at 120MPa of initial silicon nitride stress

$$S_1 = (1e-6).w_c{}^3 - (6e-4).w_c{}^2 + 0.0818.w_c + 1.9228$$

$$S_2 = (4e-6).w_c{}^3 - (0.0018).w_c{}^2 + 0.2324.w_c + 1.7295$$

$$S_3 = -(1e-7).w_c{}^4 + (7e-5).w_c{}^3 - (0.0114).w_c{}^2 + 0.7084.w_c - 1.4439$$

where, S_1, S_2 *and* S_3 are acoustic sensitivity of the 1, 2 and 3 number of corrugations, respectively and w_c is the corrugation width.

Experimental Results

The acoustic compliance of the fabricated MEMS microphone with silicon nitride membrane is characterized using Lased Doppler Vibrometer

(LDV). The below table compares the measured and predicted acoustic sensitivity for two different corrugation width of 15um and 35um.

Table 2
Microphone Acoustic Compliance

	#1 Corr.		#2 Corr.		#3 Corr.	
Corrugation width (um)	15um	35um	15um	35um	15um	35um
Simulated prediction (nm/Pa)	1.45	1.86	2.5	3.74	3.73	6.1
Experimental value (nm/Pa)	1.47	1.75	2.3	3.7	3.7	5.8

The measurement shows very good agreement with the simulated values using FEM at 220MPa of initial silicon nitride stress. This validates that the model can predict the performance of the corrugated membrane designs within good acceptable limits.

Conclusion

Finite element simulations can be really handy if scope of the analytical equations become limited to represent the true nature of the membrane mechanical behavior using stresses and stiffness. The analytical equations for the optimized acoustic compliance are simplified to predict the ideal corrugation width and initial stress in the film. The acoustic compliance is strongly dependent not only on the corrugation height and membrane thickness but also on the corrugation width. The simulations have been successfully verified by measurements of silicon nitride membranes. As demonstrated the acoustic sensitivity can be improved by approximately 30% for 3 corrugations from 6nm/Pa for 35um corrugation width to 7.75nm/Pa for 65um corrugation width at 220MPa of initial silicon nitride stress.

Acknowledgements

The author would like to thank colleagues Mark da Silva and Jim Guo at Knowles who provided their continuous support and peer review of the results.

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