Design and Mathematical Model of a ZnO-based MEMS Acoustic sensor

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***Abstract*—The paper presents the design and mathematical model of ZnO-based MEMS acoustic sensor. The structure consists of piezoelectric ZnO layer of thickness 3.0 µm, sandwiched between a pair of aluminum electrodes at the centre of 30 µm thick Si diaphragm. The size of silicon diaphragm is 3.1 x 3.1 mm^2. By harmonic analysis, the resonance frequency is found to be 41.8 KHz. The sensitivity of acoustic sensor with and without the effect of residual stress is 334.7µV/Pa and 221.6µV/Pa respectively.**

***Index term*—Silicon diaphragm, ZnO layer, sensitivity.**

I. Introduction

ZnO layer has been extensively used in Micro-electromechanical systems (MEMS) due to high coupling coefficient and low dielectric coefficient. It is an excellent material which is used in micro-actuators, micro-sensors [1] etc. In the present paper, ZnO is used in d_{31} mode to convert mechanical loads to electrical signals. Many different shapes for diaphragms are possible but square diaphragms are mostly preferred as they are easy to fabricate and result in maximum stress generation compared to circular or rectangular diaphragm [2], [3].

II. Design and Simulation

Schematic diagram of designed acoustic sensor is shown in Fig.1. A ZnO layer of 3 µm thickness is sandwiched between two Al electrodes (1.0 µm thick) covered with 0.1µm thick PECVD oxide layer on a 30 µm thick silicon diaphragm. The diaphragm size is 3.1 mm ×3.1 mm. Al electrodes placing on center of diaphragm has size 1.5mm×1.5mm. A simplified model, in which very thin insulating oxide layers were neglected, was used to carry out simulations.

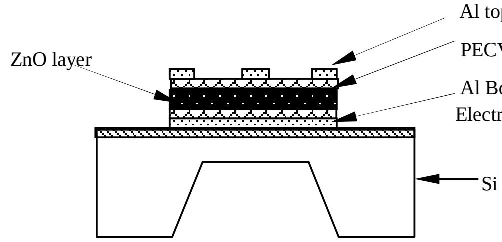
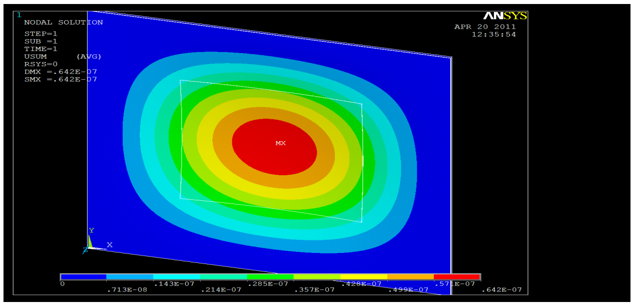
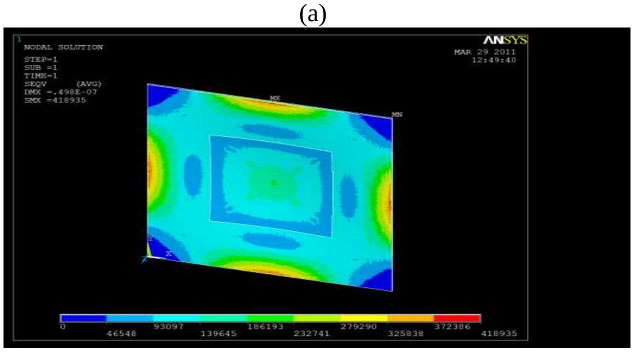


FIG. 1. Schematic diagram of designed acoustic sensor

Simulations of the structure were carried using ANSYS. A 3-D plot of deformation by applying pressure (400 Pa) on the square diaphragm was also drawn using ANSYS and is shown in Fig. 2(a). The maximum deflection in z-axis is observed at the center of the diaphragm. Fig. 2(b) shows the in-plane components of stress. It is seen from this Fig. that, maximum stress is generated at center and a part of the edges of the square diaphragm. This gives the proper placing of electrodes on the diaphragm to get the maximum sensitivity of acoustic sensor. The resonance frequency, calculated using ANSYS harmonic analysis, was found to be 41.8 kHz.



(a)



(b)

FIG. 2. 30 µm thick silicon (a) displacement in z- axis at 400 Pa, (b) stress distribution at 400 Pa.

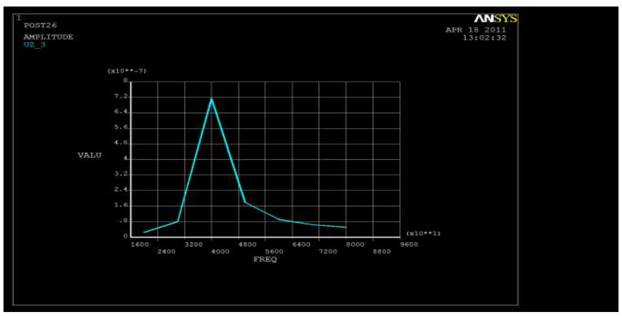


FIG. 3. Harmonic Analysis of 30 µm thick silicon diaphragm.

Mathematical equation for resonance frequency of thin square diaphragm is [4]

$$f_r = \frac{1.654 c_p h}{a^2} \quad (1)$$

where, $c_p = \sqrt{E/\rho_0(1-\nu^2)}$, ρ_0 is the density of the substrate, ν is poisson ratio.

As expected from equation (1), large diaphragm size and small thickness leads to low resonance frequency. Larger dimensions increase the maximum stress developed but they decrease the resonance frequency.

III. Mathematical Model for Sensitivity

The acoustically induced voltage between the pair of electrodes can be calculated by integrating the average induced polarization across the electrode area and then dividing by the capacitance of the dielectric ZnO layer is given by [5].

$$V_o = \frac{z_o - z_i}{A_o \varepsilon_{33}} \int_{A_o} \int_{z_o}^{z_i} \frac{P_{z\,(x,y,z)}}{z_o - z_i}\, dz\, dA_o$$

$$= \frac{z_o - z_i}{A_o \varepsilon_{33}} \left(\frac{-d31}{s^{E11} + s^{E12}} \right) S_o \left(\frac{z_o + z_i}{2} \right) \quad (2)$$

where z_o and z_i are the distances from the neutral plane to the outer and inner zinc oxide surfaces respectively, A_o is the electrode area, ε_{33} is the z-direction permittivity component of the zinc oxide, φ is the applied pressure, and S_o is the dimension integration constant for an electrode pattern on a square plate given by:

$$S_o = \int_{Ao} \left(\frac{d^2 w}{dx^2} + \frac{d^2 w}{dy^2} \right) dA_o \quad (3)$$

For the value of partial differentials, first w (out of plane deflection) has to be computed using the equations for clamped square diaphragms. The solution to w is given by [6]

$$w = \frac{w_o}{4} \left(1 + \cos\frac{2\Pi x}{L}\right)\left(1 + \cos\frac{2\Pi y}{L}\right) \quad (4)$$

where $w_0 = \dfrac{p\left(\frac{L}{2}\right)^4}{c_b 12 D}$ (5)

c_b=4.06, D is flexural rigidity, $L/2$ is the half length of diaphragm. Solving for S_0 and substituting its value in equation (2), a sensitivity of 334.7μV/Pa is obtained.

IV. Thickness of Piezoelectric layer for maximum Sensitivity.

Simulations with different values of thickness of ZnO layer have been done keeping thickness of Si diaphragm constant. The results obtained are shown in Fig. 4. It is seen that sensitivity is saturated after 12 μm thick ZnO layer.

Residual stress also plays a key role in thickness of ZnO layer for sensitivity saturation. Fig. 5 shows the results obtained through mathematical model for thickness of ZnO layer for sensitivity saturation with and without residual stress. Variations of residual stress with thickness of ZnO layer helps in finding the optimum thickness of ZnO layer. For maximum sensitivity, thickness of piezoelectric layer should be 2μm for a 30 μm thick Si diaphragm.

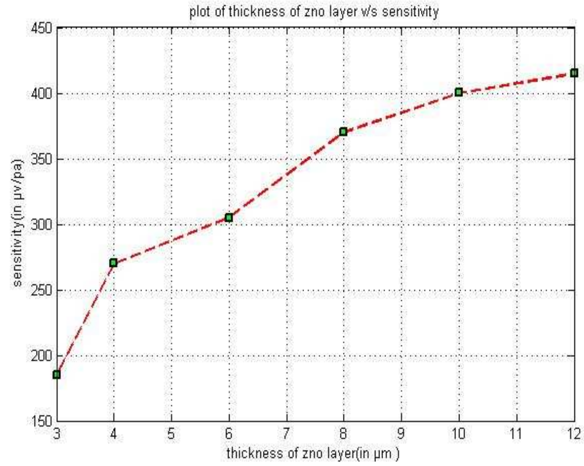


FIG. 4. Variation of sensitivity with ZnO thickness.

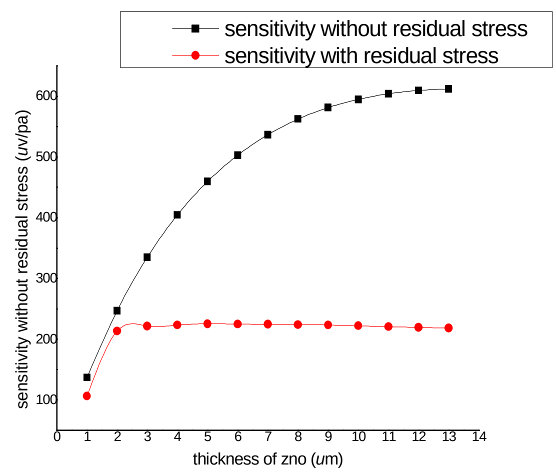


FIG. 5 Variation of sensitivity with ZnO thickness, with and without residual stress.

V. Conclusions

In this paper a piezoelectric ZnO-based acoustic sensor was designed and mathematically modeled. Static analysis was done using ANSYS. Harmonic analysis was done to find bandwidth and resonance frequency. The effects of residual stress, ZnO thickness and diaphragm thickness on sensitivity of acoustic sensor have been studied in this paper.

VI. References

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