A Novel High Sensitive MEMS Acoustic Sensor Using Corrugated Diaphragm

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ABSTRACT:
In this paper we presented a novel MEMS acoustic sensor using corrugated diaphragm. The corrugated diaphragm is used to decrease the effect of residual stress and thus improve the sensitivity of micromachined acoustic sensor. The displacement and mechanical sensitivity of flat and corrugated diaphragms, and also open-circuit sensitivity and pull-in voltage of sensors are calculated using MATLAB and simulated using FEM (finite element method). The results show that the displacement and mechanical sensitivity of corrugated diaphragm are bigger than the flat one. The pull-in voltage of corrugated sensor is smaller and the open-circuit sensitivity is much higher than the sensor with flat diaphragm. The results also show that the analytical model is very close with FEM simulation results.

KEYWORDS: MEMS, Acoustic sensor, Corrugated diaphragm, Stress, Sensitivity.

1. INTRODUCTION

Acoustic sensor is a transducer that converts acoustic energy into electrical energy. It is widely used in voice communications, hearing aids, noise and vibration control and biomedical applications [1-3]. During the past years, the capacitive acoustic sensors have been studied by many researchers because of their superior performances, e.g. high sensitivities, low power consumption, flat frequency responses in wide bandwidth, low noise level, stability and reliability [4-6].

The capacitive acoustic sensors are provided with a thin diaphragm. Several kinds of diaphragms, such as flat and corrugated, have been applied. The sensitivity of acoustic sensors to a sound pressure is strongly dependent on the stress in the diaphragm. The stress in diaphragms is determined by the diaphragm fabrication process. The initial stress can be controlled within certain limits by the parameters of the deposition process. It is advantageous if the mechanical sensitivity of the sensor diaphragms is not determined by deposition process parameters. A possible method to reduce the initial stress effect is the application of a corrugated diaphragm. The application of corrugated diaphragms in acoustic sensors offer the possibility to control the mechanical sensitivity of the diaphragm by means of the dimensions of the corrugations, which are often easier to control than the parameters of a deposition process [7-10].

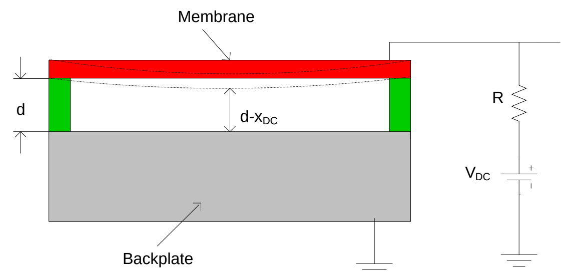

Fig. 1. Schematic of condenser acoustic sensor.

In this paper, different types of acoustic sensors, including flat and corrugated diaphragms with various corrugation depths and initial stresses are studied. It will be shown that the corrugated diaphragm can reduce the effect of initial stress sufficiently to improve the performance of sensor.

2. ANALYSES OF THE ACOUSTIC SENSORS USING FLAT AND CORRUGATED DIAPHRAGMS

Figure 1 shows the basic structure of the condenser acoustic sensor. In its simplest form, a diaphragm is stretched over a conductive back plate and supported by post so that there is a gap between the membrane and the back plate. A diaphragm is stretched by a tensile force put front of a fixed conducting back plate by means of a surrounding border which assures a separation distance, d, to create a capacitance with respect to the back plate and biased with a DC voltage.

An acoustic wave striking the diaphragm causes its flexural vibration and changes the average distance from the back plate. The change of distance will produce a change in capacitance and charge, giving rise to a time varying voltage on the electrodes.

The centre deflection, *w*, of a flat circular diaphragm with clamped edges and with initial stress, due to a homogeneous pressure, *P*, can be calculated from [11]:

$$\frac{PR^4}{Et^4} = \left(\frac{5.33}{1-v^2} + \frac{4\sigma_o R^2}{Et^2}\right)\frac{w}{t} + \frac{2.83}{1-v^2}\left(\frac{w}{t}\right)^3 \quad (1)$$

Where E, v, R, t and σ_o are Young's modulus, Poisson's ratio, radius, thickness and residual stress of the diaphragm, respectively. For a condenser acoustic sensor, the open-circuit sensitivity is the product of diaphragm mechanical sensitivity Sm and electrical sensitivity Se.

$$S_o = S_e.S_m \quad (2)$$

The mechanical sensitivity of a diaphragm is defined as:

$$S_m = \frac{dw}{dp} \quad (3)$$

For small deflection (less than 30% of diaphragm thickness), the mechanical sensitivity of a flat circular diaphragm, by neglecting the 3rd order term of equation (1), can be expressed as:

$$S_m = \frac{dw}{dp} = \frac{R^2}{4t\ [\sigma_0 + \frac{4Et^2}{3(1-v^2)R^2}]} \quad (4)$$

In the case of a piston diaphragm, the electrical field strength in the air gap is homogeneous. The charge on the plates of the diaphragm remains constant for fast diaphragm movements under sound pressure. The electrical sensitivity of the diaphragm can be expressed as [12]:

$$S_m = \frac{\Delta V_b}{\Delta d} = \frac{V_b}{d} \quad (5)$$

where V_b is the bias voltage and *d* is the initial capacitive gap. Thus, applying higher bias voltage results in higher open-circuit sensitivity. Unfortunately, the bias voltage cannot be increased without limits due to the pull-in instability phenomenon of the diaphragm. Moreover, increasing the bias voltage is not preferred in many low-voltage applications of acoustic sensors. The open-circuit sensitivity of the acoustic sensor using circular flat diaphragm can be calculated as:

$$S = S_e.S_m = \frac{V_b}{d}.\frac{R^2}{4t.\,[\sigma_0 + \frac{4E\,t^2}{3(1-v^2).R^2}]} \quad (6)$$

As can be seen from equation (6), increasing the mechanical sensitivity of the diaphragm results in higher open circuit sensitivity of the acoustic sensor. However, it is noted from equation (4) that mechanical sensitivity is inversely proportional to residual stress. Thus, in the case where the mechanical stiffness of diaphragm is reduced (so mechanical sensitivity is increased), the open-circuit sensitivity of the acoustic sensor will also be increased.

The residual stress of diaphragm depends on fabrication process, but it can be controlled within certain limits by the parameters of the deposition process. Annealing and impurity diffusion are another methods to decrease the residual stress. Since accurate control of thin film stress in processing are rather difficult, a possible method to reduce the residual stress effect is the application of corrugated diaphragm. Figure 2 shows the corrugated diaphragm and figure 3 shows a geometric model of a corrugated structure that consists of flat and corrugated zone. In this figure *R*, *S*, *L* and h_c are radius, spatial period, arc length and depth of corrugations, respectively. The equilibrium stress of corrugated diaphragm, σ, can be calculated as:

$$\sigma = \eta\sigma_0 \qquad \eta < 1 \quad (7)$$

where η is the attenuation coefficient of residual stress.

The attenuation coefficient of residual stress for corrugated diaphragm is given by [13]:

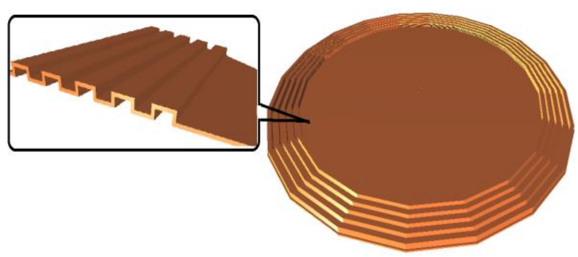

Fig. 2. Corrugated diaphragm.

Fig. 3. Cross section of corrugated diaphragm.

$$\eta = \frac{\sigma}{\sigma_0} = \frac{R.t^2}{R.t^2 + 6N_c.h_c^2.w_c.\sin\beta + 8N_c.h_c^3.\sin^2\beta} \quad (8)$$

Where w_c, h_c, N_C and β are width, height, corrugation numbers and angle between width and height of corrugation , respectively. The centre deflection of a corrugated circular diaphragm with clamped edges and without residual stress is given approximately by [14]:

$$P = a_p E \frac{t^4}{R^4}.\frac{w}{t} + b_p \frac{E}{(1-v^2)}.\frac{t^4}{R^4}.\frac{w^3}{t^3} \quad (9)$$

Where

$$a_p = \frac{2(q+1)(q+3)}{3(1-\frac{v^2}{q^2})} \quad (10)$$

$$b_p = 32\frac{1-v^2}{q^2-9}(\frac{1}{6} - \frac{3-v}{(q-v)(q+3)}) \quad (11)$$

$$q^2 = \frac{S}{L}(1+1.5\frac{h_c^2}{t^2}) \quad (12)$$

where a_p is the dimensionless linear coefficient, b_p the dimensionless non-linear coefficient and q the corrugation profile factor which is larger than 1 for corrugated diaphragms, h_c is the depth of the corrugations, L is the corrugation spatial period, S is the corrugation arc length (see Fig. 3). For large value of stress, the centre deflection of a corrugated circular diaphragm can be represented by [14]:

$$\frac{PR^4}{Et^4} = \frac{4\eta.\sigma_0 R^2}{Et^2}(\frac{w}{t}) \quad (13)$$

This resistance to bending due to initial stress can be added to equation (9) using the principle of superposition, i.e.,

$$P = [a_p E\frac{t^4}{R^4} + \frac{4t^2\eta.\sigma_0}{R^2}]\frac{w}{t} + b_p \frac{E}{(1-v^2)}.\frac{t^4}{R^4}.\frac{w^3}{t^3} \quad (14)$$

For a circular corrugated diaphragm with initial stress, for small deflections, the mechanical sensitivity, S_m, by neglecting the third-order term in equation (14), can be expressed as:

$$S_m = \frac{R^2}{t.[4\eta.\sigma_0 + E.ap.\frac{t^2}{R^2}]} \quad (15)$$

The open-circuit sensitivity of MEMS acoustic sensor with circular corrugated diaphragm can be given as:

$$S = S_e.S_m = \frac{V_b}{d}.S_m = \frac{V_b}{d}.\frac{R^2}{t.[4\eta.\sigma_0 + E.ap.\frac{t^2}{R^2}]} \quad (16)$$

3. RESULTS AND DISCUSSION

In this research, we used MATLAB software for mathematical analysis and IntelliSuite MEMS design and simulation tool for Finite Element Analysis (FEA) to investigate the sensor behaviors. Figure 4 shows the simulation setup of the MEMS acoustic sensor with clamped circular flat diaphragm and Figure 5 shows the simulation setup of sensor with clamped circular corrugated diaphragm. The silicon wafer faces and lateral faces of diaphragm are fixed. A DC bias voltage is provided between the diaphragm and the back plate. Table 1 shows a summary of design parameters of sensors with flat and corrugated diaphragms.

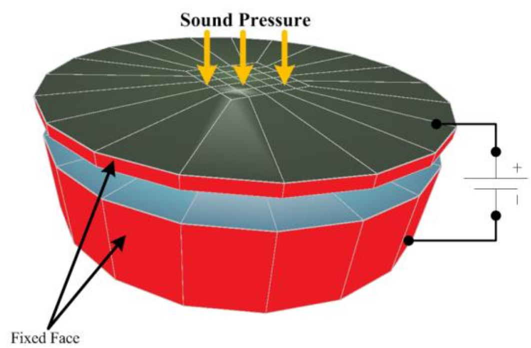

Fig. 4. Simulation setup for flat sensor.

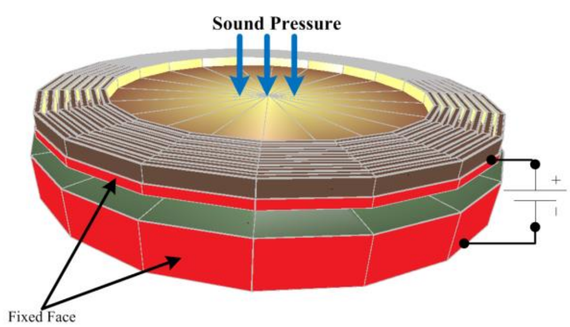

Fig. 5. Simulation setup for corrugated sensor.

Figure 6 shows the central deflection of diaphragm versus pressure with residual stress of 20 MPa. It can be seen that the flat diaphragm is stiffer than corrugated diaphragm. There is good agreement between simulation and analytical results.

In Figure 7 we compare mechanical sensitivity of flat and corrugated circular diaphragms versus residual stress. In case of low stress, the flat diaphragm has higher mechanical sensitivity than the corrugated one. In the case of high stress, the corrugated diaphragm has higher mechanical sensitivity than the flat one. As shown in figure 7, the mechanical sensitivity of flat diaphragm is extremely depended on residual stress but the effect of residual stress has been decreased in corrugated diaphragm.

Table 1. The design parameters of acoustic sensors with flat and corrugated diaphragms.

Parameters	Flat	Corrugated
Diaphragm radius	0.270 µm	0.270 µm
Diaphragm thickness	1 µm	1 µm
Air gap thickness	1 µm	1 µm
Diaphragm material	Polysilicon	Polysilicon
Backplate material	Silicon	Silicon
Young's modulus, *E*	160 GPa	160 GPa
Poisson's ratio, *v*	0.22	0.22
h_c	-----	2.5 µm
N_c	-----	5
w_c	-----	4 µm
β	-----	90°
Diaphragm radius	0.270 µm	0.270 µm
Diaphragm thickness	1 µm	1 µm
Air gap thickness	1 µm	1 µm
Diaphragm material	Polysilicon	Polysilicon

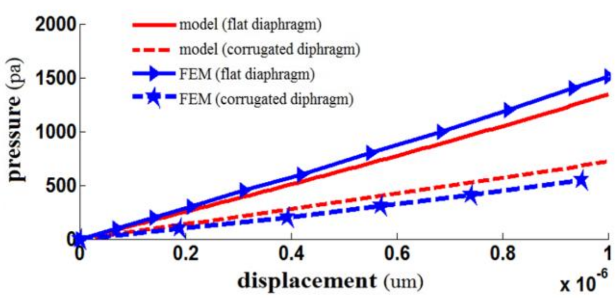

Fig. 6. Central deflection of diaphragms.

The calculated attenuation coefficient of corrugated diaphragm using new model is 0.17. Figure 8 shows the pull-in voltage of sensor versus residual stress. It is clear that the pull-in voltage is almost independent on residual stress of corrugated diaphragm compared with flat one. The open circuit sensitivity of acoustic sensor versus residual stress is shown in figure 9. The result shows that the sensors with flat and corrugated diaphragms have same sensitivity in zero stress. In high residual stress, the open-circuit sensitivity of sensor with corrugated diaphragm is much higher than the flat one.

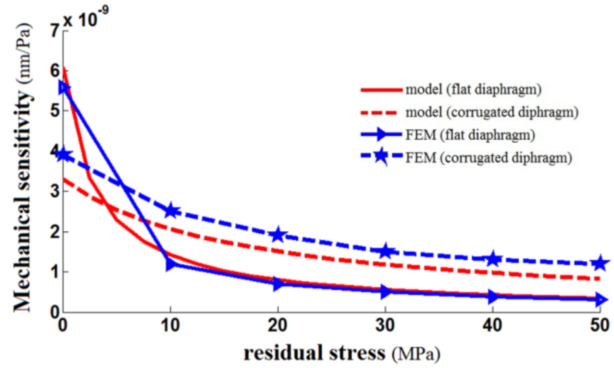

Fig. 7. Mechanical sensitivity of corrugated and flat diaphragm.

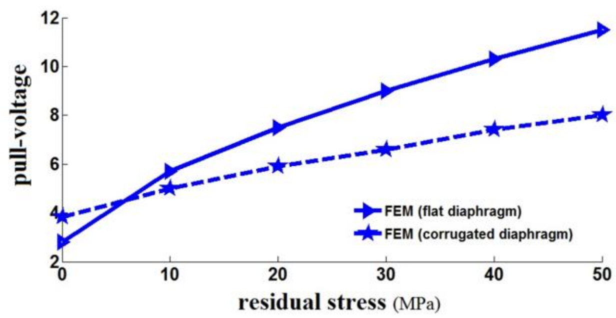

Fig. 8. Pull-in voltage of sensor

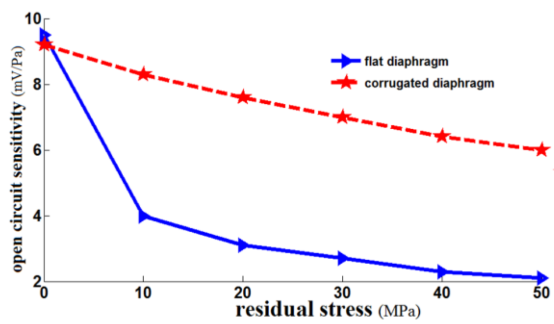

Fig. 9. Open-circuit sensitivity of acoustic sensor.

4. CONCLUSION

In this paper, we presented a novel MEMS acoustic sensor using corrugated diaphragm. The corrugations reduce the effect of residual stress of diaphragm, thus the sensitivity of sensor can be increased. The open-circuit sensitivity and pull-in voltage of sensors are calculated and simulated. The results show that the sensitivity of sensor with corrugated diaphragm has been increased and the pull-in voltage is decreased compared with sensor using flat diaphragm. The results show that the analytical model is very close with FEA simulation results.

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