Design of High Performance Condenser Microphone Using Porous Silicon

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Abstract

The material, Porous Silicon (PS) can easily be formed by electrochemical etching of silicon in HF based electrolytes at room temperature [1]. Since, PS is compatible with silicon IC technology; it finds lot of applications in the fabrication of MEMS devices. Generally, PS has been used as a sacrificial layer to release the free standing structure of the MEMS devices, due to its high etch rate in KOH [2, 3]. In this paper, we make use of the mechanical properties of PS. The mechanical property of Porous Silicon shows a much lower value of Young's Modulus compared to the Young's Modulus of silicon. Also, the Young's Modulus of PS can be varied by varying the porosity [4, 5]. Earlier, the fabrication and simulation of Silicon/Porous Silicon composite membrane for pressure sensor application has been reported [6, 7]. In this paper, we discuss the design of a condenser microphone using a Silicon/ Porous Silicon composite membrane as a movable plate. The performance analysis of this structure has been carried out by Finite Element Analysis of COMSOL package. Simulation was carried out for condenser microphone with PS membrane and it has been compared to condenser microphone with silicon membrane. We found that the capacitance obtained using PS membrane is 1.52 times more than that of condenser microphone with pure silicon membrane for an applied load of 50 Pa. Then the performance of Si/PS composite membrane for condenser microphone has been discussed. It is found that the capacitance obtained on Si/PS composite membrane increases with PS layer thickness for the same applied pressure.

Keywords: MEMS, Porous Silicon (PS), Young's modulus, capacitance, microphone

1. Introduction: MEMS Condenser Microphones

Due to better performance and lower cost, Micro Electro Mechanical Systems (MEMS) microphones are getting more and more importance in consumer electronics such as mobile phones, laptops, and PDAs. However, MEMS sensing devices with much higher sensitivity and better low-frequency characteristics are required in hearing aids and hand-held device. The MEMS microphones made by semiconductor processes are emerging to replace the traditional Electret Condenser Microphones (ECMs) made of polymer diaphragms because of compact size, high signal - to - noise ratio, high sensitivity, quick response and long-term stability [8]. In addition, the diaphragms made by single crystalline silicon or Polycrystalline silicon provide high temperature stability and are compatible with soldering reflow process. Thus, the MEMS microphones are highly applied into market especially in mobile phone.

Capacitor microphones are able to respond to very high audio frequencies, and they are usually much more sensitive than their dynamic counterparts. In other words, they require less amplification than dynamic models to produce the same output level from the same signal source, making them more suitable for quieter or distant sound sources. The reason capacitor microphones have such a good frequency response is that their diaphragms can be made much thinner and lighter than those of dynamic models, as they don't have to drag the mass of a voice coil along with them.

The material Porous Silicon (PS) finds lot of applications in the field of MEMS due to its unique features. PS as sacrificial layer in MEMS due to its high etch rate in KOH or as a functional layer in humidity or chemical sensors due to its large surface to volume ratio have been reported [3, 9]. The mechanical property of PS shows that the Young's Modulus of PS is very low and it varies with porosity [4,5]. This mechanical property of PS for pressure sensors to improve its sensitivity has already been reported [6, 7]. Also, it was found that the Si/PS composite membranes are linear at low pressures and so they are viable for low pressure applications. In this paper, we discuss about the use of PS for improving the sensitivity in condenser microphones for the applied pressure in the range (20µPa to 100Pa) corresponding to the human voice [10]. The performance analysis of this structure has been carried out by Finite Element Analysis of COMSOL 3.5a package.

2. Principle of Operation

Generally, a thin silicon diaphragm is formed as a movable plate with respect to the silicon substrate which is the fixed plate of a parallel plate capacitor. When the membrane moves or deforms with the voice pressure, the distance between the fixed plate and the movable plate reduces. This gives increase in capacitance because the capacitance is inversely proportional to the distance between the plates as mentioned in the Eq. (1).

$$C = \frac{A\varepsilon}{d} \quad \text{------------- (1)}$$

where C is the capacitance in Farads, A is the area of the parallel plates in meter square and ε is the permittivity of the dielectric material.

In our study, we recommend to use the PS membrane instead of a silicon membrane. Since the Young's Modulus of PS is very low compared to silicon, the PS membrane can deform more than the silicon membrane for the same amount of applied pressure and hence the change in capacitance is also higher. But the PS membrane has some practical difficulties such as high fragility of the material and higher stiction effect by the electrostatic force. Hence, we have carried out the simulation to find the performance of Si/ PS composite membranes which can easily be formed by converting a part of the silicon membrane into PS. In this composite membrane, the effective Young's modulus of the membrane is lower than the Young's modulus of the silicon membrane which again gives more deformation compared to the silicon membrane for the same applied pressure.

3. Structure and dimensions of Diaphragm for study

Case 1: Silicon membrane thickness of 10µm with dimension of 500 µm×500 µm square membrane has been designed. The Young's Modulus of silicon is taken as 170 GPa

Case 2: PS membrane thickness of 10µm with dimension of 500 µm×500 µm square membrane has been designed. The Young's Modulus of PS is taken as 0.16 GPa as mentioned in [6].

Case 3: The total membrane thickness is selected as 10µm and a part of the membrane is converted into PS by changing the Young's modulus to 0.16 G Pa. The size of the membrane is the same 500 µm×500 µm for Si and PS layers.

The performance of the composite membrane has been studied with the variation in the thickness of PS layer. The following dimensions were chosen to form the composite membrane of the diaphragm to study:

- Thickness of 5 µm PS out of total 10 µm
- Thickness of 2µm PS out of total 10 µm

4. Use of COMSOL Multiphysics

Simulation was done using COMSOL Multiphysics. For case 1 and case 2 the membranes have been made using a single layer with the respective Young's Moudulus values. For case 3 the composite diaphragm has been made by a two layer structure of silicon and porous silicon with the respective Young's Modulus values as mentioned in Sec. 3. The pressure in the range (20µPa to 100Pa) corresponding to the human voice has been

applied and the membranes behavior have been studied. The capacitance with the applied pressure has been observed on all the types of membranes.

5. Results and Discussions

5.1 Deformation

The displacement obtained due to a load of 50 Pa on pure silicon (E_S = 170 G Pa) as mentioned as case 1 and on PS membrane (E_{PS} = 0.16 G Pa) as mentioned as case 2 are given in Fig. 1 and 2 respectively. We can see that the maximum displacement on Silicon membrane (case 1) is 5.31×10^{-4} µm whereas the maximum displacement on PS membrane (case 2) is 0.579 µm. The capacitance on PS membrane is 3 orders higher than on silicon membrane of same dimension for the applied pressure of 50 Pa.
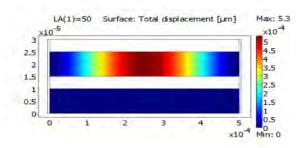

Figure 1. Total displacement of the membrane made up of pure Silicon (10µm) for a load pressure of 50Pa.
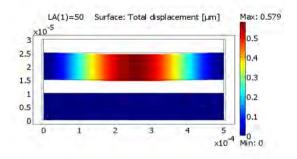

Figure 2. Total displacement of the membrane made up of Porous Silicon (10µm) for a load pressure of 50Pa.

The reason for the very high value of capacitance obtained on PS membrane is due to the high value of deformation. The PS which we have considered with Young's Modulus of 0.16 G Pa corresponds to 90 % porosity as mentioned in [6]. This high porosity membrane cannot be realized in practice due to poor mechanical stability. Also, this type of membrane will result in stiction with the substrate by electrostatic force and may lead to hysteresis behavior.
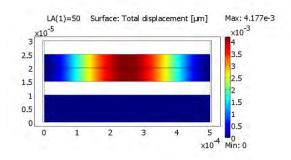

Figure 3. Total displacement of the composite membrane made up of Silicon (5 µm) and Porous Silicon (5µm) for a load pressure of 50Pa.
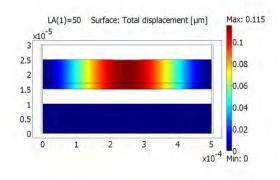

Figure 4. Total displacement of the composite membrane made up of Silicon (2 µm) and Porous Silicon (8µm) for a load pressure of 50Pa.

For improved mechanical stability and to obtain higher sensitivity in condenser microphones, we can use composite membranes as mentioned as case 3 in Sec 3. The deformation on composite structure with PS thickness of 5 µm and 8 µm out of the total membrane thickness of 10 µm are shown in Fig. 3 and 4 respectively. The

displacement of 4.177 x 10 $^{-3}$ µm is obtained on 5 µm PS thickness composite membrane which is nearly one order higher than the silicon membrane.The composite structure in which the thickness of the PS increased to 8 µm, maintaining the total thickness as 10 µm gives the maximum displacement of 0.115 µm.

5.2 Capacitance

The capacitance obtained on silicon membrane (case 1) is 0.625 nF and the capacitance on PS membrane (case 2) is 9.5 nF for a load of 50 Pa. Remarkable improvement in sensitivity is obtained. Fig. 5 shows the resulting capacitance versus load on the pure silicon and PS membranes.
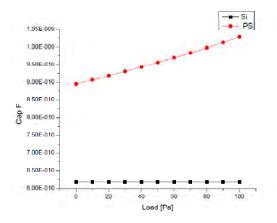

Figure5. Comparison of Load versus Capacitance plots for the diaphragm made of pure silicon only with that of PS only

The capacitance versus load on membranes of case 1, case 2 and case 3 are shown in Fig 6. It shows the capacitance is very high in PS membranes and it is of reasonably higher in composite membranes. Also, as the thickness of PS increases, the capacitance or the sensitivity of the device increases.
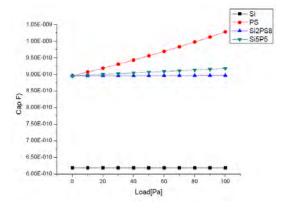

Figure 6. Comparison of Load versus Capacitance plots for the diaphragm made of pure silicon only with that of composite Si/ PS structure
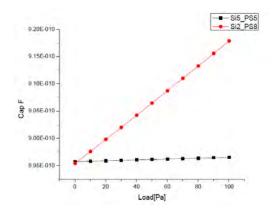

Figure7. Comparison of Load versus Capacitance plots for 5 µm PS and 8 µm PS

Fig 7 shows the capacitance versus load on the composite membranes with PS layer thickness of 2 µm and 8 µm. We can see that the PS layer thickness of 8 µm gives very large range of capacitance variation (0.025nF) whereas the composite membrane with PS layer of 2 µm gives less range of capacitance variation (0.001 nF) for the load variation of 0 to 100 Pa

Table 1. Maximum Z displacement and capacitance (for a load of 50Pa) for various membranes.

Sample no.	Type of membrane	Thickness (μm)	Maximum Z displacement (μm)	Capacitance(nF)
1	Silicon	10	0.000531	0.625
2	PS	10	0.579	0.95
3	Si/PS	5/5	0.004177	0.895
4	Si/PS	2/8	0.115	0.9075

Table 2. Maximum and minimum capacitances for various membranes.

Sample no.	Type of membrane	Thickness (μm)	Max. Capacitance(nF)	Min. Capacitance(nF)
1	Silicon	10	0.625	0.621
2	PS	10	1.025	0.895
3	Si/PS	5/5	0.897	0.895
4	Si/PS	2/8	0.917	0.895

The results of displacement and capacitance for the applied pressure of 50 Pa on various membrane types – case 1, 2 and 3 are summarized in Table 1. Also, the maximum and minimum capacitances for the above membranes are listed in Table 2.

6. Conclusion

Diaphragms made of porous silicon membrane exhibit good sensitivity in capacitor microphones. In Si/PS composite membranes, if the thickness of PS is 8 µm with 90 % porosity, the maximum capacitance is increased by 1.46 times than the silicon membrane. During fabrication condenser microphones, the use of PS as composite membrane structure with suitable porosity and thickness can tremendously improve the sensitivity of the device.

Acknowledgement

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