Mechanical Performance of SiC based MEMS Capacitive Microphone for Ultrasonic Detection in Harsh Environment

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ABSTRACT

In this project, SiC based MEMS capacitive microphone was developed for detecting leaked gas in extremely harsh environment such as coal mines and petroleum processing plants via ultrasonic detection. The MEMS capacitive microphone consists of two parallel plates; top plate (movable diaphragm) and bottom (fixed) plate, which separated by an air gap. While, the vent holes were fabricated on the back plate to release trapped air and reduce damping. In order to withstand high temperature and pressure, a 1.0 μm thick SiC diaphragm was utilized as the top membrane. The developed SiC could withstand a temperature up to 1400°C. Moreover, the 3 μm air gap is invented between the top membrane and the bottom plate via wafer bonding. COMSOL Multiphysics simulation software was used for design optimization. Various diaphragms with sizes of 600 μm^2 , 700 μm^2 , 800 μm^2 , 900 μm^2 and 1000 μm^2 are loaded with external pressure. From this analysis, it was observed that SiC microphone with diaphragm width of 1000 μm^2 produced optimal surface vibrations, with first-mode resonant frequency of approximately 36 kHz. The maximum deflection value at resonant frequency is less than the air gap thickness of 8 μm , thus eliminating the possibility of shortage between plates during operation. As summary, the designed SiC capacitive microphone has high potential and it is suitable to be applied in ultrasonic gas leaking detection in harsh environment.

Keywords: Silicon carbide, MEMS capacitive microphone, ultrasonic detection.

1. INTRODUCTION

Currently, the MicroElectro Mechanical System (MEMS) microphone converting acoustical input to electrical output has large market potential in electronics component, actuator and sensor devices. The low cost and high yield of MEMS microphone can be fabricated using combination of surface and bulk micromachining techniques [1,2]. Basically, MEMS microphones are widely applied in mobile devices [3], aeroacoustic measurement [4], hearing aid [5-9], and biomedical devices [10]. One of the most successfully-developed MEMS sensors is capacitive microphone consisting of thin and movable diaphragm separated by air gap with rigid perforated backplate. The desired design of this MEMS capacitive microphone is smaller in size and able to perform at high mechanical sensitivity [11]. Unfortunately, the size consideration limits the microphone performance in terms of frequency response and sensitivity [12].

As been reported by Torkkeli et al., [13] the movable diaphragm greatly affect the mechanical performance of microphone devices and the types of diaphragm material also plays an important role as an in-plane stress. This is due to the dissimilar mechanical properties of each material which resulted in different mechanical sensitivity of the diaphragm. Bahram *et al.*, [14] reported the similar issue about the material properties such as Young Modulus and Poison ratio which determines the mechanical sensitivity of the diaphragm performance.

Various diaphragm materials that have been used such as silicon nitride [15-18] silicon [19-21], polysilicon [22-24], aluminum [25-27] and polyimide [28]. However, the listed materials have their drawback such as the deformable silicon diaphragm due to the high processing process [29] and suffer from low sensitivity [5] and aluminum that require a pull-in voltage of 105 V because of the high stiffness of the Al diaphragm [14]. In harsh environment application, silicon exhibit several limitation such as operating temperature and radiation limit because of its properties [30]

Silicon carbide (SiC) material has several advantages over other material; it has superior mechanical properties in terms of density, thermal conductivity and Young's modulus. The quantitative comparison can be found in Table 1 of [31]. Other than that, the SiC is also superior over Si chemically in term of chemical inertness and corrosion resistance. The in-plane stress of SiC is found to be tensile with the maximum value of 1500 MPa. The main application of the SiC diaphragm will be as sensitive sensors applied in extreme environments. The material properties of SiC is summarized in Table I. The main objective of this paper is to investigate the superiority of employing SiC as diaphragm material of a capacitive microphone for sonic detection through a series of simulation.

Table 1. Material properties of SiC.

Material properties	SiC
Young's modulus, (GPa)	4.70
Poisson's ratio	0.22
Density ($\text{kg}/\mu\text{m}^3$)	3.2×10^{-15}
Thermal conductivity ($\text{pW}/\mu\text{mK}$)	5.0×10^8
Specific heat (PJ/kgK)	1.34×10^{15}

2. THEORY

2.1 Maximum deflection and stress analysis of square diaphragm.

The maximum deflection, w of square diaphragm is measured at the center of the diaphragm due to uniform applied pressure, p on its surface. The deflection of the diaphragm greatly depends on the material's properties such as Young's Modulus, Poisson's ratio and prestress [32]. The general equation for deflection of the diaphragm can be derived by analyzing the balance conditions between forces and bending moments for each side area of diaphragm, $dx dy$, as given by the following differential equation 1 and 2 [31]:

$$D = \left[\frac{\partial^4 w}{\partial x^4} + 2 \frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} \right] = p \quad (1)$$

where D is flexural rigidity given by:

$$D = \frac{E \cdot h^3}{12(1 - \nu^2)} \quad (2)$$

where E , ν and h are Young's Modulus, Poisson's Ratio and diaphragm's thickness respectively.

Various approximate equations are presented to describe the pressure-deflection for a square diaphragm with a side length of $2a$ as shown in Figure 1. Considering the square diaphragm with small-deflection theory, the diaphragm deflect is small enough compare to the thickness of the diaphragm due to uniform applied pressure ($w/h < 1/10$). Then, the simplest relation between the pressure-deflection with small deflection for square diaphragm can be express by equation 3 [33]:

$$P = 3.41 \frac{\sigma_o h^2}{a^2} \left(\frac{w}{h} \right) + 4.13 \frac{E h^4}{a^4 (1 - \nu^2)} \left(\frac{w}{h} \right) \quad (3)$$

where σ_0 and a are residual stress and half of side length of diaphragm respectively.

Figure 1. Schematic cross section of a square diaphragm.

As above-mentioned equation, the maximum deflection mainly affected by properties of diaphragm's material, dimension of diaphragm and residual stress. In addition, the maximum deflection increase linearly with driving voltage and influenced by diaphragm's thickness [33]. The residual stress should be included in order to determine the maximum total stress for small deflection condition [35]. Meanwhile the strain at the center of the deflection can be neglected as the maximum deflection is higher compare to the diaphragm's thickness [31].

Thus, only the maximum stress which is perpendicular to the edge is considered in this study. Therefore, the relationship of the maximum total stress, σ_{total} and pressure, p for square diaphragm can be calculated as following equation 4 [35]:

$$\sigma_{total} = 1.76 \frac{E h^2}{a^2} \left(\frac{w}{h} \right) \quad (4)$$

2.2 Design of condenser microphone

A structural model for capacitive microphone consists of a parallel-plates, which is separated by an air gap as shown in Figure 2. The first is the top moveable diaphragm, made of back-etched SiC thin film. The second is a fixed bottom plate (or commonly referred as back plate) is made of Si wafer which contains acoustic holes (and herein referred as perforated plate) to reduce acoustic damping. Anodic bonding is used to join the SiC and Si wafers together. The SiC film undergo stress-deformation when an external pressure contacting its top surface. The change of the distance between these two plates is transduced into the differential capacitance value that being measured at the contact pads of both plates as the electrical output. While, the parameters used for this simulation are summarized in Table 2.

Figure 2. Structural model for capacitive microphone.

Table 2. Design parameters for the required capacitive microphone.

Parameter	Value
Diaphragm thickness	1.00 μm
Diaphragm side length	600 μm , 700 μm , 800 μm , 900 μm , 1000 μm
Air gap	8 μm
Vent hole radius	5 mm

3. SIMULATION AND ANALYSIS

3.1 Simulation setting

The Comsol Multiphysics ver.5.3 simulation software was used in this research to design and simulate the mechanical performance of MEMS capacitive microphone. Meanwhile, the finite element method (FEM) was used to solve the implemented model design by resolving differential equation that are formulated in mesh structure step [36]. The design parameters (Table 2) was used to build the geometry and simulation output created by meshing process. The novelty of SiC with its respected electrical and mechanical properties is used to simulate the movable diaphragm, which was never been reported before. The separation between the top plate (SiC) and bottom plate (Si) is set to be 8 μm , varied at applied pressure range between -26 dB to 0 dB as the device used to detect gas at ultrasonic range.

3.2 Resonant frequency

Initially, the simulation has been focused on the resonant frequency of 36 kHz by varying the size of the diaphragm. Six modes of resonant frequencies were computed with difference diaphragm's deflection. First mode deflection is considered as resonant frequency as the deflection of the diaphragm occur at the center as shown in Figure 3. The comparison between side length and resonant frequency are summarized in Figure 4. Square diaphragm with five difference sizes are computed and it is observed that the larger diaphragm's size give the lowest resonant frequency. The diaphragm with side length of 1000 μm is shown to have the lowest resonant frequency and this resonant frequency value increased by decreasing diaphragm's size. Therefore, we concluded that the simulation result presented by Figure 4 indicated that the resonant frequency of the diaphragm affected by the diaphragm's size.

Figure 3. First mode of resonant frequency for 1000 x 1000 μm^2 diaphragm.

Figure 4. Resonant frequency at difference diaphragm's side length.

3.3 Deflection versus applied pressure

Figure 5 represent the center deflection of the diaphragm at a series of external pressure load. Approximately, the applied pressure on the surface of the diaphragm is between -26 dB to 0 dB. It is observed that the center maximum deflection increases with the increase of applied pressure. Comparing the simulation result between the diaphragm's size and deflection, the deflection of wide diaphragm is less than the deflection by small diaphragm. Deflection of the diaphragm's side length of 1000 μm , 900 μm , 800 μm and 700 μm increase in order with applied pressure and achieved the maximum deflection at 700 μm diaphragm. The diaphragm start to decrease its deflection at 600 μm diaphragm for the same applied pressure. It is revealed that the limitation of diaphragm's deflection greatly depends on the size of diaphragm.

Figure 5. Deflection-pressure at various diaphragm's size.

The effect of the diaphragm's size on the von Mises stress is studied. The simulation of center deflection and stress analysis for the 1000 x 1000 μm^2 diaphragm are shown in Figure 6 and Figure 7 respectively. The central maximum deflection of the diaphragm is 3.05 μm and the maximum stress at 1.52 N/m^2 . The default applied pressure for these analysis is 2.6 μPa as the diaphragm's deformation is half from the air gap between the plates for all the diaphragm's size as shown in Figure 8.

Figure 6. Deflection analysis of 1000 x 1000 μm^2

Figure 7. Von Mises stress analysis of 1000 x 1000 μm^2

Figure 8. Touch-mode deflection

4. CONCLUSION

The MEMS capacitive microphone is designed through iterative simulation to study the mechanical performance such as maximum deflection, stress and resonant frequency of the device. Diaphragm with size of 1000 x 1000 μm^2 employing SiC thin film as a sensing diaphragm gives great mechanical performance for ultrasonic range detection at harsh environment. The damping effect and electrical performance of the proposed device will study in future work.

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