Thermal and Load-deflection FE Analysis of Parylene Diaphragms

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ABSTRACT

In this study, the finite-element method(FEM) is employed in order to analyze the mechanical behavior of parylene diaphragm. Thermal and load-deflection FE analyses of flat and corrugated parylene diaphragm are performed to find an effect of the residual stress on the stiffness of the diaphragm. The simulation results show that the mechanical sensitivity of diaphragm is greatly influenced by the residual stress caused by the thermal process(silicon wet etching). The measurement is consistent with simulation result that takes the effect of residual stress into account. Optimum shape of corrugated diaphragm that considers the corrugation depth and number is determined.

Keywords: Parylene, Corrugated diaphragm, Load-deflection, Residual stress

1 INTRODUCTION

The micromachining technology and many actuation principles have been applied to micropump, microvlave, microphone etc.[1,2,3]. Most of these actuators have a membrane and it moves back and forth to transfer some pressure into working fluid. Therefore, the performance of those actuators strongly depends upon the characteristics of diaphragm.

Recently, parylene has been used for a diaphragm material for micromachined devices because of its excellent properties such as low Young's modulus and bio-compatibility etc.[4]. In order to know the characteristics of parylene diaphragm, the experimental study on the parylene diaphragm was first reported by our group[5]. We compared the load-deflection relationship between the flat and corrugated diaphragm.

For corrugated diaphragm, parametric FEM study is needed to find the accurate behavior of the parylene diaphragm under various conditions because the optimum design is necessary to improve the efficiency of the device. In this point of view, this paper shows the thermal and load-deflection FE analyses of parylene diaphragm to figure out the influence of the residual stress on the stiffness of the diaphragm. Also, the mechanical performance of the corrugated diaphragm under various corrugation depths and numbers is estimated to find the optimum shape, and their results are presented and discussed.

2 DIAPHRAGM STRUCTURE

The diaphragms used in experiment are fabricated by using two-mask process that provides high yield. Two kinds of diaphragms are fabricated. One is the planar diaphragm and the other is the corrugated one. For the planar diaphragm, the diaphragm sizes are 2.8 x 2.8 mm^2 and 4.3 x 4.3 mm^2 and the thickness of parylene diaphragm is 3 µm. For the corrugated diaphragm, the width and depth of the corrugation are 80 µm and 20 µm, respectively. The detail fabrication process of corrugated diaphragm is described in [5]. The schematic view of the corrugated diaphragm is shown in Fig. 1 and its characteristic parameters are listed in Table 1.

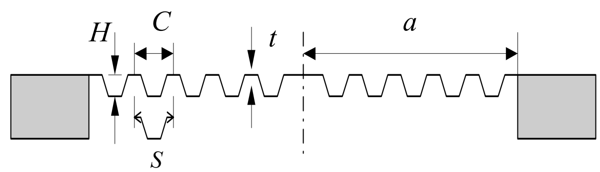


Figure 1: The schematic cross-sectional view of the corrugated parylene diaphragm.

Parameter	Symbol	Value
Radius	*a*	2.15 mm
Diaphragm thickness	*t*	3 µm
Corrugation depth	*H*	20 µm
Corrugation arc length	*S*	209 µm
Corrugation pitch	*C*	160 µm

Table 1: The characteristic parameters of the corrugated diaphragm.

3 THEORY

3.1 Load-deflection relationship

A square flat diaphragm under applied pressure is shown in Fig. 2. Such membrane can be modeled as a square plate with clamped boundaries. With an assumption of large deflection of thin film(h>>t)[6], the load-deflection relationship of diaphragm can be described as

$$p(h) = C_1 \frac{t\sigma}{a^2} h + C_2(v) \frac{tE}{a^4} h^3 \qquad (1)$$

Where C_1 and C_2 (v) are numerical constants, p is the applied pressure, h the center deflection, a one half of the diaphragm's edge length, t the thickness, E Young's modulus, σ the residual stress, and v the Poisson's ratio. The value of C_1 is 3.45 and C_2 can be written in the form $C_2(v)$=1.994(1-0.271v)/(1-v)[7].

3.2 Thermal stress

The difference in thermal expansion coefficient between silicon substrate and parylene layer causes the thermal stress when temperature changes occur. The thermal expansion coefficient of silicon and parylene are 2.6×10^{-6} /°C and 3.5×10^{-5} /°C, respectively. The two layers can be modeled as a biaxial state. With an assumption of $\sigma_x = \sigma_z$ and strain compatibility, we obtain

$$\alpha_{si} \Delta T = \varepsilon_{Pa} = \frac{\sigma_x - v_{Pa}\sigma_z}{\mathrm{E}_{pa}} + \alpha_{pa} \Delta T \qquad (2)$$

$$\sigma_x = \sigma_z = \frac{\mathrm{E}_{pa}}{1 - v_{pa}} (\alpha_{si} - \alpha_{pa}) \Delta T \qquad (3)$$

During the silicon etching in EDP solution, the temperature is increased up to about 100°C. Thus, temperature change of ΔT=75°C results in the residual stress. The physical and mechanical properties of parylene-C are presented in Table 2. These data will be used both on theoretical calculation and simulation. Poisson's ratio of parylene is assumed to be 0.4.

4 EXPERIMENT

The experiment setup for measuring load-deflection of a diaphragm is shown in Fig. 3. The diaphragm is mounted on the pressure chamber and tested under various pressures and then the corresponding deflection is measured using laser displacement meter(KEYENCE-LC 2420). The applied pressure is monitered by a digital display that is connected to a pressure sensor. The pressure level is controlled by a syringe pump(KDS 100, kdScientific co.).

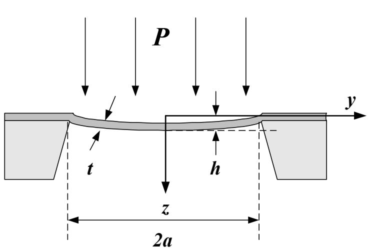


Figure 2: A deflected square diaphragm due to applied pressure.

Property	Value
Density	1.289 g/cm^3
Young's modulus	4.5 GPa
Poisson's ratio	0.4
Thermal expansion coefficient	3.5 x 10^{-5}/°C
Tensile strength	69 MPa
Melting point	290°C

Table 2: The mechanical and physical properties of parylene-C.

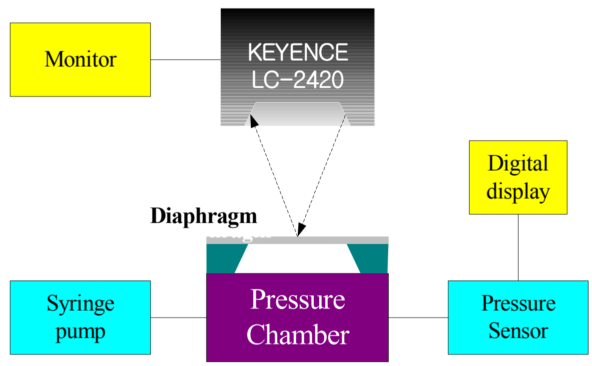


Figure 3: Experimental set-up for measuring the deflection.

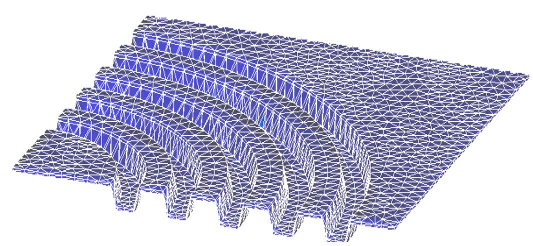


Figure 4: One-quarter view of the tetrahedral-mesh FE model for the corrugated diaphragm.

5 SIMULATION

Thermal and load-deflection analyses are performed to obtain residual stress and load-deflection relationship of the parylene diaphragm. FE analysis is necessary in order to model and simulate the corrugated diaphragm because it has a complex structure which makes stress distributed non-uniformly. The commercial finite element code, CoventorWare^{TM}, is used for the simulation. In order to reduce the computation time, a quarter symmetric modeling technique is employed. For solving the governing differential equation, FE model for the flat diaphragm is meshed with brick elements and the tetrahedral elements are taken for the corrugated diaphragm due to its complex geometry. The FE model for the corrugated diaphragm is created as shown in Fig. 4. In the procedure of FEM analysis, first, thermal analysis is performed on the constructed 3D model with known material properties and symmetric boundary conditions. Afterward, the given pressures are applied to the pre-stressed diaphragm. Thus, the superposition technique is used to analyze the effect of internal stress on the behavior of the parylene diaphragm.

6 RESULTS AND DISCUSSION

6.1 Residual stress

We assume that the stress induced by the process of parylene deposition should be negligible because the temperature in reaction chamber does not rise more than a few degrees above the ambient. Therefore, it is considered that temperature change during silicon wet etching process is the major reason for the residual stress of the parylene layer. The thermal stress on the parylene layer caused by the difference in thermal expansion coefficients is obtained by analytical and finite element calculations and their results are compared as shown in Fig. 5. After temperature change occurs in the silicon wet etching process, the residual stress of flat diaphragm under Δ T=75°C is analytically 18.2 MPa. Fig. 6 shows the simulated stress contours of flat and corrugated diaphragm at Δ T=75°C. The internal stress on the flat one is uniformly distributed. For the corrugated one, however, the value of stress on the center of diaphragm is almost zero and it is increased as it goes to the edge. The corrugation structure reduces the residual stress and this effect allows the corrugated diaphragm to achieve large deflection relatively.

6.2 Load-deflection relationship

With an assumption of 18.2 MPa initial stress obtained by above thermal analysis, the comparison among the experimental, theoretical and simulated load-deflection results of flat diaphragm with the size of 2.8 mm^2 and 4.3 mm^2 are shown in Fig. 7. The simulation results considering the effect of residual stress and experimental results are well matched for both sizes. Therefore, our prediction that the residual stress is mainly caused by the thermal process(silicon wet etching) is proved to be correct. Some deviations between experiment and FEM data seems to be measurement errors. Based on these results, we can know that our FEM analyses are reliable approach. Thus, we apply this FEM technique to the corrugated diaphragm. Fig. 8 shows the comparison between simulation and experiment results of the deflection of corrugated diaphragm under various pressures. In this case, the deflection of the corrugated diaphragm is much larger than that of the flat one under the same pressure applied because the corrugations reduce the residual stress significantly. However, the effect of internal stress on the corresponding deflection still cannot be ignored.

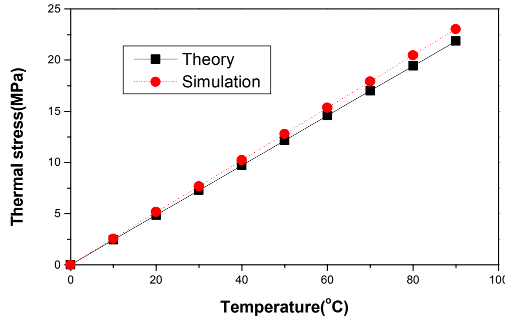
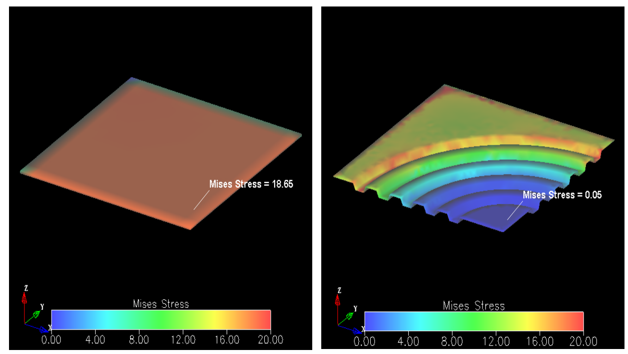
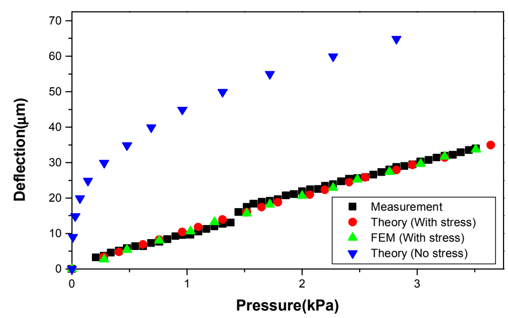


Figure 5: The thermal stress of flat diaphragm according to differences in temp.

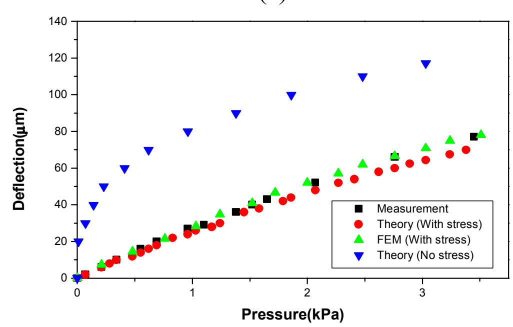


(a) Flat diaphragm (b) Corrugated diaphragm

Figure 6: Stress distribution, at ΔT=75°C. Units in figures are MPa.



(a)



(b)

Figure 7: Comparison among theoretical, measured and simulated deflection of flat diaphragm with residual stress, 18.2 MPa, corresponding to the various pressures in the case of size (a)2.8mm^2 and (b)4.3mm^2.

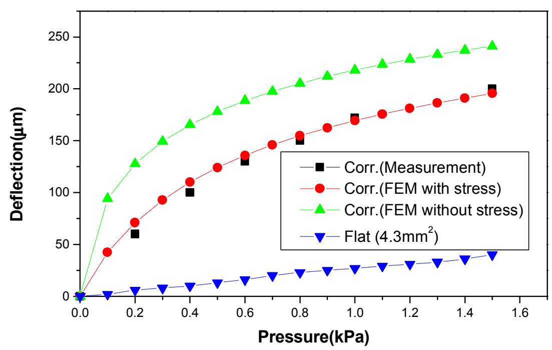


Figure 8: Comparison of the simulated and measured deflection of a corrugated diaphragm(4.3 mm^2) according to various applied pressures.

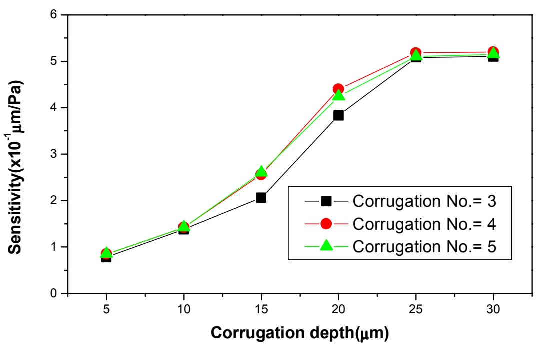


Figure 9: The mechanical sensitivity of diaphragm according to the variation of corrugation number and corrugation depth.

6.3 Parametric study

The influence of the number of corrugation and corrugation depth on the mechanical sensitivity of the corrugated diaphragm is studied to find optimum shape. The mechanical sensitivity is defined as the ratio of the center deflection to the corresponding applied pressure. The value of residual stress is considered to be constant under the condition that the temperature change in thermal process is kept at Δ T=75°C. a, S and C are taken as 2.15 mm, 209 μm and 160 μm, respectively. When the uniform pressure P = 100 Pa is applied to the corrugated diaphragm, the mechanical sensitivity of corrugated diaphragm with respect to the various corrugation numbers and depths is studied as shown in Fig. 9. According to the simulation results, increasing the corrugation number enhances the sensitivity of diaphragm until the number is less than 4. The number of corrugation more than 4 results in an increase in the stiffness of diaphragm. Therefore, when the corrugation number becomes 5, the value of sensitivity is decreased. Also, increase in corrugation depth makes the sensitivity better. However, the values of mechanical sensitivity are not changed when the depth of corrugation is more than 25μm.

7 CONCLUSION

FE analyses of flat and corrugated diaphragm have been performed to find the accurate behavior of the diaphragm. The residual stress on the parylene diaphragm results from difference in thermal expansion coefficient between two layers and this residual stress significantly affects the load-deflection relationship of both flat and corrugated diaphragm.

For the corrugated diaphragm, the parametric study is conducted in order to improve the performance of the mechanical sensitivity. FEM results show that the optimum corrugation number is 4 and corrugation depth is about 25 μm.

The results show that FE methods used for thermal and load-deflection analyses are successfully applicable to predict the characteristics of both the flat and corrugated diaphragm. This technique can be used as a design guideline for the application to the parylene diaphragm in microsystems.

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