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Capacitive Micromachined Ultrasonic Transducer (CMUT): Analytical Evaluation of Membranes Performance Under Fabrication Related Stress

Kapasitif Mikro İşlenmiş Ultrasonik Çevirgeç (KMUÇ): Üretim Kaynaklı Stresin Diyaframların Performansına Etkisinin Analitik Olarak Değerlendirilmesi

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ABSTRACT

High power transmission from CMUT (capacitive micromachined ultrasonic transducer) surface depends on output pressure and membrane displacement. Moreover, fabrication process related stress on membrane should also be considered because it affects CMUT performance in terms of collapse voltage, resonance frequency and gap distance. Therefore, stress on membrane becomes important criteria for CMUT modelling and fabrication. Surface micromachining and wafer bonding technologies are widely used for CMUT fabrications. These fabrication processes include several depositions and etching steps that those induce stress on CMUT membrane. Fabrication process related stress are classified as compressive or tensile. In this study, three common CMUT membranes, Si_3Ni_4, Poly-Si and SiC, were selected for analytic calculations and displacement and output pressure of these CMUT membranes were evaluated under built in stress. It was shown that stress on membrane has significant effect on membrane deflection and pressure from device surface for three membranes. As a result, stress on vibrating membrane should be minimized and optimized for reliable and high performance device fabrication when considering wide range of CMUT applications.

Keywords: CMUT, Stress, Displacement, Fabrication, Pressure

ÖZET

Kapasitif Mikro İşlenmiş Ultrasonik Çevirgeç (KMUÇ)'in yüzeyinden yük güç çıkışı elde edilmesi çıkış basıncı ve diyaframın yerdeğiştirmesine bağlıdır. Buna ek olarak, üretimden dolayı diyaframda oluşan stres de göz önünde bulundurulmalıdır. Çünkü diyaframda oluşan stres, çöküş voltajı, rezonans frekansı ve kavite derinliği açısından KMUÇ'ın performansını etkilemektedir Bu yüzden diyaframdaki stres, KMUÇ modellenmesi ve üretimi için önemli bir kriterdir. Yüzey işleme veya wafer bonding teknolojileri KMUÇ üretiminde sıkça kullanılan teknolojilerdir. Bu üretim teknolojileri, KMUÇ'ın diyaframı üzerinde strese neden olan birçok kaplama ve dağlama sürecinden oluşmaktadır. Diyaframda oluşan bu stresler sıkıştırma veya gerilme stresi olarak adlandırılır. Bu çalışmada, analitik hesaplamalar için KMUÇ üretiminde yaygın olarak kullanılan Si_3Ni_4,Poly-Si ve SiC diyaframları seçilmiştir ve stresin diyaframların yerdeğiştirmesi ve çıkış basıncı üzerindeki etkileri değerlendirilmiştir. Üretim sırasında diyaframda oluşan stresin diyaframların yerdeğiştirmesini ve dolayısıyla da diyaframın çıkış basıncını önemli ölçüde etkilediği gösterilmiştir. Sonuç olarak, yüksek performansta ve daha güvenilir KMUÇ üretilmesi için ve ayrıca geniş çaplı KMUÇ uygulamaları göz önünde bulundurulduğunda üretim kaynaklı stres minimize ve optimize edilmelidir.

Anahtar Kelimeler: KMUÇ, Stres, Yerdeğiştirme, Üretim, Basınç

1. INTRODUCTION

Capacitive Micromachined Ultrasonic Transducer (CMUT) is an advanced ultrasonic technology based on micro electromechanical system (MEMS). Fabrication and electronic packaging of CMUT using different materials and methods have been under investigation for recent years. CMUT simply includes a cavity (gap) under vibrating membrane and electrodes (top and bottom) to drive device for ultrasound generation and reception (Ergun, Yaralioglu, and Khuri-Yakub 2003). There are two CMUT fabrication technologies: surface micromachining and wafer bonding technology. Surface micromachining uses integrated circuits (IC) fabrications techniques in which many depositions and etching processes on single substrate are required to construct final device. Wafer bonding technology, on the other hand, needs two different substrates. One is to bottom electrodes patterning and deposition, other is to membrane and top electrode formation. Bonding of two substrates under high vacuum is final step of fabrication process (Ergun et al. 2005). Figure 1 shows basic structure of CMUT device. Some of the drawbacks of CMUT compared to present PZT transducers are low SNR (signal to noise ratio) and low output pressure due to dimension of vibrating CMUT cells (Mills and Smith 2003; Olcum et al. 2011). Main purpose of researchers in this area, therefore, is to develop high performance CMUT in terms of SNR and output pressure (F. Yalçin Yamaner et al. 2012). To adress this aim, there many attemps to increase CMUT output performance (Bayram et al. 2005; Olcum et al. 2005, 2011; F. Y. Yamaner et al. 2012) Determination of fabrication process related stress on vibrating membrane is one of these attemps because it affects CMUT membrane performance in terms of collapse voltage, resonance frequency and gap distance (Bahette et al. 2016; Yaralioglu et al. 2001) . It is known that membrane formation using surface micromachining induces stress on membrane due to variety deposition processes (Ergun et al. 2005).Similar to surface micromachining, CMUT fabrication with wafer bonding technology has cause stress on membrane due to high bonding temperature.

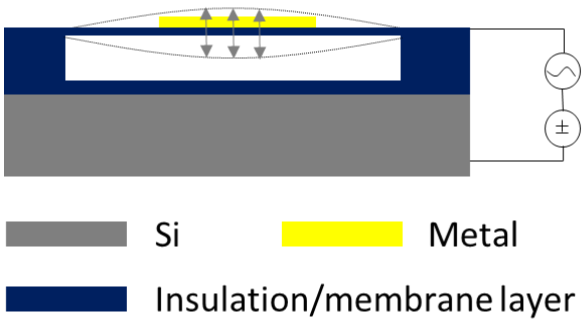

Figure 1. Cross-Sectional View of a CMUT

Previous studies were shown that membrane deflection of CMUT cells in upward direction was measured experimentally as a result of anodic bonding of LTCC (Low Temperature Co-Fired Ceramic)-Si wafer. Si substrate was used as a membrane for fabrication of CMUT.It was assumed in this study that compressive stress due to bonding temperature caused deflection of membrane in upward direction by comparing experimental and numerical results. Topography measurement system (TMS) (Polytec Inc.) was used for experimental measurement of membrane deflection and 3D FEM results were obtained by Femtet (Murata Software Co., Ltd., Japan). Numerical and experimental results of membrane deflection were 181 nm and 177 nm for 120 µm CMUT membrane made of Si. It was also indicated that cracks/holes were observed on some parts of membranes after fabrication process (handling layer removing) and this was explained by reduction of membrane stiffness as a result of tensile stress. Final results of this study emphasized that device operation in air and water was unsuccessful due to abovementioned reasons(F Yildiz, Matsunaga, and Haga 2016; Fikret Yildiz, Matsunaga, and Haga 2016). It can be concluded that this undesired deflection of membrane due to stress on membrane can change electromechanical behaviour of CMUT device and finally alter output pressure and sensitivity (SNR) of CMUT. Thus, analytical evaluation of CMUT membranes before fabrication is crucial to calculate and control membrane parametes for reliable device fabrication.Moreover, analytical evaluation provide fast and easiest results to decide CMUT parameters compared to FEM modelling.

The work in this study is presents comparison of displacement profile of three different CMUT membranes under with and without stress. First, displacements of CMUT membranes made of Si_3Ni_4, Poly-silicon and SiC with a radius of 60 um were evaluated analytically under uniform pressure condition. Then stress was added on cMUT membranes and displacement and output pressure of CMUT membranes were calculated. Finally, performance of CMUT membranes with /without of stress compared in terms of displacement and output pressure.

2. THEORY

CMUT is basically a parallel plate capacitor with a gap between vibrating membrane and fixed electrodes. By applying ac signal on the biased membrane, CMUT transducer transmits ultrasonic signal and also enables to collect signal from environment due to capacitance change between plates. Analytical and numerical modeling have been studied to understand mechanical behavior of device during both reception and transmission. MEMS capacitor can be modeled as a resonator and system behavior is described with second order differential equation as following Eq.(1) (Raskin et al. 2000).

$$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = F_{elect}(x,t) \tag{1}$$

Such modeling helps us to calculate mass (m), spring (k) and damping coefficient (b) to understand mechanical behavior of vibrating membrane. Simple CMUT mass-spring model is obtained when damping effect is ignored. Deflection profile of a CMUT membrane under uniform pressure is given as a function of radial distance, r, membrane radius, a, and flexural rigidity (D) of membrane by Eq.(2)(Wygant, Kupnik, and Khuri-yakub 2008)(S. Timoshenko and S. Woinowsky-Kreiger 1964).

$$\omega(r) = \frac{P_O a^4}{64D}\left(1 - \frac{r^2}{a^2}\right)^2 = \omega_{pk(}1 - \frac{r^2}{a^2})^2 \tag{2}$$

Pressure applied on membrane, P_0 , is sum of the electrical force, F_E , between top and bottom electrode and atmospheric pressure as shown in Eq.(3) and flexural rigidity is given, D , as by Eq.(4) where t_m is plate thickness, E and v are the plate material's Young's modulus and Poisson ratio, respectively. It simply shows that maximum membrane displacement is occurs at the plate center and average membrane displacement is equals to 1/3 of maximum membrane displacement as shown in Eqs.(5-6).

$$P_O = P_{atm} + \frac{F_e}{\pi a^2} \tag{3}$$

$$D = \frac{Et_m^3}{12(1-v^2)} \tag{4}$$

$$\omega_{pk} = \frac{P_0 a^4}{64D} \tag{5}$$

$$\omega_{avg} = \frac{\int_0^a 2\pi r\omega(r)dr}{\pi a^2} = \frac{P_0 a^4}{192D} = \frac{\omega_{pk}}{3} \tag{6}$$

As mentioned in introduction section of manuscript, using wafer bonding or surface micromachining induces stress on membrane during CMUT fabrication. In the case of membrane with stress, deflection profile of membrane is described in Eq.(7)(Eaton et al. 99).

$$\omega(r) = \frac{Pa^2}{4\sigma_i t_m}(1-(\frac{r}{a})^2) \tag{7}$$

Where σ_i is the built-in intrinsic stress of plate. Stress on thin film can be calculated using Stoney equation when film thickness is lower than substrate (Laconte, J., Flandre, D. et Raskin 2006). A circular CMUT membrane displacement under uniform pressure is illustrated in Figure 2.

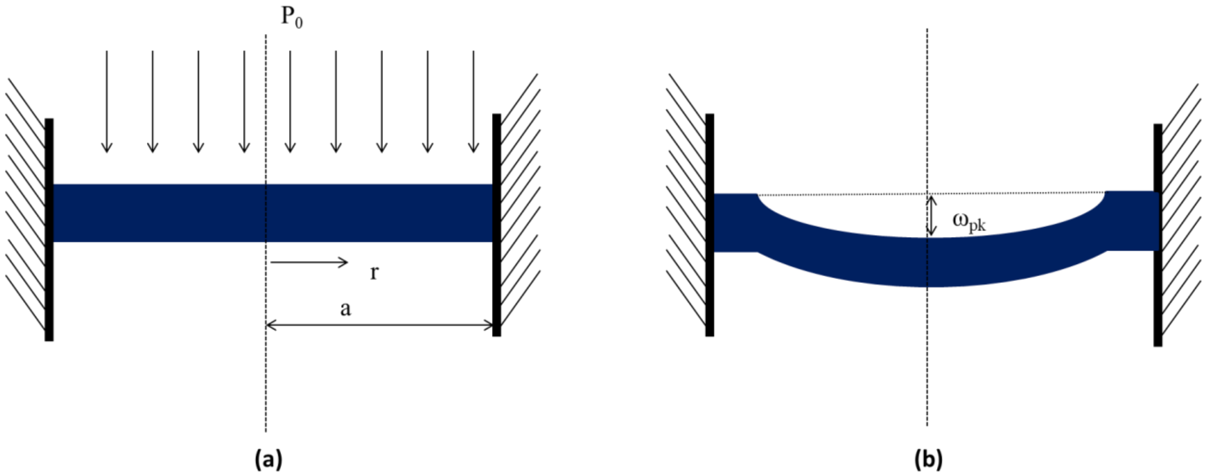

Figure 2. A Circular Plate with Clamped Edges. (a) CMUT Membrane under Uniform Pressure and (b) Maximum Membrane Displacement at the Center of Plate

Maximum membrane displacement and the maximum pressure of the acoustic wave emitted from transducer surface are used to determine the performance of the transducer. Pressure of clamped circular shape CMUT plate can be calculated under a prescribed membrane deflection as following Eq.(8) (Chen et al. 2008). P refers to the uniform pressure applied on the membrane, y is the center deflection, σ is the intrinsic stress of the membrane material and R is the radius of membrane.

$$P = \frac{Eh^4}{R^4}\left[\frac{16y}{3(1-v^2)h} + \frac{(7-v)y^3}{3(1-v^2)h^3} + \frac{4R^2\sigma y}{(1-v)Eh^3}\right] \tag{8}$$

3. RESULTS

Intrinsic stress on membrane deposited on thick substrate can categorized in two groups: compressive and tensile stress. Tensile stress has positive value and compressive stress has negative value. Intrinsic stress can be controlled by changing deposition rate, deposition temperature, pressure in the deposition chamber, incorporation of impurities during growth, fabrication process defects, etc. (Laconte, J., Flandre, D. et Raskin 2006). High tensile stress and compressive stress are problematic for reliable device fabrication because they can change both the static deflection under atmospheric pressure and resonance frequency of the membrane. Moreover, high compressive stress causes a problem during sacrificial layer releasing. Membrane is vulnerable to break in the case of high compressive stress (Ergun et al. 2005). All of above reasons of stress on membrane should be considered for designing and making reliable device. Stoney equation describes as below can be used to calculate stress on thin film (under conditions of dm/ds<10%)(Laconte, J., Flandre, D. et Raskin 2006).

$$\sigma_f = \frac{E_s d_s^2}{6(1-v_s)} \cdot \frac{1}{d_f} \cdot \frac{1}{R} \tag{9}$$

s sub-indices refer to substrate and f sub-indices refers to film on substrate. R is the curvature of film after deposition. Si_3N_4, Poly-silicon and SiC are commonly used CMUT membranes for surface micromachining and wafer bonding process. These three different membranes, therefore, were selected and used for analytical calculation of displacement and output pressure. Properties of these materials are summarized in Table 1.

Table 1. Materials Properties of Si_3N_4, Poly-Silicon and SiC Membrane

	Young's Modulus (E-GPa)	**Poisson's Ratio (v)**	**d_s (um)**	**d_f (um)**	**a (radius-um)**
Si_3Ni_4	320	0.26	500	5	60
Poly-Si	169	0.22	500	5	60
SiC	476	0.19	500	5	60

This study aims to show effect of built-in stress on membranes performance in terms of deflection and pressure. Figure 3-(a,b) present a circular shape membrane deflections made of Si_3N_4 and SiC under uniform pressure, respectively . Built-in stress on membranes was calculated as 208,6 GPa using Eq. (9) where 0.1 um maximum membrane bending of flat membrane is used. Deflection of membrane made of Poly-Si with built-in stress is shown in Figure 3(c). It was founded that deflection of membranes with stress is very low compared stress free deflection of membrane as shown in Figure 3. Membrane displacements profile of three different materials with stress are calculated using Eq. (7) and all parameters such as atmospheric pressure, membrane thickness and membrane diameter were accepted as same for three membranes. Moreover, Eq. (8) enables to find pressures of membranes with/without stress using known parameters. Pressures of three membranes under 3 MPa uniform pressure are summarized in Table 2. Maximum displacement of membranes (at the center of plate) are used for pressure calculation. Pressure level of Poly-Si membrane without stress is higher than the membrane with built-in stress. However, membranes made of Si_3N_4, and SiC with stress show higher pressure level compared to membrane without stress. Therefore, there are significant differences between membrane deflections of three materials under same conditions. For example, it was founded that maximum deflection of a membrane made of Si_3N_4 without stress was calculated around 170 nm, however, SiC membrane without stress has maximum deflection around 120 nm as shown in Figure 3-(a,b). These results show that membrane with stress positively affects Si3N4, and SiC membrane performance in terms of pressure, however, stress is not desired for Poly-Si membrane when high output pressure is required. Moreover, it can be concluded that CMUT membrane material would be selected considering analytical results of three membrane, which are obtained in this study.

Table 2. Pressure Level of Circular Membranes Made of Si_3Ni_4, Poly-Si and SiC with and without Built–In Stress

Material	**Pressure without stress (MPa)**	**Pressure with stress (MPa)**
Si_3Ni_4	3	4,1
Poly-Si	5,6	3,8
SiC	3,2	3.7

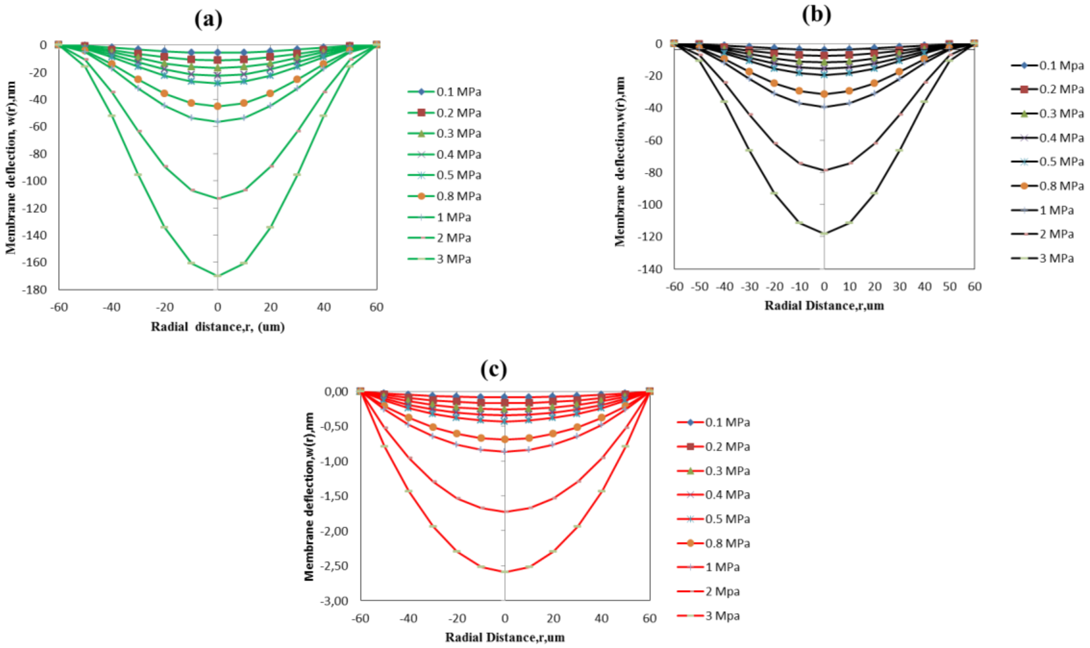

Figure 3. (a) Deflection of a Circular Si_3Ni_4 Membrane with a Radius of 60 um under Uniform Pressure, (b) SiC Membrane with a Radius of 60 um under Uniform Pressure and (c) Displacement Profile of Poly-Si Membrane with 208,6 GPa Built-In Stress

4. CONCLUSION

Deflections of circular shape clamped membrane with/without built-in stress were presented. Membrane displacement and pressure of vibrating membranes were evaluated for three different CMUT membranes. Our results showed that stress on membrane significantly alter displacement of membranes. Pressure from membranes surface were also calculated and compared. Higher output pressure can be obtained with a Poly-Si membrane without stress compared to membrane with stress. For Si_3N_4 and SiC, stress on membrane increases pressure level of membranes. As a result, high performance and reliable CMUT device requires special care to determine stress on vibrating membrane to eliminate undesired effects on electromechanical behaviours of CMUT device. Fabrication and experimental characterization of CMUT having Si_3N_4 membrane are future work of this study.

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