RESIDUAL STRESS AND YOUNG'S MODULUS MEASUREMENT OF CAPACITIVE MICROMACHINED ULTRASONIC TRANSDUCER MEMBRANES

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Abstract— **Membranes supported by posts are used as vibrating elements of capacitive micromachined ultrasonic transducers (CMUTs). The residual stress built up during the fabrication process determines the transducer properties such as resonance frequency, collapse voltage, and gap distance. Hence, it is important to evaluate and control the stress in thin film CMUT membranes. The residual stress in the membrane causes significant vertical displacements at the center of the membrane. The stress bends the membrane posts, and the slope at the membrane edges result in amplified displacement at the center by the radius of the membrane. By measuring the center displacement, it is possible to determine the stress provided that Young's modulus of the thin film is known accurately. Usually, in thin film structures Young's modulus differs from that of bulk materials and it depends on thin film deposition technique. In this paper, we propose a novel technique for the measurement of stress and Young's modulus of CMUT membranes. The technique depends on the measurement of membrane deflection and resonance frequency. We modeled the stress and Young's modulus dependence of membrane deflection and resonance frequency using finite element analysis. We used the atomic force microscope (AFM) to measure the membrane deflection and the laser interferometer to determine the resonance frequency of the membrane. The technique is tested on a CMUT membrane. We found that our LPCVD deposition technique yields residual stress of around 100 MPa and Young's modulus of around 300 GPa.**

Keywords— **residual Stress, micromachined membranes, capacitive micromachined ultrasonic transducer, atomic force microscopy.**

I. INTRODUCTION

Capacitive ultrasonic transducers have existed for decades and used for the excitation and detection of acoustic waves [1]. Recent advances in the silicon micromachining techniques enabled the fabrication of thin membranes (0.1μ-2μ) over very small gaps (0.05μ-1μ) [2], [3], [4]. This geometry results in very efficient transducers for air borne and immersion applications, indeed, it makes possible transducers that can compete with piezoelectric transducers in terms of efficiency and bandwidth. One advantage of these transducers is that they have greater potential for electronics integration since the fabrication steps are the same as the CMOS device fabrication process. Another is the potential for fabricating a 2D-array of transducers using simple photolithography. Hence, capacitive micromachined ultrasonic transducers (CMUTs) have gained remarkable popularity during the last decade.

The operation parameters such as resonance frequency, collapse voltage, mechanical sensitivity of a CMUT membrane are determined by the thin film properties. Hence, it is important to evaluate and control Young's modulus, Poisson's ratio, and residual stress of the deposited thin films. In this paper, we propose a new method to measure Young's modulus and the residual stress of CMUT membranes where the radius is usually on the order of tens of microns, and thickness ranges from 0.1 μm to 2 μm. A number of different techniques have been used to determine Young's modulus and residual stress in thin films. These methods include wafer curvature method, load-deflection method, resonance techniques and so on. The wafer curvature method [5] measures the average tensile or compressive residual stress in thin films. In this method, a wafer is coated by a thin film. The stress in the film bends the wafer. The deflection of the wafer is then measured using optical methods. However, the stress in the released structures could be different from that measured using this technique. Another popular method is the load-deflection method [6]. This method requires forming a vacuum chamber at the back side of the membrane. As the pressure in the chamber is decreased, the membrane bends inward. An interferometer measures the displacement at the membrane center. Then, an analytical expression is fitted to the displacement versus pressure curve to get residual stress and Young's modulus. This method can be employed for CMUT membranes provided that both the displacement measurement device and the membranes are placed in a vacuum chamber. By changing the pressure inside the vacuum chamber, the membrane deflection can be changed if the membranes are sealed. However, operating the measurement system inside a vacuum chamber may not be feasible. In resonance techniques [7], the resonance frequency of the structure is measured. This technique yields either residual stress or Young's modulus. Since, there is only one measurement it is not possible to determine stress and Young's modulus simultaneously. There are also other methods that propose the fabrication of small structures besides actual devices on the same wafer [8], [9]. However, these methods are not suitable for the accurate determination of stress and Young's modulus of an actual CMUT membrane.

Our method uses both the deflection and resonance frequency measurements. The CMUT membranes sitting on posts bend downward or upward depending whether the stress is tensile or compressive. Moreover, the air pressure pushes the membranes towards the substrate if the membranes are vacuum sealed. The deflection at the center is determined by the stress and Young's modulus. We find the center deflection by using the atomic force microscope.

Laser interferometer measurements yield the resonance frequency. Combining both measurements through finite element modeling provides the stress and Young's modulus of the membrane.

II. FINITE ELEMENT MODELING

Most of the previous work investigating membrane[1] dynamics has been based on the analytical model by Mason [10]. Mason provided the differential equation governing the particle motion on a membrane surface. His analysis includes both the membrane stiffness due to finite Young's modulus and the residual stress in the membrane. Mason's model assumes that the membrane is clamped at its edges, besides his analysis does not include the effect of the metal electrode. Most of the micromachined membranes have the geometry shown in Fig 1. The post thickness is usually equal to the thickness of the membrane, and the electrode thickness is a fraction of a micron. For these structures, Mason's equation predicts the membrane dynamics to a limited extent, but finite element analysis (FEA) provides much more accurate results.

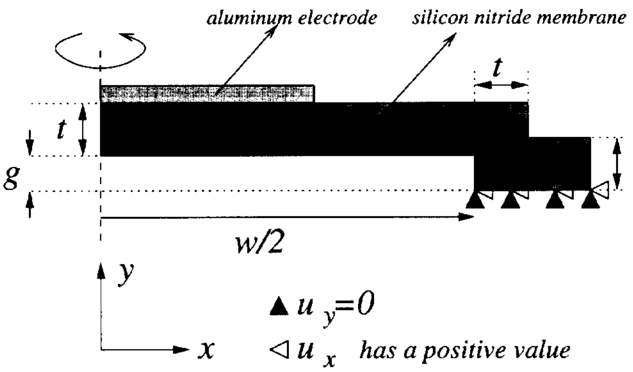

Fig. 1. Cross-section of a CMUT membrane. w is the diameter, t is the membrane thickness, g is the gap distance. An aluminum electrode covers half of the membrane radius.

Figure 1 shows the finite element modeling of a CMUT membrane. The residual stress is included by applying a finite displacement load at the bottom of the post. The lateral stress (T_{xx}) in the membrane is not constant across the y-direction. It linearly decreases from the top surface to the bottom surface. At the top and bottom surfaces, it typically deviates 20% from the average stress. The main effect of the residual stress on the membrane shape is that the center of the membrane deflects down or up depending on whether the stress is tensile or compressive. If the residual stress is tensile, the posts are pulled towards the center of the membrane, and they bend. The membrane follows the slope where it is connected to the posts, and this results in a considerable deflection at the center. If there is a vacuum sealed cavity at the back side of the membrane, the air pressure deflects the membrane more. In the case of compressive stress, the membrane pushes the posts outwards and the membrane moves up at the center.

Material	Young's modulus (GPa)	Poisson ratio	density (kg/m^3)
Silicon Nitride		0.263	3270
Aluminum	67.6	0.355	2700

Table 1

MATERIAL PARAMETERS USED IN THE FEM CALCULATIONS.

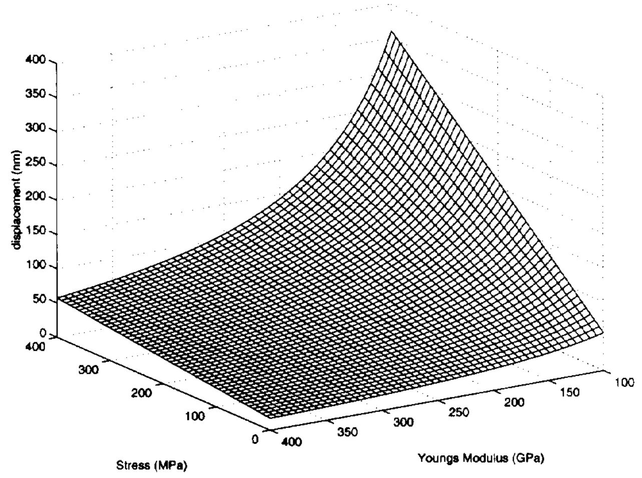

Fig. 2. Deflection at the center of the membrane. Membrane diameter is 46 μm. t = 0.88 μm, g = 0.113 μm, electrode thickness is 0.3 μm.

Our CMUT fabrication process yields tensile stress in the membrane. Hence our membranes are always deflected down. Figure 2 shows the center deflection as a function of residual stress and Young's modulus for a membrane 46 μm in diameter. The membrane thickness and the gap distance

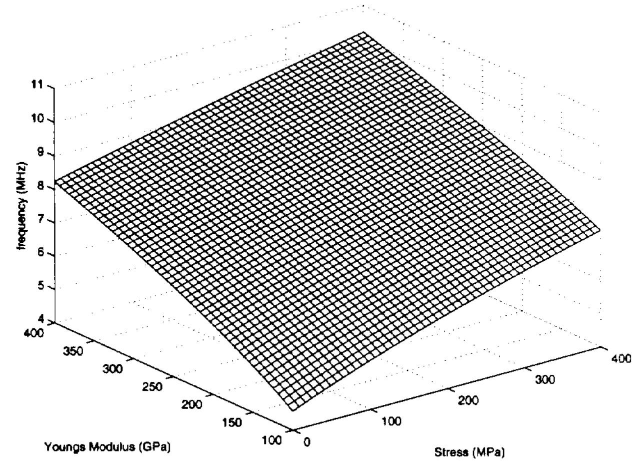

Fig. 3. Resonance frequency. Membrane dimensions are indicated on the Fig. 2

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[1] In this study 'membrane' indicates a structure with both stress and bending stiffness. In literature 'membrane' is usually used for the structures where the thickness is neglected and stress determines the dynamics. For structures where the stress is neglected 'plate' is used.

are 0.88 μm and 0.113 μm, respectively. The thickness of the aluminum electrode is 0.3 μm. The air pressure is assumed to be 101325 Pascal (1 Atm). The material properties for aluminum and silicon nitride are summarized in Table 1. As the Young's modulus increases, the membrane becomes more stiff and the deflection at the center decreases. However, the deflection increases with the increasing tensile stress since the posts are more and more pulled towards the center. Although the deflection due to the air pressure decreases as the stress increases, the net deflection increases at the center.

For a given center deflection, the Young's modulus and stress form a curve on the graph shown in Fig. 2. To determine the Young's modulus and stress, one needs another independent equation. Resonance frequency could be used for this purpose. Figure 3 shows the resonance frequency of the same membrane. As the Young's modulus and the stress increase, resonance frequency increases as expected.

So far we have calculated two curves, deflection and resonance frequency, as a function of the Young's modulus and residual stress. Next, we will measure actual deflection and resonance frequency of the membrane.

III. MEASUREMENTS

An atomic force microscope (AFM) is used to measure the membrane topography by tracing a sharp stylus on the surface. It is a very versatile and easy to use device since it does not require vacuum. We operated the AFM[2] in tapping mode since this mode minimizes the interaction force between the surface and the AFM tip. Figure 4 shows the AFM image of a single CMUT membrane. The holes at the corners are the etch holes. The enchant enters through these holes, follows the channel, and finally reaches the cavity at the back side of the membrane which is filled with the sacrificial layer. The radius of the aluminum electrode is the half of the membrane radius. The four connections to the electrode are neglected in the FEM calculations.

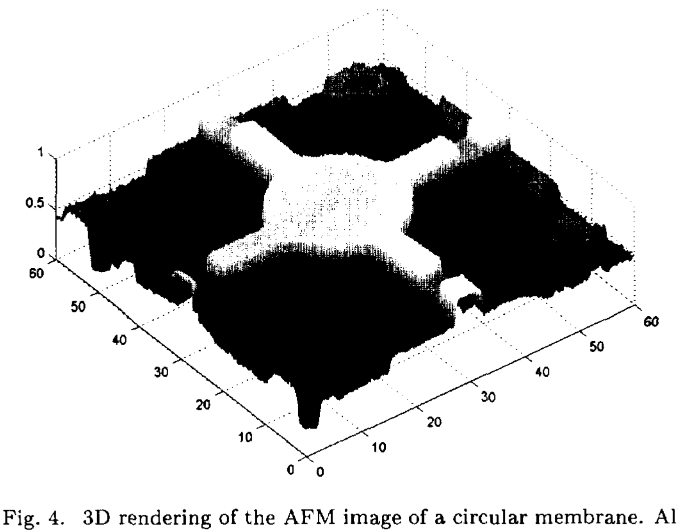

Fig. 4. 3D rendering of the AFM image of a circular membrane. All the scales are in microns. (w=46 μm, t=0.88 μm, g=0.113 μm)

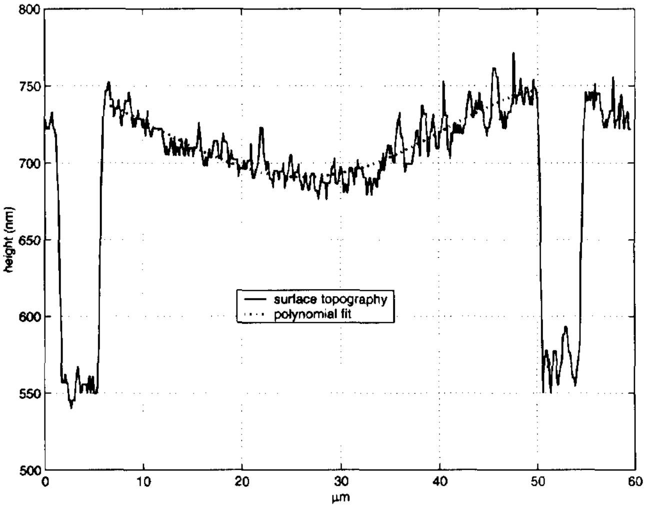

Fig. 5. A scan line from the AFM image shown in Fig. 4. The scan is taken on a straight line passing through the center of the membrane.

The line scan shown in Fig. 5 clearly reveals the displacement at the center. Although the vertical resolution of the microscope is less than 0.1 nm, the surface roughness limits the measurement accuracy. Note that the line scan is measured on top of the aluminum electrode. To find the displacement, we took a number of line scans passing through the center and calculated the average of the center displacements. We found out that the displacement is 50 nm.

The resonance frequency of the membrane is determined by finding the peak vibration amplitude of the membrane. We measured the membrane vibrations by using a heterodyne laser interferometer. The membrane was driven electrically. Figure 6 shows the vibration amplitude as a function of frequency. The first resonance peak is found at 7.54 MHz.

After these measurements, the next step is to obtain two sets of equations. By using Fig. 2, it is possible to define

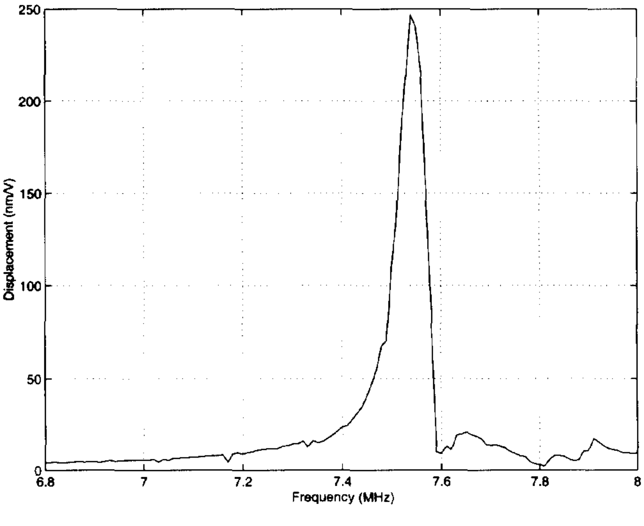

Fig. 6. Membrane vibration amplitude.

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[2] We have used Dimension 3000 AFM from DI in the measurements.

a curve on which the deflection equals to 50 nm as shown in Fig. 7. Similarly, for the resonance frequency another curve can be obtained by using Fig. 3. The intersection of these two curves should yield the Young's modulus and the residual stress inside the membrane. For our fabrication process, these two curves intersect when Young's modulus is 255.4 GPa and the stress is 124.5 MPa.

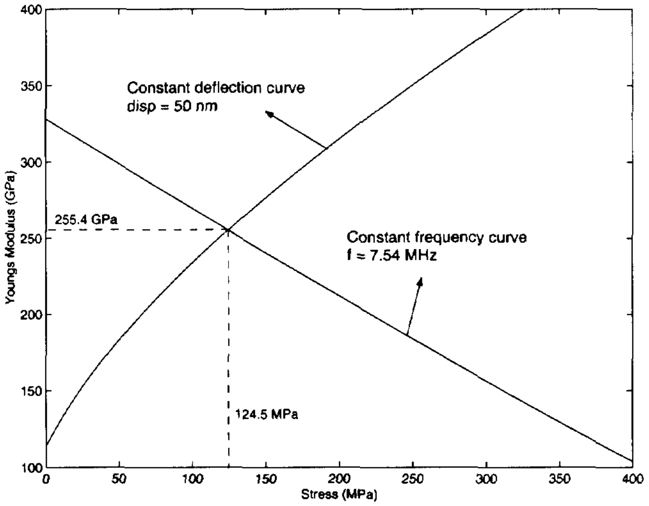

Fig. 7. Constant deflection and constant resonance frequency curves

CONCLUSION

We have demonstrated a method for the determination of the residual stress and the Young's modulus of CMUT membranes. The method depends on the measurement of the deflection and the resonance frequency of the membrane. These measurements provide two independent equations in terms of residual stress and the Young's modulus. FEM analysis provides an accurate modeling of membrane geometry including metal electrode and post compliance. In the future, we will apply our analysis for membranes with different diameters.

ACKNOWLEDGMENTS

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