Ultra-thin Gold Membrane Transducer

Yunho Kim, Misun Cha, Hyungchul Kim, Sungjun Lee, Jaeha Shin, and Junghoon Lee

School of Mechanical and Aerospace Engineering, Institute of Bioengineering
Seoul National University, Seoul, Korea
E-mail: jleenano@snu.ac.kr

ABSTRACT

This work deals with ultra-thin metal-based nano-mechanical transducers that have potentials for extraordinary sensitivity. This nano membrane transducer (NMT) consists of a flat thin film of gold with 30-60 nm thickness freely suspended over large square openings with the side dimensions of 50-500 µm. This work involves the fabrication process and the testing method to obtain pressure sensitivity.

Keywords: NMT, ultra-thin gold film, pressure sensitivity

1 INTRODUCTION

After microcantilever showed potentials as a new approach in sensor technology, many applications have been demonstrated [1-3]. Recently, membrane transducers as chemo-mechanical sensing elements have been introduced, offering advantages over the cantilever approaches [4-6]. Instead of the optical detection method, highly sensitive capacitive detection was readily realized because of the dry cavity under the membrane. The membrane structure not fully immersed in liquid was inherently robust against the flow disturbance compared to the cantilever in liquid.

Membrane sensitivity is affected by the material and the dimension of the membrane. To improve the sensitivity, polymer materials with small elasticity, such as parylene and PDMS, were employed. However, the reliability of the polymer was questioned due to swelling in liquid. It was also difficult to handle the polymer during the fabrication. Also it was hard to immobilize molecules on the polymer surface. To functionalize the surface, other ladder immobilization layer was necessary, possibly leading to reduce the sensitivity.

In this paper, we introduce the use of a pure metal to achieve the high sensitivity and reliability. It is, however, critical to sufficiently reduce the thickness for desirable sensitivity. Therefore our study is focused on dimensional effect of the membrane with fabrication methods. As the membrane thickness is decreased, the sensitivity is highly increased. To achieve the sensitivity level of the polymer membrane with extremely low elasticity, there needs to be a significant reduction of the thickness.

Here we present the use of extremely thin gold that will improve the reliability and immobilization chemistry while good sensitivities are maintained.

2 EXPERIMENT

2.1 Fabrication process

To use the gold membrane, a fabrication process was developed as shown in Figure 1. The gold nano-membrane transducer consists of the upper and the bottom parts.

The gold membrane with the thickness of 30-60 nm was fabricated by anisotropic wet etching process (a). Low stress silicon nitride (Si_3N_4) was deposited on a <100> silicon wafer using the low pressure chemical vapor deposition (LPCVD). The gold layer was deposited on the nitride layer by sputtering (ULTECH, SPS Series). Then, the topside gold layer and backside nitride layer were patterned by photolithography process. By dry etching process, the backside nitride layer was etched (Oxford, RIE 80 plus). For anisotropic wet etching, the wafer was dipped in KOH solution. During this step, single side etching was critical to successfully suspend the extremely thin membrane. After the KOH etching the nitride layer under gold layer was etched by the same method explained above. Then, the gold layer freely suspended as a thin membrane. This membrane was used as a molecular reaction surface on one side, but also used as the upper electrode for capacitive measurement.

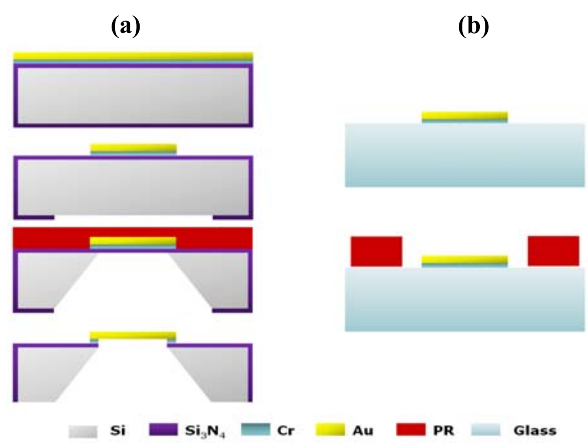

Figure 1. Fabrication process flow of gold TMT
(a) Upper part, (b) lower part

A Lower electrode part was fabricated by metal film patterning on the glass substrate (b). The gold layer was deposited on the glass substrate, and patterned. After patterning the gold layer, photoresist was patterned by photolithography process. The photoresist maintains a gap (1.5 μm) between the upper and the bottom part, creating a capacitor.

2.2 Gold membrane

Figure 2 shows the gold membrane inspected with a light microscope and a scanning electron microscope (SEM, Hitachi S-4800). The gold membranes are 150 x 150 μm^2 and 200 × 200 μm^2 in size. Small size membrane under 100 × 100 μm^2 was easier to fabricate than larger ones. As the size became larger, the yield of the process decreased. For example, in the case of 100 × 100 μm^2 membrane, the yield was over 85 %. However, in the case of 500 × 500 μm^2, the yield was under 40 %.

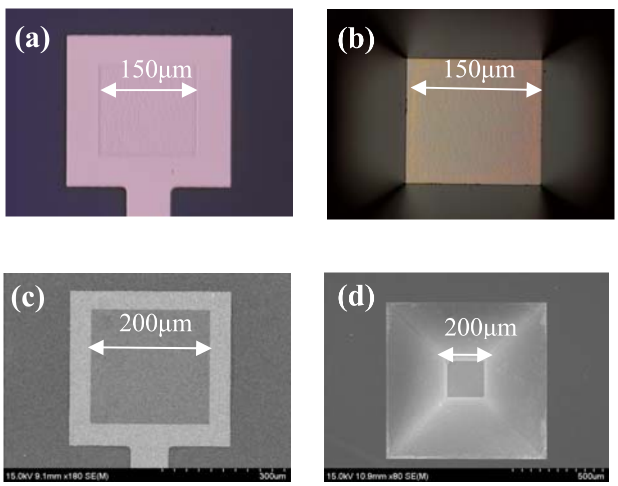

Figure 2. Microscope & Scanning Electron Microscope (SEM) images of gold membranes. (a),(c) Top-side view (b),(d) Backside view

The upper gold membranes in the top view, (a) and (c), show two overlapped squares. The inner squares represent the freely suspended gold membranes and the outer squares are gold layers on the nitride and silicon substrate. With these observations, it is certain that the ultra-thin membrane was created. The backside view, (b) and (d), clearly show the gold membrane suspended, clean and flat.

2.3 Measurement method

The upper gold membrane part and bottom electrode part were bonded together with the photoresist spacer that maintained the gap (1.5 μm). To accurately measure the capacitance between the upper and bottom electrodes, both parts were aligned each other. When the gold membrane deformed, the distance of two electrodes changed. The distance change resulted in the capacitance change which was measured using GLK instruments Model 3000.

We used a compact setup that can exert a hydraulic pressure to the sample. Figure 3 shows the schematic diagram of the setup. The capacitance change was caused by the deformation of gold membrane due to a small hydraulic pressure. Hydraulic pressure was easy to control, and used as a better choice compared with air pressure system which has a pressure fluctuation large enough to break the fine gold membrane.

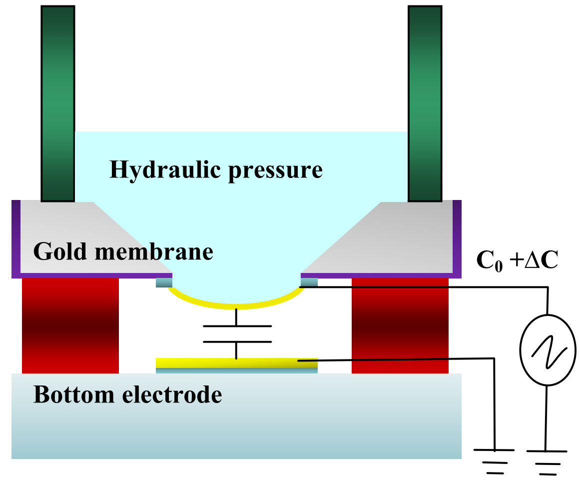

Figure 3. Schematic diagram of hydraulic pressure test to measure capacitance change

3 MODELING AND ANALYSIS

If we assume the square gold membrane as a circular plate with edge fixed conditions, the central deflection can be calculated. Figure 4 is a model for capacitance change of the gold membrane deflection. Upper gold membrane part deforms by pressure. The changed in distance between the two metal plates causes the capacitance variation.

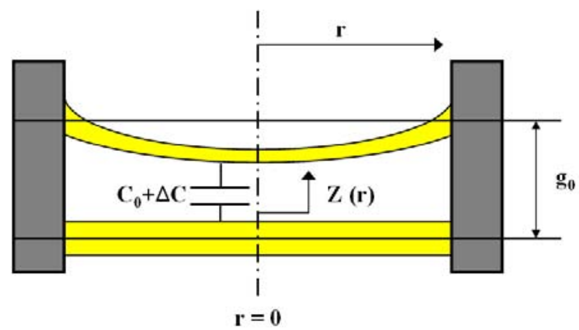

Figure 4. Membrane modeling for capacitance change

r: distance from center, R: radius of membrane
$Z(r)$: gap from the center $Z(0)$: central deflection
g_o: initial gap distance between two electrodes
C_0: initial capacitance between two electrodes
ΔC: capacitance change
ε_o: permittivity of free space

In order to meet the clamped boundary condition, the membrane deflection can be expressed as in (1) with Z(0) the central deflection, and r the distance from the center.

$$Z(r) \cong Z(0)\left[1-\left(\frac{r}{R}\right)^2\right] \quad (1)$$

The capacitance change due to deflection can be calculated as in (2) using the circular plate deflection.

$$\Delta C = \int dc = \int_A \frac{\varepsilon_0}{g_0 + Z(r)} dA$$
$$= \int_0^{2\pi}\int_0^R \frac{\varepsilon_0}{g_0 + Z(0)\left[1-\left(\frac{r}{R}\right)^2\right]} r dr d\theta \quad (2)$$
$$= \frac{\pi \varepsilon_0 R^2}{\sqrt{g_0 Z(0)}} \tan^{-1}\sqrt{\frac{Z(0)}{g_0}}$$

4 RESULTS

The capacitance changes were measured due to the deformation of gold membrane caused by the hydraulic pressure. In that hydraulic test, we added or subtracted a droplet of water by 50 µl at each step. The hydraulic pressure can be calculated from the water height and membrane area. This amount is equivalent to the water head change of 1.7 mm cross sectional area of 91.56 mm^2. The membrane are varied between 100 × 100 μm^2 to 300 × 300 μm^2. Then, the hydraulic pressure of 50 µl water is estimated to 16.7 Pa.

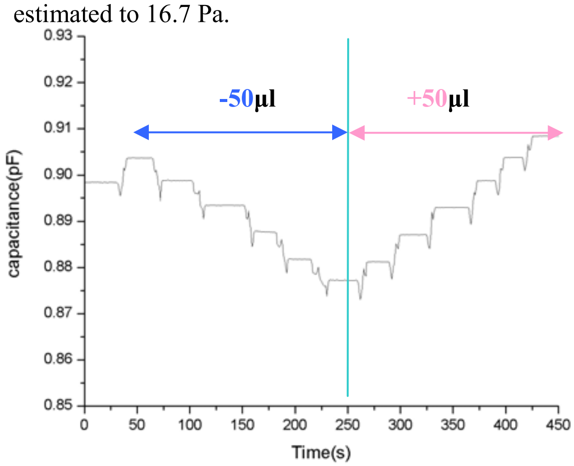

Figure 5. Capacitance changes during the hydraulic pressure test: The volume of water either decreases or increases by 50 µl at each step.

Figure 5 shows the result of test. At every step from 50 s to 250 s, the amount of 50 µl water was subtracted. In this period, total amount of subtracted water was 250 µl and the total capacitance change was 260 fF. In the same manner, the same amount of 50 µl water was added after 250 s. Also, the amount of water at the initial (at 50 s) and the final (at 400 s) states were the same. This result shows the uniform and discrete changes with respect to the varying pressure.

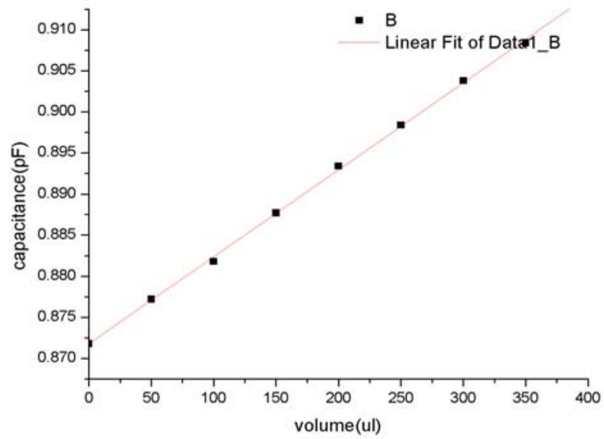

Figure 6. Capacitance according to hydraulic pressure: The capacitance change is 5 fF at each step

The average value of capacitance per unit amount of droplet, 50 µl water was ~5 fF. In Figure 6, the capacitance changed between 0.872 and 0.907 pF when the amount of water varied between 0 to 350 µl. The standard deviation is very small and the capacitance change is linear to hydraulic pressure. The pressure sensitivity calculated using (1) and (2) is 0.3 fF/Pa.

5 DISCUSSION

The noise signal with current setup is ~ 0.5 fF and accordingly the detectable limit of pressure is ~ 1 Pa which is comparable to the state of the art performance (25 mPa) [8]. However, we believe that the noise limit can be substantially reduced with low noise circuit, and our device can easily challenge the best limit of detection. More importantly, the gold nano membrane offers the structure particularly suitable for molecular monitoring through chemo-mechanical sensing mode. Gold surface has broad range of chemistry useful for immobilizing chemicals. Furthermore gold provides stable chemical properties and structural integrity.

6 SUMMARY

Freely suspend gold membrane was fabricated and tested to evaluate mechanical properties. The capacitance change was measured and used to estimate pressure sensitivity. Even though the pressure sensor is not our ultimate goal, this result is promising for the further development in this direction as well as the use for the chemo-mechanical sensing. As a transducer, the ultra-thin gold membrane has many advantages. To achieve the sensitivity demonstrated by the previous polymer devices, the thickness of the gold membrane should be less than 50 nm.

ACKNOWLEGEMENT

This work was supported by the Korea Science and Engineering Foundation (KOSEF) grant funded by the Korea government (MOST) (R0A–2007–000 –10051-0).

REFERENCES

[1] Michael Sepaniak, Panos Datskos, Nickolay Lavrik, Christopher Tipple, "Microcantilever Transducers: A New Approach in Sensor Technology," *Analytical chemistry*, 569A, November 1, 2002

[2] Vincent Tabard-Cossa, et al, "A differential microcantilever-based system for measuring surface stress changes induced by electrochemical reactions," *Sensors and Actuators B*, vol.107, pp.233–241, 2005

[3] Si-Hyung "Shawn" Lim, et al, "Nano-chemo-mechanical sensor array platform for high-throughput chemical analysis," *Sensors and Actuators B*: vol.119, pp.466-474, 2006

[4] R. Rodriguez, J. Chung, K. Lee, J. Lee, "Bio/chemical Sensing by Thin Membrane Trasducers," ASME International Mechanical Engineering Congress and Exposition, Anaheim, California, 2004

[5] Srinath Satyanarayana, Daniel T. McCormick, and Arun Majumdar, "Parylene micro membrane capacitive sensor array for chemical and biological sensing," *Sensors and Actuators B: Chemical*, vol. 115, pp.494-502, 2005

[6] Misun Cha, Ilchaeck Kim, Junbo Choi, Junghoon Lee, "Single-nucleotide polymorphism detection with thin membrane transducer," the proceeding of *Micro TAS*, Tokyo, 2006

[7] Stephen P. Timoshenko, S. Woinowsky-Kreger, "Theory of plate and shells-second edition," McGRAW-HILL International editions, 1959

[8] 6100 Ultra high accuracy digital pressure sensor, http://www.sensorsone.co.uk/products/0/79/6100-Ultra-High-Accuracy-Digital-Pressure-Sensor.html, SensorsONE, 2008