Digital Object Identifier: 10.1109/ULTSYM.2008.0123

Optimum design of circular CMUT membranes for high quality factor in air

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***Abstract*— This paper presents optimum design of circular membrane for high quality factor. A quality factor of CMUT, we designed for resonant chemical sensor, is dominated by Q_{air} and $Q_{support}$. We investigated these two factors independently. We calculate Q_{air} of circular silicon membrane analytically, and numerically. Calculated Q_{air} is compared to measured value. In order to find $Q_{support}$ empirically, we measured quality factor of CMUT in vacuum chamber. Q_{air} is proportional to (radius/thickness)$^{-2}$ and $Q_{support}$ is proportional to (radius/thickness)^{3}. Thus the optimum aspect ratio of membrane exists for maximum quality factor.**

Keywords-component; CMUT, Quality factor, Air damping, Circular membrane

I. INTRODUCTION

Chemical sensors have gained interest continuously in several fields such as homeland security to detect biohazard and explosive materials. With the increasing demand, there are many active research projects on chemical sensors based on micro/nano fabrication. The devices detect changes in material properties such as resistivity, permeability and loaded mass, when volatile analyte is absorbed.

Resonant chemical sensors, which detect changes in mass, are widely investigated. The absorbed molecules change the effective mass of the device, resulting in a shift in resonant frequency. In this application, different resonant modes are used, such as bulk acoustic mode (*e.g.* FBAR) [1], flexural mode (*e.g.* cantilever) [2], and surface acoustic mode (*e.g.* SAW) [3].

Capacitive micromachined ultrasonic transducers (CMUTs) have been investigated for flexural mode resonator. A single CMUT cell is a circular membrane actuated by electrostatic force (Fig. 1). Due to the vacuum sealed cavity under the membrane, the CMUT dissipates energy only on one side of the membrane exposed to air. Thus, the CMUT achieves a higher quality factor than that of resonant structures exposed to air from all sides. In addition, multiple membranes can easily be connected in parallel to achieve design flexibility and robustness.

Mass sensitivity per unit area is one important figure of merit of mass loading system, which is defined as

$$\frac{\Delta m / A}{\Delta f} = -\frac{2\rho t}{f}, \qquad (1)$$

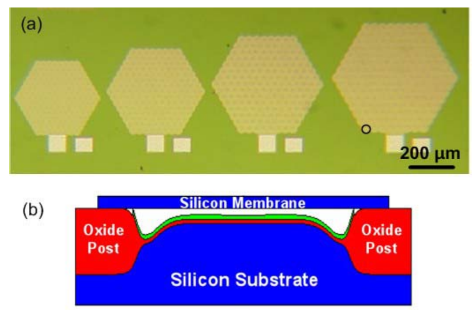

Figure 1. (a) Optical picture of CMUT. Circled area is single cell. (b) Schematic of cross section of single cell.

where *m, A, f,* ρ and *t* are the mass, area, resonant frequency, density and thickness of a membrane. In order to improve the sensitivity, a thin and light membrane with a high resonant frequency is required.

The mass resolution of a sensor is limited by noise level of measurement unit as

$$\frac{\Delta m}{A} = -\frac{2\rho t}{f} f_n, \qquad (2)$$

where f_n is frequency noise of the resonator.

Resolution is another important figure of merit, which is limited by frequency noise or phase noise. In order to accomplish low frequency noise, low motional impedance and high quality factor is required. For a single resonator, these two factors are inversely correlated. Specific motional impedance can be achieved by varying the number of membranes as CMUT is made of multiple membranes connected in parallel. Thus, a CMUT resonator should be designed to have the following characteristics.

- High frequency with thin and light membrane.
- High quality factor to decrease frequency noise.
- Large number of membranes to reduce motional impedance to decrease phase noise.

The resonant frequency of a circular membrane is well known for given design and material. In addition, design criteria, such as size of a device, determine the number of membrane. However, quality factor of circular membrane in air has not been investigated in detail compared to other flexural

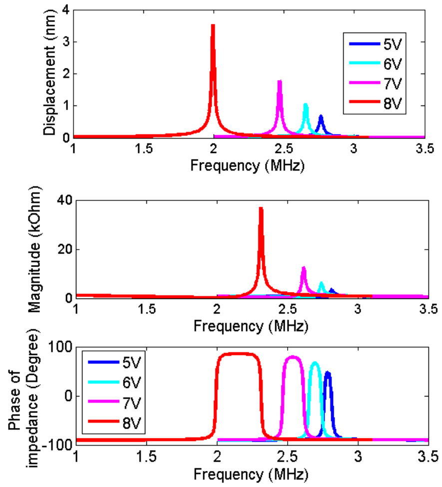

Figure 2. FEA result. Membrane displacement (top) and input impedance (bottom)

mode resonators such as micro-cantilever [4-5]. Therefore, motivated to improve frequency noise and hence resolution, this paper investigates the quality factor of a circular membrane in CMUT devices.

II. Theory

Quality factor (Q) is defined in frequency domain as

$$Q = \frac{f}{f_{BW}}, \tag{3}$$

where f_{BW} is the 3dB bandwidth at resonance. Q can be defined based on the measurement of displacement or input impedance. In the physical domain, quality factor is defined as

$$Q = 2\pi \frac{E_{stored}}{W_{cycle}}, \tag{4}$$

where E_{stored} is the stored energy in the resonator and W_{cycle} is the energy dissipation during the single resonating cycle.

For the flexural mode resonator, several loss mechanisms have been investigated such as air loss, support loss, thermoelastic loss (TED) and surface loss. Adding these losses, the overall Q of a resonator is determined as

$$\frac{1}{Q} = \frac{1}{Q_{air}} + \frac{1}{Q_{support}} + \frac{1}{Q_{TED}} + \frac{1}{Q_{etc}}, \tag{5}$$

where Q is dominated by the mechanisms with large losses.

In this paper, we cover two main loss mechanisms, air loss and support loss, because the effects of other loss mechanism are minimal. For example, estimated Q_{TED} ranges from 10^4 to 10^6 for our design.

This work is supported by DARPA, Microsystems Technology Office under grant N66001-06-1-2030

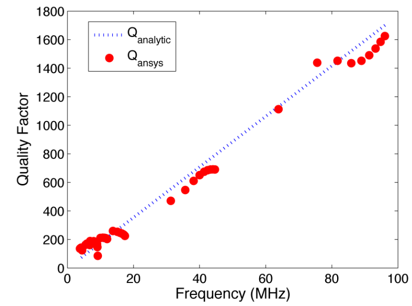

Figure 3. Q_{air} calculated from FEA and analytic method.

TABLE I. Design of CMUT cell

Membrane material	Single crystal silicon
Radius	4 - 25 µm
Thickness	0.5 µm
Insulator	Oxide 0.7 µm
Gap height	50 nm
Number of membrane	169, 331

A. *Air loss*

When the membrane vibrates, it dissipates energy to the surrounding media (*e.g.* air). Q_{air} is the most dominant Q factor for flexural mode resonators in air. For the cantilever, Q_{air} has been investigated empirically, numerically, and analytically. Q_{air} of cantilever with a length of L and a thickness of t is [4]

$$Q_{air} \approx \frac{2\pi f m}{AP}\sqrt{\frac{RT}{M}} \propto \frac{tf}{P}. \tag{6}$$

Based on similar approach, Q_{air} of a CMUT membrane is calculated as,

$$Q_{air} \approx \frac{2\pi f t \rho}{Z_{air}} \propto \frac{tf}{P}, \tag{7}$$

where P is the pressure of air and Z_{air} is the acoustic impedance of air. In this equation, we used Z_{air} to be 410 Pa·s/m, assuming the acoustic impedance is resistive. Based on (7), Q_{air}/f is dependent on design parameters as

$$\frac{Q_{air}}{f} \approx \frac{2\pi t \rho}{Z_{air}}. \tag{8}$$

Based on Table 1 and (8), Q_{air}/f is 17.7/MHz.

B. *Support loss*

When the membrane resonates, the edge of the membrane harmonically applies stress and it transfers energy to the substrate in the form of acoustic waves. $Q_{support}$ for cantilever

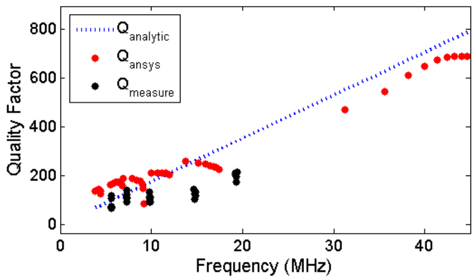

Figure 4. Measured Q_{air} compared to FEA and analytic method

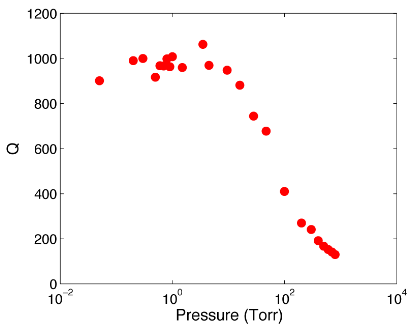

Figure 5. Measured quality factor in different pressure

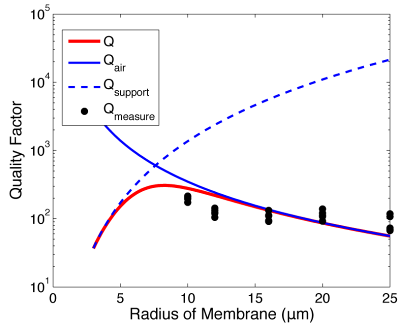

Figure 6. Estimated quality factor of silicon membrane of 0.5 μm thickness and measured quality factor

has been researched empirically and analytically [5]. The $Q_{support}$ can be expressed as follows.

$$Q_{support} = \gamma \left(\frac{L}{t} \right)^3 \tag{9}$$

where γ is proportionality constant. This relation is valid for both clamped-free and clamped-clamped resonator. The CMUT is similar to the clamped-clamped cantilever since the circular membrane is supported by circular oxide posts at the edge. Thus, we apply a similar relation to $Q_{support}$ in the next section.

III. AIR LOSS OF CIRCULAR MEMBRANE

A. *Modeling*

We perform finite element analysis (FEA) on fabricated CMUT membrane based on commercial FEA tool, ANSYS™. The details of the FEA methods are described in [6]. In this paper, we used harmonic analysis on the 2D axisymmetric mode. Due to the liquid-solid interaction, the resonating membrane dissipates energy and it generates sound pressure. Based on current flow through transducer elements, the input impedance is calculated. In addition, the membrane displacement is simulated based on the center point of membrane at 1 mV_{AC} input. Fig. 2 shows that the resonant frequency decrease as applied bias voltage increases due to the spring softening effect.

Q can be derived at three different points; Q_{oc}, Q_{sc} and $Q_{membrane}$. Each Q can be calculated from peak frequency and 3dB bandwidth of impedance, admittance and membrane displacement in frequency domain. Q_{oc}, Q_{sc} and $Q_{membrane}$ are identical, when they are in same frequency.

According to (8), quality factor of a CMUT membrane is proportional to the resonant frequency. Fig. 3 shows the relationship between Q_{air} and f of a circular silicon membrane with thickness of 0.5 μm. Q_{air} calculated from FEA well matched with theoretical Q_{air} based on (8).

B. *Exprimemtal methods*

Q_{air} is estimated by measuring the membrane displacement as a function of applied AC frequency. An AC actuation voltage, which is superposed on a DC bias voltage, is applied on each CMUT device. At each frequency of AC input, displacement of each membrane is measured by laser interferometer. Applied AC voltage must be controlled to produce a reasonable displacement of the membrane and at the same time, to avoid nonlinear effects.

Five different devices with radii of membranes ranging from 10 μm to 25 μm were measured. In each device, five membranes were randomly selected. Q_{air} is calculated from normalized displacement of each membrane based on (3) (Fig. 4). Based on the measurement, Q_{air}/f is calculated to be 10.4/MHz, which is 41% smaller than the analytical results. .

IV. SUPPORT LOSS OF CIRCULAR MEMBRANE

CMUT with a circular membrane is similar to clamped-clamped beam with all the edges clamped to the substrate. Hao *et. al.*, analytically calculated $Q_{support}$ of such a clamped-clamped beam structure [5]. When elastic wavelength is large compared to beam length (L), $Q_{support}$ of the first mode is as follows.

$$Q_{support} \approx 0.638 \left(\frac{L}{t} \right)^3 \tag{10}$$

For the beam with aspect ratio (L/t) ranging from 70 to 100, $Q_{support}$ range from 5 x 10^4 to 1 x 10^5. The fabricated CMUT has smaller aspect ratios (r/t) ranging from 5 to 50. Thus $Q_{support}$ becomes the second dominant factor compared to other loss mechanism. Further, the support substrate of CMUT is not considered as an infinite block. The membrane is only supported at the bottom side, thus support substrate can be considered to be softer. In addition, the membrane is supported by silicon oxide with tapered angle (Fig. 1), thus $Q_{support}$ of a

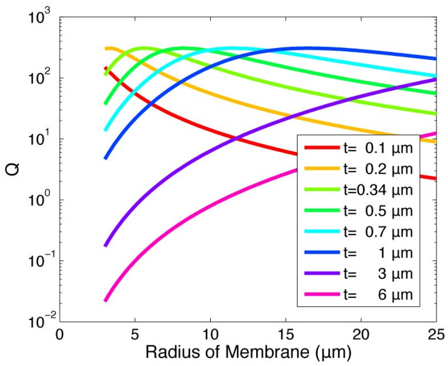

Figure 7. Estimated quality factor of silicon membranes with different thicknesses.

CMUT can be smaller than the beam used in [5] even with a similar aspect ratio.

In order to eliminate Q_{air}, which is the dominant factor at the atmospheric pressure, the device was measured in a vacuum chamber to eliminate the most dominant loss mechanism (*e.g.* air damping). Electrical input impedance was measured in various pressures, where Q is calculated from the peak at open circuit resonance. When the pressure is less than 10 torr, Q saturates as shown in Fig. 5. Measured $Q_{support}$ of the device with a silicon membrane of radius of 9 μm and thickness of 0.5 μm is 1000.

V. Quality Factor Optimization

Quality factor of a circular membrane is expressed as follows, if air loss and support loss are two dominant factors.

$$Q_{air} = \alpha\left(\frac{t}{r}\right)^2 \tag{11}$$

$$Q_{support} = \beta\left(\frac{r}{t}\right)^3 \tag{12}$$

$$Q = \left(\frac{1}{\alpha}\left(\frac{r}{t}\right)^2 + \frac{1}{\beta}\left(\frac{t}{r}\right)^3\right)^{-1} \tag{13}$$

Q_{air} of a circular silicon membrane of CMUT is estimated based on analytical solution and $Q_{support}$ is calculated from the measurement. For a circular silicon membrane with thickness of 0.5 μm, Q is estimated to be the maximum when the radius is 8.2 μm with a resonant frequency of 29 MHz (Fig. 6).

In general, Q is maximized at a certain aspect ratio when two dominant losses have the same magnitude. The optimal aspect ratio of the membrane and calculated Q are as follows.

$$\left(\frac{r}{t}\right)_{optimal} = \sqrt[5]{\frac{3\alpha}{2\beta}} \tag{14}$$

$$Q = \left(\frac{2^{0.4}3^{0.6}}{5}\right)\alpha^{0.6}\beta^{0.4} \approx 0.51\alpha^{0.6}\beta^{0.4} \tag{15}$$

Fig. 7 shows Q of several circular membranes with different thicknesses. When the membrane becomes thinner, the optimal radius becomes smaller. With the optimal design to maximize Q, the expected resonant frequency is

$$f_{optimal} \propto \frac{\left((r/t)_{optimal}\right)^{-2}}{t} \propto \frac{1}{t}. \tag{16}$$

Thus, a thinner membrane requires a higher frequency, which implies higher Q.

VI. Conclusion and Future Work

We modeled and measured two dominant loss mechanisms for CMUT: air loss and support loss. Since both of the losses depend on the dimension of the resonator, there is an optimal design to maximize quality factor at a given thickness of material or resonant frequency. We plan to examine support loss in more details and derive an analytic model for support loss in axisymmetric coordinate. In addition, support loss mechanism of the design made of multiple materials, such as silicon membrane on oxide support, should be investigated numerically and analytically, followed by measurement of support loss for CMUTs with different radii and thickness of membrane.

VII. Acknowledgment

This work was funded by DARPA's MTO office under contract number: N66001-06-1-2030. Work was performed in part at the Stanford Nanofabrication Facility (a member of the National Nanotechnology Infrastructure Network), which is supported by the National Science Foundation under Grant ECS-9731293.

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