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High Sensitivity and Wide Bandwidth Airborne CMUTs with Low Driving Voltage

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***Abstract*—This paper presents a novel method to significantly broaden the bandwidth of airborne capacitive micromachined ultrasonic transducers (CMUTs) by introducing a gaseous squeeze film as a damping mechanism. The damping and stiffening effects of the squeeze film can be tuned to lower the pull-in voltage while improving the sensitivity by optimizing fluidic trenches of various heights within the gap. By only adjusting the trench height, we can control the bandwidth from 0.89% to 8.1% while keeping the pull-in voltage under 55 V and achieving the minimum detectable pressure (MDP) from 2.2 µPa/√Hz to 4.88 µPa/√Hz. We also present a vacuum CMUT with high sensitivity and extremely low MDP as low as to 1.2 µPa/√Hz with 0.93 kHz bandwidth, in which a thick plate is chosen to reduce the geometric nonlinearity. This demonstration of the high sensitivity and wide bandwidth CMUTs with low driving voltage make them applicable to medical imaging, thermoacoustics, and nondestructive testing.**

Keywords*—*CMUTs, squeeze film, high sensitivity, wide bandwidth, low driving voltage

I. Introduction

Capacitive Micromachined Ultrasonic Transducers (CMUTs) have emerged as an alternative to piezoelectric transducers, offering advantages such as wide bandwidth, ease of fabricating large arrays, and easy integration with supporting electronic circuits. As such, CMUTs are ideal for applications in medical imaging, therapeutics, chemical sensing, and air-coupled ultrasound. In airborne applications, both high sensitivity and wide bandwidth are desired. Conventional vacuum CMUTs have high sensitivity but with limited bandwidth [1]. As such, attempts have been made to widen the bandwidth. For example, Zhang *et al.* used a thin plate to broaden the bandwidth of a CMUT array [2]. Unlugedik *et al.* employed the stiffening effect created by atmospheric pressure to improve the bandwidth [3]. Kupnik *et al.* designed a CMUT array with different sizes connecting in parallel to get a larger bandwidth at the expense of gain and transducer size [4]. Apte *et al.* explored a gaseous squeeze film to broaden the bandwidth [5]. However, introducing the squeeze film results in a significant decrease in sensitivity and dramatic increase in the pull-in voltage.

In this paper, we present a novel method to widen CMUT bandwidth while obtaining high sensitivity. This method is based on tuning the damping and stiffening effects of the squeeze film by creating and optimizing fluidic trenches in the substrate. The gap height can be lowered to the order of 1.0 µm, reducing the driving voltage significantly. Based on the optimal design, the fractional bandwidth can be easily controlled by merely changing the trench height. A vacuum CMUT with a thick plate was also designed to improve the receive sensitivity. Finally, the designed CMUTs with different sensitivity and bandwidth have all been fabricated on a single wafer based on our multilayer hard mask microfabrication technology.

II. Equivalent Circuit Modeling

A. Small-Signal Equivalent Circuit

A CMUT is a variable capacitor coupled to an acoustic medium, which consists of a flexible plate, an insulation layer, and a fixed substrate, as shown in Fig. 1 (a). In typical operation, the CMUT is biased with a direct current (DC) voltage, which generates an electrostatic force that deflects the flexible plate towards the substrate and forms an active capacitor. Based on Mason's theory, under a small AC voltage or acoustic pressure, a conventional CMUT can be modeled as a small-signal equivalent circuit [6], as shown in Fig. 1 (c) without added squeeze film. In the equivalent circuit model, the mechanical impedance consisting of the equivalent mass and spring is represented by an inductor and a capacitor, respectively. The acoustic impedance comprising of a damping load R_m and a mass load m_m is described as the medium resistance and inductance. According to the equivalent circuit model, the

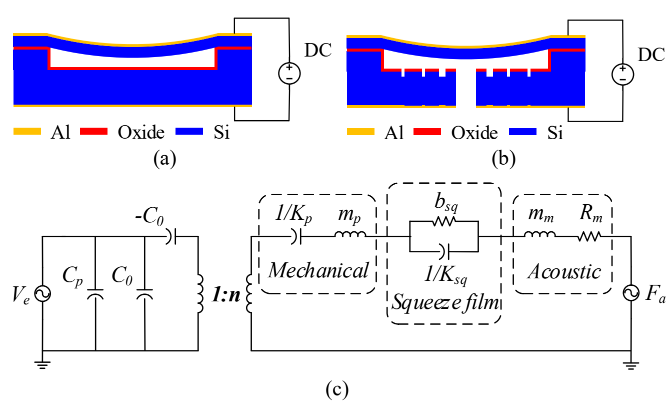

Fig. 1. Schematic of (a) a vacuum CMUT and (b) a vented CMUT, and (c) the equivalent circuit model with added squeeze film.

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transfer function of a conventional CMUT can be derived in the transmit mode by setting the acoustic source F_a to zero, or in the receive mode by setting the electrical source V_e zero. The maximum transmit and receive sensitivities occur at their resonant frequencies are given by [6]

$$\begin{aligned} S_{Tx,\max} &= n/A_{plate} \\ S_{Rx,\max} &= nA_{plate}/R_m \end{aligned}, \tag{1}$$

where $n = E_0 C_0$ is the electromechanical transformer ratio, which represents the energy conversion efficiency. E_0 is the strength of the electric field at the given DC bias. The maximum transmit and receive sensitivities mainly depend on the transformer ratio. Therefore, increasing the transformer ratio remains the primary means of improving sensitivities. Here we choose a thick plate to reduce the geometrical nonlinearity, at the meanwhile, lowering the gap height under 1.0 μm to significantly improve the receive sensitivity.

The fractional bandwidth FBW is

$$FBW = \frac{R_m}{\sqrt{m_{tot} K_{tot}}} \tag{2}$$

where the total mass m_{tot} includes the medium and equivalent plate mass, while the total spring stiffness K_{tot} consists of the equivalent plate stiffness and the electrostatic spring softening effect. To achieve a wider bandwidth, one could design a CMUT with a thinner plate that yields a smaller mass but results in a lower sensitivity. Adding other damping sources may become an alternative way to broaden the bandwidth without sacrificing its sensitivity.

B. *Gaseous Squeeze Film Damping*

The motion of a Micro-Electro-Mechanical Systems (MEMS) structure can be significantly affected by the surrounding gas or fluid. When the gas film is on the order of micrometers, the squeeze film dominates the dynamic behavior of the microstructures [7]. Here we take advantage of the damping effect of the squeeze film to broaden the bandwidth in CMUTs. As Fig. 1 (b) shows, the squeeze film is introduced by venting through the cavity and creating fluidic trenches in the substrate. According to the normalized Reynolds equation and the Laplace transform of the spring-mass-damper system, the squeeze film can be modeled as a lumped spring-damping mechanical system after neglecting the mass of gas molecules [8]. Then it can be converted into a resistor b_{sq} in parallel with a capacitor $1/K_{sq}$ in the equivalent circuit.

By replacing R_m with $R_m + R_{sq}$ in (2), the bandwidth can be re-written as

$$FBW = \frac{R_m + R_{sq}}{\sqrt{m_{tot} K_{tot}}}, \tag{3}$$

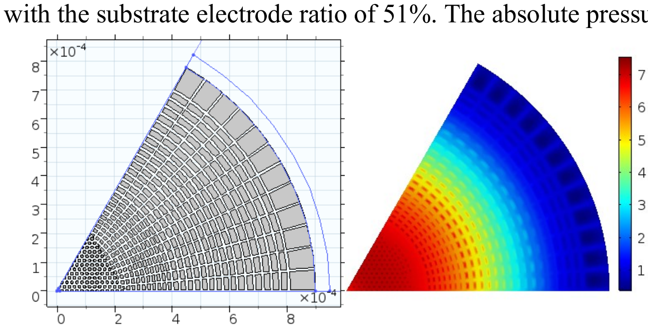
where R_{sq} is the resistance derived from the squeeze film, and the total spring constant K_{tot} consists of the stiffness of the equivalent plate, electrostatic spring softening effect and squeeze film stiffening effect. For low frequencies, the squeeze film acts as a viscous damper with damping constant b_{sq}. For high frequencies, the squeeze film acts as a spring in which the stiffness can be written as $K_{sq} = 2.15 P_a r_0^2 / g$. The squeeze number determines the proportion of the damping and stiffening component. The higher the squeeze number, the harder it is for the fluid to move in and out of the film gap. Hence the squeeze force mostly contributes to stiffening of the squeeze number. For a lower squeeze number, the squeeze force mostly contributes to damping. Therefore, we could tune the damping and stiffening effects in the squeeze film to control the bandwidth and sensitivity of CMUTs.

III. Design and Fabrication

To increase the sensitivity, a thick plate is chosen to decrease the geometrical nonlinearity. Therefore, we can design a vacuum CMUT with a great quality factor of more than 135 without the geometric stiffening effect. To broaden the bandwidth, the squeeze film was introduced and fluidic trenches were created and optimized. The distribution of the absolute pressure caused by the squeeze film on the substrate is nonuniform. It can be divided into three regions: the central region, which is the most active; the middle region (i.e., the linear region); the edge region (i.e., the dead region). The most active region contributes to the most significant vibration, thus resulting in a higher pressure on the substrate. Also, this region provides the most significant output pressure. In the linear region, the absolute pressure on the substrate behaves linearly in relationship with the radius and has a decreasing trend. The dead region has nearly no contribution to the output pressure and pull-in voltage, but contributes to the most parasitic capacitance. According to this distribution map, the optimization of fluidic trenches also can be divided into three types of structures to make the most effective use of the area of the substrate electrode.

A. *Design of Fluidic Trenches*

Increasing the gap height to adjust the damping effect of the squeeze film will increase the pull-in voltage significantly. On the contrary, reducing the gap height will make the stiffening effect dominate the behavior of the squeeze film, which causes the resonant frequency to increase significantly. As such, a circle array of cylindric micropillars is an efficient way to tune the stiffening and damping effects with the same distribution of the perforated holes [9], as shown in Fig. 2 at the center of the CMUT cell. Micropillar array trenches can make the gap height lower than 1.0 μm, but keep the resonant frequency as designed with the substrate electrode ratio of 51%. The absolute pressure



(a) (b)

Fig. 2. Hybrid fluidic trenches. (a) Distribution and (b) absolute pressure on the surface of the substrate electrodes.

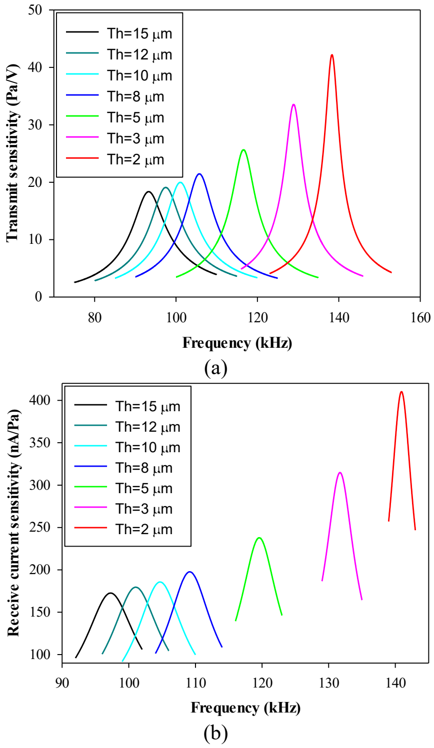


Fig. 3. (a) Transmit sensitivity and (b) receive current sensitivity versus frequency. *Th means trench height

can consequently be lowered to one-tenth of that without fluidic trenches in the substrate. To make full use of the substrate electrode, a fan-shaped structure is used at the periphery of the CMUT cell, which can make the area of the electrode be adjusted nearly linearly with the radius. The fan-shaped fluidic trenches significantly improve the uniformity of the absolute pressure on the substrate at the linear region. The area ratio of the electrode can be increased to 88%, which in turn reduces the pull-in voltage further. The hybrid fluidic trenches combining the micropillar array and fan-shaped fluidic trenches can reduce the squeeze film most effectively while maintaining a large electrode area. The area ratio of the electrode reaches 86%, which decreases 10% of the pull-in voltage further. Fig. 2 also shows that the absolute pressure on the surface of the hybrid fluidic trenches distributes much more uniformly.

B. Optimization Results

After optimizing the geometry and distribution of the fluidic trenches, the trench height is used as a unique control parameter to tune the damping effect, and thus, control the bandwidth of the vented CMUTs. Fig. 3 shows the transmit and receive sensitivities as a function of the trench height. By increasing trench height, the transmit and receive sensitivities both reduce gradually. Accordingly, the bandwidth would increase significantly. The fractional bandwidth can be improved from 0.74% to 7.4% at the cost of compromising some sensitivity.

C. Fabrication

We have developed a novel multilayer hard mask microfabrication process [8], in which CMUTs with different sensitivity and bandwidth, i.e., different cavities and trench heights can be fabricated on a single wafer. This is typically not

TABLE I.
PARAMETERS OF THE VACUUM AND VENTED CMUTS

Parameter	Value			
	Vacuum CMUT	*Vented CMUTs*		
Plate radius (μm)	1500			
Plate thickness (μm)	50.5			
Gap height (μm)	6.4	1.01		
Oxide thickness (μm)	0.93			
Trench height (μm)	0	0	7.6	14.3

possible as the cavities and trenches for the entire wafer are defined by a single etch. The developed process is based on the wafer-bonding technology, which provides the advantage of low residual stress and uniform plate thickness. We could successfully fabricate devices that are very close to the design values. The deviation from the desired values for the gap height is less than 1%, and the maximum variation for the trench etching is less than 3%. The parameters are listed in Table I.

IV. CHARACTERIZATIONS

To verify the design theory, we have conducted impedance measurements and maximum sensitivity tests, then compared these results with finite element method (FEM) simulations. The comparison is made at the same percentage of DC bias of the pull-in voltage.

A. Pull-in Voltage

Fig. 4 shows that the measured pull-in voltage has been lowered to less than 55 V, which is 3.0 times lower than the previous design [9]. Due to the residual stress in the SOI wafer, the fabricated plate bows up around 0.1 μm, which results in approximately a 10% higher pull-in voltage. The pull-in voltage does not change much with the trench height because the area of the substrate electrode stays nearly fixed. Low pull-in voltage makes these wide-bandwidth CMUTs a feasible choice for medical imaging, as well as smart wearable/implantable medical devices, which requires low power consumption.

B. Maximum Displacement Sensitivity

The maximum displacement sensitivities were measured by Laser Doppler Vibrometer (LDV, Polytec OFV 2700 and OFV 511). As Fig. 5 shows, the displacement sensitivities for the vacuum and vented CMUTs matched the FEM simulation results very well. The vacuum CMUT has the highest sensitivity but with narrow bandwidth. The bandwidth of the vented CMUTs has been widened significantly by introducing

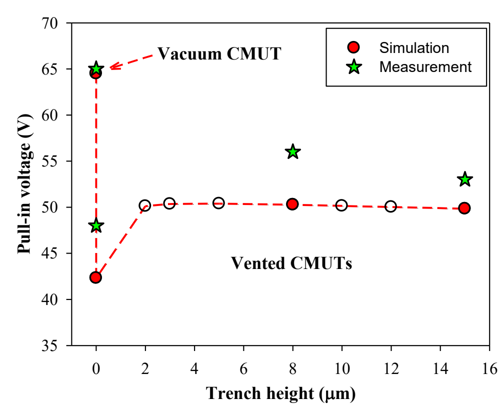


Fig. 4. Pull-in voltage versus trench height.

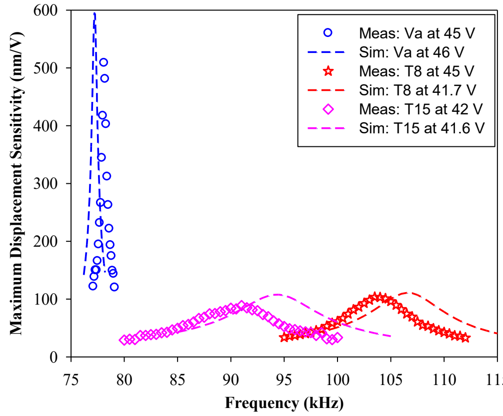


Fig. 5. Measured maximum displacement sensitivity of the vacuum and vented CMUTs with 7.6 µm and14.3 µm trenches and comparison with simulations.

squeeze film, from 0.89% to 8.1% when increasing the trench height. By increasing the DC bias, the sensitivities of the vented CMUTs can be improved. However, the resonant frequency would shift to a lower frequency, which is caused by the so-called electrostatic spring softening effect. We can offset this effect by increasing the stiffening effect of the squeeze film.

C. *Minimum Detectable Pressure*

According to the equivalent circuit, the minimum detectable pressure (MDP) in receive mode is associated with the noise contribution of the medium damping and the squeeze film damping. Based on the measured impedance, the MDP of the fabricated vacuum CMUT is as low as 1.20 µPa/√Hz with a 0.93 kHz bandwidth. The MDP of the vented CMUTs is 4.77 µPa/√Hz with a 6.24 kHz bandwidth for the vented CMUT with 7.6 µm fluidic trenches at the DC bias of 80% of the pull-in voltage, while the MDP is 4.88 µPa/√Hz with a 7.48 kHz bandwidth for the vented CMUT with 14.3 µm. These values well match the simulation results.

V. Conclusion

We have developed a novel method to broaden the bandwidth of airborne CMUTs, in which a gaseous squeeze film is used as a damping mechanism. By optimizing fluidic trenches with various heights, the behavior of the stiffening effect versus the damping mechanism of the squeeze film can be controlled. We also designed a high sensitivity vacuum CMUT with a thick plate to reduce the geometrical nonlinearity. Finally, the various CMUTs with different sensitivity and bandwidth were fabricated on the same wafer using a multilayer hard mask microfabrication process. The measured pull-in voltage, electrical impedance and maximum displacement sensitivity agree well with theory and FEM simulations. The designed high sensitivity and bandwidth CMUTs with low driving voltage are capable of detecting weak signals for applications in biomedical and thermoacoustic imaging, as well as in nondestructive testing.

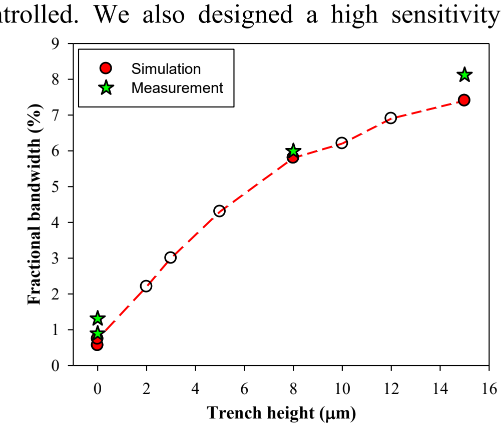


Fig. 6. Fractional bandwidth versus trench height.

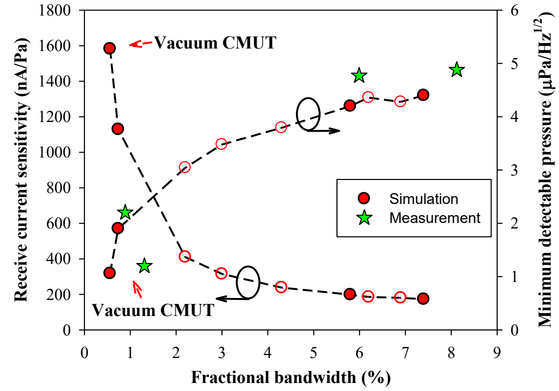


Fig. 7. Receive current sensitivity and minimum detectable pressure versus fractional bandwidth.

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