A Double-Layer Capacitive Micromechanical Ultrasonic Transducer

Weipeng Ren[1, a], Zhaohui Xiao[1, b], Jie Li [1, c*], Kuiwei Shi[1, d], Yihe Zhao,[2, e] and Zhikang Li [2, f] [1]

[1] College of Mechanical and Electrical Engineering, Shaanxi University of Science and Technology, Xi'an, 710021, China;

[2] State Key Laboratory for Manufacturing Systems Engineering, International Joint Laboratory for Micro/Nano Manufacturing and Measurement Technologies, Xi'an Jiaotong University, Xi'an, 710049, China.

ABSTRACT.

CMUTs are characterized by high electromechanical coupling coefficients and high sensitivity to ultrasonic emission, and the develop deeply in medical ultrasound imaging, non-destructive testing and other medical fields. However, the safety hazards brought by high voltage and the shortcomings of high power loss limit the scope of its application. Therefore, how to reduce the operating voltage of CMUTs are the key to realizing their application in portable, low-power and long-term online inspection. In this manuscript, a low-power and double-layer CMUTs cells structure are proposed, in which the circular CMUT cells are on the top part and annular CMUT structural cells are on the bottom part. When the DC bias voltage is loaded, it forms a bending moment at the top pillar, under its influence, the bottom unit produces a displacement. Consequently, the electrostatic deformation of the CMUTs are increased, which makes the ultrasonic transducer have a lower collapse voltage. Ultimately, the effect of reducing the collapse voltage and power consumption without changing the height of the cavity is achieved. In this manuscript, the advantages of double-layer CMUTs are verified by simulation.

Keywords: Dual-layer CMUTs; low collapse voltage; low power consumption.

1. INTRODUCTION

With the rapid rise of micro-electro-mechanical system technology, capacitive micromachined ultrasonic transducers and piezoelectric micromachined ultrasonic transducers have been developed rapidly. They not only effectively overcome the traditional piezoelectric ceramic ultrasonic transducers in fluid and human tissue applications of acoustic impedance mismatch, small bandwidth, two-dimensional arrays, such as the preparation of difficulties, but also has a miniaturisation, integration (and ICs integration), and batch low-cost preparation and other outstanding advantages, has rapidly become the mainstream of the current ultrasonic transducer research.

The research team led by Professor Khuri-Yakub of the Department of Electrical Engineering at Stanford University first reported the CMUTs prototype in 1994 [1]. The domestic research started relatively late, but under the leadership of research teams such as Xue C Y [2] from North Central University and Zhang H [3] from Tianjin University, the domestic research related to CMUTs has also gained great progress. Along with the development of MEMS technology, scholars in various countries have designed various CMUTs structures and proposed new control and excitation methods to reduce the collapse voltage and power consumption of CMUTs. Yaralioglu G. G. et al [4] proposed an expression for the calculation of the electromechanical coupling coefficient by using the ratio of fixed capacitance CS and free capacitance CT and introduced parasitic capacitance CP. It was shown that the larger the bias voltage, the higher the electromechanical coupling coefficient and the better the electromechanical conversion efficiency. Therefore, CMUTs usually apply sufficient DC bias voltage (80%~90% of collapse voltage) between the upper and lower electrodes to improve the electromechanical coupling characteristics of CMUTs, thus enhancing the ultrasonic transmission power. However, too high bias voltage will bring production safety risks, high power consumption, and other disadvantages. For this reason, the collapse voltage is usually reduced during the design process with a view to reducing the power consumption while ensuring the high electromechanical coupling efficiency of CMUTs. According to the computational expression for the collapse voltage of CMUTs [5,6], The main way to reduce the collapse voltage is to increase the size of the membrane or reduce the cavity height. For example, Canadian Zemp R. J. et al [7] used the addition of an

[1] [a]rwpeng@126.com, [b]2621864916@qq.com, [c*]lijie@sust.edu.cn, [d]s17691003997@163.com, [e]johnzhaoyihe@stu.xjtu.edu.cn, [f] zhikangli@xjtu.edu.cn

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electrode post in the low part of the cavity to reduce the relative cavity height to achieve the purpose of reducing the operating voltage and improving the electromechanical coupling efficiency. However, increasing the size of membrane will significantly reduce the operating frequency of CMUTs, reduce the number of cells under the same array area conditions, and thus reduce the ultrasonic emission characteristics of CMUTs, however, reducing the cavity height will limit the vibration amplitude of the membrane, limiting the ultrasonic emission performance, and will also increase the difficulty of preparation. Therefore, the difficulty of realizing the low power consumption of CMUTs lies in how to reduce the collapse voltage of CMUTs while ensuring the cavity height.

For this reason, this paper proposes a low-power and double-layer CMUTs, which can achieve the reduction of collapse voltage and power consumption without changing the cavity height. The advantages of the double-layer CMUTs are verified by simulation.

2. DESIGN AND MODEL

2.1 Structural comparison

The traditional CMUTs have fixed pillars, as shown in Figure. 1, which do not undergo electrostatic deformation and vibration under electrostatic excitation. With this structure, the vibration frequency will be higher and the collapse voltage will be larger due to the very high stiffness. Therefore, it needs to be loaded with a larger operating voltage during normal operation and causes greater power consumption.

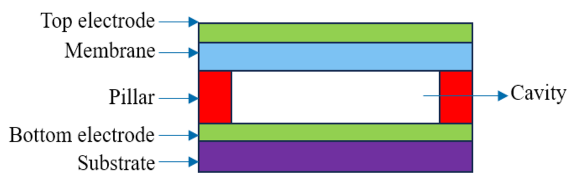


Figure. 1 Traditional CMUTs structure

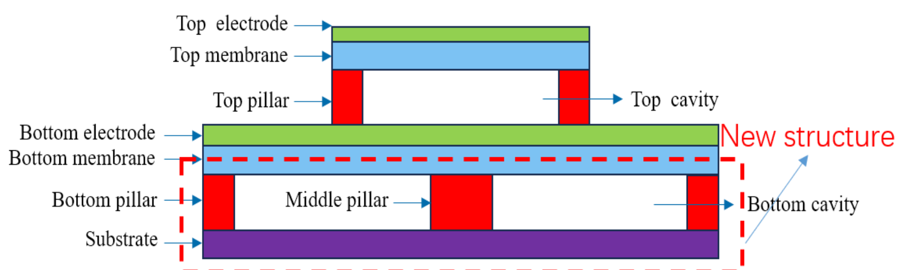


Figure. 2 Double-layer CMUTs structure

The top pillar of the double-layer CMUTs is movable and the bottom pillar is fixed, as shown in Figure. 2. the top of the double-layer CMUTs is a circular CMUTs unit, which is similar to the traditional CMUTs, and the bottom is a ring-shaped CMUTs structural unit, which forms a bending moment at the top pillar when loaded with a DC bias voltage loading, and under the influence of the pillar, the bottom membrane undergoes deformation, which then increases the electrostatic deformation of the CMUTs, and induces the ultrasonic transducer to collapse at a lower voltage, which achieves the effect of lowering the collapsing voltage and reducing the power consumption without changing the height of the cavity.

2.2 Model and analysis.

In order to validate the benefits of bilayer CMUTs, this paper is simulated with the help of COMSOL 6.1 software, and the parameters used in the model throughout the process are shown in Table 1.

In order to make a comparative analysis between the traditional CMUTs and the double-layer CMUTs, two models are built separately in COMSOL 6.1 software in this paper. Since the two CMUTs are circular and completely symmetric, axisymmetric models can be directly established, as shown in Figure. 3, where the blue area represents the water area. In order to obtain more accurate results, both models are single-layer immersed in the water area with the same electrostatic field and basically the same mesh division. The double-layer CMUTs top round CMUTs unit is also the same size as the traditional CMUTs.

Table 1 Parameter setting

Parameter	Value	Parameter	Value
Top Si membrane Radius (um)	50	Top Si membrane Thickness (um)	1
Bottom Si membrane Radius (um)	100	Bottom Si membrane Thickness (um)	1
Si substrate Radius	100	Si substrate Thickness	1
Density of Si	2332kg/m^3	Poisson's ratio of Si	0.28
Young modulus of Si	130GPa	Relative permittivity of Si	11.7
Top SiO_2 Post Width	5	Top SiO_2 Post Height	0.5
Bottom SiO_2 Post Width	5	Bottom SiO_2 Post Height	0.5
Middle SiO_2 Post Radius	5	Middle SiO_2 Post Thickness	0.5
Density of SiO2	2200 kg/m^3	Poisson's ratio of SiO2	0.17
Young modulus of SiO2	70GPa	Relative permittivity of SiO2	4.2
Top Cavity Radius	45	Top Cavity Thickness	0.5
Bottom Cavity Width	90	Bottom Cavity Thickness	0.5
Density of water	1000 kg/m^3	The velocity of water	1500m/s

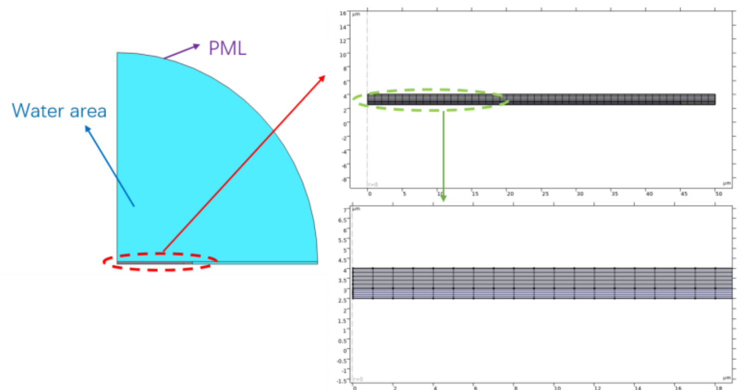


Figure. 3(a) Traditional CMUTs model

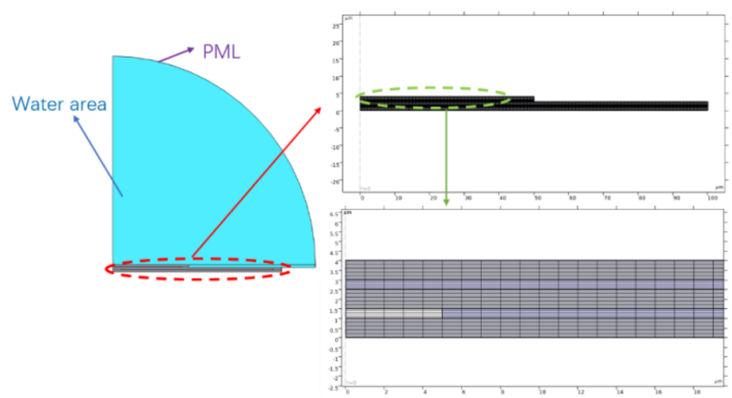


Figure. 3(b) Double-layer CMUTs model

3. RESULTS AND DISCUSSION

3.1 Collapse voltage

The collapse voltage is a key parameter in achieving low power consumption, the smaller the collapse voltage, the smaller the DC operating voltage and thus the lower the power consumption. As shown in Figure. 4, the larger the voltage, the larger the center deformation of both structures. The collapse voltage of the traditional CMUTs is 33.4 V, and the collapse voltage of the double-layer CMUTs is 25.5 V, The reduction of the collapse voltage is 23.7%. The double-layer CMUTs greatly reduce the collapse voltage, of course, we can also adjust the size of the double-layer CMUTs to reduce the ratio of collapse voltage reduction even more, and at the same time, the displacement of the double-layer CMUTs is larger than that of the traditional CMUTs at the same voltage.

The main reasons for the decrease of collapse voltage are as follows: 1, When DC bias voltage is loaded, a bending moment is formed at the top pillar, and the bottom membrane deforms under the influence of the pillar. thereby the electrostatic deformation of CMUTs is increased, which causes the collapse of the ultrasonic transducer under lower voltage. 2, the fixed way changes, the top pillar becomes mobile, stiffness decreases, which is also one of the reasons for the reduction of collapse voltage.

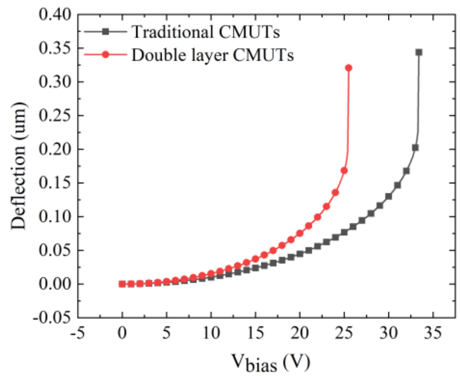


Figure. 4 Center deformation under different bias pressures

3.2 Frequency

For different bias DC voltage under the resonance frequency shown in Figure 5, due to the reduction of stiffness, the frequency of the double-layer CMUTs will be lower than the frequency of the traditional CMUTs, in order to achieve the effect of low-power consumption, the general requirements of the sensor has a low resonance frequency, for the traditional CMUTs, it needs to increase the cost of upgrading the membrane thickness in order to reach the requirements, while the double-layer CMUTs, you can easily meet the requirements, and at the same time have the advantages of low collapse voltage, low power consumption and low cost. Of course, the lower frequency may reduce the sensitivity of the sensor.

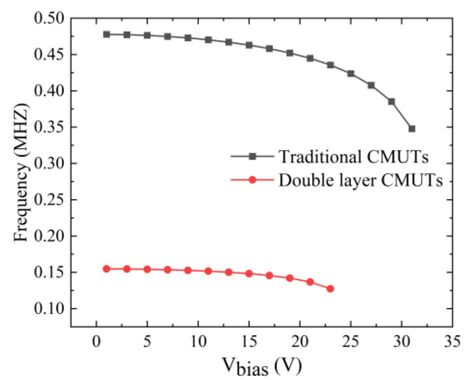


Figure. 5 Resonant frequencies for different bias voltages

3.3 Amplitude

The harmonic response analyses of the two models were carried out separately by loading 20 V DC voltage and 0.5 V AC voltage at the same time to obtain the different amplitudes of the two models at the resonant frequency. As shown in Figure. 6, when loaded with DC bias voltage loading, the double-layer CMUTs form at the pillars will form a bending moment, and under the influence of the pillars, the lower membrane is displaced, which in turn increases the electrostatic deformation of the CMUTs. Traditional CMUTs cannot be displaced downward by the pillar because the pillar is fixed. At the same time the reduced stiffness of the double-layer CMUTs leads to easier deformation of the upper membrane of the double-layer CMUTs.

According to the plate and shell theory, the displacement relation equation for bilayer CMUTs can be established as

$$w(r_1) = w_c(r_1) + w_p(r_1) \quad (1)$$

$$w(r_2) = w_c(r_2) \quad (2)$$

$$w_c(r_1) > w_c(r_2) \quad (3)$$

where $w(r_1)$, $w_c(r_1)$, $w_p(r_1)$ are the total displacement, top membrane deformation and top pillar displacement of bilayer CMUTs, respectively, where $w(r_2)$, $w_c(r_2)$ are the total displacement, membrane deformation of traditional CMUTs, respectively.

According to formula (1), (2) and (3), the amplitude of double-layer CMUTs is larger than that of traditional CMUTs.

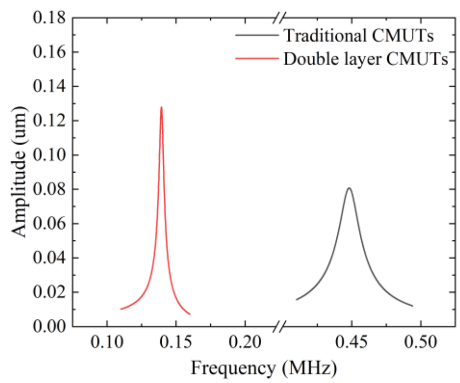
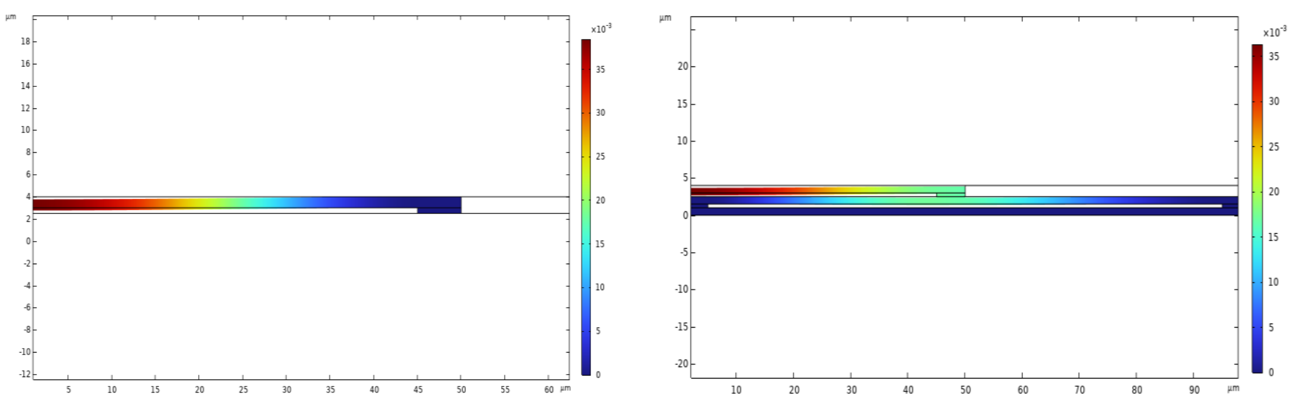


Figure. 6 Amplitude at resonant frequency



(a) Traditional CMUTs

(b) Double-layer CMUTs

Figure. 7 COMSOL model 2D displacement diagram

The amplitudes of the resonant frequencies of the two CMUTs at the same voltage are shown in Figure. 6, and the amplitudes of the bilayer CMUTs are larger than those of the traditional CMUTs. Meanwhile, the simulation results of the double-layer CMUTs model in Figure. 7(b) verified that the pillars were movable and the lower membrane was displaced.

4. CONCLUSION

In this paper, a double-layer CMUTs is proposed, and two CMUTs models are respectively established for comparative analysis by COMSOL6.1 software, and the results show that the dual-layer CMUTs have a good performance. The double-layer CMUTs have a movable upper pillar compared to traditional CMUTs, so the stiffness of double-layer CMUTs will be lower than that of traditional CMUTs, and the frequency will be reduced. At the same time, when loaded with DC bias voltage loading, a bending moment is formed at the pillar and the lower membrane is displaced under the influence of the top pillar. This in turn increases the electrostatic deformation of the CMUTs, prompting the ultrasonic transducer to collapse at a lower voltage. The effect of reducing the collapse voltage and power consumption without changing the cavity height is achieved.

5. ACKNOWLEDGMENT

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