Micro-electro-mechanical systems capacitive ultrasonic transducer with a higher electromechanical coupling coefficient

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Since the proposing of capacitive micromachined ultrasonic transducer by Khuri Yakub group in 1994 that this kind of transducer occupying the advantages of wide bandwidth, impedance matching well with the propagation medium especially in fluid and air and high sensitivity, has shown a great potential for wide ranges of applications. This Letter reports kind of micro-electro-mechanical systems (MEMS) capacitive ultrasonic transducer with the novel cavities embedded in the device layer of silicon on insulator wafer bonded with a glass substrate. The optimum geometric dimensions are confirmed by both mechanical vibrating of the membrane and the electrical characteristics analysis. Finite-element analysis is adopted to determine the operation mode. The safety and reliability of the proposed device is ensured by the obtained deflections and equivalent stress under operation/collapse voltage. The bottom electrodes of the proposed transducer are fabricated on the top surface of the glass substrate. The parallel parasitic capacitance is reduced, thus improving the electromechanical coupling coefficient. The test results show that the electromechanical coupling coefficient is 69.65%, which demonstrates that this proposed MEMS capacitive ultrasonic transducer structure can enhance the performance significantly.

1. Introduction: Ultrasonic transducer can detect the target with small damages and are widely used in the field of non-destructive evaluation, medical imaging and underwater detection. With the development of micro-electro-mechanical systems (MEMS) technology, which can enable device miniaturisation, the Khuri Yakub group introduced the capacitive micromachined ultrasonic transducer (CMUT) [1] occupying the advantages of impedance matching with propagation medium and wider bandwidth over current piezoelectric transducer [2, 3]. Owing to these advantages, many researchers have designed different kinds of CMUT and studied their characteristics.

Two basic categories of CMUT according to their fabrication methods are: sacrificial processed CMUT [4–8] and wafer-bonding processed CMUT [9–12]. The second-generation CMUT with wafer-bonding methods provide more predictable mechanical properties attributed to precise control over device dimensions, and have a simpler process steps compared with the sacrificial-processing CMUT.

The electromechanical coupling coefficient is an important parameter to take into consideration when designing CMUT. A higher value of this character is preferable. As by definition, it is the ratio of mechanical energy delivered to the stored total energy in the CMUT [13]. Generally, there are three kinds of methods for calculation and measurement of the electromechanical coupling coefficient: parallel plate structure approximating based on electrical field and electric displacement method [14], charge and voltage derivation method [13], and resonant frequency and anti-resonant frequency comparison method [12, 15]. The third method is the most simple and accurate one. We adopt it to measure the electromechanical coupling coefficient in this Letter, because all the parameters for the calculation can be directly measured and no approximations are needed.

In this Letter, we propose a novel CMUT based on wafer-bonding technology. The advantages of the CMUT lie in simple process with vacuum sealed vibrating cavities, low parallel parasitic capacitance and high electromechanical coupling coefficient. The cavities are embedded among the silicon on insulator (SOI) device layer without other supporting materials. The inherent great insulation characteristic of glass substrate and the placement of the patterned electrodes limit the parallel parasitic capacitance to a very low level, which result in the improvement of the electromechanical coupling coefficient to be obtained finally.

In the following sections, we will discuss the design strategy, finite-element analysis (FEA) simulation, and fabrication and testing results for MEMS-based capacitive ultrasonic transducer.

2. Transducer design: The schematic of the MEMS-based capacitive ultrasonic transducer we proposed is presented in Fig. 1. Briefly, the transducer consists of the substrate, bottom and up electrodes, vibrating membrane and the cavities embedded in the post parts for the moving of the membrane.

When the ultrasonic waves come to the membrane biased at a certain operating voltage, the membrane will be forced to vibrate so that the height between the up and bottom electrodes will be changed, which leads to a capacitance variation and an induced electrical current generation.

With the demand of the appropriate operating frequency, herein 350 kHz, we study the vibration characteristic of the membrane.

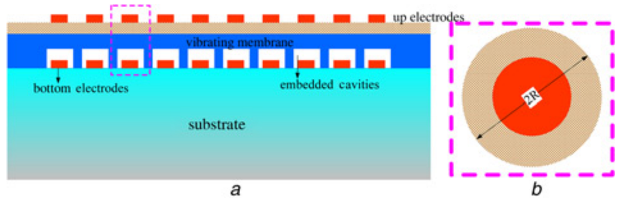

Fig. 1 *Schematic of the MEMS capacitive ultrasonic transducer*
a Cross-section of the sensor
b Top view of the local amplification

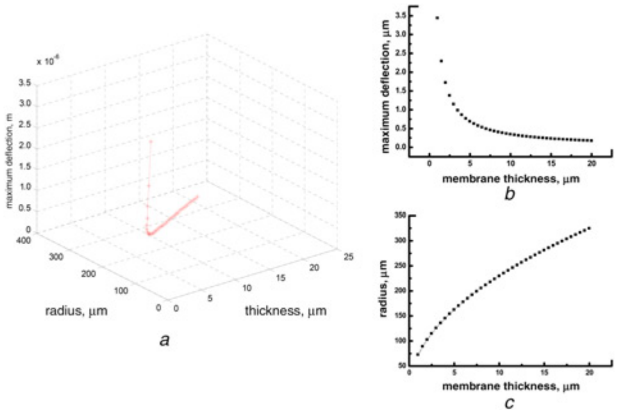

Fig. 2 *Mechanical vibration analysis of the membranes*

The geometric dimensions (membrane thickness and radius) of the vibrating membrane, which are the dominant character, are analysed as depicted in Fig. 2.

The maximum deflection occurring in the middle point of the membrane decreases with the increasing of its thickness in Fig. 2*b*. While Fig. 2*c* shows a group of combinations of membrane thickness and radius that meet the desired operating frequency.

Hence, in order to determine the accurate size of the transducer further, we study the electrical properties of the proposed device. Fig. 3 states that the collapse voltage neither increases nor decreases monotonously with the increase of the membrane thickness or radius, but has a concave point when the thickness and radius of the membrane reaches to 5 and 162 μm, respectively, these numbers are used for the dimensions of CMUT membrane so that the device has the lowest working voltage.

3. FEA simulation and fabrication

3.1. Mode frequency analysis: With the obtained size of the device from the previous part, we utilise the FEA software to simulate the resonant frequencies and vibration modes of the transducer further. The first three-order modes of the structure are shown in Fig. 4.

The first mode is chosen for the operation, because only in this mode the membranes can vibrate up and down alternately and consistently, which are suitable for the transform of ultrasonic waves. The simulation result for the first-order frequency is 347.24 kHz, which is quite consistent with the previous theoretical analysis to meet the required demand.

3.2. Electrical–structural coupling simulation: To analyse the collapse voltage and operation voltage of the proposed device, electrical–structural coupling simulation is performed. During the simulation process, an initial imposed electrostatic force can cause a tiny deflection of the membrane. The new position of the membrane will feedback to the electrostatic force. These two kinds of processes alter until a final equilibrium position of convergence is obtained. We extract the deflection distribution and equivalent stress distribution of the collapse state and operation state, respectively; the results are shown in Fig. 5.

As seen from Fig. 5, when biased at the collapse voltage (121 V), the membrane will make a contact with the bottom electrodes. During the operation mode (72 V), even the maximum equivalent stress of the structure is below 80 MPa, which is far below the fracture strength of silicon. So the safety and reliability of the proposed device can be ensured.

3.3. Fabrication: The capacitive ultrasonic transducer is fabricated using MEMS technology, and Fig. 6 explains the fabrication process in details. Fig. 6*a* shows the cleaning and oxygen plasma processing of the SOI wafer. Fig. 6*b* shows the deposition of the vacuum-seal-line by plasma-enhanced chemical vapour deposition and magnetron sputtering. Fig. 6*c* illustrates the silicon deep etching of the SOI to form cavities. Fig. 6*d* presents the deposition of the lower electrodes by magnetron sputtering. Figs. 6*e* and *f* are the bonding of the processed SOI with glass

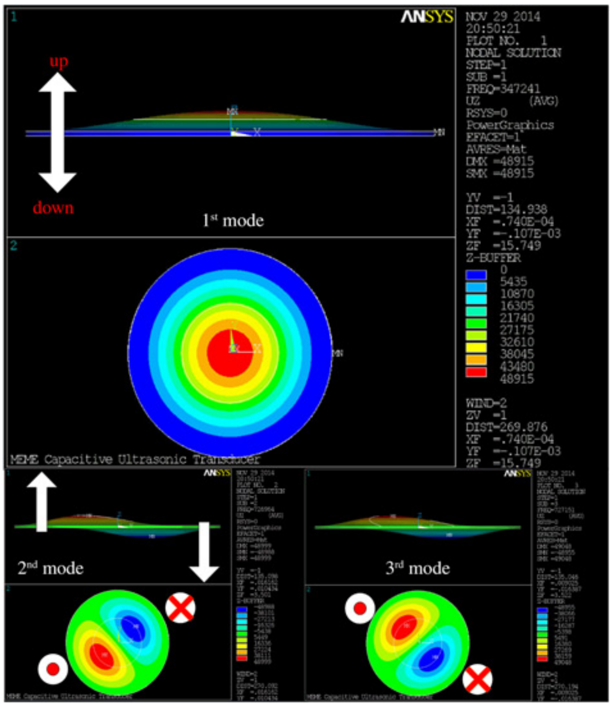

Fig. 4 *First three-order modes of the single cell of the transducer*

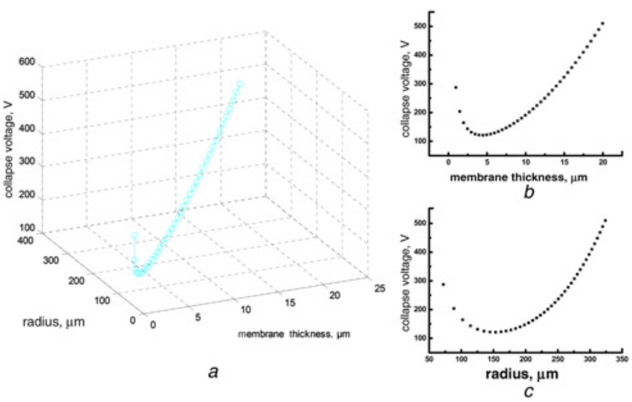

Fig. 3 *Electrical performance analysis of the transducer*

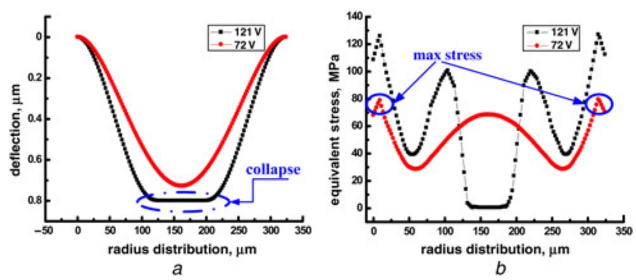

Fig. 5 *Deflection distribution and equivalent stress distribution of the collapse state and operation state*
a Deflection distribution
b Equivalent stress distribution

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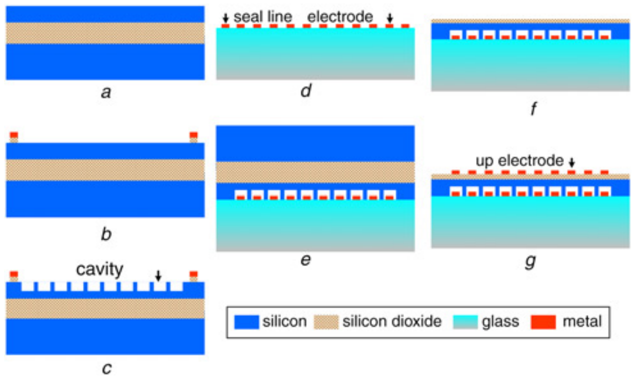

Fig. 6 *Microfabrication process for MEMS capacitive ultrasonic transducer*

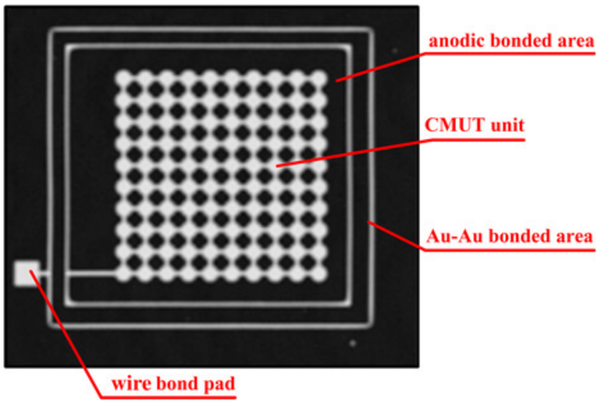

Fig. 8 *SAM image of the fabricated transducer*

wafer and the removing of the handle layer of the SOI. Fig. 6*g* demonstrates the deposition and pattern of the up electrodes and pad.

To monitor the fabricated process carefully, every single step is inspected before going into the next step. Fig. 7 shows the photomicrograph of the transducer during processed, where Fig. 7*a* is the cavities embedded in the device layer of the SOI and Fig. 7*b* is the bottom electrodes on the top of the glass substrate. As known, the glass substrate we used is an electrical insulator at the room temperature. In addition, the bottom electrodes are on the top surface of the glass substrate. So no other parallel parasitic capacitance will come into being of the fabricated device. The low level of this kind of parasitic capacitance may significantly improve the electromechanical coupling coefficient for the CMUT device.

4. Experimental results and discussion: To evaluate the bonding quality of the fabricated device, scanning acoustic microscope (SAM) is utilised. Fig. 8 shows the image obtained from SAM. The bonded areas are in solid black colour. There are no defects or bubbles observed at the bonding interface. This indicates a good bonding quality. The cavities array is vacuum sealed inside the metal bonding line. Meanwhile, the electrical pass from vacuum cavities to the outside is also formed through the metal bonding line.

As mentioned previously, we measure the electromechanical coupling coefficient of the proposed device based on the resonant frequency and anti-resonant frequency comparison method. The value of the electromechanical coupling coefficient (k_T^2) with relation to resonant frequency (f_Y) and anti-resonant (f_R) frequency can be calculated by the formula as [15]

$$k_T^2 = 1 - \left(\frac{f_Y}{f_R}\right)^2 \qquad (1)$$

where f_Y and f_R can be directly measured from the admittance and impedance curves, respectively. The experimental setup is mainly

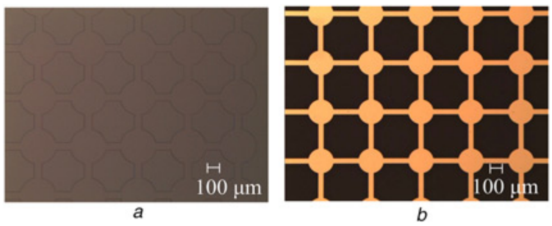

Fig. 7 *Photomicrograph of the transducer during the device fabrication*
a Cavities embedded
b Bottom electrodes

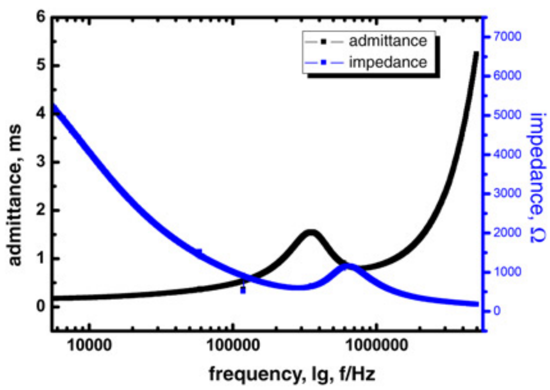

Fig. 9 *Admittance and impedance of the transducer as the function of frequency*

based on the semiconductor parameter analyser (AGLIENT B1500) with its embedded module, multi-frequency capacitance measurement unit. Fig. 9 is the admittance and impedance of the transducer as the function of frequency detected by the semiconductor parameter analyser.

To show the peak value more clearly, the abscissa axis in Fig. 9 is set to be the logarithm coordinate. The electrical anti-resonance frequency is 642.03 kHz, and the electrical resonance frequency is 353.7 kHz. According to formula (1), the electromechanical coupling coefficient is calculated to be 69.65%. This value is much higher when compared with the value found in the literature [12].

5. Conclusion: On the basis of the development of MEMS technology and wide imaging applications, a kind of capacitive ultrasonic transducer with the novel structure and fabricated process has been successfully demonstrated. The design of the key parameters of the device has been confirmed and optimised from both mechanical analysis and electronical analysis in theory. The collapse and operation voltage from the FEA is 121 and 72 V, respectively. Compared with the previous work, the main advantage of the MEMS capacitive ultrasonic transducer in this Letter is its high electromechanical coupling coefficient (69.65%), with a relatively low ratio of imposed voltage to collapse voltage. All the results show that this device with a higher electromechanical coupling coefficient value is quite capable for the further underwater imaging applications.

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7. References

[1] Haller M.I., Khuri-Yakub B.T.: 'A surface micromachined electrostatic ultrasonic air transducer', *Ultrason. Symp.*, 1994, **2**, p. 4
[2] Khuri-Yakub B.T., Oralkan Ö.: 'Capacitive micromachined ultrasonic transducers for medical imaging and therapy', *J. Micromech. Microeng.*, 2011, **21**, pp. 54004–54014
[3] Hansen S.T., Ergun A.S., Liou W., ET AL.: 'Wideband micromachined capacitive microphones with radio frequency detection', *J. Acoust. Soc. Am.*, 2004, **116**, p. 828
[4] Haller M.I., Khuri-Yakub B.T.: 'A surface micromachined electrostatic ultrasonic air transducer', *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, 1996, **43**, p. 6
[5] Spoliansky D., Ladabaum I., Khuri-Yakub B.T.: 'Micromachined ultrasonic air-transducers (MUTs)', *Microelectron. Eng.*, 1996, **30**, p. 4
[6] Soh H.T., Ladabaum I., Atalar A., ET AL.: 'Silicon micromachined ultrasonic immersion transducers', *Appl. Phys. Lett.*, 1996, **69**, p. 3
[7] Johnson J., Oralkan Ö., Demirci U., ET AL.: 'Medical imaging using capacitive micromachined ultrasonic transducer arrays', *Ultrasonics*, 2002, **40**, p. 6
[8] Cianci E., Visigalli L., Foglietti V., ET AL.: 'Improvements towards a reliable fabrication process for cMUT', *Microelectron. Eng.*, 2003, **67–68**, pp. 602–608
[9] Huang Y., Ergun A.S., Haeggstrom E., ET AL.: 'Fabricating capacitive micromachined ultrasonic transducers with wafer-bonding technology', *J. Microelectromech. Syst.*, 2003, **12**, p. 10
[10] Wong S., Kupnik M., Zhuang X., ET AL.: 'Evaluation of wafer bonded CMUTs with rectangular membranes featuring high fill factor', *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, 2008, **55**, pp. 2053–2065
[11] Zhuang X., Lin D.-S., Oralkan Ö., ET AL.: 'Fabrication of flexible transducer arrays with through-wafer electrical interconnects based on trench refilling with PDMS', *J. Microelectromech. Syst.*, 2008, **17**, p. 6
[12] Bellaredj M., Bourbon G., Walter V., ET AL.: 'Anodic bonding using SOI wafer for fabrication of capacitive micromachined ultrasonic transducers', *J. Micromech. Microeng.*, 2014, **24**, p. 12
[13] Yaralioglu G.G., Ergun A.S., Bayram B., ET AL.: 'Calculation and measurement of electromechanical coupling coefficient of capacitive micromachined ultrasonic transducers', *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, 2003, **50**, p. 8
[14] Senturia S.D.: 'Microsystems design' (Kluwer Academic, Pub, Boston, 2001)
[15] Hunt F.V.: 'The analysis of transduction, and its historical background' (Harvard University Press, Cambridge, MA, 1954)

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