Sensors & Transducers, Vol. 178, Issue 9, September 2014, pp. 6-13

Sensors & Transducers

Design and Test of Capacitive Micromachined Ultrasonic Transducer

[1, 2] Hongliang Wang, [1] Xiangjun Wang, [2] Changde He, [2] Chenyang Xue, [2] Jijun Xiong, [2] Wendong Zhang, [2] Jing Miao, [2] Yuping Li

[1] State Key Laboratory of Precision Measuring Technology and Instruments,
MOEMS Education Ministry Key Laboratory, Tianjin University, Tianjin 300072, China
[2] National Key Laboratory for Electronic Measurement Technology,
Key Laboratory of Instrumentation Science & Dynamic Measurement (North University of China),
Ministry of Education, North University of China, Taiyuan 030051, China
Tel: 0351-3557385
E-mail: nucwanghongliang@163.com

Received: 18 June 2014 /Accepted: 29 August 2014 /Published: 30 September 2014

Abstract: Currently, most capacitive micromachined ultrasound transducers, adopting surface sacrificial technology encounter various problems such as difficult cavity etch, low controllability of membrane thickness etc., and their operating frequencies are more concentrated in several MHz bandwidths that cannot meet the requirements of long-distance imaging applications. In order to solve these problems, this paper proposes a new capacitive ultrasound transducer based on Si-Si bonding technology, which consists of an integration vibration membrane requiring no extra separate metal film and having high sensitivity, uniform thickness and more controllable frequencies. This transducer has several great advantages such as: easy processing, simple structure and process technology, and a high degree of integration. The structure and size of the transducer is determined by theoretical analysis and finite element analysis software ANSYS, and a process flow is also presented. Through scanning by SEM and Polytec MSA-400, the processed transducer is tested and analyzed, and the results are consonant with the simulation, verifying the reliability of the design and fabrication. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: MEMS, Capacitive micromachined ultrasonic transducer, Integration vibration membrane, Si-Si bonding technology, Resonant frequency.

1. Introduction

Devices based on a Micro-electro-mechanical system (MEMS), have some advantages such as compact volume, light weight, low power consumption and high integration etc. [1]. It has become a research focus in the ultrasonic transducer image field to introduce MEMS into a capacitive ultrasonic transducer. The capacitive ultrasonic transducers are urgently demanded and widely applied in industrial control, environmental protection equipment, medical equipment, aerospace, military weapons and other fields, so the research on these transducers is of great practical value [2]. In the field of electronic components, a capacitive ultrasonic transducer is an electrostatic transducer that has good usage. An ultrasonic transducer can work in liquids, solids, gases and other mediums. They have been used in medicine diagnosis and treatment, non-destructive testing, sonar,

communications, proximity sensors, flow measurement, real-time process control, ultrasound microscopy and other related fields [3].

Capacitive micromachined ultrasonic transducers (CMUT) is an important research direction of MEMS technology, its acoustic impedance is close to gas and liquid, thus a matching layer is not needed; [4-5] It also has good mechanical and electrical properties and higher resonance frequencies (up to tens of MHz) and a quality factor (up to several hundred); all of these good properties make it possible to achieve high sensitivity and small-scale pressure measurements. Meanwhile, it has such advantages as: simple structure, low cost, mass production, integration of complexity circuits and process compatibility with CMOS, [6] etc. So there is a wide range of applications in underwater ultrasound imaging, seabed resource exploitation, naval security and other fields. However the existing capacitive ultrasonic transducers still have the following drawbacks: firstly, the present domestic and international research on the capacitive ultrasonic transducers is mainly concentrated in the above MHz band, [7-10] which cannot meet the demand for long-distance imaging applications, secondly, most current capacitive micromachined ultrasound transducers adopt surface sacrificial technology [11-12]. For example, in one patent of application, No. 201210068681, disclosing a low range pressure sensor based on CMUT, the inventor devised a capacitive transducer whose overall structure from up to down is metal aluminum top electrode, silicon oxide membrane, single crystal silicon substrate, silicon oxide support, silicon nitride insulation layer and metal aluminum bottom electrode [13]. Defects of this structure are that the silicon oxide membrane is formed by an oxidation process, which makes the controllability of the membrane thickness low and the membrane surface rough, and directly affects the uniformity of the entire membrane deformation. Then, a discrete metal electrode is needed to deposit on its surface since the membrane is made of an insulating material, silicon oxide. This will lead to an increase in the membrane frequency, which is not conducive to the realization of the desired frequency sensors and limits the scope of the sensor application.

Aiming for the existing problems of higher frequency and also the surface sacrificial technology which is widely adopted, this paper proposes a sensor structure based on silicon-silicon bonding technology without a discrete upper metal electrode depositing on the integrated membrane. The simulation analysis of the designed transducer is conducted by ANSYS software, and the processed transducer is tested by Polytec MSA-400.

2. Structure Design and Simulation

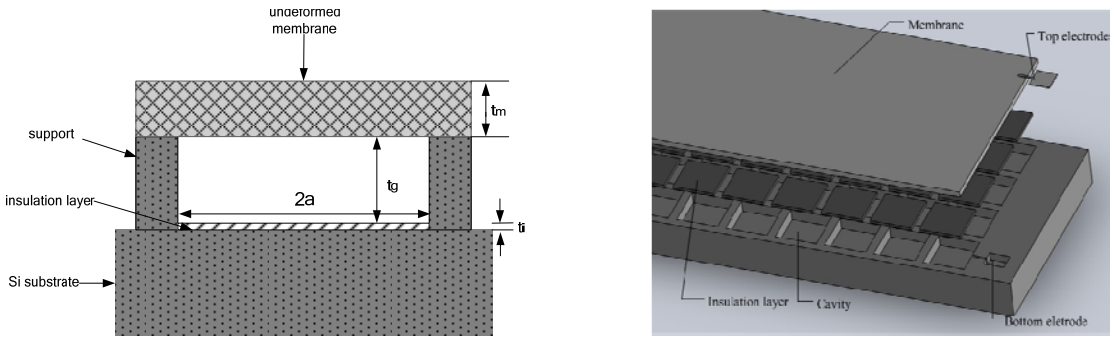
2.1. Structure Design

In order to solve the problems and deficiencies of extant research, the designed cell structure of the capacitive micromachined ultrasonic transducer is shown in Fig. 1(a). This structure includes the silicon substrate doped heavily for the formation of the bottom electrode and the cavity is formed by etching the silicon substrate. The bottom of this cavity is an insulation layer which can ensure electrical insulation between the top and bottom electrodes, and prevent short circuiting caused by the occasional engagement of the top and bottom electrode; the top of the cavity is the integration membrane made by SOI top silicon. When the sensor is operating in water, in order to avoid the hydrolysis caused by a strong electric field in the cavity, the vibration must be a vacuum-sealed cavity. The top and bottom electrodes are deposited on the membrane and substrate respectively. Meanwhile, a MEMS capacitive ultrasonic transducer is composed of many cells which are connected parallel and distributed in a certain order, as is shown in Fig. 1(b).

The characteristics of the structure are as follows:

1) The membrane of the transducer is defined on the SOI with better thickness uniformity and lower residual stress, which will make the vibration membrane achieve good thickness uniformity;

2) The structure consists of the integration vibration membrane, of which additional electrode deposition is not required to be discrete on the surface, thus the frequency deviation is low;



(a) sectional view of transducer units

(b) transducer structure

Fig. 1. Capacitive micromachined ultrasonic transducer with integration vibration membrane.

3) The transducer is produced by Si-Si bonding technology, which can avoid the problems of traditional surface sacrificial technology such as having some difficulty in the cavity etch, the limitation in membrane size which leads to the decrease in sensitivity and a narrow band in the frequency range.

2.2. Theory and Simulation Analysis

The operating frequency is the main performance index to be considered when capacitive micromachined ultrasonic transducers are designed. The size of the transducer structure is determined by the requirements of the actually demanded device frequency. According to the theory, the resonance frequency is [14]:

$$f = \frac{\lambda_x^2}{2\pi a^2}\sqrt{\frac{E t_m^2}{12\rho(1-\sigma^2)}}, \quad (1)$$

where λ_x is the natural frequency factor, t_m is the membrane thickness, a is the membrane length, E, ρ, σ is the Young's modulus, Poisson's ratio and density of membrane materials respectively. In this paper, the membrane material is Si, and its parameters are: $E = 1.69\times10^{11} Pa$, $\rho = 2332 kg/m^3$, $\sigma = 0.299$, $\lambda_x = 35.08$, the frequency for theoretical supposition is 1 MHz.

According to the theoretical presupposition, the transducer size range can be preliminary determined by the required frequency. The final size of the sensor needs to be revised by the ANSYS finite element simulation. The finite element analysis model is established and meshed freely according to the designed structure and materials used in each part, Trans126 is chosen as the cavity unit type and the remaining parts selected are Solid95. The final size and each vibration frequency are determined by static analysis and modal analysis to the designed transducer, as is shown in Table 1 and Table 2.

The first-order to sixth-order vibration mode of the designed transducer is shown in Fig. 2. From the figure only in the first-order vibration mode, the largest displacement amplitude appears at the center of the vibration membrane and it decreases gradually along the edge diffusion direction; the vibration mode is in an up-down mode along the z axis vertically like a drum that meets the demands of ultrasonic receiving and transmitting. Therefore, the first frequency is defined as the best working frequency of the transducer. The error amount between working frequency (1016.8 kHz) and theoretical presuppositions (1000 kHz) is only 1.68 %, which verifies the reliability of the theoretical model.

Except for the first-order modal, the other modes are interference motion. From Table 2, it varied widely between the second mode frequency (2280.2 kHz) and the working frequency, which can reach 1263.4 kHz. Therefore, the cross coupling between each order frequency can be effectively reduced; the Anti-disturbance capability can be improved and the working frequency bandwidth of the transducer can be widened.

Table 1. Transducer final size.

Structure Name	Size (μm)
Membrane width (a)	200
Membrane thickness (t_m)	3
Cavity height (t_g)	7
Insulation thickness (t_i)	0.2
Silicon substrate thickness (t_s)	500
Number of cells (n)	100

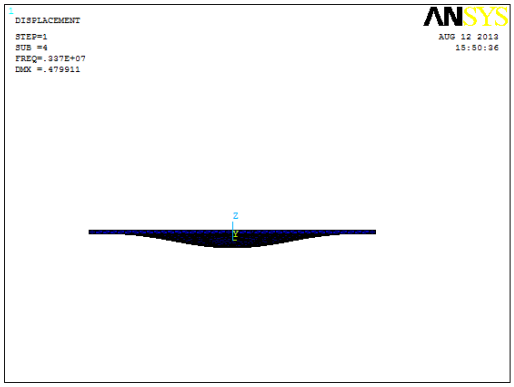
Table 2. Transducer frequency.

Frequency Order	Amplitude (kHz)
First-order frequency	1016.8
Second-order frequency	2280.2
Third-order frequency	2280.4
Fourth-order frequency	3366.0
Fifth-order frequency	4095.9
Sixth-order frequency	4116.2

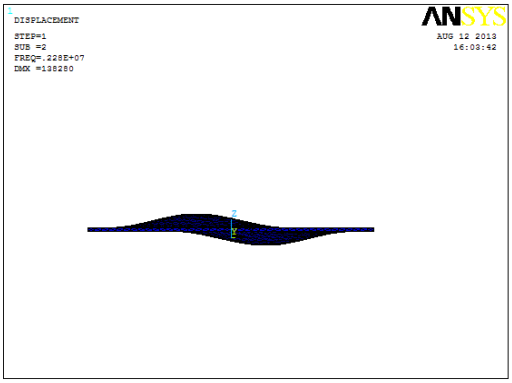
3 Fabricating Process Flow

Currently, there are two methods of processing capacitive micromachined ultrasound transducers. One is the sacrificial layer release process, that is the sacrificial layer is deposited on the fixed substrate by the method of growth or deposition; the membrane is deposited on the surface of the sacrificial layer, and etching openings through the membrane surface, with the high selection ratio of the etchant to remove the sacrificial layer, and the membrane material is retained. Another is the direct wafer bonding method, in which two wafers (one having cavity patterning and the other having the membrane material) are directly bonded under vacuum [15]. Of these Micromachining methods, direct wafer bonding technology is more economical, offers better process control, higher yield, and more novelties in CMUT designs than the sacrificial releasing process.

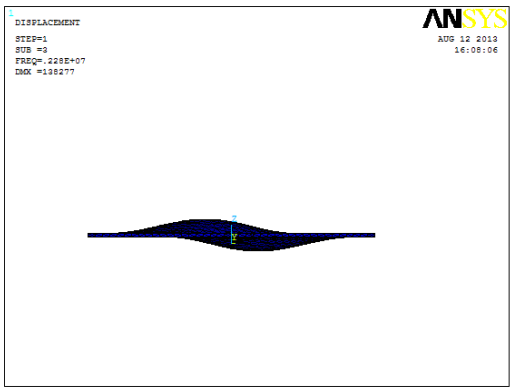
Based on the advantages of silicon-silicon bonding technology in this paper, the designed sensor adopts silicon- silicon bonding technology, and the technological process is (a) Prepare tablets: 6-inch N-type silicon wafer W1, 6-inch N-type SOI wafer W2; RCA cleaning wafers W1 and W2, and a 1 um thermal oxidation layer is grown on the surface of W1 and 0.2 um on W2; (b) An alignment mark is formed by photolithographic on the back of W1, and a cavity is formed by etching oxidation layer 1 um and etching Si 6um; (c) RCA cleans W1, then 0.2 um thermal oxidation is grown as an electrical isolation layer;



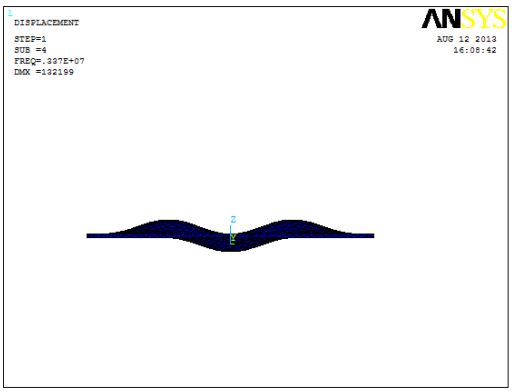
(a) First-order vibration mode



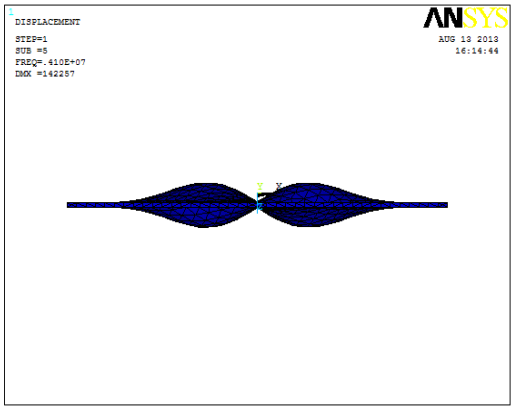
(b) Second-order vibration mode



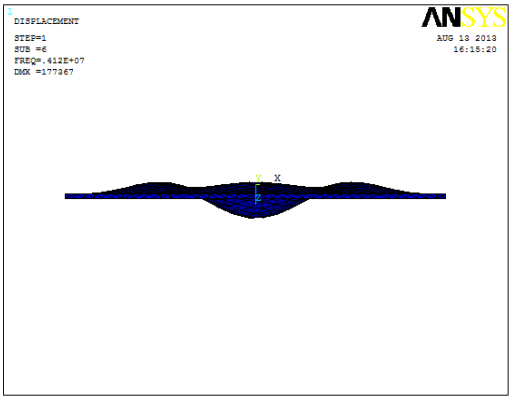
(c) Third-order vibration mode



(d) Fourth-order vibration mode



(e) Fifth-order vibration mode



(f) Sixth-order vibration mode

Fig. 2. Transducer vibration modes.

(d) Cleaning and polishing are the key for wafer bonding, so the wafer needs to be activated and cleaned before bonding. The wafer bonding is done and the bonded wafers are annealed to make the bond permanent, and then form a dry bonding layer; (e) 1 um low stress silicon nitride is deposited using PECVD, ICP etching silicon nitride and silicon oxide layer on the back of SOI; (f) Grinding machine thinning the Handle layer of W2 to 50 um and TMAH-KOH removes the rest; the BOX layer of W2 is removed by BOE, whose ratio is: NH_4F : HF: = 6:1, etching stops at the device layer, then exposing the top silicon as the full integration vibration membrane; (g) Vibration membrane is subsequently patterned by DRIE etch silicon 3 um; (h) The purpose of etching Oxide layer 1.2 um is to open a via through the top layer to provide contact to the bottom electrode, and Oxide layer etch 1.2 um; (i) Aluminum is deposited and patterned as the electrodes, then fabrication of the device is completed. The major steps are shown in Fig. 3.

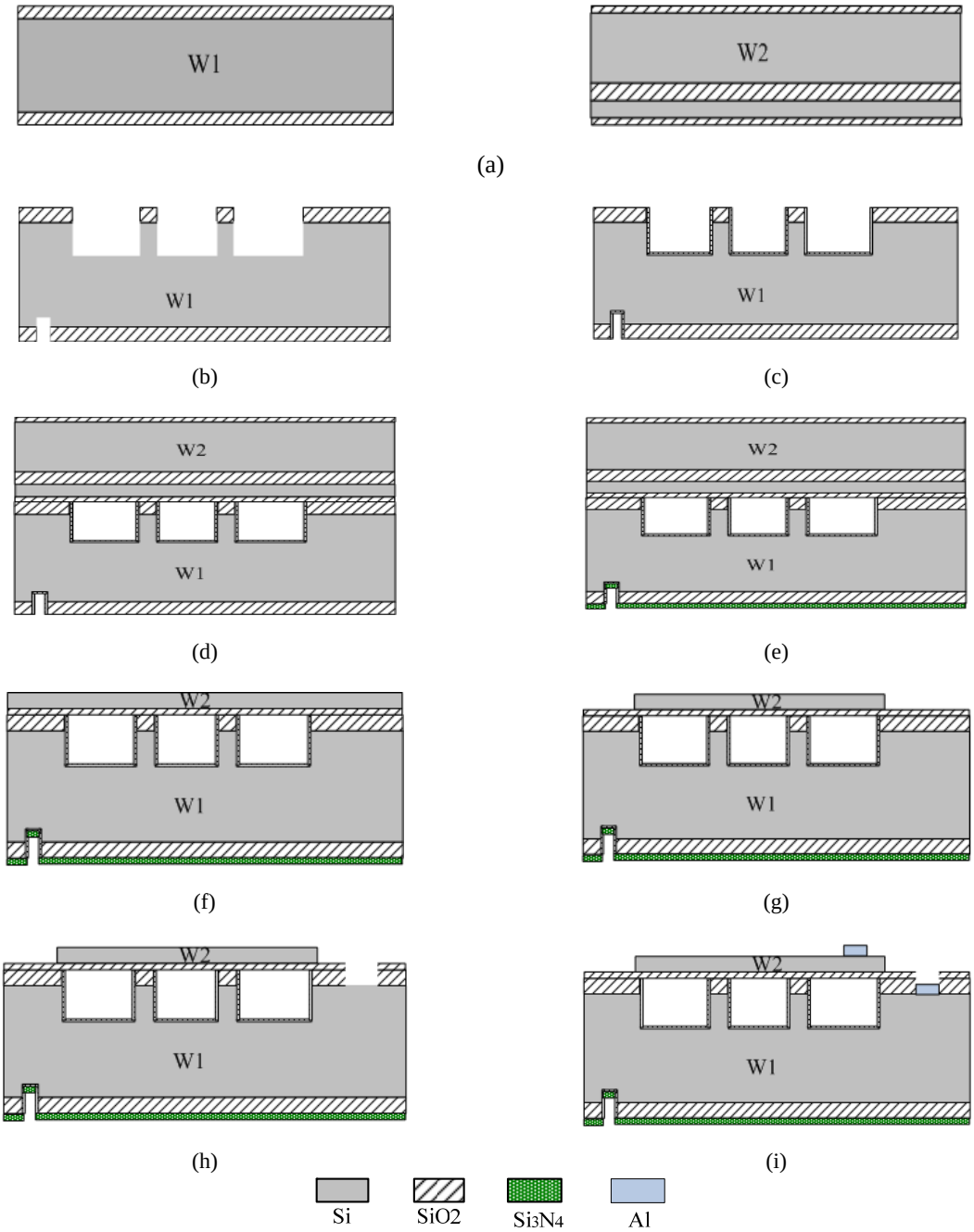


Fig. 3. Major steps of CMUT fabrication.

4. Test and Analysis

4.1. Topography Test

With the development of the MEMS, the great benefit brought by a microsensor has shown its charm. But the uncertainty in fabrication still significantly affects the cavity height and membrane thickness of the device, which also causes the deviation between simulation and the actual result. So the topography test of the fabricated device is necessary to make sure of the actual dimensions and property. Fig. 4 is the result of a topography test of the device given by Veeco.

It can be seen that the depth of the continuous vibration is uniform with 7.11725 um, and the sidewall is steep vertical, which is almost at the bottom of the vertical sidewall without any obvious etching angles. The test result has demonstrated the processing is well enough to meet the needs.

A scanning electron microscope (SEM) image of the cross section of this device is shown in Fig. 5. With a scanning electron microscope, the sample is taken by: Incising the sample along the crystal orientation and traversing the center of the membrane, then the cross section of this sensor microstructure is obtained. The etching depth and bonding membrane thickness are measured on this cross section. The right figure shows the particulars of side support of the device.

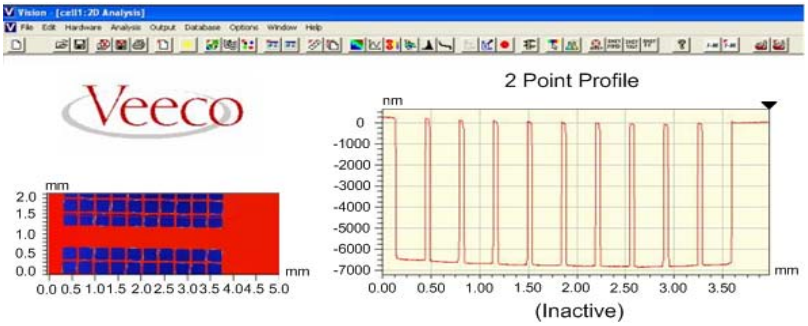


Fig. 4. Morphology test of vibration cavity.

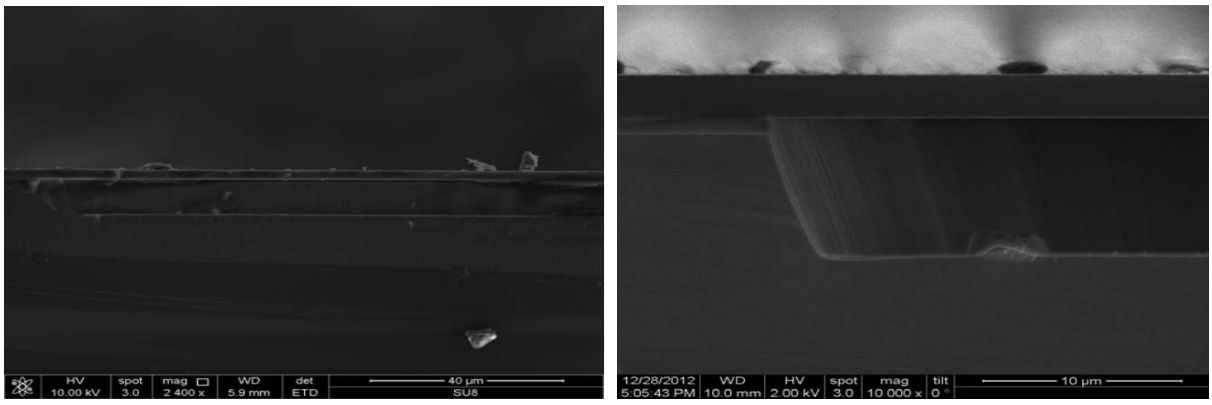


Fig. 5. Scanning electron microscope (SEM) test.

The micro transducer is composed of multiple small units. if there is a big deviation in the structure machining process of these small units, and the vibration consistency of the transducer and device performance will be effected seriously. So 10 units of micro transducers are randomly selected for structure consistency test. The test result of the cavity height and membrane thickness by the Veeco optical contourgraph and SEM respectively for many times is shown as Table 3. Comparison between the test results and the theoretical design parameters shows that the consistency between machining and designing, and standard deviation of the vacuum cavity height and the film thickness in 10 times random sampling measurements is in the acceptable range. Therefore the feasibility of the Si-Si bonding processing for good uniformity is demonstrated.

Table 3. Structural parameters of the optical morphology random sampling test.

Parameters	Design value	Average value of 10 times random sampling Veeco measurements	Average value of 10 times random sampling SEM Measurements	Standard deviation of 10 times random sampling measurements
Cavity height (tg)	7 um	7.11725 um	7.1 um	0.008
Membrane thickness (tm)	3 um		3 um	0.039

4.2. Doppler Vibration Test

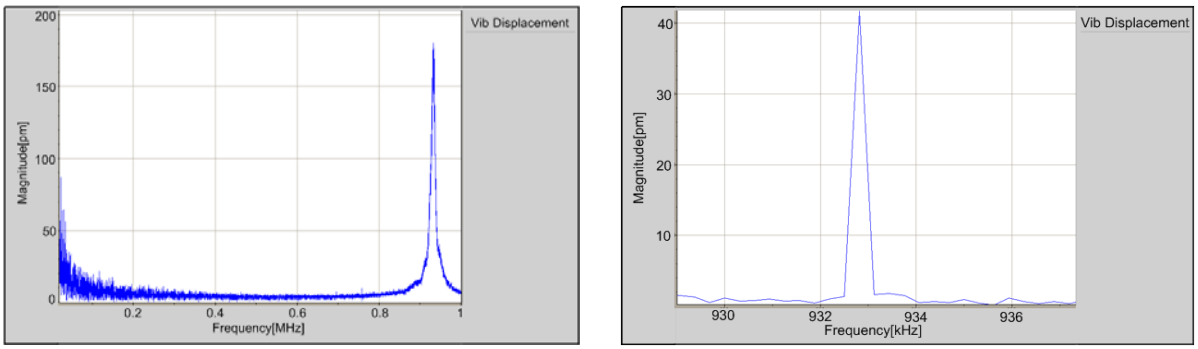
The dynamic vibratory characteristics of the micro sensor are tested by the Micro System Analyzer (Model MSA-400, Polytec, Germany) on a present testing condition. With observing the relationship between the vibration displacement and the vibration velocity varying with frequency, and analyzing the data, the resonant frequency and vibration mode of the micro-sensor is obtained.

4.2.1. Single Sweep Test

The single sweep test is implemented by using the sweep frequency test of the Polytec analyzer. Detailed experimental procedures and methods are as follows: Firstly, the laser point of the analyzer is aimed at the center of the membrane to pick up the center amplitude. Then the AC excitation voltage is applied to both ends of the device, of which the amplitude value is 1 V and is magnified 20 times through the power amplifier. Besides, the device is

biased with DC voltage of 100 V. Based on the finite element simulation on the frequency characteristics, the sweep range is preset as 0 Hz~1 MHz and the frequency step is 100 Hz.

Fig. 6(a) is the frequency-displacement curves tested by the above process. The results show that the sensor diaphragm center amplitude appears more obvious at the peak of frequency set range from 0 Hz to 1 MHz. The peak appears when the frequency is 932.8 kHz as shown in Fig. 6(b), which has a deviation of 9.005 % compared with the simulation value of 1016.8 kHz. This deviation is produced because of only considering the impact of the environmental stress during the simulation, and the DC bias of the test results is the decrease of the center frequency compared with the simulated value.



(a) (b)

Fig. 6. Sweep frequency characteristic curve.

4.2.2. The Multi-point Fixed-frequency Test

After getting the peak displacement of each mode vibrational frequency of the device by a single sweep test, the multi-point fixed-frequency test is undertaken to set the frequency point and obtain the overall position morphology of the vibration membrane, each vibration mode, and validate the vibration characteristics. In the test, the white-light fringe is firstly regulated to make the black and white stripe at equal intervals with no drift in order to get a sharp image of the device. In addition, we also pick up the laser spot and move it within the positions of the three points to determine the scan plane. And then the range is set as 360 mP×360 mP, scan points as 60×60 and the vibration frequency is 932.8 kHz, which is the same as the resonance frequency. Furthermore, the center of the scan range must coincide with the center of the membrane. So, the real-time vibration state of the membrane can be obtained and Fig. 7 shows the multi-point fixed-frequency vibration characteristics at the determined frequency.

From Fig. 7, it can be determined that micro-sensor vibration patterns at 932.8 kHz performance is up and down the vibration along the vertical direction, which is fully consistent with a finite element simulation of the first-order vibration mode.

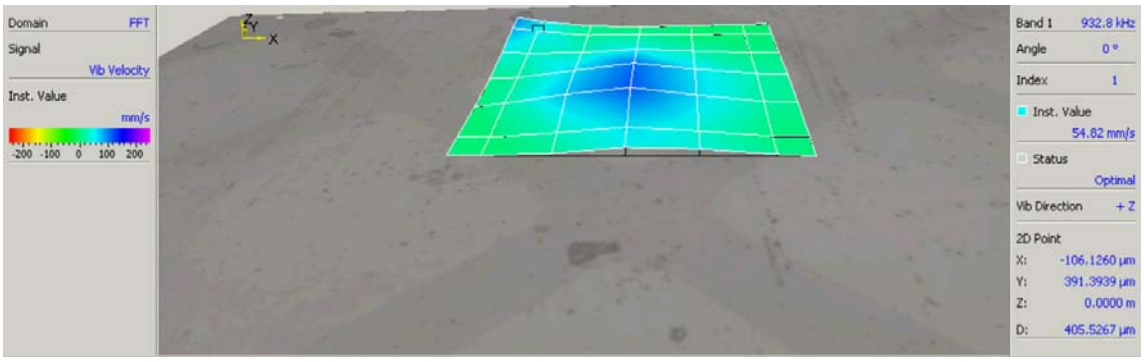


Fig. 7. Multi-point fixed-frequency vibration characteristics.

5. Conclusions

This paper introduced a capacitive micromachined ultrasound transducer based on Si-Si bonding technology. The resonance frequency and the vibration mode were determined by theoretical analysis and simulation, and the device was fabricated by MEMS technology. The topography measurement result from SEM shows that the cavity has a high etching accuracy and the membrane

thickness is of great uniformity. Besides, the machining technology is simple and short in cycle, which allows volume production. The frequency test implemented by Polytec MSA-400 shows that the resonance frequency is 932.8 kHz, which can meet all the requirements. The designed CMUT will surely have broad prospects in the application of long-distance ultrasound imaging and testing.

Acknowledgment

The authors wish to thank the Special Fund of the National Natural Science Foundation for project support, funded project (61127008). And this work is supported in part by the National 863 Program (No. 2011AA040404).

References

[1]. Binwu Lu, Design and Simulation of CMUT, MS Thesis, *Jilin University*, China, 2006.

[2]. Zhijian Guan, Simulation and manufactured process of capacitive microfabricated ultrasonic transducers, MS Thesis, *College of Precision Instrument and Opto-electronics Engineering of Tianjin University*, 2007.

[3]. Ladabaum Igal, Jin Xuecheng, Soh Hyongsok T., Surface micromachined capacitive ultrasonic transducers, *IEEE Transaction on Ultrasonic, Ferroelectrics, and Frequency Control*, 45, 3, 1998, pp. 678–690.

[4]. Mengli Wang, Capacitive Micromachined Ultrasonic Transducer Arrays for Blood Flow Ultrasound Doppler and Photoacoustic Imaging Applications, MS Thesis, *University of New Mexico*, 2010.

[5]. Ahmet Murat Cetin, Design and Verification of Diamond Based Capacitive Micromachined Ultrasonic Transducer, MS Thesis, *Middle East Technical University*, 2011.

[6]. Eccardtp Eterchristian, Niederer K., Scheurer T., Surface micromachined ultrasound transducers in CMOS technology, in *Proceedings of the IEEE Ultrasonics Symposium*, 2, 1996, pp. 959-962.

[7]. Guifen Shen, Hongqing Zhang, Yu Han, Study and Analysis of MEMS, *Journal of Sensors and Actuators*, 3, 1, 2004, pp. 168-171.

[8]. Jung Woo Choe, Amin Nikoozadeh, Matthew O'donnell, Volumetric Real-Time Imaging Using a CMUT Ring Array, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 59, 6, 2012, pp. 1201-1210.

[9]. Hui Zhang, Guangde Song, Zhijian Guan, *et al.*, Analysis of the Effect of structural parameters of CMUT, *Journal of Sensors and Actuators*, 6, 2008, pp. 951-953.

[10]. Hui Zhang, Guangde Song, Dachao Su, *et al.*, Design of a Micromachined Ultrasonic Transducer, *Journal of Tianjin University*, 41, 1, 2008, pp. 17-20.

[11]. Tugrul Zure, Sazzadur Chowdhury, Fabrication and measurements of dynamic response of an SOI based non-planar CMUT array, 2012, 18, 2012, pp. 629–638.

[12]. Ira O. Wygant, Xuefeng Zhuang, Integration of 2D CMUT Arrays with Front-End Electronics for Volumetric Ultrasound Imaging, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 55, 2, 2008, pp. 327-341.

[13]. Zhuangde Jiang, Zhikang Li, *et al.*, Design and Fabrication of low range pressure sensor based on CMUT, 2012, CN: 201210068681.

[14]. Blevins R. D., Fomulas for Natural Frequency and ModeShape, Reprint Edition, *Krieger Publish Company, MalaBar*, Florida, 2001.

[15]. Ahmet Murat Cetin, Baris Bayram, Diamond-Based Capacitive Micromachined Ultrasonic Transducers in Immersion, *IEEE Trans.*, 60, 2, 2013, pp. 414–420.