Fabricating Capacitive Micromachined Ultrasonic Transducers with Wafer-Bonding Technology

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Abstract— **This paper introduces a new method for fabricating Capacitive Micromachined Ultrasonic Transducers (cMUT) using a wafer-bonding technique. The transducer membrane and cavity are defined on a SOI wafer and on a prime wafer, respectively. Then, using silicon direct bonding in a vacuum environment, two wafers are bonded together forming the transducer. This new technique offers many advantages over conventional surface micromachining. First, forming a vacuum-sealed cavity is relatively easy since the wafer-bonding is performed in a vacuum chamber. Second, this process enables more control over the gap height than the surface micro-machining does, making it possible to fabricate very small gaps. The process results in a reduced collapse voltage of the membrane and a high sensitivity of the device. Third, since the membrane is made of single crystal silicon, the mechanical properties of the membrane are fairly easy to control. Moreover, this kind of membrane does not suffer from the stress and density variations associated with thin film membranes. Fourth, the number of steps involved in making the cMUTs are reduced considerably, making the device turn-around time shorter. All of the advantages allow fabrication of cMUTs capable of more reliable operation. We present the fabrication process and experimental results obtained from the fabrication of wafer-bonded devices with different membrane sizes**.

***Index Terms*—cMUT, wafer-bonding, ultrasonic transducer, SOI wafer.**

I. Introduction

CMUTS have been considered an attractive alternative to conventional piezoelectric transducers in many areas of application [1]. Micro-machined cMUTs provide certain advantages over piezoelectric transducers. CMUTs can, for example, operate in a wider temperature range than a PZT device [2]. Moreover, their acoustical impedance match to air is better than that of PZT based transducers. cMUT fabrication can be performed with a standard IC process which means that near-electronics can be integrated with the transducer [3].

Active research work on cMUTs has been reported in the last decade [4-6]. Recently, surface micro-machined cMUTs have been successfully fabricated and tested in air and in water [4,7]. These results demonstrate that optimized cMUTs can perform comparably to piezoelectric transducers with fewer limitations on their design.

Silicon based surface micro-machining has met with success as a means to fabricate cMUTs. There are, however, problems associated with this technology in relation to cMUT fabrication. The surface micro-machining process introduces a limitation on the cavity and membrane size of a cMUT [8]. Moreover, due to the relative complex fabrication process, it is difficult to batch produce surface micro-machined cMUTs to tight quality specifications. The wafer-bonding technique can simplify the cMUT fabrication process as well as provide solutions for many of the above mentioned problems.

In this work, cMUTs designed for sub-MHz operation are fabricated by a wafer-bonding technique for the first time. Fabricated devices are tested in air and in vegetable oil in order to assess their function.

II. MOTIVATION

There are a several advantages associated with fabrication of cMUTs by wafer-bonding technology:

A. *Vacuum Cavity Formation*

Forming a vacuum cavity is easier with the wafer-bonding technique than with the surface micromachining process. The new technique makes the complex via open and refill process obsolete. Wafer-bonding is done in vacuum so the vacuum in the cMUT cavity can be better than that obtained with the surface micromachined technique. In the earlier technique the obtainable vacuum is limited by LPCVD working pressure (200-400 mTorr).

Wafer-bonding also avoids adding unwanted materials onto the membrane's inner surface during the via refill process.

B. *Fill factor*

Because the vacuum cavity is formed during the wafer-bonding process, a via is no longer needed. The area of the vias, even 35% of the device face, can be utilized as active transducer area in the cMUT.

C. *Cavity Size and Shape*

There are two advantages in forming the cavity with a wafer-bonding technique: First, the cavity shape is independent on the membrane shape. Second, the aspect ratio of the cavity is no longer limited by the slow sacrificial-layer-etch.

D. *Membrane Size and Shape*

Since the cMUT membranes and cavities are fabricated on different wafers before bonding, the wafer-bonding technique provides more flexibility to design cMUTs with different sized and shaped membranes. This translates into fewer limitations on the device design when trying to obtain a desired dynamic response, membrane mode shape or mode separations.

E. *Membrane Material*

The membrane is made from single crystal silicon, which has better mechanical properties (fewer internal defects, lower internal mechanical loss) than thin-film deposited materials. The single crystal membrane will improve the reliability as well as the performance of the device.

By using a SOI wafer to form the membrane, one can achieve better uniformity, stress controllability, and process repeatability. This is relevant with respect to commercialization of cMUT device fabrication.

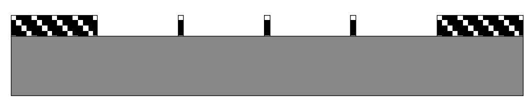
F. *Integration with Wafer-through Process*

A large cMUT array transducer, needs a through-wafer electrical connection to minimize its long routing line and parasitic capacitance. The wafer-bonding technique can be integrated into the through-wafer connection process. First, a through-wafer electrode is made in one wafer, then a cavity is formed on the same wafer. This wafer is finally bonded to a SOI wafer with a desired membrane configuration.

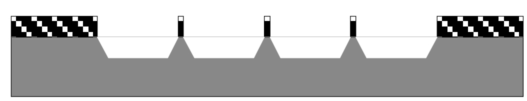
Exploring the advantages, cMUTs can be designed and fabricated to meet specifications in the different application areas.

III. FABRICATION PROCESS

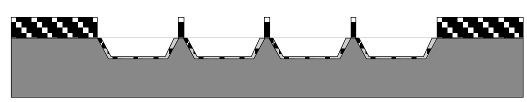
Fabrication of cMUTs by the wafer-bonding technique is a four-mask process as shown in Fig.1.



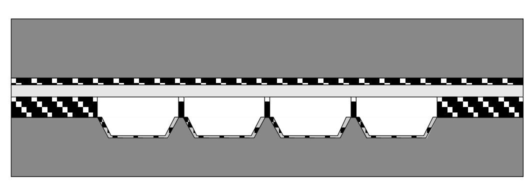
1. Thermal oxidation and etch.



2. Silicon etch (only for deep cavity).



3. Thermal oxidation for electrical isolation.



4. Silicon wafer fusion bonding.

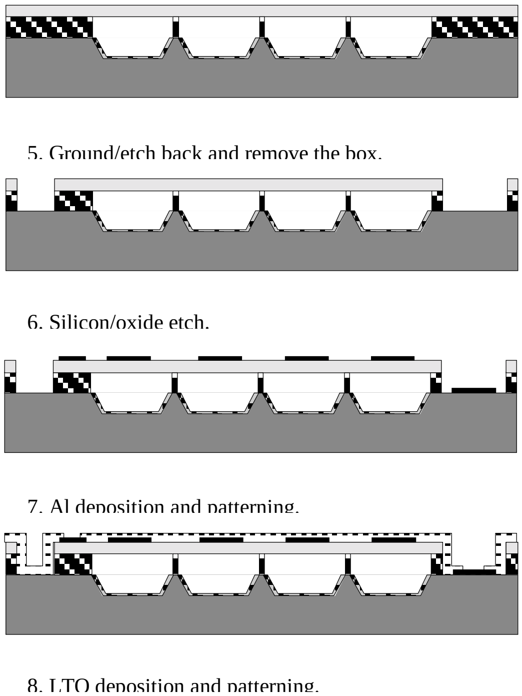


Fig.1. Major steps of cMUT fabrication.

The process starts with a 4-inch N type <100> silicon wafer. The wafer is heavily doped with Antimony to achieve resistance in the range of 0.008 to 0.02 $\Omega\cdot cm^2$. Depending on the required electrode separation of the cMUT, one of two different processes form shallow or deep cavities before wafer-bonding is preferred. When the separation distance is less than 2μm, one can use a thermal oxide layer to form the cavity. A layer of thermal oxide is grown and patterned using the photoresist. After photoresist removal, another thermal oxide layer is grown as an isolation layer for the cMUT.

When the separation distance is larger than 2μm, a thin layer of thermal oxide is grown to protect the clean wafer surface. This oxide layer is then patterned by the cavity mask and used as the hard mask for silicon etching as well. The cavity is formed by silicon etching in KOH. After this, the oxide mask layer is removed by BOE. Finally, a 4000Å layer of thermal oxide is grown as electrical isolation. The wafers with cavities will bond with the SOI wafers. The active silicon layer on SOI wafer will be used as cMUT membranes.

Two kinds of SOI wafers are used in the current process. Before wafer-bonding, the wafers are cleaned, first, in Piranha for 20 minutes, then in 50:1 HF for 15 seconds. Finally, their surfaces are treated in RCA1 for 10 minutes. The wafer-bonding is done with a Karl Süss bonder at $1x10^{-5}$ mbar vacuum, the temperature being 150°C. The bonded wafers are annealed at 1100°C for two hours. The wafers are ground and etched back to the box (oxide layer) of the SOI wafer to form the membrane. The box layer is removed with BOE. Then a via is etched by DRIE on the active silicon layer and the oxide within the via is removed with BOE. The via is used to contact the bottom electrode of the cMUT. After this 3300 Å Al is sputtered and patterned. Trenches are etched into the silicon layer to serve as isolation between the devices. A 4000 Å LTO is deposited as a passivation layer. Finally, the LTO layer is patterned to open vias for wire bonds.

Two kinds of SOI wafers with an active layer thickness of 0.34μm and 4.5μm are used in the fabrication. The cell sizes of the 0.34μm membranes varies from 12μm-150μm. The cell sizes of 4.5μm membranes ranges from 600μm to 750μm. Fig.2 shows a fabricated device.

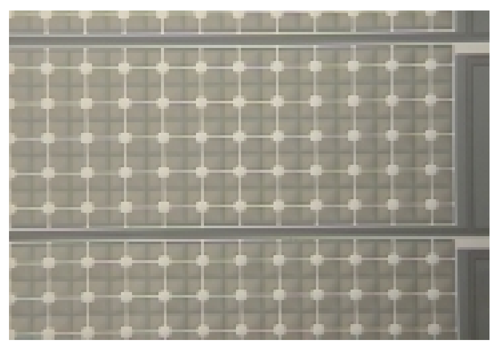


Fig.2. Close view of a 128 element array of 36μmx36μm cMUTs with a 0.34μm thick silicon membrane.

IV. DEVICE CHARACTERIZATION

A. *Mechanical Characterization*

In order to fabricate cMUTs with desired characteristics, one needs to control the separation between the two electrodes of the device very accurately. In the silicon wafer-bonding process, single crystal silicon is used as membrane material of the cMUT. Therefore, the membrane profile under atmosphere pressure can be predicted.

The membrane deflection was simulated by Ansys®, as described previously [9] using the material parameters of ideal single crystal silicon for the membrane. The measured membrane deflection match those obtained with the simulation well. More important, the measured membrane deflection results are similar between different finished wafers and different process runs. The detailed results are listed in Table1.

Membrane Size (μm)	Thickness (μm)	Ansys Result (μm)	Wyco Result (μm)
150	0.34	2.7	2.29-2.33
100	0.34	1.55	1.69-1.79
50	0.34	0.54	0.54-0.57
40	0.34	0.34	0.32-0.34
36	0.34	0.15	0.21-0.23
30	0.34	0.15	0.21-0.22
20	0.34	0.016	0.033-0.038
10	0.34	0.001	0.014
600	4.5	5.969	6.1
650	4.5	6.816	6.7
700	4.5	7.931	8.2
750	4.5	8.711	8.8

Table 1. Membrane deflection under atmospheric pressure.

B. *Electric Characterization*

The cMUTs were analyzed with a standard network analyzer measurement in air. Their complex impedance as a function of bias voltage was obtained with a computerized set-up. These measurements allow the analysis of the parameters of the electrical equivalent circuit of the transducer [1]. Resonance frequency and bandwidth of the acoustically unloaded device were first obtained. The real part of the impedance indicates the mechanical losses of the device while the imaginary part reveals the ground capacitance as well as the parasitic capacitance [1]. From the imaginary impedance curve it was also possible to estimate the electro-mechanical coupling coefficient, k_T^2, of the device [10].

Devices were designed for sub-MHz operation (membrane diameter 650 μm, membrane thickness 4.5 μm and gap height 4 μm), as well as for operation on a higher frequency (membrane diameter 20 μm, membrane thickness 0.34 μm and gap height 0.3 μm). The high frequency device is an efficient acoustic source (ReZ=1.7 kohm) while the low-frequency device is acoustically less efficient (ReZ=20 ohm). A series resistance of a few ohms is present as a baseline in the graphs of the real part of the impedance.

The imaginary impedance of the low frequency device shows a reactive load, approximately four times the resistive load of the low frequency device at resonance. This indicates the need for reduced capacitance of the device. For this device the capacitance (C_{par}+C_o) was 5.8 nF and the k_T^2-value was 0.3. These values compare well with the simulated values that were 1.0 nF and 0.3. The collapse voltage of the devices was higher than 170 V. This was expected since the simulated value was 400 V for these devices designed for operation at 100 m depth in water.

C. *Ultrasonic Characterization*

Two parameters are central for characterizing the operation of ultrasonic transducers. These are frequency band of operation and transduction capability. The latter is seen as peak acoustic pressure when transmitting, and pressure sensitivity when receiving. In order to characterize the operation of the large cMUT hydrophones designed for sub-MHz operation, pitch-catch (PC) and pulse-echo (PE) tests were conducted in air and in vegetable oil [11]. Additional transmission tests were conducted in oil with a small broadband calibrated cMUT as the receiver, in order to determine the output of acoustic power of the device [11]. The measurements conducted in oil were performed in the far field of the device while the airborne measurements were performed both in the near field and in the far field of the device.

During these tests the transducers were biased with 40-170 V. In the PC set-up, the same bias was applied to both the transmitter and the receiver. The transmitter was excitated either with a 200 V unipolar pulse of 100 ns duration or with a 6-16 V sinusoidal burst. The burst contained either one cycle or 80 cycles. Two test targets were used: a 300x400 mm, 2 mm thick polished steel plate placed 1 m from the transducer in the airborne test and a 100x200 mm, 10 mm thick polished steel brick placed 10 cm from the transducer in the immersion test. The transducer was manually aligned in order to achieve maximum amplitude of the received signal.

The received signal was sampled by an oscilloscope at a rate of 50 MHz. The uncorrected spectrum and the attenuation and diffraction corrected [12] spectrum of a signal received in the PC tests is shown in Fig. 3.

A PE measurement was also performed in air. A recorded A-scan line is shown in Fig. 4. The –6dB bandwidth measured in air was 306-314 kHz with a SNR of 31 dB the corresponding values in vegetable oil were 50-230 kHz and 24 dB.

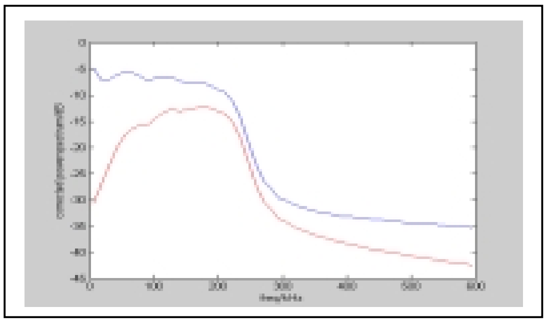


Fig. 3. The uncorrected spectrum (red line) and the spectrum corrected for attenuation and diffraction (blue line) of the pulse in figure 11.

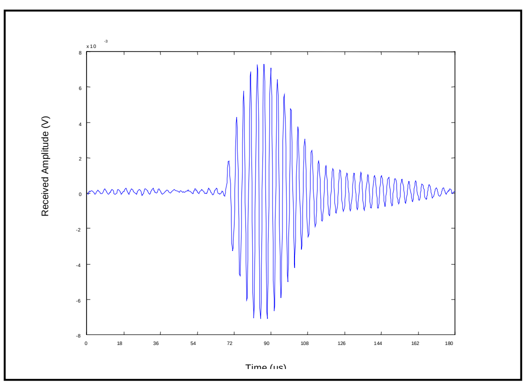


Figure.4. Pulse-echo test with a large cMUT device in air. Excitation of the 100V biased transducer with one 200V unipolar pulse. The received signal was filtered with a 30 kHz high-pass filter and amplified 40 dB. Target: a 250x450x1 mm steel plate placed 100 cm from the transducer. The received signal was averaged 64 times.

V. CONCLUSION

This paper presents the first low-frequency cMUTs fabricated with a wafer-bonding technique. Large cMUTs with membranes of different size and thickness have successfully been fabricated. The devices performed well in pitch-catch and pulse–echo tests both in air and in vegetable oil. Compared to surface micro-machining techniques, the wafer-bonding process involves fewer process steps, which reduces the process turnaround time and potentially increases the yield.

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