Fabrication of Capacitive Micromachined Ultrasonic Transducers (CMUTs) Using Wafer Bonding Technology for Low Frequency (10 kHz-150 kHz) Sonar Applications

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Abstract-**This paper introduces a new method for fabricating Capacitive Micromachined Ultrasonic Transducers (CMUT) that uses a wafer-bonding technique. The transducer membrane and cavity are defined separately on a Silicon-On-Insulator (SOI) wafer and on a prime quality silicon wafer, respectively. Using silicon direct bonding in a vacuum environment, the two wafers are bonded forming the transducer. Among the many advantages this wafer-bonding technique, and probably the most important for low frequency transducer applications, is the ability to define relatively large membranes and large gaps easily. The particular device reported in this paper is designed to operate in the 10 kHz - 150 kHz range as a transmitter only for a sonar application. In this paper, we describe the new fabrication process to build CMUTs, and present the first experimental results obtained from this particular device that demonstrate wide-band operation in the above mentioned frequency range.**

I. INTRODUCTION

CMUTs have been considered an attractive alternative to conventional piezoelectric transducers in many areas of application, because they provide certain advantages over piezoelectric transducers [1,2]. Most of these advantages are inherent to the way the devices are built and operated. CMUTs are made of a plurality of thin membranes that are suspended over a conductive silicon substrate with insulating posts. The membrane is coated with metal on top to create a parallel plate capacitor. By applying an AC signal between the plates, the membranes can be put into vibration, and generate ultrasound. The mechanical impedance of the thin membranes is usually very small. In air-borne applications this enables a better coupling into the medium. In immersion applications the mechanical impedance of the membranes is over-damped with the large acoustical impedance of the medium enabling a wideband frequency of operation.

Traditionally, CMUTs are fabricated on silicon using surface micromachining techniques, such as thin film deposition, photolithography, and thin film etching [3]. Surface micromachining provides most of the advantages of the IC manufacturing technology which has been developed in the last 40 years. The transducers manufactured in this way can be tailored into virtually any shape and number. This allows the fabrication of a wide variety of transducers into high density one dimensional and two dimensional arrays relatively easily.

Active research work on CMUTs has been reported in the last decade. Recently, surface micro-machined CMUTs have been successfully fabricated and tested in air and in water [4-6]. 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. These problems mainly arise from the thin film deposition and sacrificial membrane release steps involved in the traditional fabrication process of the CMUTs. The membranes cannot be made arbitrarily large because of the stress issues of the thin films, and the sacrificial release process [7]. The frequency characteristic and the performance of CMUTs are solely determined by the geometrical parameters of the membranes and the gap. Therefore, the aforementioned limitation in the fabrication process limits the application areas of the CMUTs, particularly into higher ultrasound frequencies. In this paper, we introduce the wafer-bonding technique into the CMUT fabrication process, which solves most of the short-comings of the traditional technique. The details of the fabrication process are described in section III. Using this new technique, we fabricated CMUTs that operate in the 10 kHz – 150 kHz range. The experimental results are reported in section V.

II. MOTIVATION

There are a several advantages associated with fabrication of CMUTs by wafer-bonding as compared to the traditional one:

A. Vacuum Cavity Formation

In the traditional case, the vacuum cavity is formed as follows. First, a sacrificial layer is deposited and patterned into the shape of the gaps of the capacitors. Then, the membrane is deposited over the sacrificial layer uniformly. Later, small holes are etched through the membrane to get access to the sacrificial layer. The sacrificial layer is removed, and the membrane is released with a wet etch process. The small etch holes are subsequently sealed under vacuum to create the vacuum sealed gap. These steps are the ones that introduce most of the limitations of this process. Because of the high stresses involved with the thin film depositions. It is very difficult and unpractical to deposit

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arbitrarily thick sacrificial layers. It is also not possible to release arbitrarily large membranes.

Forming a vacuum cavity with the wafer-bonding technique solves these practical problems. The cavity and the membrane are defined on separate wafers. They are brought together in vacuum, and bonded using direct silicon bonding. The new technique makes the sacrificial layer formation, and the complex via open and refill process steps of the traditional method obsolete. Therefore it does not have the limitations of the sacrificial release process enabling the fabrication of very large membranes.

B. Fill factor

One other limitation the sacrificial release process brings is the need for etch channels to be able to vacuum seal the gap. These channels have to be labyrinth-like shapes to ensure the sealing which consumes a lot of real estate on the silicon wafer. In the case of wafer bonding, the vacuum cavities are formed during the bonding process, and therefore etch holes and channels are no longer needed. The transducer area can be solely dedicated to the active membranes.

C. Membrane Material

In the traditional CMUT fabrication, the membrane is usually made of silicon nitride which is deposited using a Liquid Phase Chemical Vapor Deposition (LPCVD). Two gases are brought together inside a reactor at an elevated temperature to create the silicon nitride layer on the silicon wafer. The temperature of the reactor and the concentrations of the gases determine the electrical and mechanical properties of the silicon nitride, including the residual stress. Because of the nature of the process, silicon nitride films deposited in this way turn out with high residual stress. Even if the deposition conditions are adjusted to achieve low stress, the resulting membranes are limited in size for safe sacrificial release process. Moreover, the resulting mechanical properties of the silicon nitride membrane vary due to process variations and are thus somewhat unpredictable.

In wafer-bonding 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. Most important, the mechanical properties are very well known and very well controlled. Therefore, the single crystal silicon membrane improves the reliability and predictability as well as the performance of the device.

These advantages brought by the wafer-bonding technique are more pronounced in the application of interest, where the intended frequency of operation requires the fabrication of CMUTs with very large membranes. In the following sections we will describe the realization of such a device.

III. FABRICATION PROCESS

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

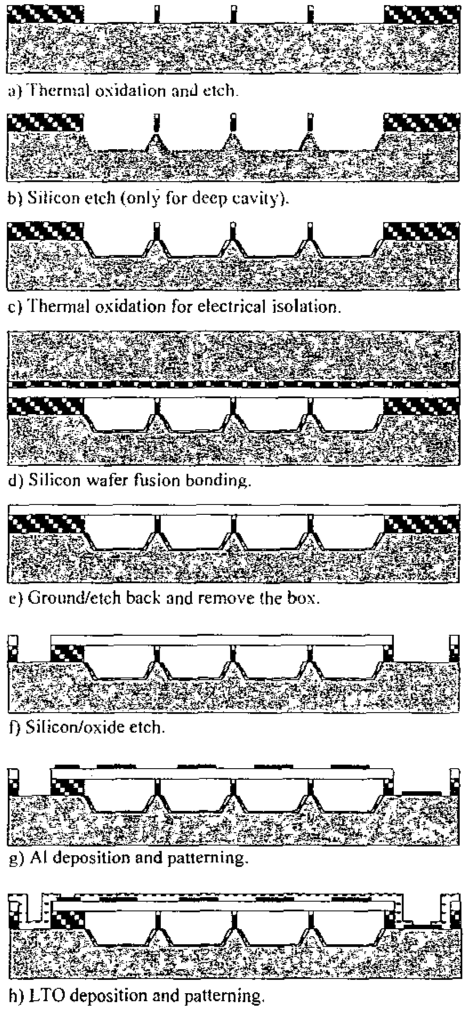

Fig. 1: Major steps of CMUT fabrication using wafer-bonding technique.

electrode separation of the cMUT, one of two different processes forms shallow or deep cavities before wafer-bonding (Fig. 1.a or 1.b). 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 conventional photolithography.

When the separation 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. The cavity is formed by silicon etching in KOH. After this, the oxide mask layer is removed by BOE.

After the cavity definition and photoresist removal, another thermal oxide layer of 4000Å is grown as an isolation layer for the CMUT (Fig. 1.c). The wafer with cavities is then bonded with the SOI wafer under vacuum as shown in Fig. 1(d). The wafer-bonding is done with a Karl Süss bonder at $1x10^{-5}$ mbar vacuum, at 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 active silicon layer on the SOI wafer now constitutes the membranes of the CMUT transducer. Therefore, the thickness of the active silicon layer becomes the membrane thickness.

To gain access to the ground layer on the carrier silicon wafer an opening in the membrane silicon and insulating silicon dioxide layers is etched. Subsequently, a 3300 Å film of aluminum (Al) is sputtered and patterned to establish the connections to the top and bottom electrodes. A thin layer (4000 Å) of LPCVD Low-Temperature-Oxide (LTO) is deposited as a passivation layer. Finally, the LTO layer is patterned and etched to open pads for wire bonds.

IV. DEVICE DESIGN AND FABRICATION

As briefly mentioned earlier, the principle of operation of CMUTs in transmit relies on the electrostatic attraction force between opposite charges. When a DC voltage is applied to the electrodes of the membrane, the membrane deflects towards the substrate which is the ground electrode. The electrostatic attraction force is balanced by the restoring force of the mechanical spring formed by the membrane. The amount of deflection can be calculated if the mechanical spring constant of the membrane is known. Now, one can imagine vibrating the membrane by adding a small AC signal on top of the DC signal. A vibrating membrane then couples mechanical energy into the surrounding medium. The details of CMUT operation can be found in [1,3,4]. The measure of the efficiency of the CMUT is the electromechanical coupling efficiency which shows how efficient the electrical energy is converted into mechanical energy. It turns out that, as shown in [8], the electromechanical coupling efficiency increases with increasing DC bias voltage. However, the bias voltage with which we can operate CMUTs has an upper bound. Increasing the DC voltage increases the electrostatic attraction force, and stretches the membrane further towards the substrate. Getting closer to the substrate increases the attraction force on the membrane further, because it is inversely proportional to the separation between the two plates. The attraction force is balanced by the spring force of the membrane which is linear with deflection. Therefore, there comes a point while increasing the bias voltage where the restoring force of the mechanical spring cannot balance the electrostatic attraction force. This voltage is called the collapse voltage beyond which the membrane sticks to the substrate with the electrostatic attraction force, and does not vibrate. That is, the CMUT is not usable beyond the collapse voltage, and the DC operating voltage has to be kept below but close to this voltage. One important aspect of the CMUT design is to keep this voltage low to enable low-voltage operation.

The mechanical spring constant of the membrane together with its mass determines the dynamic behavior of the membrane, and the frequency characteristics. Therefore, CMUT design starts with the design of the geometrical parameters of the membrane. Specifically, the size and the thickness of the membrane are optimized for best performance. The cavity beneath the membrane is vacuum sealed. Therefore, the membrane deflects under ambient pressure. The design of the gap has two considerations. The gap should be wide enough such that when deflected under ambient pressure, the membranes do not touch the substrate. It shouldn't be too wide as well to assure low voltage operation. To ensure these, the static deflection of the membranes under ambient pressure, and the corresponding collapse voltage are calculated and optimized using finite element analysis.

For this particular application, square shaped membranes are used to maximize the area efficiency. The membrane thickness is determined by the thickness of the active silicon layer of the SOI wafer, which is 4.5 μm. The size of the membranes is determined to be around 650-700 μm. To obtain several data points, the devices are fabricated using a variety of membrane sizes, particularly 600 μm, 650 μm, 700 μm and 750 μm membranes. The static deflection for these membranes under one atmospheric pressure is calculated using finite element analysis. The simulation results together with the measurements are discussed in the next section, and shown in Table 1.

The final device is circular with a diameter of 7.5 cm. It is divided into four quadrants each with a different membrane size. The quadrants have their own individual electrical connection, and are tested separately. An optical picture of a device is shown in Fig. 2.

V. 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 atmospheric pressure can be predicted. The membrane deflection is simulated by ANSYS using the material parameters of single crystal silicon for the membrane. After the fabrication process, the static membrane deflections are measured using a white light interferometer by WYCO. A sample picture obtained from such a measurement is shown

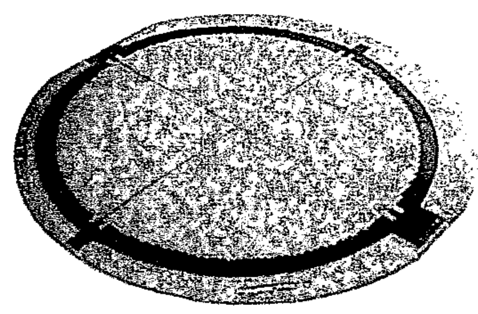

Fig. 2: An optical picture of a finished device.

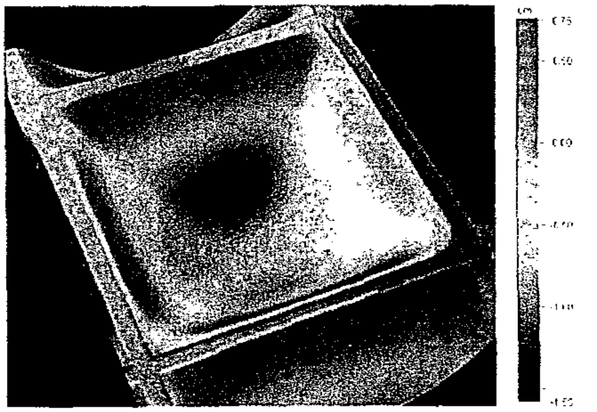

Fig. 3: An image showing the surface profile of a membrane deflected under atmospheric pressure obtained.

in Fig. 3. The measured peak membrane deflections for different membrane sizes match those obtained with the simulations very well. More important, the measured membrane deflection results are similar between different finished wafers and different process runs demonstrating the repeatability, uniformity and reliability of the process. The detailed results are listed in Table1.

B. Electrical Characterization

The electrical characterization of a CMUT is the first measure of the acoustical activity. It is done with a vector network analyzer which measures the input impedance of the transducer. The measurement setup is shown in Fig. 4. The network analyzer is connected to the CMUT through a capacitor which blocks the DC, but allows the AC to pass. The DC bias is supplied through a resistor which is small compared to the CMUT impedance to provide a constant DC voltage across the transducer. The complex impedance of the transducer as a function of frequency is obtained with a computerized set-up. These measurements allow the analysis of the parameters of the electrical equivalent circuit of the transducer [4]. Such a measurement result is shown in Fig. 5. This particular device is made of 650 μm size membranes. The real part of the impedance indicates the mechanical losses of the device while the imaginary part reveals the device capacitance as well as the parasitic capacitance [4]. The resonant behavior observed in the real part shows a significant energy loss at that frequency which is a measure

TABLE 1

CALCULATED AND MEASURED MEMBRANE DEFLECTIONS UNDER ATMOSPHERIC PRESSURE FOR VARIOUS MEMBRANE SIZES.

Membrane Size (μm)	Thickness (μm)	ANSYS Result (μm)	Wyco Result (μm)
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

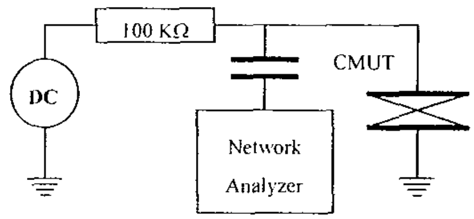

Fig. 4: Experimental setup used for measuring the electrical input impedance of the CMUT.

of the acoustical power coupled into the air. This particular device has a collapse voltage of 150 V, and a resonance frequency of 288 kHz, which are very close to those predicted by ANSYS.

C. Ultrasonic Characterization

Two parameters are of prime importance for characterizing the operation of ultrasonic transducers. These are frequency band of operation and transduction capability. For this application, the latter is seen as peak acoustic pressure in transmit. In order to characterize the operation of the CMUT under test, pulse-echo measurements were conducted in air and in vegetable oil. These tests provide us with the frequency band shape of the transducer. In addition, pitch catch experiments are performed in oil using a needle hydrophone as a receiver. This test provides us the output pressure capability of the CMUT. For these tests, the CMUT under test is biased in the same way as shown in Fig. 4. In the pulse echo measurements, the network analyzer is replaced with a signal generator and an oscilloscope. The signal generator generates an electrical pulse that launches an acoustic signal in the propagation medium. The echo is received by the same transducer which generates a voltage that is read by the oscilloscope. Fig. 6 shows the result of the pulse-echo experiment performed in air.

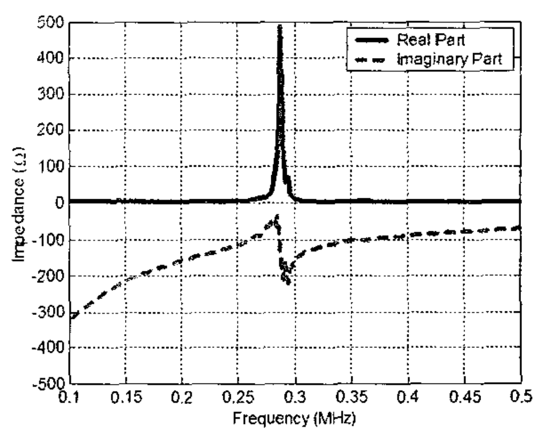

Fig. 5 Electrical input impedance of the CMUT as measured by the vector network analyzer.

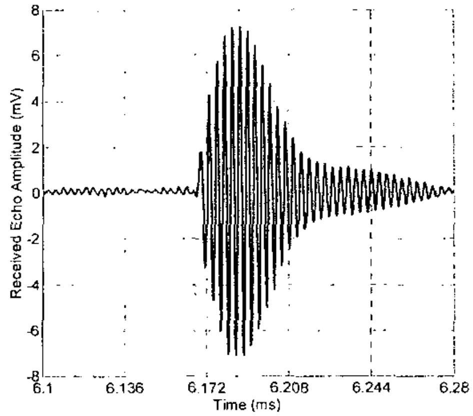

Fig. 6: The result of the pulse echo experiment in air, showing a narrow frequency band operation.

The transducer is excited with a 200 V unipolar pulse. The received echo signal has a narrow band response around 278 kHz as expected in an air-borne measurement. The frequency of the echo signal is very close to the resonance frequency measured by the network analyzer. The reason for the slightly lower frequency of operation observed in the pulse-echo measurement is because of the band shaping of the frequency dependent acoustical loss in air. The same pulse-echo experiment is repeated in oil. Although these devices are coated with a thin layer of LTO to protect the hot electrodes from the environment, it was not fully successful. Therefore, this experiment is performed in oil instead of water. In this experiment, the acoustical impedance of the medium dominates the mechanical impedance of the CMUT transducer creating an over-damped system. The received echo signal shown in Fig. 7 indicates a broadband frequency response. The Fourier spectrum of the received pulse is calculated and plotted in Fig. 8.

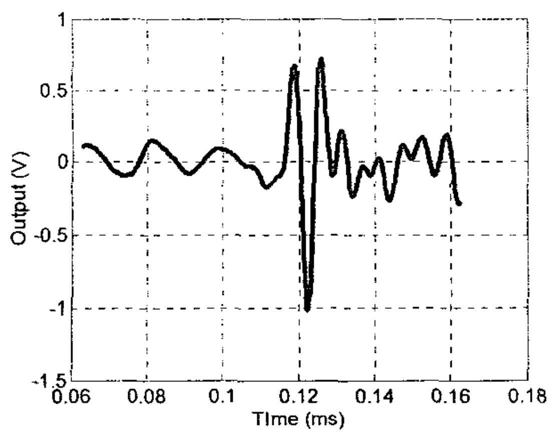

Fig. 7: Impulse Response of the CMUT transducer.

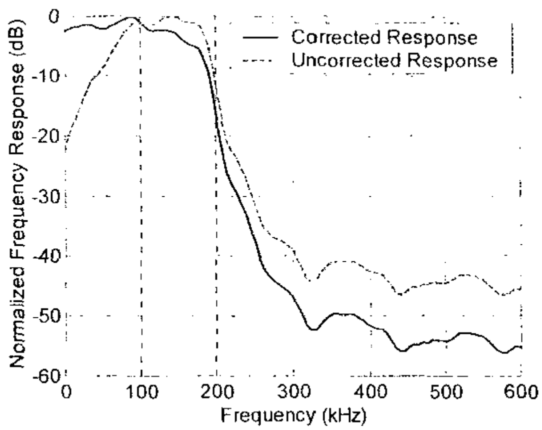

Fig. 8: The uncorrected spectrum (red) and the spectrum corrected for attenuation and diffraction (blue) of the pulse in Fig. 7.

The resulting frequency response is corrected for the diffraction [9,10] and attenuation losses in the medium, which is also shown in Fig. 8 (blue). The results show that the CMUT transducer indeed has a wide frequency 3-dB bandwidth that extends from 10 kHz to over 150 KHz.

VI. CONCLUSION

This paper presents the first fabrication of low-frequency CMUTs using the wafer-bonding technique. The wafer bonding technique eliminates the limitations of the traditional surface micromachining techniques, and allows us to build CMUTs with relatively large membranes. In return, this technique enables the fabrication of CMUTs that operate in the low ultrasound frequencies. For the scope of this work, the transducers are specifically designed to operate in the 10 kHz - 150 kHz range for sonar applications. We have shown that CMUTs that are fabricated using this new technique indeed operate in this frequency range. The operation of these devices is demonstrated with pulse-echo experiments in air and in immersion, and with calibrated hydrophones. In conclusion, wafer bonding technique provides a solution to the limitations of the traditional surface micromachining techniques in low frequency applications. This new technique involves fewer process steps, which reduces the process turnaround time and potentially increases the yield. Therefore, it is also a strong alternative to surface micromachining in higher frequency applications as well, such as medical and underwater imaging in the MHz range.

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