NEW FABRICATION PROCESS FOR CAPACITIVE MICROMACHINED ULTRASONIC TRANSDUCERS

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ABSTRACT

In this paper, we introduce a new method to fabricate 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. This new process offers many advantages over surface micromachining on the fabrication of the transducers with different cavity and membrane configurations. CMUTs with different dimensions have been successfully fabricated and characterized. For the first time, sub-MHz operation is achieved with CMUTs. The test results show that the new process is a promising method to fabricate CMUTs for operation in air and water at different frequency ranges.

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. An AC voltage applied between the plates generates an AC force on the membranes and acoustic waves in the surrounding medium by vibrating the membranes. 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 loading 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 that has been developed in the last 40 years. The transducers manufactured in this way can be tailored to 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. Surface micro-machined CMUTs have been successfully fabricated and tested in air and in water [4-6]. The results demonstrate that optimized CMUTs can perform comparably to piezoelectric transducers with fewer limitations on their design.

Silicon based surface micromachining 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 restricts the application areas of the CMUTs, particularly into higher ultrasound frequencies.

In this paper, we introduce a wafer-bonding technique into the CMUT fabrication process, which solves most of the shortcomings of the traditional technique. The wafer-bonding technique significantly simplifies the vacuum cavity formation process which is the cavity between the membrane and the substrate. To form the vacuum cavity with the wafer-bonding technique, 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. In addition, because the vacuum cavities are formed during the bonding process, etch holes and channels, which exist in the traditional process and consume a lot of real estate, are no longer needed. The transducer fill factor significantly improved, especially for the high frequency CMUTS. 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.

The details of the fabrication process are described in the next section followed by the experimental results obtained from devices that are fabricated with the new method.

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FABRICATION PROCESS

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

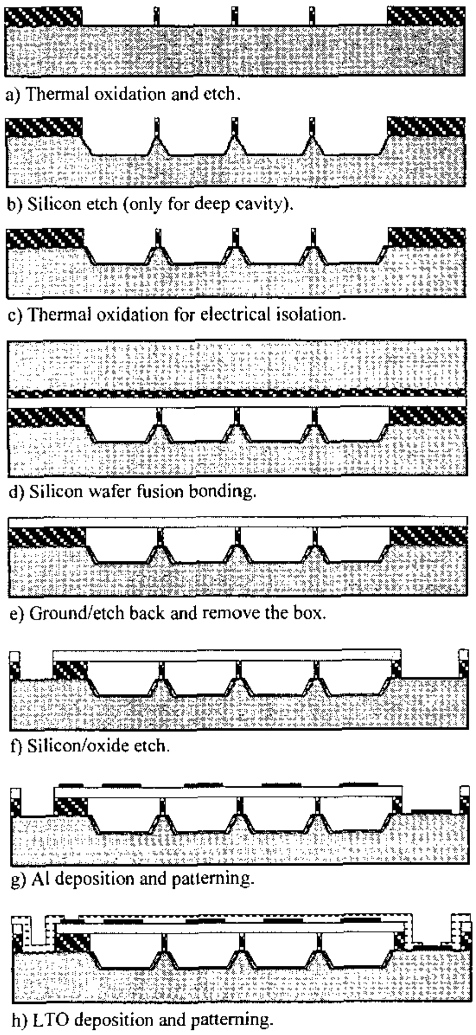

Fig. 1: Major steps of CMUT fabrication using wafer-bonding technique.

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 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 1×10^{-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 create pads for wire bonds.

CMUTs that work in the different frequency ranges have been designed and fabricated. Fig. 2 shows a CMUT array with an operation frequency of 3MHz for immersion ultrasonic imaging application. Fig. 3 shows a device with 10kHz – 150kHz bandwidth for a sonar applications.

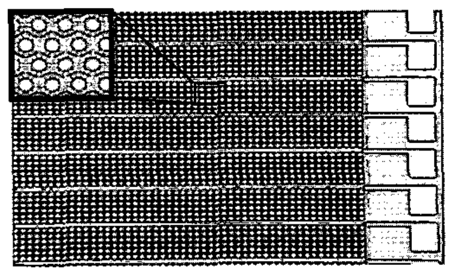

Fig. 2: 128 element CMUT array of 36μm hexagonal, and 0.34μm thick membranes for a ultrasonic imaging application.

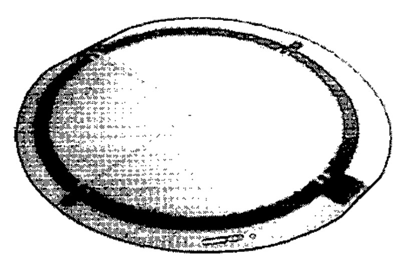

Fig. 3: A 75μm low frequency CMUT made of 4.5μm thick and 650mm wide square membranes for a sonar application.

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. 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.

Table 1: The simulated vs. measured values of a 650 µm diameter 4.2 µm thick CMUT membrane. The measurements were performed in air. The bias voltage was 100V.

	Resonance Frequency (KHz)	Membrane Deflection (µm)	Collapse Voltage (V)
Ansys	310	7.3	132
Measured	306	7.28	130

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]. A sample of the measurement result is shown in Fig. 5. 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 of the acoustical power coupled into the air.

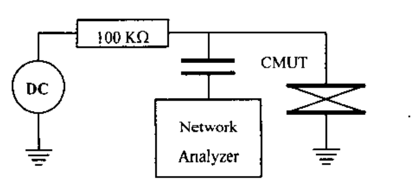

Fig. 4: Experimental setup used for measuring the electrical input impedance of the CMUT.

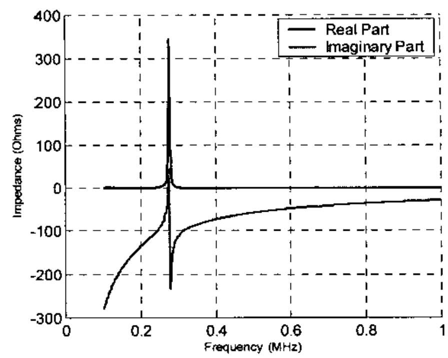

Fig. 5 Electrical input impedance of the CMUT as measured by the vector network analyzer.

C. Ultrasonic Characterization

Two parameters are of prime importance for characterizing the operation of ultrasonic transducers. These are bandwidth and transduction capability. For this application, the latter is seen as peak acoustic pressure in transmit. In order to characterize the operation of a CMUT, 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 were performed in oil using a needle hydrophone as a receiver. This test provides us the output pressure generated by the CMUT. For these tests, the CMUT is biased in the same way as shown in Fig. 4. In the pulse echo measurements, the network analyzer is replaced by a signal generator and an oscilloscope. The signal generator generates an electrical pulse that launches an acoustic signal into 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.

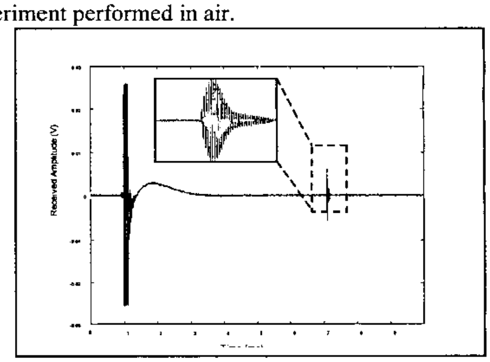

Fig. 6: The pulse-echo experiment result of a low frequency CMUT in the air. The enlarged window shows the reflected pulse. The reflector is a steel block 1meter from the transducer.

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 the band shaping due to frequency dependent acoustical loss in air. The same pulse-echo experiment is repeated in oil. 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 the smaller window in Fig. 8 indicates a broadband frequency response. The power spectrum of the received pulse is calculated and plotted in Fig. 7.

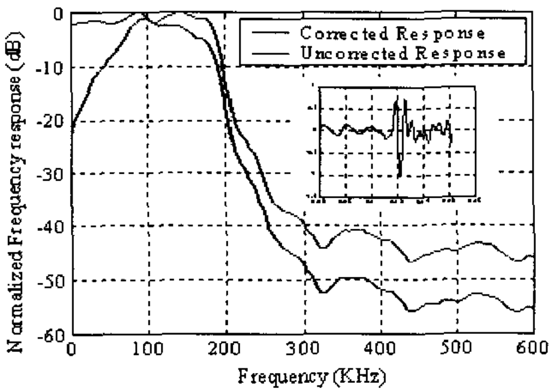

Fig. 7: The uncorrected spectrum (red) and the spectrum corrected for attenuation and diffraction (blue) of the pulse in oil

The resulting frequency response is corrected for the diffraction [9,10] and attenuation losses in the medium, which is also shown in Fig. 7 (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.

CONCLUSION

The wafer bonding technique eliminates the limitations of the traditional surface micromachining techniques, and allows us to build the first low frequency CMUTs. We have shown that CMUTs that are fabricated using this new technique indeed operated as designed. The operation of these devices is demonstrated with pulse-echo experiments in air and in immersion. In conclusion, the 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.

REFERENCES

[1] I. Ladabaum, X.C. Jin, H.T. Soh, A. Atalar, and B.T. Khuri-Yakub, "Surface micromachined capacitive ultrasonic transducers ," IEEE Trans. Ultrason, Freq. Contr., vol. 45, p.678-690, May 1998.

[2] D.W. Schindel, D.A. Hutchins, L. Zhoou, and M. Sayer, "The design and characterization of micromachined air coupled capacitance transducers," IEEE Trans. Ultrason, Freq. Contr., vol. 42, p.42-50, May 1995.

[3] X.C. Jin, I. Ladabaum, L. Degertekin, S. Calmes, and B.T. Khuri-Yakub, "Fabrication and characterization of surface micromachined capacitive ultrasonic transducers," IEEE J. Microelectromechanical Systems., vol. 8(1), p.100-114, Mar. 1999.

[4] X.C. Jin, Ö. Oralkan, F. Levent Degertekin, and Butrus T. Khuri-Yakub, "Characterization of one-dimensional capacitive micromachined ultrasonic immersion transducer arrays, " IEEE Trans. on UFFC, vol 48, pp. 750-760, May 2001.

[5] A. Caronti, G. Caliano, A. Iula, and M. Pappalardo, "Electrical impedance mismatch in capacitive micromachined ultrasonic transducers," in Proc. Ultrason. Symp., p.925-930, 2000.

[6] A. G. Bashford, D.W. Schindel, and D.A. Hutchins "Micromachined ultrasonic capacitance transducers for immersion applications," in IEEE Trans. Ultrason, Freq. Contr., vol. 45, p.367-375, Mar. 1998.

[7] G. G. Yaralioglu, A.S. Ergun, B. Bayram, T. Marentis, and B.T. Khuri-Yakub, "Residual stress and Young's modulus measurement of capacitive micromachined ultrasonic transducer membranes," in Proc. Ultrason. Symp., p.953-956, 2001.

[8] F. V. Hunt, in Electroacoustics, 2nd ed., American Institute of Physics., 1982

[9] G. S. Kino, in Acoustic Waves: Devices, Imaging and Analog Signal Processing, New York: Prentice-Hall, Inc, 1987.

[10] A. Atalar, "A fast method for calculating diffraction loss between two facing transducers," IEEE Trans. Ultrason, Freq. Contr., vol. 35, p.612-617, Sept. 1988.