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Capacitive Micromachined Ultrasonic Transducers for Robotic Sensing Applications

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***Abstract*— Ultrasonic ranging is the most common method used in robotic systems for distance or proximity sensing. The heart of the method is an ultrasonic transducer that emits and detects ultrasound. There are mainly two types of transducers existing in the market today; piezoelectric and electrostatic. In this paper, we propose the use of a new type of transducer, which is capacitive micromachined ultrasonic transducer (CMUT). CMUTs were introduced about a decade ago, and were shown to be a good alternative for conventional transducers in various aspects, such as sensitivity, efficiency and bandwidth. CMUTs are basically the micromachined versions of the electrostatic transducers. Many enhanced features of the transducer are enabled with the micromachining technology. Micromachining allows miniaturization of the device dimensions and produces capacitive transducers that outperform their piezoelectric and electrostatic counterparts. This paper describes the fabrication process briefly, and the performance of the CMUT transducers is evaluated by demonstrating characterization results. It is also shown that CMUTs can be used for pulse-echo measurements in air up to MHz frequencies.**

***Index Terms*—Capacitive Micromachined Ultrasonic Transducers (CMUTs), ultrasonic ranging, robotic.**

I. INTRODUCTION

Ultrosonic ranging is the method of choice in today's many robotic systems, due to their low cost implementation. The ultrasonic ranging technique measures the distance by detecting the time of flight of the reflecting waves from the obstacles. The ultrasonic waves, which are usually between 20 kHz and 300 kHz, are generated and detected by the transducer. The transducer is the key component of the system since it determines the overall performance. Today most of the systems use either piezoelectric or electrostatic transducers. Generally speaking, the electrostatic transducers perform better than piezoelectric ones in the above mentioned frequency range. In the simplest form, an electrostatic transducer is composed of a thin conducting membrane stretched above a fixed metal plate forming a small gap between the two electrodes. The gap distance determines the sensitivity of this device. As the gap decreases, the electric field increases, and the sensitivity increases. On the other hand, the sensitivity of the piezoelectric transducers is limited by the piezoelectric coupling coefficient.

Recently, silicon micro-machining techniques enabled fabrication of sub-micron gaps. This approach allows the fabrication of very efficient transducers at ultrasonic frequencies. These devices are called capacitive micromachined ultrasonic transducers CMUTs [1,2,3]. In contrast to conventional electrostatic transducers, which are composed of a single membrane, CMUTs are made of a plurality of small and thin membranes suspended over a conductive silicon substrate by insulating posts. Fig. 1 shows an optical picture of such a device where the large circles are the membranes. The diameters of the membranes range from 10 μm to hundreds of μm. The corresponding operation frequency can range from a few kHz to a hundred MHz. The gap between the membrane and the substrate is vacuum-sealed or left unsealed at will, and it can be as small as 500 Angstrom. The membranes are either conductive or coated with a conductive electrode, and essentially create small capacitors together with the substrate. This structure results in very efficient transducers that compete with conventional transducers in terms of sensitivity and bandwidth.

Like electrostatic transducers, the CMUTs require a DC bias. The DC bias is essential in order to achieve harmonic motion in transmit, and high sensitivity in receive mode. The electrostatic forces on the biased membrane attract it toward the substrate. The bending stiffness and the residual stress in the membrane balance the electrostatic attraction forces. Driving the membrane with an alternating voltage generates ultrasound. In

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receive mode, if an ultrasonic field impinges on the biased membrane, detection currents are generated.

One important advantage of the electrostatic transducer when compared to other types of transducers such as piezoelectric and magnetostrictive, is the excellent mechanical impedance match between the transducer and the surrounding medium. The low mechanical impedance of the membrane is usually negligible. This results in very efficient coupling of the sound waves into the sound-bearing medium.

The small and thin membranes that constitute the CMUT transducer are micromachined onto a silicon substrate. Micromachining has evolved from the integrated circuit (IC) manufacturing technology as a means of fabricating micro-electromechanical systems, and therefore has all the abilities that the IC technology offers. These abilities include, but are not limited to: batch fabrication, high level of integration and scalability, and electronic integration. That is, with this technology batch fabrication of high-density transducer arrays as well as single elements are enabled. In addition, the scalability provides the ability to fabricate transducers with a wide range of size and shapes. Because the transducer response is primarily determined by the size and the shape of the membranes, scalability translates into the ability to fabricate wide range of devices for operation at different frequency spans and regimes. Therefore it is possible to build long range and short range ranging transducers on the same substrate.

II. Fabrication

A. *Thin film deposition*

The fabrication process starts with a deposition of an insulator layer on top of a highly doped silicon wafer. The highly doped substrate later forms the bottom electrode of the membranes. Poly-crystalline silicon is used as the sacrificial layer, which is deposited by LPCVD (Liquid Phase Chemical Vapor Deposition). The sacrificial layer is patterned with photolithography and dry-etch to define the active (gap) area. The membrane is made of LPCVD silicon nitride (Si_3N_4), which is deposited over the sacrificial layer. Small holes are dry etched in the Si_3N_4 membrane and potassium hydroxide (KOH) is used to selectively etch the sacrificial poly-silicon layer. After the release, the etch holes are sealed and the membranes are isolated from each other by another Si_3N_4 deposition at low pressure (~ 8 Pa). The rest of the process steps involve finalizing the membrane thickness, and making the necessary electrical connections and isolations. The details of the process can be found in [1-4].

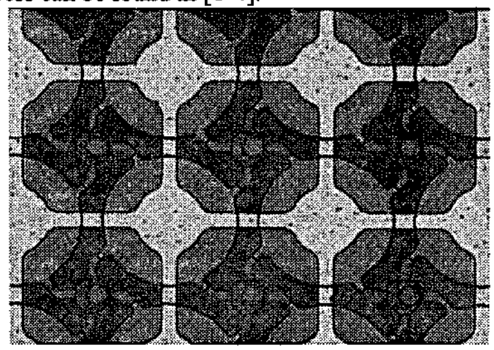

Figure 1. 60 μm membranes fabricated using thin film deposition technique.

B. *Wafer bonding technique*

The process starts with a low resistivity silicon wafer and a silicon-on-insulator (SOI) wafer (Fig. 2a). The first step is to grow silicon dioxide (SiO_2) on the silicon wafer prior to cavity definition. Depending on the required cavity depth for the membranes, either a dry or wet etch is employed to define the cavity (Fig. 2b). Next, the silicon wafer with the cavities is bonded to the SOI wafer (Fig. 2c). The thick silicon layer (also known as the handle) and the thin oxide layer are removed (Fig. 2d) leaving only the active silicon layer of the SOI wafer, which forms the membrane. The rest of the process is identical to that of the thin film deposition technique.

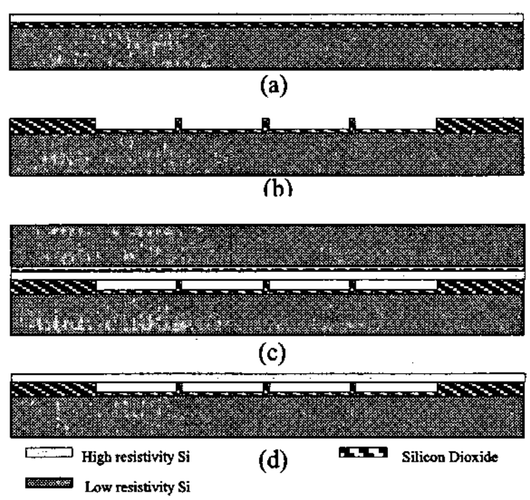

Figure 2: Simplified process flow of CMUT fabrication with wafer-bonding technique, (a) SOI wafer (b) low resistivity silicon wafer: oxidized and patterned for cavity definition, (c) wafer bonding, (d) grinding and etching the handle of the SOI wafer.

The wafer bonding technique enables more control over the membrane material. The membranes obtained by using thin film deposition usually suffer from a repeatability problem since the quality of the film varies from run to run. In addition, the wafer bonding technique reduces the number of process steps and decreases the device turnaround time. Fig. 3 is an optical picture of such a device fabricated for low frequency applications.

Figure 3. An optical picture of a 7.5 cm diameter single element CMUT device which is made of 650 μm wide square membranes.

III. PRINCIPLE OF OPERATION

A. DC operation

As a first order approximation, a CMUT membrane can be modeled by a parallel plate capacitor as shown in Fig.4. This model ignores the deflection of the membrane clamped at its rim and assumes that membrane moves as a piston. The electrostatic forces are balanced by the stiffness (k_s) of the membrane. The capacitance of the device under a DC bias is

$$C(x) = \frac{A\varepsilon_0}{\dfrac{d_i + d_m}{\varepsilon_r} + d_0 - x}.$$

Where A is the area. ε_0 is the permittivity of vacuum and ε_r is the relative permittivity of the insulator and the membrane material. d_0 is the initial gap distance under zero bias voltage. d_i and d_m are the insulator and the membrane thickness, respectively. Effective gap distance can be defined as

$$d_{eff} = d_0 + \frac{d_t}{\varepsilon_r}.$$

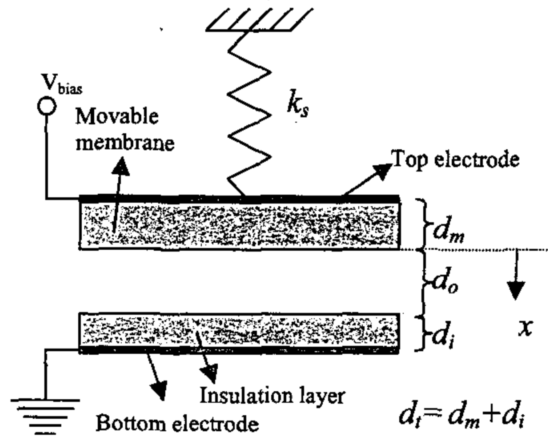

Figure 4. Parallel plate transducer. d_0 is the gap distance under zero bias.

The electrostatic force on the top electrode is given by

$$F_E = \frac{1}{2}\frac{C(x)}{d_{eff} - x}V^2.$$

At the equilibrium this force is balanced by the restoring force and the relation between the voltage and the displacement is

$$V = \sqrt{\frac{2k_s x}{A\varepsilon_0}}\left(d_{eff} - x\right).$$

Therefore as the voltage increases, the membrane displacement increases. However, at a certain voltage the electrical force gradient is larger than that of the restoring force. At this voltage, the membrane collapses onto the substrate. This voltage is called collapse voltage and given by

$$V_{col} = \sqrt{\frac{8k_s d_{eff}^{\ 3}}{27A\varepsilon_0}}.$$

Collapse voltage is an important parameter of the transducer. For maximum efficiency, the transducer should be operated close to the collapse voltage. On the other hand, the bias voltage should not exceed the collapse voltage.

B. Harmonic analysis

Harmonic analysis of the transducer can be performed easily by using an electrical equivalent circuit approach [6]. The equivalent circuit model is shown in Fig. 5.

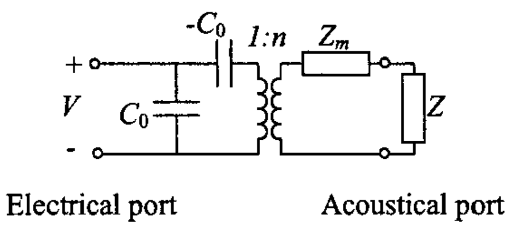

Figure 5. Equivalent circuit model.

In the equivalent circuit shown in Fig. 4, the capacitor on the electrical side is simply the device capacitance of the CMUT element, which is calculated in the previous subsection. The negative capacitance accounts for the spring softening effect due to the electromechanical interaction [6]. On the acoustical side, Z_m represents the complex mechanical impedance of the CMUT, whereas the impedance Z is the acoustical impedance of the surrounding medium. Finally, the transformer represents the electro-mechanical conversion between the electrical and the acoustical ports. The transformer ratio is given by

$$n = V\frac{\varepsilon_0 A}{(d_{eff} - x)^2}$$

In general, the sensitivity of a transducer is determined by the transformer ratio, which is inversely proportional to the square of the cavity depth. One can achieve high transformation ratios with CMUTs because surface micromachining allows us to make relatively small gaps (as low as 0.05 μm). Therefore, it is possible to achieve high sensitivity values.

The main advantage of the equivalent circuit model of Fig. 4 is that it enables quick prediction of the response of the transducer in different media. As the equivalent circuit suggests, a CMUT transducer is normally a resonant structure. The Q factor of this resonant structure is determined by the acoustical impedance of the medium, Z. In air, the transducer impedance at resonance is comparable in value to the radiation impedance into air. Thus, the transducer behaves as an RLC resonant circuit. The bandwidth of the transducer can be altered by introducing loss sources such as squeezed film damping. These losses can be easily incorporated into equivalent circuit by adding appropriate electrical elements.

IV. EXPERIMENTAL RESULTS

A. Electrical input impedance

The electrical input impedance measurements provide a first proxy of the acoustical activity of the transducer. The measurements were performed with a vector network analyzer (HP 8751A) that measured the complex input impedance of the transducer as a function of frequency. The analyzer was connected to the device through a large DC decoupling capacitor. The transducer was then connected to the DC bias in series with a large resistor. The network analyzer applies a small AC signal to measure the input impedance of the CMUT while sweeping the frequency. The input impedance of a device is shown in Fig. 6.

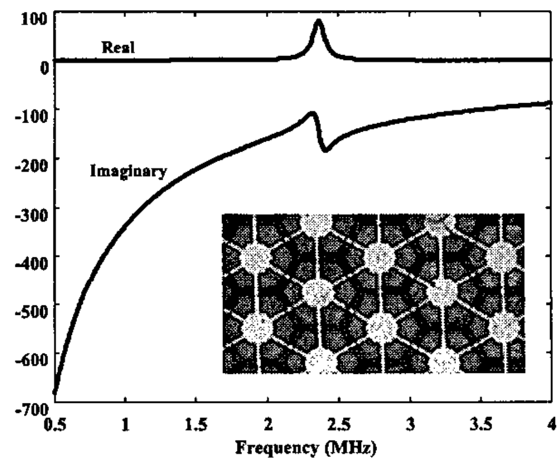

Figure 6. Input impedance of a CMUT with resonance frequency at 2.35 MHz.

B. Through transmission in air

Fig. 7 shows a through-transmission experiment performed in air using two identical CMUT transducers facing each other in a pitch-catch form. The transducers are biased using the same circuit described in the previous subsection. One of them is operated as a transmitter and the other one as a receiver with a front-end amplifier. A 3 mm thick aluminum (Al) block is placed between the transducers to measure the through-transmission. The separation between the transducers is 9 mm. The experiment is performed at 2.3 MHz. At this frequency, the total loss in air and in the Al block is calculated to be 87 dB, most of which is due to the impedance mismatch between air and Al. The received signal shown in Fig. 7 has 16 dB of signal-to-noise-ratio (SNR), without any signal averaging. This translates into a dynamic range of 103 dB per 1 V excitation on the transmitter without any matching neither in transmit nor in receive.

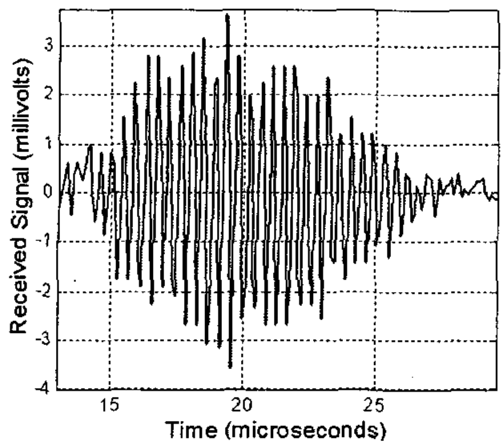

Figure 7. Through transmission experiment in air through a 3 mm thick aluminum block at 2.3 MHz.

C. *Pulse-echo in air*

For pulse-echo measurements, the transducer shown in Fig 3. is used. The input impedance of the device is depicted in Fig. 8.

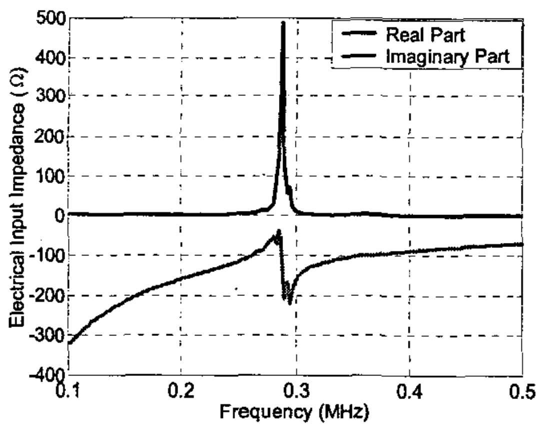

Figure 8. Electrical input impedance

The transducer is placed 1.06 meter away from a plane reflector and excited by a voltage pulse. The reflection is shown in Fig. 9. The sound speed in air is 344 m/sec. The time of flight is then approximately 6.17 msec. The pulse width is approximately 0.1 msec, which is determined by the quality factor of the transducer. This typical transducer has a Q of approximately 20 and the corresponding fractional bandwidth is 5 percent.

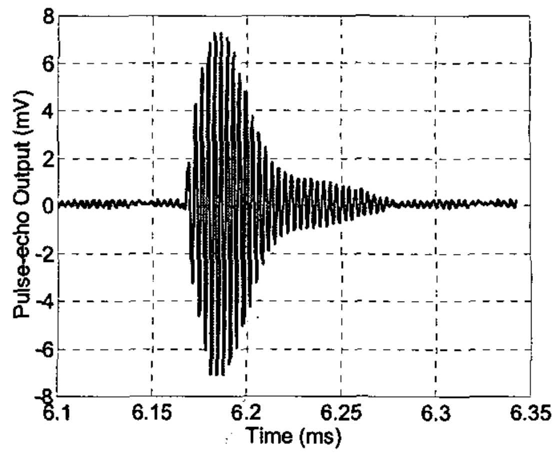

Figure 9. Pulse echo from a plane reflector.

V. DISCUSSION

As shown in the experimental part, micromachined capacitive ultrasonic transducers (CMUTs) could be very sensitive such that they enable systems with enough SNR to overcome attenuation in air at high frequencies. In section IV.B, we have shown the detection of ultrasonic waves through aluminum block over 100 dB dynamic range. Without aluminum block, this translates into 10 cm of propagation in air at 2.3 MHz. The ultrasonic pulse width is around 15 μsec. Therefore it is possible to use this transducer for ultrasonic ranging from 2 mm to 10 cm. On the other hand, the transducer demonstrated in section IV.C can detect ultrasonic reflections up to 10 meters. The pulse width is approximately 0.1 msec, corresponding to 15 cm of propagation in air. Therefore by using these two transducers one can detect distances from 2 mm to 10 meters. Since, simple lithography determines the membrane shapes and therefore the frequency response, one can integrate these two transducers on the same substrate. Moreover, micromachining allows fabrication of array of transducers. The above distance resolutions can be improved by several orders of magnitude with sensitive phase measurement systems.

VI. CONCLUSION

This paper describes capacitive micromachined ultrasonic transducers that could be used for ultrasonic ranging applications. In ranging applications, one of the common problems is that the increased attenuation of ultrasonic waves while propagating in air at high frequencies. The attenuation increases with the frequency limiting the maximum operation frequency. This results in reduced spatial resolution. CMUTs can be used to solve this problem. High dynamic range of the CMUTs allows them to operate high frequencies and they can measure reflections over long distances despite high attenuation in air.

ACKNOWLEDGMENT

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