CAPACITIVE MICROMACHINED ULTRASONIC TRANSDUCERS (CMUTS) WITH ISOLATION POSTS

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Abstract— **We report on a capacitive micromachined ultrasonic transducer (CMUT) featuring isolation posts (PostCMUT) to solve a device reliability problem caused by charging during fabrication and operation, and to extend the device operation range beyond collapse voltage. The PostCMUTs were fabricated using a newly developed process based on the wafer-bonding technique. Paired tests showed the superior reliability characteristics of the PostCMUT design compared to those of earlier CMUT designs. The PostCMUTs showed no hysteresis during membrane-post contact.**

Keywords- CMUT; Post; Charging; Hysteresis

I. INTRODUCTION

Extensive research and development efforts to commercialize the CMUT as an alternative to piezoelectric ultrasonic transducers have been carried out during the last decade [1, 2, 3]. Generally, CMUTs provide a wider bandwidth than current piezoelectric transducers [4]. However, there are still issues to be addressed, such as device reliability [5] and performance improvement—specifically, to increase their capability to image deep-laying structures in the body [6].

Like most MEMS devices [7, 8], CMUTs exhibit reliability problems in both their electronic and mechanical parts. Single crystal silicon membrane CMUTs [3] show improved mechanical reliability and yield compared to surface micro-machined CMUTs [1]. However, they still suffer from charging problems created by trapped charges in the thin dielectric layer (e.g. silicon nitride or dioxide) used to insulate the electrodes. The charges generated within this layer come from at least two possible sources. One is the fabrication process and the other is the strong electrical field created in the transducer cavities during operation. Charges can be trapped both in surface/interface states and in sites within the dielectric layer. These charges may interfere with both input and output signals, causing deleterious effects.

An increased imaging depth can be achieved by improving the transduction efficiency of the transducers. In order to improve the transmission/reception efficiency, the intensity of the electrical field in the device must be increased. In conventional CMUTs operating in the pre-collapsed region, the collapse voltage of the device [9] restricts the maximum electrical field intensity. CMUTs operated in the collapsed region have better TX and RX performance than those operated in the pre-collapse region. However, devices operated in the collapse region suffer from hysteresis [9]. PostCMUTs perform the same as conventional CMUTs in pre-collapse region. Their operation can, however, be extended past the collapse voltage, into the post-contact region, without hysteresis. This operation makes it possible to attain a higher output pressure than that attained in conventional region operation (but not as high as in collapsed region operation). Most importantly, this gain in output pressure is possible without charging of the devices or hysteresis in the device operation.

This paper reports on the design, fabrication and characterization of PostCMUTs. The main emphasis is on the ultrasonic characterization of the PostCMUTs. Paired tests have recently indicated the superior reliability characteristics of the PostCMUT design, compared to those of earlier CMUT designs [5]. The PostCMUTs also showed no hysteresis during membrane-post contact.

II. Device Design, Fabrication and Characterization

The basic structure of a CMUT is a parallel plate capacitor with a rigid bottom electrode and a top electrode that resides on a flexible membrane. The membrane is used to transmit and detect acoustic waves in the adjacent medium [3]. To prevent the devices from shorting, a conventional CMUT has at least one dielectric layer that fully covers one of its electrodes. In contrast, the PostCMUTs have one or a few oxide posts. The posts are of desired height, size and location so that they substitute for a dielectric isolation layer between their electrodes. Figure 1(a) shows the schematic cross-sectional view of a PostCMUT.

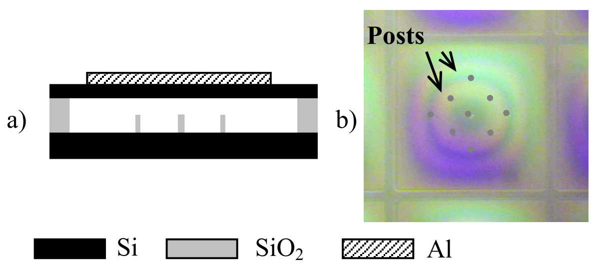

Figure 1. a) Cross-sectional view of a PostCMUT. b) Photograph of fabricated devices with 9-point post patterns.

There are three design criteria for PostCMUT designs: 1) the area of the oxide posts should be small enough so that charges trapped in them have a negligible effect on device operation; 2) the configuration of the posts should prevent the devices from shorting in the entire region of operation; and 3) if post contact operation is required, the configuration of the posts should provide, without hysteresis, the frequency response desired after the membrane makes contact with the post.

Because they are difficult to manufacture using surface micro-machining techniques, the PostCMUTs were fabricated by a newly adapted wafer-bonding technique [3]. The PostCMUTs were fabricated as described earlier [3] with one additional lithography step: patterning the silicon oxide layer using a designed post-feature mask. Fig. 1(b) shows a photograph of a device with a 9-point (3 µm by 3 µm) post pattern. PostCMUTs were fabricated with single crystal silicon membranes. The square membranes were 1 µm thick and either 88 µm or 102 µm on a side.

PostCMUT characterization includes capacitance-bias voltage (CV), and ultrasonic transmission (TX) and reception (RX) measurements. To characterize the devices, capacitance measurements and ultrasonic pitch-catch and pulse-echo measurements were made in vegetable oil. In the capacitance measurements, a negative DC bias source and a signal generator were used to generate a 5 kHz, 60 mVp-p, AC signal. An oscilloscope was used to measure the signal from a voltage divider consisting of a 130 kΩ resistor and the CMUT.

In the TX measurements, the distance between the hydrophone and the CMUT transmitter was 10.96 mm (Seki = 1.05). A 2.5 MHz sinusoidal wave train with 30 cycles and amplitude of 5 V was applied to the CMUT. The hydrophone (PZT-Z44-0400, Specialty Engineering Associates) was positioned by an Aerotech HDZ2 linear translation stage with an accuracy of 1 µm. Before it was read into the oscilloscope, the signal from the hydrophone was amplified by a 17 dB, 10 kHz to 25 MHz, 50 Ω preamplifier. The transducers were aligned so that a maximum reception voltage was obtained.

In the RX measurements, the distance between the PZT transducer and the CMUT was 86.1 mm. A 2.5 MHz, 5 Vp-p sinusoidal, 35-50 cycle wave train was applied to the transmitting 12.5 mm diameter Panametrics V109 circular flat focus transducer. The amplitude and bandwidth of the transmitted signal were measured as a function of bias voltage, and the received signal amplitude was measured as a function of applied AC amplitude. A reception calibration experiment was carried out to calculate the sensitivity of the CMUT. Here, in order to determine the acoustic pressure generated by the PZT onto the CMUT surface, the CMUT was exchanged for the hydrophone.

With conventional CMUTs, the CV curve shifts during initial tests due to a redistribution of trapped charges caused by the fabrication process. An 80 hour, 30 VDC and 140 VAC, 2 kHz spiking paired test caused conventional CMUTs to show either a shift in their operating point or permanent stiction of their membrane to the bottom electrode [4]. These effects were due to the field from induced charges trapped in the oxide layer. In contrast, such charging was not observed with the PostCMUTs. The CV curve of the PostCMUTs looked almost identical in the initial test and after the pulse test.

No hysteresis was observed after the membrane had been in contact with the posts, either in the ultrasonic transmission tests, Fig. 2, or in the reception tests, Fig. 3. Thus, the PostCMUT design remedied the hysteresis seen with conventional CMUTs operating in the collapsed region.

Comparing Figs. 2 and 3, the PostCMUT and the conventional CMUT show comparable performance before membrane-post contact. After contact, the PostCMUT allowed application of a higher bias voltage, and hence, a corresponding performance increase without inducing hysteresis or charging. Compared to conventional CMUTs operated in collapsed region, the PostCMUTs showed a slightly smaller transmission and reception efficiency, but also negligible hysteresis and charging. We measured a transmission efficiency during contact of 6.25 kPa/VAC, and a reception sensitivity of 8.25 mV/kPa. Both measurements were made at 70 VDC, with a 2.5 MHz signal. The uncorrected fractional bandwidth was 163%, with the same bias in transmission.

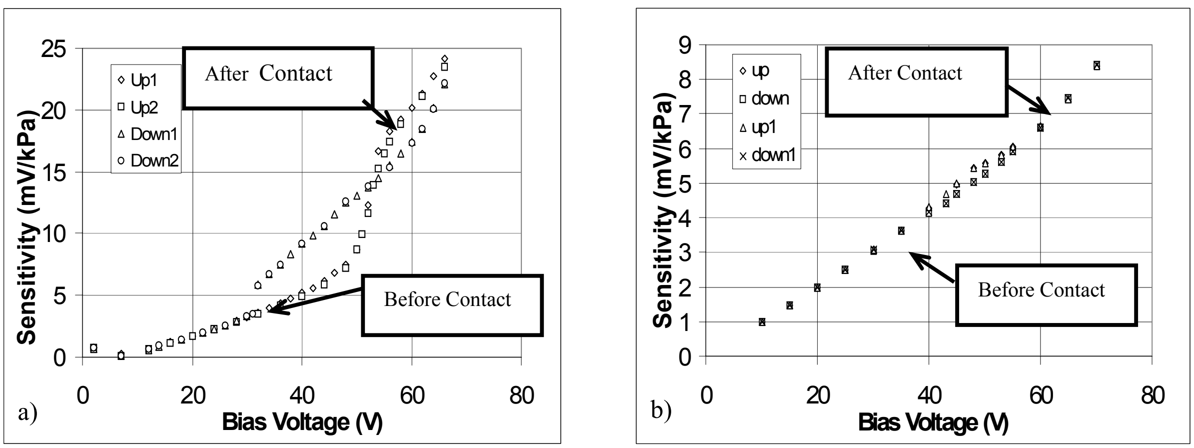

Figure 2. Ultrasonic reception by CMUT as a function of bias voltage. Source: a PZT transducer with a constant output. a) Conventional CMUT: hysteresis is evident after membrane-bottom electrode contact (collapsed region operation). b) PostCMUT: good repeatability and no hysteresis after membrane-post contact.

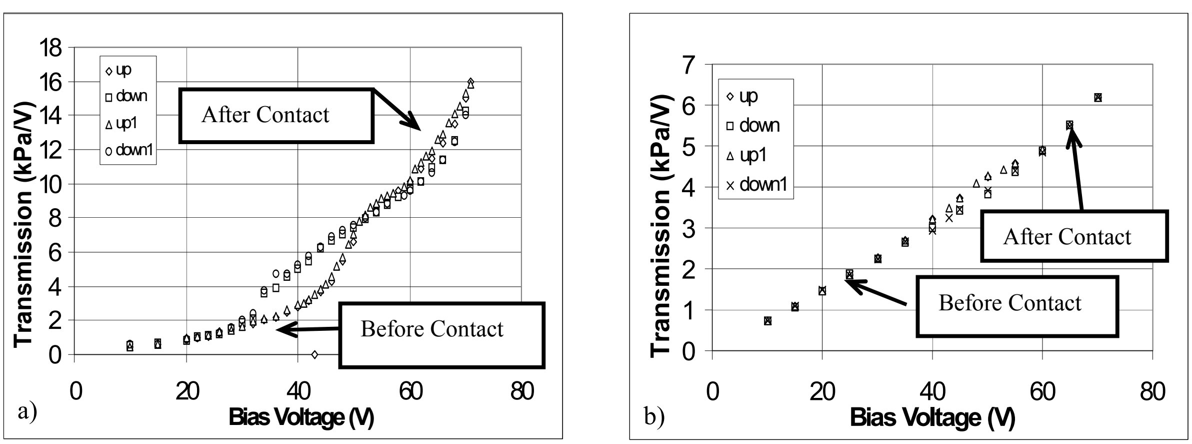

Figure 3. Ultrasonic transmission by CMUT received by a broad band hydrophone as a function of bias voltage. a) Conventional CMUT: hysteresis is evident after membrane-bottom electrode contact (collapsed region operation). b) PostCMUT: good repeatability, normal looking curve shape and no hysteresis after membrane-post contact.

In pre-collapse, 35 VDC, the corresponding numbers were 2.75 kPa/VAC transmission efficiency, 3.75 mV/kPa reception sensitivity, and 123% uncorrected fractional bandwidth. Waveforms transmitted and received by the PostCMUTs are shown in Figs. 4 and 5.

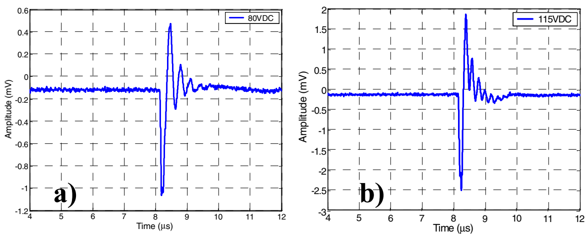

Figure 4. Transmission pulses obtained by a hydrophone from a PostCMUT operating a) before contact and b) after contact. The input AC signal was a 5V step function.

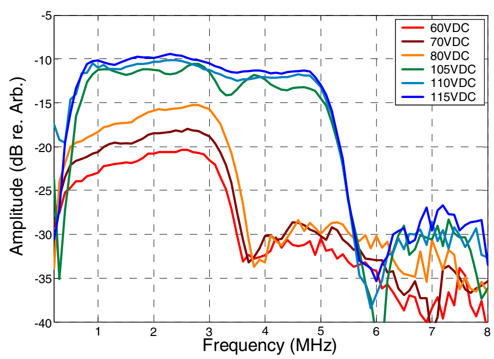

Figure 5. Transmission spectrum (uncorrected) of a PostCMUT at different bias voltages.

III. Conclusion

The results indicate that incorporating isolation posts into the CMUT design could solve the device charging problem seen in conventional CMUTs. No deleterious side effects of the new design were observed in the ultrasonic tests. The PostCMUTs were fabricated using a slight modification of a newly developed process based on the wafer-bonding technique, which improved the reliability of CMUTs.

The experimental results obtained with the PostCMUTs showed that they provide gains in maximum output pressure and reception sensitivity, compared to CMUTs operating in the conventional region. The fractional bandwidth of the PostCMUT was greater than the bandwidth of CMUTs operated in the conventional region.

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