A 2D CMUT Hydrophone Array: Characterization Results

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Abstract— **As the use of ultrasonic transducers has increased so has the need to measure and characterize their pressure fields. Currently available hydrophones are limited by long scan times, and multiple source pulses to measure large area fields. Using a 2D capacitive micro-machined ultrasonic transducer (CMUT) array and associated electronics we are able to improve on these limitations. The CMUT inherently allows for a tunable sensitivity by changing DC bias. Motivated by the need to improve the characterization of megasonic cleaners used in semiconductor processing we were able to implement such an area hydrophone.**

Keywords: Hydrophone, CMUT, Array, Megasonic Cleaning

I. Introduction

The development of hydrophone technology has not been as fast as the increase in ultrasound applications. Yet to ensure safety the ultrasound pressure field needs to be characterized and measured before widespread use. Ultrasound fields are currently characterized using piezoelectric and optical fiber hydrophones. The current hydrophones are limited by small apertures which require long mechanical scans to measure large fields. These scans require multiple pulses from the same source which may not be uniform from pulse to pulse. Also, the mechanical motion of the hydrophone can disturb the medium and thus the field pattern that is being measured. Current hydrophones are also limited by fixed sensitivity and dynamic pressure range. Lastly current hydrophones are not easily packaged to operate in non-ideal environments.

Many applications could benefit from improvements in hydrophone technology. For example the sonic field is almost never characterized for megasonic cleaning equipment used in semiconductor manufacturing. In semiconductor manufacturing yield is critical so any damage generated during megasonic cleaning can be extremely costly. One major obstacle is that the small aperture and shape of current hydrophones cannot mimic the large disruption caused by the wafer or mask being cleaned. Another application is the characterization of medical transducers which is done in water tanks which do not perfectly match tissue [1]. Embedding hydrophones in tissue mimicking phantoms could provide better characterization. Measuring lithotripsy equipment suffers greatly from the pulse to pulse variation of the ultrasound source [2].

Using a capacitive micro-machined ultrasonic transducer (CMUT) as a hydrophone appeared as an extension from medical imaging. Array CMUTs with integrated electronics have been demonstrated for medical imaging [3]. Using an array architecture allows large areas to be measured without the need for mechanical scanning. Also, electronic switching means no motion artifacts are present during the area scan. By changing the DC bias on the CMUT the sensitivity and measureable pressure range can be tuned for the application of interest. CMUTs are inherently broadband and the bandwidth can be further increased with conventional and collapse mode operations. For all the above reasons the CMUT should make a very versatile hydrophone. With integrated electronics the CMUT has a better minimum detectable pressure than current hydrophones. Here a 2D CMUT array with integrated frontend electronics has been packaged, and calibrated as a hydrophone to demonstrate tunable sensitivity, pressure range, and area measurement. This work was motivated by the need to measure megasonic cleaners used in semiconductor manufacturing. Results for a test megasonic cleaner are presented.

II. Methods

A. Packaging

The first implementation of a 2D hydrophone based on a CMUT array used an existing array developed for medical imaging. The array which was reported on in [3] had 256 element arranged in a 16 x 16 grid. The element pitch was 250 µm giving a total measurement area of 4 mm x 4 mm. The array was flip chip bonded to an ASIC developed for medical imaging. The ASIC provides both transmit and receive functionality. For the hydrophone measurements only the receive functionality was used. The array and electronics were then attached and wire bonded to a ceramic chip carrier.

Next the array needed to be packaged as a hydrophone for measurements in de-ionized (DI) water. Exposed electrical connections on the top of the CMUT were protected by coating a 100 µm thick layer of Polydimethylsiloxane (PDMS) on the surface of the CMUT and chip carrier. After the PDMS coating the pulse-echo device response was maximum at 3.4 MHz with a 103% 6-dB fractional bandwidth. The PDMS

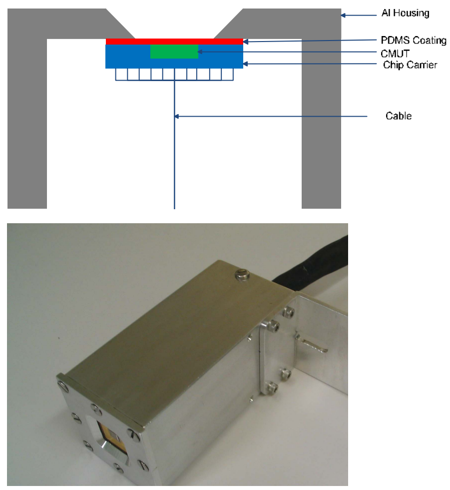

Figure 1. Diagram and picture of hydrophone package.

coated device was then bonded to an aluminum plate and housing. A read out cable was built as well. Fig. 1 shows a schematic of the transducer housing and an optical picture.

B. *Calibration*

The final preparation was to calibrate the array. To calibrate the CMUT a 2.25 MHz unfocused ultrasound transducer (Model: A306S-SU, Olympus-NDT Inc., Waltham, MA) driven at 1.86 MHz was used as a reference source. The frequency of 1.86 MHz was chosen for the application of characterizing megasonic cleaning equipment. The reference source was then measured with a commercial calibrated hydrophone (Model: Hydrophone HNP-0400 Pre-Amplifier AH 2010, Onda Corp., Sunnyvale, CA) at S = 1 to find the peak pressure output at this distance. The commercial hydrophone gave a mapping of input voltage of the reference source to the output pressure at S = 1.

Next the CMUT array was positioned over the same reference source at the same height and the output voltage of the CMUT was measured. Using a mechanical stage all 256 elements in the CMUT array were stepped to the same location above the reference source. By stepping to the same location the output voltage from each element was found for a given input pressure to the element. Knowing both values, output voltage and input pressure, a calibration look up table could be generated in units of V/Pa. The raw output voltage was then divided by the calibration data to produce a calibrated image of the acoustic field.

To test the calibration the reference source was mechanically scanned using the commercial hydrophone to obtain a reference beam profile. The mechanically scanned pressure field by the commercial hydrophone and the electronically scanned pressure field by the CMUT array are shown in Fig. 2. The lack of mechanical scanning did increase the speed of data acquisition. Also, by having no mechanical scanning there was no disruption of the measurement fluid. Thus another potential error source produced by the motion of the hydrophone in the medium was eliminated.

III. RESULTS

The sensitivity of the CMUT array can be tuned with changing DC bias as demonstrated during the calibration. The tunable sensitivity led to a tunable dynamic range. The maximum and minimum pressure ranges were set by the amplifier saturation and electronic noise, respectively. The output voltage of the CMUT hydrophone saturates due to amplifier saturation in the imaging electronics. By changing the DC bias the measurable pressure range of the device changes (Fig. 3). The sensitivity changed from 1 to 76 μV/Pa with a DC bias ranging from 0.95 to 30.85 V (Fig. 4). This array had a minimum detectable pressure of 1.8 mPa/√Hz at

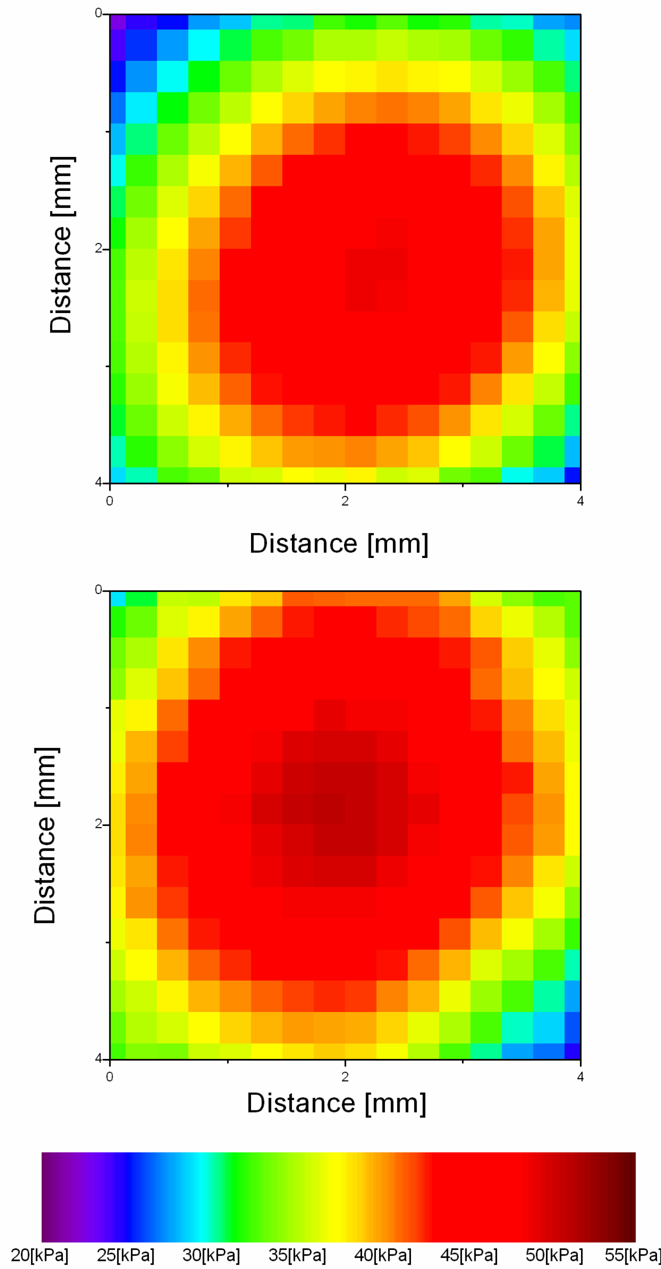

Figure 2. Mechanically scanned calibrated image (Top). Electrically scanned CMUT hydrophone image (Bottom)

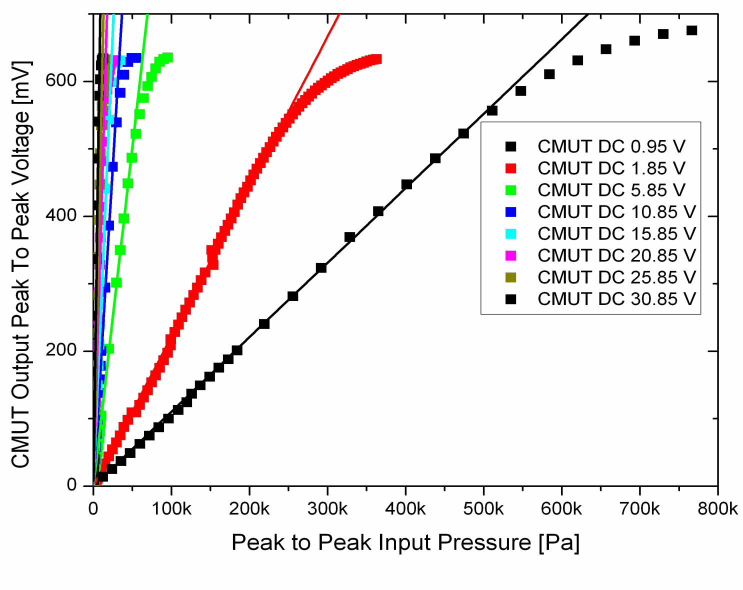

Figure 3. CMUT response as a function of input pressure and CMUT DC bias voltage. Linear fit to find sensitivity of device.

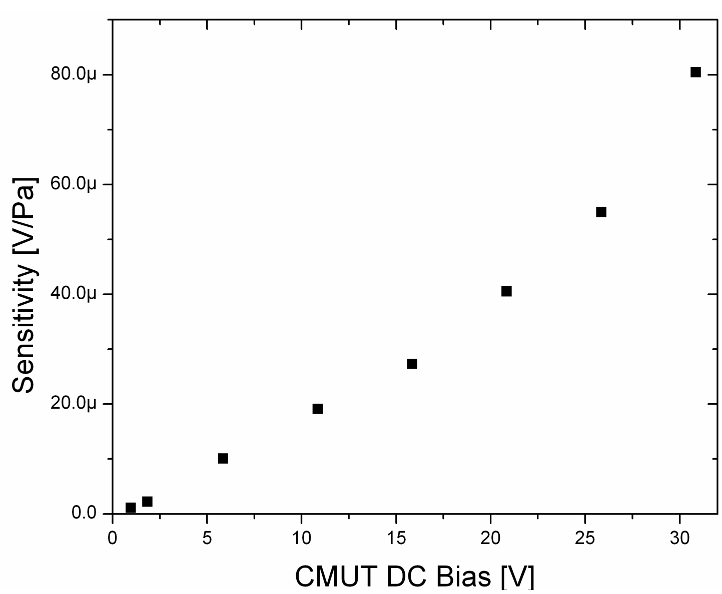

Figure 4. CMUT sensitivity as a function of DC bias.

30.85 V DC bias. The maximum detectable pressure for the CMUT array was 800 kPa peak to peak at 0.95 V DC bias. The peak pressure was measured at the 1-dB compression of output voltage due to the amplifier saturation. Some DC bias is necessary to obtain a good measurement. The minimum and maximum pressures both span two orders of magnitude with DC bias varying form less than 10 % to more than 90 % of the collapse voltage.

The CMUT hydrophone was used to measure the acoustic field in a commercially available megasonic cleaner (Model: Spot Shower, Kaijo Corp., Tokyo, Japan). The Spot Shower

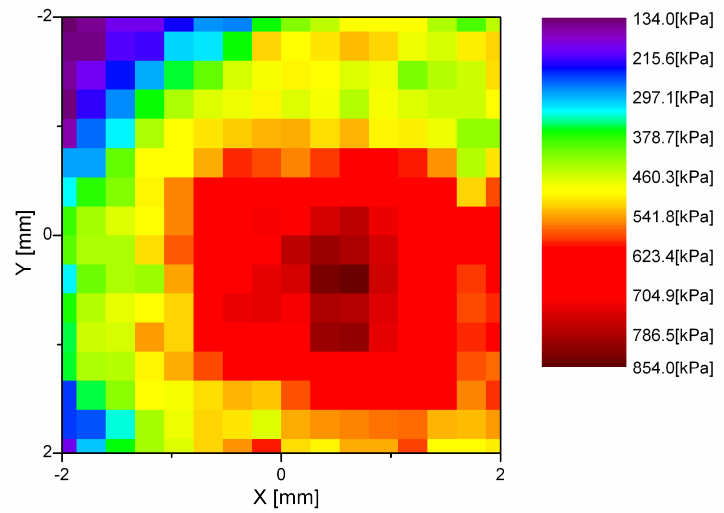

Figure 5. Spot Shower measured at 5 W of input power.

system operates at a frequency of 0.95 MHz. The calibration procedure described above was repeated at 0.95 MHz before measuring the Spot Shower. Measuring the field with a standard hydrophone is difficult and not representative of the surface of a wafer or mask. The Spot Shower system produces a circular jet of cleaning solution in this case DI water with a sonic field in the jet. The field from the Spot Shower is shown in Fig. 5 and was measured at 5 W of input power and a distance of 10 mm from the nozzle head. Measurements at different power levels and distances gave consistent results suggesting a circular source. Since a medical imaging transducer designed to measure low pressure was used in the first implementation, it was difficult to measure the high pressure fields used in megasonic cleaning due to amplifier saturation.

IV. Conclusion

It was shown in this work that the CMUT has been successfully implemented as a 2D tunable hydrophone. A wide range of sensitivities from 1 to 76 μV/Pa was demonstrated. Also an excellent minimum detectable pressure of 1.8 mPa/√Hz was measured. The array measured a 4 mm x 4 mm area with no mechanical scanning. The array was used to measure a megasonic cleaner which would be difficult with a commercial hydrophone.

Operating the CMUT array in receive only mode allows for greater flexibility in front end electronics design. Removing the transmit function from the electronics gives more space for output amplifier design. The output amplifier can be made with variable gain to further improve the measurable range of pressures and frequencies of the CMUT. The packaging flexibility of the CMUT array will allow the hydrophone to correctly match the boundary conditions in the desired application. This is critical in the characterization of megasonic cleaners where the presence of the wafer can significantly impact the pressure field. Several such arrays could be positioned on a silicon wafer to measure the pressure field across the entire wafer with nearly identical boundary conditions as the real wafers. By adjusting the DC bias of the CMUT the sensitivity of the hydrophone array can be optimized for the pressure range of interest. The CMUT array can measure a wide range of pressures and frequencies. The CMUT makes a perfect candidate for measuring area pressure distributions without mechanical scanning. The number of elements, element size, element frequency, and element sensitivity can all be optimized for high sensitivity and bandwidth for the desired application. The initial results from this first implementation are promising for CMUT array hydrophones.

ACKNOWLEDGMENT

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