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Kawasaki, Shinnosuke; Saccher, Marta; de Wijs, Willem-Jan ; van den Brand, Jeroen; Dekker, Ronald

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Shinnosuke Kawasaki
TNO/Holst Centre
Eindhoven, the Netherlands
shin.kawasaki@tno.nl

Marta Saccher
Delft University of Technology
Delft, the Netherlands
m.saccher@tudelft.nl

Willem-Jan de Wijs
MEMS & Micro Devices, Philips
Eindhoven, the Netherlands
willem.jan.de.wijs@philips.com

Jeroen van den Brand
TNO/Holst Centre
Eindhoven, the Netherlands
jeroen.vandenbrand@tno.nl

Ronald Dekker
MEMS & Micro Devices, Philips
Delft University of Technology
Eindhoven, the Netherlands
ronald.dekker@philips.com

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***Abstract*— Capacitive micromachined ultrasonic transducers (CMUTs) with a built-in charge layer are known as a pre-charged CMUT. In our prior work, we have shown how to model and characterize the charges inside the pre-charged collapse-mode CMUT and conducted life-time test that showed that the charges trapped inside the dielectric were stable in the order of years [1]. However, our prior work focused on the use of pre-charged collapse-mode CMUTs as a way to achieve ultrasound power reception, which does not require the CMUT to be actively driven. In this work, for the first time we use pre-charged collapse-mode CMUTs with an Al_2O_3 charge-trapping layer to create a B-mode ultrasound image. Thus, this work shows the first example that pre-charged collapse-mode CMUTs can fully operate with only an AC voltage.**

***Keywords*— CMUT, pre-charged CMUT, wearable ultrasound**

I. Introduction

The wearable medical patch market is projected to grow at at CAGR (continuous annual growth rate) of 23 % and up to nearly USD 3 billion by 2030 [2]. With this increasing interest in wearable medical patches it is expected that wearable ultrasound transducers will be more common in the coming years [3]. The non-invasive and safe nature of ultrasound and its relatively portable hardware compared to other in-body imaging techniques (i.e. MRI, CT-scan, X-ray) makes them suitable for this emerging market. A broad application area is anticipated as well: ranging from intermittent monitoring of the human bladder volume for incontinence care [4] to continuous monitoring of the cardiac functions for managing critically ill or surgical patients [5].

Such wearable ultrasound technology will need to have a light weight, wearable form factor and ideally be operated by a battery. Thus, the development of an ultrasound transducer technology with a small footprint with high transmit and receive efficiency is essential. In this regard, micromachined ultrasonic transducers (MUTs) will play a prominent role in this market. A MUT consists of a membrane that is suspended over a vacuum gap that can be electrostatically or piezoelectrically actuated. The former is known as the CMUT (capacitive micromachined ultrasonic transducer) and the latter being the PMUT (piezoelectric micromachined ultrasonic transducer). In comparison to traditional bulk piezoelectric transducers (bulk PZT), this technology has the important advantage that it can be manufactured at scale through silicon based microfabrication techniques while not requiring extensive matching and backing materials making the transducer component lighter and smaller.

In terms of acoustic performance, in recent years CMUTs have improved significantly to compete with traditional bulk PZT [6]. However, the drawback of using a CMUT is that it requires a DC bias voltage (≈100 V). This means that although the size of the transducer itself is smaller compared to bulk PZT, it requires additional resistors and capacitors to decouple the AC and DC voltage along with protection diodes to prevent undesired short circuiting events making the overall size including the electronics to be large. Furthermore, additional DC bias voltage generators will be needed which will increase the size of the peripheral electronics. As a result, compared to a bulk PZT or PMUT which natively works with only AC signals, CMUTs require additional electronics making the implementation more complicated. Finally, from a safetey prespective, it is concerning to have a high DC bias voltage source on the body especially for wearable applications.

Alternatively, pre-charged CMUTs [1], [7], [8] could be used. These CMUTs have a charge trapping layer in the dielectric between the top and bottom electrodes. Charges are trapped into the charge layer after the fabrication of the device by tunneling electrons from one of either the top or bottom electrode. This internally built-in charge acts as an internal DC bias voltage, such that the CMUT only requires an AC signal during its operation.

In our prior work, we have shown that such devices could be modelled with an electric polarization inside the dielectric material similar to an electret microphone [1]. Furthermore, the transmit (8.8 kPa/V) and receive sensitivity (13.1 V/MPa) was high enough for imaging applications and we showed that the retention of the charges is in the order of years. In this work, we present the first ultrasound image acquisition with pre-charged collapse-mode CMUTs.

II. Material and Method

The CMUT arrays used in this work consist of 128 elements. In each element, 56 circular cells with a diameter of 135 µm are connected in parallel. The elevational length of each element is 7.6 mm with a lateral pitch of 140 µm. The detailed layer stack and fabrication method of the CMUT can be found in [1]. After the CMUT was fabricated, the CMUT die was wirebonded to a PCB substrate and coated with a thin PBR (polybutadiene rubber) layer. This forms the transducer module as shown on the left of Fig.

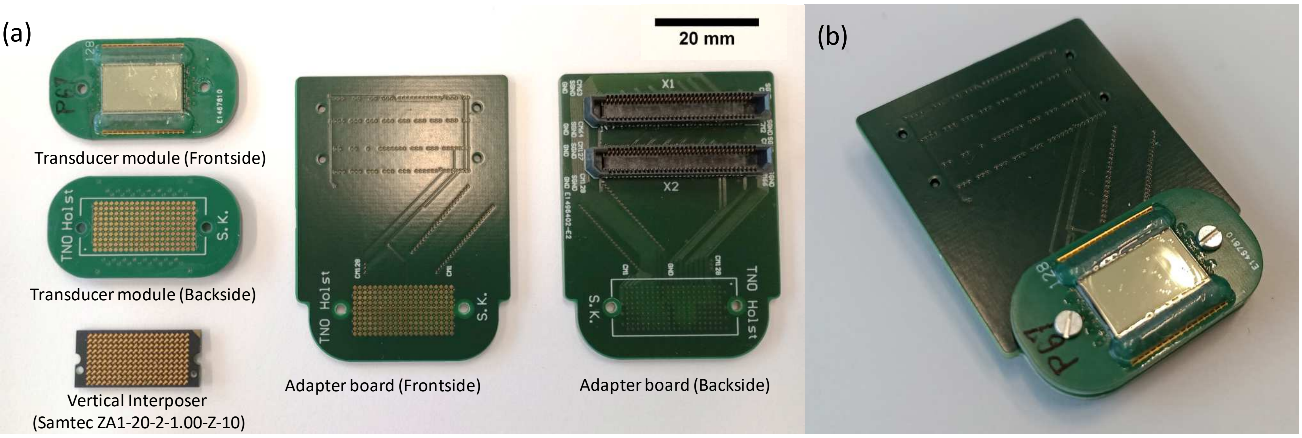

Fig. 1. (a) The individual components (transducer module, adapter board, and the vertical interposer) used to make the ultrasound image. (b) The assembled transducer module ready for imaging.

1(a). The PCB substrate was designed such that it routed all of the ultrasound signals from the CMUT to the gold pads on the backside of the PCB as shown in the same figure. Then a vertical interposer (SAMTEC ZA1-20-2-1.00-Z-10) was used to route the signals to another adapter PCB which then connected to the ultrasound driver system. The assmebled module can be seen in Fig 1(b). This modular design was used in this work to acheive maximum flexibility to connect to different ultrasound driver systems by simply redesigning the adapter board. The parasitic capacitance caused by the short interconnects on the transducer module is negligible compared to the capacitance of the CMUT elements.

A probe station was used to probe the individual gold pads on the backside of the transducer module to charge half of the aperture (i.e. 64 elements). The DC bias voltage corresponding to an electric field strength of 8 MV/cm in the dielectric layer stack, which was previously demonstrated to produce pre-charged collapse-mode CMUTs [1]. The charging time was adjusted for each element by measuring the impedance spectrum (Keysight 4294A, U.S.A) and by confirming that all of the CMUTs were in collapse-mode. Fig. 2 shows the CMUT die after charging the right side (64 elements) of the aperture. The region where the CMUT is in a pre-charged collapse-mode state has a difference in the membrane height of 500 nm. This can be seen from the difference in reflectance of the ambient light.

Finally, the ultrasound transducer was connected to a Cicada 64 ultrasound system (Cephasonics, U.S.A) to acquire ultrasound images and to check the influence of the ultrasound parameters in the CUSDK software to the image quality.

III. Results and Discussion

Fig 3. shows the resonance frequency of a pristine CMUT measured with an impedance spectrum analyzer in air with respect to an external bias voltage. This figure shows that the CMUT goes into collapsed-state at 50 V because there is a jump in the 1st order resonance frequency at this voltage. Then, another third order resonance peak appears at a higher frequency (5 MHz). The frequency then increases with the external bias voltage because the suspended membrane region decreases. Table 1 shows the result of the bandwidth measurement of the CMUT. For this measurement, the impulse response was measured from a pristine CMUT when an external DC bias voltage was swept from 60 V to 100 V in steps of 10 V and for a pre-charged CMUT. A fiber optic hydrophone (Precision Acoustic, UK) was positioned at 2.6 mm distance from the CMUT and 6 ultrsaound elments were connected in parallel. The impulse response showed that the center frequency of the CMUT is between 4.74 MHz to 6.31 MHz depending on the external bias voltage. In comparison, the center frequency of the pre-charged CMUT was 5.1 MHz. Thus, we can see that the effective amount of internal bias voltage is nearly 60 to 70 V.

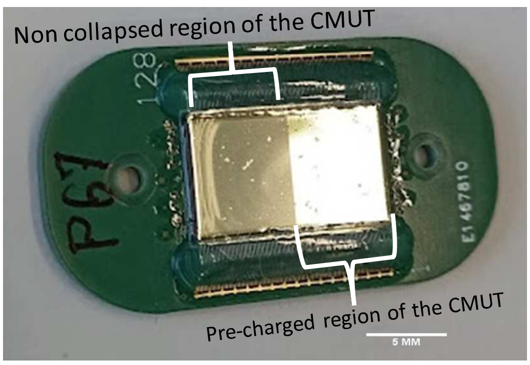

Fig 2. Pre-charged CMUT array after charging. The device in collapse-mode can be seen clearly in the ambient light reflection,

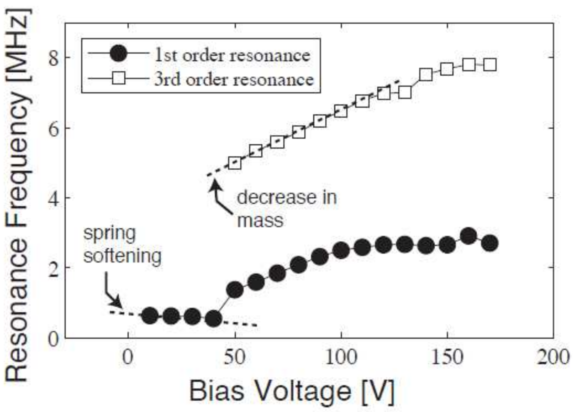

Fig. 3. Resonance frequency with respect to bias voltage of the CMUT

Table 1: Bandwidth measurement result of CMUTs

Bias Voltage [V]	f_1 [MHz]	f_c [MHz]	f_2 [MHz]	-6dB Bandwidth [%]
60	1.93	4.74	7.54	118
70	2.07	5.0	7.93	117
80	2.1	5.8	9.5	128
90	2.6	6.2	9.75	115
100	2.71	6.31	9.9	114
pre-charged CMUT (negative)	2.2	5.1	7.9	113

Fig. 4 shows the UltraiQ general purpose phantom (Cablon medical, the Netherlands) that was used for the imaging experiment. Fig. 5 shows the B-mode ultrasound image that was taken at 4.8 MHz with 3 cycles of unipolar 30 V amplitude on a phantom with a repetition frequency of 1 kHz. The polarity of the applied voltage was opposite to the polarity that was used for charging the CMUT device. This guaranteed that the applied voltage was working additively to the built-in bias voltage. The frequency was selected within the bandwidth of pre-charged collapse-mode CMUT and it also showed the cleanest ultrasound image. In this image the reflectors could be clearly distinguished down to 4 cm depth. The depth was limited due to the electrical noise in the system that could be seen as the white region streaming from the bottom of the image. This may be caused by the long cable length (1.5 m) between the Cicada 64 ultrasound system to the transducer module. This should be greatly improved by shortening or shielding the cable. In addition, applying an acoustic lens to focus the ultrasound signal in the elevational direction will increase the acoustic output from the transducer module which should futher enhance the image quality at larger depths. In this image, the larger echoic reflectors at 2.5 cm depth can be seen while the anechoic reflectors are a bit more difficult to distinguish. This was because the image was centered only at the smaller reflecting elements along the center of the transducer array. A video was taken at 29.3 fps and in this video, a rocking motion is applied where the larger anechoic and echoic reflectors can also be seen [9]. The two bright lines that are coming from the top of the image near the transducer are due

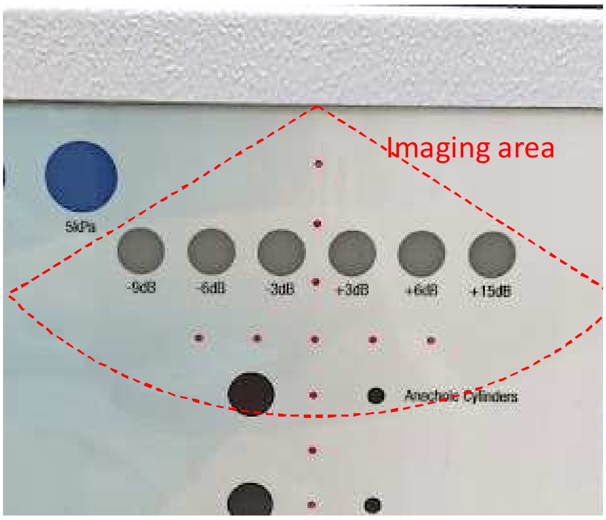

Fig 4. Picture of the ultrasound phantom

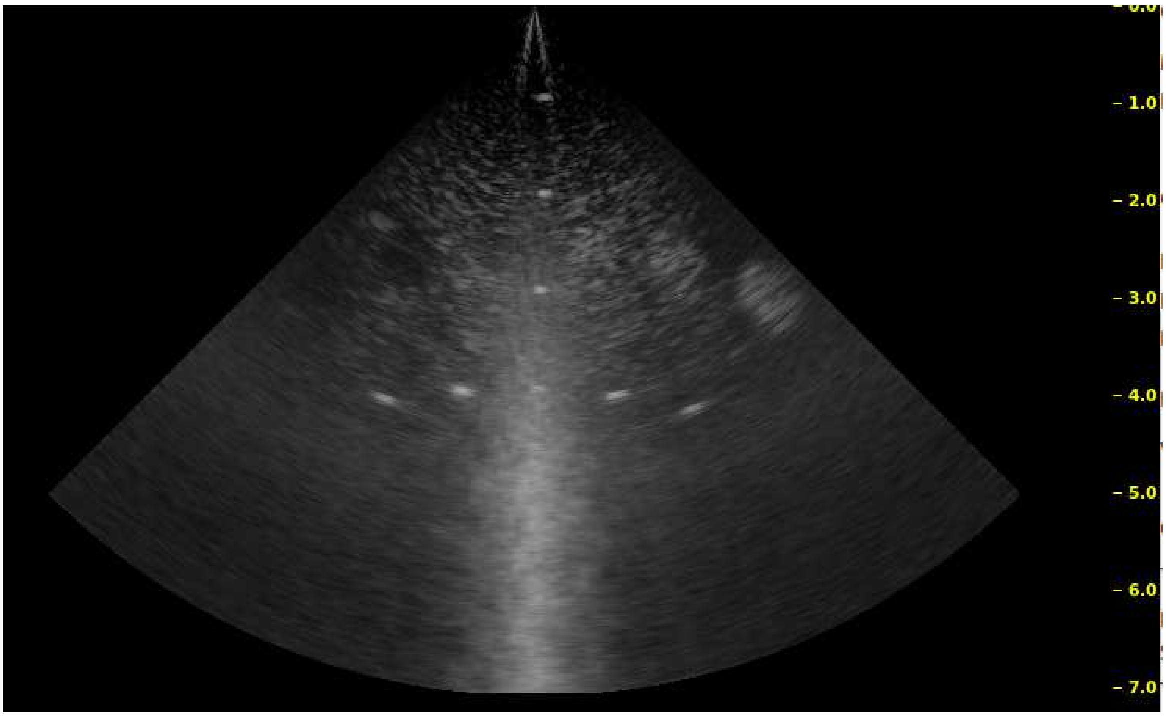

Fig 3. Ultrasound imaging result using pre-charged collapse-mode CMUT.

to the two broken CMUT elements during the charging process.

IV. Conclusion

This work for the first time showed that pre-charged collapse-mode CMUTs can be used for ultrasound imaging. The internal charges that were trapped within the CMUT were stable enough against the external AC voltage making the CMUT a purely AC operating device. This opens vast opportunity for pre-charged collapse-mode CMUTs as a complete replacement for bulk-PZT while having a smaller footprint. Applications such as wearable ultrasound, minimally invasive catheters, and implantable ultrasound devices will greatly benifit from this work because of the elimination of the high DC bias voltage.

For future work an accurate way to control/monitor the amount of internal charge inside the CMUT is needed. Finally, the most significant contribution of this work is that the concept of a built-in charging layer can be easily translated to different collapse-mode CMUT designs that operate at different frequency ranges, without impacting the performance of the device.

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