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Pre-charged collapse-mode capacitive micromachined ultrasonic transducer (CMUT) for broadband ultrasound power transfer

Shinnosuke Kawasaki[1*], Youri Westhoek[1], Indulakshmi Subramaniam[1], Marta Saccher[1], Ronald Dekker[1,2**]
[1]Department of Microelectronics, Delft University of Technology, the Netherlands,[2]Philips Research, the Netherlands
[*]shinnosuke.kawasaki@philips.com, [**]ronald.dekker@philips.com

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***Abstract*— Using ultrasound to power deeply implanted biomedical devices is a promising technique due to its low attenuation in body tissue and its short wavelength that allows precise focusing of the energy. Ultrasound energy harvesting conventionally has been done using lead zirconate titanate (PZT) ultrasound transducers, which uses the piezoelectric effect to convert mechanical vibration to an electrical voltage. However, PZT is typically bulky, and is not bio-compatible, and cannot be monolithically integrated with application-specific integrated circuits (ASIC).**

In this work, a pre-charged collapse-mode capacitive micromachined ultrasonic transducer (CMUT) was fabricated to harvest ultrasound energy. The pre-charged CMUT has a high power transfer efficiency over a wide bandwidth at optimal loading conditions; 43 % at 2.15 MHz and 47 % at 5.85 MHz. For the last 1.4 years, the device has been in collapse-mode, and it is still functional without any additional charging. This device will enable the development of smaller implantable biomedical devices in the future.

***Keywords*— Ultrasound power transfer, capacitive micromachined ultrasonic transducer, pre-charged CMUT, zero-bias transducers**

I. INTRODUCTION

Implantable biomedical devices (IMD) are becoming smaller, smarter, and more energy efficient. Yet, one of the significant challenges for these devices is the large volume of the battery. For example, cardiac pacemakers and vagus nerve stimulators have a battery positioned at the infraclavicular area. The lead at the stimulus location is connected to the battery by a cable that runs through the body. The complexity of the lead, cable, and battery increases the potential for infection during the surgery. Therefore, significant research interest has been devoted to the development of wireless power transfer techniques that could recharge the IMD from outside of the body, relaxing the requirement for the battery, therefore enabling the development of smaller and leadless implants [1]. Several methods have been investigated to wirelessly transfer power into the human body which are, ultrasound, radiofrequency (RF), and inductive coupling. Among them, ultrasound offers the best trade-off to power deep miniaturized IMDs due to its low attenuation through body tissue and its short wavelength, allowing precise focusing of energy to deep locations within the body.

Lead zirconate titanate (PZT) is conventionally used for ultrasound transducers. However, PZT is not biocompatible and will require a hermetic encapsulation for long term use within the body. In addition, PZT is typically bulky and requires specialized assembly process to integrate it with miniature IMDs such as dicing or wire bonding. This leads to an increase in the device's overall size and limits the scalability of the technology. Advancement in microfabrication techniques, accelerated the development of Micro-electro-mechanical systems (MEMS) based ultrasound transducers such as the broadband piezoelectric ultrasonic energy harvester (PUEH) [2]. PUEH uses microfabricated PZT diaphragm arrays to receive ultrasound power. Thus, they can be integrated more easily with ASICs compared to bulk PZT. B. Herrera et al. presented an AlN based piezo micromachined ultrasonic transducer (PMUT) replacing PZT material for a more biocompatible alternative. However, the reported efficiency was less than a percent [3]. Therefore, further investigation must be done to establish a biocompatible, highly efficient ultrasound transducer technology that can be monolithically integrated with an ASIC for the next generation of miniature IMDs.

In this work, we propose a pre-charged collapse-mode capacitive micromachined ultrasonic transducer (CMUT). A CMUT is a device with a top and bottom electrode. The bottom electrode is fixed to the silicon substrate, and the top electrode is suspended over the bottom electrode via a vacuum gap facing the medium. By applying an AC voltage to the two electrodes, ultrasound can be transmitted into the medium by vibrating the top electrode. In receiving mode, an external DC bias voltage is applied to the CMUT to transduce the movement of the top electrode into a displacement current. To increase the transmission and reception sensitivity, the CMUT is typically operated in collapse-mode, which is to apply a DC voltage of several tens of volts to pull the top electrode down to the bottom electrode. However, this voltage level is dangerous for an IMD. The pre-charged collapse-mode CMUT substitutes this external DC bias voltage with an internal charge storage layer embedded between the top and bottom electrode. The amount of charge trapped is sufficient to keep the CMUT in permanent collapse-mode.

The pre-charge CMUT fabricated in this work is biocompatible because they are passivated with a thick Si_3N_4 layer. Furthermore, the fabrication of these devices is done with standard IC-based fabrication process, which allows them to be monolithically integrated with an ASIC. An additional feature of these pre-charged CMUTs is their broadband performance which is not possible with bulk PZT transducers. The broadband performance is beneficial for an IMD for several reasons. First, depending on the depth of the implantation, the operation frequency could be adjusted; for a deeper implant, a lower frequency could be used, and for a miniature implant that requires accurate focusing, a higher frequency could be used. Second, by shifting the frequency, destructive interference at the CMUT can be avoided [2]. Finally, a communication link that exploits the broadband property of the pre-charged CMUT will allow communication strategies analogous to RF communication to be developed in the future.

In this work, the ultrasound power transfer efficiency was measured at two frequencies (2.15 MHz and 5.85 MHz). Preliminary results of charge retention for 1.4 years were also conducted, showing that this pre-charged CMUT would be a suitable candidate for miniature IMDs.

II. Sample Preparation

The CMUT fabricated in this work has a diameter of 135 µm. Compared to previously fabricated versions [4], the pre-charged CMUT includes a 200 nm thick Al_2O_3 for the charge storage layer between the top and bottom electrode. An Al_2O_3 layer was used as the charge storage layer for its known charging capabilities [5]. Figure 1 is the cross-sectional diagram along with the optical microscope view of the CMUT, showing part of the 56 rows and 128 columns of CMUTs that were fabricated. The device was mounted on a PCB where every 6 columns were connected in parallel to a single SMB connector. Therefore, one SMB connector was connected to a surface area of 6.3 mm^2 (0.84 mm × 7.56 mm). After the CMUT was fabricated, a DC voltage of 200 V was applied for 3 hours to pull the CMUT into collapse-mode, and charges were tunneled into the charge storage layer.

III. Result

A. *Characterization of the pre-charged CMUT*

A pre-charged CMUT can be modelled as a CMUT with an external DC bias voltage [6]. In this section, the value of

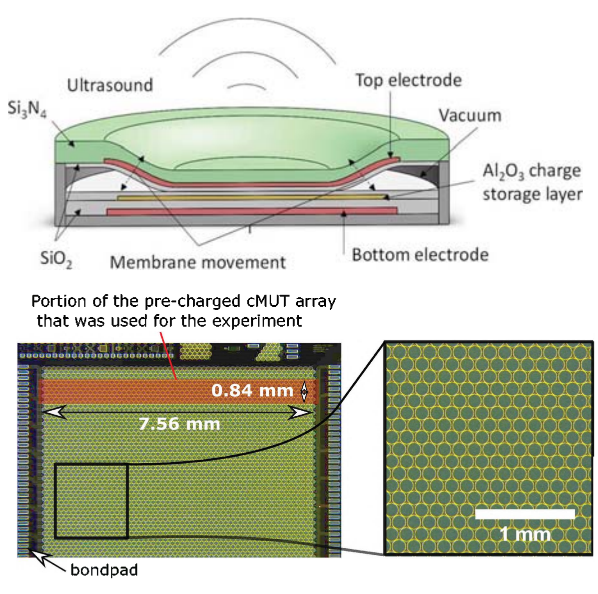

Figure 1 Cross sectional diagram of a pre-charged collapse-mode CMUT and an optical microscope photo of the ultrasound transducer.

the external bias voltage equivalent to the amount of charge trapped within the pre-charged CMUT was determined by comparing the impedance spectrums.

First, the bias voltage and the bias duration that initiates charge trapping within the pre-charged CMUT were measured. An external DC bias voltage was applied to a pristine CMUT via a 100 kΩ current limiting resistor, and the bias voltage was increased from 50 V in 25 V increments. For each bias voltage, the duration in which the bias was applied was increased from 0.1 seconds to 10 minutes. After the bias was applied, the two terminals of the CMUT were shorted to remove any stray charges. Next, the impedance spectrum was measured. The bias duration and the bias voltage were controlled by a programmable power source (Keithley interactive source meter model 2450). Within this experiment, the first change in the impedance spectrum occurred when the bias voltage reached 125 V for a bias duration of 5 minutes. A resonance peak at 566 kHz appeared in the impedance spectrum, indicating that charges were beginning to be trapped. This determines the beginning of the charging of the CMUTs. If the bias voltage or the bias duration does not exceed 125 V for 5 minutes, it would be possible to measure the characteristic of a CMUT without tunneling charges into the charge storage layer.

Second, the impedance spectrum of a CMUT with an external bias voltage was measured from 10 V to 120 V in 10 V steps. Each measurement was finished within 10 seconds, therefore below the 5 minutes threshold that was previously found to initiate charging. Figure 2 compares the impedance spectrum of the pre-charged CMUT with the 100 V externally biased CMUT. The impedance spectrums are nearly identical, meaning that the pre-charged CMUT has an equivalent external bias voltage of approximately 100 V

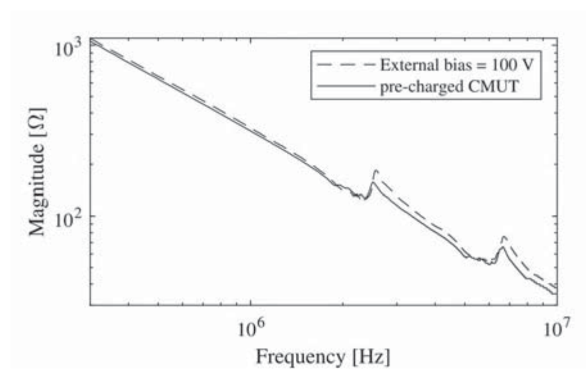

Figure 2 Impedance Spectrum of the pre-charged CMUT compared

B. *The bandwidth of the pre-charged CMUT*

An impulse response measurement could be used to determine the bandwidth of a CMUT. However, by applying an impulse signal, the amount of charge inside the charge storage layer may change. Since the equivalent bias voltage is known, instead of measuring the pre-charged CMUT directly, a CMUT with an external bias voltage was used to measure the bandwidth. The external bias voltage was increased from 60 V to 100 V in 10 V steps. The applied impulse signal was a positive pulse with a peak amplitude of 23.8 V and a fall and rise time of 19 ns and 35 ns, respectively. The acoustic pressure was measured with a calibrated hydrophone needle (Precision acoustics) that was positioned at a 2.5 mm distance from the pre-charged CMUT in water.

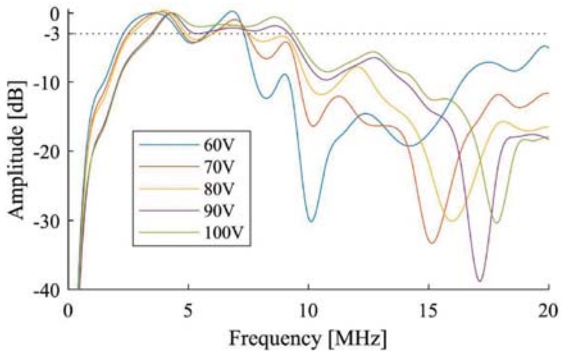

Figure 3 Impulse response showing the bandwidth of the CMUT for different external bias voltage.

C. *Maximum power transfer*

Figure 4 shows the equivalent circuit model when ultrasound is harvested with the CMUT. In this model, the electrical capacitance of the CMUT is represented as C_e, and the mechanical properties of the CMUT are described by the series connection of R_m, L_m and C_m, where R_m is the medium resistance, L_m and C_m expresses the resonating behavior of the CMUT. The incoming ultrasound is represented as a voltage source. A load composed of an inductor and a resistor connected in parallel was used. The reason for using such a load can be explained by the maximum power transfer theorem, which states that Z_{load}, must be equal to the complex conjugate of the source impedance Z_{source}, for maximum power transfer. From this electrical circuit model, Z_{source} is the series impedance of R_m, L_m and C_m, and Z_{load} is the parallel impedance of R_{load}, L_{load} and C_e. At resonance, L_m and C_m cancels each other, and the source impedance reduces to R_m. Therefore, C_e must be tuned out using L_{load} and R_m must be equal to R_{load}.

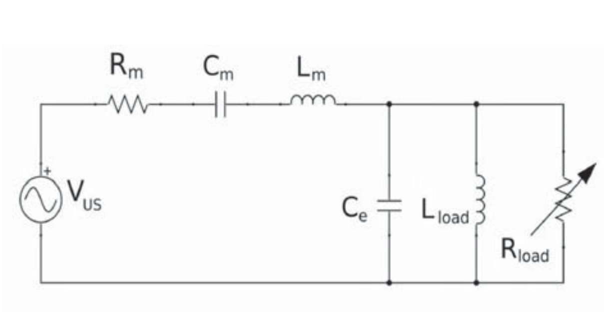

Figure 4 Equivalent circuit model of the CMUT during ultrasound power transfer.

Figure 5 is the experimental setup to measure the maximum power transfer. The two ultrasound frequencies tested were 2.15 MHz and 5.85 MHz. On the left side of the figure is the PZT transducer and on the right side is the pre-charged CMUT at 70.4 mm for 2.15 MHz and 176 mm for 5.85 MHz. The PZT transducer and the CMUT were aligned carefully using micromanipulators so that the natural focus of the PZT was at the surface of the CMUT. A burst signal was applied to the PZT transducer with an amplitude of 40 V and 10 cycles at a pulse repetition frequency of 10 kHz.

The C_e for the pre-charged CMUT was extracted from the impedance spectrum, which was 465 pF. For a matched condition, L_{load} was chosen with the following equation:

$$L_{load} = \frac{1}{2\pi f_{US}^2 C_e} \tag{1}$$

where, f_{US} is the ultrasound frequency. Based on this equation, the L_{load} required to tune out C_e at 2.15 MHz and 5.85 MHz was 9.1 μH and 1.3 μH, respectively.

Finally, Z_{source} must be equal to R_{load} for maximum power transfer. This was found by sweeping the R_{load} using a potentiometer and by looking for the maximum power point. The power consumed at R_{load} was calculated by $P = 1/8 R_{load} V_{pp}^2$ where, V_{pp} is the peak to peak voltage seen at the pre-charged CMUT. Figure 6 shows the result of sweeping R_{load}. From this figure, the maximum power harvested at the pre-charged CMUT was 420 μW for 2.15 MHz and 780 μW for 5.85 MHz. The values used for R_{load} and L_{load} are summarized in Table 1. It is important to note that the calculated power consumption assumes a continuous wave, while the experiment was done in bursts to avoid the influence of reflections. Therefore, the actual power should be scaled by the duty cycle.

The power transfer efficiency was calculated by measuring the incoming power to the pre-charged CMUT by replacing the pre-charged CMUT with a hydrophone and by scanning the pressure profile over the pre-charged CMUT area. The measured intensity profile was integrated over the entire surface area of the pre-charged CMUT to obtain the incoming power. From this measurement, the incoming power was determined to be 975 μW and 1650 μW for 2.15 MHz and 5.85 MHz, respectively. The acoustic to electrical conversion efficiency was 43 % and 47 % for 2.15 MHz and 5.85 MHz, respectively (see Table 1).

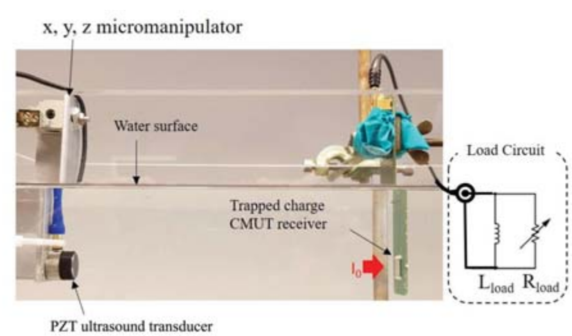

Figure 5 Experimental setup for testing maximum power transfer.

Table 1: Summary of the ultrasound power transfer measurement

f_{US}	Distance	Area	C_c	R_{load}	L_{load}	Harvested power	Incoming power	Efficiency
2.15 MHz	70.4 mm	6.3 mm^2	465 pF	1640 Ω	9.1 μH	420 μW	975 μW	43 %
5.85 MHz	176 mm	6.3 mm^2	465 pF	130 Ω	1.3 μH	780 μW	1650 μW	47 %

The optimal R_{load} was higher for 2.15 MHz than 5.85 MHz because 2.15 MHz is further away from the center frequency of the pre-charged CMUT, which increases the source impedance. Nonetheless, the energy conversion efficiency was only 4 % lower than when the CMUT was operated at 5.85 MHz, which further proves the broadband performance of the pre-charged CMUT.

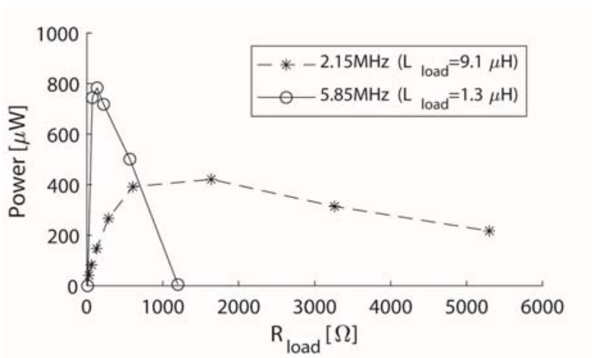

Figure 6 Ultrasound power transfer against load resistance.

D. Charge retention

Charge retention was studied by storing the pre-charged CMUT at room temperature. The impedance spectrum after 0.7 years and 1.4 years was measured. The initial amount of charge, which was equivalent to 100 V, decreased to 80 V after 0.7 years and then to 70 V after 1.4 years. During the total duration of the experiment, the pre-charged CMUT was occasionally tested in water to confirm that the device was functional. This result shows that the bandwidth of the CMUT will shift to a lower frequency as the charge leak from the charge storage layer. Nonetheless, at least for 1.4 years, the pre-charged CMUT has been in collapse-mode and has been able to receive power.

IV. Discussion and Conclusion

The -3dB bandwidth of the pre-charged collapse-mode CMUT was from 3.5 MHz to 9.4 MHz. If the application can allow lower efficiency, the pre-charged CMUT can operate beyond this bandwidth. This was shown by the power transfer efficiency experiment at 2.15 MHz which still exceeded a power transfer efficiency of 40 %. The efficiency that was achieved in this work was comparable to PZT transducers.

The operation frequency of the pre-charged CMUT was controlled by changing the matching inductor. This is interesting from a manufacturing perspective because the same pre-charged CMUT can be used at different ultrasound frequencies by simply changing the matching inductor. This will unify the fabrication process for different frequencies, unlike PZT transducers, where each frequency requires a different thickness of the PZT material to be fabricated. However, if we envision a single chip IMD in the future, which integrates all of the necessary electronics such as power harvesting capabilities and electrodes/sensors on a single chip, this additional matching inductor of several μH will become a bottleneck since ASICs cannot incorporate large inductances. This should be addressed in future work, perhaps by modifying the structure of the pre-charged CMUT to have a larger capacitance, thus reducing the matching inductance (see equation 1).

Finally, for a simple demonstration of ultrasound power transfer, a video was recorded powering a green LED (≈ 1 mW) using ultrasound, which can be seen in the following link [8].

Acknowledgement

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