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The long-term reliability of pre-charged CMUTs for the powering of deep implanted devices

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***Abstract*—Recently, focused ultrasound has been proposed to power deeply implanted medical devices. Almost exclusively, lead zirconate titanate (PZT) transducers are used to convert acoustic energy into electrical energy. Unfortunately, these lead containing devices cannot be hermetically encapsulated since that would block the ultrasound. We propose the use of biocompatible Capacitive Micromachined Ultrasonic Transducer (CMUT) elements to replace traditional PZT transducers. In addition, to eliminate the external bias voltage, we introduced a charge trapping Al_2O_3 layer inside the CMUT to create a built-in bias voltage. These devices can be pre-charged and used as a receiver for US power. In this work, the viability of charged CMUTs to power deep implants was explored by investigating the effect of the charging parameters and by performing Accelerated Lifetime Tests (ALT). The estimated lifetime at body temperature ranges between 2.5 to 3.5 years at body temperature, which significantly depends on the charging parameters.**

Keywords—capacitive micromachined ultrasound transducers, pre-charged CMUT, zero-bias transducers, ultrasound power transfer, accelerated lifetime test

I. Introduction

Implantable medical devices are revolutionising the world of medicine, and thanks to the progress in technology and materials they are becoming smaller and smarter, allowing them to be placed near the area to be treated [1]. However, one of the biggest challenges is the miniaturisation of the power source. In the past decades, research focused on alternative methods to power deeply implanted devices and focused ultrasound has been demonstrated to be the best trade-off compared to other methods such as inductive coupling or radio frequency (RF) [2]. Due to its short wavelength and low attenuation within the body, ultrasound can be precisely focused, and energy can be delivered to large implantation depths (> 5 cm), requiring smaller sized receivers, in the order of few square millimetres.

One of the most common methods to convert ultrasound energy to electrical energy is to use lead zirconate titanate (PZT) material. However, these lead-containing devices require hermetic encapsulation for in-body use, which will significantly deteriorate the power conversion efficiency. Alternatively, polyvinylidene fluoride (PVDF), barium titanate ($BaTiO_3$) and other lead-free piezoelectric transducers can be made biocompatible, yet their piezoelectric constant needs further improvement compared to conventional PZT. In addition, both bulk thin film piezoelectric-based (e.g. aluminium nitride (AlN)) transducers and micromachined ultrasound transducers are being studied. The main advantage of CMUT is their compatibility at traditional ultrasound frequencies (< 1 MHz), whereas AlN films operate at frequencies > 100 MHz [3]. The higher the frequency, the higher the attenuation of ultrasound along its travelling path, hence lower frequencies needs to be used for optimal power transfer. Moreover, CMUTs can be seamlessly integrated in CMOS processes.

In this work, we propose the use of biocompatible pre-charged Capacitive Micromachined Ultrasonic Transducer (CMUT) elements as a receiver for ultrasound energy. CMUTs are composed of a top and bottom electrode, separated by a dielectric layer, that passivates the electrode, and a vacuum gap. In transmitting mode, an AC voltage is applied across the two electrodes, causing the top electrode to displace relative to the bottom electrode, generating acoustic waves in the surrounding medium. In receiving mode, a fixed DC voltage is applied between the two electrodes, and the incoming pressure wave vibrates the top membrane generating a displacement AC current. To perform in optimal conditions, CMUTs need an external DC bias voltage of 50 V to 150 V that keeps them in collapse mode. However, this is not suitable for in-body applications due to the very high voltages. To eliminate the need for an external bias voltage, we use a traditionally unwanted behaviour of dielectric charging in CMUTs to our advantage [4-6]. Therefore, by introducing a charge trapping Al_2O_3 layer inside the CMUT we created a built-in bias voltage.

The concept of charge trapping in the dielectric is not new, and it was studied in the past in the context of EEPROM memories and electrets, and, in recent years, in relation to RF MEMS switches [7-14]. However, the long-term reliability or the charge retention of these CMUTs has not been well understood. Recently, other groups have performed long-term measurements of pre-charged CMUTs. However, their research aimed to study the stability of the trapped charges in the dielectric rather than estimating the duration of the charge retention [15, 16].

In our past work, we have seen our pre-charged CMUTs perform well over time. As shown in [17], a preliminary lifetime test over 1.4 years was conducted. In this preliminary lifetime test, the devices were stored at room temperature and measured every few months. Impedance measurements were done to confirm that the devices were still operational and in collapse mode, hence able to receive power. Therefore, to estimate the viability of pre-charged CMUTs, Accelerated Lifetime Test (ALT) must be performed. Among the most common accelerated test conditions, high temperature was used as an accelerating factor. To estimate the lifetime of the devices in the body and at ambient temperature, ALTs were performed at temperatures ranging from 100 to 150 °C. In

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addition, the effect of different charging parameters on the performance of the devices was also investigated.

II. Experimental Procedure

A. Characterisation of the devices

The CMUTs used in this work have a diameter of 135 µm with a vacuum gap of 500 nm, and they include a 200 nm thick layer of Al_2O_3, used as a charge storage layer between the top and bottom electrode (Fig. 1). Each CMUT element investigated in this work is composed of 56 CMUT cells connected in parallel, and they do not have any coating layer on the top.

The CMUT elements were characterised by measuring the membrane profile with a Digital Holographic Microscope (DHM), and an impedance analyser (Keysight E4990A, 20 Hz - 30 MHz) was programmed to measure the impedance spectrum of the element under test at regular intervals of time during the entire duration of the experiment.

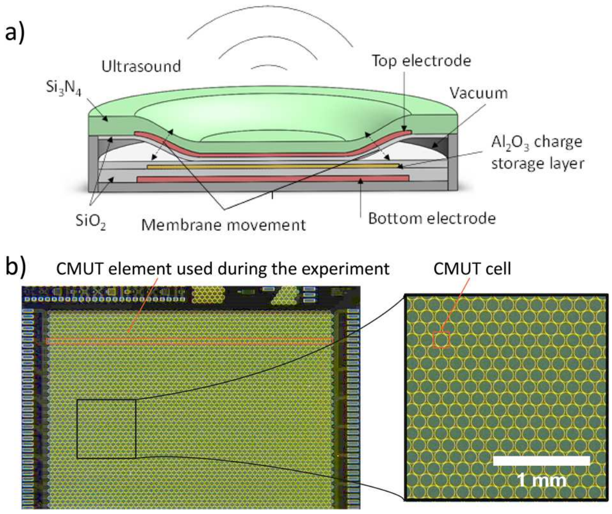

Fig. 1. a) Cross-section of a CMUT cell with an Al_2O_3 charge trapping layer. b) Microscope view of an array of CMUT elements

B. Pre-charging of the CMUTs

Pristine CMUT elements were charged at room temperature by applying an external DC bias voltage of 170 V, which is high enough to bring the CMUT into deep collapse mode, which is to have the top membrane touching the bottom layer such that the tunnelling of the charges begins. A programmable source meter (Keithley 2450) was used to control the charging duration.

C. High-temperature accelerated test

To perform the accelerated lifetime test, a probe station equipped with a programmable thermal chuck was used. The needles of the probe station were connected to the impedance analyser. The CMUTs were charged at room temperature after which they were brought at the test temperature, set on the thermal chuck. Each experiment was stopped at the failure of the CMUTs, defined as when more than half of the CMUT cells under test have gone out of collapse mode. Tests were performed at temperatures ranging from 100 °C to 150 °C.

III. Results and Discussion

A. Membrane profile shape

The membrane profile of the CMUTs measured with a DHM before and after the charging is shown in Fig. 2a. In this figure, the devices after charge show multiple rings of interference pattern which signify a larger deflection profile. Thus, whether the CMUT is charged or not can be distinguished by its larger deflection profile observed on the DHM. The membrane profile of a CMUT cell, when charged for different durations (0s, 60s, 300s, and 600s), is shown in Fig. 2b. In this figure, and in the following ones, the membrane profile is plotted with the reference at the rim of the CMUT cell. In addition, when the CMUT is unbiased, it has a slight deflection which is caused by the ambient pressure that is higher than the pressure inside the cavity. Increasing the charging time resulted in a larger part of the membrane in contact with the bottom, indicating a deeper state of collapse. However, the portion of the top membrane in contact with the bottom does not increase proportionally to the charging duration, reaching a plateau.

Fig. 2c shows a change in the membrane profile over time when the device temperature was kept at 150 °C. The membrane profile transitioned from a deep collapse state to a state of near-collapse and eventually out of collapse. This behaviour can be related to the different time constants of the de-trapping processes involved. Two main types of trapped charges are present: surface charges, with a short time constant, and bulk charges, with a longer time constant [13]. The change in the shape of the CMUT membrane from the state of deep-collapse to near-collapse can be explained by the release of the surface charges. After this, the shape of the membrane does not significantly change throughout the experiment until it goes out of collapse, which can be

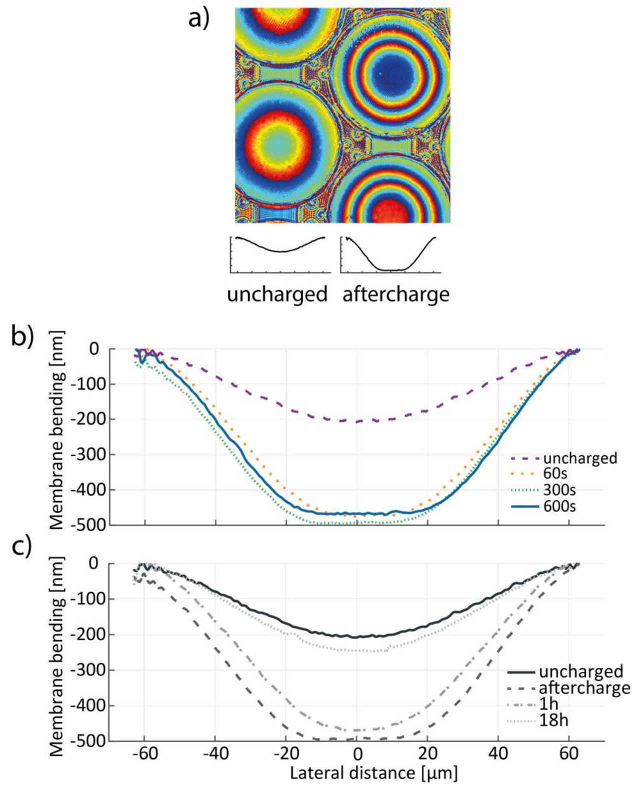

Fig. 2. a) Holographic microscope view of CMUTs before and after charging. b) Membrane profile of CMUTs for different charging durations. c) Variation of membrane profile at the key points in time at 150 °C, for a device charged for 300 s.

explained by the slower de-trapping and redistribution of bulk charges [8].

B. Impedance spectrum

The impedance of each CMUT element used in the experiment was measured before and after charging and at constant intervals of 15 minutes. A relation between the changes in the membrane profile and variations in the impedance spectrum was found. For example, in Fig. 3a, the impedance spectrum of one of the CMUT elements used in the experiment is shown for different points in time during the experiment. The most significant changes happen in the first hours of the experiment, namely, the position of the resonance peak shifts to slightly lower frequencies directly after the charging. This corresponds to the release of surface charges. Afterwards, the position of the resonance peak does not move significantly until the CMUT membrane goes out of collapse, which can be identified by a resonance peak appearing at a much lower frequency, around 1.5 MHz. This phenomenon is depicted in Fig. 3b, where the position of the predominant resonance peak is shown for one of the experiments.

C. Failure of the device

A CMUT cell is defined as failed when it goes out collapse, since in this state it will not be able to harvest ultrasound power. Carefully observing the DHM images, it has been found that not all the CMUT cells that undergo the same testing conditions go out of collapse at the same time, even for the same CMUT element, but they rather tend to fail randomly in different locations of the element. To verify that not all the CMUT cells go out of collapse simultaneously, a new CMUT element was externally biased with a DC bias source. At the same time, the shape of the membrane of a few CMUT cells was observed with the DHM. The voltage of the DC bias source was gradually swept from 0 V to 130 V, and back to 0 V. It was observed that when biased around the collapse voltage, the CMUT cells go in and out collapse in random order and not all at the same time, regardless of their position with respect to the edge of the device. This confirms the asynchronous failure of the CMUT cells. A short video was recorded during this experiment[1].

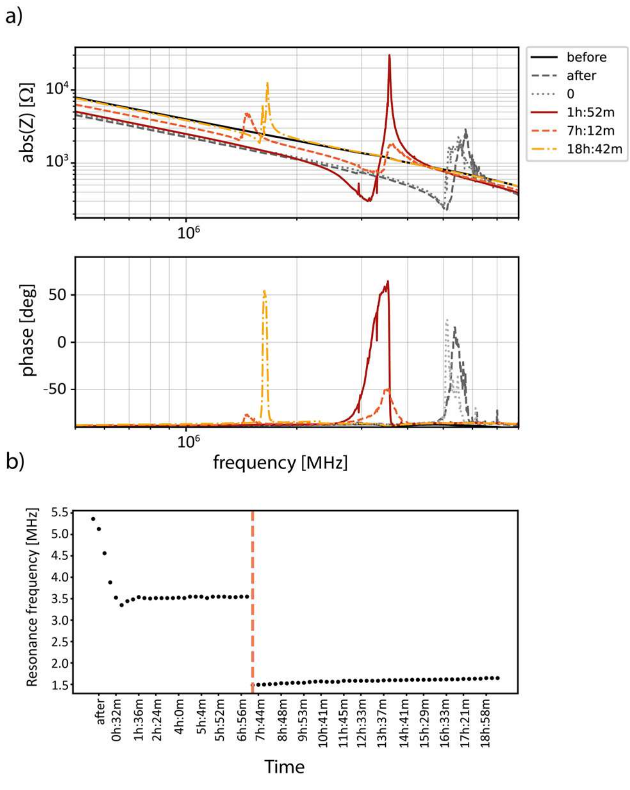

Fig. 3. a) Frequency spectrum at different points in time of one of the CMUTs used during the experiment. The CMUT was charged with 170 V for 300 seconds and tested at 150 °C. b) Predominant resonance frequency peak over time, extracted from the dataset relative to the device in a).

This is also observed in the impedance spectrum as peaks simultaneously appear in the phase plot at non-collapsed (around 1.5 MHz) and collapsed (around 5 MHz) mode frequencies. When looking at the phase plot of the impedance spectrum in Fig. 3a, the height of the resonance peaks at both high and low-frequency changes over time. This has been found to correlate with the number of CMUT cells in collapse and non-collapse. Namely, the height of the high-frequency peak relates to the number of CMUT cells in collapse, and the height of the low-frequency peak relates to the number of CMUTs cells out of collapse. Hence, the point in time at which the height of the peak at low frequency is predominant over the height of the peak at high frequency is when more than half of the CMUT cells are out of collapse, namely more than 28, which is defined as the failure time of the device.

D. Lifetime estimation

Accelerated Lifetime Tests involve physical stresses to accelerate the product failure. In this work, temperature has been chosen as a stress mechanism, and it is assumed that the lifetime of the CMUT elements can be fitted with the Arrhenius model:

$$\tau(T) = \tau_0 \cdot \exp\left(\frac{E_A}{k_B \cdot T}\right) \quad (1)$$

Where E_A is the activation energy of the discharge process and k_B is the Boltzmann's constant 8.617 x 10^{-5} eV/K. τ_0 is a constant that depends on the device geometry, size, test method and other factors, and it is estimated from the test data. Hence,

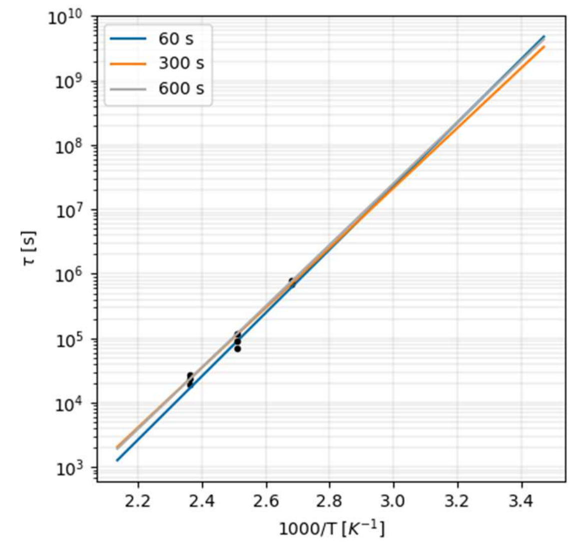

Fig. 4. Estimated failure time, depending on temperature and charging parameters, calculated fitting the experimental data with the Arrenhius model.

[1] URL link to CMUT with external DC bias video: https://doi.org/10.4121/16635193

the lifetime test results of the CMUT elements at different test temperatures were fitted with the Arrhenius model, and the lifetime at body temperature and ambient temperature was estimated (Fig. 4). The estimated lifetime is summarised in Table I. The results show that these CMUTs have a lifetime of more than two years at body temperature (37 °C) and that the shelf life (20 °C) is 3 to 5 times longer than at body temperature. The expected lifetime is dependent on the charging parameters, and the longer the charging duration, the longer the lifetime. It is expected that pre-charging the CMUT devices using a higher DC bias voltage will tunnel more charges in the charge trapping layer, resulting in a longer lifetime. Although the accelerated test conditions used in this work may have hastened the failure mechanisms observable in actual operation conditions, these results provide a starting point for optimising both the CMUT's energy harvesting capabilities and lifetime.

TABLE I. ESTIMATED LIFETIME FOR THE DEVICES UNDER TEST

Estimated lifetime at temperature T	**Charging duration [s]**		
	30	***300***	***600***
T = 20°C	3610 days (9.9 years)	3920 days (10.7 years)	5292 days (14.5 years)
T = 37°C	850 days (2.3 years)	935 days (2.6 years)	1136 days (3.1 years)

IV. CONCLUSION

In this work, Accelerated Lifetime Tests were performed to estimate the lifetime of pre-charged CMUTs for the powering of deeply implanted devices. The devices were characterised throughout the experiment showing changes in the membrane profile due to the release of trapped charges. The time of failure of the device under investigation was then extrapolated from the impedance spectrum. Lifetime at body temperature and ambient temperature were estimated, showing promising results. Future work will focus on optimising the CMUT layer stack in combination with optimal charging parameters to increase both the energy harvesting capabilities and the lifetime of the pre-charged CMUTs.

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