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# A Comparative Study of $Si_3N_4$ and $Al_2O_3$ as Dielectric Materials for Pre-Charged Collapse-Mode CMUTs

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***Abstract*—Capacitive Micromachined Ultrasound Transducers (CMUTs) have many advantages compared to other ultrasonic transducer technologies, especially for implantable devices. However, they require a high bias voltage for efficient operation. To eliminate the need for an external bias voltage, a charge storage layer can be embedded in the dielectric. This study aims to compare the performance of $Si_3N_4$ and $Al_2O_3$ when used as a charge storage layer. By measuring the shift in the C-V curve, $Si_3N_4$ exhibits a larger shift than $Al_2O_3$, indicating a better charge-trapping capability. When using the pre-charged CMUTs as power receivers, the $Si_3N_4$ version harvested up to $80\,\mathrm{mW}$ - only a few mW more than the $Al_2O_3$ - with an efficiency of about $50\,\%$. Accelerated Lifetime Tests predict a lifetime of about 7.8 and 1.2 years for $Si_3N_4$ and $Al_2O_3$ respectively.**

***Index Terms*—pre-charged CMUT, Capacitive Micromachined Ultrasound Transducers, zero-bias transducers, ultrasonic power transfer**

## I. Introduction

Capacitive Micromachined Ultrasonic Transducers (CMUTs) have gained increasing attention as power receivers for biomedical implants due to their manufacturing scalability and biocompatibility. CMUTs can be operated in two modes: non-collapse-mode, and collapse-mode. The collapse-mode occurs when the top membrane makes partial contact with the dielectric layer above the bottom electrode, achieved by applying a high DC voltage that causes the top membrane to snap down. The bias voltage typically ranges from $30\,\mathrm{V}$ to $70\,\mathrm{V}$, resulting in enhanced transmit and receive sensitivity, and an output pressure up to three times greater compared to conventional mode [1], [2]. This increase is due to the higher electric field in the vacuum cavity caused by the high bias voltage and smaller effective gap height. However, such high DC biases are better avoided in the body.

To address the issue of external bias voltage, a charge storage layer, such as $Al_2O_3$, can be incorporated into the dielectric stack. By trapping a sufficient amount of charge in this layer, a built-in bias is created, ensuring that the CMUT remains in permanent collapse-mode [3], [4]. Besides $Al_2O_3$, other materials capable of retaining enough charge can also be employed. Previous studies have utilized pre-charged CMUTs with $Si_3N_4$ or $SiO_2$ in the dielectric [2], [5]–[7]. Park et al. [7] and Choi et al. [5] have demonstrated the feasibility of pre-charged CMUTs with $Si_3N_4$ as the dielectric, exhibiting good charge retention over time, even at high temperatures. However, the reported pre-charged CMUTs are mostly focused on non-collapse-mode operation, with the exception of Ho et al. [6]. It is evident from these studies that trapping sufficient charge to achieve a pre-charged collapse-mode CMUT is challenging, and the choice of material for the charge-trapping layer is crucial. Choi et al. [5] compared the performance of $Si_3N_4$-$SiO_2$ and $SiO_2$ as charging layers, concluding that $Si_3N_4$ maintains its performance for a longer duration due to superior charge retention. The objective of this study is to compare the performance of $Si_3N_4$ and $Al_2O_3$ as charge storage layers in the dielectric of collapse-mode CMUTs. Additionally, the performance of CMUTs as power receivers is evaluated.

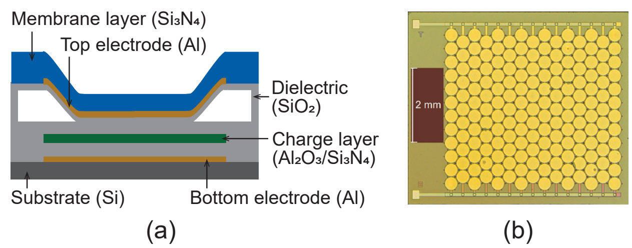


Fig. 1. (a) Schematic of collapse-mode CMUT with charge trapping layer in the dielectric. (b) Microscope view of the fabricated CMUT array.

## II. Device preparation and characterization

### A. CMUT fabrication

The CMUTs utilized in this study are circular cells with a diameter of $355\,\mu\mathrm{m}$, fabricated using a standard sacrificial release processing technique. The dielectric layer consists of a

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stack of $SiO_2$\charge layer\$SiO_2$, a vacuum gap, and an additional layer of $SiO_2$. Two versions of CMUTs were fabricated and analyzed: the first version has an ALD-deposited $Al_2O_3$ charge layer, while the second has a PECVD-deposited $Si_3N_4$ charge layer. Both variants have a charge layer thickness of $200\,\mathrm{nm}$, and the Equivalent Oxide Thickness (EOT) measures $320\,\mathrm{nm}$ and $350\,\mathrm{nm}$ for the $Al_2O_3$ and $Si_3N_4$ variant, respectively. A $5 \times 5\,\mathrm{mm}^2$ single-element transducer, consisting of 173 CMUT cells electrically connected in parallel, was fabricated. Figure 1 depicts the schematic cross-section of the CMUT, and a microscope photograph of the fabricated device.

### B. CMUT pre-charging and characterization

In a previous study, we established that by applying an electric field above $7 - 8\,\mathrm{MV/cm}$ for a few minutes, a stable pre-charged CMUT is produced [4]. In this study, we investigated the impact of charging the devices with varying electric fields. We selected charging voltages corresponding to electric fields ranging from 7.5 to $8.5\,\mathrm{MV/cm}$, both with positive and negative polarity with respect to the bottom electrode. Each charging voltage was applied to a pristine device for 5 minutes. Subsequently, we measured the Capacitance-Voltage (C-V) curves to assess the shift in collapse voltage resulting from the charge stored in the dielectric. To minimize any alteration of the stored charge in the device, we employed a fast C-V protocol, with a voltage sweep rate of $80\,\mathrm{V/ms}$. For the C-V measurement, a small AC signal at $125\,\mathrm{MHz}$ was superimposed on a $200\,\mathrm{Hz}$ triangular wave varying between $0\,\mathrm{V}$ and $\pm 120\,\mathrm{V}$. The change in the phase of the impedance when the CMUT goes in and out of collapse is used to draw the C-V curve. Two measurement protocols were used: a DC bipolar sweep between positive and negative voltages for uncharged devices, and a DC unipolar sweep for either only positive or negative voltages, for devices charged with positive and negative polarity, respectively.

## III. Results and Discussion

### A. Comparison of charge trapping

In Fig. 2(a), we compare the C-V curves of the two CMUT variants when charged with an electric field of $8\,\mathrm{MV/cm}$ with positive or negative polarity, to that of corresponding pristine devices. The C-V curve of both pristine devices exhibits symmetry around $0\,\mathrm{V}$, indicating that the CMUT is not in a collapsed state and has no charge stored in the dielectric. Conversely, the pre-charged devices show a shift in the point of minimum capacitance of 60 to $80\,\mathrm{V}$, indicating that they are in a collapsed state even at $0\,\mathrm{V}$ bias, and the presence of charge stored in the dielectric. Furthermore, we observe that the $Si_3N_4$ variant exhibits a larger shift in the C-V curve compared to $Al_2O_3$ for both polarities (Fig. 2(a)). This could be due to the different deposition method (ALD vs PECVD) and not (only) the different dielectric material of the two devices, and will be investigated in the future. Additionally, charging the device with a negative polarity results in a slightly larger shift in the C-V curve compared to positive polarity.

Figures 2(b) and (c) depict the impact of different charging electric fields on the shift in the C-V curves for the $Si_3N_4$ and $Al_2O_3$ variants, respectively. As expected, the shift becomes more significant for higher charging electric fields due to increased current tunneling through the CMUT dielectric. Moreover, charging $Al_2O_3$ devices with an electric field exceeding $8\,\mathrm{MV/cm}$ was only feasible with negative polarity, as devices charged with positive polarity experienced dielectric breakdown. In contrast, the $Si_3N_4$ variant tolerated charging electric fields up to $8.5\,\mathrm{MV/cm}$ without encountering any breakdown, regardless of polarity. Although the observed difference in breakdown points between positive and negative polarity was not evident for $Si_3N_4$, it is possible that the difference exists but is smaller compared to $Al_2O_3$. This can be attributed to the differing charging mechanisms and characteristics of the two dielectric materials.

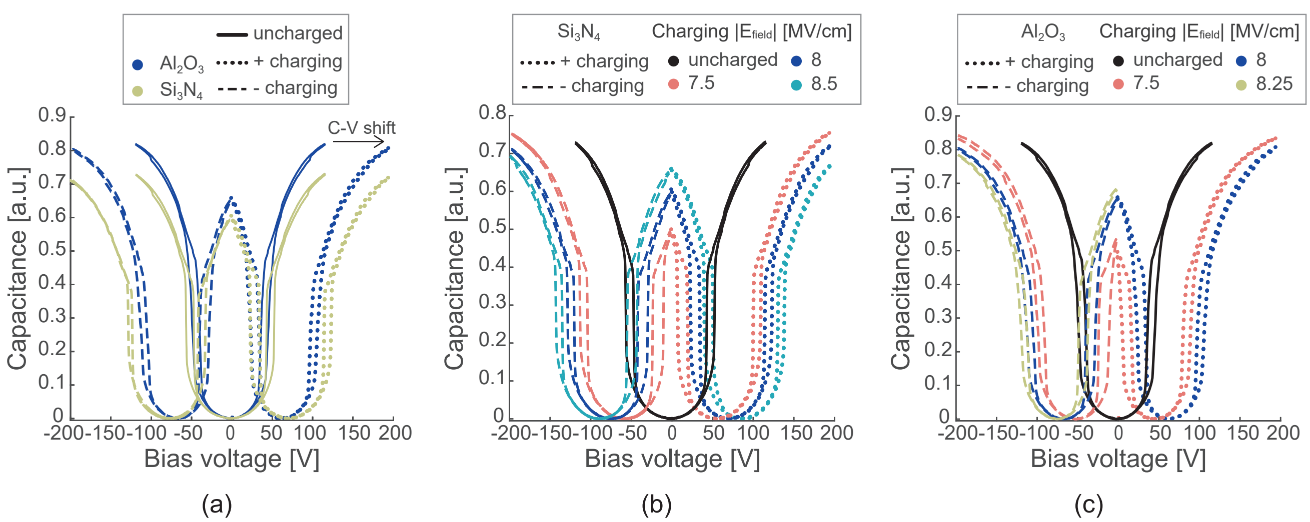


Fig. 2. (a) Comparison of C-V curve shift between $Si_3N_4$ and $Al_2O_3$ samples when charged with $\pm 8\,\mathrm{MV/cm}$ electric field. (b) Comparison of C-V curve shift for $Si_3N_4$ samples when charged with different electric fields and polarity. (c) Same as (b) but for $Al_2O_3$.

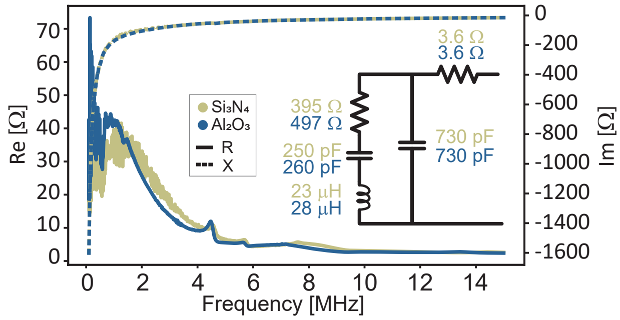


Fig. 3. Electrical impedance of the pre-charged collapse-mode CMUTs measured in water and corresponding BVD model values for the two device variants.

### *B. Pre-charged CMUT electro-mechanical characteristics*

To evaluate the pre-charged collapse-mode CMUTs as wireless power receivers, we chose to compare devices charged with an electric field of $-8\,\mathrm{MV/cm}$ as this was the highest electric field with which both variants could be charged. The CMUTs were wire-bonded to a PCB and coated with a thin layer of PBR (polybutadiene rubber). After charging the CMUTs, the shift in the C-V curve was $77\,\mathrm{V}$ and $68\,\mathrm{V}$ for the $Si_3N_4$ and $Al_2O_3$ variants, respectively, which can be considered as a built-in DC bias.

After charging, we measured their impedance in water with an impedance analyzer (Keithley E4990A, Keysight Technologies), and extracted the values of the Butterworth-Van Dyke (BVD) model components (Fig. 3). Both devices have a center frequency of around $2\,\mathrm{MHz}$ in water, and a typical bandwidth between $105\,\%$ and $120\,\%$. Additionally, the BVD model incorporates a $3.6\,\Omega$ parasitic resistance connected in series with the CMUT model. This resistance arises from the electrical interconnects between the CMUT array and the wire-bonding pads.

### *C. Maximum power transfer*

To evaluate the pre-charged collapse-mode CMUTs as ultrasound power receivers, we conducted a power transfer experiment. A lower power carrier frequency is favorable in ultrasonic power delivery since it results in lower propagation losses for ultrasonic waves traveling through the tissue. Therefore, for this study, we chose a carrier frequency of $1\,\mathrm{MHz}$. We used a circular single-element PZT piston transducer with a center frequency of $1\,\mathrm{MHz}$ and a diameter of $39\,\mathrm{mm}$ as the transmitting (TX) transducer. The receiving (RX) transducers were the two pre-charged CMUT variants. Both the TX and RX transducers were immersed in a water tank and aligned at the center, with a distance of $22\,\mathrm{cm}$ between them, which corresponds to the TX's natural focus distance. The pressure field generated by the TX transducer at this distance was previously measured by scanning a plane using a needle hydrophone parallel to the surface of the TX (Fig. 4(a)).

To maximize the power transfer efficiency, a matching network was connected to the CMUTs. In this study, we opted for a parallel matching approach, where the value of the optimal load is the conjugate of the measured impedance at the chosen frequency. At $1\,\mathrm{MHz}$, the BVD model of the two CMUTs devices can be simplified with a resistor in parallel with a capacitor. According to the maximum power transfer theorem, the optimal load connected in parallel to the CMUTs, consists of an inductor ($\mathrm{L_{load}}$) and a resistor ($\mathrm{R_{load}}$). The optimal inductor compensates for the equivalent capacitance of the BVD model, while the resistor should have the same value as the equivalent resistor of the BVD model. We determined the value of the matching inductor by testing components with values close to the conjugate of the equivalent electrical capacitance of the CMUT variants. A potentiometer was then used to find the optimal resistance value for maximizing the received power (Fig. 4(b)).

We applied a sine burst signal with an amplitude of $70\,\mathrm{V}$ and 10 cycles at a pulse repetition frequency of $1\,\mathrm{kHz}$ to the TX transducer, resulting in an instant acoustic intensity of $720\,\mathrm{mW/cm^2}$ averaged across the CMUT surface. This intensity adheres to the FDA safety limit for the use of ultrasound in the body. The power at $\mathrm{R_{load}}$ was calculated using $\mathrm{P} = \mathrm{V_{pp}^2}/(8 \cdot \mathrm{R_{load}})$, where $\mathrm{V_{pp}}$ is the peak-to-peak voltage at the load. The maximum harvested power was $80\,\mathrm{mW}$ with the $Si_3N_4$ CMUT and $77\,\mathrm{mW}$ with the $Al_2O_3$ variant. The inset in Fig. 4(b) shows the corresponding acoustic-to-electrical power conversion efficiency of the CMUTs, calculated as the ratio between the acoustic power at the CMUT surface (instant acoustic intensity $\times$ CMUT area) and the maximum harvested power, which reaches approximately $50\,\%$. The marginal difference in the maximum harvested power between the two devices can be attributed to an imperfect load matching for the $Al_2O_3$ version, primarily due to the limitations in available inductor values. However, it is important to note that this discrepancy is not significant enough to give preference to one material over the other.

Considering the integration of the CMUT devices into an ASIC, the requirement for a matching inductor poses a significant challenge, especially when inductors of tens of µH are needed, as in this case. To address this issue, we evaluated the power conversion efficiency with a purely resistive load by repeating the previous experiment. In this case, the load value needs to be matched to the modulus of the impedance of the simplified BVD model. Under these conditions, the maximum harvested power was $35\,\mathrm{mW}$ with the $Si_3N_4$ variant and $30\,\mathrm{mW}$ with the $Al_2O_3$ variant (Fig. 4(c)). The corresponding power conversion efficiency was approximately $20\,\%$. Table I summarizes the data obtained from the power transfer experiment.

### *D. Lifetime*

To estimate the lifetime of the devices, Accelerated Lifetime Tests (ALT) have been performed with temperature as an accelerating factor. We placed the pre-charged CMUTs on a hotplate set at temperatures ranging from $140\,^{\circ}\mathrm{C}$ to $160\,^{\circ}\mathrm{C}$, and the impedance was measured at regular time intervals. The time to failure at different test temperatures, defined as when more than half of the CMUT membranes are out of collapse-

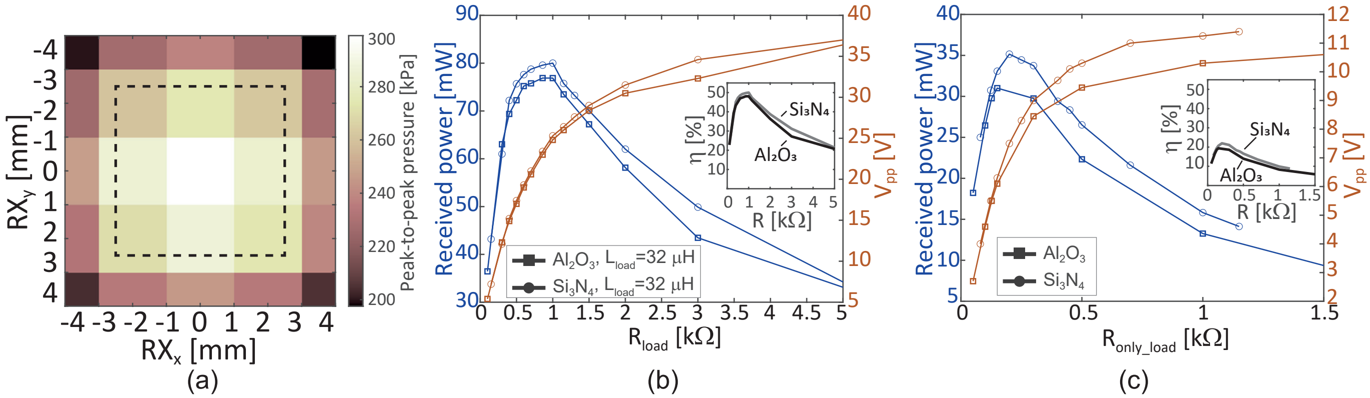


Fig. 4. (a) Pressure field at the location of the RX CMUT. The dashed line indicates the position of the CMUT. (b) and (c) Measurements with and without the matching inductor, respectively; power at $R_{load}$, and corresponding peak-to-peak voltage at load, for the two CMUT variants. Figure insets indicate the acoustic to electrical power conversion efficiency.

TABLE I
SUMMARY OF POWER TRANSFER EXPERIMENT

| | | $R_{eq}$[Ω] | $C_{eq}$ [pF] | $L_{load}$ [µH] | $R_{load}$ [Ω] | $R_{only\_load}$[Ω] |
|---|---|---|---|---|---|---|
| $Si_3N_4$ | | 900 | 920 | 32 | 1000 | 200 |
| | Power | | | | 80 | 35 |
| | $\eta$ [%] | | | | 50 | 22 |
| $Al_2O_3$ | | 800 | 880 | 32 | 860 | 150 |
| | Power | | | | 77 | 31 |
| | $\eta$ [%] | | | | 48 | 19 |

mode, was fitted using a previously defined method [4] to estimate the lifetime of the two CMUT variants at 37 °C (Fig. 5). The predicted lifetime of the $Si_3N_4$ variant is about 7.8 years, and 1.2 years for the $Al_2O_3$ variant. It should be noted that, although these ALT conditions may have accelerated the failure mechanisms, further tests are necessary to evaluate their lifetime under actual operational conditions. Nonetheless, these results demonstrate the potential of these devices.

## IV. Conclusion

In this study, the performance of CMUTs with $Si_3N_4$ and $Al_2O_3$ charge storage layers was compared in terms of charge trapping and power conversion efficiency. It was observed that, under the same charging electric field, a higher amount of charge could be stored in the $Si_3N_4$ variant compared to the $Al_2O_3$ variant. Furthermore, the $Si_3N_4$ variant demonstrated slightly higher power conversion efficiency than $Al_2O_3$, with both variants achieving approximately 50 % efficiency for a matched load and around 20 % efficiency for a purely resistive load, indicating promising potentials for their integration into an ASIC to produce a single chip implantable medical device. Moreover, the estimated lifetime at body temperature yielded promising results for both variants. In conclusion, both materials showed good performance, and when selecting the dielectric material for pre-charged collapse-mode CMUTs, a trade-off between other factors such as ease of deposition, charging time, and charge retention should be carefully considered.

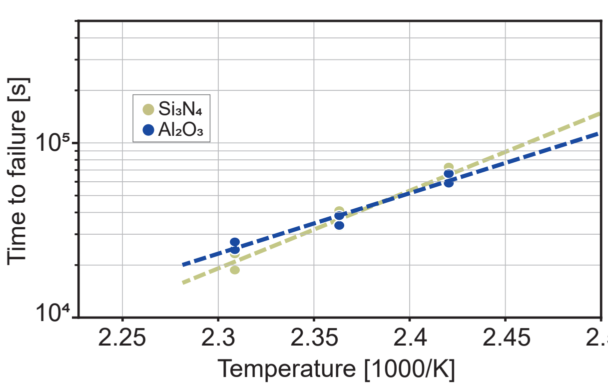


Fig. 5. Fitting of the ALT results to predict the CMUT lifetime.

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