Long-term measurement results of pre-charged CMUTs with zero external bias operation

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***Abstract*—We present long-term measurement results (> 1.5 years) of CMUTs, which have been pre-charged for zero external bias operation. The fabrication is based on a direct wafer bonding process with a thick-buried-oxide-layer, which allows the realization of only partially connected, donut-shaped bottom electrodes. The only partially connected bottom electrode has a central portion that is completely encapsulated by 3-µm-thick thermally-grown silicon dioxide, and, thus, electrically floating. The devices are pre-charged by applying a dc voltage higher than the pull-in voltage, which injects charges into the electrically floating portion and creates a sufficiently strong intrinsic electric field in the gap. Measurements of resonant frequency at various bias voltages show that the charges have completely remained in the floating portion for the last 19 months. We prove the zero-external-bias operations with the pre-charged CMUTs by measuring the electrical input impedance, the ac signal displacement, and pitch-catch measurements under zero external dc bias voltage. Our results show that pre-charging CMUTs is feasible, and that the devices are capable of long-term, zero external bias voltage operation.**

***Index Terms*—** CMUT, charging, partial electrode, thick BOX fabrication process, zero-external-bias operation.

I. Introduction

Unlike piezoelectric ultrasonic transducers, capacitive micro-machined ultrasonic transducers (CMUTs) require a dc bias voltage to establish an electric field across the two electrodes for operation. Before reaching the pull-in voltage, the larger the dc bias is, the more efficient the CMUT operates [1]. However, the requirement of dc bias for CMUTs also imposes additional challenges such as complications in circuitry design for external dc bias, difficulty to scale for mobile or low power applications, and extra protective schemes [4] needed to comply with the safety regulations for medical applications.

Charging effects are generally undesirable in MEMS devices, because they can degrade the device performance and increase the chance of electrical breakdown. On the other hand, if charges can be injected in a controlled manner, either during or after the fabrication, without causing the insulation layer to breakdown, they can be beneficial. The charges can be used to create part or all of the electric field required for CMUT operation.

There are previously reported examples of using pre-charged CMUTs for zero-external-bias operation. In [2], the charges were intentionally injected, by biasing the devices at 160% of pull-in point for 30 seconds, into the oxide-nitride layer of CMUTs fabricated using a LOCOS and wafer bonding process. It was also successfully demonstrated that these CMUTs can be used as resonant sensors without external bias voltages applied. For temporal stability, it is reported in [2] that these CMUTs show no obvious charge leakage for 7 days at room temperature.

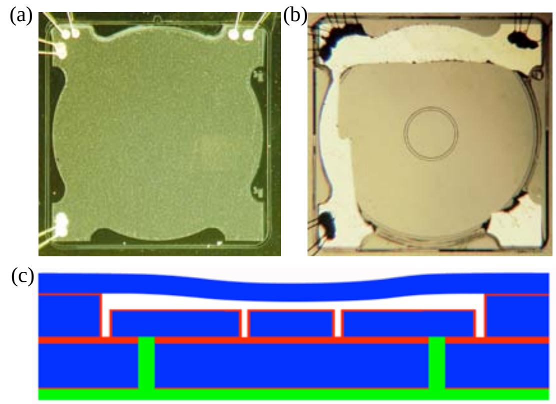

Fig. 1 shows a single CMUT cell with a donut-shape, partially connected bottom electrode, similar to the structure proposed in [3]: (a) shows an intact single-cell device, while in (b) the plate of the cell is intentionally removed to reveal the partial electrode structure underneath. The cross-sectional schematic is shown in (c). The central island in the bottom electrode is floating. Note that the CMUTs in [3] operate in a permanent contact mode, while here we focus on CMUTs which operate in the conventional mode, as illustrated in (c).

For this work, we use a CMUT structure that is similar to the partial-electrode CMUTs introduced in [3], but with a focus on the conventional operation instead of permanent-contact mode [Fig. 1(c)]. These CMUTs are fabricated using the direct wafer bonding process with a 3-µm thick-buried-oxide (BOX) layer [4], which allows for a donut-shape, partially connected bottom electrode with a silicon island in the center that is electrically floating [Figs. 1(b) and (c)]. The idea is that, with this electrically floating silicon island, in addition to only a dielectric layer (the 3-µm thick insulation oxide), the charges injected will remain there for a longer time.

In this paper, we report on the charging process and long-term measurement results for such CMUTs, and we demonstrate that the charges show great temporal stability for more than 1.5 years. In addition, zero-external-bias operations for these pre-charged CMUTs are demonstrated by performing electrical input impedance, ac displacement, and pitch-catch measurements.

II. The Charging process and Characterization

The fabricated CMUTs, before charging, operated in the conventional mode (no contact between the plate and the

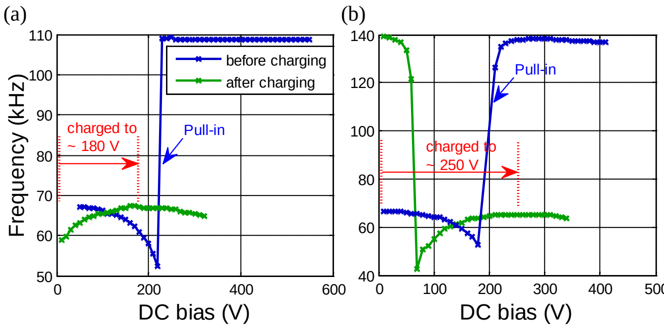

Fig. 2: The short circuit resonant frequency of two CMUTs before and after charging: (a) A CMUT that is charged to ~82% of the original pull-in voltage; (b) A CMUT charged to ~ 139% of the original pull-in voltage.

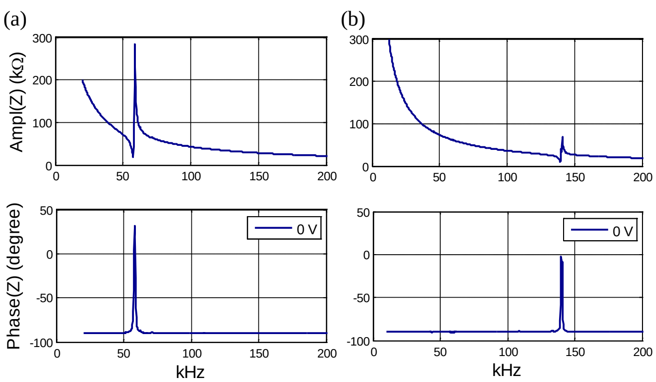

Fig. 3: The electrical impedance of CMUTs at zero-external-bias after charging: (a) A CMUT that is charged to ~82% of the original pull-in voltage; (b) A CMUT charged to ~ 139% of the original pull-in voltage.

bottom electrode under zero dc bias voltage). The devices tested include a range of variations in dimensions: a cell radius of 1800 μm, a plate thickness of 30 or 60 μm, a gap height of ~33 or ~8 μm, and pull-in voltages ranging from 180 – 290 V. The partial electrode size is defined as the portion of the electrically connected donut in the radial length, as compared to the full CMUT cell radius, same as the definition in [3], and our devices have either 50% or 75% partial electrodes. For comparison purpose, one device with a fully connected bottom electrode (100%, no floating silicon island) is also tested.

To charge up a CMUT and to monitor the process, the electrical impedance is measured while in the mean time a dc charging voltage is applied, stepping from 0 V to ~ 2.5 times of the pull-in voltage. This results in a large electric field (~ 2 MV/cm) in the insulation layer, which injects charges into the electrically floating portion of the bottom electrode. Afterwards, the large dc voltage is reduced in steps down to 0 V. During this process the electrical impedance will first show a decreasing peak until the dc bias reaches the equivalent charged voltage. Then when the dc voltage further decreases, the peak of the electrical impedance increases again, i.e. that internal charges provide the electric field in the gap. At this stage the device operates at zero external bias voltage.

For example, one of the devices has a cell radius of 1800 μm, a 60-μm thick plate, an 8-μm gap height, a 3-μm thick insulation layer, and a 50% partial electrode. The pull-in voltage of this device originally was 220 V. A dc charging voltage was applied, which increased gradually until it reached 550 V. Afterwards, the dc charging voltage was removed, and this device is charged to an equivalent bias voltage of ~180 V.

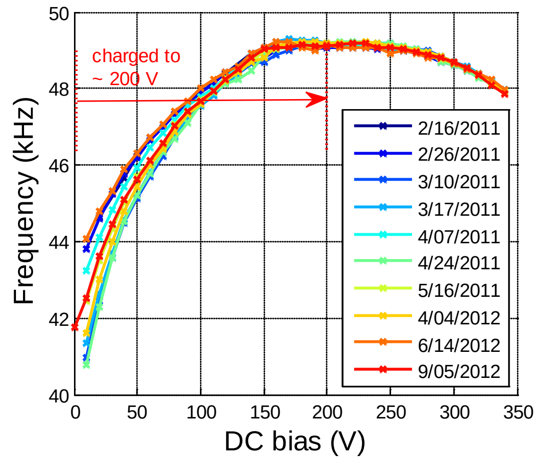

Fig. 4: The long-term measurement of the short circuit resonance of a pre-charged CMUT. The equivalent charged voltage stays nearly constant ~ 200 V over a period of 19 months.

The short circuit resonant frequency of this CMUT, extracted from the electrical impedance data, before and after charging is shown in Fig. 2(a). The curve before charging reveals a pull-in voltage of 220 V, and before pull-in, the device had a maximum resonant frequency at 0 V. As the dc voltage deviates from this 0 V maximum frequency point, the resonant frequency drops due to the spring softening effect. After charging, the maximum resonant frequency moves to ~ 180 V, which implies that the charges injected into the device cancel the electric field created by the 180 V external dc bias. Therefore, we know that this device is charged up to an equivalent dc bias voltage of 180 V when no external bias voltage is applied. This corresponds to ~ 82% of pull-in point.

Another CMUT with a pull-in voltage of 180 V was charged to an equivalent voltage of 250 V. Its short circuit resonant frequencies before and after charging are shown in Fig. 2(b). The electric field created by the injected charges is so large that the device operates in pull-in mode when there is no external dc bias voltage applied.

The electrical input impedance of the two previously mentioned CMUTs at zero-external-bias is shown in Fig. 3. The external-bias-voltage-free conventional CMUT operates at ~ 60 kHz, while the external-bias-free CMUT in pull-in mode operates at ~ 140 kHz. Note that even though these CMUTs appear to operate at an equivalent charged voltage, they don't really operate with a constant voltage - they follow a constant charge operation instead of a constant voltage operation.

For our long-term measurements, the CMUT measured has a cell radius of 1800 μm radius, a 30-μm thick plate, a ~33-μm gap height, a 3-μm thick insulation layer, a floating portion that is 25% in radius of the bottom electrode (75% partial electrode), and a pull-in voltage that was 290 V originally. A maximum charging dc voltage of 680 V was applied on this device, and it is charged to an equivalent charged voltage of 200 V, as shown in Fig. 4. This CMUT was monitored over a time period of 19 months, and the charges injected have remained nearly constant. During this long-term period, the CMUT has been repetitively stressed by both ac (up to 10 V_{pp} for pitch-catch measurements) and dc (up to 320 V for impedance measurement) signals. So far no shift in the equivalent charged voltage has been observed.

Similar results have been repeated on other devices, which also show stable charge storage for 3 months so far, even with ac and dc stressing applied in between measurements. One device with no floating portion in the bottom electrode was also measured; the charges injected dissipated in ~ 1 hour of time.

This proves that it is the floating silicon portion below the CMUT gap, encapsulated by silicon dioxide, which is the reason why these devices can be used for long-term operation without any external dc bias voltage applied.

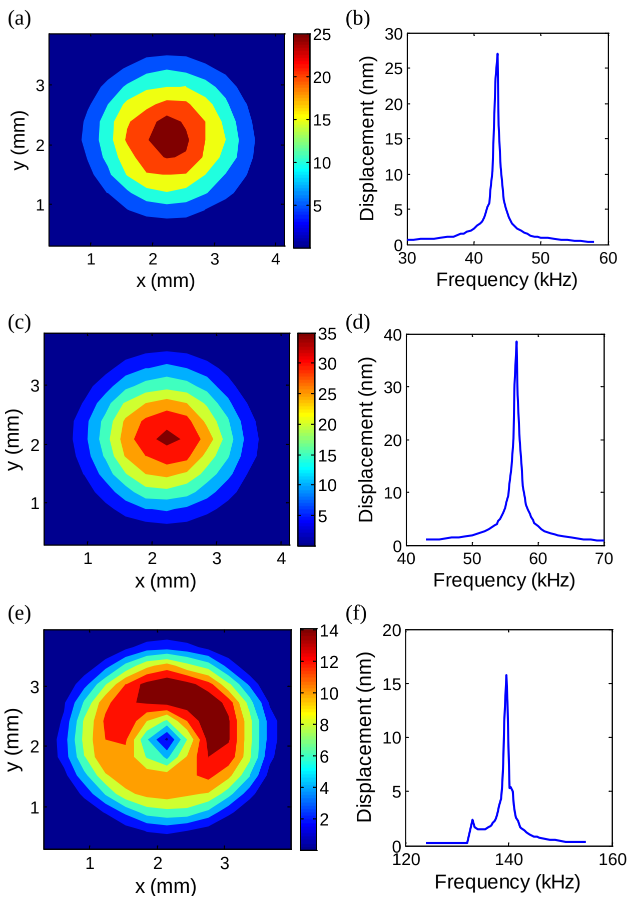

Fig. 5: The peak-to-peak displacement (in nm) of three pre-charged CMUTs measured by Polytec vibrometer: (a), (c), and (e) are the 2-dimensional displacement profile of the device at their individual resonant frequencies; (b), (d), and (f) are the maximum displacement of the CMUTs as a function of ac input frequency, *i.e.* the frequency response of the device in transmitting mode. The device in (a) & (b) has a thinner plate (30 μm) and larger gap (33 μm), while the device in (c) & (d) has a thicker plate (60 μm) and smaller gap (8 μm), and thus smaller deflection-to-thickness ratio. Both devices are in the conventional mode at zero external bias. The device in (e) & (f) also has a smaller deflection-to-thickness ratio (60-μm plate, 8-μm gap), but it operates in the pull-in mode with no external dc bias voltage.

III. Zero-External-Bias Operations

We performed displacement and pitch-catch measurements using these CMUTs without any external dc bias voltage applied to demonstrate the external-bias-voltage-free operations for these pre-charged CMUTs.

i. Displacement measurements

An ac displacement measurement characterizes CMUTs as transmitting devices, and helps us to visualize the plate movement. It also provides information on the frequency response and the transmitting sensitivity of the devices.

Fig. 5 shows the displacement measurements of three pre-charged CMUTs by a laser Doppler vibrometer (Polytec, Irvine, CA, USA). The device in Figs. 5(a) and (b) has a radius of 1800 μm, a 30-μm thick plate, a 33-μm gap, and a 75% partial electrode. The device has a resonant frequency at 43.5 kHz, and gives a maximum displacement of 27 nm at 60 mV_{pp} ac input. If we assume the displacement scales linearly with the ac input, this device can achieve 140 dB SPL (re 20 μPa) with a mere 11.8 V_{pp} ac input, which gives ~ 1.77 μm average displacement. The device in Figs. 5(c) and (d) has a thicker plate (60 μm), smaller gap (8 μm), and a 50% partial electrode. The device performance under zero external bias voltage is equally impressive: at the resonant frequency at 56.75 kHz, it gives a maximum displacement of 38 nm at 60 mV_{pp} ac input. Again, if we assume the displacement scales linearly with the ac input, this device can achieve 140 dB SPL with a mere 6.44 V_{pp} ac input, which gives ~ 1.36 μm average displacement.

Similar results can be found in CMUTs charged to pull-in mode. The device in Figs. 5(e) and (f) has a radius of 1800 μm, a 60-μm thick plate, an 8-μm gap, a 50% partial electrode, and was charged to 139% of the original pull-in voltage. The device has a higher resonant frequency at 139.5 kHz, and gives a maximum displacement of 15 nm at 60 mV_{pp} ac input.

Based on these three devices, the transmitting sensitivity for our devices is in the range of 17 – 31 Pa/V.

ii. Pitch-catch measurements

Two pre-charged CMUTs are chosen for the pitch-catch measurements. Device A is the same device as in Figs. 2(a) and 3(a), which was charged to ~82% of the pull-in voltage and has a 59 kHz resonance at zero external bias voltage. Device B has similar dimensions, but was only charged to ~59% of its pull-in voltage of 270 V, and has a 64 kHz resonance at zero external bias voltage.

The pitch-catch measurement is carried out with both no external bias voltages on any of the two devices, as well as with a 50 V applied to the receiving Device A to match the frequencies of the pair at ~ 64 kHz. The method of frequency matching between the pitch-catch device pair is described in

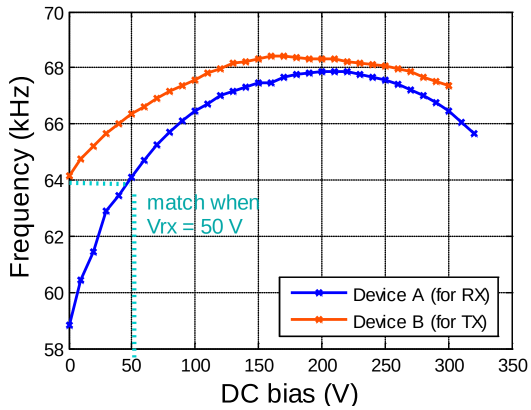

Fig. 6: The resonant frequencies of the pitch-catch pair at various external dc bias voltages. The two CMUTs operate at ~ 64 kHz and ~ 59 kHz, respectively, with no external bias voltage. Frequencies of the 2 devices match when a 50 V external bias voltage is applied to the receiving CMUT.

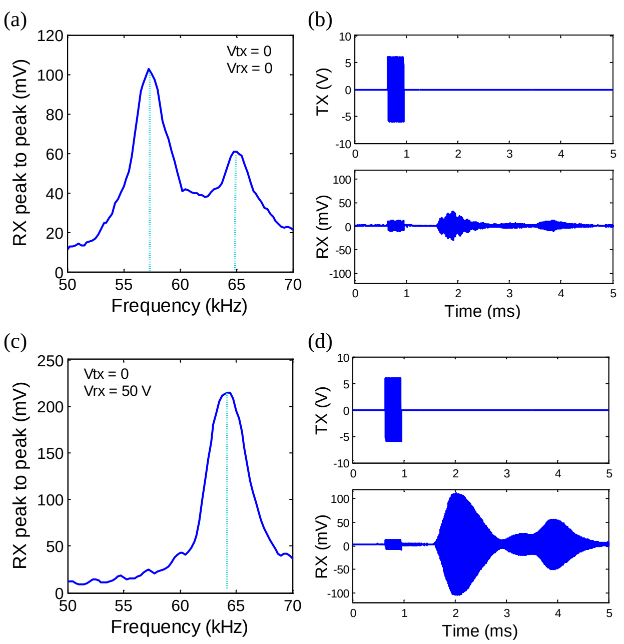

Fig. 7: The pitch catch measurement of a pair of pre-charged CMUTs. (a) and (b) show the results of no external bias applied to any of the CMUTs, while (c) and (d) show those of 50 V applied to the receiving device to match the frequencies of the pair. (a) and (c) are the peak to peak value of the receiving signal at different frequencies, while (b) and (d) are the time domain transmitting (TX) and receiving (RX) signals of the pitch-catch at ~ 64.5 kHz.

[5], which matches the open circuit resonance of the receiving CMUT to the short circuit resonance of the transmitting one by individually tuning the dc bias voltages of the two devices (Fig. 6).

The measurement is done at a distance of 30 cm, with an ac excitation signal of 20-cycle, sinusoidal burst with 12 V_{pp}, and a non-inverting pre-amplifier of 40 dB gain on the receiving side. The pitch-catch measurements are performed with various excitation frequencies, and the peak-to-peak value of the received signal is measured [Figs. 7(a) and (c)]. Due to the frequency mismatch of the pair of the devices, the pitch-catch signal with no-external-bias voltage applied shows two peaks in the spectrum [Fig. 7(a)], and there is beating in the time domain signal [Fig. 7(b)]. With a low external dc bias of 50 V applied to only one of the devices, now the pitch-catch frequency response [Fig. 7(c)] has only one single peak at the expected 64 kHz, and the time domain signal [Fig. 7(d)] shows a nice trend of ring up and ring down without any sign of beating.

In either case, it is evident that these pre-charged CMUTs are capable of pitch-catch operation under low or zero external dc bias voltage and can still give signals with good signal-to-noise ratio.

IV. Conclusion

We present the long-term measurement result (19 months) of CMUTs, which have been pre-charged by biasing beyond pull-in point. By injecting charges into the partially floating bottom electrode for long-term charge storage, the devices are capable of zero-external-bias-voltage operation. Such CMUT structure can simplify the integration to the front-end electronics, and also open up new possibilities in mobile applications, low power designs, and medical applications involving safety regulations.

For the future, it is important to identify the optimal device design for pre-charged CMUTs, such as to determine the optimal partial electrode size for efficient zero-external-bias operation. Moreover, it is still not clear whether the injected charges are stored in the dielectric (silicon dioxide) layer or in the floating conductive silicon. It is essential to better understand the charging and charge storage mechanisms, which can potentially show us a way to better control the equivalent charged voltage for each pre-charged CMUT.

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