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Improved Evaluation of CMUT Collapse and Snapback Voltages via Charge Control using Fast Dynamic Current Excitation

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***Abstract*—This work describes a method to estimate the mean collapse and snapback voltages of CMUT elements and their statistical distribution by extracting the voltage-dependent capacitance from fast dynamic excitation of the device, enabling fast analysis of fabrication-related intra-element and inter-element variability. While both voltage excitation and current excitation of the CMUT element provide comparable array-level results in terms of mean and deviation of positive and negative collapse and snapback voltages, it is demonstrated that improved detection of isolated collapse and snapback events is achieved through current-driven excitation, implementing charge-controlled actuation of the membranes.**

***Keywords*—CMUTs, Collapse voltage, Nonuniformity, Snapback voltage, Source Measure Unit, Variability.**

I. INTRODUCTION

Different approaches for the fast evaluation of Capacitance-Voltage (C-V) curves of CMUT array elements, aimed at estimating collapse and snapback voltages through fast dynamic voltage excitation, have recently been demonstrated [1],[2]. These methods overcome some of the limitations of traditional impedance analysis, such as the long measurement time required for high-resolution measurements, and mitigate the risk of inducing early collapse, either due to the effect of the excitation amplitude or to charge trapping in the in-cavity dielectric layers caused by prolonged exposure to high fields.

C-V curves clearly show the onset and completion of collapse and snapback of all element cells over a voltage interval [3]; however, they do not ensure unambiguous determination of the collapse and snapback voltage values, V_c and V_{sb}.

In this work, we propose a method to estimate the mean V_c and V_{sb} of CMUT elements and their statistical distribution over arbitrary voltages steps, enabling fast analysis of intra-element and inter-element V_c and V_{sb} nonuniformity. This unevenness is closely related to the microfabrication process variability, particularly the sacrificial layer thickness [4] and, in some cases, the plate thickness as well [5]. Furthermore, we demonstrate that improved collapse and snapback events detection can be achieved through current-driven dynamic excitation, thereby implementing charge-controlled transducer actuation.

II. MATERIALS AND METHODS

A. *Technique description*

The main steps of the proposed technique for evaluating the V_c and V_{sb} distribution are summarized in Fig. 1. First, the CMUT is driven with a dynamic waveform that varies slowly with respect to the membrane dynamics. Current and voltage are measured simultaneously during excitation. The collected data are then processed to extract the voltage-dependent capacitance, $C(V_m)$, obtained by dividing the time-dependent charge $Q(t)$ by the measured voltage V_m, where $Q(t)$ is computed via time integration of the measured current $I_m(t)$. Point-by-point mapping of C versus V_m is enabled by the quasi-static operating condition. Finally, a dedicated numerical procedure implemented in MATLAB (MathWorks Inc. Natick, MA) is applied to perform the distribution analysis. This processing generates histograms of the number of membranes undergoing collapse or snapback within user-defined voltage intervals.

B. *Experimental setup*

The described technique was implemented using a Keysight B2912B Precision Source/Measure Unit, which was employed both to excite the devices with an arbitrary waveform and to simultaneously acquire voltage and current

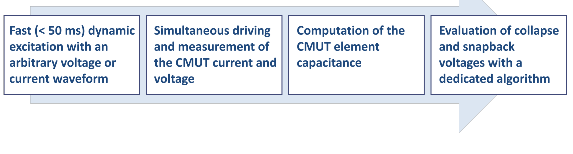

Fig. 1. Summary of the main steps of the proposed technique for evaluating the V_c and V_{sb} distribution.

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data for capacitance extraction. A bipolar triangular voltage signal and a bipolar square current signal were used to drive the CMUT, therefore implementing voltage-controlled and charge-controlled membrane actuation [6], respectively. Both waveforms had a duration below 50 ms and an amplitude sufficient to induce collapse and snapback of all the element's membranes, while providing the same charge profile. Experiments were carried out on a XIVER CM5 64-element 1-D CMUT array. The experimental setup is shown in Fig. 2.

III. RESULTS

A. Voltage-controlled approach

Fig. 3 shows the results of the voltage distribution analysis performed on a representative element of the tested CMUT using the voltage-controlled approach. The algorithm identifies the regions of C (black) corresponding to collapse and snapback during the forward and backward sweeps of the excitation signal, based on peak detection of the moving average of I_m (red). The quantity dC/dV_m in these regions is then used to compute the histograms shown in Fig. 3. As can

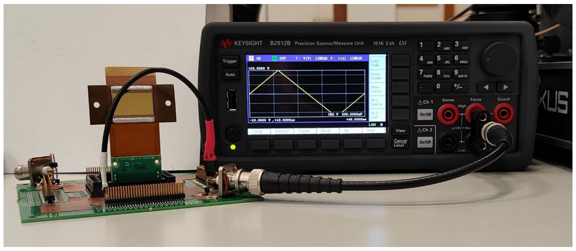
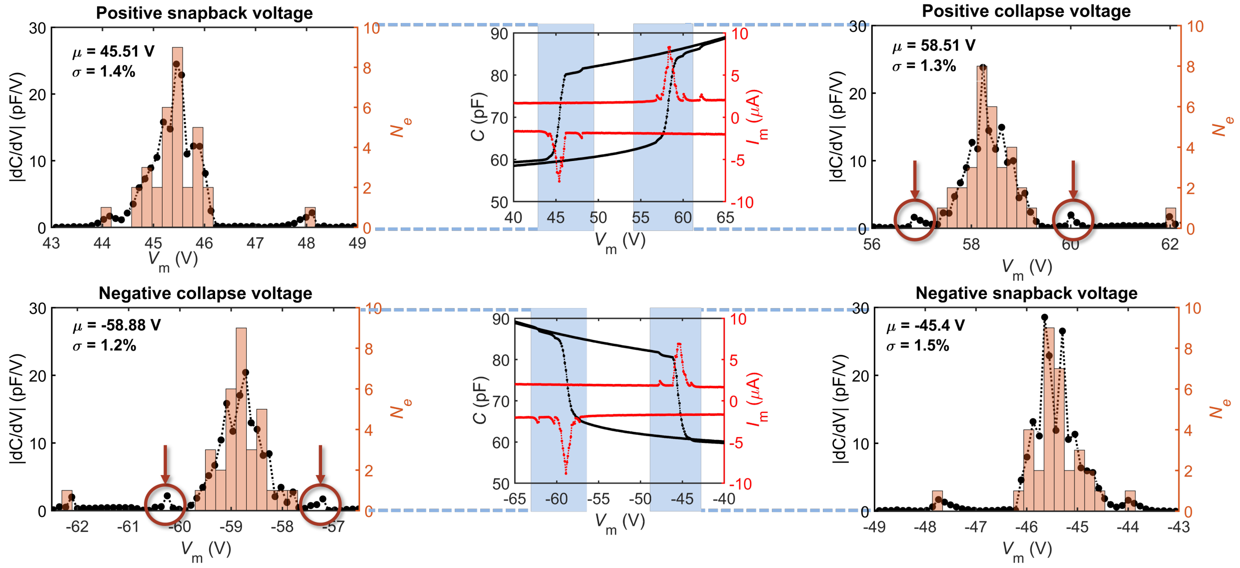


Fig. 2. Experimental setup including a SMU and a 64-element linear CMUT array.



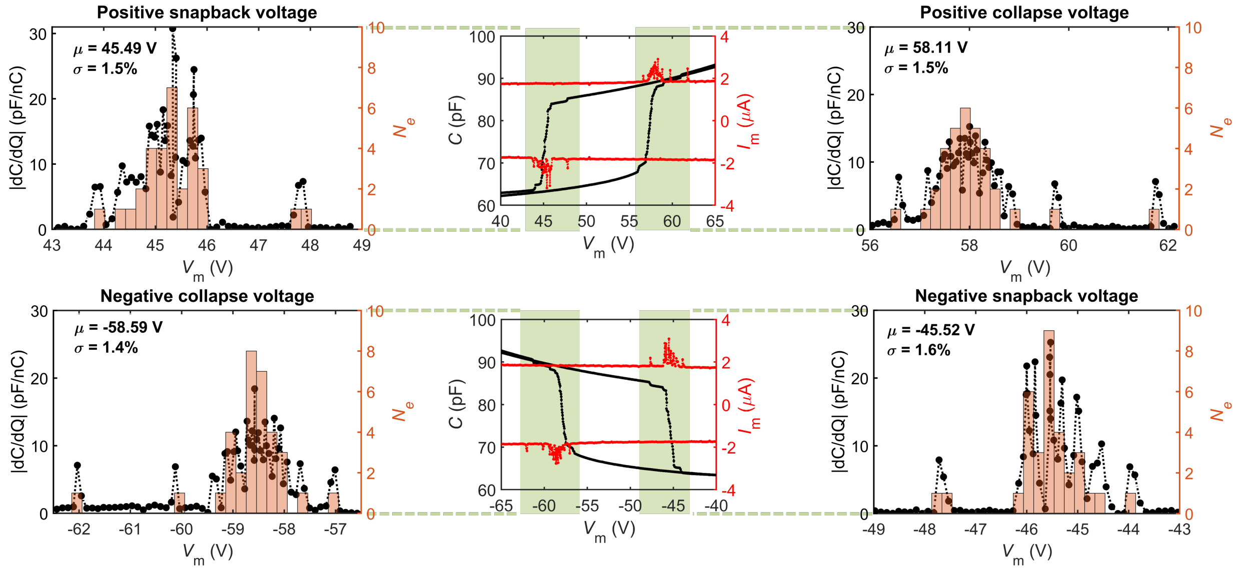
Positive snapback voltage

Positive collapse voltage

Negative collapse voltage

Negative snapback voltage

Fig. 3. Results of the distribution analysis of V_c and V_{sb} obtained by exciting the CMUT with a voltage signal (voltage-controlled actuation).



Positive snapback voltage

Positive collapse voltage

Negative collapse voltage

Negative snapback voltage

Fig. 4. Results of the distribution analysis of V_c and V_{sb} obtained by exciting the CMUT with a current signal (charge-controlled actuation).

be noticed, $\mathrm{d}C/\mathrm{d}V_\mathrm{m}$ is mostly smooth around the main peak, shadowing sharp variations relatable to single events and thereby hindering accurate detection of the collapse and snapback events. In addition, the algorithms occasionally fails to detect isolated events, as highlighted by the red circles.

B. Charge-controlled approach

Fig. 4 presents the results of the voltage distribution analysis carried out on the same element using the charge-controlled approach. In this case, the quantity employed to reconstruct the histograms is $\mathrm{d}C/\mathrm{d}Q$. It can be observed that the peaks associated with individual collapse and snapback events are much more distinguishable compared to the previous approach. Consequently, the detection of isolated events is successfully achieved by the algorithm, demonstrating that current driving provides higher resolution and ensures more robust identification of collapse and snapback events.

C. Comparison of the two approaches

Both voltage-controlled and charge-controlled actuation were used to characterize the 64 elements of the array, computing the element means μ of the positive collapse voltage, V_c^+, positive snapback voltage, V_sb^+, negative collapse voltage, V_c^-, and negative snapback voltage, V_sb^-. These element means were then used to derive the array mean and deviation values, μ_a and σ_a, as reported in Table I. At the array level, the two approaches provide comparable results, with the largest difference between the means being $\Delta V_\mathrm{c}^- = 0.3$ V.

TABLE I. COMPARISON BETWEEN VOLTAGE-CONTROLLED AND CHARGE-CONTROLLED APPROACH RESULTS

	Voltage control		**Charge control**	
	μ_a (V)	***σ_a***	***μ_a (V)***	***σ_a***
V_c^+	58.43	1.6%	58.16	1.6%
V_sb^+	45.58	1.1%	45.52	1.1%
V_c^-	−58.87	1.5%	−58.57	1.6%
V_sb^-	−45.56	1.1%	−45.60	1.1%

IV. DISCUSSION

The proposed technique for the fast evaluation of collapse and snapback voltages can be successfully applied using either voltage excitation or current excitation. However, driving the CMUT with a current waveform provides greater control over the injected charge, resulting in sharper peaks of the differential capacitance that enable more reliable detection of isolated collapse or snapback events. The impact of missed detections is expected to be more significant when the undetected event occurs at a voltage that strongly deviates from the mean.

Since each element is composed of multiple membranes, the effect of occasional missed detections is overall mitigated when computing the array means, making both approaches suitable for fast array-level voltage distribution analysis and variability assessment.

V. CONCLUSIONS

This work presented a technique for the fast evaluation of collapse and snapback voltages of CMUTs and assessment of their variability at both the element and array levels. Both voltage-controlled and charge-controlled membrane actuation were implemented, showing that charge control, achieved by exciting the CMUT with a square current waveform, enables improved detection of individual collapse and snapback events, thereby providing more reliable mean voltage and deviation results. The proposed method can be implemented with a benchtop SMU, without the need for bulky or expensive equipment. Furthermore, it is scalable to wafer-level testing, where automatic element switching can enable fast, element-wise characterization of high-count CMUT arrays.

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