DYNAMIC ANALYSIS OF CMUTs IN DIFFERENT REGIMES OF OPERATION

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Abstract – This paper reports on dynamic analysis of an immersed single capacitive micromachined ultrasonic transducer (CMUT) cell transmitting. A water loaded 24 μm circular silicon membrane of a transducer was modeled. The calculated collapse and snapback voltages were 80 V and 50 V, respectively.

The resonance frequency, output pressure and nonlinearity of the CMUT in three regimes of operation were determined. These regimes were: a) the conventional regime in which the membrane does not make contact with the substrate, b) the collapsed regime in which the center of the membrane is in constant contact with the substrate, and c) the collapse-snapback regime in which the membrane intermittently makes contact with the substrate and releases.

The average membrane displacement was compared as the CMUT was operated in these regimes. A displacement of 70 Å in the collapsed regime and 39 Å in conventional regime operation were predicted when a 5 V pulse was applied to the CMUT cell biased at 70 V. The CMUT showed a 2nd harmonic at –16 dB and –26 dB in conventional and collapsed regimes of operation, respectively. Collapse-snapback operation provided increased output pressure at the expense of a 3rd harmonic at –10 dB. Our simulations predicted that the average output pressure at the membrane could be 90 kPa/V with collapse-snapback operation compared to 4 kPa/V with conventional operation.

I. INTRODUCTION

The performance of a capacitive micromachined ultrasonic transducer (CMUT) [1, 2] depends on the DC bias applied to it. The bias should be close to the collapse voltage in order to maximize transduction efficiency of the transducer in conventional regime operation [3]. When the bias is close to collapse voltage, the maximum excitation voltage amplitude is limited by the requirement that the total applied voltage should not exceed the collapse voltage of the CMUT. Finite element calculations of a collapsed CMUT have predicted that a higher coupling efficiency and output pressure could be achieved when the CMUT is operated in its collapsed regime [4]. That work assumed a quasitatic situation in which the membrane could respond to an applied signal without delay. Hence dynamic effects were not taken into consideration. This work is a continuation of the quasistatic work and presents the dynamic analysis of an immersed single CMUT cell. We investigate conventional, collapsed and collapse-snapback operation regimes for gains in transmit power and linearity.

II. FINITE ELEMENT CALCULATIONS

Finite element methods (FEM) were used to analyze the CMUT using a commercially available FEM package (ANSYS 7.1, ANSYS Inc., Canonsburg, PA) [5]. The FEM model of an immersed single CMUT cell is shown in Fig. 1. The structure is axi-symmetric allowing 2D modeling. A conductive silicon substrate, covered with 0.1 μm silicon oxide insulation layer, was separated by a 0.2 μm vacuum gap from the 1.65 μm thick conductive silicon membrane, which was supported on the outer circular silicon oxide post. The radius of the circular membrane was 24 μm and the center frequency of the membrane was 5 MHz in water. This CMUT design features collapse and snapback voltages of 80 V and 50 V, respectively. The bottom of the substrate was clamped and the center of the CMUT was guided along the y-axis. An air pressure of 1 atm was applied onto the membrane to model the vacuum in the gap beneath the membrane. The interface between the silicon substrate and the silicon oxide insulation layer forms the ground electrode. The top electrode is placed on the lower face of the silicon membrane. Two element types, PLANE42 and PLANE121, were used as structural and electrostatic

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elements interchangeably for the membrane, substrate and the gap. The collapse of the membrane onto the substrate was modeled by means of contact-target pair elements (CONTA172 and TARGE169). The FLUID29 element was used to model the fluid medium covering the transducer. An absorbing boundary condition was applied on the circular boundary surrounding the fluid medium [5].

The CMUT cell was statically biased at a voltage within the intended operation regime prior to the transient analysis. A pulse was subsequently applied to determine output pressure and resonance frequency. A sinusoidal (AC) voltage was applied to determine the generation of harmonics by the CMUT.

III. RESULTS

The CMUT cell was biased at 70 V both in the conventional and in the collapsed regime of operation. A 5V, 20 ns pulse was then applied and the transient response of the average displacement and pressure across the membrane were recorded. The response is shown in Fig. 2 and Fig. 3, respectively. A displacement (p-p) of 70 Å in collapsed regime of operation and of 39 Å in conventional regime of operation were seen. The center frequencies were 8.7 MHz in the collapsed regime and 3.8 MHz in the conventional regime of operation, respectively. When the bias voltage was changed between the collapse and snapback voltages, the average displacement and center frequency varied as depicted in Fig. 4 and Fig. 5, respectively. The average membrane displacement in the conventional regime of operation increased with bias voltage whereas the average membrane displacement in the collapsed regime operation showed a peak at 70 V bias. The center frequency in conventional regime operation decreased due to the spring softening effect [3] with increasing bias. That effect was also seen as a decrease in center frequency in collapsed regime operation up to 65 V bias. A further increase in bias voltage reduced the moving area of the membrane by increasing the contact radius. This contact radius effect caused the center frequency to increase at higher bias voltages.

In the linearity tests the CMUT cell was biased to 65V both in the conventional and collapsed regimes of operation. A sinusoidal voltage (1MHz) was applied to determine the 2nd harmonic generation as a

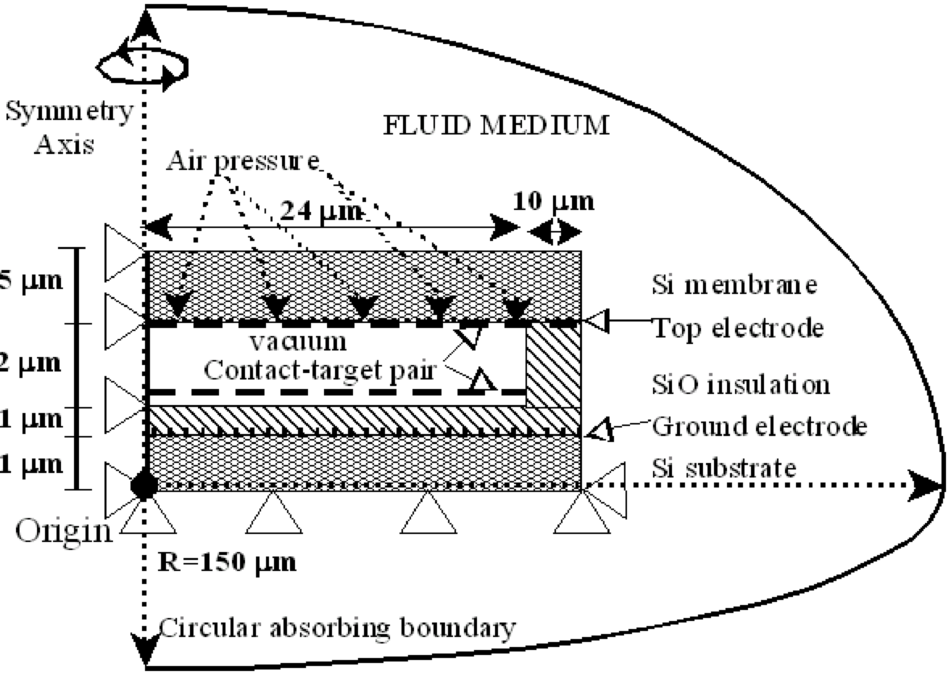

Fig. 1. The CMUT simulation model

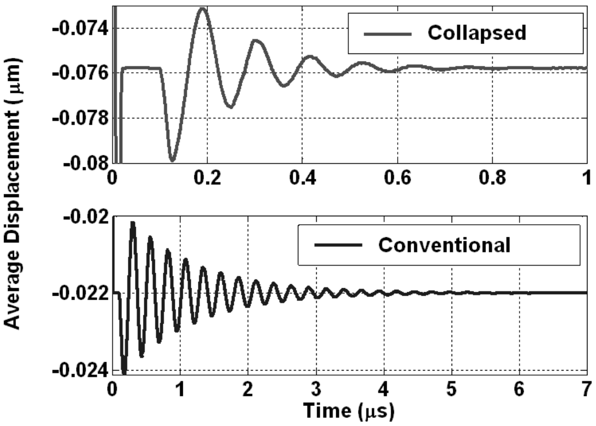

Fig. 2. Average displacement as a function of time.

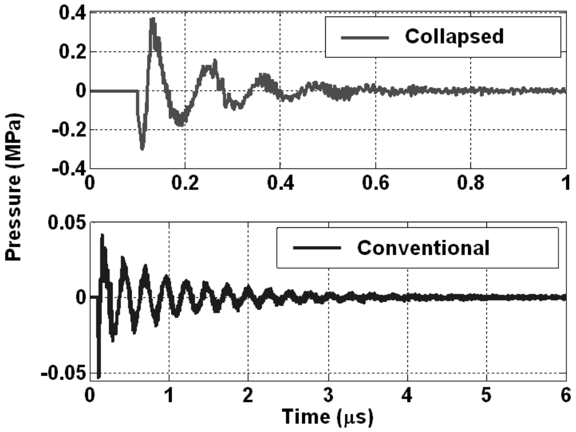

Fig. 3. Pressure as a function of time.

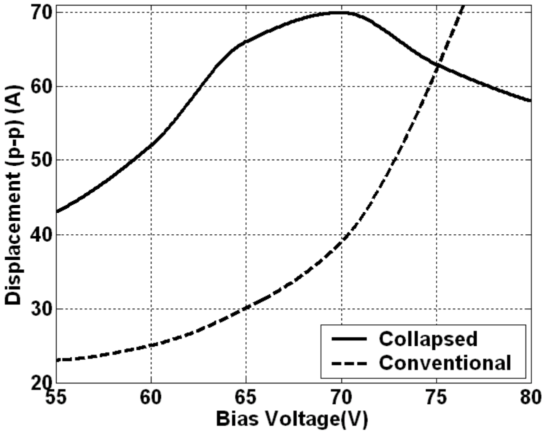

Fig. 4. Displacement (p-p) for different bias voltages.

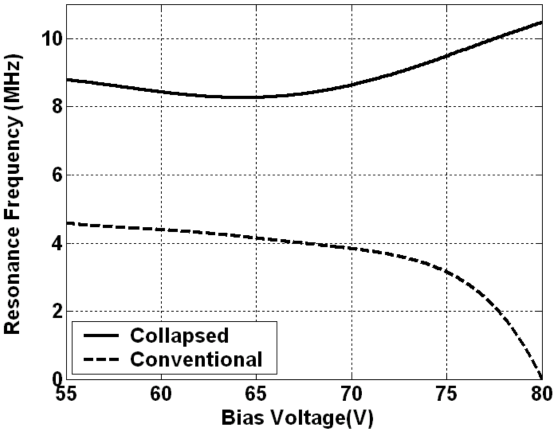

Fig. 5. Resonance frequency for different bias voltages.

function of AC amplitude, Fig. 6. The collapsed regime operation showed a 2nd harmonic of –26 dB compared to –16 dB in the conventional regime operation at 5V AC excitation. Increasing the AC amplitude decreased the linearity of the CMUT in both regimes of operation.

When the CMUT was operated in the collapse-snapback regime, the average membrane displacement was increased compared to what was attained in the two other regimes of operation (10 Å/V in conventional, 30 Å/V in collapse-snapback), however, with increased nonlinear output (3rd harmonic of –10 dB).

The simulation results are summarized in Table I. Collapsed and collapse-snapback operations required a lower bias voltage than the conventional operation. Additionally, the collapsed regime operation showed a higher linearity and output pressure than the conventional regime operation. The collapse-snapback operation offered the highest output pressure of all regimes with a trade-off in linearity.

IV. DISCUSSION

Several assumptions underlie the simulation.

The contact and target pairs were defined on the bottom of the membrane and slightly above the top of the insulation layer. This offset, required to remorph or remesh the gap for the deformed membrane, was 2 % of the gap. It will slightly increase the equivalent insulation layer thickness of the CMUT.

The contact behavior was assumed to be ideal without friction. A linear wave equation was used to describe the propagation of the acoustic wave in the immersion fluid even though instant pressures in the order of MPa were generated.

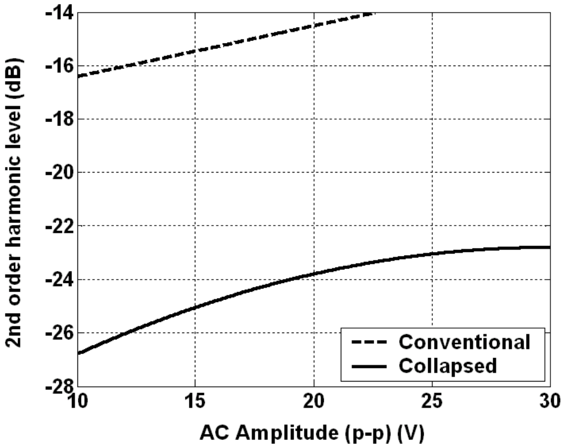

Fig. 6. Second harmonic for different AC voltages.

An exact absorbing boundary equation was implemented in order to truncate the infinite immersion domain to a finite size model. It was assumed (and observed) that the boundary does not cause significant spurious reflections.

Table I. Comparison of operation regimes

Performance	Conventional	Collapsed	Collapse-Snapback
V_{BIAS}	High	Low	Low
V_{TOTAL}	$<V_{COLLAPSE}$	$>V_{SNAPBACK}$	$>V_{COLLAPSE}$ $<V_{SNAPBACK}$
Output Power	Low	Medium	High
Linearity	Good	Better	Worse

V. CONCLUSION

Finite element calculations were performed to analyze, in time domain, a single CMUT cell in different regimes of operation. Two predictions were obtained: 1) Collapsed regime operation offers the benefit of designing CMUTs with lower bias voltage, higher linearity and center frequency than offered in conventional operation. 2) Collapse-snapback regime operation offers a higher output pressure with reduced linearity. Future work will focus on the 3D dynamic analysis of multiple CMUT cells.

ACKNOWLEDGMENT

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