A Tethered Front-Plate Electrode CMUT for Broadband Air-Coupled Ultrasound

William M. D. Wright and Sean G. McSweeney
Department of Electrical and Electronic Engineering
University College Cork
Cork, Ireland
bill.wright@ucc.ie

***Abstract*— Capacitive micromachined ultrasonic transducers (CMUTs) typically consist of a back-plate electrode on a substrate wafer, separated from a front-plate electrode by a small cavity. The electrode structures are usually sealed and when operating in air the majority of these CMUTs are highly resonant. However, for air-coupled applications, this sealing is not strictly necessary allowing other more open electrode structures to be explored. A CMUT structure specifically for air-coupled operation was investigated, consisting of a front-plate electrode that was tethered at only a few points around its periphery. The front-plate was also perforated to increase the overall squeeze-film damping and hence the bandwidth of the device. A series of CMUTs up to 800 µm by 800 µm square was manufactured in a standard CMOS process, using a sacrificial polyimide etch to leave a free-standing aluminum front-plate electrode 1.0 µm thick with a nominal electrode gap of 1.5 µm. A number of thin tethers along the device edges attached the front-plate electrode to the substrate, producing a CMUT structure that was completely open at the edges, with low front-plate stiffness and high squeeze-film damping. A one-dimensional analytical model was formulated to predict the response of the devices, and compared to the measured response of the manufactured CMUTs. The structures were not optimized, but initial results on the prototypes were promising. The devices had a pull-in voltage of only 5 V and a nominal capacitance of 70 pF. The devices were tested as transmitters and receivers over a 15 mm path in air, using a well-characterized broadband transducer as a standard transmitter or receiver. The tethered CMUTs had a center frequency of 400 kHz with a usable bandwidth of over 1 MHz in air, giving a Q-factor of less than 1. However, the devices were not very efficient, with an insertion loss of almost 70 dB and highly damped, as expected. The analytical model also gave reasonably good agreement with the experimental measurements.**

Keywords - aluminum front-plate electrode; tethered CMUT; broadband air-coupled ultrasound; squeeze-film damping; analytical model.

I. Introduction

Capacitive micromachined ultrasonic transducers (CMUTs) are a well-established technology for generating and detecting ultrasound in a wide variety of media. CMUTs typically consist of a back-plate electrode on a substrate wafer, separated from a front-plate electrode by a small cavity. Various micromachining and wafer bonding techniques of CMUT manufacture have been described previously in the literature [1-12]. When operating in air, the majority of these CMUTs are highly resonant and the CMUT structures are usually sealed. However, for air-coupled applications, this sealing is not strictly necessary, allowing other more open CMUT structures to be explored. Parameters that influence CMUT bandwidth include the front-plate electrode mass and stiffness, the compliance of the electrode gap, and damping of the front-plate electrode. In this work, an open-edged CMUT with a tethered aluminum front-plate electrode was investigated for broadband air-coupled operation.

II. Device Fabrication and Modeling

A. *Fabrication steps*

A cross-section of the CMUT structure is shown schematically in Fig. 1. The CMUTs were manufactured using standard CMOS processes on a p-type {100} wafer. First, a passivation layer of SiO_2 0.5 µm thick was deposited using PEVCD. Then 0.5 µm of 99%Al/1%Si was sputtered and patterned with a mask and plasma etching to produce the lower electrodes, tracks and bond pads. A sub-passivation layer of 100 nm SiO_2 was then added using PEVCD and patterned via plasma etching. A sacrificial layer of polyimide 3.0 µm thick was then spun on and patterned, followed by sputtering of the structural aluminum layer 1.0 µm thick which was then patterned and plasma etched. Finally, the sacrificial polyimide layer was removed by plasma ashing.

A plan schematic of a typical CMUT is shown in Fig. 2. The devices were up to 800 µm x 800 µm square with two thin supporting tethers at each of the corners. This gave an open-sided electrode structure to provide squeeze-film damping at the edges and additional damping from the open etch holes in the aluminum front-plate electrode.

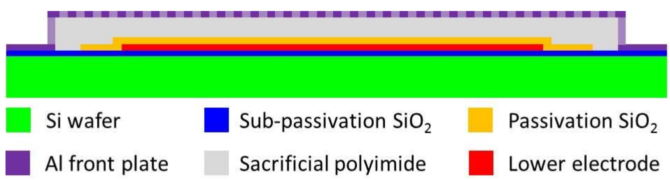

Figure 1. Schematic cross-section of a tethered CMUT (not to scale).

This work was supported by Science Foundation Ireland (SFI) Research Frontiers Programme grant no 11/RFP.1/ECE/3119, and NAP awards 35 and 225 from the Tyndall National Institute, University College Cork.

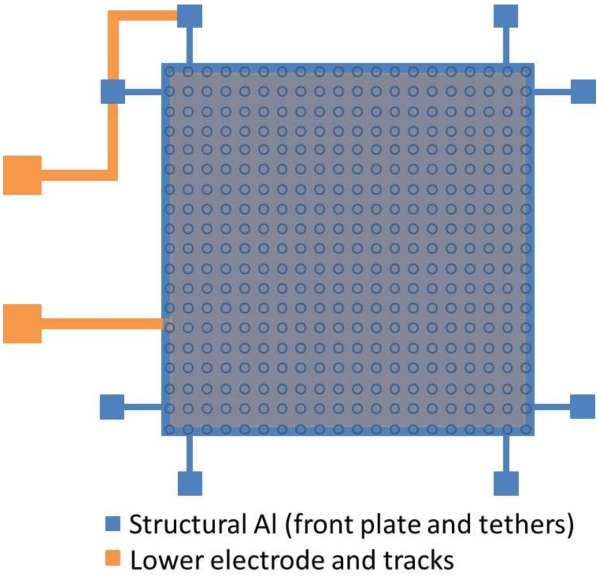

Figure 2. Schematic plan of a tethered CMUT (not to scale).

A photograph of typical devices as manufactured is shown in Fig. 3. There is a row of six rectangular test structures at the top of the image above a 2x2 array of square devices of side 800 µm with two tethers at each corner. Each device die was mounted and wirebonded in a standard 24-pin DIL package

B. *Modeling*

A one-dimensional model of the tethered CMUT structure based on previous work by Ge [13], Steneken [14] and Skvor [15] was developed to include the effects of squeeze-film damping through the etch holes, slip flow at the open edges and fringing fields between the square electrodes, as follows:

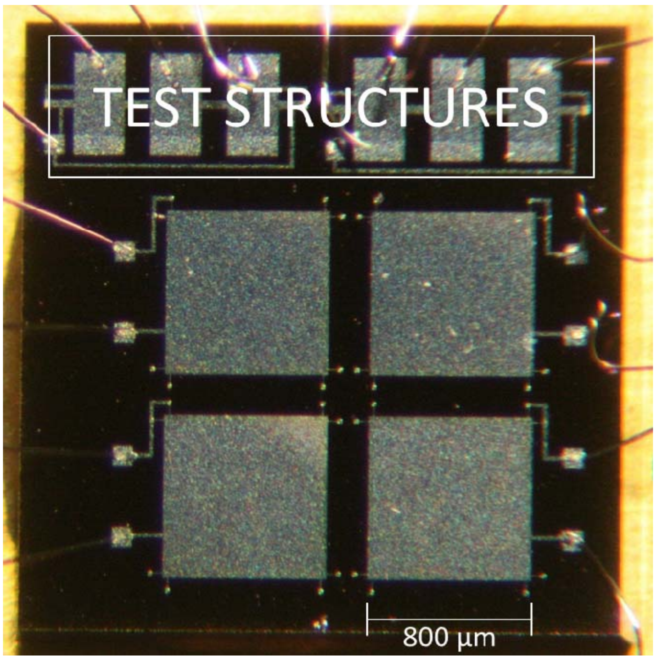

Figure 3. Typical tethered CMUT package (2x2 array).

$$f(t) = m\ddot{x} + \frac{b}{x^3 + 9\lambda x^2}\dot{x} + k(x_0 - x) + A_{el}\varepsilon_0 \upsilon^2\left(\frac{1}{2x^2} + \frac{1}{\pi W_s x}\right), \quad (1)$$

where

$$W_s = \frac{A}{2a + N_h^2 \pi r}, \quad (2)$$

$$\upsilon = \frac{q(x_0 - x)}{\gamma(x) A_{el}\varepsilon_0}, \quad (3)$$

$$\gamma(x) = 1 + \frac{2x}{\pi W_s}\left(1 + \ln\left[\frac{\pi W_s}{2x}\right]\right). \quad (4)$$

The model nomenclature is shown below in Table I.

TABLE I. MODEL NOMENCLATURE

Parameter	Symbol
Front plate mass	m
Damping coefficient	b
Spring constant	k
Area of electrode	A_{el}
Permittivity of free space	ε_0
Area of front plate	A
Side length of front plate	a
Number of front plate holes	N_h
Hole radius	r
Charge	q
Mean free path length	λ
Effective width	W_s

III. CMUT CHARACTERIZATION

The tethered CMUTs were first characterized by *C-V* measurements and the typical trace shown in Fig. 4 shows a pull-in voltage of 5 V and a nominal device capacitance of 70 pF before pull-in and 84 pF after pull-in. The devices were then characterized using a Polytec laser vibrometer, with a typical surface velocity plot shown in Fig. 5 measured at the center of the front-plate when driven with a 50% duty cycle square wave. The vibrometer measurements showed typical front-plate surface velocities of up to 3.6 mm/s and well-damped pull-in and pull-out responses, as expected. Surface scans showed that different plate vibrational modes were set up in the front-plate when the devices were driven with sinusoidal signals that corresponded to the resonance frequencies. It was also apparent that the front-plate had deformed into a dome, as shown by the white-light interferometer profile in Fig. 6, where

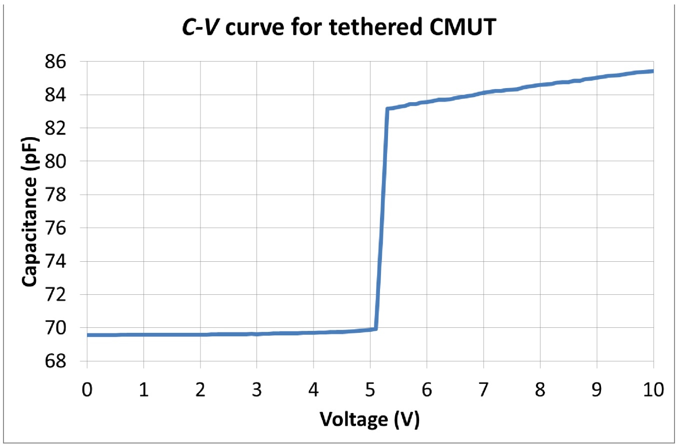

Figure 4. Typical tethered CMUT pull-in *C-V* curve measurement.

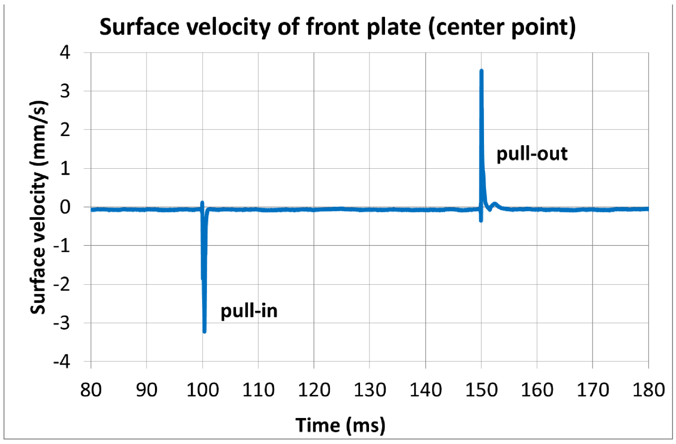

Figure 5. Typical tethered CMUT surface velocity measurement.

it can be seen that the height of the front-plate electrode had increased to 6.0 µm in the center of the device.

IV. Experimental Procedure

The tethered CMUTs were then used as either a receiver or a transmitter in an air-coupled pitch-catch system, shown schematically in Fig. 7. The other transducer in each case was a broadband capacitive ultrasonic transducer (CUT) with a 5 µm thick metallized PET membrane electrode and a high-*k* coated pitted back plate electrode. These devices have been shown previously to have a center frequency of 500 kHz and a bandwidth of over 1.0 MHz [16]. When the CMUT was used as a transmitter it was connected to a Thurlby Thandar Instruments TG1010A arbitrary waveform generator, producing an 8 V Gaussian pulse at a PRF of 100 Hz with an –8 V bias and the CUT receiver was biased to 100 V via the Cooknell Electronics CA6/C amplifier and SU2/C and bias unit. When used as a receiver, the tethered CMUT was biased to approximately 5–10 V via the CA6/C and SU2/C, but the exact bias was difficult to determine due to the resolution of the equipment controls. The CUT transmitter signal came from a Panametrics 5800, delivering a 12.5 µJ impulse at a PRF of 100 Hz. Additional gain was provided by an EG&G Princeton 5113 pre-amplifier. The propagation path length in air between transmitter and receiver was 15 mm. The tethered CMUTs were placed in aluminum housings with 5.0 mm diameter apertures to provide additional electrical screening, as the wirebonds to the electrode bond pads were exposed.

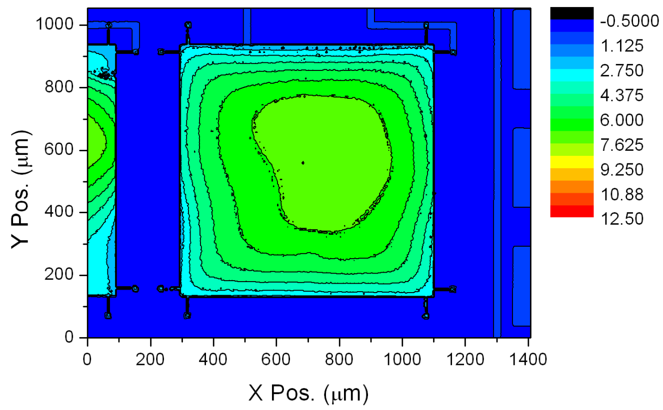

Figure 6. White light interferometer profile of CMUT dome.

V. Results and Discussion

Typical received ultrasonic signals and their corresponding frequency spectra are shown in Fig. 8 and Fig. 9, respectively. The tethered CMUT devices produced a well-damped ultrasonic response in air and were broadband, as expected. The output of the CMUT model is also included in Fig. 8 and Fig. 9, for comparison. It should be noted that both of the experimental traces contain reflections from the aluminum housing at times of approximately 70 µs and 90 µs in Fig. 8, which do not appear in the model output. There is reasonable agreement between the model and experiments. The deviations between the model and experiments are thought to be due to:

- the one-dimensional approximations used;
- distortion of the CMUT front plates into a dome, as shown in Fig. 6, due to residual stress in the aluminum front-plate. This initial shape was not included in the model, which assumed a flat profile and a constant electrode gap of 3.0 µm;
- difficulties in applying a precise bias to the CMUT as a receiver, due to the limitations of the equipment;

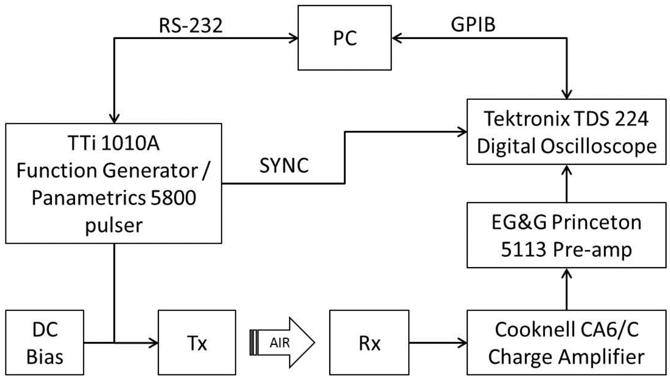

Figure 7. Schematic diagram of experimental apparatus.

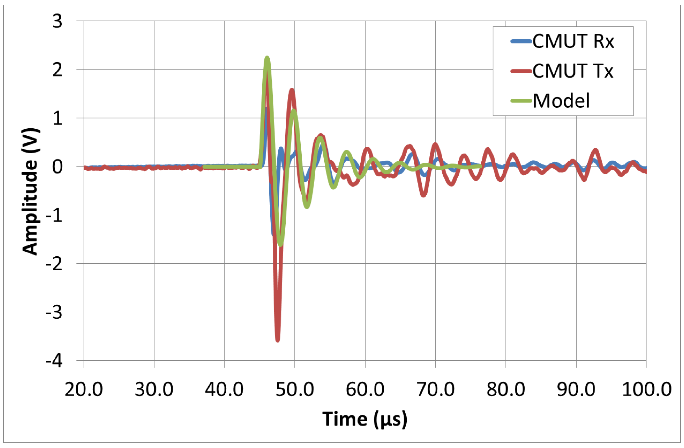

Figure 7. Typical waveforms with the CMUT as receiver (Rx) and transmitter (Tx), compared to the model.

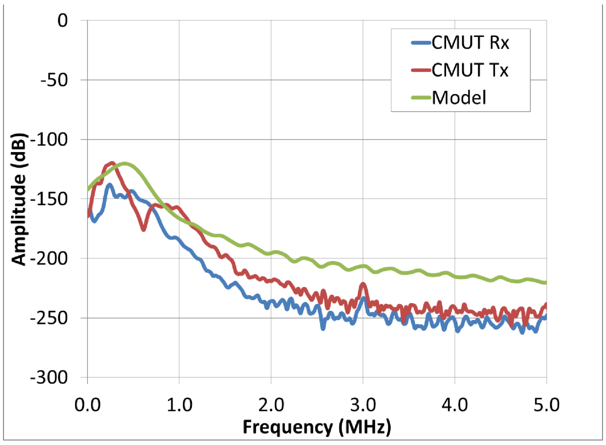

Figure 8. Typical frequency responses with the CMUT as receiver (Rx) and transmitter (Tx), compared to the model.

- variations in the assumed values of density, elastic modulus and residual stress of the structural aluminum used in the model.

VI. Conclusions and Future Work

An open-edged CMUT with a tethered aluminum front-plate electrode was successfully manufactured, modeled and characterized, and produced a well-damped broadband response in air at a center frequency of 400 kHz.

Future work will investigate alternative front-plate and tether geometries, refinements to the analytical model, improvements to the manufacturing process and packaging, and additional broadband air-coupled applications.

Acknowledgments

The authors would like to thank Conor O'Mahony, Zbigniew Olszewski and Jaap Verheggen from the Tyndall National Institute for their assistance in characterizing the devices with the white light interferometer and laser vibrometer.

References

[1] K. Suzuki, K. Higuchi, and H. Tanigawa, "A silicon electrostatic ultrasonic transducer", *IEEE Trans. Ultrason., Ferroelec., Freq. Contr.*, vol. 36, no. 6, pp. 620–627, 1989.

[2] I. Ladabaum, X. Jin, H. T. Soh, A. Atalar, and B. T. Khuri-Yakub, "Surface micromachined capacitive ultrasonic transducers", *IEEE Trans. Ultrason., Ferroelec., Freq. Contr.*, vol. 45, no. 3, pp. 678–690, 1998.

[3] D. Memmi, V. Foglietti, E. Cianci, G. Caliano and M. Pappalardo, "Fabrication of capacitive micromechanical ultrasonic transducers by low-temperature process", *Sensor Actuat. A-Phys*., vol. 99, no. 1–2, pp. 85–91, 2002.

[4] P.-C. Eccardt, K. Niederer, and B. Fischer. Micromachined transducers for ultrasound applications", *Proc. IEEE Symp. Ultrasonics*, vol. 2, pp. 1609–1618, 1997.

[5] G. Caliano, F. Galanello, A. Caronti, R. Carotenuto, M. Pappalardo, V. Foglietti and N. Lamberti, "Micromachined ultrasonic transducers using silicon nitride membrane fabricated in PECVD technology", *Proc. IEEE Ultrason. Symp*., vol. 1, pp. 963- 968, 2000.

[6] A. Buhrdorf, A. Lohfink, S. Junge, P.-C. Eccardt and W. Benecke, "Fabrication and characterization of a new capacitive micromachined ultrasonic transducer (cMUT) using polysilicon as membrane and sacrificial layer material", *Proc. IEEE Symp. Ultrason*., vol. 2, pp. 1951-1954, 2003.

[7] M. Pappalardo, G. Caliano, A. Caronti, F. D'Alessio, C. Cucco, E. Cianci and V. Foglietti, "Capacitive ultrasonic transducers with a new vibrating structure", *Proc. IEEE Symp. Ultrason*., vol. 2, pp. 1955-1959, 2003.

[8] A. Caronti, G. Caliano, R. Carotenuto, A. Savoia, M. Pappalardo, E. Cianci and V. Foglietti, "Capacitive micromachined ultrasonic transducer (CMUT) arrays for medical imaging", *Microelectr. J*., vol. 37, no. 8, pp. 770–777, 2006.

[9] G. Caliano, V. Foglietti, E. Cianci, and M. Pappalardo, "A silicon microfabricated electrostatic transducer: 1 MHz transmission in air and in water", *Microelectron. Eng*., vol. 53, no. 1, pp. 573–576, 2000.

[10] R. A. Noble, R. J. Bozeat, T. J. Robertson, D. R. Billson, and D. A. Hutchins, "Novel silicon nitride micromachined wide bandwidth ultrasonic transducers", *Proc. IEEE Symp. Ultrason*., vol. 2, pp. 1081–1084, 1998.

[11] K. K. Park, H. Lee, M. Kupnik, and B. T. Khuri-Yakub, "Fabrication of capacitive micromachined ultrasonic transducers via local oxidation and direct wafer bonding", *J. Microelectromech. S*., vol. 20, no. 1, pp. 95–103, 2011.

[12] M. Kupnik, M.-C. Ho, S. Vaithilingam, and B. T. Khuri-Yakub, "CMUTs for air coupled ultrasound with improved bandwidth," *Proc. IEEE Ultrason. Symp*., pp. 592-595, 2011.

[13] L. F. Ge, "Electrostatic airborne ultrasonic transducers: modeling and characterization", *IEEE Trans. Ultrason., Ferroelec., Freq. Contr.*, vol. 46, no. 5, pp. 1120–1127, 1999.

[14] P. G. Steeneken, T. G. S. M. Rijks, J. T. M. Beek, M. J. E. Ulenaers, J. D. Coster, and R. Puers, "Dynamics and squeeze film gas damping of a capacitive RF MEMS switch", *J. Micromech. Microeng*., vol. 15, no. 1, pp. 176-184, 2005.

[15] Z. Skvor, "On acoustical resistance due to viscous losses in the air gap of electrostatic transducers", *Acoustica*, vol. 19, pp. 295-297, 1967.

[16] S. G. McSweeney and W. M. D. Wright, "HfO2 High-k Dielectric Layers in Air-Coupled Capacitive Ultrasonic Transducers", *Proc. IEEE Internat. Ultrason. Symp*., pp. 864-867, 2011.