

Characterization of cMUT by Dynamic Holography Microscopy

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Abstract—The comparison of numerical simulations to real cMUT behavior is essential to assess and optimize the process. For a complete characterization multiple devices (FIB, SEM, impedancemetry, laser interferometry,...) are needed. In this context, we propose to use a full-field measurement device, a Digital Holography Microscopy (DHM Lynceotec®), which acquires static and dynamic in-plane and out-of-plane information of membranes population in a single acquisition and then provides most of required parameters. This paper presents the principle of this device, its performances comparing to other ones and its limits.

Index Terms— cMUT – initial stress membrane– Young’s modulus membrane – Dynamic Holography Microscope.

I. INTRODUCTION

The characterization of transducer array based on cMUT technology after micromachining process is an essential step of the production line. Aims of this procedure are numerous. The most important are first to provide to the transducer manufacturer information on the state of cMUT membrane in order to control their position: deflection, geometry and electrode alignment. Second objective is to establish a set of physical membrane properties in order to use them as input data of numerical models and thus predict electroacoustic performances of the final devices. Main difficulty in the characterization of these devices is their “multiple” scale of observation. At nanometric scale, since the deflection of the membrane has to be controlled with few nanometers of resolution. At microscopic scale, membranes have typically dimensions of few micrometers square. And finally, at millimetric scale, it corresponds to the final size of transducer. With these aims, electrical impedancemetry is able to provide both a set of electrical and mechanical properties using simple fit method with numerical modeling, assuming membrane is not deflected [Cyril meynier]. In addition, the electroacoustic and capacitive measurements provide an indication about the uniformity of membranes. However, it can not give precisely the collapse voltage and initial deflection of one lonely membrane. The laser interferometry can help in this control at the scale of a membrane, allowing to measure local displacement/voltage cycle, and thus, the collapse/snapback voltages of the investigated cMUT. Furthermore, it gives the impulse response of membranes taking into account inter-membrane cross-talk and coupling, that can be used as input data for field simulation tools. However, the static and initial deflection can not be obtained with this system, and cMUT must be controlled one by one leading to very long experiment. To measure static deflection, AFM and

profilometer are able to detect few nanometers of amplitude over few micrometers of width. Again measurement times are long (one by one) and the evolution of membrane can not be observed with the bias voltage variations. Confocal microscopy offers the ability to simultaneously image several cMUTs but vertical resolution is too poor (10 nm) to be accurate technique as compared to vertical geometry of the cMUT. The holographic microscopy is a trade off between AFM or profilometer systems and interferometry technique. It can observe static membrane position over a large field of view with optical resolution (better than 1 nm) and if membranes are biased, the displacement/voltage cycle can be measured too. Today using pulsed laser, stroboscopic method can be used to sample the displacement of the membrane when it moves in real time. Of course a specific treatment on amplitude measurements must be done when values are greater than the half of optical wavelength, i.e. unwrapping phase methods and/or two different optical wavelength sources.

Based on a holographic microscope, commercially available, we propose in this paper a strategy to characterize cMUTs. First part of this paper briefly reviews principle of the measurement and different kinds of measurement than can be performed. Second part is an exploitation to control parameter design of cMUT after process: roughness and mechanical conditions of the membranes. A particular attention to the collapse voltage determination is dealt in the third part. This is a key feature of the cMUT due to the fact that the distribution of collapse voltage over a population of cells is an indicator of membranes homogeneity. The control of the displacement amplitude reached when membrane is collapsed verifies that cMUT can deflect all over the height of the cavity. Finally, the last part is a method for determining and discriminating membrane stress and Young’s modulus values. The main solution proposed in MEMS community is to manufacture specific test devices such as clamped-clamped bridge or clamped-free cantilever [1]. Then using simple analytical relationships and experimental deflection values, stress and Young’s modulus can be determined. Unfortunately, the status after process of these devices is too far from the one of membranes which are partially metalized. Thus, the characterization conditions are not satisfying enough to measure with precision the Young’s modulus and stress. Here, we propose to realize test devices with the same electrode patterning than the final transducer and with several geometries. Then, confrontation between theoretical abacus (computed with finite element code) and experimental deflection values we will show that stress and Young’s modulus can be determined without any ambiguity.

II. DHM PRESENTATION – MATERIAL AND METHODS

DHM (LynceeTec®) generates cMUT 3D images using the principle of holography [2]. Holograms are induced by combining a coherent reference wave with the wave received from the cMUT by reflection and recorded by a CCD camera, as shown Figure 1.

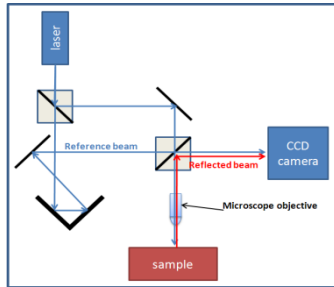


Figure 1 : Principle of holography microscopy.

Their reconstructions are dealt numerically in real-time and provide an intensity image and a phase image where out-of-plane quantitative data are extracted (Figure 2). However, as heterodyne interferometer, it needs a good reflectivity to measure correctly the out-of-plane geometries.

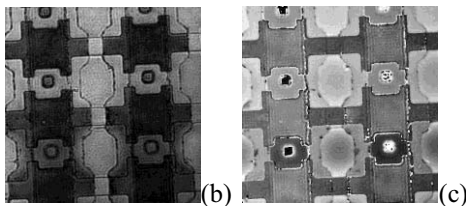
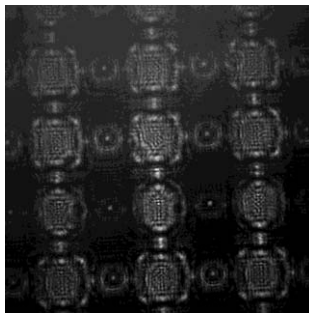


Figure 2 : Visualization of images provided by the microscope (a) the original hologram, (b) the intensity image (c) the phase reconstructed image.

A stroboscopic module is added to the DHM device to provide dynamical measurements to 100 kHz up to 25 MHz.

III. CONTROL OF CMUT DESIGN PARAMETER

A. Roughness

Micromachining processes provide roughness in layer deposition. This roughness becomes an essential parameter to evaluate correctly the thickness of layers and membrane deflection of cMUT. We propose to measure it on the metalized surface (for example, the electrode pad).

Roughness Parameters	Value (nm)
Average of value R_a	1.32
Maximum valley depth R_v	-6.64
Maximum peak height R_p	4.95
Maximum Height of the Profile R_t	11.59

Table 1 : Values of roughness parameters for cMUT electrode

B. Gap height and initial deflection

The height difference between the edge top electrode surface and inter-membrane metallization area is used to estimate the gap height (see Figure 3 with the value of 200nm).

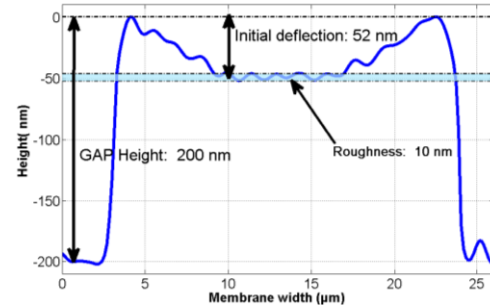


Figure 3 : Initial deflection of the membrane

Indeed, it is allowed by the conformity of deposition of silicon nitride membrane and electrode. The Figure 3 shows that the initial deflection of a 20 μm squared membrane is measured on the top electrode and equals to 52 ± 6 nm. This accuracy is given by the roughness ($\pm Rt/2$).

For sharp edge measurements (typically the gap height), it has to be less than the half of laser wavelength (around 340 nm). Beyond this value, the phase unwrapping could not count the number of wrap made. Nevertheless, the use of the double-wavelength (with two lasers) could avoid this limitation [3].

IV. COLLAPSE VOLTAGE DETERMINATION

A. Static determination

It is now proposed to measure the 20 μm cell profile supplied by a rising DC voltage applied on cMUT element. On Figure 4, some deflections could be observed for several voltage values. As the voltage increases, the membrane deflection increases too. Then, the static collapse is reached at 45V.

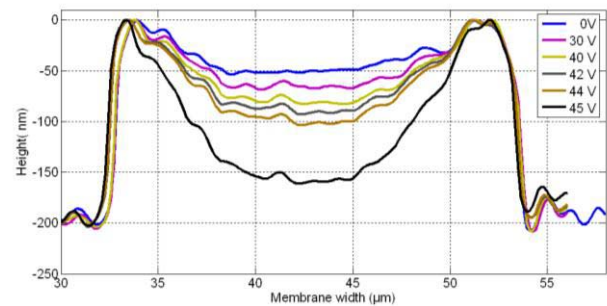


Figure 4 : Deformation of the membrane with the bias voltage.

Figure 5 shows the hysteretic cycle behavior of the membrane center deflection versus bias voltage. The collapse and snapback voltage is respectively equal to 45 and 26 V.

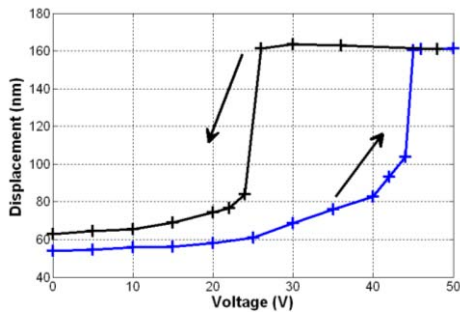


Figure 5 : Static hysteresis cycle of the membrane, the displacement versus dc polarization voltage.

Figure 6 presents a large area of an array which includes 32 cMUT cells. For this zone, three different collapse voltages (45, 48 and 60 V) are observed.

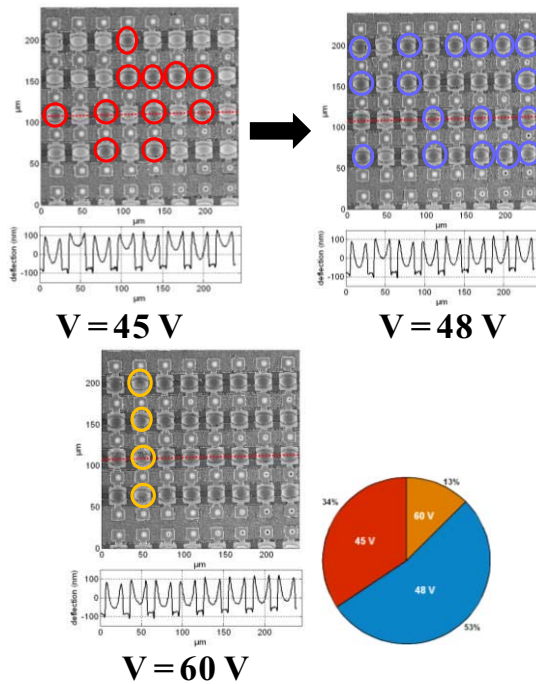


Figure 6 : Visualization of collapsed membranes at 45V, 48V and 60 V. Percentage of distribution cMUT numbers per collapse voltage value.

B. Comparison with impedancemetry measurements

An electromechanical study was made by impedancemetry on the element where the previous cells come from (Figure 7). This provided collapse voltage value (48V) presents a good agreement with the most measured value with DHM. The low electromechanical coupling coefficient ($k_t=0.4$) could be then explained by the relative dispersion of membrane behavior.

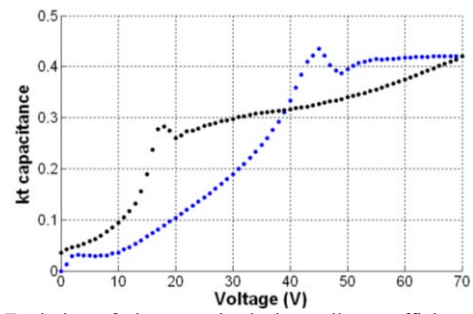


Figure 7 : Evolution of electromechanical coupling coefficient of the array element with the bias voltage.

C. Comparison with laser interferometry measurements

The measurement is performed by localizing the laser interferometer laser spot on a membrane center. A low frequency 200kHz cycle high AC voltage excitation ($70V_{pp}$) is superimposed with a DC bias voltage of 35V to the cMUT element to follow the collapse-snapback cycle. This dynamic hysteric cycle reminds static cycle measured by DHM with an increase of collapse and snapback voltage (60 V and 43 V respectively), as shown figure 8.

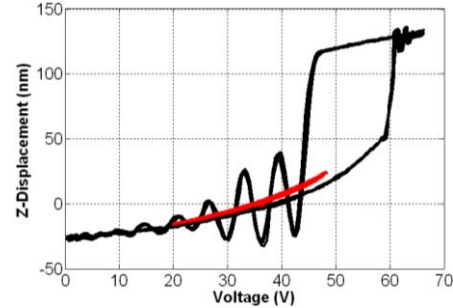


Figure 8 : Displacement / voltage cycle measured with laser interferometer at 200 kHz excitation frequency. (Red : 30 Vpp AC excitation, Black : 70 Vpp excitation)

V. MECHANICAL PROPERTIES CHARACTERIZATION

This part proposes a local method to determine mechanical properties of membrane (Young's modulus E_m and the initial stress T_0). These data could be used as input parameters of numerical modeling tools.

Many techniques exist to estimate Young modulus and Initial stress both [1,4]. The chosen study was the measurement of initial deflections on two square devices with different geometries completed with a FEM modeling of static displacement of these devices.

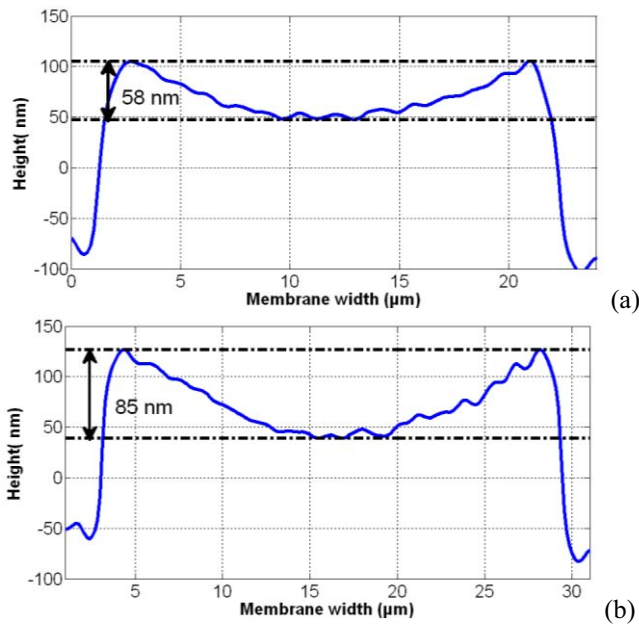


Figure 9 : Initial deflection of 20 μm (a) and 25 μm (b) width membranes

The methodology employed:

1. Initial deflection measurements of two geometries from the same wafer, shown by figure 9.
2. FEM modeling for a large range of Young's Modulus and Initial stress, shown by figure 10.
3. Determination of the set of value (T_0 , E_m) for the measured initial deflections of the two cases. The crossing of the two curves corresponds to the couple (T_0 , E_m) of the studied materials, as shown figure 11.

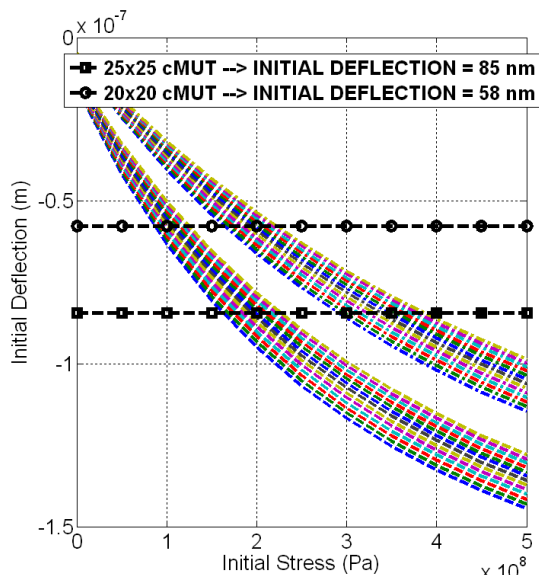


Figure 10 : Variations of initial deflection with initial stress for 20 μm and 25 μm width membranes. The Young modulus is changed from 180 GPa to 300 GPa.

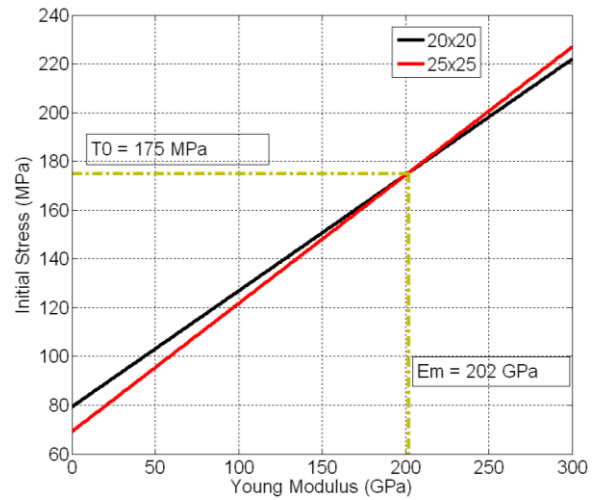


Figure 11 : Variations of initial stress with Young modulus for 20 μm and 25 μm width membranes when initial deflexion is respectively fixed to 58 nm and 85 nm.

The Young's modulus and the initial stress in the nitride membrane are evaluated to 202 GPa and 175 MPa respectively.

VI. CONCLUSION

The Digital Holographic Microscope is an efficient candidate for vertical static measurements and then, estimation of both cMUT static hysteretic cycle and its material mechanical properties. Furthermore, its ability to perform fast large field of view characterization provides one of the best tool statistical evaluation of cMUT.

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