Program Digest, 2019 IEEE International Ultrasonics Symposium (IUS)
Glasgow, Scotland, October 6-9, 2019

High Density Arrays of Carbon Nanomembrane Ultrasonic MEMS

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***Abstract*— Ultrathin carbon membranes are proposed for implementation as vibrating part for ultrasonic transducers. The mechanical properties of these membranes allow a significant operation in forced oscillations mode. Unlike resonant systems, the frequency range of operation is very wide, and the design of the transducers more flexible. Dense arrays of small size transducers are suitable to phased array techniques. The first test devices were manufactured and characterized; the feasibility of emitting and receiving acoustic waves with such devices has been demonstrated.**

Keywords—Ultrasound, Capacitive micromachined ultrasonic transducer, Nano-membrane, Carbon, Array

I. Introduction

Ultrasonic probing techniques provide data for complex processing and analysis systems in various domains, such as robotics and medicine. Multi-element technologies increase the accuracy of data collected. The small size and the technologies of the micro-electromechanical systems (MEMS) are actual assets to meet these challenges.

Micromachined Ultrasonic Transducers (MUT) emit and detect pressure waves via the vibrations of suspended membranes; they are most often operated at their natural resonance frequency in order to maximize the membrane displacement. Considering the MUT membrane thicknesses usually range from one tenth of a micrometer to several micrometers, with a diameter of several tens or hundreds of micrometers [1],[2], the mechanical resonant behavior of these membranes is ruled by the Young modulus of the materials [3]. The design of the transducer sets their natural frequency, and therefore sets the frequency of operation.

Making devices operable at a frequency different from resonance would allow greater flexibility in the design of the transducers, and enlarge the range of operating frequencies.

The presents study considers using ultrathin membrane to equip a new type of MUT. As deflection increases when the membrane thickness decreases, the implementation of an ultrathin membrane is expected to bring higher deflection, and higher transduction efficiency, provided the membrane material is strong enough. The challenge is to induce large displacements in forced oscillation mode, so that ultrasonic transduction is effective at low frequencies and over the entire frequency range below resonance.

This paper describes the concept and the preliminary devices fabricated for experimental validation, and reports the results demonstrating non-resonant ultrasonic transduction.

II. Device Description

A. Ultrathin carbon membranes as mobile part for MEMS

Due to their good mechanical properties combining elasticity and toughness [4], [5], Diamond-Like Carbon (DLC) seem to be particularly well suited to this ultra-thin layer application. The DLCs are an amorphous form of carbon material with two types of carbon atoms arrangements: sp2-hybridized with sigma and pi bonds as in graphite and graphene, and sp3-hybridized with only sigma bonds as in diamond. The ratio of these two types of carbon bonds in the material sets its properties between graphite-like (soft, flexible, electrically conductive) and diamond-like (hard, strong, electrically resistive). Moreover, DLCs are widely used for coatings because of their chemical inertness and their tribology.

The present study considers ultrasonic devices equipped with 10nm DLC membrane as suspended mobile part. 80% sp2-rich DLC have been targeted in order to achieve sufficient flexibility.

A previous study [6],[7] has reported the mechanical behavior of similar membranes suspended above micrometer large trenches and deflected by an electrostatic force. Large displacements of several tens of nanometers at low frequencies and up to a hundred nanometer were measured, together with natural frequencies up to above 100MHz. These carbon membranes exhibit outstanding flexibility and strength. The measurements were performed in air at ambient pressure.

The DLC is synthetized using magnetron sputtering. The sp2/sp3 ratio is tunable as sp2 content increases with the substrate temperature [8]. The thickness and the sp2 content of

This work was supported by the French ANR via Carnot funding.

the resulting film are controlled by X-Ray reflectometry (XRR) and X-ray Photoemission Spectroscopy (XPS) respectively.

B. Unitary ultrasound transducer

The structure of the unitary transducer is a stack of two conductive layers spaced by an insulator; a cavity is etched in the top electrode and the insulator. A flexible membrane closes the cavity, mechanically anchored on the surface and in electrical contact with the top electrode. The membrane and the bottom electrode form a capacitor having a variable capacitance depending on the membrane deflection. The scheme of the elementary transducer is presented in Fig. 1. The insulator is a 1µm thick SiO2 layer. The cavity is 10µm in diameter, etched 900nm deep in the insulator. A thin insulating layer remains at the bottom to prevent from short circuit. The conductive layers are Cr/Au 100nm thick. The membrane material is a composite carbon (10 nm) and Pt (5 nm). bilayer. The carbon face is on the top; the platinum layer ensures the electrical contact with the top electrode. A narrow vent (<1µm large) open in the top layer below the membrane connects the cavity to the ambient pressure.

C. High density arrays

The small size of the elementary transducers makes it possible to arrange them in dense array. The devices considered in this study provide 250000 (500x500) elementary transducers with a pitch of 15µm, over a square surface of 7.5mm on the side.
The base part of the device is processed using standard microfabrication techniques. Bottom electrodes are a set of 10 parallel lines, 750µm wide and 800µm pitch. Each of the lines addresses 25000 elementary transducers. The scheme of the device is presented in Fig. 2.
The membrane is processed onto a secondary substrate and then reported over the whole array in a single stamping transfer [6]. The membrane acts as a common electrode for all the elementary transducers of the array. For each row, a common vent connects all the aligned cavities to ambient pressure.
In the current state of the transfer process, local tearing of the membrane still occurs during the operation. The analysis of microscope images let estimate that 80% of the elementary transducers are functional. (Fig. 3).

D. Device impedance

The theoretical overall capacitance between lines and membrane for the whole device is about 3nF. However the device behavior let infer a large capacitance is in series with the cavities capacitors. The biasing of the active capacitance is hampered by charges trapped in the thin insulating layer of SiO_2 above the bottom electrode. Then only AC voltages are applied to operate the device in this study.
Despite the parasitic capacitance, the impedance measurements clearly show a resonant behavior in the 1MHz range. This resonance is not detected on a similar device with no membrane reported. This suggest the mechanical resonance of the membranes in the array is around 1MHz.

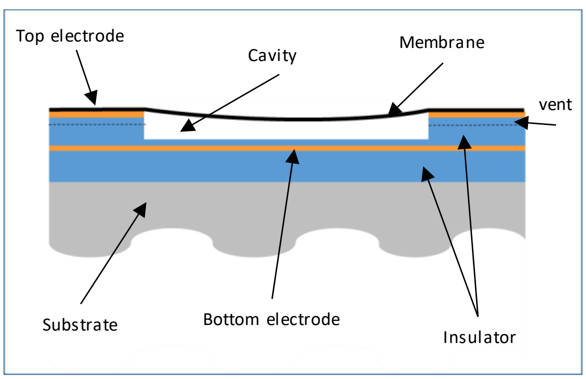

Fig. 1. Scheme of the structure of the elementary transducer

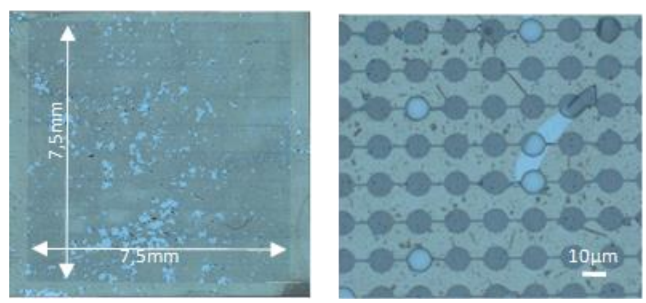

Fig. 3. Optical images of a device after report of the membrane. Left : view of the whole array (500x500 transducers on a square area 7.5mm x 7.5mm. - Right : zoomed view

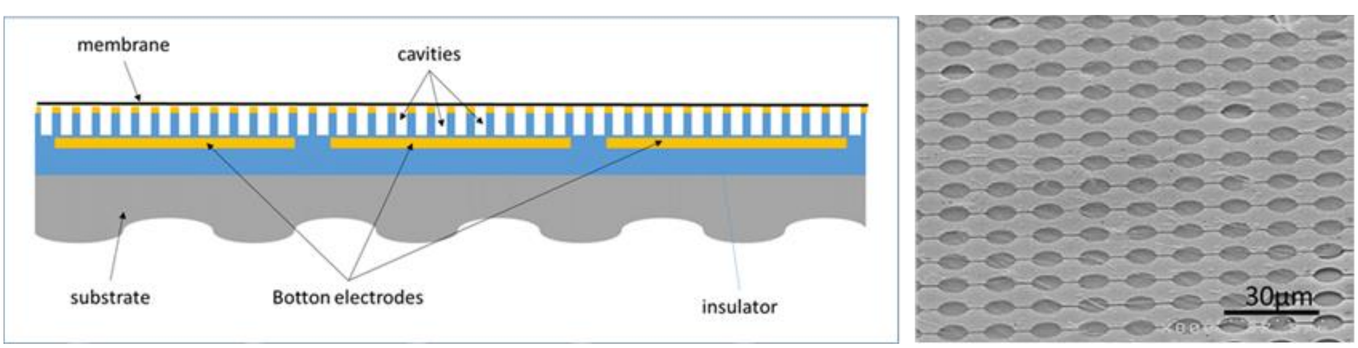

Fig. 2. . Left : scheme of the array of transducers ; 500x500 cavities, diameter of 10µm, pitch 15µm ; 10 bottom electrodes 750µm large, pitch 800µm. Top electrode common (in this design) to all cavities. – Right : SEM image of an array. Of the 120 cavities in the shown area, 5 present a membrane defect.

III. Ultrasonic Transduction

A. Ultrasound emission

The device is excited capacitively by an alternating voltage applied between the lower electrodes and the membrane. The electrostatic force that deflects the membrane depends on the square of the applied voltage. As no DC bias is applied, the frequency of the emitted wave is twice the frequency of the excitation voltage.

The emitted pressure wave is recorded using a microphone BK4138, which operates at frequencies up to 140kHz. The microphone is placed facing the array, centered, at a distance of 5cm. The output signal provided by the microphone is amplified and recorded.

In Fig. 4 is reported the response of the array when a burst of 5 periods at 70kHz is applied as an excitation voltage. The pressure signal is 10 periods at 140kHz, delayed by 150µs after the excitation voltage, in accordance with the propagation time in air for a pressure wave along a 5cm path. More, the envelope of the response has a rectangular shape. This indicate the transducers response is immediate, thus differing from high quality factor resonant systems.

When the excitation voltage is applied in continuous wave mode (CW), the magnitude of the microphone output signal at twice the excitation frequency is recorded. (Fig. 5). In the microphone range, the signal increases with the frequency. For ±20 V applied at 70 kHz, the measured pressure at 140 kHz is 70 dB SPL. The emitted pressure increases linearly as the square of the applied voltage. 90 dB SPL have been obtained for ±60 V applied.

B. Ultrasound detection

An incident pressure wave deflecting the membranes varies the capacitance of the cavity. A charge amplifier is connected to the membrane terminal to measure the charge displacement. To minimize electromagnetic perturbations, the assembly of the array is placed in a metal housing

The emitter of the pressure wave is an ultrasonic transducer operating at 200kHz (Multicomp MCUSD19A200), placed facing the array, centered, at a distance of 5cm. The emitted pressure is not known. The measured response is presented Fig. 6. A detection signal is recorded with a delay of 150µs corresponding to the propagation time along the 5cm path.

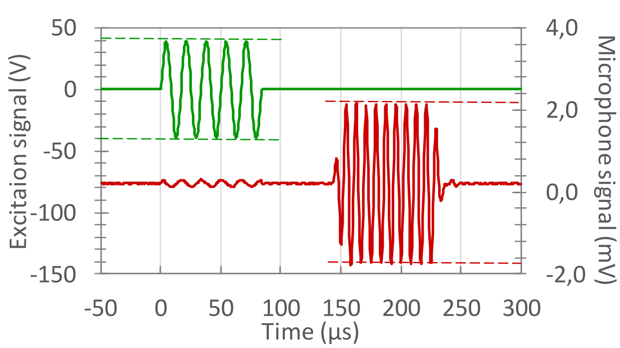

Fig. 4. Signal from microphone (red line, right axis) when excitation signal (green line, left axis) is a burst of 5 periods at 70kHz.Ultrasound signal is at 140kHz, the delay is the pressure wave propagation time over 5cm. The square envelope of the response signal points out the immediacy of the transduction

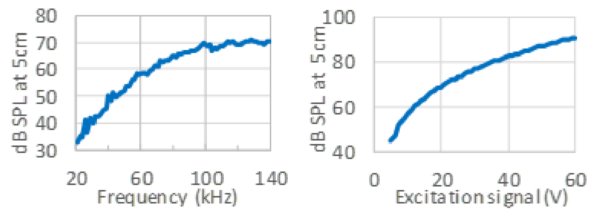

Fig. 5. Ultrasound emission performances. Left : pressure level depending on frequency, measured at 5cm, excitation voltage ±20V. Right : pressure level depending on excitation voltage, measures at 5cm, frequency 140kHz.

Several replica follow, each delayed by 300µs. These replica are due to the multiple reflections of the wave between the housing of the array and the emitter set up.

IV. Comments and Results Analysis

The study presented above is at its very beginning and many related task are currently on work to complete the panel of early measurements. Namely, the future measurement of the deflection of the membrane depending on the frequency will be essential to build a mechanical model. The technological processes and the geometry, as cavity diameter, cavity depth, and density of the array, need optimization.

Though the present basic design makes it difficult to extract key features, acoustic measurements have demonstrated the feasibility of the basic functions of both emission and detection of ultrasonic waves. This confirms ultrathin carbon membrane are strong enough to actually wave air.

The measurements were made at set-up dependent frequencies, up to 140kHz in transmission, and 200KHz in detection. If the mechanical resonance of the membrane is around 1MHz, as the impedance measurements suggest, the operational frequency range in forced oscillation mode could range from 20KHz to 800KHz or more. Future experimental validation will be conducted with emitter and receiver of the same type.

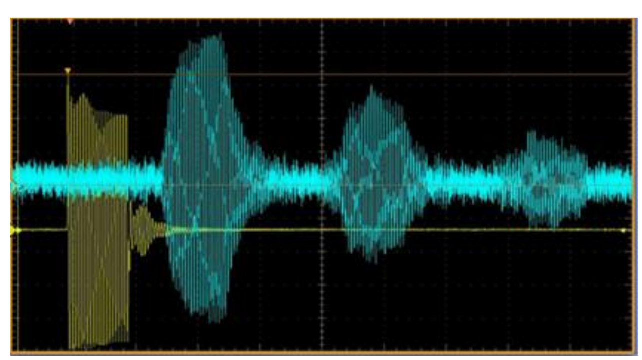

Fig. 6. Scope screen capture : un yellow (10V/div), the excitation signal applied to the piezo source; in blue (5mV/div), the detection signal output from the array. 100µs/div, 10ns/pt, average 32. The first burst is detected 150µs after the excitation burst. The following echoes due to multiple acoustic reflections between the emitter set up and the array set up.

V. PERSPECTIVES

These new types of MUT operating in forced oscillation mode provide with original feature that open new potentialities for acoustic probing.

First, the sizing constraints are relaxed since it is not necessary to match the operating frequency with the mechanical resonance of the membrane. These devices thus expected to operate at any frequency lower than their resonance frequency; the actual operating frequency can be adjusted directly and flexibly via the analog front end.

Second, the small size of the elementary transducer allows for defining subsets addressable in line-column matrix, by the design of the top and bottom electrodes geometries. As the upper frequency limit for beam forming implementation is related to the size of the matrix elements, multi-frequency phased array acoustic antenna can be implemented.

Ultrasonic MEMS equipped with ultrafine carbon membranes offer real and innovative application potential.

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