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Mechanical Characterization of Ultrathin DLC Suspended Membranes for CMUT Applications

Sébastien Thiberta,*, Anne Ghisa, Marc Delaunayb,

aCEA, LETI, MINATEC Campus, F-38054 Grenoble, France
bCEA INAC-SP2M, F-38054 Grenoble, France

Abstract

To increase the spatial resolution of CMUT based ultrasound imaging, the feasibility of devices made of arrays of vibrating areas in the square micrometer range is investigated. The manufacturing and characterization of ultrathin diamond like carbon suspended membranes that can act as the mobile electrode of capacitive micromachined ultrasonic transducers are described. To get significant displacements, the membrane thickness must be reduced to the nanometer range. Consequently, a 5 to 20 nm thick Ni/DLC/Ni stack is first deposited by electron cyclotron resonance. The three-layer stack is then transferred on test devices to form suspended membranes over 0.5 to 2 μm wide trenches. The device characterization includes SEM imaging and AFM force measurements. The mechanical properties of the suspended sheets were extracted, which allows the determination of the bending rigidity (1 x 10^{-14} to 20 x10^{-14}N.m) of the mobile part of the transducer. This parameter is required for device modelling as it integrates the properties of the final membrane (material, thickness, surface alteration, etc.).

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* Sébastien Thibert. Tel.: +33 (0)4 .38.78.93.00
E-mail address: sebastien.thibert@cea.fr
1. Introduction

Advances in Micromachined Ultrasonic Transducer technology, piezoresistive (PMUT) or capacitive (CMUT), directly enable for advances in applicative field [1-3]. In addition to a higher imaging resolution, the increase in the operating frequency of ultrasound transducers provides new tools for close observation and exploration. The resonant frequency of these devices is mainly set by the transducer geometry and material properties. Progresses in technological process control and novelty in the components structures allow the realization of CMUTs with operating frequencies of several tens of Megahertz [1-5]. Furthermore, devices having multiple operating frequencies are needed to combine operations in medical applications, such as imaging at high frequency and treatment by ultrasound focusing at lower frequency. In the current state, CMUTS are mostly operated at frequencies close to their resonant frequency. Expanding the bandwidth is a current issue.

This work addresses the feasibility and use opportunities of CMUT having a vibrating surface in the micrometric range. Reducing the vibrating area induces an increase in the spatial resolution. To get significant displacements of the membrane, either at the resonant frequency or in quasi-static operation, the thickness of the membrane is lowered down to the nanometer range. Ghis et al. [6] have already reported the manufacturing of suspended membranes based on a few nm thick Diamond Like Carbon (DLC) layer. Membrane displacements ranging from 5 to 20 nm were measured for applied DC voltages from 10 to 30V. However, the supporting test devices used in their work were not suitable for high resonance frequency measurements as the electrode design was highly capacitive. In order to measure the resonance frequency of these micrometer-sized CMUTs, the process is now being transferred on new test devices with electrodes designed as a coplanar waveguide.

2. Experimental

2.1. Device manufacturing

The new test devices, which are suitable for high frequency actuation of freestanding membranes, were manufactured using classical microelectronic processes. From the contact pad, a signal line is connected (using metal vias) to an electrode buried below an insulating layer. The ground pads are connected to the top electrodes, which are locally patterned in order to provide a 150-200 nm deep trench (figure 1a and 1b). On each test chip, the width \( w \) and the length \( l \) of the trenches range from 0.5 \( \mu \)m to 2 \( \mu \)m and from 1 to 100 \( \mu \)m, respectively.

Fig. 1. Scheme of the process used in this work (a). SEM images of a typical test device before (b) and after a 15 nm thick Ni/DLC/Ni membrane deposition (c,d).
To produce the mobile part of the CMUT, a sacrificial layer was first deposited by spin coating on a secondary Si substrate. Then, a very thin DLC (from 2nm to 15nm) layer is deposited using an Electron Cyclotron Resonance (ECR) process [7]. To improve the conductivity of the membrane and selectively remove the sacrificial layer, the ECR process was also used to deposit 2 to 10 nm thick nickel layers before and after the DLC deposition. As illustrated on figure 1a, this so coated secondary substrate was then flipped over a test device to stamp the deposited layers onto the top electrodes by removal of the sacrificial layer. Figures 1c and 1d show membranes suspended over very long trenches using this method. The resulting mobile part of the devices are made of a Ni/DLC/Ni stack with a final thickness \( t \) ranging from 6 to 20 nm, depending on the process conditions.

At the end of the process, the suspended part of the grounded membrane and the underlying signal electrode are the two components of a capacitor that can be operated as a high frequency CMUT type device.

2.2. Mechanical characterization

The mechanical properties of the freestanding membranes were extracted from force curve measurements performed with an AFM (force spectroscopy mode). First, a topographic image of the device was performed. Then, the AFM tip was moved toward the surface of the device in different locations (50 columns parallel -y direction- per 10 lines perpendicular -x direction- to the trench) to apply a point load, while recording the AFM cantilever deflection. To extract useful information, after calibration of the AFM, the raw data were converted according to classical procedures used on other suspended membranes [8,9]. This methodology allows recording the membrane deflection \( \delta \) (m) as a function of the applied force \( F \) (N).

3. Results and discussion

Figure 2 shows an overview of the results obtained on a 15 nm Ni/DLC/Ni stack suspended over a 2 \( \mu \)m wide trench. Figures 2a and 2b illustrate the effect of the applied force on the membrane displacement. For \( F=10 \) nN, the membrane deflection is almost negligible, whereas for \( F=400 \) nN, the mean deflection reached 65 nm at the center of the trench. It is worth noting that the error bars on figure 2b are relatively small, which demonstrates the good homogeneity of the sample. To further evaluate the mechanical properties of the device, the deflection at the membrane center was represented as a function of the applied force (figure 2c). The relationship between both variables is given by [8,10,11]:

\[
F = -k_1 \delta - k_2 \delta^3
\]  

where \( k_1 \) (N/m) and \( k_2 \) (N/m³) are the linear and the nonlinear spring constants, which are linked to the plate (bending) and to the membrane (stretching) behaviors. Experimental data fit the theoretical equation as presented in figure 2c, validating the relevance of this model. For small membrane displacements (\( \delta/t<1 \)), the force-displacement behaviour is linear and depends only on the linear spring constant \( k_1 \). Assuming an unstressed membrane, \( k_1 \) is defined as [8,10-13]:

\[
k_1 = \frac{D}{\alpha w^2}
\]  

where \( D \) (N/m²) is the bending rigidity of the membrane. For the geometrical embodiment studied in this work, the constant \( \alpha \) is equal to 0.00725 when the length-to-width ratio of the trench is very high (\( l/w \to \infty \)) [12,13]. For this sample, a linear spring constant \( k_1 \) of 1.8 N/m was extracted, which corresponds to a 5.2 x 10⁻¹⁴ N.m bending rigidity according to equation (2). Depending on the process conditions and layer thicknesses, bending rigidities ranging from 1 x 10⁻¹⁴ N.m to 20 x 10⁻¹⁴ N.m were measured on various samples, which is close to the results reported on graphene devices [9].
Fig. 2. Membrane deflection for an applied force $F=400\text{nN}$ (a). Evolution of the mean profile of the membrane deflection as a function of the applied force (b). $F=f(\delta)$ at the center of the membrane (c). The inset in (c) is a SEM image of the analyzed region after the AFM measurements.

4. Conclusion

The stamping approach was used to transfer a Ni/DLC/Ni stack deposited by ECR on test devices specifically optimized for high frequency actuation. This process allows the manufacturing of few nm thick membranes suspended over 0.5 to $2\mu\text{m}$ wide trenches. The resulting devices were characterized by means of SEM imaging and AFM force spectroscopy. The measurement of the linear spring constant at the center of the membrane allows the extraction of the bending rigidity, which ranges from $1 \times 10^{-14} \text{N.m}$ to $20 \times 10^{-14} \text{N.m}$ on the tested devices.

Using these values in preliminary finite element simulations (Comsol software), the mechanical resonance frequency of the membrane was assessed between 15 MHz (for $D=1 \times 10^{-14} \text{N.m}$, $w=2 \mu\text{m}$) and 1 Ghz (for $D=20 \times 10^{-14} \text{N.m}$, $w=0.5 \mu\text{m}$). Consequently, this work paves the way for new DLC-based CMUT devices that can be operated at high frequency. Further work will mainly focus on the electrical actuation and characterization of the devices, including the experimental determination of these frequencies.

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References

[1] Oralkan, O., Hansen, S., 2004. High-frequency CMUT arrays for high-resolution medical imaging, in: IEEE Ultrasonics Symposium. pp. 399–402.
[2] Xu, T., Tekes, C., Satir, S., Arkan, E., Ghovanloo, M., Degertekin, F.L., 2013. Design, modeling and characterization of a 35MHz 1-D CMUT phased array, in: 2013 IEEE International Ultrasonics Symposium (IUS). IEEE, pp. 1987–1990.
[3] Lamberti, N., Caliano, G., Iula, A., Savoia, A.S., 2011. A high frequency cMUT probe for ultrasound imaging of fingerprints. Sensors Actuators A Phys. 172, 561–569.
[4] Certon, D., Legros, M., Gross, D., 2014. Ultrasound pre-clinical platform for diagnosis and targeted therapy, in: 2014 IEEE International Ultrasonics Symposium. pp. 329–332.
[5] Gross, D., Perroteau, M., Certon, D., Coutier, C., Legros, M., 2014. Fabrication and characterization of wafer-bonded cMUT arrays dedicated to ultrasound-image-guided FUS, in: 2014 IEEE International Ultrasonics Symposium. IEEE, pp. 181–184.
[6] Ghis, A., Sridi, N., Delaunay, M., Gabriel, J.-C.P., 2015. Implementation and mechanical characterization of 2nm thin diamond like carbon suspended membranes. Diam. Relat. Mater. 6–10.
[7] Delaunay, M., Touchais, E., 1998. Electron cyclotron resonance plasma ion source for material depositions. Rev. Sci. Instrum. 69, 2320.
[8] Annamalai, M., Mathew, S., Jamali, M., Zhan, D., Palaniapan, M., 2012. Elastic and nonlinear response of nanomechanical graphene devices. J. Micromechanics Microengineering 22, 105024.
[9] Poot, M., van der Zant, H.S.J., 2008. Nanomechanical properties of few-layer graphene membranes. Appl. Phys. Lett. 92, 063111.
[10] Foilane, C., Delobelle, P., Lexcellent, C., Hayashi, S., Tobushi, H., 2000. Analysis of the mechanical behavior of shape memory polymer membranes by nanoindentation, bulging and point membrane deflection tests. Thin Solid Films 379, 156–165.
[11] Łojwicz, M., Delobelle, P., Gorecki, C., Sabac, a., Nieradko, L., Meunier, C., Munnik, F., 2004. Optomechanical characterisation of compressively prestressed silicon oxynitride films deposited by plasma-enhanced chemical vapour deposition on silicon membranes. Thin Solid Films 468, 84–92.
[12] Sridi, N., Lebental, B., Azevedo, J., Gabriel, J.C.P., Ghis, A., 2013. Electrostatic method to estimate the mechanical properties of suspended membranes applied to nickel-coated graphene oxide. Appl. Phys. Lett. 103, 051907.
[13] Martins, P. (2009). Caractérisation mécanique des matériaux pour les micro/nanosystèmes. Procédés applicables aux épaissiers submicroniques. In french