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Residual stress in capacitive micromachined ultrasonic transducers fabricated with Anodic Bonding using SOI wafer

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Abstract

This paper focuses on a fabrication process for CMUTs using anodic bonding of a silicon on insulator wafer on a glass wafer. This technology makes possible the fabrication of large membranes and can extend the frequency range of CMUTs to lower frequencies of operation. Silicon membranes having radii of 50, 70, 100 and 150 µm and a 1.5 µm thickness are fabricated and electromechanically characterized. Resonant frequencies from 0.6 to 2.3 MHz and an electromechanical coupling coefficient around 58% are reported. The discrepancies between experimental and theoretical values of the first resonance frequency can be explained by a combined effect of a tensile residual stress (between 90 and 110 MPa) in the membranes and experimental boundary conditions that can be modeled by a torsional stiffness of 2.10^{-7} N.m.rad^{-1} instead of a perfectly clamped ring.

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Keywords: CMUTs; Anodic Bonding; Residual stress

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1. Introduction

Capacitive Micromachined Ultrasonic Transducers were introduced in 1994 as an alternative to lead zirconium titanate based transducers [1]. A CMUT is a capacitor structure composed of a thin plate and a bottom electrode. The sensitivity and the frequency response of CMUTs are determined by the physical dimensions and the material properties. Therefore, a stringent process control is decisive for CMUT fabrication. Two fabrication methods for CMUTs are mainly used [2]: sacrificial release process [1,3,4] and wafer bonding process.

This paper reports an original low-temperature fabrication technique for CMUTs based on anodic bonding of a SOI wafer on a glass wafer. With the proposed manufacturing process, it is possible to fabricate very accurate

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thickness determined by the device layer thickness of the SOI wafer. The active gap between the bottom electrode and the membrane is determined during the process by both the cavity depth and the bottom electrode thickness. These parameters will thus influence the electromechanical response of the CMUT. This electromechanical response is measured with two experimental approaches related to two different measuring instruments: a laser vibrometer (POLYTEC) to detect the first eigenfrequency by frequency sweeping and an auto-balanced bridge impedance analyzer (AGILENT HP4294A) for the measurement of membranes impedance and admittance as a function of the frequency. Finally, the difference between the experimental and theoretical eigenfrequencies is explained by the amount of residual stress in the membranes (between 90 MPa and 110 MPa) and by boundary conditions falling between a clamped rim and a simply supported rim. The actual boundary conditions can be modeled with a torsional stiffness of 2.10^{-7} N.m/rad.

2. Process flow and design

The glass wafer is a 520 µm thick glass Pyrex 7740 substrate. The cavity etching step defines both the membrane radius and the gap height. The first photolithography step defines the cavity shape on the glass Pyrex 7740 substrate. The glass is etched in a buffered hydrofluoric acid solution through the photoresist to form 1.35 µm deep cavities. The 250 nm thick titanium-gold bottom electrodes are fabricated by lift off technology. The cavity depth and the electrode thickness result in an electrostatic gap around 1.1 µm ± 0.025 µm RMS.

The membrane thickness is defined by the 1.5 µm silicon device layer of the SOI wafer. The contact between the SOI wafer and the processed Pyrex 7740 wafer is operated at ambient temperature, and then the coupled wafers are heated to 350 °C, previously to the electrical bonding procedure of the anodic bonding. The release of the membranes is achieved by removing the handle layer using potassium hydroxide (KOH) wet etching and then the buried oxide layer of the SOI wafer using a buffered hydrofluoric acid (BHF) wet etching. The Aluminum top electrode is deposited and wet etched in the third photoresist level. The last step is a silicon dry etching, using aluminum as a hard mask, to get access to the pad.

3. Electromechanical characterization

The CMUT characterization is made on unit cells, i.e. on single membranes. The mechanical resonance frequency and the electrical impedance in air are measured. In a first experimental step, the resonance frequency is measured without DC voltage using a POLYTEC laser vibrometer. As expected, the eigenfrequencies decrease as a function of the membrane radius. However, some discrepancies, strongly tied to the membrane radius, can be noticed compared to the theoretical values issued from FEM calculations. The next section will propose to relate these discrepancies to residual stress in the membranes possibly induced by the fabrication process of the SOI wafer.

In a second experimental step, the input electrical impedance in air is measured as a function of frequency and for different values of the bias voltage. Measurements are performed using an auto-balanced bridge impedance analyzer (AGILENT HP4294A). The DC bias voltage varies from 50 V to 170 V, with a step of 10 V, for the tested membrane, having a radius of 50 µm. The impedance measurement is used to determine the electromechanical coupling coefficient. The evolution of the real part of impedance as a function of frequency can be seen in figure 1 for four values of the DC bias voltage, out of thirteen, for clarity reasons.

From these curves, the electrical antiresonance frequencies (f_R) are determined, corresponding to the mechanical resonance frequencies. The electrical resonance frequencies (f_Y) can be calculated from the curves showing the evolution of the imaginary part of impedance as a function of frequency. The electromechanical coupling coefficient is then defined by the following relation [5,6]:

$$k_T^2 = 1 - \left(\frac{f_Y}{f_R} \right)^2 \qquad (1)$$

For a DC voltage of 170 V, corresponding to 90% of the theoretical collapse voltage (185 V) for a 50 µm radius membrane, this coefficient is about 58% (i.e., 34% for the square of the coupling coefficient). This value is in the same order of what is usually found in the literature (30% for the square in [4,6]) for structures that exhibit similar significant parasitic capacitances

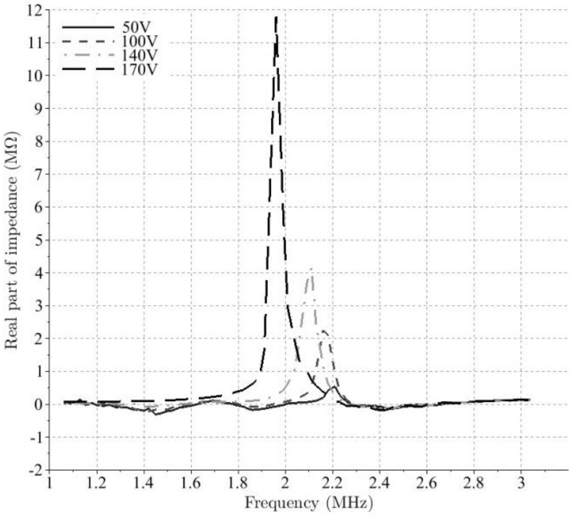

Fig. 1 Evolution of the real part of impedance as a function of frequency for different values of the DC bias voltage. The AC voltage is set to 0.5 V peak to peak.

4. Residual stress in the silicon membranes

There is a significant difference between the experimental frequencies and the eigenfrequencies computed using ANSYS FEM simulations. These results suggest that the hypotheses used in the theoretical approach are not correct. The simulation indeed assumes that the internal stress was zero and that the rim of the membrane was perfectly clamped (no displacement and no rotation at the rim of the membrane).

The evolution of the resonance frequency as a function of the residual stress is investigated, with both configurations of boundary conditions, with all the degrees of freedom restrained (diamond points in figure 2) and with the rotations released (circle points in figure 2). The diamond points are always above the circle points because, for a given geometry, a clamped diaphragm has a higher resonant frequency than a simply supported one. On the same plot, the experimental resonance frequency is drawn with a dashed line and an area corresponding to the values of ±10% around the experimental resonance frequency is plotted (gray area). This percentage approximately corresponds to the measurement scatterings of the experimental eigenfrequency over about ten cells for each radius. The curves for the different values of the membrane radius are shown on figure 2.

Using these curves, the lowest upper value of the residual stress and the highest lower value of the residual stress are found. To do so, it is assumed that the effective boundary conditions must lie between the first case (all degrees of freedom restrained) and the second case (rotations released). In this condition, the lowest upper value of the residual stress is found for each curve when the circle points is above the +10% limit, corresponding to the top line of the gray area. The highest lower value of the residual stress is found when the diamond points are under the -10% limit, corresponding to the bottom line of the gray area. Assuming that the residual stress has to be independent of the radius of the membrane, this residual stress has to be included in the boundaries 70 MPa –120 MPa.

To go one step further in this investigation, a torsional stiffness is added to the nodes of the membrane rim, in the numerical model. Then, for each value of the residual stress within the range 70 MPa –120 MPa in steps of 10 MPa, the first eigenfrequency is computed for different values of the torsional stiffness within the range 10^{-9}N.m/rad and 10^{-4} N.m/rad. At the end of the calculations, the possible values of the residual stress are in the range 90 MPa – 110 MPa for a torsional stiffness around 2.10^{-7} N.m/rad.

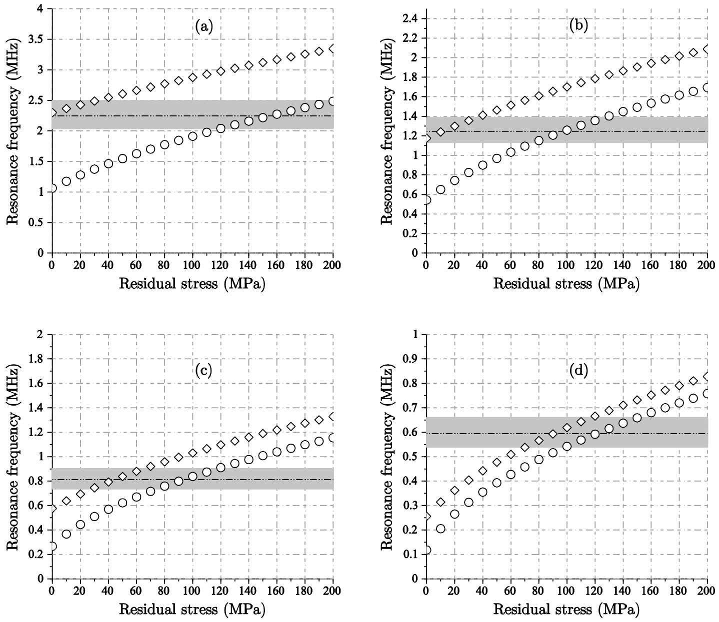

Fig. 2. Evolution of the resonance frequency as a function of the residual stress, with two configurations of boundary conditions, with all the degrees of freedom restrained (diamond points) and with the rotations released (circle points) for different values of the membrane radius: 50 µm (a), 70 µm (b), 100 µm (c) and 150 µm (d). The dashed line represents the experimental resonance frequency and the gray area corresponds to the values of ±10% around the experimental resonance frequency.

5. Conclusion

In this paper, the anodic bonding of an SOI wafer and a glass wafer is now proved to be a relevant alternative fabrication method for CMUTs. This method takes advantage of usual benefits of Si-wafer bonding, i.e. uniform membrane thicknesses and well-controlled mechanical properties of single crystal silicon. The very first results of electromechanical characterization lead to a quite good electromechanical coupling coefficient around 58% for a DC voltage representing 90% of the theoretical collapse voltage. However, the experimental eigenfrequencies do not confirm the theoretical calculation, which means that fabricated membranes cannot be considered as clamped free-stressed circular plates. The vibrating membranes are thus prestressed (with a tensile stress between 90 MPa – 110 MPa) and the actual boundary condition of the membranes is between the clamped and the simply supported membrane. This state can be modeled by a torsional stiffness of 2.10^{-7} N.m/rad.

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