The Influence of Residual Stress Induced by Anodic Wafer Bonding on MEMS Membrane Properties

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***Abstract*—The bonding is one of the common processes performed during MEMS fabrication. It allows creating advanced microstructures and specific encapsulation. However, this process induces a residual stress into the structure as the annealing process is required. In this paper the bonding of silicon and pyrex glass is taken into account as these materials have different coefficients of thermal expansion. We analyze the bonding process performed in optimal temperature that induces residual stress as small as possible. The simulations show the influence of residual stress on membrane deflection in typical temperature range of operation.**

***Keywords*—MEMS, membrane, residual stress, bonding**

I. INTRODUCTION

The bonding process is commonly used in fabrication of MEMS devices [1]. It is the method used i.e. for fabricating the substrate for MEMS [2] and their encapsulation [3]. It allows joining the two surfaces of different or the same materials. The strength of the bond is then obtained in annealing process. Although this method provides fabricating advanced microstructures, it has a significant drawback. The annealing process is performed in the temperature different from the temperature that the device operates at. If two different materials are bonded, the residual stress appears in the structure affecting the device operation. Therefore, if we need to predict the real device performance, one needs to take into account the influence of residual stress.

In our work we analyze the bonding of two different materials because the coefficients of thermal expansion (CTE) are different. Therefore, the annealing process induces much higher residual stress than in case of joining two same materials (theoretically, the residual stress should not appear). The bonding process is usually performed in optimal temperatures that provides the match of CTE leading to stress-free process. In case of silicon and pyrex joining, the anodic bonding is used as a relatively low temperature annealing is required. Nevertheless, the stress-free temperature exists for a specific room temperature. As the device will be operating in some range of ambient temperature, the residual stress depends on this operating temperature. Therefore, the performance of the device will vary.

In this paper, we investigate the influence of residual stress on membrane deflection that operates in a typical range of operational temperature. We use ANSYS environment to simulate the silicon membrane fabricated on pyrex substrate.

II. MEMBRANE FABRICATION

In this work a membrane structure was chosen for analysis as it is commonly used in variety of MEMS devices [4]. We assume that the thin membrane is made on silicon wafer. The Si wafer is etched in KOH to obtain the membrane of desired dimensions. Next, the pyrex substrate is etched in HF to create the cavity beneath the membrane. Then, both wafers are bonded in the way that the membrane surface is the bonding surface. This process is presented in figure below:

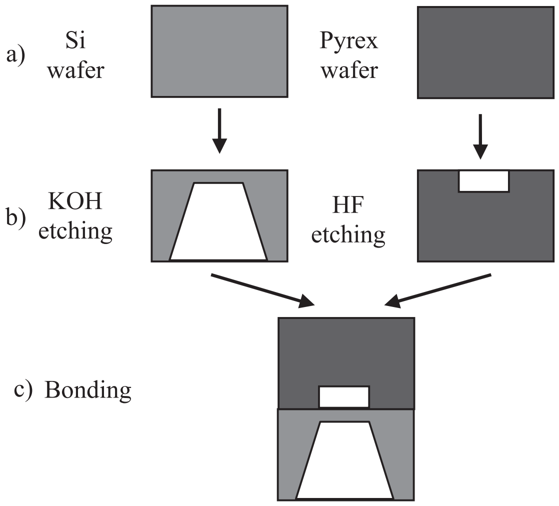

Fig. 1. Typical process of membrane fabrication using bonding technique

Our considerations are also valid in case of membrane fabricated on SOI wafers. The difference is then only on thickness of Si layer around the membrane. As we are investigating the residual stress within the membrane induced from membrane stretching/compression, the thickness of Si layer can be neglected.

The bonding process should be performed in stress-free temperature. To find that temperature, one has to investigate the thermal coefficient of expansion for both materials (Fig. 2).

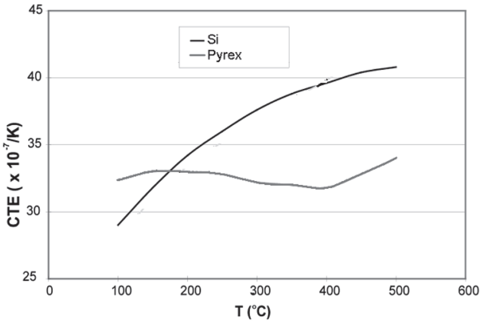

Fig. 2. Instantaneous coefficient of thermal expansion for silicon and pyrex

As one can see, the TCE of pyrex is almost constant. In case of silicon it is lower than for pyrex up to temperature of 175°C and higher above this temperature. Because the typical operational temperature of the devices is much lower than the TCE match point, the bonding temperature should be much higher that this point to compensate the expansion of silicon. It can be found that the stress-free temperature is around 270°C [5]. It has to be emphasized that this temperature is correct when the structure returns to room temperature (about 20°C). Each change of operational temperature shifts the stress-free temperature. Thus, if the operational temperature is not stable, the residual stress will vary with this temperature affecting the device performance.

III. SIMULATIONS

In our work the membrane presented in the Fig. 3 was simulated in ANSYS.

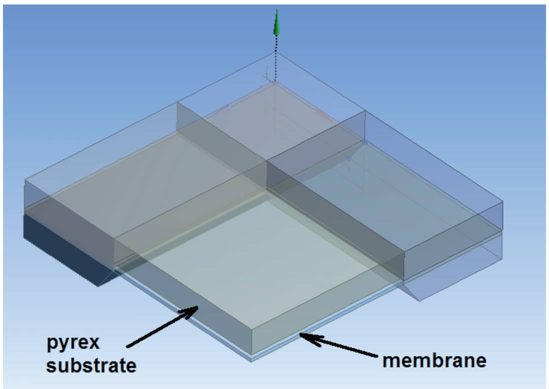

Fig. 3. The 3-D view of the structure simulated in ANSYS

The membrane dimensions are set to (4600 x 4600 x 50) µm. The cavity depth is 50 µm. In order to obtain the level of reference for our simulations, the response of the membrane before bonding to the pressure was simulated (Fig. 4).

We assume that there are no other sources of residual stress and the membrane operates in the region of small deflection (linear dependence of the deflection on the pressure). Therefore, the pressure should not exceed 50 kPa. The results are presented in the Fig. 5.

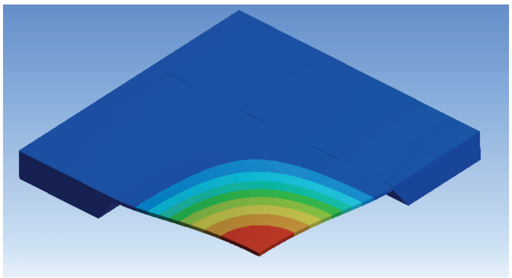

Fig. 4. Membrane deflection due to applied pressure

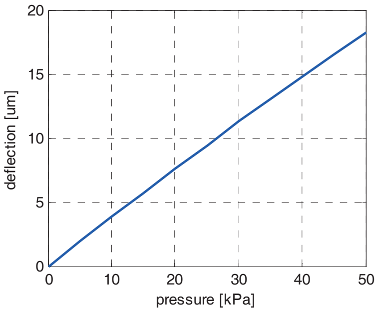

Fig. 5. Membrane deflection as a function of applied pressure

A. *Membrane at the room temperature and stress-free temperature*

Now let us investigate the bonded membrane in room temperature that should provide null residual stress within the membrane. We performed the simulation of the membrane bonded with pyrex at 270°C and then returned to 20°C without any external load applied. The figure below shows the total deformation of the structure:

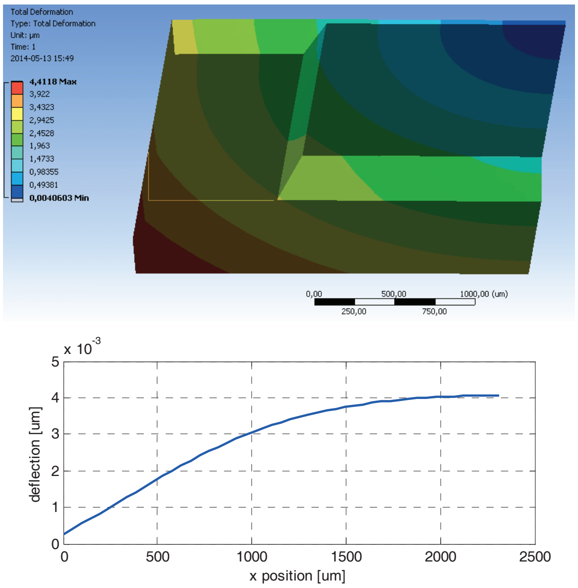

Fig. 6. Membrane deformation at 20°C fabricated with bonding process: the whole structure (top), deflection in the membrane centre (bottom)

As one can see, the whole structure is deformed due to the existence of residual stress. The temperature of 20°C is not perfectly stress-free but the deformation in Z axis is in range of nanometres. The silicon is slightly extended by pyrex that means that the stress-free temperature was not reached. The simulations showed that the stress-free temperature is about 13°C. Then the curvature of the silicon changes its direction and silicon becomes compressed. The figure below presents the structure in the temperature lower than the stress-free temperature:

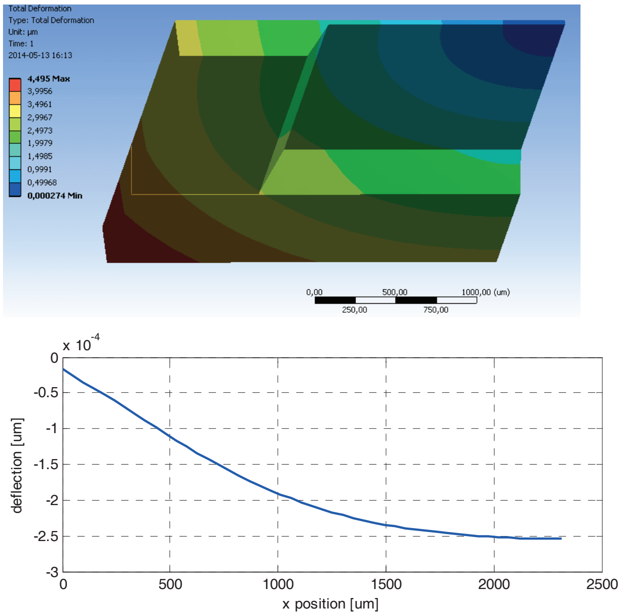

Fig. 7. Membrane deformation at 13°C fabricated with bonding process: the whole structure (top), deflection in the membrane centre (bottom)

B. Membrane Deflection

The most important information that gives the membrane is its deflection to the load. If we operate in the linear region of the membrane bending, we can simply extract the membrane spring constant that should be constant. Because the residual stress change the membrane stiffness, the spring constant will vary with the strength of membrane compression/extension. Near the stress-free temperature the change in membrane stiffness will be negligible.

Let us now investigate the influence when the device operates in variable temperature in range of 0-50°C (Fig. 8).

As it was expected, the spring constant are equal for stress-free temperature. At higher and lower temperature the membrane is more and less stiff, respectively. The difference in stiffness is 3% in whole range of temperature. Moreover, this parameter is higher by 2.3% and lower by 0.7% from non stressed membrane for the highest and the lowest temperature in range, respectively. It means that the membrane will deflect more at 0°C than at 50°C. It seems that the change is rather small and should not affect the device performance. However, devices transforms the membrane deflection into electrical signal in a way that is not linearly dependent on the deflection. For example the capacitive transformation reads the capacitance between the membrane and substrate. It is inversely proportional to the distance between the electrodes [6]:

$$C=\iint \varepsilon \frac{1}{\left(d-w\left(x,y\right)\right)}\partial x\partial y \tag{1}$$

where C is the capacitance, ε is the electrical permittivity, d is the distance between the membrane and substrate and $w(x,y)$ is the membrane deflection. Thus, the temperature influence will be most important for as large as possible deflection of the membrane. The 3% change in deflection can then change the capacitance up to 10% what cannot be neglected in estimating the device performance.

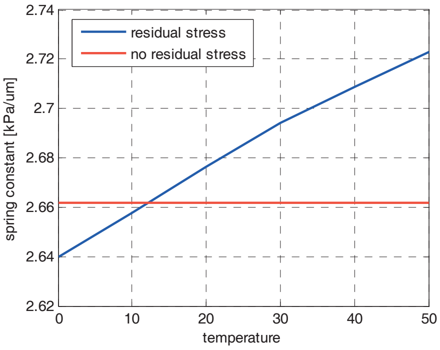

Fig. 8. Membrane spring constant as a function of temperature

C. Membrane Stress

The other way to convert the membrane deflection into the electrical signal is the use of piezoresistors that "read" the stress (dependent on membrane deflection). Thus, we extracted the stress distribution within the membrane. The most important point in the square membrane is the centre of the edge where the stress value is the highest. One can deduce that the stress change with the temperature should be the same as the deflection as they are linearly dependent. It is true if we take into account only the stress generated due to membrane bending. However, the residual stress also affect the piezoresistor response. The figure below shows the value of residual stress with temperature:

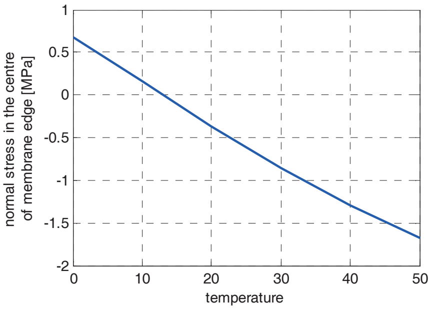

Fig. 9. Normal stress within themembrane as a function of temperature

Compared to the value of 19.7 MPa obtained for unstressed membrane with applied pressure of 30 kPa we get near 8% for the worst case. Thus, if we add the membrane spring constant change, the influence on stress is even stronger what is shown in the figure below:

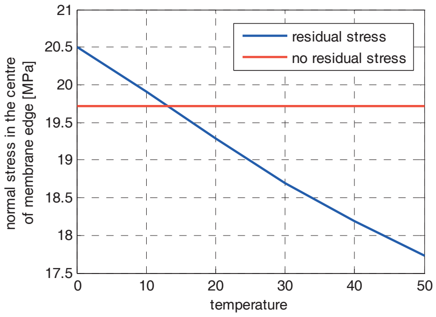

Fig. 10. Normal stress within themembrane as a function of temperature

Therefore, the stress difference reaches 15% in analyzed temperature range. Moreover, this parameter is higher by 4% and lower by 10% from non stressed membrane for the highest and the lowest temperature in range, respectively. As the piezoresistors response is linearly dependent on the stress value, the output electrical signal will vary in range presented above depending on the temperature which the membrane operates at.

IV. CONCLUSIONS

In this paper the investigation of temperature dependence on membrane properties fabricated in bonding process was presented. It was assumed that membrane was fabricated using low temperature bonding that should provide negligible residual stress. The membrane properties were obtained by FEM simulations in very wide range of operational temperature (0°C to 50°C) and compared to the non stressed membrane. The simulations showed that the stress-free temperature occurs near 13°C. Therefore, the membrane deflection can be smaller or larger in considered temperature range from the non-stressed membrane . It was found that the maximal difference reaches 2.3%. As the membrane deflection is read indirectly, the influence of bonding was investigated for two methods: capacitive and piezoresistive. In first case, the capacitance difference reaches 10%. In second case, the stress difference reaches also 10%. Concluding, the residual stress induced in bonding process significantly affects the membrane performance. If the membrane operates in wide range of temperatures, the designer has to take into account the influence of residual stress. As the membrane will have variable performance with the temperature, the designer should provide accurate temperature compensation to achieve reliable operation of the device. Even if the membrane operates in stable temperature near the stress-free temperature, one has to confirm that this temperature is really the one we assume because the simulations showed the deviation from the value found in the literature.

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