A novel anti-shock silicon etching apparatus for solving diaphragm release problems

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This paper presents a novel anti-shock bulk silicon etching apparatus for solving a universal problem which occurs when releasing the diaphragm (e.g. SiNx), that the diaphragm tends to be probably cracked by the impact of heating-induced bubbles, the swirling of heating-induced etchant, dithering of the hand and imbalanced etchant pressure during the wafer being taken out. Through finite element methods, the causes of the diaphragm cracking are analysed. The impact of heating-induced bubbles could be the main factor which results in the failure stress of the SiNx diaphragm and the rupture of it. In order to reduce the four potential effects on the cracking of the released diaphragm, an anti-shock bulk silicon etching apparatus is proposed for using during the last etching process of the diaphragm release. That is, the silicon wafer is first put into the regular constant temperature etching apparatus or ultrasonic plus, and when the residual bulk silicon to be etched reaches near the interface of the silicon and SiNx diaphragm, within a distance of 50–80 μm (the exact value is determined by the thickness, surface area and intensity of the released diaphragm), the wafer is taken out carefully and put into the said anti-shock silicon etching apparatus. The wafer's position is at the geometrical centre, also the centre of gravity of the etching vessel. An etchant outlet is built at the bottom. The wafer is etched continuously, and at the same time the etchant flows out of the vessel. Optionally, two symmetrically placed low-power heating resistors are put in the anti-shock silicon etching apparatus to quicken the etching process. The heating resistors' power should be low enough to avoid the swirling of the heating-induced etchant and the impact of the heating-induced bubbles on the released diaphragm. According to the experimental results, the released SiNx diaphragm thus treated is unbroken, which proves the practicality of the said anti-shock bulk silicon etching apparatus.

Keywords: anti-shock bulk silicon etching apparatus, releasing, diaphragm, finite element analysis
PACC: 0710C, 4360N, 8140N, 8160B, 4700

1. Introduction

Reliability studies are the key for practical application and commercialization of today's advanced micro electromechanical systems (MEMS). Many current and potential applications of MEMS are not really practical, because their mechanical properties have not been established, and are, to a large extent, still unknown.[1−3]

Studies of fatigue in the materials used in MEMS devices have already been carried out. However, such studies have mainly been investigations of behaviour under bending stress conditions using beam, cantilever[4] and resonating structures.[5−7] Fatigue or cracking under a current impact condition has, however, been little studied.

Bulk silicon etching is commonly used in MEMS device fabrication. In our group, there is a common problem which occurs when releasing the diaphragm (e.g. SiNx), that the diaphragm (thickness$\leq$2 μm) tends to be cracked during the wafer being taken out. Sometimes, the released diaphragm even cracks when immerged in the etchant.

The suspended diaphragms in MEMS structures are movable or unmovable in function. Our low-pressure chemical vapour deposition (LPCVD) prepared SiNx diaphragms are usually less than 2 μm in thickness. According to our group's experience, movable SiNx diaphragms are more easily cracked. If the unmovable SiNx diaphragm surface area is large, they also tend to be cracked, for example the MEMS released structure array which is 2 cm×2 cm in area and 2 μm in thickness.

Such cracking problems as described above have seldom been reported. This paper presents an upbuilt novel anti-shock bulk silicon etching apparatus for use during the last etching process of the diaphragm release to avoid breaking it. By using finite element

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analysis, the causes of diaphragm cracking are analysed. According to the experimental results, the released SiNx diaphragm is unbroken under the treatment in our etching apparatus. Combining the finite element analysis with the experimental results, we can conclude that the anti-shock bulk silicon etching setup is validated to be applicable in MEMS device fabrication technology.

2. Principles

The causes resulting in the released diaphragm cracking may be many, but the main parts could include: imbalanced etchant pressure, swirling of the heating-induced etchant, impact of heating-induced bubbles and dithering of the hand while picking up the wafer.

2.1. Etchant pressure analysis

The regular etching vessel including a silicon wafer inside is shown in Fig. 1, in which the wafer is being taken out by hand. The angle between the wafer surface and the gravitational direction at the centre of gravity is defined as θ. Since the conditions of etching are various, the forces acting on the wafer are determined by the wafer position relative to the etchant in the vessel. In order to make the analysis universal, the case is simplified as shown in Fig. 2. The released diaphragm is situated at the wafer centre and the wafer is immovable by forceps. We focus on the analysis of force within the dashed rectangle. This case is equal to that where the wafer is put at the centre of the etchant. The diaphragm to be released on the wafer is subjected to etchant pressures from four directions. The diaphragm's gravity weight and buoyancy can be ignored in MEMS formulae. The horizontal forces balance at the same point and the same height, and the component of the total force is determined by the height differences at different point. The total force can be described as

$$\begin{aligned} \boldsymbol{F} &= \boldsymbol{F}_{\text{horizontal}} + \boldsymbol{F}_{\text{vertical}} \\ &= 0 + \iint \rho_{\text{etchant}} g h(x,y)_{\text{difference}} \mathrm{d}x\mathrm{d}y, \end{aligned} \quad (1)$$

where $\boldsymbol{F}_{\text{horizontal}}$ is zero, and thus the total of force $\boldsymbol{F}$ equals the vertical net pressure focused on the centre of the released diaphragm; ρ_{etchant}, g and $h(x,y)_{\text{difference}}$ are the etchant density, acceleration of gravity and height difference at different points, respectively.

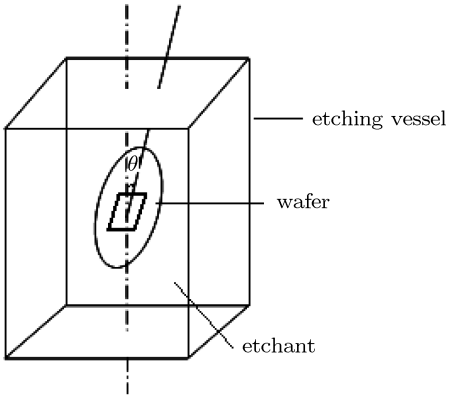


Fig. 1. Regular silicon wafer etching vessel.

According to Eq. (1) and Fig. 2, the forces acting on the released diaphragm are less than one gravity inertia load, which can be ignored in MEMS formulae, like ignoring gravity weight and buoyancy in MEMS devices. So the imbalanced etchant pressure for acting on the cracking of the released diaphragm is small.

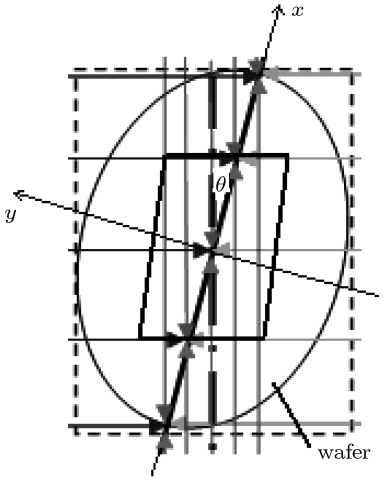


Fig. 2. Simplified case from Fig. 1.

2.2. Dithering of the hand while picking up the wafer

When the hand with pliers is picking up the released wafer from the etching vessel, the wafer tends to slope and the hand tends to wobble. The effect of the slope of the wafer on the cracking of the released diaphragm can be analysed, similar to that in Subsection 2.1, and the imbalanced etchant pressure is found to be also negligible. To simplify the analysis process, a successfully released SiNx diaphragm

on silicon wafer is used in our experiment. The wafer with released SiNx diaphragm is put into the etchant and then is picked up by the usual operation. It is found that the diaphragm is unbroken, so dithering of the hand alone while picking up wafer process will not have a serious effect on the cracking of the diaphragm.

2.3. Swirling of the heating-induced etchant

Our commonly used silicon etching vessel has an opened symmetrical cube shape with a cross sectional area of 0.1 m×0.1 m. The silicon is placed parallel to the cross sectional plane. The properties of the etchant are simulated by finite element methods to find the influence of the swirling of the heating-induced etchant on the released SiNx diaphragm. The meshing model is set as shown in Fig. 3, and the initial and boundary conditions include velocity, gravity and temperature. The etching vessel is heated on the heating stove at a temperature of 358 K, and the open end connects with the air environment, in which the temperature is set to be 288 K. Since the top end and the bottom end are both at the same atmospheric pressure, the air pressure loads are ignored. The velocities near the vessel wall are set to be zero since there are no slippages. It is an incompressible flow. Density variations can drive the flow only through gravitational acceleration. Temperature changes will cause variations of density. The velocity vector distribution of the etchant is simulated as shown in Fig. 4. The maximum velocity occurs at the centre with 0.1075 m/s in the y-axis direction.

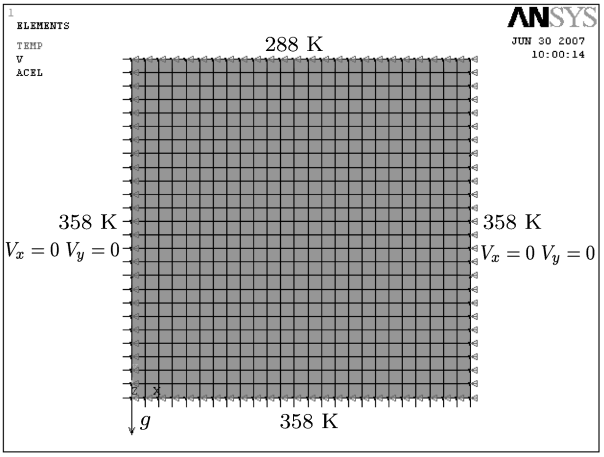


Fig. 3. Meshing model and loads.

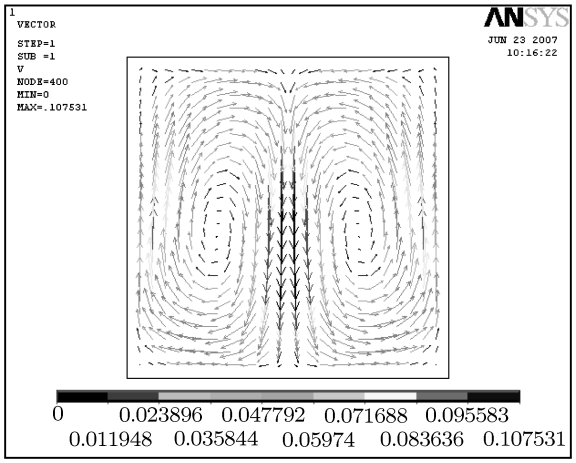


Fig. 4. Velocity vector distribution of the etchant.

The released diaphragm resides with the velocity boundary layer (Fig. 4) in which the velocity changes from zero to the maximum value. The shear stress is in direct proportion to the viscosity of the etchant and the flow velocity grads.[8] The shear stress distribution driven from the flow velocity grads is simulated as shown in Fig. 5, from which the maximum shear stress is 5.3×10^4 Pa. The modulus of rupture of SiNx is ∼GPa,[9] and the maximum shear stress of 5.3×10^4 Pa accounts for almost 50% of the modulus of rupture. So swirling of the heating-induced etchant has a partial effect on the cracking of the released SiNx diaphragm, but it is not the main factor.

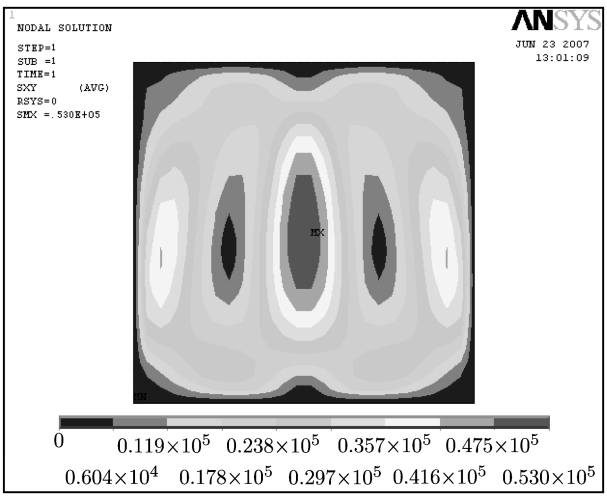


Fig. 5. Shear stress distribution driven from the flow velocity grads (Fig. 4).

2.4. Impact of heating-induced bubbles

Following the analysis in Subsection 2.3, the temperature distribution of the etchant is simulated as fig-

ure 6 shows. Heating-induced bubbles tend to be created in the position where temperature grads undergo big changes. When the change of temperature grads is larger, the heating-induced bubbles have a more intensive impact on the released diaphragm. Doing a quantitative analysis of such an impact is a complicated process, and many factors are difficult to determine.

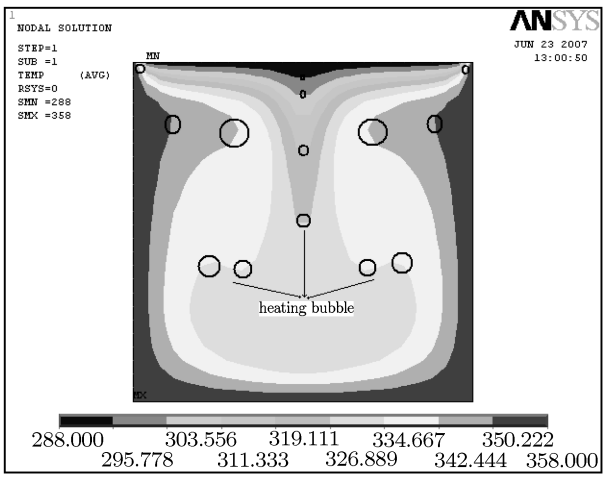


Fig. 6. Temperature distribution of the etchant.

According to the analysis in Subsections 2.1 to 2.3, the imbalanced etchant pressure acting on the cracking of the released diaphragm is small; dithering of the hand while picking up the wafer will not have a serious effect on the cracking of the diaphragm; and swirling of the heating-induced etchant has a partial effect on the cracking of the released SiNx diaphragm; it could therefore be concluded that the impact of heating-induced bubbles is the main factor resulting in the cracking of the released diaphragm in all probability.

3. Solutions

In order to reduce the above four effects on the cracking of the released diaphragm analysed in Section 2, a novel anti-shock bulk silicon etching apparatus is proposed for use during the last etching process of the diaphragm release. That is, the silicon wafer is first put into the regular constant temperature etching apparatus or ultrasonic plus, and when the residual bulk silicon to be etched reaches near to the interface of the silicon and SiNx diaphragm, with a distance of 50 μm–80 μm (in which the exact value is determined by the thickness, surface area and intensity of the released diaphragm), the wafer is taken out carefully and is put into the anti-shock silicon etching apparatus. The wafer is put in the geometrical centre, also the centre of gravity of the etching vessel. An etchant outlet is located at the bottom. The wafer is etched continuously, and at the same time the etchant flows out of the vessel. Optionally, two symmetrically placed low-power heating resistors are put in the anti-shock silicon etching apparatus to quicken the etching process. The heating resistors' power should be low enough to avoid the swirling of the heating-induced etchant and the impact of the heating-induced bubbles on the released diaphragm. A sketch map of the anti-shock bulk silicon etching apparatus is shown in Fig. 7, illustrating the construction of the apparatus. The simulated fluid velocity vector distributions of the etchant in the vessel are symmetrical and vertically streamlined, which is quite different from the case in Fig. 4 and will not lead to swirling of the etchant. Through experiments, silicon wafers etched using this apparatus and not using it are contrasted. The experimental results are shown in Fig. 8; the released SiNx diaphragm with 5000 μm×5000 μm in area and 1 μm in thickness is unbroken by using this apparatus, which proves the practicality of the anti-shock bulk silicon etching apparatus.

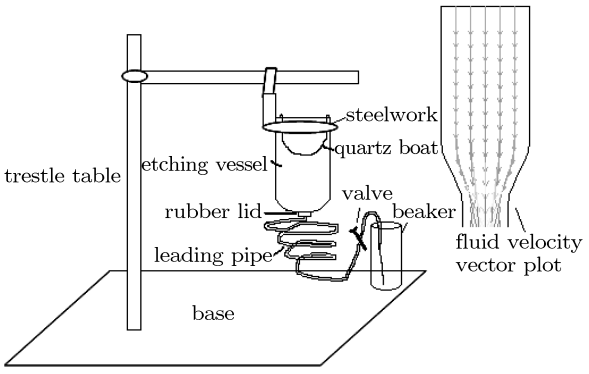
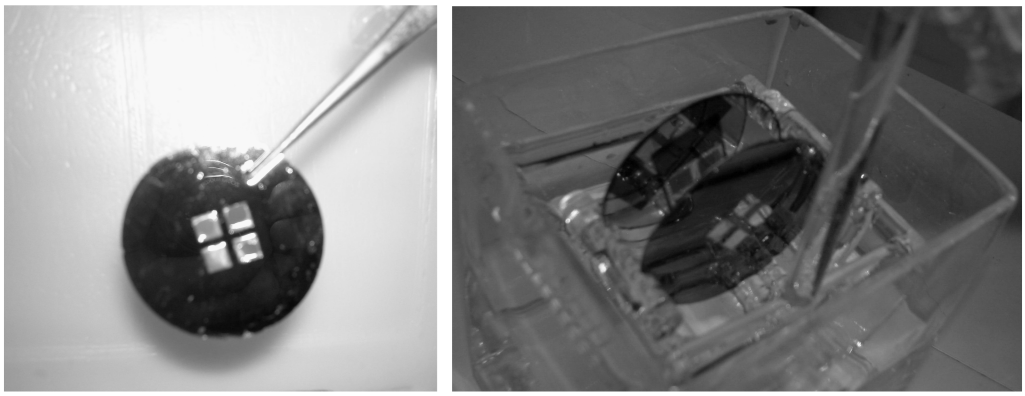


Fig. 7. Sketch map of the anti-shock bulk silicon etching apparatus.



(a) (b)

Fig. 8. Experimental results: (a) released SiNx diaphragm is broken by not using the anti-shock bulk silicon etching apparatus; (b) released SiNx diaphragm is unbroken by using the anti-shock bulk silicon etching apparatus.

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