Mechanical strength of anchor–microbeam combined structure fabricated by silicon-on-glass process

Jun He, Xian Huang, Li Zhang, Danqi Zhao, Fang Yang, Wei Wang, Dacheng Zhang

National Key Laboratory of Nano/Micro Fabrication Technology, Peking University, Beijing 100871, People's Republic of China
E-mail: dchzhang@ime.pku.edu.cn

Published in Micro & Nano Letters; Received on 13th May 2014; Revised on 29th July 2014; Accepted on 18th August 2014

To investigate the mechanical strength of the anchor–microbeam combined structure, two series of devices (bonding quality testing devices and torsional strength testing devices) are designed and fabricated by the silicon-on-glass process. A novel array-shaped anchor scheme is presented, which has been compared with the conventional single anchor. The experimental results have shown that the bonding quality of the anchor degenerated severely when the bonding area became very small (<400 μm^2). The testing results of bonding quality testing devices demonstrated that the presented array-shaped anchor design helped to improve the anodic bonding yield. According to the bending fracture test of the torsional strength testing devices, the array-shaped anchor design had an almost equal torsional strength compared with the single anchor with the same occupied area. Moreover, the torsional strength of the array-shaped anchor was even greater when the bonding area was the same. In the fracture test, the fracture would happen in the anchor since the structure size was small. When the structure was larger, the fracture happened in the cantilever beam, rather than the anchor.

1. Introduction: The silicon-on-glass (SOG) process, mainly using silicon/glass wafer bonding and deep reactive ion etching (DRIE), has become a standard process for manufacturing various microelectromechanical systems (MEMS) devices (such as inertial microaccelerometers and gyroscopes [1, 2]). The fixed beam, namely the anchor–microbeam combined structure, is an indispensable part in these capacitance-sensitive devices fabricated by the SOG process. It provides mechanical support of the movable sensing/actuating functional components [3]. Thus, the mechanical strength of this anchor–microbeam combined structure is vital to the reliability of these devices. However, the details of these structures' mechanical strength has not been studied yet. The microbeam is etched by the DRIE process and the anchor is constructed by anodic bonding. Many factors will lead to a severe degradation of mechanical strength, such as the particles/contaminations on the bonding surface and the roughness/crack on the etched beam surface. Especially, when the structure is small, the degradation of the mechanical strength cannot be ignored anymore.

In this Letter, the mechanical strength of the anchor–microbeam combined structure fabricated by the SOG process is investigated. To achieve this purpose, a series of testing devices were designed. Through bending fracture measurement, the torsional strength of the anchor–microbeam structures with different sizes was obtained. A novel array-shaped anchor (consisting of four identical square sub-anchors) is presented, which has been compared with the conventional single anchor one.

2. Design of testing devices

2.1. Bonding quality testing device: The cross-sectional view of the bonding wafers is shown in Fig. 1. The silicon wafer and glass wafer will not be in intimate contact over the whole interface (e.g. 'A' interface in Fig. 1) before the bonding procedure [4–6]. Then successful bonding depends on whether the intimate contact would happen over the whole interface during the bonding procedure. Numerous factors will hinder intimate contact, such as the total thickness variation of the wafer, the curvature of wafer bow, roughness of the surface, particles and so on.

On application of a voltage across the two wafers in the anodic bonding process, an electrostatic field is set up in the air gaps between the two surfaces. This will generate a dominating attractive force, which helps to pull the two surfaces into intimate contact. The generated electrostatic force of the bonding surface is much larger than that of the non-bonding surface (Fig. 1), so that it is more difficult for small anchors to achieve full intimate contact. The bonding quality will be weakened as the anchor size becomes small. In other words, there is a critical size of the anchor, below which the bonding of the anchor will fail.

For the purpose of investigating the extreme successful bonding size of the conventional single anchor and the proposed array-shaped anchor, the bonding quality testing device was designed as shown in Fig. 2*a*. A similar failure-accelerating method in reliability analysis was introduced here. On the one hand, the anchor was designed to be high (anchor height of 30 μm). As seen above, with a higher anchor, the generated electrostatic force of non-bonding surfaces would reduce. Then the bonding quality of the testing anchor would be poorer. On the other hand, the neighbouring anchor in a certain direction was designed in large distance. This was because the farther neighbouring anchor had less assist in anodic bonding of the testing anchor. In Fig. 2*a*, the testing array-shaped anchor (top) and single anchor (bottom) had the same bonding area. For the testing array-shaped anchors, the neighbouring anchors in the downward direction were at the same distance with the same bonding area. This design was aimed to exclude the effect of other anchors below. Differently, the neighbouring anchors in the upward direction were the reference anchors, which were at different distances with the same bonding area. From the above analysis, it could be concluded that the bonding quality of the testing array-shaped anchor would be poorer if the distance between the testing array-shaped anchor and the reference

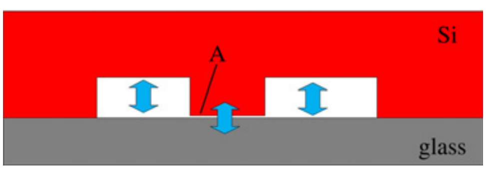

Figure 1 *Cross-sectional view of bonding wafers*

doi: 10.1049/mnl.2014.0251

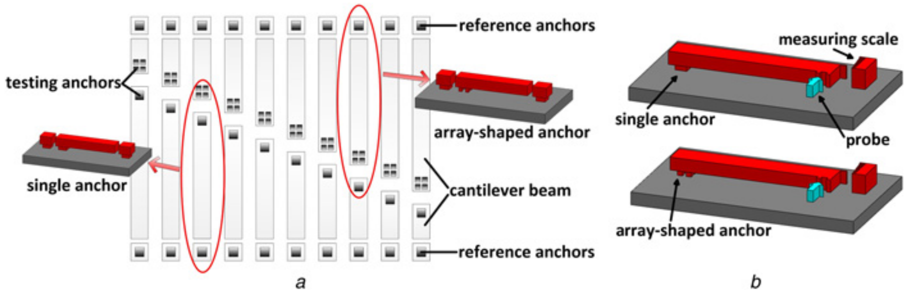

Figure 2 *Structure of the two kinds of testing devices*
a Bonding quality testing device
b Torsional strength testing device

anchor was farther. For the testing single anchor (bottom), the situation was the same.

2.2. Torsional strength testing device: Horizontal movement is the most common operation mode for the capacitance-sensitive devices fabricated by the SOG process. Thus the conventional measuring methods [3, 7–9] of strength cannot directly reflect the strength of the anchor–microbeam combined structure in practical applications. To research the mechanical reliability of this anchor–microbeam combined structure in MEMS devices, a simple torsional strength testing structure was utilised (as seen in Fig. 2*b*). The testing structure was composed of an anchor–microbeam structure (to be measured) and the measuring scale. The specific measuring process went as follows: (i) apply force to the flank of the cantilever beam by the probe of the probe station; (ii) increase the displacement of the probe gradually and record the displacement when the bonding surface fractures; (iii) use the displacement [from step (ii)] to calculate torque by finite element analysis. This torque would be utilised to evaluate the mechanical strength of the anchor–microbeam combined structure.

3. Experimental results and discussion

3.1. Experimental results: Both the above testing devices were fabricated by the SOG process. The process primarily consisted of reactive ion etching and anodic bonding, as shown in Fig. 3. The anchor height of the bonding quality testing device was set to be 30 μm with a beam thickness of 45 μm. As for the torsional strength testing device, the anchor height was 4 μm and the beam thickness was 70 μm.

Fig. 4 shows the scanning electron microscope (SEM) photograph of the two series of testing devices. The bonding quality testing devices can be seen in Figs. 4*a–d*, whereas the other two (Figs. 4*e* and *f*) are about the torsional strength testing devices. The anchor (both array-shaped and single anchor) and the glass substrate bonded successfully when the bonding area was larger than 400 μm^2 (Fig. 4*a*), whereas the detachment happened frequently when the bonding area was small (e.g. 196 μm^2 in Fig. 4*b*). In addition, another two conclusions can also be drawn from Fig. 4*b*. One is that the detachment situation of the single anchor is more severe than that of the array-shaped anchor, and the other one is that the testing anchor with a farther neighbouring reference anchor has poorer bonding quality. For the purpose of obtaining the bonding yield of different size anchors, 100 anchor–microbeam structures at each bonding area were selected by an optical microscope and their detachment situations were observed.

The statistical result is shown in Fig. 5. It can be seen that the bonding quality of the array-shaped anchor was higher than that of the single anchor when the anchor size was small (as for the array-shaped anchor, both the gap between the sub-anchors and the side length of the sub-anchors was half of the side length of the single anchor). The bonding yield increased as anchor size increased and the bonding yield achieved 100% when the anchor size was bigger than 484 μm^2.

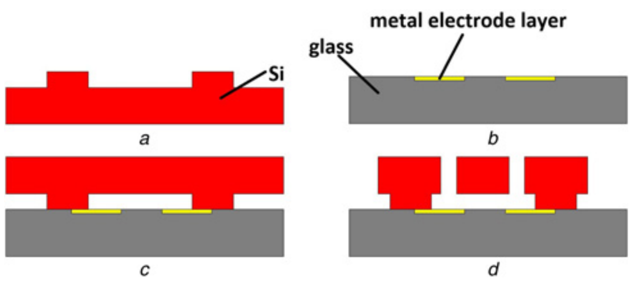

Figure 3 *Basic flow of the SOG process*
a Defining anchor by RIE
b Forming interconncts by lift-off process
c Anodic bonding
d Releasing by DRIE

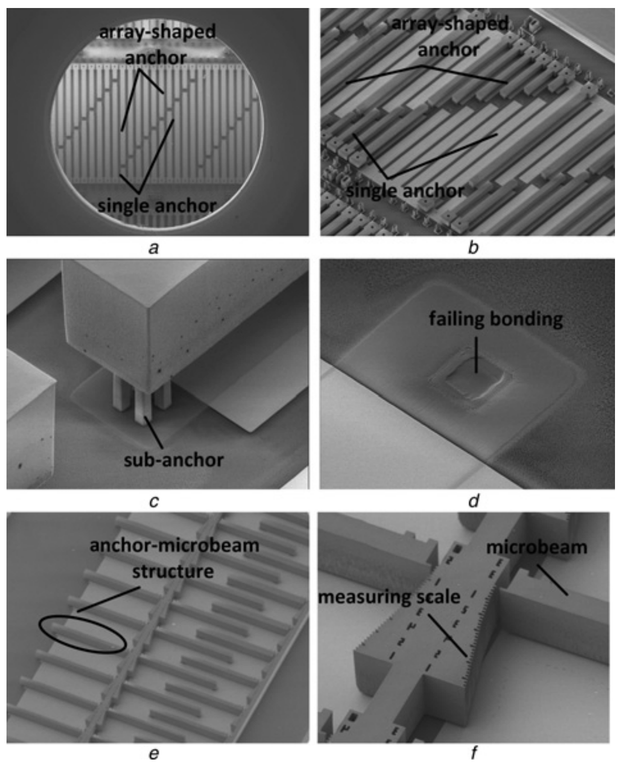

Figure 4 *SEM photographs of bonding quality and torsional strength testing devices*
a–d Bonding quality testing devices
e, *f* Torsional strength testing devices

doi: 10.1049/mnl.2014.0251

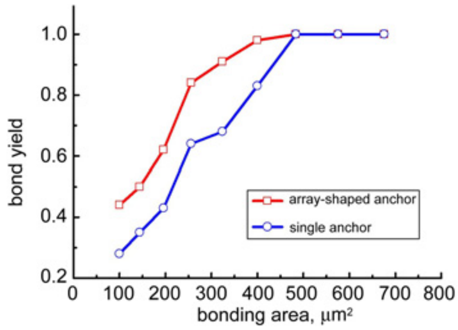

Figure 5 *Statistical relationship between bonding yield and bonding area*

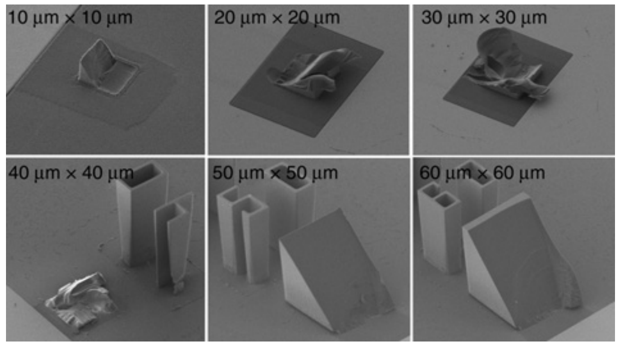

Figure 7 *SEM photograph of fracture morphology*

By the bending fracture test for the torsional strength testing devices, the correlation between mechanical strength and anchor size was obtained, as shown in Fig. 6. In our experiments, the presented array-shaped anchor has been compared with the conventional single anchor of both the same bonding area and the same occupied area. In the case of the same bonding area, both the gap between sub-anchors and the side length of the sub-anchor for the array-shaped anchor was half of the side length of the single anchor; in the case of the same occupied area, the gap between sub-anchors was 4 µm, so the side length of the sub-anchor was 2 µm smaller than half of the side length of the single anchor. From Fig. 6, it can be concluded that the mechanical strength of the array-shaped anchor with the same bonding area is greater than that of the single anchor (Fig. 6*a*), while with the same occupied area, the array-shaped anchor and single anchor has the almost equal mechanical strength (Fig. 6*b*). Fig. 7 shows the fracture morphology of the anchor–microbeam combined structure. It can be seen that the fracture would happened in the anchor when the anchor size was small. As the anchor was larger, the fracture would happen in the cantilever beam, rather than the anchor.

3.2. Discussion: As mentioned before, the chemical bond between the silicon and glass surface forms only after intimate contact is achieved during anodic bonding. When the anchor size is very small, the electrostatic force is not strong enough to pull the two surfaces into intimate contact. Thus, the detachment happens frequently for both the single anchor and array-shaped anchor (Fig. 4*b*). However, the situation of the array-shaped anchor is much better than that of the single anchor with the same bonding area. It is assumed that they bear the same electrostatic force during the bonding procedure. The authors of [10, 11] have demonstrated that the smaller bonding wafers had a bigger initial area of intimate contact during anodic bonding. This means that bonding with a smaller area would achieve intimate contact more easily. Hence, when the single anchor is divided into four identical sub-anchors (array-shaped anchor), the bonding quality would be improved because of the easier growth of the intimate contact under the same electrostatic force.

For the capacitance-sensitive devices fabricated by the SOG process, the anchor–microbeam structure bears a horizontal bending moment. Fig. 8 shows the stress distribution of the anchor obtained

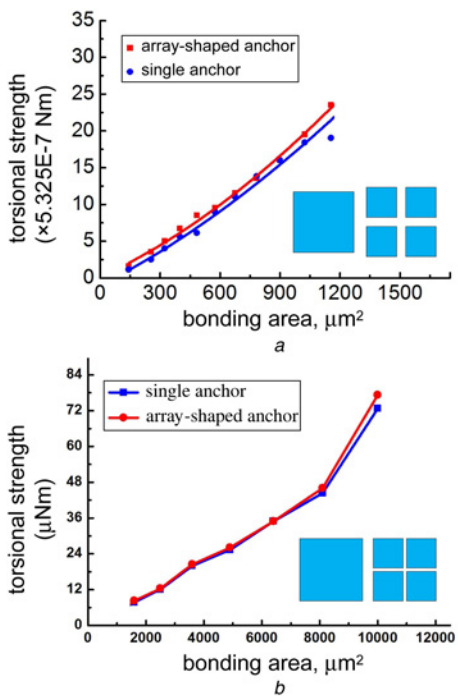

Figure 6 *Correlation between torsional strength and bonding area for the two kinds of anchor design*
a Same bonding area
b Same occupied area

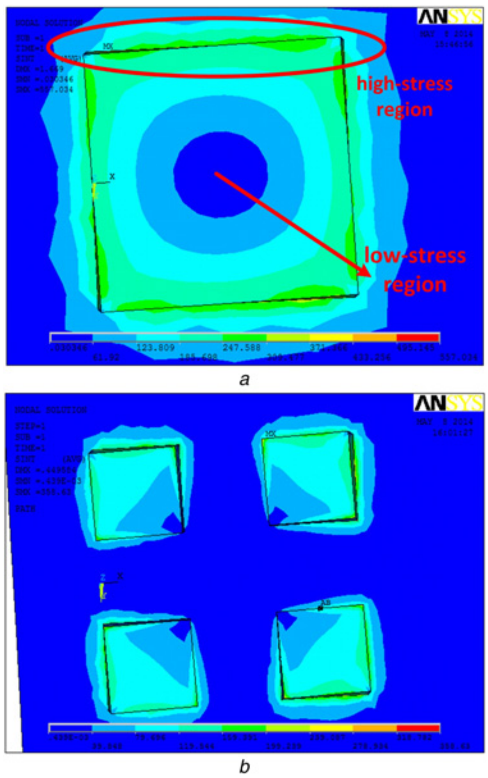

Figure 8 *Stress contour plot of anchor under torsional load*
a Single anchor
b Array-shaped anchor

Micro & Nano Letters, 2014, Vol. 9, Iss. 10, pp. 660–663
doi: 10.1049/mnl.2014.0251

by ANSYS when the anchor–microbeam structure is under bending moment. From Fig. 8*a*, it can be seen that there is a low-stress region in the middle of the single anchor (Fig. 8*a*). In the anti-bending process, the high-stress region is more essential than the low-stress one. Thus, although the area in the middle of the anchor to be bonded is lost when the single anchor is divided into the array-shaped anchor, the mechanical strength of the array-shaped anchor is still almost equal to that of the single anchor with the same occupied area (Fig. 6*b*). From Fig. 8*b*, it can be seen qualitatively that the proportion of the low-stress area is less than that of Fig. 8*a*. It can be concluded that the array-shaped anchor utilises the bonding area more effectively than the single anchor when bearing torque.

From the fracture morphology of the samples (Fig. 7), it can be seen that the fracture happens in the silicon or glass, rather than the bonding interface. This proves that the bonding strength of the anodic bonding is as large as that of the bulk silicon or glass (if the bonding is successful). When the anchor–microbeam structure is small, the fracture will happen in the anchor, which can be seen from the first four pictures of Fig. 7. This means that the mechanical weakest part of the anchor-microcombined structure is the anchor when the whole structure is small. As the anchor size is larger than $50\,\mu m \times 50\,\mu m$, the weakest part changes from the anchor into the root of the cantilever beam (Fig. 7). This is because the anti-torsion strength of the anchor is proportional to the cube of the side length of the anchor, whereas the anti-bending strength of the beam is proportional to the square of the width of the beam. Thus, the anchor becomes stronger than the cantilever beam when the size of the whole structure is increased.

4. Conclusion: To investigate the mechanical strength of the anchor–microbeam combined structure, two series of devices (a bonding quality testing device and a torsional strength testing device) were designed and fabricated by the SOG process. By the bending fracture test, the torsional strength of the anchor–microbeam structures with different sizes has been obtained. A novel array-shaped anchor is presented, which has been compared with the conventional single anchor. From the obtained results, it can be concluded that:

1. The bonding quality of the anchor degenerates severely when the anchor size becomes very small. The presented array-shaped anchor improves the bonding quality.
2. The mechanical strength of the anchor–microbeam increases quickly as the anchor size increases. The array-shaped anchor has almost equal mechanical strength as the single anchor with the same occupied area, while even larger with the same bonding area.
3. The anchor is the weakest part of the anchor–microbeam combined structure when the whole structure is small, whereas as the structure size increases (e.g. when the anchor is larger than $50\,\mu m \times 50\,\mu m$ in our experiments), the weakest part will move into the root of the cantilever beam.

5. Acknowledgments: The authors thank the staff of the National Key Laboratory of Nano/Micro Fabrication Technology for their cooperation and help in the fabrications. This work is financially supported by the National High Technology Research and Development Program of China (863 Program) under no. 2011AA040401 and the National Basic Research Program of China (973) under program no.2011CB309502.

6 References

[1] Fan J., Zhu Y., Yang Z., Zhou J., Liu X., Yan G.: 'An improved method employed in anodic bonded glass-silicon gyroscopes to avoid footing effect in DRIE', Proc. Solid-State and Integrated Circuit Technology Conf., Guilin, China, 2004, **3**, pp. 1896–1899

[2] Wang J., Yang Z., Yan G.: 'A silicon-on-glass Z-axis accelerometer with vertical sensing comb capacitors', Proc. Nano/Micro Engineered and Molecular Systems (NEMS) Conf., Kyoto, Japan, 2012, pp. 583–586

[3] Hu Y., Zhao Y., Yu T.: 'Tensile tests of micro anchors anodically bonded between Pyrex glass and aluminum thin film coated on silicon wafer', *Microelectron. Reliab.*, 2008, **48**, (10), pp. 1720–1723

[4] Wallis G., Pomerantz D.I.: 'Field assisted glass-metal sealing', *J. Appl. Phys.*, 1969, **40**, (10), pp. 3946–3949

[5] Morsy M.A., Ikevchi K., Ushio M., Abe H.: 'Mechanism of enlargement of intimately contacted area in anodic bonding of Kovar alloy to borosilicate glass', *Mater. Trans.*, 1996, **37**, (9), pp. 1511–1517

[6] Yoshiaki A., *et al.*: 'Pressure and field-assisted bonding of glass to aluminum (materials, metallurgy and weldability)', *Trans. JWRI*, 1984, **13**, (1), pp. 35–40

[7] Hurd D.S., Caretta R., Gerberich W.W.: 'An experimental fracture mechanics study of a strong interface: the silicon/glass anodic bond', *J. Mater. Res.*, 1995, **10**, (2), pp. 387–400

[8] Ericson F., Schweitz J.: 'Micromechanical fracture strength of silicon', *J. Appl. Phys.*, 1990, **68**, (11), pp. 5840–5844

[9] De Coster J., Picco A., De Wolf I.: 'Device and method for the measurement of anchor shear strength in MEMS devices', Proc. Micro Electro Mechanical Systems (MEMS) Conf., Paris, France, 2012, pp. 416–419

[10] Carlson D.E., Hang K.W., Stockdale G.F.: 'Electrode "polarization" in alkali – containing glasses', *J. Am. Ceramic Soc.*, 1972, **55**, (7), pp. 337–341

[11] Knowles K.M., Van Helvoort A.T.J.: 'Anodic bonding', *Int. Mater. Rev.*, 2006, **51**, (5), pp. 273–311