Anchor Design for Microdevice Fabricated by Silicon-on-Glass Process Based on Bonding Strength Consideration

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Abstract In this paper, an array-shaped anchor for microdevice (fabricated by silicon-on-glass (SOG) process) was designed for improving its bonding strength. This design scheme aims to release the coefficient of thermal expansion (CTE) mismatch induced residual stress and decrease the metal electrode layer or particles induced bonding failure risk. To evaluate the bonding performance of the proposed anchor design scheme, numerical simulation and mechanical experiments are carried out on well-established anchor-beam MEMS devices. The scanning electron microscope (SEM) results indicated that the bond yield of the array-shaped anchor was higher than the single anchor. The fracture tests results demonstrated that the torsional bonding strength of the array-shaped anchor was stronger than that of the conventional single anchor in practical application.

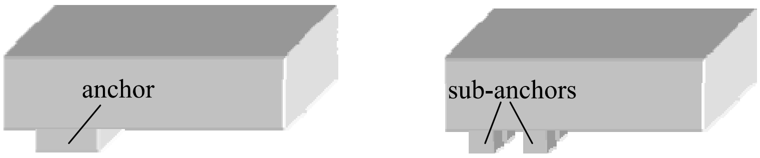
Keywords Particles, Bond yield, Torsional bonding strength, Fracture test

1. Introduction

Due to the development of micromachining technology, various micro electro-mechanical system (MEMS) devices (e.g. inertial micro accelerometers, RF/Microwave Devices, microfluidic devices, optical devices) can be fabricated [1–5]. As an important technique in micromachining, the anodic bonding, also known as field-assisted bonding, was firstly developed in the late 1960s by Wallis and Pomerantz [6–8]. Nowadays it has matured into a flexible technology with lots of applications [9]. One of the important applications is constructing micro anchor (bonded structure) for MEMS devices fabricated by the silicon-on-glass (SOG) process, which provides mechanical support or electrical connect to the movable sensing/actuating functional components. Therefore the bond yield and bonding strength of anchors are two of the main aspects for the reliability of MEMS devices [10].With the devices scaling, the bonding strength need to be considered carefully with limited bonding area. Besides, many factors on the bonding surface will lead to a dramatic degradation of the bonding quality and even the bonding failure when the anchor is small; for instance, the metal electrode layer, particles, contaminations and the CTE mismatch induced residual stress [11]. As a result, conventional single anchor is not the optimal choice for small devices. In this paper, a novel array-shaped anchor is proposed to address the above mentioned bonding degradation issues by dividing the single anchor into four identical sub-anchors. For the first time, the correlation between shape/size and bonding strength of the anchor is studied. Theoretical analysis demonstrates the array-shaped anchor improves bond yield and the shock resistance by reducing the bonding failure risk. In addition, the array-shaped anchor is proved to be a perfect way to release the residual stress for the high anchor (Fig 3) as well. Two series of well-established anchor-beam MEMS devices are fabricated by SOG process. The bond yield and torsional bonding strength of the anchors (both conventional and the array-shaped) are measured for comparison. The experimental results indicated that the proposed array-shaped anchor is performing well and superior to the conventional single anchor ones.

2. Theoretical analysis

The array-shaped anchor design, consisting of four identical square sub-anchors, is illustrated in Fig.1(b). Bonding parameters, the metal electrode layer, particles, other contaminations on the surface within the bonding area, and the residual thermal stress, all these factors affect bonding strength of microdevices. Theoretical comparison between array-shaped anchor and single anchor on bonding quality and residual thermal stress is conducted.



(a) conventional single anchor (b) array-shaped anchor

Figure 1. The different anchor designs

2.1 Bonding quality

When the anchor is small, the metal electrode layer, particles or other contaminations may lead to a dramatic degradation of the bonding quality, even the bonding failure (Fig. 2(a)). But if it happens to array-shaped anchor, the unaffected sub-anchors without particles can be still bonded successfully (Fig. 2(b)), therefore the average bonding quality is better than that of single anchor ones, namely, the array-shaped anchor design improves the bond yield.

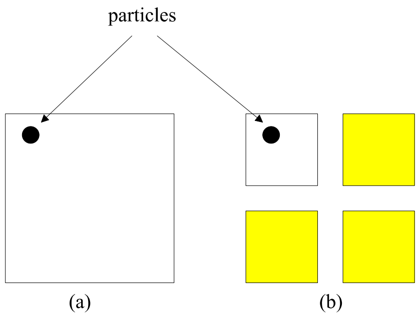


Figure 2. The particles on the surface within the bonding area:
(a) single anchor (b) array-shaped anchor

In addition, the existence of the metal electrode layer or particles will generate defect points on the surface. It is assumed that the ultimate strength of the defect points and normal bonding region is σ_1 and σ_2 respectively ($\sigma_2 > \sigma_1$). When the single anchor's surface stress reaches σ_1, the crack will arise from the defect point, and then propagates until the single anchor fractured because of the brittleness of the monocrystalline silicon (Fig. 2(a)). With regard to array-shaped anchors, when the surface stress reaches σ_1, the crack will also arise from the defect point, but owing to the sub-anchors without particle contaminations the crack will not propagate. So the ultimate strength of the array-shaped anchor is σ ($\sigma_1 < \sigma < \sigma_2$), which is larger than σ_1, the single anchor's ultimate strength, i.e. improving the shock resistance.

2.2 Residual thermal stress

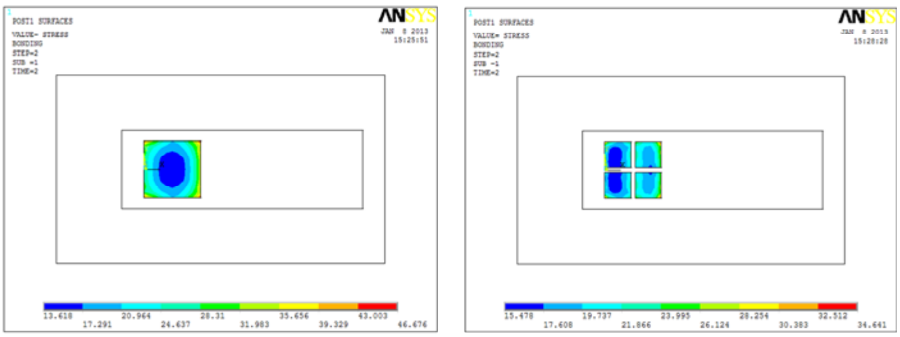
The array-shaped anchor is conducive to release residual stress caused by CTE mismatch. As a result of the size decrease of the bonding surface, the thermal stress of every sub-anchor surface is much lower than that of the single anchor one [12]. The CTE mismatch between different sub-anchors can be remitted by the bending of sub-anchors. In order to demonstrate advantages of the array-shaped anchor the finite element analysis (FEA) is performed. For silicon and glass, parameters applied in the simulation are shown in table 1. Figure 3 shows the residual thermal stress contour of the bonding surface. The highest stress on the bonding surface of single anchor is 46 MPa, while that of the array-shaped anchor is 34 MPa (table 2). It can be concluded from the FEA results that the array-shaped anchor is beneficial to release the thermal stress.

Table 1. Parameters in FEA

	Young modulus	Poisson ratio	CTE	Bonding temperature	Operating temperature
Glass	62.75 Gpa	0.20	3.25E-6	623 K	300 K
Si	169 Gpa	0.28	2.6E-6	623 K	300 K

Table 2. FEA results of Fig. 3

	Type	Anchor height	Side length of anchor (sub-anchor)	Gap between sub-anchors	Highest stress
Figure 3(a)	Single anchor	40 μm	26 μm		46 MPa
Figure 3(b)	Array-shaped anchor	40 μm	12 μm	2 μm	34 MPa



(a)conventional single anchor (b)array-shaped anchor

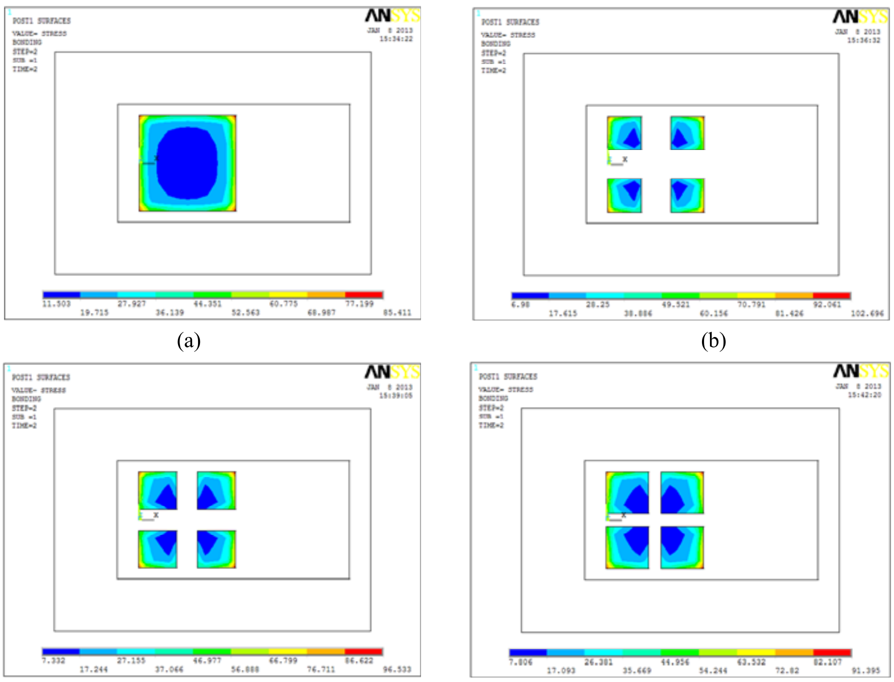
Figure 3. Contour plot of residual thermal stress of bonding surface (anchor height of 40μm)

Besides, effects of anchor height on thermal stress of the array-shaped anchor are also analyzed.

Figure 4 shows the residual thermal stress contour of bonding surface for the anchor with a height of 4 μm. And detailed results are listed in table 3. It can be concluded that the thermal stress of array-shaped anchor is higher than that of the single anchor. Furthermore, the stress discrepancy reduces as the gap between sub-anchors decreases. The reasons are that sub-anchors could hardly bend when the height of anchors is small, therefore thermal stress cannot be released by bending of the sub-anchors but only by the deformations of the bonding surface. In addition, due to the loss of the bonding surface, the thermal stress of array-shaped anchor is higher. However, this effect can be ignored comparing with ultimate strength in an order of GPa.

Table 3. FEA results of Fig.4

	Type	Anchor height	Side length of anchor (sub-anchor)	Gap between sub-anchors	Highest stress
Figure 4(a)	Single anchor	4 μm	46 μm		85 MPa
Figure 4(b)	Array-shaped anchor	4 μm	16 μm	14 μm	102 MPa
Figure 4(c)	Array-shaped anchor	4 μm	18 μm	10 μm	96 MPa
Figure 4(d)	Array-shaped anchor	4 μm	20 μm	6 μm	91 MPa



(a) (b) (c) (d)

Figure 4. Contour plot of residual thermal stress of bonding surface (anchor height of 4 μm)

3. Experiments

To evaluate the bonding performance of the proposed anchor design experimentally, two series of

well-established anchor-beam MEMS devices (both conventional and the array-shaped) fabricated by SOG process were carried out to test the bonding quality and the bonding strength in practical application. The basic flow of SOG process (Fig. 5) is described as follows:
(a)Define bonding area, i.e. anchor, by advanced silicon etch (ASE).
(b)Form interconnects on glass wafer by lift-off process.
(c)Anodic bonding and KOH etch.
(d)Release structure by deep reactive ion etching (DRIE).

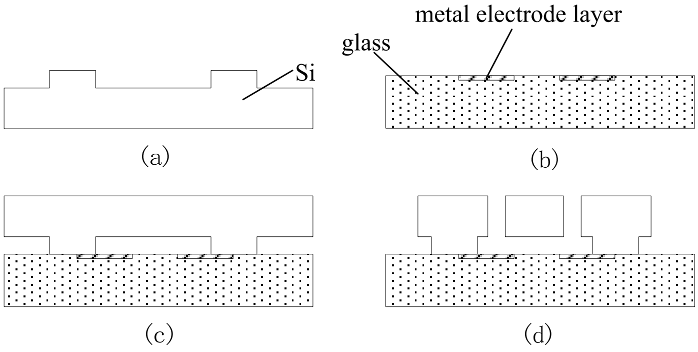


Figure 5. Basic flow of SOG process

3.1 Bonding quality testing device

The bond yield is utilized to evaluate the bonding quality. And various bonding areas are designed to investigate its influence on bond yield for both anchor design schemes. To compare the bond yield conveniently, a similar failure-accelerating method in reliability analysis is introduced. Microdevices are intentionally designed to extreme sizes. On one hand, the anchor is designed to be high enough (anchor height of 30μm). With a higher anchor, the electrostatic force of non-bonding surfaces will reduce and the pressure of bonding surface will decrease accordingly in anodic bonding. As a result, the bonding quality will be poor. On the other hand, the adjacent anchor in a certain direction is designed far enough, because the further adjacent anchor has less assist in anodic bonding of the anchor here.

The structure of the microdevice is shown in Fig. 6. The array-shaped anchor (top) and single anchor (bottom) have the same bonding area. For the array-shaped anchors, in the downward direction, the adjacent anchors are at the same distance with the same bonding area, which excluded the effect of other anchors below. And in the upward direction, the adjacent anchors are the reference anchors, which were at different distances with the same bonding area. From the above analysis it can be concluded that if the distance between the array-shaped anchor and the reference anchor is farther, the bonding quality of the array-shaped anchor would be poorer. For the single anchor, the situation is the same.

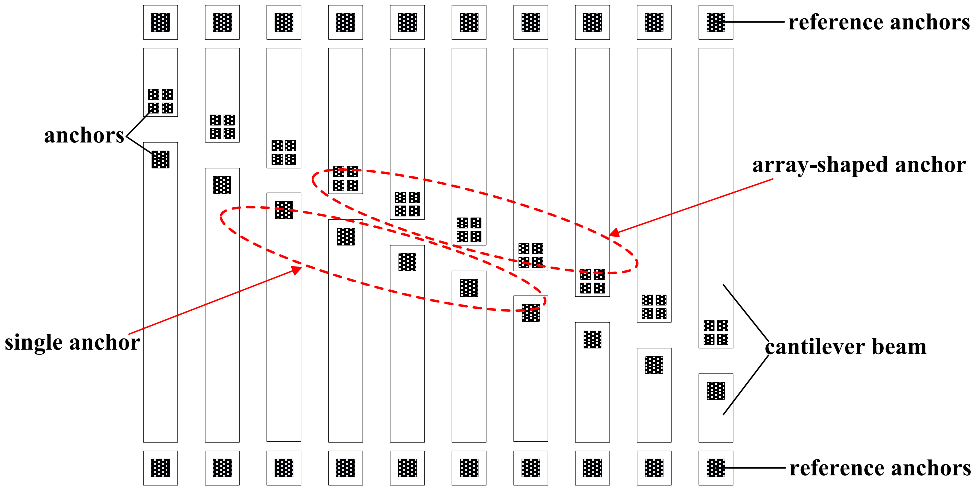


Figure 6. Structure of bonding quality testing device

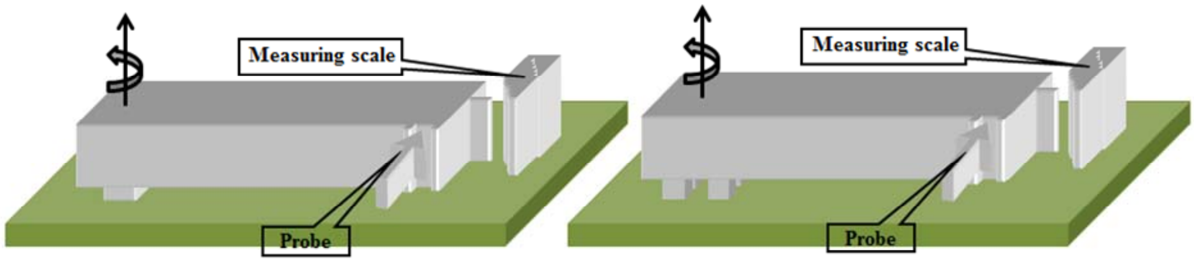
3.2 Torsional bonding strength testing device

For the horizontal-movable MEMS devices fabricated by SOG process, the conventional measuring methods of bonding strength cannot directly reflect the anchor strength in practical application, because the anchor stands torque when the devices are functioning. Therefore, torsional bonding strength testing device with anchor height of 4 μm and beam thickness of 71 μm is proposed (Fig. 7). The anchor bearing torque when the bonding surface fractures is used to characterize the torsional bonding strength. Specific measuring process goes as follows:

(1) Apply force to the top of the cantilever beam by the probe of the probe station;

(2) Increase the displacement of the probe step by step and record the displacement when the bonding surface fractures;

(3) Use the displacement (from (2)) and calculate the torque by FEA.



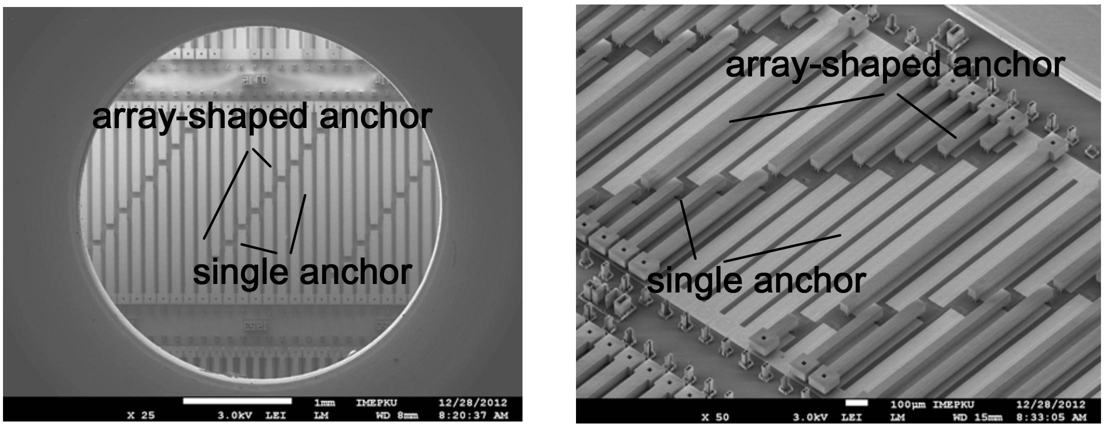
(a) conventional single anchor (b) array-shaped anchor

Figure 7. Structure of torsional bonding strength testing device

4. Results and discussion

4.1 Comparison of bonding quality

Figure 8 shows a scanning electron microscope (SEM) photograph of bonding quality testing devices. The cantilever beams of both array-shaped anchor and single anchor don’t drop out when the bonding area was large (Fig. 8(a)). And dropping out happens tempestuously when the bonding area is small (Fig. 8(b)). The result also shows that the situation of single anchor is severer than that of array-shaped anchor (Fig. 8(b)). It can be concluded that the bonding quality of array-shaped anchor (Fig. 9) is higher than that of the conventional single one and the bonding quality become poorer with a further adjacent reference anchor (Fig. 8(b)).



(a) Bonding area of 900 um^2 (b) Bonding area of 196 um^2

Figure 8. SEM photograph of bonding quality testing devices

In order to obtain the bond yield of array-shaped anchor and single anchor, 100 cantilever beams at each bonding area are selected by optical microscope and dropping out situations of them are observed. Figure 10 shows the statistical result, which proves the bonding quality of array-shaped anchor is higher than that of single anchor again. In addition, with the increasing of the bonding area, the bond yield become higher and the bond yield is 100% when the bonding area is bigger than 484μm^2.

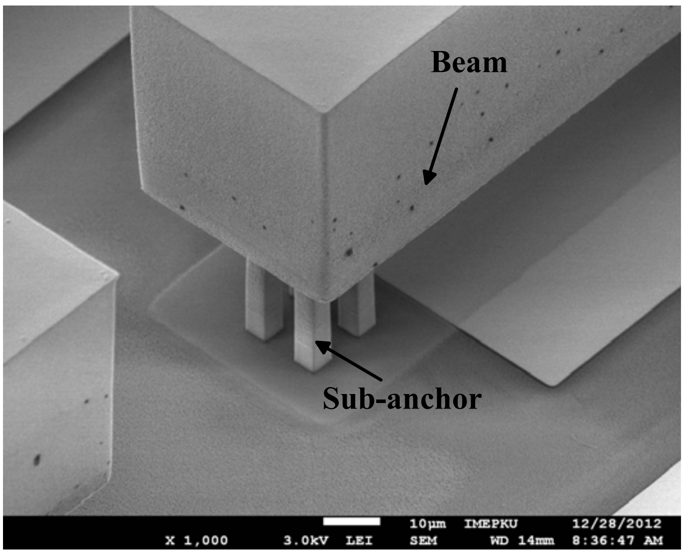


Figure 9. SEM photograph of array-shaped anchor

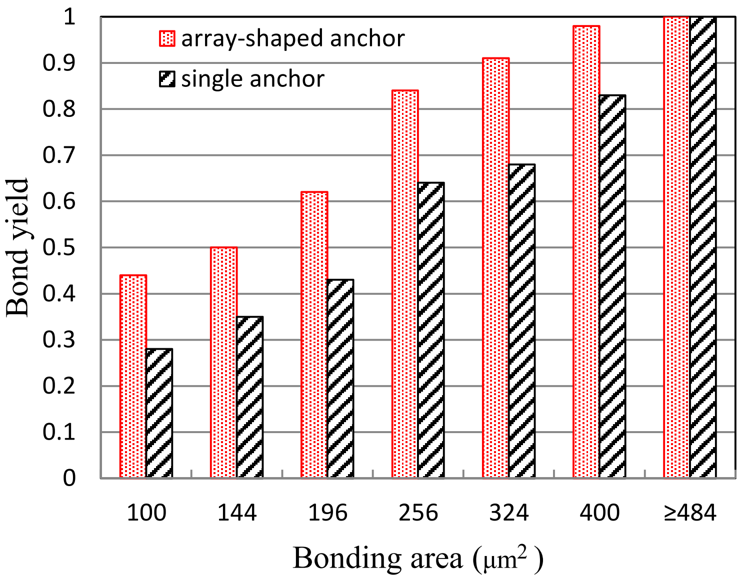
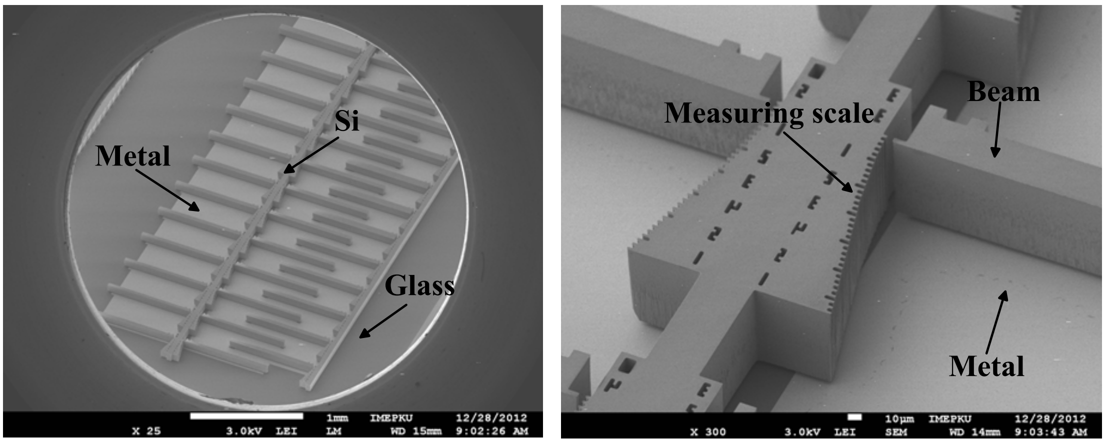


Figure 10. Correlation between bond yield and bonding area

4.2 Comparison of torsional bonding strength

Figure 11 shows a SEM photograph of torsional bonding strength testing devices. To avoid footing effect in DRIE process, protecting metal layer is deposited on glass wafer (Fig. 11(a)). As a result, the actual size of the beam (41.7μm), shown in Fig. 12, is almost the designed size (43μm).



(a) (b)

Figure 11. SEM photograph of torsional bonding strength testing devices

Torsional fracture tests were carried out for both array-shaped anchor and single anchor. Based on the fractured displacements from the fracture tests, the torsional bonding strength is obtained by FEA. Figure 13 shows the correlation between torsional bonding strength and bonding area. The strength of array-shaped anchor is stronger than that of single anchor. And one reason is that the average bonding quality of array-shaped anchor is better than that of single anchor, which can be seen in section 4.1. Another reason is expressed below. There is a low-stress region in the middle of single anchor bonding surface when the anchor stands torque, and this region contributes little to the bonding strength. However, there is no such low stress region in the array-shaped anchor when it stands torque. Therefore, array-shaped anchor has a stronger torsional bonding strength.

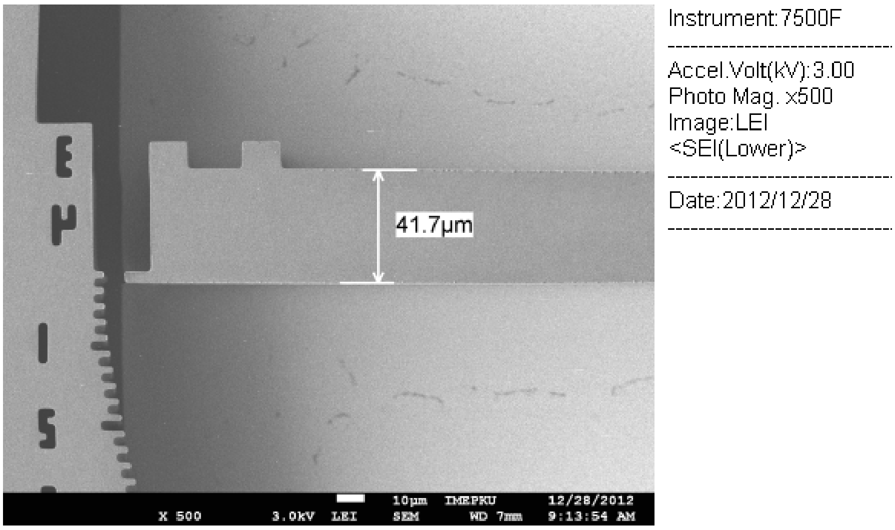


Figure 12. SEM photograph of cantilever beam and measuring scale

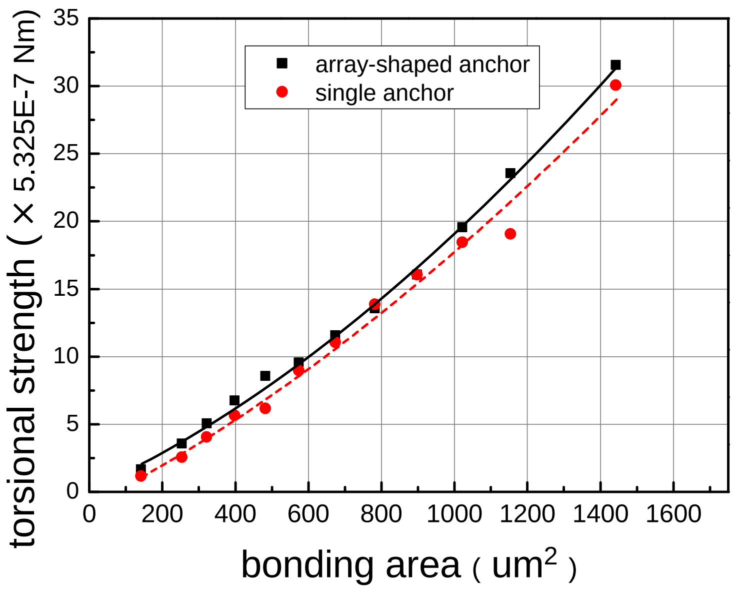


Figure 13. Correlation between torsional bonding strength and bonding area

5. Conclusion

A novel array-shaped anchor design scheme for microdevices fabricated by silicon-on-glass process was proposed. This anchor design was based on bonding strength consideration and consisted of four identical sub-anchors. The bonding quality test has verified that, compared with conventional single anchor, the proposed array-shaped anchor is beneficial to release the CTE mismatch induced residual stress and decrease the metal electrode layer or particles induced bonding failure risk. Thus the new scheme would achieve a stronger bonding quality and a higher bond yield. From the torsional fracture tests of well-established anchor-beam MEMS devices, we conclude that the torsional bonding strength of array-shaped anchor is stronger than that of single anchor in practical application. This array-shaped anchor has a promising application in microdevice design with scaling-down.

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