A UNIVERSAL STRUCTURE FOR SELF-ALIGNED IN SITU ON-CHIP MICRO TENSILE FRACTURE STRENGTH TEST

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ABSTRACT

This paper presents a universal self-aligned in situ on-chip micro tensile fracture strength tester designed for tensile strength extraction and process evaluation, which will provide, for the first time as far as the authors know, great force(above 100mN) to in situ on-chip specimen without the introduction of precise instrument, especially suitable for bulk micromachining related tests. The whole structure and process is simple, so it meets the requirements of various process in massive production, the feasibility and universality have been proved by practical evaluation of the several foundries. Its advantages also include self-position, self-measure and self-adaption for loading. In our tests, tensile fracture strength of the etched Si film is between 0.13 to 1.2GPa.

INTRODUCTION

Reliability could be a hidden barrier to successful commercialization of MEMS. Instead of just focus on product design, manufacture, function, etc, we need to consider even design reliability in advance to accelerate design circle and commercialization process. However, the study of MEMS reliability is difficult as the individual and overall impacts of processing are complex. Therefore, we should first quantitate some parameters then further understand the failure mode and mechanism.

The mechanical properties are of fundamental importance to MEMS devices. To date, there are three typical ways to extract mechanical parameters: (1) extracting directly by precise instruments. W.C. Oliver et al use load and displacement sensing nanoindentation to acquire hardness and elastic modulus [1]. U.M. Mescheder utilized transmission spectroscopy to in situ monitor the thickness of Si membranes during anisotropic wet etching; (2) precise instruments aided with special designed on-chip specimens. The force and displacement measured by instruments can be used to calculate the tensile fracture strength [2-5], Young's module [2-4] and residual stress [3], according to specific designed specimen; (3) on-chip testers contain measuring modules, combining with regular equipment such as microscope and probe station. Together with an in-situ displacement gage [6] or just depend on itself [7], electrothermal actuator could get the force and displacement relevant to tensile test. Among these methods, on-chip testers would be the most favorable way since its operation is convenient in massive production.

In massive production, standard process is preferable for more applicable conditions, that is also why there is urgent need of universal reliability evaluation method with simple test requirements, on-chip tester ready to test and actually reveal the characteristics of devices. Microtensile technique performed for the first time at the wafer-scale reported in MEMS 2008 [4], accompanied by other MEMS stage based tensile tests [8, 9], they acquired abundant valuable parameters not limited to tensile facture strength. But the real devices may differ notably with the test results, tens of milli-Newton or less force probably not enough in some circumstances and the universality in massive fabrication remain to be solved. Our tester will take care of the mentioned problems.

STRUCTURE DESIGN

Self-aligned part

It takes advantage of hinge to align itself with the change of force direction. The rectangle frame A transforms push force to pull force, thus predisposed the testing beam to tensile test. The anchored column serves to limit the move of concentric annulus, combining with the movement of frame A, the tensile force is applied to the specimen. Figure 1a shows the schematic of this part.

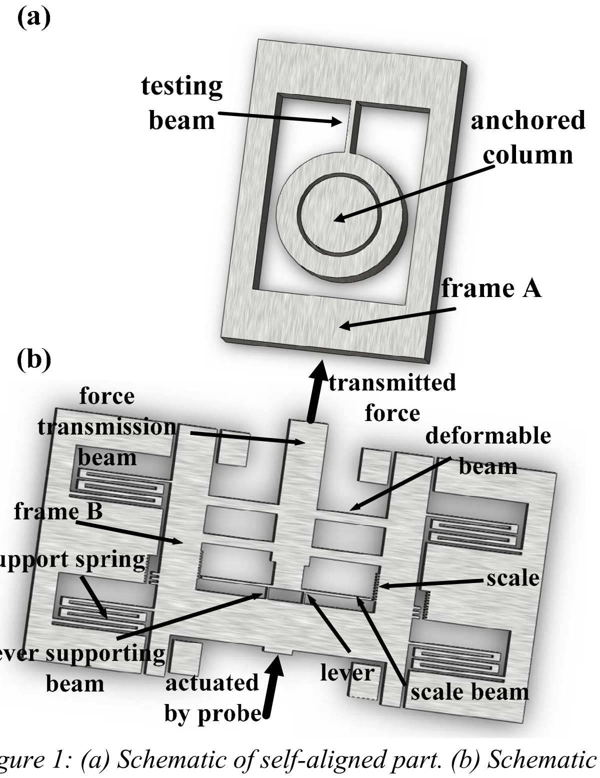

Figure 1: (a) Schematic of self-aligned part. (b) Schematic of force transmission part.

Force transmission part

This part is designed for orientation and force measurement, as shown in Figure 1b. The on-chip force transmission beam attached to hinge-shaped structure is self-positioning initially. As the elongation of the specimen is small, we add a lever to magnify the elongation to get the tensile force more precisely. From the ANSYS simulation results shown in Figure 2, we can see that in different deformable beam width, the displacement reflected by scale increases almost linearly with the force in force transmission beam. That means we can utilize scale to measure the tensile force base on the width of deformable beams independent of other factors. We can also adjust the width of the deformable beams to match up sundry test requirements. Scale refers to the force applied to the specimen, combining specimen specification and the line width loss measured by SEM, the tensile fracture strength can then be deduced. The structure is supported by four micro springs, the probe station apply force at the embossment of frame B. To avoid structure damage caused by unpredicted reasons, as well as align perfectly, we introduce four limit pillars. The designed parameters of this part listed in Table 1.

In bulk micromachining process, it is hard to construct consecutive slender lines whose width down to 1μm to be used as scale. To solve the problem, we use dual width scale (one scale width 3μm, the other 5μm) to distinguish 1μm, shown as in Figure 3.

Table 1: Design parameters of the structure.

Parameter	Value(μm)
Thickness of the structure	70
Width of the test beam	3
Length of the test beam	70
Width of the scale beam	5
Length of deformable beam	150
Width of deformable beam	16
Length of lever supporting beam	20
Width of lever supporting beam	3

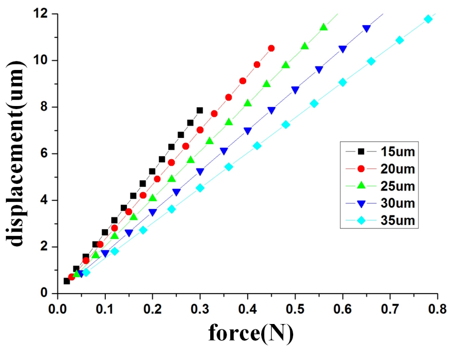

Figure 2: ANSYS stimulation results of different width of deformable beam: Scale B displacement vs. transmitted force.

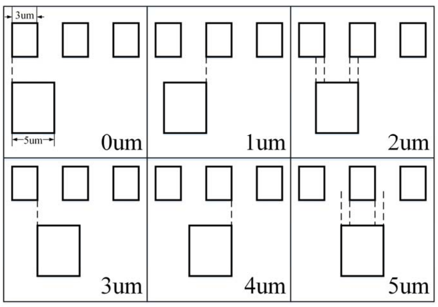

Figure 3: Schematic of dual width scale

ERROR ANALYSES

Traditional tensile testing process is shown in Figure 4a, one end of the specimen is fixed to one structure and force is applied to the other end of the film. The offset error and angle error of applied force will substantially affect the testing results, especially when two errors combine together. While in our tensile testing (Figure 4b), the fixed end turns to connect to a self-aligned part. This change can self-adapt to the force direction, so effectively avoid the influence of the errors mentioned before. Nevertheless, the walls of structure are not vertical because imperfect etching process results to obliquity error. The analyses of these errors will be introduced as follows.

Offset error and angle error

We assume the cantilever is of rectangular cross section, l, w, t denote to length, width, thickness of the cantilever respectively. In ideal case of uniaxial tensile test, the stress along the film is identical, expressed as

$$\sigma_0 = \frac{f}{wt} \tag{1}$$

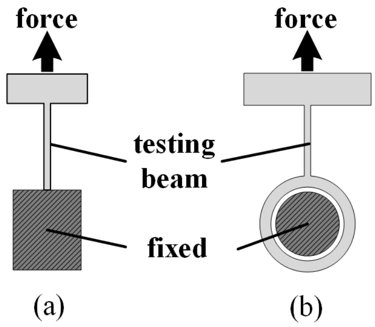

Figure 4: (a) traditional tensile test. (b) tensile test of our structure

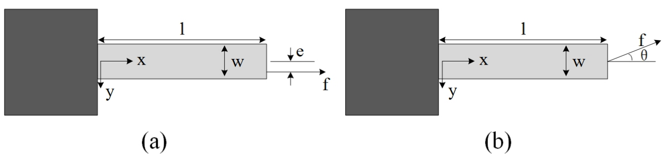

Figure 5: Schematic of the introduction of (a) offset error (b) angle error

When offset error e is introduced as shown in Figure 5a, we can infer that the offset error [10] of the result is

$$\eta_1 = \frac{\sigma_{\max 1}}{\sigma_0} - 1 = \frac{6e}{w} \tag{2}$$

If the angle error occurs as shown in Figure 5b, the angle error [10] of result is

$$\eta_2 = \frac{\sigma_{\max 2}}{\sigma_0} - 1 = \cos\theta + \frac{6l\sin\theta}{w} - 1 \tag{3}$$

Only 1μm offset error in a 20μm wide cantilever, the offset of result up to 30%. Just 1° angle error in a 40μm wide and 100μm long cantilever causes offset error of result up to 26.2%. If the testing instruments and operation are not precise enough, the offset error and angle error of the result can be several tens of percent. Unfortunately, angle error and angle error usually occur together, which further make the result controversial.

Obliquity error

In actual foundry or lab, the obliquity error basically limited to ensure the functionality of fabricated devices, not more than 1°. Provided that the obliquity angle of the walls of our structure is 1°, it will influence the initial contact condition of the self-align part as shown in Figure 6a and 6b.

To determine the actual contact condition in tensile test, we utilized ANSYS stimulation to analyze. After applying 100mN to the test structure, the relative displacement of the top and bottom of the annulus is several micrometers, which denotes the actual contact condition of the self-align part while testing is area contact not point contact, as shown in Figure 6c.

Figure 7 shows the ANSYS stimulation of the whole structure. The average tensile stress along the thickness direction is 811MPa, the deviation with the maximum tensile stress results from obliquity error is just 7.5%.

Considering the actual obliquity error is smaller, the test error of our structure is limited. On the other hand, obliquity error can’t be avoid in any test, not to mention offset error and angle error, especially when the width of the specimen is small. Hence, the tester we present is an optimized choice.

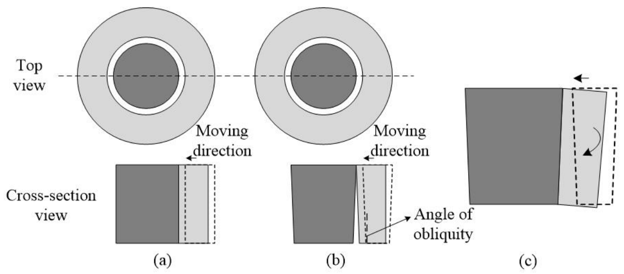

Figure 6: (a) ideal; (b) initial; (c) testing contact of the self-aligned part.

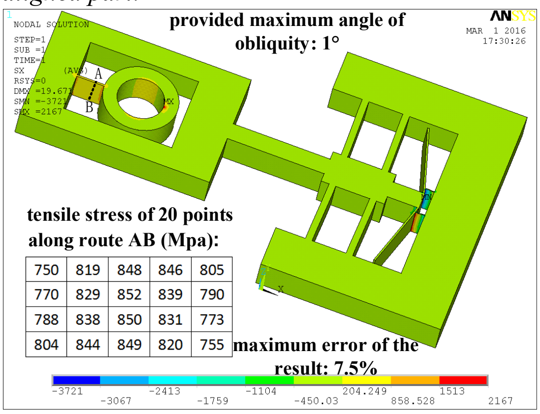

Figure 7: ANSYS stimulation result of obliquity error.

FABRICATION AND OPERATION

The tester was fabricated by the SOG (silicon on glass) fabrication process developed in our previous work [11], the fabrication sequence is summarized in Figure 8. We used 400μm thick, double side polished n-type 4-inch (100) silicon wafers as the structural material. The bounding area was defined through the first lithography, followed by anisotropic silicon etching (about 4μm) to form shallow trenches. At the same time, the metal layer (avoid footing effect in DRIE, deep reactive ion etching) patterns were defined on 4-inch Pyrex 7740 glass wafers by lift-off of Cr/Au with the assistance of the second lithography. After silicon and glass wafers bounded by anodic bounding, the silicon layers were thinned to 70μm through KOH etching. The final lithography was designed to define the structure of the tester, which was released by DRIE with an aluminium (Al) mask. Figure 9 shows the scanning electron microscope (SEM) image of the tester structure.

We used ordinary MM600 probe station as the operation platform, as illustrated in Figure 10. To begin with, we zoomed to the embossment area near the end of transmission beam and moved the probe to the embossment at the direction in parallel with transmission beam. Then, we zoomed to scale and went on moving forward the probe slowly. Concentrating on the change in scale, finally, the scale suddenly returned to the original positon (film fractured), marked the farthest position of the scale for further calculation. After the test, we used the scanning electron microscope to measure the line width loss of the structures, which help the ANSYS precisely stimulate out the actual force applied to the specimen and best reveal the width of the specimen. After that, the tensile fracture strength can be calculated.

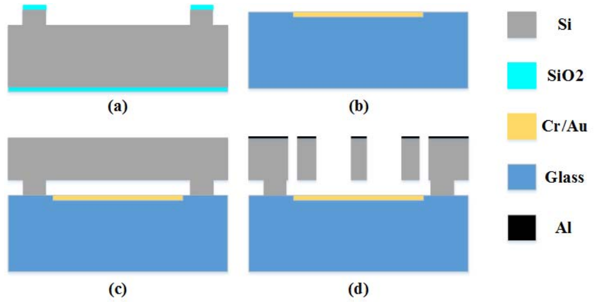

Figure 8: Fabrication process flow: (a) defining bonding area (b) forming metal layer (c) silicon-glass bonding (d) deep etching.

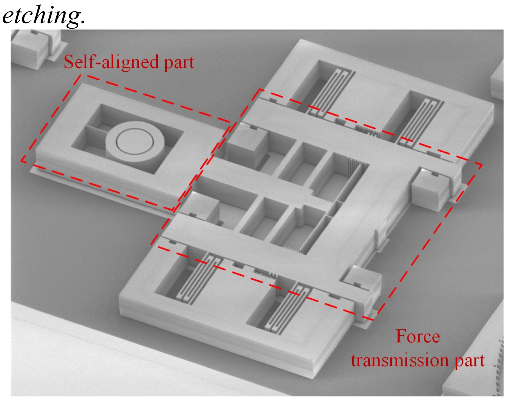

Figure 9: SEM photograph of the whole structure

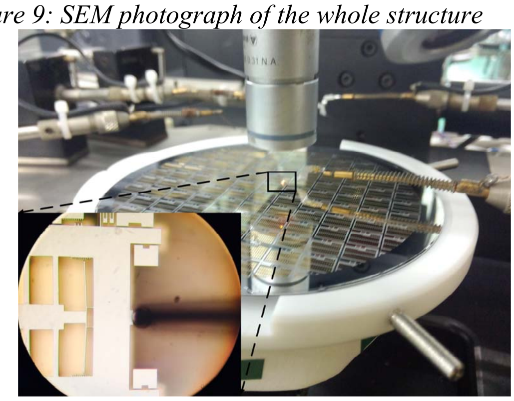

Figure 10: Images of measurement process.

RESULTS AND DISCUSSION

Figure 11a shows one of the fracture morphology, the film fractured totally with irregular notch and shred. In order to value the uniformity within a wafer, we separated specimens into 5 groups (at least 7 specimens each), as presented in Figure 11b. The regional statistics results are shown in Figure 11c and 11d. We can see that the tensile fracture strength of central part is obviously higher than that of other parts, attributing to the etching speed of the center is lower than surroundings, thus reduce the impact arose by over-etching and undercut.

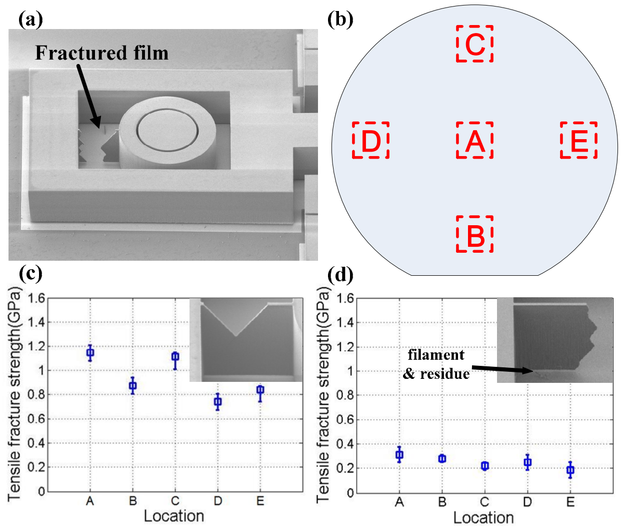

Figure 11: (a) Fracture morphology; (b) groups distribution in a wafer; statistical fracture strength: etched by (c) HRM; (d) ASE.

What's more, comparing the data of the two charts in Figure 11c and 11d, it is distinct that the tensile strength of the samples etched by STS HRM is significantly higher than STS ASE. That means the strength is highly process relevant. Further studying the etching results, the condition of etched surface under HRM is better than ASE indeed, as shown in Figure 11c and 11d. The etched surface of ASE is rough, accompanied by some vertical stripes, even some filament and residue. The surface condition of ASE etched surface is poor. On the contrary, the HRM etched surface is relatively smooth. In general, the hurt of surface introduced by ASE etching process resulted in the strength weakening of the structure. In our experiment, it is easy to find out the reason and make contrast, but in some similar images or more complex conditions, we need the tester to facilitate the analysis.

The tensile fracture strength measured was 0.13 to 1.2GPa, which is much lower than that of material growth formed films [12]. Because films are almost covered by DRIE etched surface, etching damage have a profound effect on fracture strength, and such thin films make themselves further weakened by damage.

CONCLUSION

In this paper, we have successfully designed and manufactured a single-crystal silicon on-chip self-aligned tensile fracture tester to study the strength regard to process condition, with the advantages of aligning automatically, using at ease, universality and suffice actuating force. Tensile fracture strength of the etched Si film in our tests is between 0.13 to 1.2GPa. By comparing between process and position, we come to a conclusion that surface quality of HRM etching is better than ASE and etching speed of central wafer is slower than other parts. The proposed tester can be used to evaluate the quality of process and reliability of tensile fracture strength.

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