DEGRADATION OF MECHANICAL STRENGTH AT SI/SIO_2 INTERFACE ON SOI WAFERS UNDER CYCLIC LOADING

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ABSTRACT

Fatigue tests of silicon stepped cantilevers fabricated from silicon on insulator (SOI) wafers were conducted under the bending mode to evaluate the effect of cyclic loading on fractures occurring in silicon and Si/SiO_2 interfaces. The specimen in the quasi-static mode fractured at the stress concentration site on the silicon specimens. However, during the fatigue tests the cantilever broke after 10^4 cycles with stress amplitude of nearly half of the bending strength at the fixed end comprising the Si/SiO_2 interface. The results demonstrated that the cyclic stress durability in the Si/SiO_2 interface is significantly lower than that of the silicon body.

1. INTRODUCTION

The use of silicon on insulator (SOI) wafers is expanding the possibilities for miniaturization, improved performance, and increased accuracy of microelectromechanical systems (MEMS) devices. Silicon dioxide (SiO_2) used under the top silicon layer performs a number of functions. In the fabrication process, it serves as an etch stop and as a sacrificial layer. In the device itself, it serves as an insulating layer and as a supporting plate of the floating structure from the substrate. In the fabrication process, the use of SiO_2 makes it easy to adopt conventional etching processes such as surface micromachining and bulk micromachining to the top silicon layer and the substrate, respectively. Because of the advantages they provide, MEMS devices on SOI wafers are being manufactured in increasing quantities despite their higher cost compared to that of conventional bulk silicon wafers [1]. For example, the microactuators in SOI-MEMS devices have a high-aspect ratio structure that achieves high driving force with low consumption energy [2]. AFM probes are typical examples of SOI-MEMS devices in which the cantilever or the tip is fabricated on the SOI layer [3, 4].

In a microstructure consisted of two or more layers, the interface is one of the most destructive site that includes the physical misalignment of each layer and has a high probability of stress concentration. It is well known that the silica is subjected to stress corrosion and that this causes delayed failures [5]. This phenomenon is strongly correlated to failures that occur in SiO_2 sandwiched between single crystal silicon layers in SOI wafers. In commercial devices, a great concern is their reliability and durability for a long term. To date, however, few studies have been performed on the occurrence of mechanical failures in SiO_2 or in Si/SiO_2 interfaces [6, 7].

A subject of major concern is how the forming of an SiO_2 layer over a silicon structure affects device durability. This paper reports experimental results of bending tests carried out under quasi-static and cyclic loading mode by using a newly developed testing method.

2. EXPERIMENTAL

2.1 Specimen

Figure 1 shows the schematic illustration of the test specimen used in this study. The cantilever beam specimen having a step change in width is 90 μm and 30 μm width for the larger and smaller parts, respectively. The thickness is 10 μm throughout the specimen. The external load is applied at the point 50 μm apart from the stepped site in width. When the length of the wider part of the stepped cantilever is enough shorter than that of smaller width part, the stress concentration occurs at the corner of the step change. The step corner was designed to be 5 μm in length from the fixed end. The silicon cantilever specimen is fabricated in the SOI layer and fixed to the SiO_2 intermediate layer at the end by chemical bonds.

2.2 Bending Test

Figure 2 shows our newly developed bending test device for micro-sized cyclic tests. The test device has a mass structure supported on a rigid frame by four parallel beams, shown in Figure 2 (a). The cantilever specimens were fixed to the frame towards the mass that has banks underlying the free ends of the cantilever. The bending test was carried out by driving the mass perpendicular to the device as shown in Figure 2 (b). When the frame and mass moved relatively up and down in the vertical direction, respectively, the cantilever specimen was pushed up by the

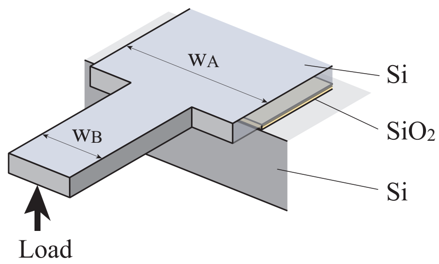
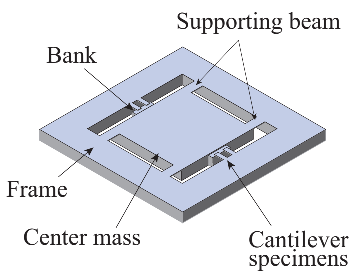
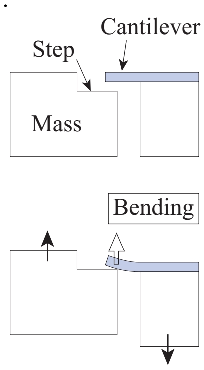


Figure 1: Schematic illustration of stepped cantilever specimen fabricated from SOI wafer.



(a) Bending test device.



(b) Experimental procedure.

Figure 2: Bending test device for quasi-static and cyclic loading test.

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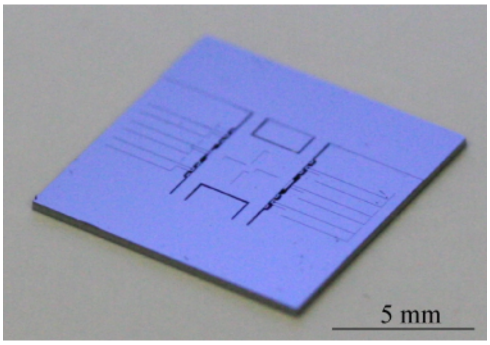
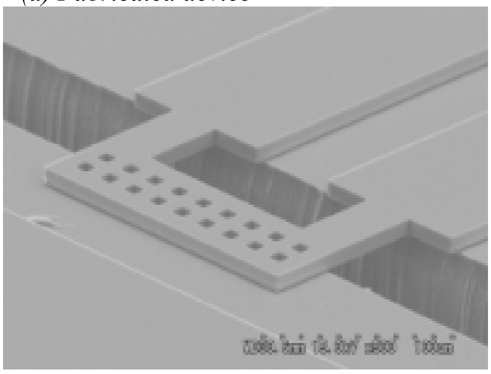


(a) Fabricated device



(b) SEM photograph of specimen.

Figure 3: SEM photographs of fabricated testing device.

bank.

The testing device was fabricated from SOI wafer by using MEMS processes. A (100) CZ-silicon layer with a thickness of 10 µm are bonded on the (100) silicon substrate through the thermally oxidized SiO_2 layer with a thickness of 1 µm. The top silicon layer is etched by deep reactive ion etching (DRIE) to form the cantilever specimen and parallel beams. The longitudinal direction of the cantilever is aligned to <110>. The 350 µm-thick silicon substrate is etched away from the back side by DRIE to attain the SiO_2 intermediate layer. The specimen is released to make it freestanding by immersing it in a buffered hydrofluoric acid (BHF) solution to etch the SiO_2 layer. Figure 3 shows the fabricated testing device (Figure 3 (a)) having four cantilever specimens (Figure 3 (b)) in total.

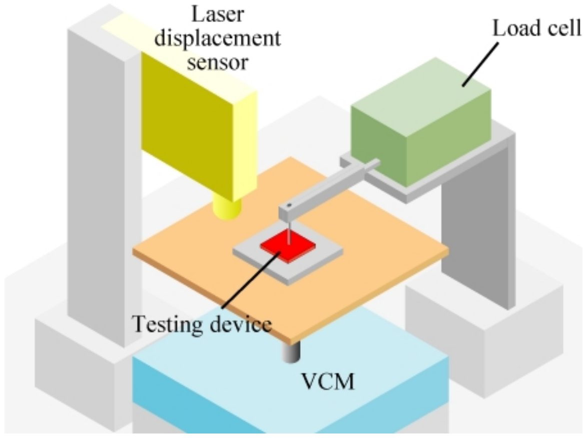
2.3 Measurement System

Figure 4 shows a schematic illustration and photograph of the measurement system. By appropriate control, a monotonic and cyclic loads were applied to the specimen by using a voice coil motor (VCM) connected to the stage. The displacement of the stage was detected and recorded by using a laser displacement sensor. The applied load was measured by a load cell connecting a quartz rod that vertically restrains the center mass of the testing device. The fatigue tests were carried out under a load-controlled mode with a sinusoidal waveform applied at a frequency of 200 Hz. All of the tests were conducted at room temperature within negligible change.

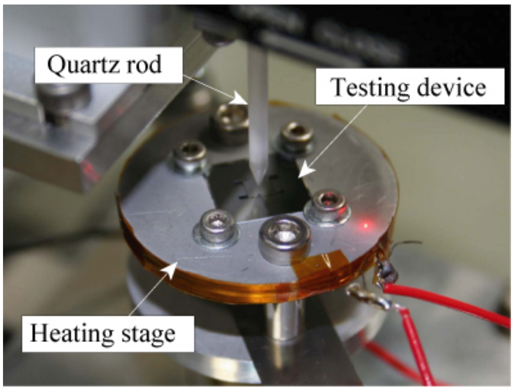
3. RESULTS AND DISCUSSION

3.1 Quasi-static Bending Test

Figure 5 shows the measured displacement and load during a quasi-static bending test. The temporal trajectories of displacement and load are almost same at first. It is noted that the elastic deformation is recognized in this field that the load linearly increases against the displacement. The load increases in proportion to time until one specimen of four fractured at the load drop point in Figure 5, while the displacement monotonically increases during the test. After the first fracture of the specimen was confirmed, the VCM was stopped even if another three specimens were not broken because the lack of the specimen produced the loss of balance in vertical drive of the frame.



(a) Schematic of measurement system.



(b) Photograph of magnified view of testing device.

Figure 4: Measurement system for quasi-static and fatigue test.

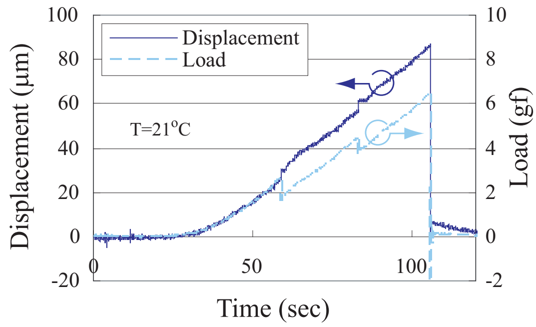
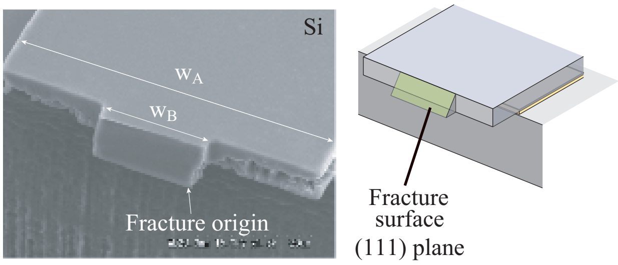


Figure 5: Measured displacement and load in quasi-static bending test.

Fracture morphology of the specimen after the bending test was observed by SEM, all specimens failed in brittle manner. A SEM photograph of the fractured specimen is shown in Figure 6. For all specimens the fracture surface appeared at the stepped area in cantilever and inclined with respect to the longitudinal axis. Based on



(a) SEM photograph of fracture specimen. *(b) Schematic of fractured surface.*

Figure 6: Fractured specimen after quasi-static bending test.

this figure, it can be said that fracture occurred from the edge and propagate across the width on (111) cleavage plane, as shown in Figure 6 (b). The stress was concentrated on the lower half of cantilever where damaged area was formed due to the DRIE process. Fracture originated at the site with a massive roughness on it.

The bending strength in this study is simply defined as the normal stress at the step, instead of troublesome analysis for stepped cantilever with inflection point. The bending strength was estimated from the amount of the drop of the load at fracture shown in Figure 5 by simply applying the formula in material mechanics to calculate the bending stress in the longitudinal direction of the cantilever.

$$\sigma = \frac{Pl}{I}\frac{h}{2},$$

where σ is maximum normal bending stress, P is applied load, l, h, I is length, thickness, moment of inertia of the specimen, respectively. The measured bending strength was 3.20±0.48 GPa.

3.2 Fatigue Test

Fatigue tests were conducted under the cyclic load in fatigue tests at a frequency of 200 Hz with various maximum stress levels. The stress ratio R was 0.1. The measured loads and displacements before and after the fracture are shown in Figure 7. The fracture of the specimen was confirmed from the change of the amplitude of the load, while the amplitude of the displacement didn't change. The change of the load amplitude enables us to evaluate the fatigue life of the specimen. The specimens fractured after over 10^4 cycles and one of them did not break even after 10^7 cycles. The relation between the bending stress and fatigue cycle for some samples is shown in Figure 8. As the stress level decreased, the fatigue life tends to increase although there is a wide range of experimental data. The specimens broke in fatigue tests at a stress around half that of the static strength. In this graph, the stress value means the amplitude of the stress at the stepped corner, instead of the bending strength calculated at the fracture point for convenience.

Fractured specimen subjected to cyclic bending load was observed under a SEM to investigate the fracture behavior. All of the specimens failed in brittle manner, same as the quasi-static test. Figure 9 shows SEM photograph of the typical fractured specimen. The fracture surface shows inclined plane that consists of (111) and

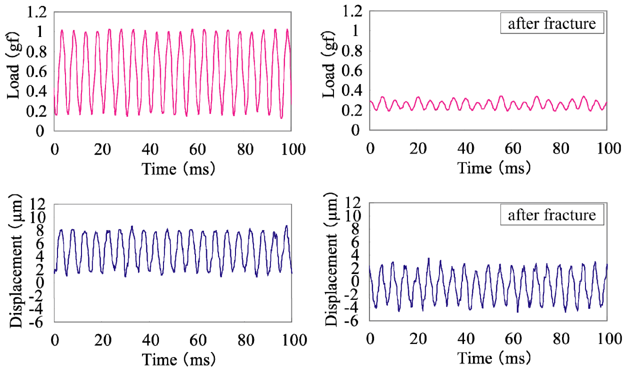


Figure 7: Obtained data of load and displacement during fatigue test.

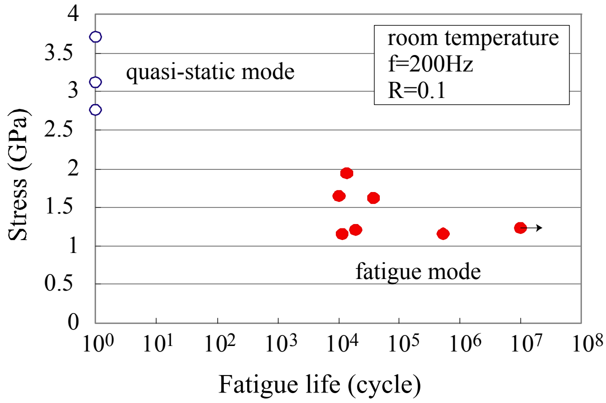
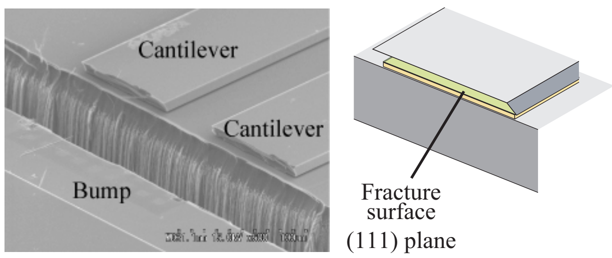
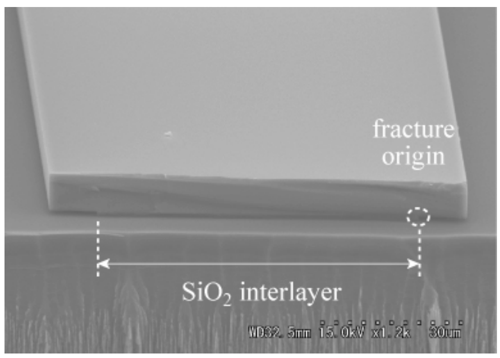


Figure 8: Relationship between fatigue life and applied maximum stress.



(a) SEM photograph of fracture specimen. *(b) Schematic of fatigue-fractured specimen.*



(c)Magnified view of fracture surface.

Figure 9: Fractured specimen after fatigue test.

crack initiation site. Unlike the specimen under the quasi-static load, in the case of fatigue tests fracture occurred at the fixed end on the edge of the interface of Si/SiO_2. The bending stress generated at the edge of the interface is intrinsically smaller than that at stepped area. It is clear that the crack initiated from the end of the interface of Si/SiO_2 by breaking a Si-O bond at the lower stress level in cyclic test. The initiated crack propagated to the silicon inside and formed the (111) plane.

As for bi-material, the interface between two different solid is weak for load applied from various directions. The vertical load applied to the thin film might cause delamination of the film from the substrate. The structure of the specimen fabricated on SOI wafer used in this study is similar to the experimental setup for delamination test of bi-layer material [8]. However, the crack propagated in silicon body instead of the interface of Si/SiO_2 and SiO_2layer. The crack initiation due to cyclic load is more likely to occur at the edge of the Si/SiO_2 interface, while the silicon is weak to propagation of the existing crack.

4. CONCLUSION

We estimated the strengths of silicon cantilevers fabricated from SOI wafers under quasi-static and cyclic loading conditions The cantilever specimens were designed to have two steps in width to enable the local stress to be concentrated in the silicon layer. In quasi-static bending tests, the specimens fractured at the stress concentration point with an average strength of 3.20±0.48 GPa. In fatigue tests with cyclic loading, the fracture origin shifted to the fixed end where the edge of the intersection of Si/SiO_2 and the applied stress amplitude was nearly half of the bending strength. The difference in the fractures in the static and fatigue modes indicates that the cyclic loading significantly affected Si/SiO2 interfaces in terms of the generation and propagation of cracks.

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