Evaluation of Size and Deformation Mode Dependencies on the Mechanical Strength of Single-Crystal Silicon Micro Beam Specimen

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Micro electro mechanical systems (MEMS) devices are derivative of semiconductor industry, so that single-crystal silicon (SCS) is being commonly used as their structural material. One of the features in MEMS is to have deformable mechanical components made of SCS. The deformation mode is typically out-of-plane bending or twisting. The purpose of this work is to examine the fracture mechanism of DRIE-fabricated SCS beams subjected to torsion/bending deformation. We have designed and developed a new materials test technique, which enables us to apply pure torsion, torsion-bending combination, and doubly-clamped bending deformations to SCS micro-beams, evaluated the influence that size and deformation mode exerted on strength of single-crystal silicon micro beam. No deformation mode dependency was observed, whereas size effect was clearly found.

1. Introduction
Microelectromechanical systems (MEMS) devices are derivative of semiconductor industry, so that single-crystal silicon (SCS) is being commonly used as their structural material [1]. One of the features in MEMS is to have deformable mechanical components made of SCS. The deformation mode is typically out-of-plane bending or twisting. Since the SCS components are commonly fabricated with deep reactive ion etching (DRIE), their sidewall consists of submicron-size scallops that become stress riser. On the other hand, the top and bottom surface are finely polished surface, so that apparent defects or cracks do not exist. Those different surface morphologies may provide different fracture mechanism by applying bending or twisting to the SCS structure. Knowledge about fracture mechanism of such the microstructure with different surface finishing processes is useful for the reliability of MEMS.

The purpose of this work is to examine the fracture mechanism of DRIE-fabricated SCS beams subjected to torsion/bending deformation. We have designed and developed a new materials test technique, which enables us to apply pure torsion, torsion-bending combination, and doubly-clamped bending deformations to SCS micro-beams [2]. This paper focuses on investigating the influences of specimen size and deformation mode on fracture strength of SCS beams.

2. Experimental Procedure
Fig. 1 shows laboratory-made combined test equipment and its specimen. The equipment consists of a piezoelectric actuator, load cell, loading pin, specimen holder, and CCD camera. In torsion and bending test, rotation angle and deflection are measured with a CCD image analysis system. The specimen was designed based on the SEM image of SCS micro-mirror device. A SCS mirror is supported by two SCS micro-beams. Five-types of specimens were fabricated through the same DRIE recipe.

Fig. 2 illustrates the experimental setup for combined mechanical test. By changing the combination of supporting and loading points, the materials test under different- types of deformation mode can be performed. When the center of the mirror is supported or non-supported by cantilever- shape jig, pure torsion (Mode I) or torsion-bending combination (Mode II) deformation can be respectively applied to SCS micro-beams by pushing on the mirror other than supporting point. When the center is pushed without any supports, doubly-clamped beam bending (Mode III) deformation can be made.

3. Results and Discussions
Fig. 3 shows representative results of pure torsion, torsion-bending combination, and bending test. In Fig. 3 (a), linear force-angle relations were obtained regardless of size. At twisting angle between 20 to 30 deg, force abruptly drops to 0 N for each specimen. This indicates that brittle fracture happened. Torsion-bending combination test result shown in Fig. 3 (b) shows a trend similar to pure torsion test result. In Fig. 3 (c), force-deflection relations are non-linear because stretching effect was produced.

To estimate fracture strength as accurate as possible, empirical equations between fracture angle/deflection and stress were constructed using finite element analyses (FEAs). The stress in the equations indicates the maximum stress produced in each specimen model, assuming that specimens had ideal flat surface in the entire area. As shown in Fig. 4, the maximum stress was produced at the side wall in pure torsion and torsion-bending combination modes, whereas that was produced at the top surface nearby fixed end in bending mode. Fig. 5 depicts Weibull plot of fracture strength. The open and closed plots indicate strength data of small (Specimen A, B, C, D) and large (Specimen E) specimens, respectively. The Weibull plot indicates that there are specimen size and deformation...
mode dependences on the strength. Bending strength data seem to be larger than torsion strength data.

Actually, all the specimens, however, have scalloping side walls. So, stress concentration factors originating from scallops were calculated using FEA, and then fracture strength was estimated again. Fig. 6 shows revised Weibull plot in consideration of stress concentration in scallops. The difference in strength among deformation modes was definitely decreased by considering stress concentration in scallops. The difference in strength among specimens in each size was not obviously changed even when deformation mode changed though a little difference was found. In Mode III, the value of shape parameter in both small and large specimens was almost the same because there is no difference in surface morphology where the maximum stress occurred between small and large specimens.

4. Conclusions

We have developed torsion-bending combination test technique to examine the effects of specimen size and deformation mode on the strength of DRIE-produced SCS beams. No deformation mode dependency was observed, whereas size effect was clearly found.

References
