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Resonance Fatigue Testing of Cantilever Specimens Prepared from Thin Films

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ABSTRACT

Fatigue properties of thin film materials are extremely important to design durable and reliable microelectromechanical systems (MEMS) devices. However, it is rather difficult to apply conventional fatigue testing method of bulk materials to thin films. Therefore, a fatigue testing method fitted to thin film materials is required. In this investigation, we have developed a fatigue testing method that uses a resonance of cantilever type specimen prepared from thin films. Cantilever beam specimens with dimensions of 1(W) x 3(L) x 0.01(t) mm^3 were prepared from Ni-P amorphous alloy thin films and gold foils. In addition, cantilever beam specimens with dimension of 3(L) x 0.3(W) x 0.005(t) mm^3 were also prepared from single crystalline silicon thin films. These specimens were fixed to a holder that is connected to an audio speaker used as an actuator, and were resonated in bending mode. In order to check the validity of this testing method, Young's moduli of these specimens were measured from resonant frequencies. The average Young's modulus of Ni-P was 108 GPa and that of gold foil specimen was 63 GPa, and these values were comparable to those measured by other techniques. This indicates that the resonance occurred theoretically-predicted manner and this method is valid for measuring the fatigue properties of thin films. Resonant fatigue tests were carried out for these specimens by changing amplitude range of resonance, and S-N curves were successfully obtained.

INTRODUCTION

The evaluation of mechanical properties including elastic modulus, tensile strength, fracture toughness and fatigue life is necessary to design microelectromechanical systems (MEMS) devices. In particular, fatigue properties of thin film materials are important to design durable and reliable MEMS devices. Fatigue tests of thin film materials have been carried out using proportionally down sized dog-born type specimen or cantilever bending specimen just same as ordinary-sized bulk materials [1]. In these testing methods, cyclic loading frequency is usually up to 10Hz, and it takes much time to obtain fatigue strength after 10^9~10^{10} cycles, which are required for designing MEMS devices. Therefore, On-chip resonating fatigue testing methods at a frequency of several tens of kHz have been developed to reduce testing time at high frequency fatigue region [3-6]. In this testing structure, however, a comb-driven actuator and a specimen are prepared concurrently by photo lithography process. This indicates that this technique can be only applicable for thin films on substrates. For a cantilever specimen, if the length is much larger than the thickness, bending resonance will easily occur by applying vibration. During the resonance vibration, cyclic stress is applied at the fixed end of the cantilever. This indicates that fatigue tests can be performed by bending resonance. In this investigation, fatigue testing method of thin films by bending resonance has been developed and fatigue tests of Ni-P amorphous alloy thin films, gold foils and single crystalline silicon films have been performed.

EXPERIMENT

Materials and Test Samples

The materials used were Ni-P amorphous alloy films, gold foils and single crystalline silicon (SCS) thin films. Ni-11.5mass% P amorphous alloy film was produced by electroless plating onto an Al-4.5mass% Mg substrate. This produced an amorphous layer of 12 μm thickness on a 0.79mm thick substrate [1-2]. The specimen was cut from the Ni-P/Al-Mg in to a rectangular parallelepiped shape, prior to removal of the substrate by dissolution in a NaOH aqueous solution. The length (L), width (W) and thickness (t) of specimens were ≈10mm, 1.5mm and 12μm, respectively as show in Fig. 1(a). Gold foil specimens were prepared from cold-rolled gold tape (99.99% purity) with a width of 1.4mm and a thickness of 10μm. This tape was cut to 10mm in length as shown in Fig. 1(b). The average grain size of the gold foil was 0.73 μm. SCS specimens were fabricated from the top layer of silicon on insulator (SOI) wafers using a photo lithography process. The cantilever beams are 3mm in length, 300μm in width and 5μm in thickness. In addition, a weight is put at the free-end of the specimen as shown in Fig. 2. For SCS specimens, notches were introduced into the center (“A” type specimen) and both sides (“B” type specimen) of the specimen by focused ion beam (FIB) machining as shown in Figs. 3(a) and (b). The notch length of “A” and “B” type specimens were 100μm and 75μm, respectively, which were located 50μm from the fixed end of the specimen.

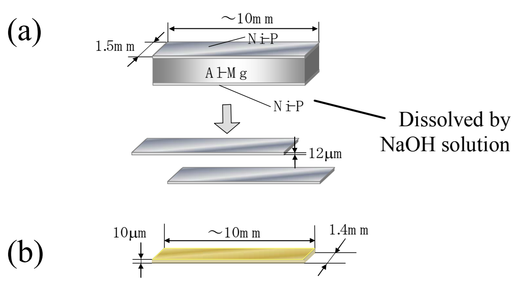

Figure 1. Geometries of (a) Ni-P amorphous alloy thin film specimen and (b) gold foil specimen.

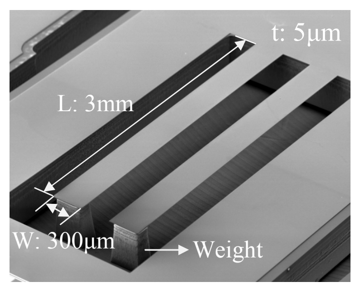

Figure 2. Scanning electron micrograph of single crystalline silicon (SCS) cantilever beam specimen.

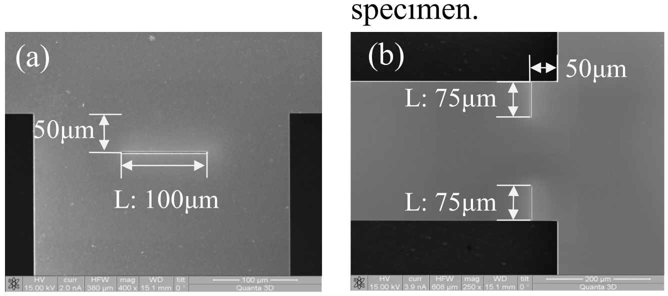

Figure 3. Scanning electron micrographs of SCS specimens. (a) Center notched specimen and (b) double-sided notched specimen.

Fatigue Testing Machine

Figure 4 shows a block diagram of fatigue testing machine. The testing machine consists of an audio speaker (FORSTER FF-77EG 8Ω/5W), a laser displacement meter (KEYENCE LK-G30), a function generator (NF WF1973) and an audio amplifier. An audio speaker is used as an actuator which causes the cantilever type specimen to vibrate. The cantilever specimen is set in a specimen holder and the holder is placed on the top of speaker corn as shown in Fig. 4. A sine wave generated by function generator was used as a driving signal of speaker. The output signal of function generator was amplified by the audio amplifier. Displacement amplitude of specimen was measured by the laser displacement meter. The resonance of specimens was monitored by a CCD camera that was set near the specimen holder. Fatigue tests were carried out at room temperature in air, and the humidity was kept to be 50~60% RH during the tests.

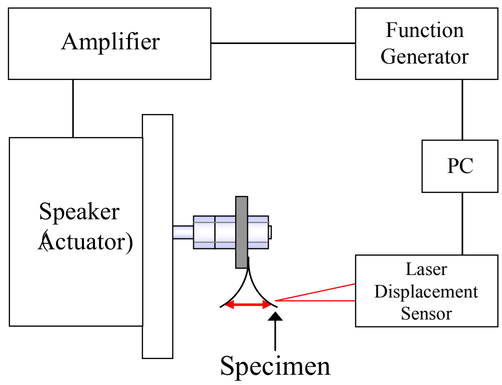

Figure 4. Block diagram of fatigue testing machine

RESULTS AND DISCUSSION

Resonant Behavior

Prior to fatigue testing, the resonant condition of specimen was examined. Figure 5 shows the relation between displacement amplitude range and frequency for Ni-P amorphous alloy thin film specimen. The resonance of specimen is observed at a frequency of 180 Hz. This type of resonance was also confirmed for gold foil and SCS specimen, and the resonant frequency of gold foil specimen was 163 Hz and that of SCS specimen was 175 Hz, respectively. In order to check the validity of this testing method, Young's moduli of the specimens were calculated from the resonant frequencies. The fundamental resonance frequency of a cantilever beam is given by

$$f_c = 0.16154 \frac{h}{L^2} \sqrt{\frac{E_e}{\rho}} \quad (1)$$

where, L and h are the length and thickness of the cantilever beam, respectively, E_e is the effective Young's modulus, and ρ is the density of the material. The effective modulus, E_e, is replaced by $E/(1-v^2)$, where v is Poisson's ratio and E is the Young's modulus, if the width of the beam, b, is relatively larger compared to its thickness, h ($b \geq 5h$) [8]. From resonant frequency, the average for Young's modulus for Ni-P amorphous alloy thin films specimen was calculated to be 108.1 GPa, which is consistent with that of the Ni-P amorphous alloy thin film measured by other technique (110 GPa) [9]. The average Young's modulus of gold foil was 62.8 GPa, which is also consistent with that of polycrystalline gold (68.4 GPa) [8]. The Young's moduli obtained were slightly lower than those having been reported values. This is due to the influence of air dumping as the measurements were made in air. These results show that the resonance of cantilever beam occurred theoretically and this technique can be used as fatigue test of thin film specimen.

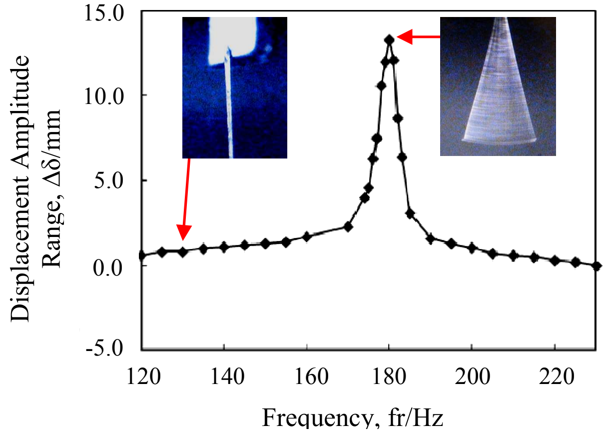

Figure 5. The relation between displacement amplitude range and frequency for Ni-P amorphous alloy thin film specimen.

Stress-Life Curves

Fatigue tests were performed by changing displacement amplitude range. The maximum stress during bending resonance was calculated by equation (2) [7].

$$\sigma_{max} = \frac{2h\delta E}{l^2} \quad (2)$$

where, σ_{max}, l, h, δ and E are maximum bending stress, length, thickness, maximum displacement and Young's modulus, respectively. Figure 6 shows the S-N plots for Ni-P amorphous alloy thin films. As the maximum stress over the fatigue cycle was lower compared to that of static strength of Ni-P amorphous alloy, only few specimens were fatigue fractured and fatigue strength was not able to be determined. Figure 7 shows the S-N plots for gold foils. The fatigue strength was 170 MPa after 10^6 cycles. Figure 8 shows S-N plots for SCS specimens. The vertical axis indicates a ratio of the applied stress to the average static strength in Fig. 8. The fatigue lives are scattered, and similar behavior is often observed for fatigue of silicon films [4-6]. The interesting feature of the plot is that the fatigue does not occur in the range between 10^4 and 10^6 cycles under the stress conditions tested in this investigation.

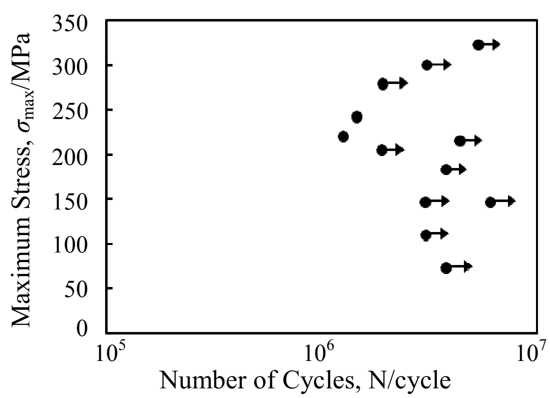

Figure 6. S-N plots for Ni-P amorphous alloy thin films.

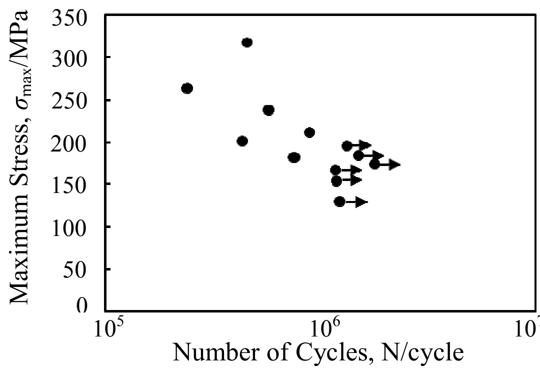

Figure 7. S-N plots for Gold foils.

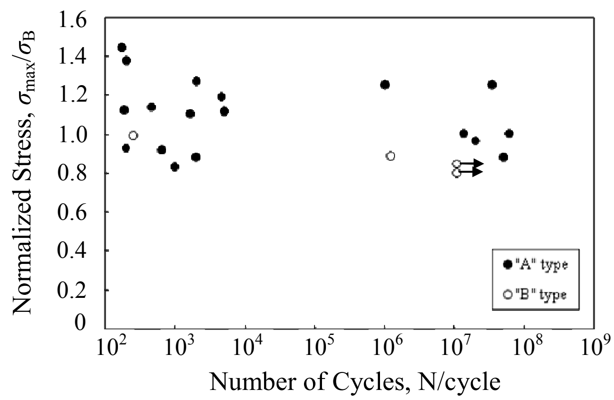

Figure 8. S-N plots for Single crystal silicon thin films.

Fracture surface

Figure 9 shows a scanning electron micrograph of the Ni-P amorphous alloy thin film specimen after a fatigue test. Striations were clearly observed on the fracture surface about 0.5μm intervals. This type of striation is also observed on fatigue surface of Ni-P thin film [2]. This indicates that the specimen was fractured by cyclic loading. In the gold foil specimen, definite asperities are observed near the crack surface, and small grains are also seen in the deformation area (Fig. 10).The size of grain is approximately 0.73μm and this size is comparable to that of grain size of this material. This suggests that the crack has propagated along grain boundary. Figure 12 shows a fracture surface of the SCS specimen. The fracture surface is very flat and shows a cleavage like feature, but some step-like regions are also found at the specimen surface.

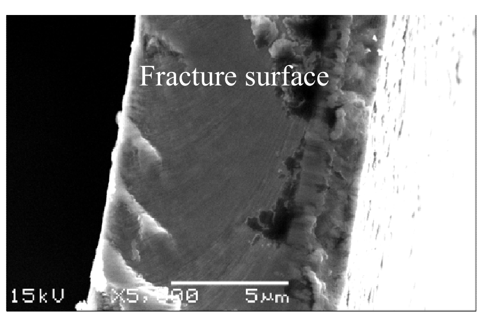

Figure 9. Scanning electron micrograph of fracture surface of Ni-P thin film after fatigue fracture.

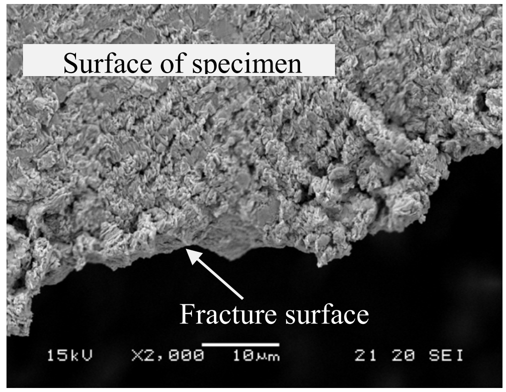

Figure 10. Scanning electron micrograph of fracture surface of Gold foil after fatigue fracture.

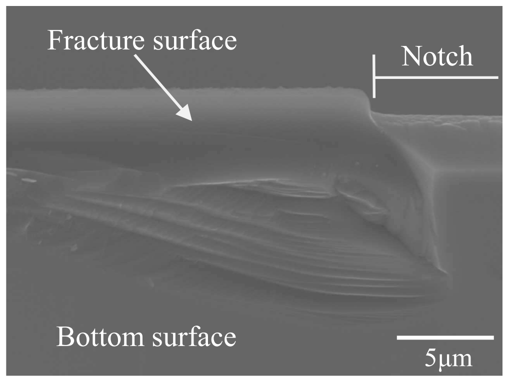

Figure 11. Scanning electron micrograph of fracture surface of SCS after fatigue fracture.

CONCLUSIONS

Bending resonance fatigue tests have been performed for micro sized cantilever beam type specimens prepared from Ni-P amorphous alloy thin films, gold foils and single crystalline silicon thin films. Resonant fatigue tests were carried out successfully for these specimens, and S-N curves were obtained. This testing method is useful for measuring fatigue life of thin film materials.

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