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High-frequency fatigue test of metallic thin films using PVDF microactuator

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Abstract: Novel high-frequency bending fatigue test method for sputtered metallic thin films using PVDF microactuator is proposed. Thin film titanium specimen as an example and a PVDF piezoelectric microactuator are fabricated. The specimen is stamped on this actuator and the actuator is vibrated at its resonance frequency until the specimen fails by fatigue. The stress in the specimen is calculated from vibration amplitude. By using the proposed method, the stress-fatigue life cycle (S-N) curve of the thin film titanium is obtained over 50 times faster than conventional method.

Keywords: fatigue test, thin film, S-N curve, resonance, PVDF, titanium

Classification: Micro- or nano-electromechanical systems

References

[1] T. Tsuchiya, O. Tabata, J. Sakata, and Y. Taga, "Specimen size effect on tensile strength of surface-Micromachined polycrystalline silicon thin films," *J. Microelectromechanical Systems*, vol. 7, no. 1, pp. 106–113, March 1998.

[2] T. Ando, M. Shikada, and K. Sato, "Tensile-mode fatigue testing of silicon films as structural materials for MEMS," *Sensors and Actuators A*, vol. 93, pp. 70–75, Aug. 2001.

[3] J.-S. Bae, C.-S. Oh, and K.-S. Park, "Development of a high cycle fatigue testing system and its application to thin aluminum film," *Engineering Fracture mechanics*, vol. 75, pp. 4958–4964, July 2008.

[4] J.-H. Park, M. S. Myung, and Y.-J. Kim, "Tensile and high cycle fatigue test of Al-3% Ti thin films," *Sensors and Actuators*, vol. 147, pp. 561–569, June 2008.

[5] J.-H. Park, Y.-B. Chun, Y.-J. Kim, Y.-H. Huh, and D.-J. Kang, "Tensile and high cycle fatigue tests of NiCo thin films," *Precedia Engineering*, vol. 10, pp. 1303–1308, June 2011.

[6] C. L. Muhlstein, S. B. Brown, and R. O. Ritchie, "High-cycle fatigue of single crystal silicon thin films," *J. Microelectromechanical Systems*, vol. 10, pp. 593–600, Dec. 2001.

[7] T. Ikehara and T. Tsuchiya, "High-cycle fatigue test of micromachined single crystal silicon measured using a parallel fatigue test system," *IEICE Electron. Express*, vol. 4, pp. 288–293, May 2007.

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[8] H. Kahn, R. Ballarini, R. L. Muller, and A. H. Heuer, "Electrostatically actuated failure of microfabricated polysilicon fracture mechanics specimens," *Proc. Royal Society of London 455*, pp. 3807–3823, Oct. 1999.
[9] H. Kapels, R. Aigner, and J. Binder, "Fracture strength and fatigue of polysilicon determined by a novel thermal actuator," *IEEE Trans. Electron Devices*, vol. 47, pp. 1522–1528, July 2000.
[10] T. Tsuchiya, M. Hirata, and N. Chiba, "Young's modulus, fracture strain, and tensile strength of sputtered titanium thin films," *Thin Solid Films*, vol. 484, pp. 245–250, April 2005.

1 Introduction

The fatigue strength of sputtered thin films is an important parameter in design of microelectromechanical systems (MEMS). The fatigue strength depends on the dimension and the processing method of the specimen and the fatigue strength based on fatigue test on bulk materials cannot be relied on for design of MEMS. Applying conventional fatigue test of macro-scale specimens to thin film microspecimens is very challenging. First, because alignment, fixing and gripping of delicate microspecimens in force applying device, or the actuator, is very difficult. Second, the loading frequency of the conventional methods is usually not higher than 100 Hz. This means that it takes many days to accomplish fatigue test under millions of cycles.

To overcome those problems, many researchers suggested novel high frequency fatigue test methods applicable to fatigue test on thin film microspecimens. These methods can be classified into two groups. In the first group, microspecimen is fabricated as a part of a larger structure and external actuator is used to apply force on the specimen similar to the conventional methods. Methods in this group have been developed either for silicon and polysilicon [1, 2] or metals [3, 4, 5]. The other group is the on-chip fatigue test method [6, 7, 8, 9]. In this method microspecimen is fabricated with a microactuator on a chip so this group of methods are free from human error involved in fixing and alignment of microspecimen to the actuator or the test device. Furthermore, it is possible to fabricate the microactuator which works at high frequencies and develop a fast fatigue test method. However, this group of methods is currently developed only for silicon and polysilicon.

In the present study, a high-frequency bending fatigue test method on sputtered metallic thin films is suggested. Besides the high-frequency of loading, this method has the advantage that it can be applied to many metals with small modification of the fabrication process. The fatigue test of titanium (Ti) thin films is presented as an example. Ti thin films sometimes show brittle fracture [10]. Thus, it is difficult to apply conventional fatigue test method to them.

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2 Principle of proposed method

A schematic drawing of test setup in cutaway view is shown in Fig. 1.a. The test setup consists of a 4 mm × 6 mm rectangular diaphragm type PolyVinylidene Fluoride (PVDF) actuator and a Ti specimen with anchors made from KMPR photoresist (Microchem Co.). The vibrating part of this actuator has both top and bottom electrodes so the actuator can vibrate when electric field is applied across its thickness. The specimen is fixed on the actuator by a thin layer of epoxy. When the actuator is driven by harmonic sinusoidal signal at the first resonance frequency of actuator, the diaphragm vibrates in a bending motion which is shown in Fig. 1.b.

As the diaphragm bends up and down, the specimen experiences a cyclic loading. Due to this loading, the stress in the middle part of the specimen increases until the specimen is broken under fatigue. The vibration of the actuator depends on its driving voltage. The vertical vibration amplitude of the specimen at different locations is measured during the test by using

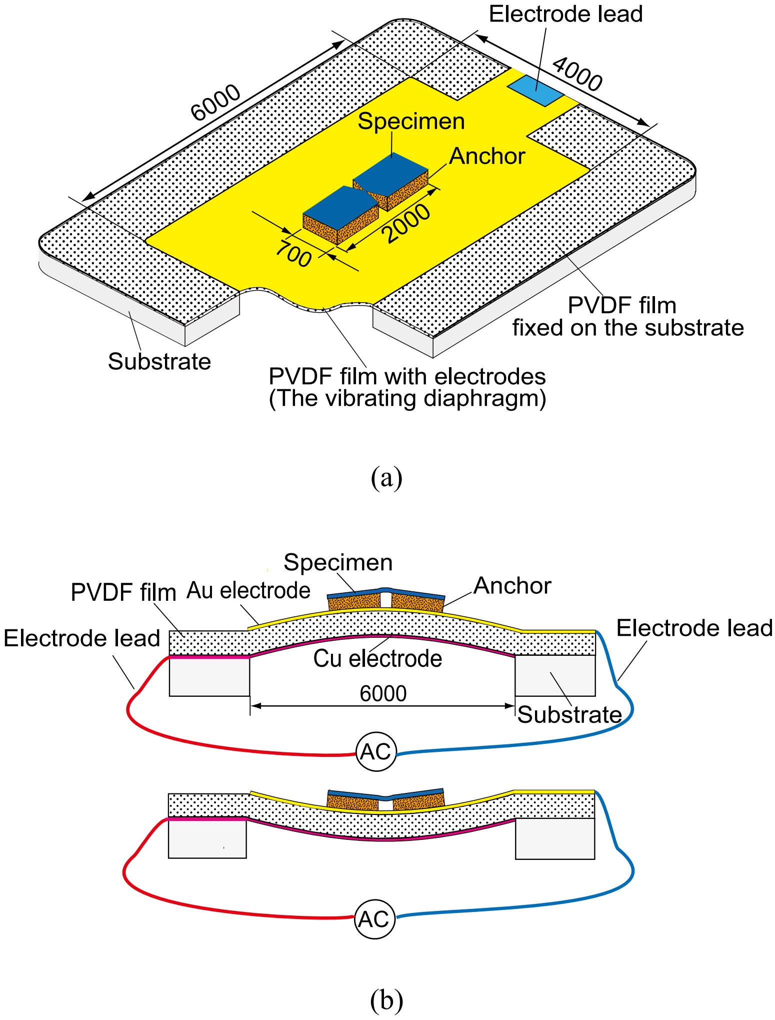

Fig. 1. (a) Three dimensional view of specimen on the PVDF actuator, (b) Side view of bending motion of the actuator and specimen. The dimensions are in micrometer

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a laser Doppler vibrometer and applied in a FEM model of the specimen. The stress in the specimen is calculated. By knowing the number of cycles after which the specimen breaks, it is possible to use this data to plot the stress-fatigue life cycles (S-N curve) of the specimen.

3 Experiment

3.1 Fabrication and testing of actuator

For the fabrication of PVDF actuator, 28 μm thick PVDF film is used. This film is covered with copper (Cu) electrodes on both sides. The top electrodes of PVDF film are removed in acid and gold (Au) is sputtered on PVDF film as top electrodes. This step is necessary because the actuator will be in contact with chromium (Cr) etchant during the stamping process of specimen on it therefore the top electrodes should be made from a metal that does not react with Cr etchant. Then the PVDF film is adhered on a ceramic substrate with a rectangular window of 6 mm × 4 mm and electrode leads are connected to the top and bottom electrodes of PVDF. Next vibration characteristic of actuator is investigated. The actuator is vibrated at a frequency range at different voltages and the vibration amplitude at the center of actuator is recorded to find the first resonance frequency. This is shown in Fig. 2.a. The peak in this graph indicates the first resonance frequency. The vertical axis is the vibration amplitude at the center of the diaphragm. The bending motion of diaphragm when the actuator is vibrated at the first resonance frequency is shown in Fig. 2.b. This figure shows the vibration amplitude along the 6 mm line which is parallel to the edges of the diaphragm and passes through the center of diaphragm.

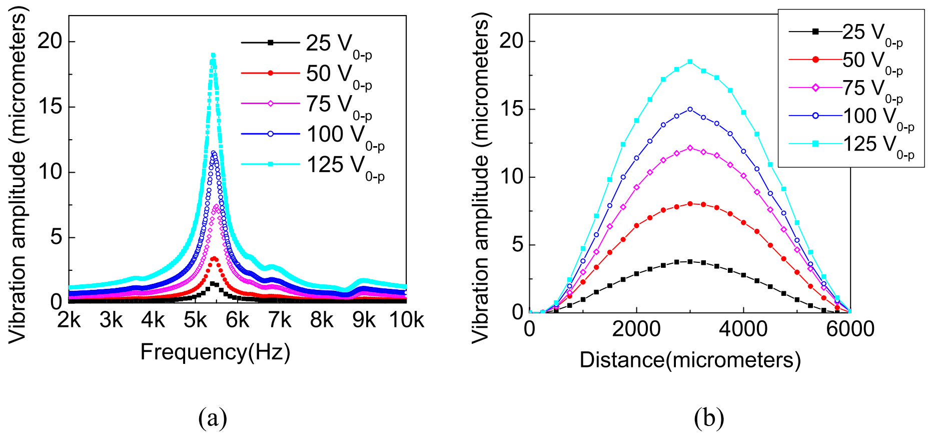

Fig. 2. (a) Vibration amplitude of specimen at the center of the diaphragm. (b) Vibration amplitude along the 6 mm line crossing the center of the diaphragm

3.2 Fabrication and stamping of specimen

For the fabrication of specimen first a sacrificial layer of 1 μm of Cu and 100 nm of Cr are sputtered on a glass substrate. Then 1.5 μm of Ti is de-

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posited using magnetron sputtering and patterned with lift-off process. Next is fabrication of 150 μm thick anchors from KMPR. KMPR is spin coated and patterned by lithography. Now the fabrication of specimen is complete. This specimen is then transferred to the center of the actuator. To do that, a small amount of epoxy is applied on the KMPR anchors. Then the specimen is stamped on the PVDF actuator. Alignments marks are designed on the sacrifier layer to make sure the specimen is stamped on the center of actuator. After the epoxy is cured, the actuator is turned over and immersed in the Cr etchant. Cr etchant removes both the Cr and Cu layers. When the Cu-Cr layer is removed, the specimen is released from the glass. Next, the actuator is rinsed and left to dry. Now, the fatigue test can be started.

3.3 Fatigue test

First, the new resonance frequency of actuator is detected by vibrating the actuator and the specimen at very low voltages. The resonance frequency is shifted due to the existence of the specimen on the actuator. The new resonance frequency is about 6 kHz. Then, the symmetry of vibration amplitude all around the specimen especially around the fatigue gauge is confirmed by vibrating the actuator at low voltage. If the vibration amplitude is asymmetric at this step, the specimen is rejected for the fatigue test. If the asymmetry was negligible, the fatigue test is applied on the specimen. To do that, the actuator is driven at the resonance frequency at high voltage of around 100 to 150 $V_{0\text{-}p}$ until specimen breaks under failure. The out-of-plane vibration amplitude of specimen during the test was measured and applied to a FEM model of specimen created by FEM software (COMSOL Multiphysics). The Young's modulus of around 77 GPa which was obtained from tensile test in experiment was applied in FEM stress calculations and the stress in the fatigue gauge of specimen is calculated. Because the specimen has very high stress concentration in the fatigue gauge, a very fine mesh was used in the FEM modeling of specimen in the fatigue gauge. By repeating the fatigue test on specimens and changing the driving voltage of actuator from 100 to 150 $V_{0\text{-}p}$ it is possible to break specimens after different number of cycles and at different stress levels. This data can be used to plot the S-N curve of the specimen.

4 Results

Many Ti thin film specimens were successfully stamped on the actuators. The dimensions of specimens are shown in Fig. 3.a. A photo of the specimen stamped on the actuator is shown in Fig. 3.b. The out-of-plane vibration amplitude of specimen at the fatigue gauge during the fatigue test was measured. If the applied voltage to the specimen is low for example 100 $V_{0\text{-}p}$, the specimen breaks at low vibration amplitude and stress level and after high number of loading cycles. If the applied voltage is high for example 200 $V_{0\text{-}p}$, the specimen fails at high vibration amplitude and stress level and after low number of loading cycles.

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Typical stress distribution in fatigue gauge of specimen is shown in Fig. 3 (c) and a photo of specimen broken in the fatigue gauge in the location of maximum stress concentration is shown in Fig. 3 (d). At the top right corner of this figure, a SEM image of the fracture surface of the specimen is also shown. The result of stress in a specimens and number of cycles after which they break was used to draw the stress-fatigue life cycles or S-N curve. Fig. 3 (e) shows this S-N curve. This figure shows that Ti thin film breaks at stress of above 750 MPa at only a few loading cycles. However, it breaks at stresses less that 300 MPa after 10^8 loading cycles. The maximum number of cycles for the fatigue test was about 10^8 cycles in this experiment. If con-

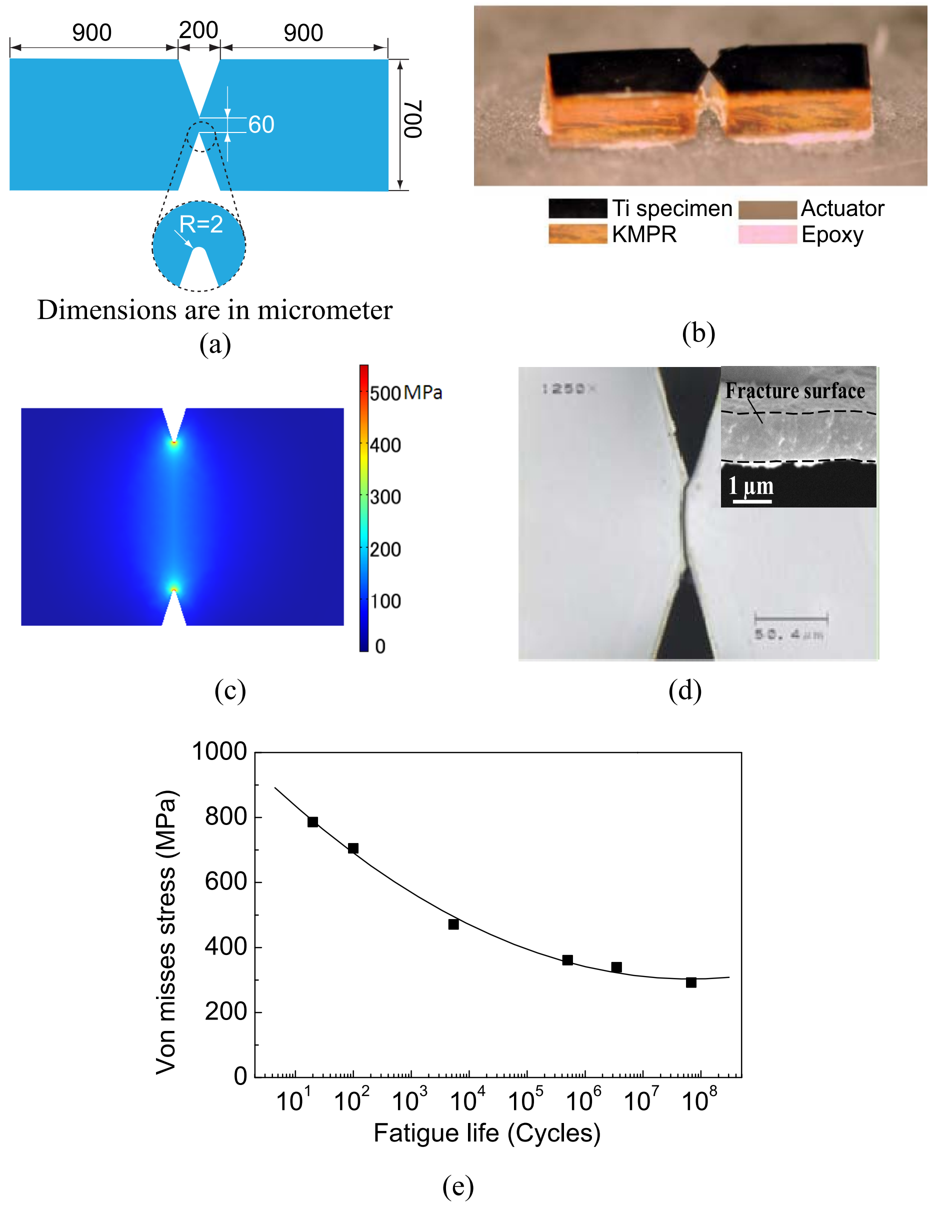

Fig. 3. (a) Dimension of specimen, (b) Specimen stamped on actuator, (c) Typical stress distribution in specimen (d) Photo of specimen broken in fatigue test (e) Stress- fatigue life cycle (S-N) curve of specimen

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ventional method with loading frequency of 100 Hz is applied for this number of cycles, the time required for fatigue test is around 3 months. In contrast, the proposed method enables the fatigue test in less than 1.5 days at 6 kHz loading frequency. So, the S-N curve of the thin film Ti was obtained over 50 times faster than the conventional methods because the loading frequency is over 50 times higher in this method compared to conventional methods.

5 Conclusions

A high-frequency fatigue test method on thin film of metals such as Ti was proposed in this research. A PVDF actuator and a Ti thin film specimen as an example were fabricated. The specimen was transferred on the actuator successfully and the fatigue test of specimen was conducted at the loading frequency of about 6 kHz. The suggested method is over 50 times faster than conventional methods with loading frequency of 100 Hz. The result of the test shows the decrease of fatigue strength of Ti as the number of loading cycles increases.

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