行政院國家科學委員會專題研究計畫成果報告

微尺度單晶矽之疲勞特性研究(II)
Fatigue Characteristics of Microscale Single Crystalline Silicon(II)

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1.中文摘要

本計畫研發一套可以定量進行微尺度單晶矽疲勞試驗的方法。疲勞試片為 300 «m 長的單晶矽懸臂樑，懸臂樑的軸向為<110>，樑的自由端以一個銅片與 PVDF 的荷重元量測外力，如此可以獲得在固定端的應力。試片係在(100)晶片上以微加工技術製成，荷重元以傳統加工方式製成。經此系統實際測試，當應力振幅為 1.35GPa、應力比 R=0 時，試片之疲勞壽命達到 10^7 數量級。

關鍵詞：疲勞、微加工、單晶矽

Abstract

A method for quantitatively evaluating the microscale fatigue characteristics of single crystalline silicon is developed. Fatigue data is acquired by exciting a 300 «m long <110>-direction single crystalline silicon cantilever beam. A copper-PVDF load cell is attached to the free end to determine the stress at its fixed end of the cantilever beam. Quantitative fatigue data on microscale single crystalline silicon has thus been directly obtained. The silicon cantilever is fabricated from a (100)-plane single crystal wafer using micromachining techniques, while the load cell is constructed using traditional methods. A nominal stress amplitude of 1.35 *GPa* with stress ratio $R = 0$ was applied. The fatigue life was found to be in the order of 10^7.

Keywords: Fatigue, Micro fabrication, Single crystalline silicon,

2.Introduction

Fatigue is considered the major cause of unexpected failure in engineering structures. Studies in the fatigue of structural materials have been wide and extensive [1]. Single crystal silicon is currently the most commonly used material in microstructures. However, the microscale fatigue properties of this material has not yet been explored. This property is not easily characterized, and the main reason for such difficulty lies in the mechanism of fatigue. Fatigue failure is believed to be caused by crack initiation and growth to failure from small deformities in the material [1]. Theoretically the higher the number of deformities existing in the material, the higher its probability of fatigue failure, i.e. the lower its fatigue life. Supposing that deformities exist uniformly in a material, then smaller structures will have fewer deformities than larger structures. It can therefore reason that the fatigue characteristics for structures in macroscopic and microscopic dimensions will be radically different.

In order to measure the microscopic fatigue characteristics of a material, the test specimen used must also be microscopic. This poses some unique difficulties in measurement and observation. Aging effects of single crystalline silicon has been studied indirectly through observation of temporal changes in resonance frequencies and quality factors [2,3].

Ye, et al. obtained Young’s modulus and residual stress for single crystalline silicon microstructures by measurement of resonance frequencies [4]. Characterization of the fatigue property was also discussed but was not observed in experiments. Nor were any quantitative stress calculations attempted in the experiment. Kahn, et al. reported on the fatigue behavior of polysilicon devices [5]. Due to the existence of residual stress and indirect calibration of applied force, the stress could not be determined accurately.

A viable and direct method for measuring the fatigue strength of single crystalline silicon was designed. In this experiment a silicon cantilever beam is coupled to a load cell as indicated in Fig. 1 and is subjected to a periodic oscillation of fixed amplitude. Using the load cell, actual stress in the silicon test specimen can be obtained and quantitative fatigue properties may be derived.

3. **Design and Fabrication**

3.1. Silicon test specimen

The silicon specimen is design according to the following restrictions:

a. The dimensions of the test specimen must be small enough to successfully demonstrate micro scale characteristics. However, it should not be so small that handling the specimen becomes too difficult.

b. The deflection must be within a reasonable limit. The height/width ratio of the beam must not be too small, or else the beam tends to act like a plate instead. The cantilever should behave linearly.

c. The number of alternating stress cycles required to induce failure should not be too high. Therefore, the fixed end stress of the cantilever is limited to a maximum value of 70% the ultimate strength of silicon. The ultimate stress of single crystalline silicon is 6.9*Gpa*; therefore the stress at the fixed end should attain a magnitude of 4.83*Gpa*.

The top and bottom drawings and two photos of the test specimen are shown in Fig. 2. There is a 2500×5500 *«m* outer structure which is needed for clamping the specimen to a shaker. The actual cantilever structure lies in a 1000×1000 *«m* opening and has dimensions 300×50×30 *«m*. Three 30×30*«m* square marks are etched at the free end for accurate positioning of the load cell. It is found that 0.165*N* of force is required to maintain a deflection of 46*«m*.

3.2. Load cell

The load cell is a cantilever beam made of pure copper, with a sliver of PVDF film attached. The PVDF film is glued to the copper beam using a conductive adhesive. Therefore, the force acting on the silicon cantilever can be found through measurement of the dynamic signal caused by beam deformation.

Assuming that the PVDF film shares the same strain as the copper beam to which it is attached, and that the film can be approximated by a parallel board capacitor, the relation between the output voltage and the force applied to the load cell is as shown below [6]：

$$V=\frac{6E_{PVDF}d_{31}(l-\frac{p+q}{2})d}{E_{Cu}h^2\pounds_0 b}\times F \qquad (1)$$

where E_{PVDF}，E_{Cu} are the respective Young’s moduli of PVDF and copper. d_{31} is the piezoelectric stress coefficient of PVDF, and p , q, h, b are the positions of the endpoints of the PVDF film attached to the beam, and the height and width of the beam, respectively. $\pounds_0$ is the permittivity。

The dimensions of the load cell is 80×1×0.2 *mm* as shown in Fig. 3. Such dimensions not only ensure a deflection/cell length ratio of 1/8, it also offers a wider range of measurements. If the fatigue strength of silicon turns out to be higher than expected, the load cell thickness may be increased, resulting in an increase in stiffness. Therefore higher load can be applied and still be kept in the linear range. From Eq. (1) it can be seen that the output of the load cell is related to the position of the PVDF film; an ideal film length of 5*mm* can be derived, and the position of the film is 1.5*mm* away from the fixed end of the load cell beam.

The load cell body is made of 200*«m* thick copper. Designing a precise die is important. The copper beam is first cast from its die. Next, the PVDF film is attached to the beam. The load cell base is made of two pieces of non-conducting bakelite. After the base is completed, two thin wires are attached to the

PVDF and the copper beam. These must not be too thick or too hard, or else the vibration of the load cell will be affected. Also, excessive thickness may cause difficulties in attaching the wires. Therefore copper wire of diameter 35*«m* is used. Since the conductive adhesive used to attach the wires is not very strong, and 35*«m* copper wire is easily broken, the wires are not directly attached to the charge amplifier. Instead, they are attached to copper plates on the nonconductive base of the load cell; copper wire of a somewhat thicker diameter is soldered to the plates. The thicker wires transfer the signal to the charge amplifier. The tip of the load cell must be sharp enough to be inserted into the position mark at the end of the specimen. Since the position marks are 30×30*«m* in size, while the thickness of the load cell body is about 200*«m*, the tip was sharpened with HNO_3.

4. Fatigue test

Fig. 4 shows the fatigue testing setup. Specimens were clamped to a shaker that provides a sinusoidal cyclic motion. The load cell was fixed to a post and its tip was inserted into the central position mark at the end of the specimen. The load cell measures the vertical force acting on the free end of the specimen. The test is conducted at a frequency of 150 *Hz*, which is much lower than the natural frequencies of both specimen and load cell. Thus inertial and damping forces can be neglected, while the applied force and stress behave quasi-statically and can be readily derived and the results are listed in Table 1.

5. Conclusion

The method developed in this research project provides a quantitative way to determine the fatigue life of microstructures. The system can perform test at very high frequency that can characterize fatigue properties very effectively. For a nominal stress amplitude of 1.35 *GPa* with stress ratio $R = 0$, the fatigue life of microscale single crystalline silicon was found to be in the order of 10^7, which is much higher than its metal counterpart.

REFERENCES

1. J. A. Collins, *Failure of Material in Mechanical Design*, John Wiley & Sons, 1981.
2. A. Pember, J. Smith, and H Kemhadjian, “Study of the effect of boron doping on the aging of micromachined silicon cantilevers,” *Appl. Phys. Lett.* 66 (5), p. 30, Jan. 1995.
3. A. Pember, J. Smith, and H Kemhadjian, “Long-term stability of silicon bridge oscillators fabricated using the boron etch stop,” Been *Sensors and Actuators* , A 46-47, pp. 51-57, 1995.
4. X.Y. Ye, Z.Y. Zhou, Y. Yang, J.H. Zhang, J. Yao, “Determination of the mechanical properties of microstructures,” *Sensors and Actuators* , A 54, pp.750-754, 1996.
5. H. Kahn, N. Tayebi, R. Ballarini, R. L. Mullen, and A. H. Heuer, “Fracture and Fatigue of Polysilicon MEMS Devices,” Transducers ‘99, 3A2.2, Sendai, Japan, 1999.
6. Technical Notes, Atochem Sensors, Inc., Penwalt Corporation, 1987.

Table 1 Fatigue life under $\pm_{amp} = 1.35 GPa,\ R = 0$

Specimen No.	Fatigue life
1	2.70×10^7
2	0.91×10^7
3	1.12×10^7
4	5.22×10^7

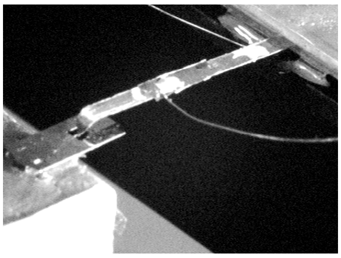

Fig. 1 Test specimen and load cell

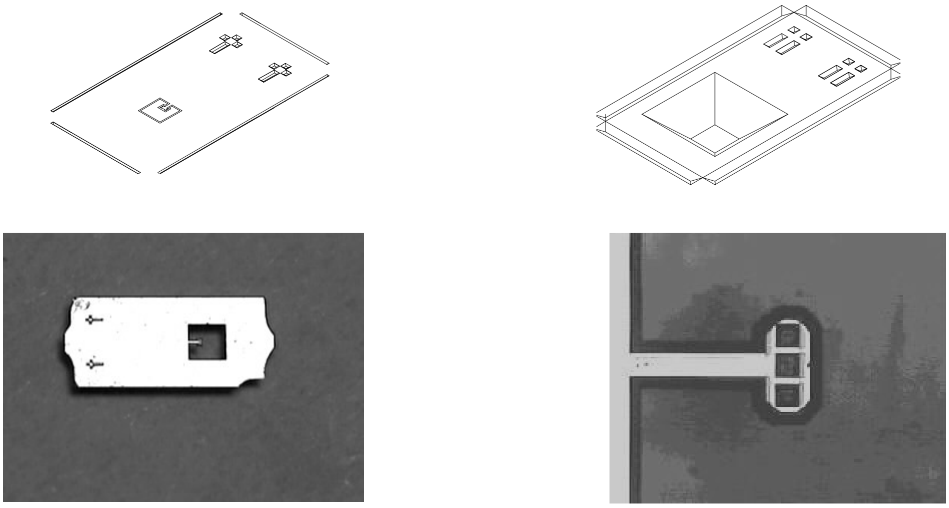

Fig. 2 Top and bottom view of specimen die, with close-up of the cantilever structure

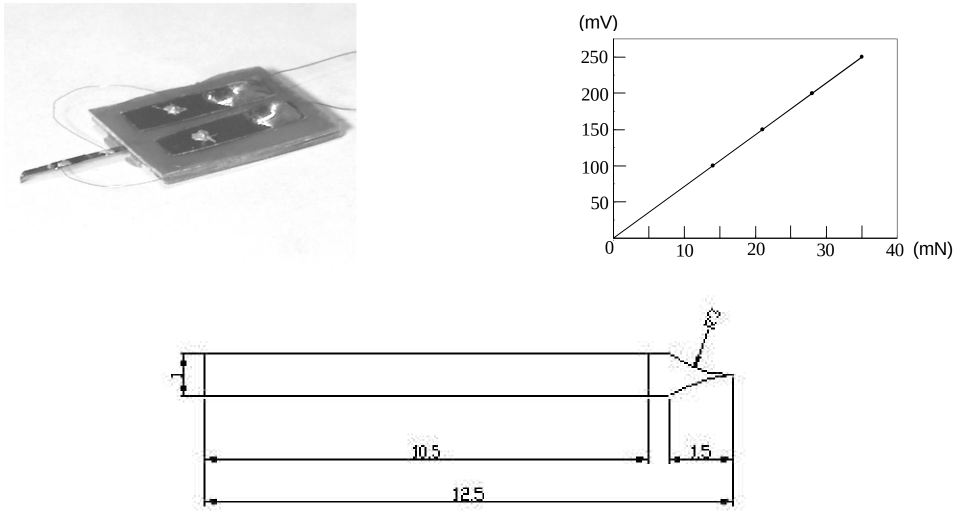

Fig. 3 Photo and drawing of load cell, with calibration results

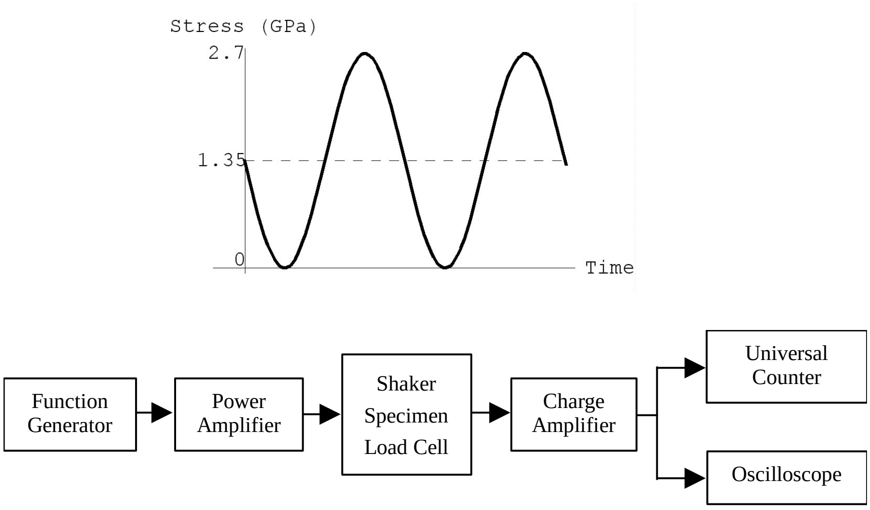

Fig. 4 Schematic of fatigue test setup, with time plot of oscillating stress