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

Fatigue Characteristics of Microscale Single Crystalline Silicon

計畫編號：NSC 88-2212-E002-009
執行期限：87 **年** 8 **月** 1 **日至** 88 **年** 7 **月** 31 **日**
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1.中文摘要

本計畫設計一套進行微尺度單晶矽疲勞試驗的方法。疲勞試片為 250 «m **長的單晶矽懸臂樑，試片係在**(100)**晶片上以微加工技術製成，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，荷重元以傳統加工方式製成。此系統經測試後證實可行；未來將進一部求得微尺度單晶矽正確的疲勞特性。**

關鍵詞：疲勞、微加工、單晶矽

Abstract

A method for evaluating the micro-scale fatigue characteristics of single crystal silicon is considered. Fatigue data is acquired using a 250 «m long single crystalline silicon cantilever beam as a test specimen, with a copper-PVDF load cell attached to its free end to measure stress in the fixed end of the cantilever. The design and fabrication of the cantilever and load cell is demonstrated. The silicon cantilever is fabricated from a (100)-plane <110>-direction single crystal wafer using micromachining techniques, while the load cell is constructed using traditional methods. Actual measurements are being carried out, and the S-N curve of micro-scale single crystalline silicon is expected to be obtained in the near future.

Keywords: Fatigue, Micro fabrication,
Single crystalline silicon,

2.Introduction

Fatigue is considered the major cause of unexpected failure in engineering structures today. Studies in the fatigue of structural materials have been wide and extensive, while fatigue behavior of new materials are often characterized before the materials are applied to practical use [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.

Here we attempt to design a viable and direct method for measuring the fatigue strength of single crystalline silicon. To date no one has offered a method of observing the fatigue behavior of microstructures quantitatively. 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.

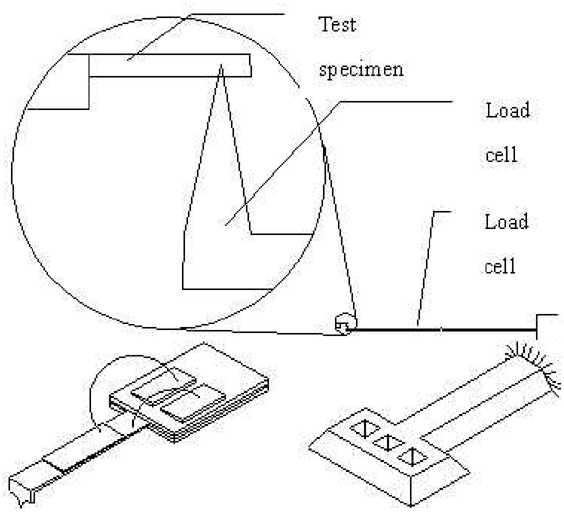

Fig. 1 Test specimen and load cell

The load cell measures the vertical force acting on the free end of the beam. The stress at the fixed end of the beam can be calculated. The periodic oscillation produces an alternating stress which, combined with the number of cycles to failure, can be used to determine the S-N curve of silicon.

3. Analysis and design

3.1. Silicon test specimen design

The following restrictions must be considered in the design of the silicon cantilever:

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 be long and thin.

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 stress 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*.

Using the above guidelines, an optimum cantilever size of dimensions 250×50×30 *«m* is obtained. It is found that 0.285*N* of force is required to maintain a deflection of 46*«m*. A drawing of the test specimen is shown in Fig. 2. There is a 2500×5500 *«m* outer structure, and a 1000×1000 *«m* opening where the actual cantilever structure lies. The load cell oscillates with the specimen in this area; the outer structure is needed for clamping the specimen to a shaker.

3.2. Load cell design

The load cell is a cantilever beam made of pure copper, with a sliver of piezoelectric 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.

A load cell with dimensions of 80×1×0.2 *mm* is designed and 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

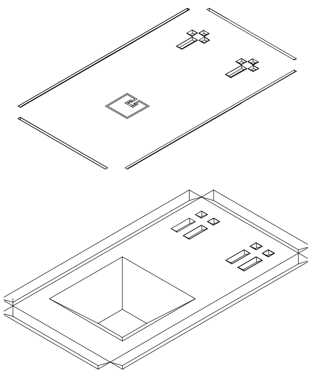

Fig. 2 Top and bottom diagrams of die

strength of silicon turns out to be higher than expected, the load cell thickness may be increased, resulting in an increase in stiffness. 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 must be sharpened with HNO_3.

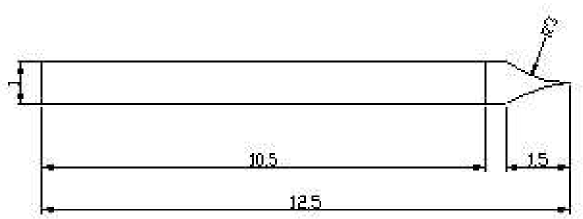

Fig. 3 Geometric shape of load cell body。

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 [5]：

$$V = \frac{6E_{PVDF}d_{31}(l - \frac{p+q}{2})d}{E_{Cu}h^2 £_0 b} \times F \qquad (1)$$

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. $£_0$ is the permittivity。

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.

4. Fabrication

4.1. Silicon test specimen fabrication

The <110>-direction test specimen is fabricated from a (100) Si wafer using KOH as an anisotropic etchant. Due to directional properties of the crystal lattice, some etchants show different etching rates for the same material [6,7]. The details of the fabrication process are given in Fig. 4. The photo of the specimen is shown in Fig. 5.

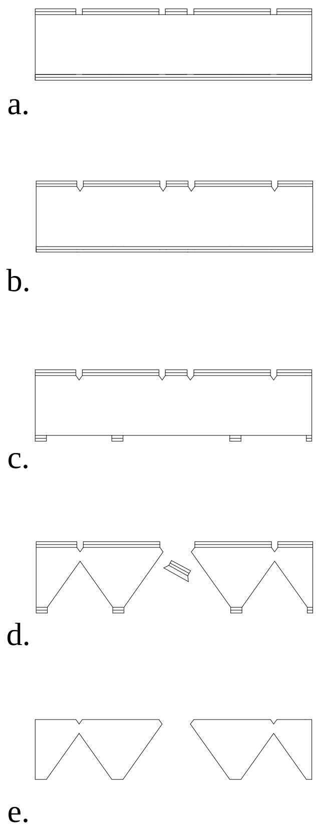

Fig. 4 Fabrication of test specimen

Fig. 5　Microscopic photograph of actual Specimen

4.2 Load cell fabrication

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. Fig. 6 is a photograph of a completed load cell with a coin beside it for comparison.

5. Conclusion

The testing setup will be calibrated in the near future. The experiment has not yet been concluded at the time of this writing. Actual fatigue measurements have yet to be completed. However, all steps and procedures have been carefully considered, and the test specimen and load cells have been successfully fabricated and calibrated. We foresee no problems with the load cell, which has excellent sensitivity and linearity characteristics. It can accept a wide range of force values. Nor have we found any problems with the test specimens, which have been fabricated according to plan. We anticipate a major increase in the ease of product life prediction and design for micromechanical devices after the S-N curve is determined. Future projects include direct integration of micro strain gages into the structure of the test specimen, eliminating the need for load cells.

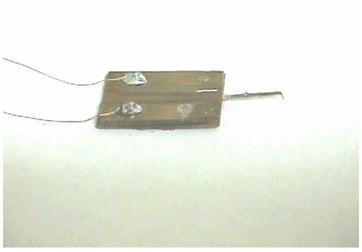

Fig. 6　A load cell

6. References

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