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Temperature Dependence on Fatigue Life of Single-Crystal Silicon in Electrostatic-Force Actuated Micro Resonator

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This paper reports the effects of stress concentration and temperature on the fatigue life of single-crystal silicon (SCS) structures for developing reliable design criterion for silicon-MEMS devices. We have prepared two types of fatigue test specimens, fabricated by deep reactive ion etching (DRIE), which have one or two notches in their specimen sections. The longitudinal direction of all the specimens was aligned to [110] direction in (001) surface. At temperatures ranging from room temperature (R.T.) to 573K, the fatigue lives of the specimens were evaluated using electrostatic force actuated MEMS resonators with natural frequencies of approximately 30 kHz. The obtained stress-life (S-N) diagram exhibited a clear tendency of the lifetime lengthen, when the resonator's amplitude decreased. The number of cycles to failure also decreased with an increase of temperature. The radius of curvature at the notch tip did not affect to the lifetime. SEM micrographs revealed that the SCS specimens were sure to fracture in the notch tip section where the maximum tensile or compressive stress was produced.

Keywords: Single-crystal silicon, Fatigue, Temperature dependency, MEMS, Resonator, Stress concentration

1. Introduction

Fatigue lifetime in single-crystal silicon (SCS) under cyclic stresses becomes the primary concern for long-term reliability of silicon-based micro electromechanical system (MEMS) devices. The application of such devices is being expanded to a wide variety of technical fields including extreme harsh environment, such as high temperature, so that properly evaluation of the lifetime of the structural materials is required by means of material testing. To date, fatigue life of SCS at ambient temperature has been well studied [1-9], but that at intermediate temperature is still under investigation because of technical difficulty in controlling very small stress or strain at elevated temperatures.

The objective of this work is to carry out high-cycle fatigue tests of SCS at intermediate temperatures in order to investigate temperature dependency on its fatigue lifetime. SCS MEMS resonator actuated by electrostatic force has been developed for the fatigue tests. The influences of stress amplitude and temperature on the lifetime are discussed.

2. Experimental Procedure

2.1 Fatigue Test Device

Figure 1 shows the photograph of fabricated test device. This device originating from that proposed by Muhlstein *et al* [9] consists of a specimen section with notch, a fun-shape resonator with gauge mark for rotation angle measurement, electrostatic comb-drive actuator, and capacitive sensor. A fun-shape resonator with the radius of 250 μm was designed using finite element analysis (FEA) to gain proper vibration amplitude by resonance. Dimension of the specimens is listed in Table 1. We have prepared two types of specimens; single-side notch (Type A) and double-side notch (Type B). For each specimen type, three different radii of notch-tip curvature were employed to investigate the effect of stress concentration on SCS fatigue characteristics.

The fabrication process is shown in Figure 2. Testing samples

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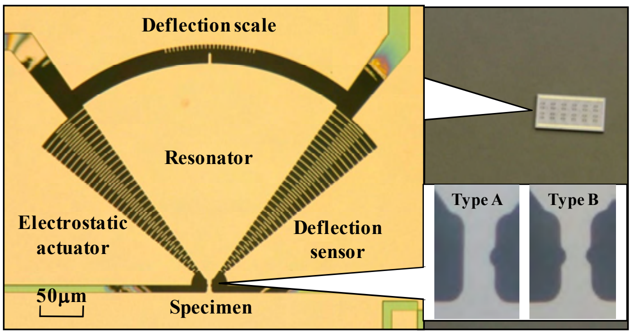


Figure 1 Photograph of fabricated fatigue test device.

Table 1 Dimension of specimens.

		Specimen size			Notch size	
		Length	Width	Thickness	Depth	Radius of tip curveture
Type A	SI	15.0	6.0	2.0	1.0	0.5
	SII					1
	SIII					1.5
Type B	DI					0.5
	DII					1
	DIII					1.5

[μm]

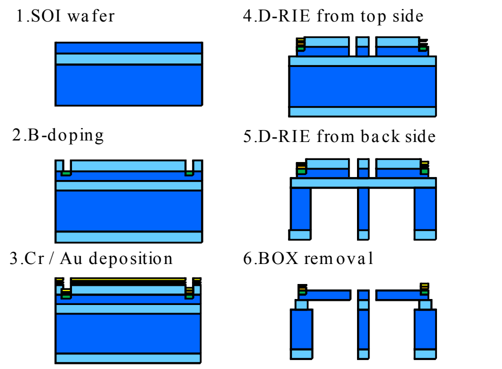
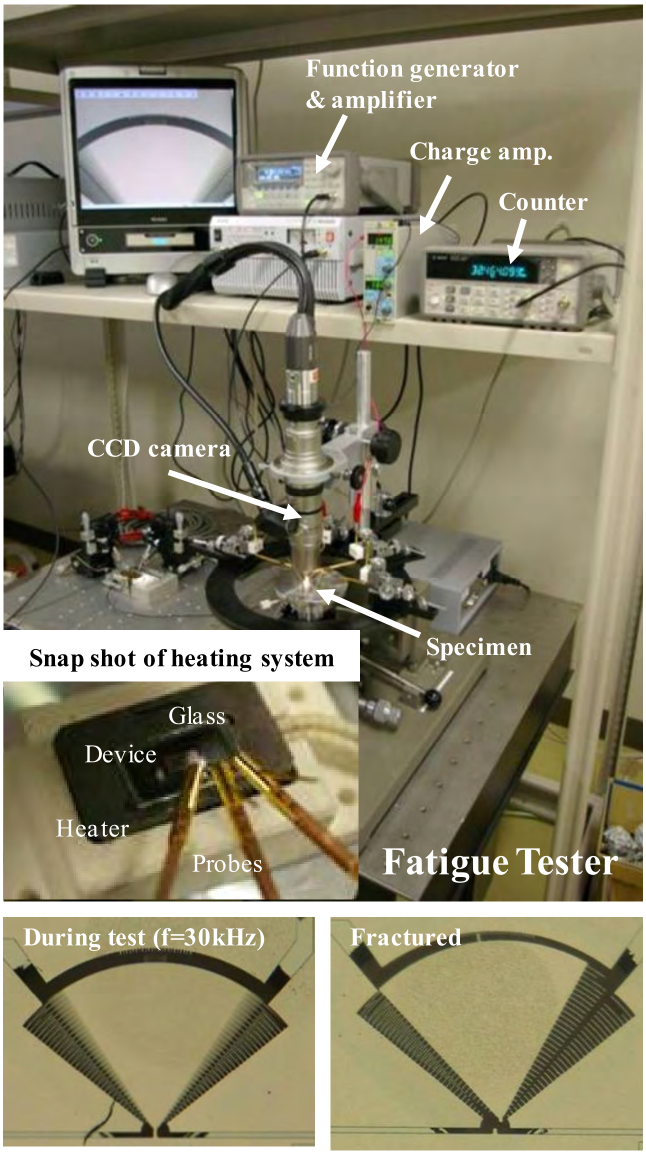
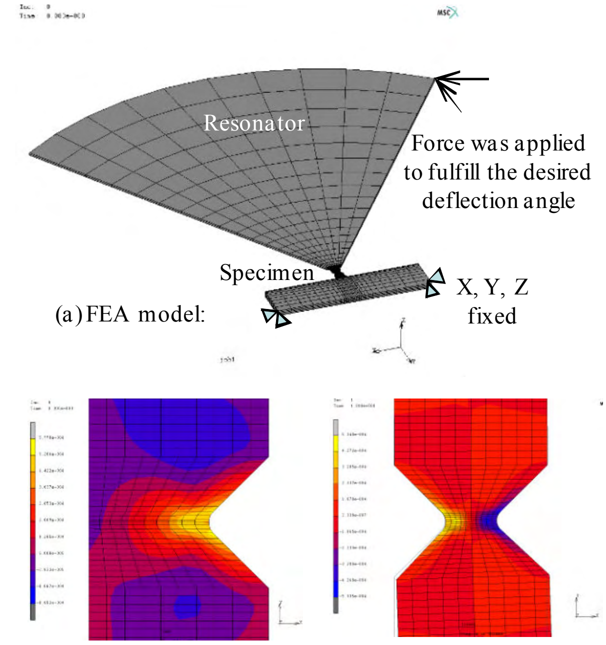


Figure 2 Fabrication process of fatigue test specimen.



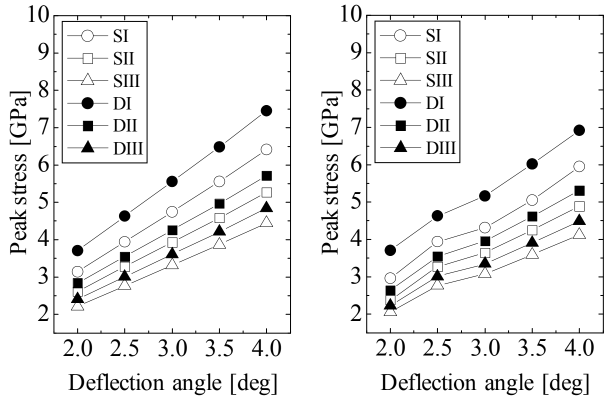
(a) During test (b) Fractured

Figure 3 Experimental setup for fatigue test.



(b) Type A (c) Type B

Figure 4 Typical FEA model and stress distribution around notch-tip in specimen.



(a) 298 K (b)573 K

Figure 5 Peak stress versus rotation angle by FEA.

were fabricated from p-type (100) silicon-on-insulator (SOI) wafer using silicon micromachining techniques with deep reactive ion etching (D-RIE). To secure the electric contact with device, device layer contains boron impurities in concentration of 1×10^{17} cm^{-3}, which was relatively low so as not to spoil the original characteristics of SCS material.

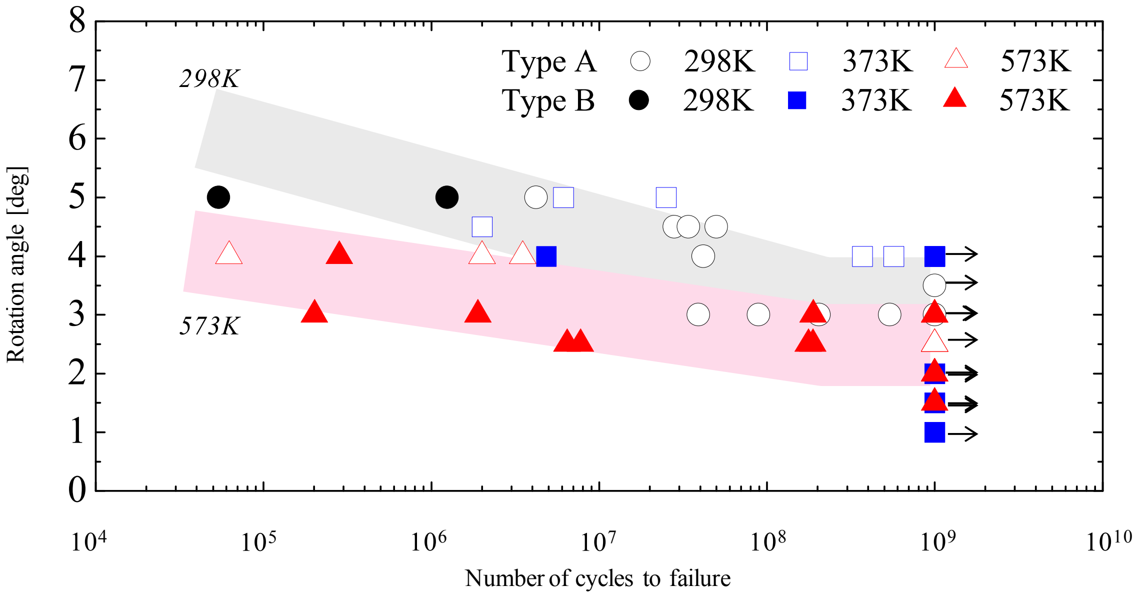
2.2 Experimental Setup

Experimental setup for fatigue test under intermediate temperature environments is shown in Figure 3. The fatigue testing system consists of function generator for producing sinusoidal waveform, high voltage amplifier for electrostatic forcing, probes made of gold for application of voltage to electrostatic comb actuator via electrode, CCD camera for positioning the probes onto electrical pads, charge amplifier for amplifying electrical charge, frequency counter for counting the number of cycles, and specimen holder with micro heater that can generate heat up to 573 K on the device chip. For temperature measurement, we have to know that the specimen is sure to be heated up to designated temperature. So, radiation thermometer was employed to directly measure the temperature on the device.

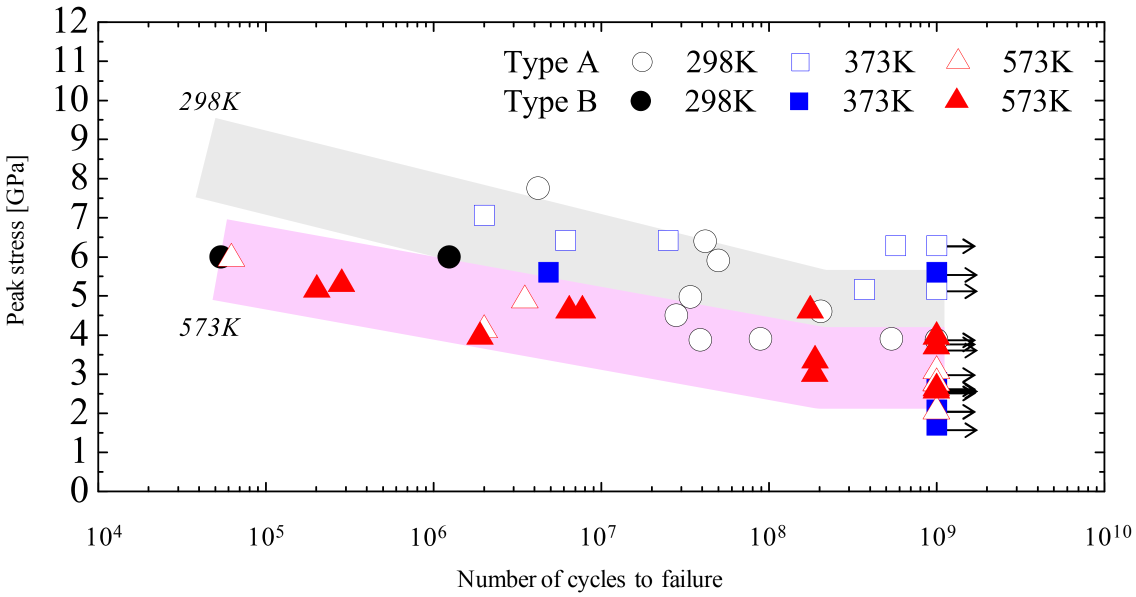
The devices were operated under resonance around 30 kHz by controlled applied voltage with sinusoidal waveform and constant amplitudes. Tests were performed at R.T., 373 K, and 573 K. The number of cycles to the failure of specimen was counted by recording the amplitude signals with frequency counter via charge amplifier. The test was terminated when the sample ran out the operation without failure at 1×10^9 cycles.

2.3 Stress Estimation at the Notch-Tip by FEA

We performed isotropic FEA to estimate stress distribution around the notch-tip during the fatigue test. Figure 4 (a) illustrates typical FEA model. In FEA calculations, the peak stress around the notch was determined by applying point loading to the edge of resonator in order to generate a rotating motion in the resonator. Figures 4 (b) and (c) show <110> stress distribution of specimens for Type A and B, respectively. These results were obtained at the rotation angle of 2 degrees. Stress concentrations occurred around notch-tips regardless of the number of notches. In case of tests in elevated temperatures, thermal effect on material characteristics should be considered. Figures 5 (a) and (b) show the peak stresses obtained by FEAs with material constants at R.T. and 573 K, respectively. The peak stress is linearly proportional to deflection angle of resonator regardless of temperature. The stresses at each



(a) Rotation angle vs. number of cycles to failure



(b) Peak stress vs. number of cycles to failure

Figure 6 The number of cycles to failure versus (a) rotation angle and (b) peak stress obtained by FEA. The circle, square, and triangle plots represent the lifetimes obtained at temperatures of R.T., 373 K, and 573 K, respectively.

angle at R.T. are a little bit higher than those at 573 K due to temperature dependence on Young's modulus of SCS [10]. By using these relations in Figs. 5 and rotation angle in testing, the peak stress produced in specimen during the fatigue test was estimated.

3. Results and Discussion

Figure 6 (a) shows a relationship between rotation angles in testing and the number of cycles to failure. The rotation angle of resonator was measured at the deflection scale set on the resonator with CCD camera. The number of cycles to failure increases with a decrease of rotation angle in testing, in spite of temperature. The SCS specimens at R.T. and 373 K have similar tendency of lifetime extension behavior when the rotation angle has decreased. At the same rotation angle, the number of cycles to failure at 573 K was less by a factor of approximately ten or hundred than that at R.T. and 373 K. This indicates that SCS have a temperature dependency on its fatigue characteristics. Using FEA results shown in Figs. 5, we rewrote Fig. 6 (a) to peak stress versus the number of cycles to failure, as shown in Fig. 6 (b). There are no obvious changes in fatigue characteristics indicating downward trend with increasing stress cycles. No manifest fatigue limit is observed.

Figures 7 (a)-(d) show scanning electron microscope (SEM) micrographs of fracture surfaces of single and double side notched specimens at R.T. and 573 K. SEM micrographs revealed that the SCS specimens were sure to fracture from the notch center section

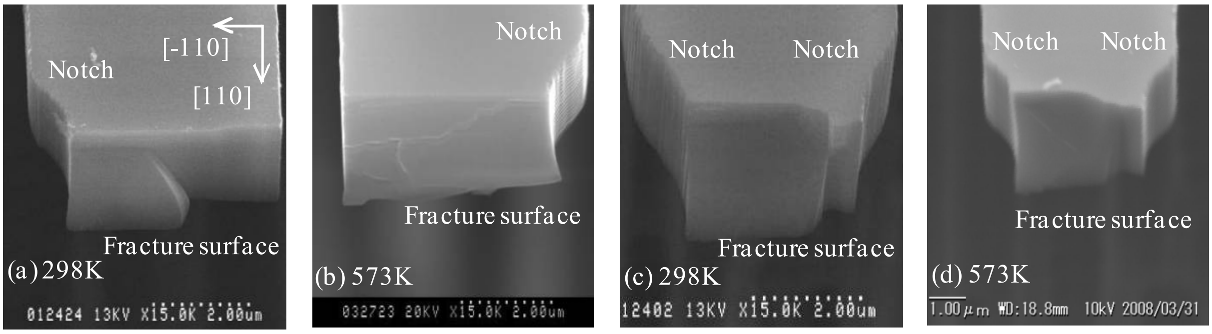


Figure 7 Fracture surface observation of type A ((a), (b)) and type B ((c), (d)) at temperature of R.T. ((a), (c)) and 573 K ((b), (d)).

where the maximum tensile or compressive stress was produced. The crack generated at the notch-tip tended to propagate towards the <110> direction in each specimen, regardless of temperature. Fractured surface of all the specimens showed mirror-like surface. Some inclined planes of {111} were observed around the notch edge. However, there were no significant difference in fracture surface between R.T. and 573 K results.

We have so far investigated temperature dependency on fatigue characteristics of SCS. From experimental results, the difference in fatigue lives by changing temperature has been found though the number of test samples is not enough. Discussion regarding fatigue fracture mechanism at intermediate temperatures cannot be concluded until further experiments have been conducted to investigate crack nucleus and growth in SCS at elevated temperatures.

4. Conclusion

We investigated the temperature dependency on fatigue life of SCS by means of high-cycle fatigue test with a MEMS resonator. The experiment results showed that the fatigue life at 573 K decreased by the factor of approximately ten or hundred compared with that of R.T. This knowledge would be useful for design of the device that operates in high temperature. However, we are going to evaluate more samples in order to carry out further investigations of the lifetime and fracture of SCS in the extreme harsh environments.

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