AFM Bending Testing of Nanometric Single Crystal Silicon Wire at Intermediate Temperatures for MEMS

Yoshitada Isono, Takahiro Namazu and Takeshi Tanaka
Kobe University and Ritsumeikan University, JAPAN

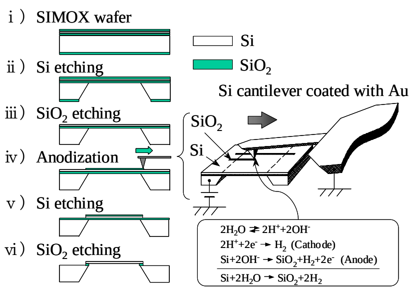
Objective ： To reveal the specimen size and temperature effects on elastic/plastic deformation behavior of nanometric Si at the temperature range from 295 to 573 K

Background

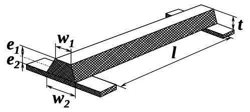
The evaluation of mechanical properties of nanometric single crystal silicon wires at intermediate temperatures is very important for the design of high-density MEMS and electronic devices, since the devices are serviced at 300 to 500 K which may induce thermal stress. However, mechanical properties of MEMS materials have just been estimated at room temperature because of difficulties in problems associated with measuring ultra-small physical phenomena in an experiment at elevated temperatures. For safe and reliable designs of high-density electronic components, nano-scale material tests of Si at intermediate temperatures are essential.

Experimental Procedure

Fabrication of nanometric Si wire

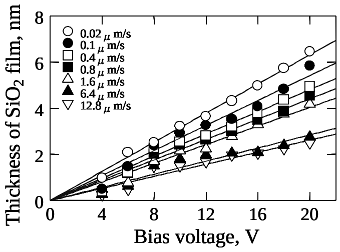


Fabrication process of nanometric Si wires using field-enhanced anodization technique

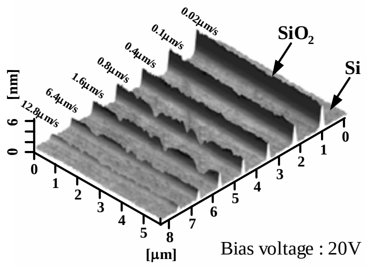


Nominal dimensions of nanometric Si wires

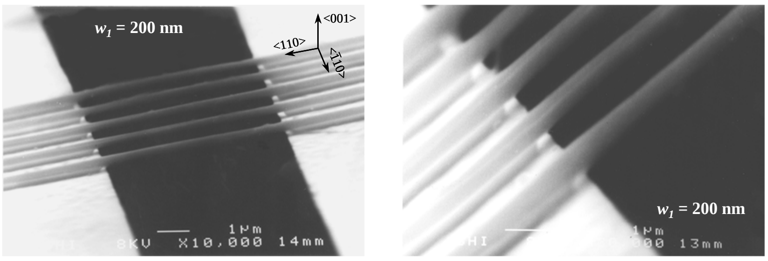
Upper width w_1 [nm]	Lower width w_2 [nm]	Thickness t [nm]	Length l [mm]
200	370	255	6
300	470	255	6
550	720	255	6
800	980	255	6



Variation of the SiO_2 film thickness with the bias voltage applied in the field-enhanced anodization process



AFM image of SiO_2 lines deposited on the SIMOX wafer at the bias voltage of 20 V

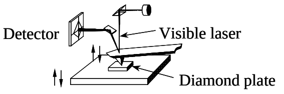


SEM photographs of nanometric Si wires with the width of 200 nm

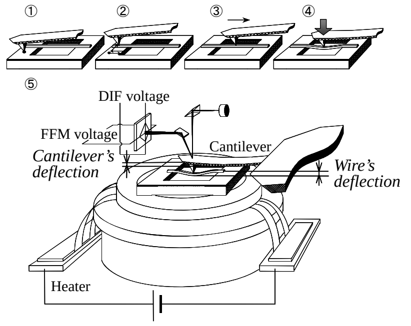
AFM bending test

< Step 1 >
Measurement of beam size using AFM

< Step 2 >
Calibration of the sensitivity of cantilever

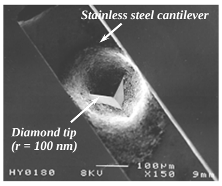


< Step 3 >
Bending test with AFM



< Step 4 >
Calculation of Young's modulus and bending stress

Schematic diagram of bending test procedure



AFM tip for bending test

Bending force F_n ;

$$F_n = ((DIF_{init} + DIF_{ex}) / Sensitivity) \times k$$

Maximum displacement in the z-direction of the wire D ;

$$D = PZT(Z) - DIF_{ex} / Sensitivity$$

Young's modulus E ;

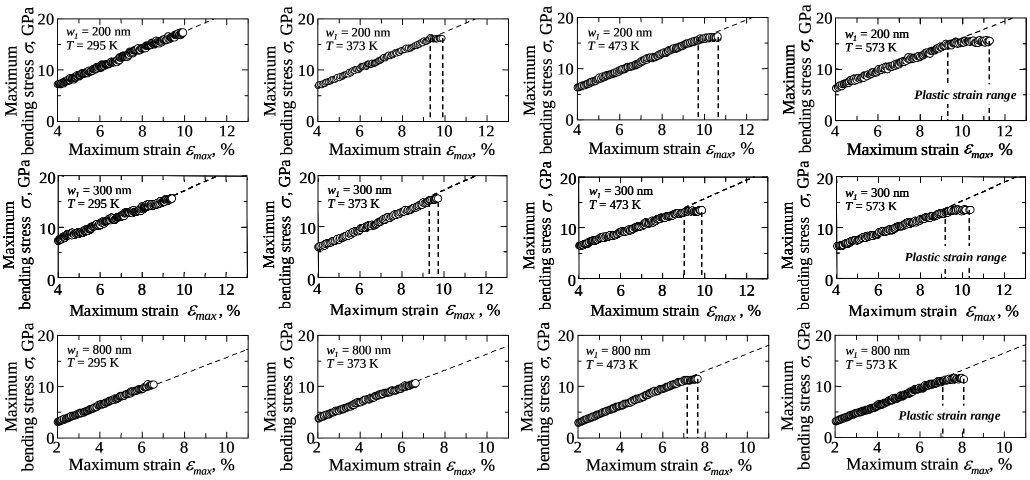
$$E = \frac{l^3}{192I} m$$

Bending stress σ_B ;

$$\sigma_B = \frac{(F_n)_{max} \cdot l \cdot e_1}{8I}$$

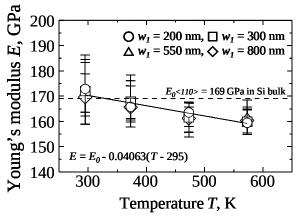
Results and discussions

Results of AFM bending test



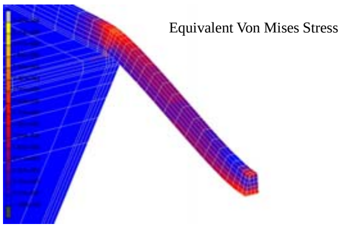
Maximum stress-strain curves during bending test

⟶ **Nanometric Si wires fracture in a brittle manner at room temperature, whereas Si wires deform plastically at intermediate temperatures.**



Variation of Young's modulus with increasing temperature

⟶ **Young's modulus decreases with an increase of the test temperature, but has no size effect.**

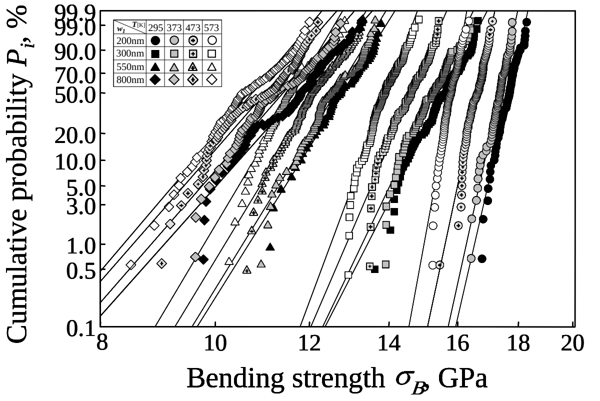


Bending analysis of fixed wire using FEM

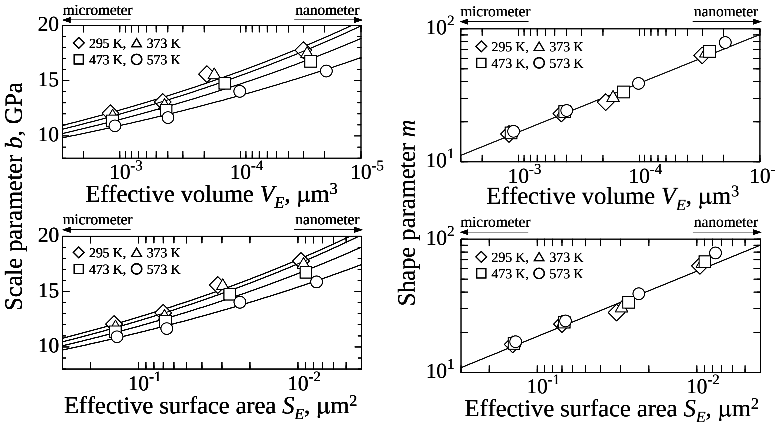
Y. Isono, T. Namazu and T. Tanaka, IEEE International Conference on Microelectromechanical Systems 2001, Interlaken, Switzerland 2001.

Results and discussions

Weibull plot of bending strength



Weibull plots of bending strength for nanometric Si wires



Wire size dependency of Weibull plots

→ **The bending strength of the 200 nm-wide wires ranges from 17.76 to 15.87GPa, which is about 1.5 times larger than the strength of the 800 nm-wide wires.**

→ **Bending strength of nanometric Si wires shows a gradual reduction with increasing the test temperature. This is caused by a reduction of the yield stress at higher temperature.**

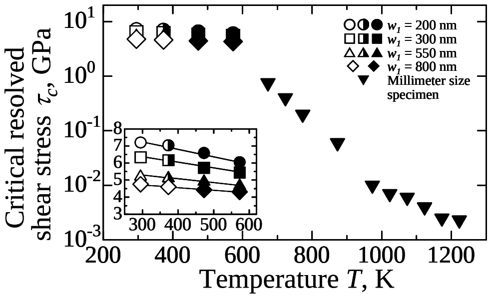
Size effect on *b* ○
Temperature effect on *b* ○

Size effect on *m* ○
Temperature effect on *m* ×

→ **Weibull parameters *b* and *m* of nanometric Si wires can be predicted by a function as the following,**

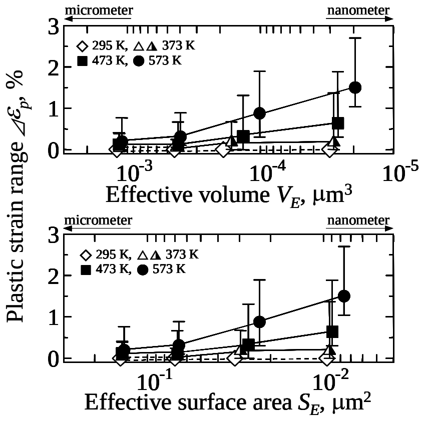
$$b = \exp(-3.07T\times10^{-4}+2.29)\cdot S_E^{5.03T\times10^{-5}-0.167} \quad \text{and} \quad m = \frac{\exp(1.78)}{S_E^{0.506}}\ .$$

Plastic deformation behavior



Correlation of critical resolved shear stress with temperature

→ **Critical resolved shear stress is inversely proportional to wire size and temperature.**



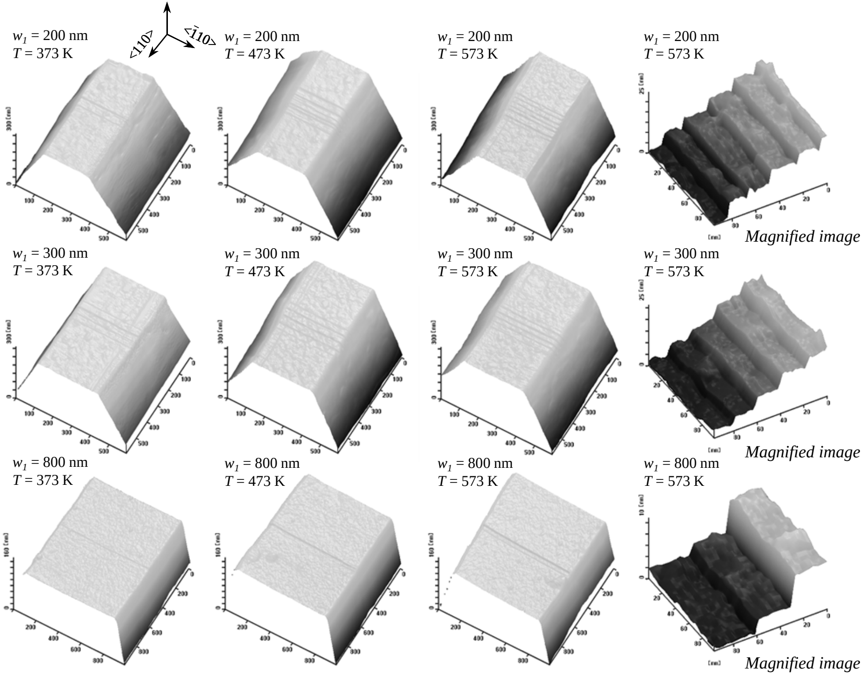
Wire size effect on plastic strain range

→ **Plastic strain range increases with decreasing the wire size, whereas it is proportional to temperature.**

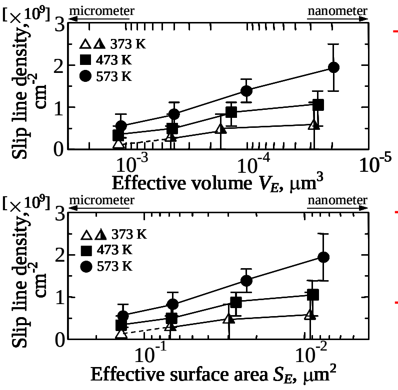
→ **Plastic flow is obtained at the temperature from 373 to 573 K in the nanometric wires.**

→ **It is possible to induce plastic deformation in a nanometer-scale specimen at even 373 K, which is close to room temperature.**

AFM observations of slip line



AFM images of slip lines at the top surface of Si wires with widths of 200, 300 and 800 nm



Variation of slip line density with decreasing wire size

→ **Several slip lines appear in the 200 nm-wide wires at higher temperature. The extent of the thermal activation of dislocation causes an increase of the number of slip lines in the wires. However, a few slip lines are observed in the 800 nm-wide wires at the temperatures applied in tests.**

→ **Building up slip lines on an atomic scale, nanometric Si wires can deform plastically at intermediate temperatures.**

→ **The slip line density increases with a decrease of the wire size at each temperature, which is likely to determine the plastic strain range during the deformation.**

Future work

Cause of specimen size effect on plastic deformation behavior ⇒

Contribution of the surface energy to an increase of the activation energy of dislocations ?

Stress dependency of the activation energy ?

} **Stress relaxation test**

Arrhenius formula ;

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \exp\left[-\frac{\Delta G(\tau,T)}{kT}\right]$$

Y. Isono, T. Namazu and T. Tanaka, IEEE International Conference on Microelectromechanical Systems 2001, Interlaken, Switzerland 2001.