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New Approach to Experimental Nanomechanics Using MEMS Technology

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1. Introduction

One of the most promising new areas of engineering is nano electro mechanical systems (NEMS), which integrate nanometer scale mechanical elements and electronics on a common silicon substrate. Single electron devices or physical sensors composed of nano structures are currently under study in order to reduce the power consumption in the devices or to increase sensitivity to physical phenomena, respectively. Some studies have succeeded in obtaining superior characteristics based on quantum effects [1]; engineers are continuing to find new applications for NEMS technology in an ever-growing range of industries.

An understanding of mechanical properties for nanometer scale materials is necessary for the task of designing and optimizing NEMS components since properties have to be defined in the design simulation. However, few mechanical characteristics for nanometer scale materials used in NEMS have performed because of problems associated with handling and alignment of the nanometric test specimen. There are also common problems, in any case, about measurement of ultra-small force and displacement of the specimen during testing.

2. Experimental Nano Mechanics

Methodologies of experimental nanomechanics proposed by Micro/Nano Mechanics Lab. in Ritsumeikan Univ. are introduced in this report. Here, bending tests for silicon nanowires and tensile tests for FIB deposited carbon nanowires were performed by using a commercial AFM and Electrostatic Actuated NAno Tensile testing devices (*EANAT*s).

2.1 Quasi-static Nano Bending Testing for Silicon Nanowires Using AFM

Quasi-static bending tests operated in an AFM were carried out for revealing specimen size and temperature effects on mechanical properties of single crystal silicon nanowires at intermediate temperatures. The fixed-fixed nanowires with widths from 200 nm to 800 nm and a thickness of 255 nm were fabricated on a silicon diaphragm by means of field-enhanced anodization with a conductive AFM cantilever and anisotropic wet etching. Field-enhanced anodization is a method used to deposit a line of SiO_2 film with a width less than 1 μm on a silicon surface [2]. The SiO_2 film was used as the high precision mask pattern for the anisotropic wet etching with a solution of 20 % TMAH. The AFM bending tests of the silicon nanowires were carried out at temperatures ranging from 295 K to 573 K in high vacuum.

Fig. 1 illustrates a schematic diagram of the test procedure. A diamond tip mounted on a stainless steel rectangular cantilever was used for the bending tests. The width, thickness and length of the silicon nanowires have to be measured by the AFM before the bending test. The sensitivity of the cantilever was also calibrated prior to the bending test, where the sensitivity is the ratio of the differential voltage obtained from the cantilever's vertical deflection to the displacement of the PZT actuator in the z-direction. The differential voltage value is detected by a built-in laser reflection technique of the AFM. All of the specimens were bent to failure.

Fig. 2 shows bending force-displacement curves of the 200 nm and 500 nm-wide silicon nanowires at temperatures of 373 K and 573 K. Nonlinear force-displacement curves were obtained, at the intermediate temperatures, owing to the plastic deformation of the nanowires in the thermal activated process. The plastic deformation range increases with an increase of temperature and a reduction of specimen size. The edge dislocation model proposed by the author was able to rationalize that the specimen size effect on plastic deformation range was determined by the correlation between the elastic strain energy stored in the nanowires and the activation Gibbs free energy [3].

Fig. 3 shows Weibull plots of the fracture strength. The fracture strength of the silicon nanowires decreases with an increase of the wire size at each temperature. The averaged fracture strength of the 200 nm-wide wires ranges from 15.8 to 17.6 GPa, which is 1.5 times larger than that of the 800 nm-wide wires. The fracture strength is inversely proportional to the test temperature although the temperature effect on the strength is smaller than the wire size effect.

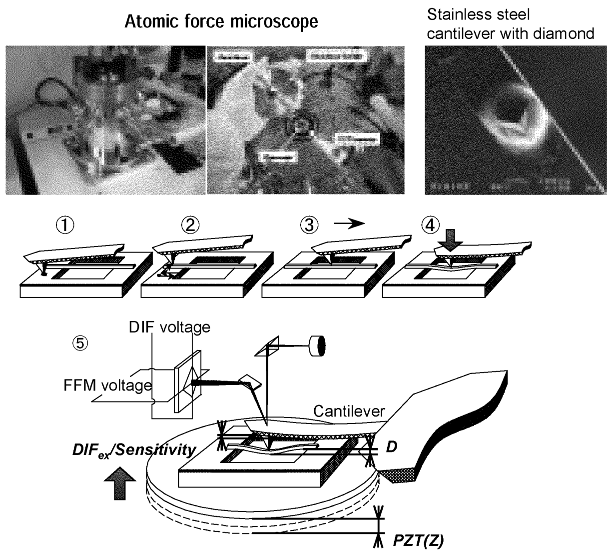

Fig. 1 Experimental procedure of quasi-static bending tests in AFM.

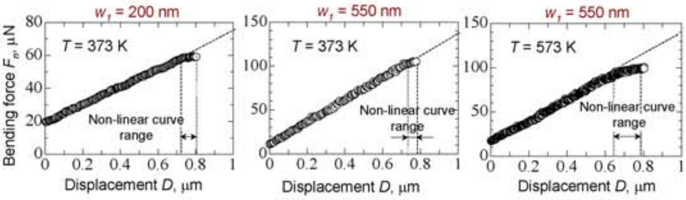

Fig. 2 Bending force-displacement curves of silison nanowires at temperatures of 373 K and 573 K.

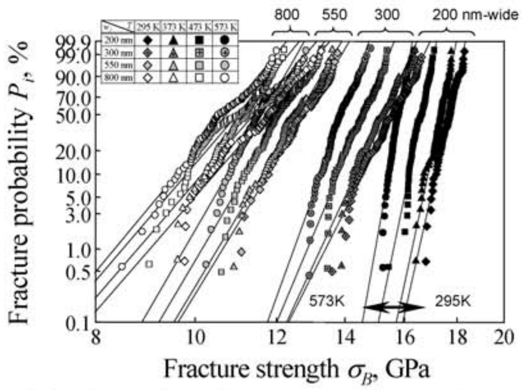

Fig. 3 Specimen size and temperature effects on fracture probability of silicon nanowires.

2.3 Electrostatic Actuated NAno Tensile Testing

Focused ion beam assisted chemical vapor deposition (FIB-CVD) using phenanthrene ($C_{14}H_{10}$) gas is a recently attractive technique used as the assembly of carbon nano-structures [4]. To confirm the suitability of the carbon nano-structures as a nano-component for use in NEMS, we have evaluated mechanical and electrical properties for the FIB deposited carbon nanowires using Electrostatic Actuated NAno Tensile Testing devices (*EANAT*s).

*EANAT*s are composed of three parts; (1) the specimen part including 5 μm-length carbon nanowires with diameters ranging from 90 nm to150 nm, (2) the actuator part with 1000, 3000 and 5000 pairs of electrostatic comb drive actuators, and (3) the measurement cantilever part used as a lever motion amplification system for calibrating tensile load and displacement. FE-SEM micrographs of the *EANAT* with 1000 pairs of comb drive actuators are shown in Fig. 4(a). The carbon nanowire with a diameter of 90 nm was prepared by FIB-CVD at the specimen part. The comb drive actuators and the measurement cantilever were also fabricated with extreme precision. Figs. 4(b) and 4(c) show external views of the *EANAT*s with 3000 and 5000 pairs of comb drive actuators, respectively. The *EANAT*s were completely integrated on about 10 mm^2-silicon chips.

Fig. 5(a) relates the deflection of the measurement cantilever with the applied voltage, obtained from the *EANAT* with 1000 pairs of comb drive actuators. The difference in the deflection between before and after tensile failure of the nanowire, at the bias voltage above 21 V, corresponds to the tensile displacement expended only on stretching the nanowire. Considering the spring constant of the *EANAT*, the load-displacement curve of the nanowire is redrawn from the cantilever deflection as shown in Fig. 5(b). No load increment below a displacement of 0.2 μm would be caused by the initial flexure of the nanowire

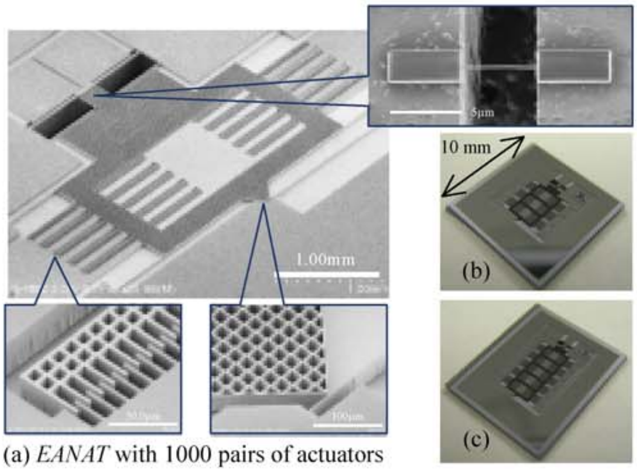

Fig. 4 Photographs of *EANAT*s with; (a) 1000 pairs of comb drive actuators and 90 nm-diametric carbon nanowire, (b) 3000 pairs and (c) 5000 pairs of actuators.

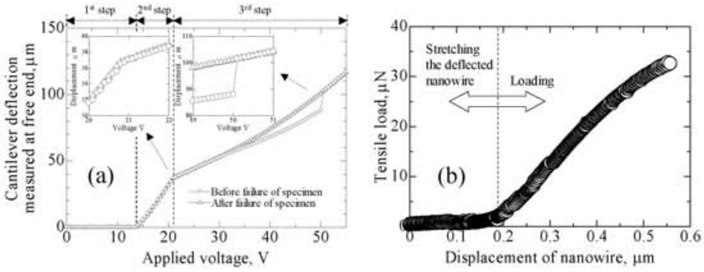

Fig 5 (a) Cantilever deflection as a function of applied voltage. (b) Tensile load-displacement curve of carbon nanowire.

produced at the FIB-CVD process. Tensile displacement under no loading in the initial stage of the tensile test was required to extend the deflected nanowires to full-length. Young's moduli for the carbon nanowires were 53.7 GPa, 51.3 GPa and 74.7 GPa for the *EANAT*s with 1000, 3000, and 5000 pairs of actuators, respectively. Fracture stress and strain ranged from 3.9 GPa to 4.6 GPa, and from 0.074 to 0.094, respectively. The electrical resitivity was about 0.0023 Ωm under no loading, whereas the resistance change ratio less than 1% with increasing tensile load was slightly obtained. The high stiffness of FIB deposited carbon nanowire would therefore be sufficient to use as a nanometric structural material in NEMS.

3. Conclusions

In the structural design of NEMS, the element size effect on mechanical properties has to be considered. As the size scale is reduced, surface effects may begin to dominate the material response; consequently, bulk properties measured on larger specimens are no longer valid. For purposes of design and engineering innovation in NEMS, it is essential to establish experimental technology for nanomechanics.

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