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

i) SIMOX wafer
ii) Si etching
iii) SiO2 etching
iv) Anodization
v) Si etching
vi) SiO2 etching

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

<table>
<thead>
<tr>
<th>Upper width</th>
<th>Lower width</th>
<th>Thickness</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>200</td>
<td>255</td>
<td>6</td>
</tr>
<tr>
<td>500</td>
<td>500</td>
<td>255</td>
<td>6</td>
</tr>
<tr>
<td>1000</td>
<td>1000</td>
<td>255</td>
<td>6</td>
</tr>
</tbody>
</table>

Nominal dimensions of nanometric Si wires

Maximum strain $\varepsilon_{\text{max}}$, %

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Maximum strain $\varepsilon_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>295 K</td>
<td>$\varepsilon_{\text{max}} = 200 \text{ nm}$</td>
</tr>
<tr>
<td>373 K</td>
<td>$\varepsilon_{\text{max}} = 300 \text{ nm}$</td>
</tr>
<tr>
<td>573 K</td>
<td>$\varepsilon_{\text{max}} = 300 \text{ nm}$</td>
</tr>
</tbody>
</table>

Results and discussions

Results of AFM bending test

Variation of Young's modulus with increasing temperature

$\rightarrow$ Young's modulus decreases with an increase of the test temperature, but has no size effect.

Nanometric Si wires fracture in a brittle manner at room temperature, whereas Si wires deform plastically at intermediate temperatures.
Results and discussions

Weibull plot of bending strength

The bending strength of the 200 nm-wide wires ranges from 17.76 to 15.87 GPa, 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.

Plastic deformation behavior

Critical resolved shear stress \( \tau_c \) is inversely proportional to wire size and temperature.

Plastic strain range \( \Delta \varepsilon_p \) 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

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

Arhenius formula: \( \dot{\varepsilon} = \dot{\varepsilon}_0 \exp \left( \frac{-\Delta G(\tau, T)}{kT} \right) \)