MEMS-BASED MECHANICAL CHARACTERIZATION OF CORE-SHELL SILICON CARBIDE NANOWIRES FOR HARSH ENVIRONMENTAL NANOMECHANICAL ELEMENTS

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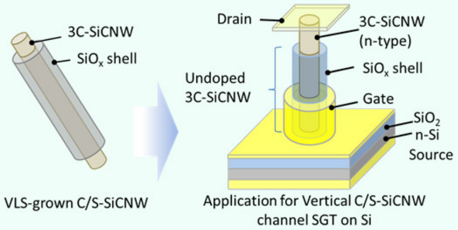
ABSTRACT **:** This research clarified mechanical properties of core-shell silicon carbide nanowires (C/S-SiCNWs) grown by a vapor-liquid-solid (VSL) technique, using newly developed Electrostatically Actuated NAnotensile Testing devices (*EANAT*s). The C/S-SiCNWs consist of a crystalline cubic silicon carbide (3C-SiC) core with <111> axis wrapped by an amorphous SiOx shell. The stress-strain relations for individual C/S-SiCNWs and 3C-SiCNWs without the SiOx shell have been successfully obtained from the nanotensile tests using *EANAT*s. Young's modulus of the C/S-SiCNWs was 247.2 GPa whereas that of the 3C-SiCNWs showed a quite different value of 498 GPa on average. The tensile strengths for C/S- and 3C-SiCNWs showed 7.0 GPa and 22.4 GPa on average, respectively, which are enough huge values as a structural material of MEMS/NEMS.

Background and Experimental Procedures

Surrounding Gate Transistors Using 3C-SiCNWs



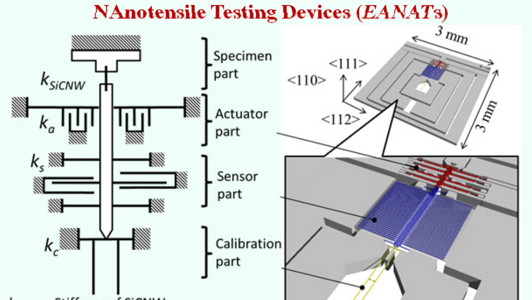
VLS-grown C/S-SiCNW

Application for Vertical C/S-SiCNW channel SGT on Si

● 3C-SiC has a lower interface level density at the MOS interface than 4H-SiC, and it shows high channel mobility. These properties of 3C-SiC is effective for MOS devices with a high electric current.

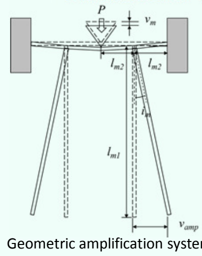
● The C/S-SiCNWs consist of a 3C-SiC core wrapped by a SiOx shell, which is directly effective for SGTs and SGT-based mechanical sensors.

Design of Electrostatically Actuated NAnotensile Testing Devices (*EANAT*s)

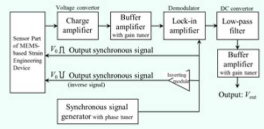


k_{SiCNW} : Stiffness of SiCNW
k_a, k_s, k_c : Stiffness of each suspension

Calibration of Tensile Displacement



Geometric amplification system

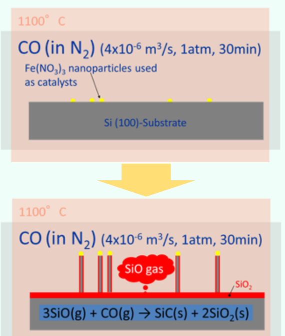


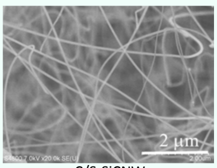
Charge amplifier connected to the displacement sensor on *EANAT*s

Accurate measurement of tensile displacement with a fine resolution of sub-nm

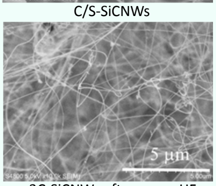
The calibration part consists of the doubly-clamped beam with two long-cantilevers symmetrically placed on the beam, which can play a role of geometric amplification system with a factor of 20 for a deflection of the beam.

VLS Growth of Core-Shell Silicon Carbide Nanowires





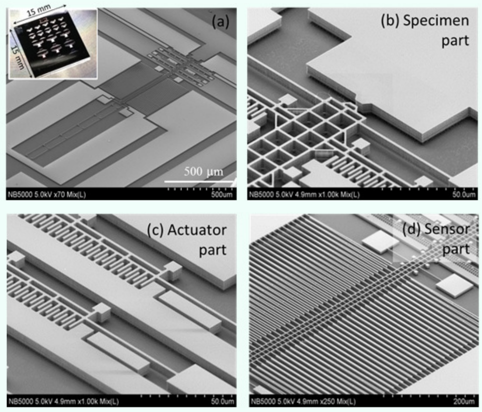
C/S-SiCNWs



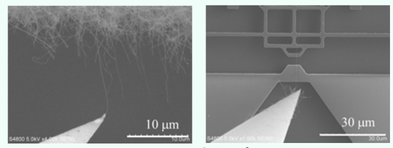
3C-SiCNWs after vapor HF

In the VLS process, any Si-related gaseous species such as SiH_4, $SiCl_4$, and SiH_2Cl_2 etc. were not supplied, but only CO and N_2 gases. The precursor of Si was probably supplied from the substrate, in particular gaseous SiO species would be released from the substrate at high temperature. Consequently, the chemical reaction to grow C/S-SiCNWs would be produced on the catalysts. The reaction products of H_2SiF_6 after the vapor HF process are not released from the surface of 3C-SiCNWs.

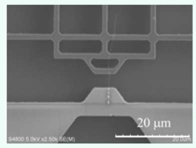
SEM Images of *EANAT*s & Nanomanipulation of SiCNWs



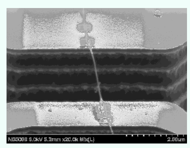
The new *EANAT*s were miniaturized in comparison with the previously proposed devices, so that 16 devices were simultaneously fabricated on a 15 × 15 mm²-chip for a sequential testing.



In-situ SEM manipulation for SiCNWs



Temporal fixing of SiCNWs by EBIC deposition

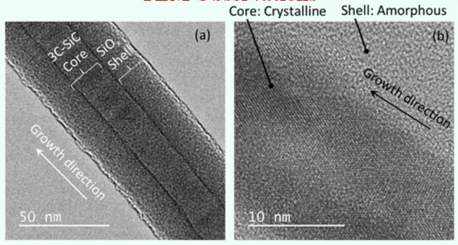


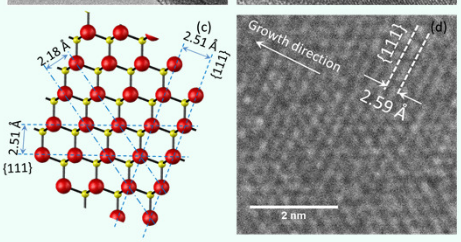
Fixing of SiCNWs by FIB

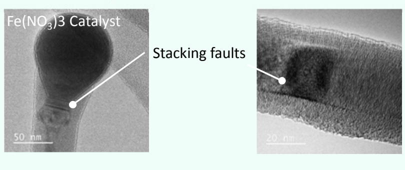
The *in-situ* SEM nanomanipulation system was employed to pick an individual C/S- or 3C-SiCNW from a substrate and to fix it on *EANAT*. The focused electron beam (EB) in the SEM can temporally fix the SiCNW on the *EANAT* with the EB-induced carbon contamination deposition.

Results and Discussions

TEM Observations

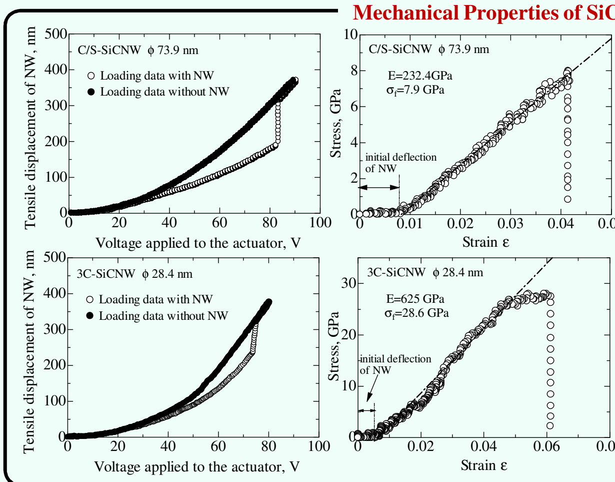


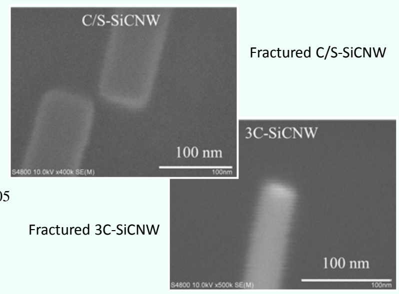




The C/S-SiCNW was formed by the crystalline core with <111> axis wrapped by an amorphous layer. The crystalline structure of core is obviously identified as a cubic with a lattice interval about 2.59 Å along the growth direction, which is consistent with the distance between {111} planes of 3C-SiC of 2.51Å. Stacking faults along {111} and amorphous regions are occasionally observed in the core.

Mechanical Properties of SiCNWs



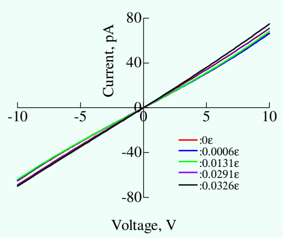


Fractured C/S-SiCNW

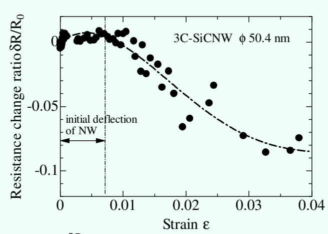
Fractured 3C-SiCNW

We have successfully examined relationships between the tensile displacement and the voltage applied to the actuator. The tensile force of sample is derived from the difference in the displacement between before and after the failure of sample. Thus, we can obtain tensile stress-strain relations, and can estimate mechanical properties of individual C/S- and 3C-SiCNWs.

Piezoresistive Effect of 3C-SiCNWs



I-V characteristics with increasing tensile strain



$\frac{\delta R}{R_0} = \varepsilon \times \text{G.F.}$ G.F. = −4.51 @ 0.017 ε

The piezoresistive effect of individual 3C-SiCNW was evaluated for an usage of nanomechanical sensing element. The resistivity of the unstrained 3C-SiCNW was 157 GΩ, but it gradually decreased with an increase of uniaxial tensile strain.

The gauge factor was estimated to be -4.51 at 0.017 ε, namely the 3C-SiCNW behaves as a n-type semiconductor, which is caused by the slight diffusion of $Fe(NO_3)_3$ in the 3C-SiCNW during the VLS process.

Although the gauge factor is small, 3C-SiCNWs are effective for a piezoresistance element in harsh environments if we add impurities to NWs.