DIRECT MEASUREMENT OF SHEAR PIEZORESISTANCE COEFFICIENT ON SINGLE CRYSTAL SILICON NANOWIRE BY ASYMMETRICAL FOUR-POINT BENDING TEST

Taiki KIMURA, Naoki SAITO, Toshimitsu TAKESITA, Koji SUGANO and Yoshitada ISONO
Graduate School Student, Graduate School of Engineering, KOBE University, JAPAN

ABSTRACT : This research evaluated the shear piezoresistance property of *p*-type single crystal silicon nanowire (SiNW) by the asymmetrical four-point bending (AFPB) technique proposed by the authors. We fabricated the *p*-type SiNW on the AFPB test specimen with "V"-shaped notches (V-notches) made of single crystal silicon. Bending the specimen by the asymmetrical four point-supports, simple shear stress can be produced at the center of the specimen. Consequently, we have succeeded in evaluating the shear piezoresistance coefficient of SiNW directly, which was found to be π_{44}=203 × 10^{-11} Pa^{-1} at an impurity concentration of 7.3 × 10^{18} cm^{-3}. This value is 2.1 times larger than that of *p*-type piezoresistors used in conventional piezoresistance sensors on a micrometer scale. The proposed evaluation technique and obtained result will be effective for design application of high-sensitivity mechanical sensors integrating SiNW piezoresistance elements.

Background

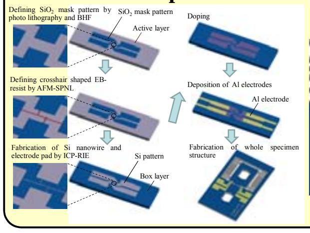
One-dimensional silicon nanowires (SiNW) : highly sensitive piezoresistance elements for mechanical force sensors because of a drastic change in the electronic structural features such as their band gap and effective mass under enormous mechanical strain.

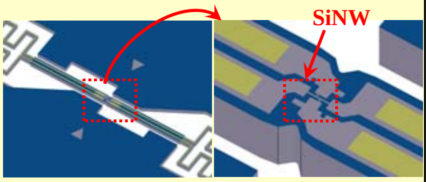
Problem : Few data of shear piezoresistance properties for SiNWs have so far hindered the reliable designing and optimizing high-sensitivity mechanical sensors.

Purpose : to evaluate the shear piezoresistance property of p-type single crystal SiNW by **the asymmetrical four-point bending (AFPB) testing** proposed by the authors.

Overview of AFPB test specimen

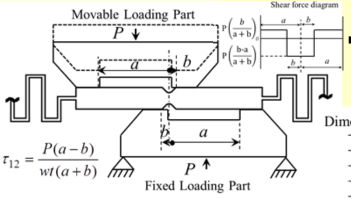
AFPB test specimen and four-terminal SiNW on the specimen part





AFPB test specimen and measurement principle

Asymmetrical four-point bending (AFPB) test specimen



$$\tau_{12} = \frac{P(a-b)}{wt(a+b)}$$

- The specimen part is sandwiched between the movable and fixed loading parts to apply a compressive load to the specimen at four point-supports.
- The bending moment is completely canceled at the center of the specimen part between the bottoms of V-notches: thus shear stress is produced at the center.

Dimensions of AFPB specimen (μm)

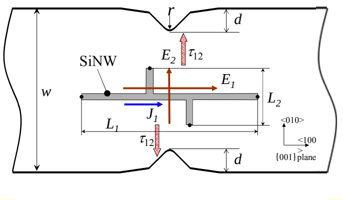
Width ,	w	29.8
Thickness,	t	39.0
Depth of notch,	d	6.0
Notch radius,	r	2.33

Dimensions of four-terminal SiNW (μm)

Length, L_1	8.66
Length, L_2	2.07
Width	0.85
Height	0.80

Four-terminal SiNW and theory of piezoresistive response

Magnified illustration at the center of AFPB specimen



$$E_i = \rho J_i + \rho \pi_{ijkl} \sigma_{kl} J_j$$

$$E_1 = \rho(1 + \pi_{11}\sigma_{11} + \pi_{12}\sigma_{22})J_1,\ E_2 = \rho \pi_{44} \tau_{12} J_1$$

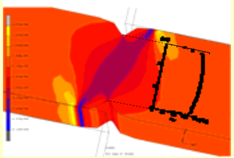
$$\left[\begin{array}{l} V_1 = \rho J_1 L_1 + \rho J_1 \int_0^{L_1} (\pi_{11}\sigma_{11} + \pi_{12}\sigma_{22})dx \\ V_1 \cong \rho J_1 L_1 \quad \text{(when } \sigma_{11} \text{ and } \sigma_{22} \text{ are negligible)} \\ V_2 = \frac{L_2}{L_1} \pi_{44} \tau_{12} V_1 \quad \therefore \boldsymbol{\pi_{44}} = \frac{L_1}{L_2}\frac{V_2}{V_1}\frac{1}{\tau_{12}} \end{array}\right.$$

π_{44} can be determined from measurement of voltages, V_1 and V_2, depending on the shear stress.

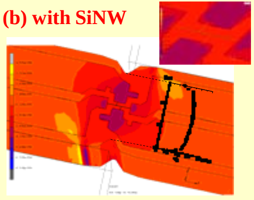
Experimental and Analytical results

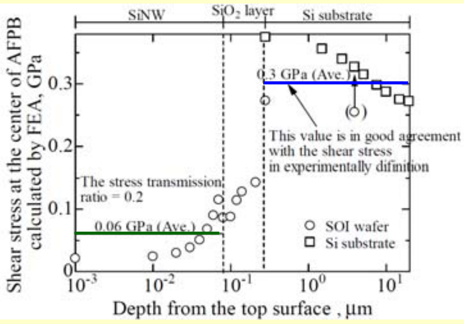
Analytical results of shear stress distribution

(a) without SiNW



(b) with SiNW

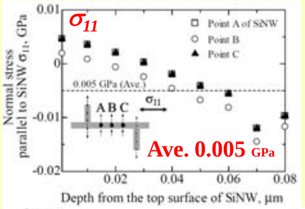


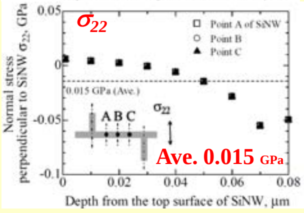


Since the shear stress of the SiNW is generated only 0.06 GPa on an average, stress generated in the silicon substrate is not fully transmitted to the SiNW.

(Ave. Shear stress of the Si substrate) = 0 .3 GPa
(Ave. Shear stress of the SiNW) = 0.06 GPa

⇒ (Stress transmission ratio) = 0.2

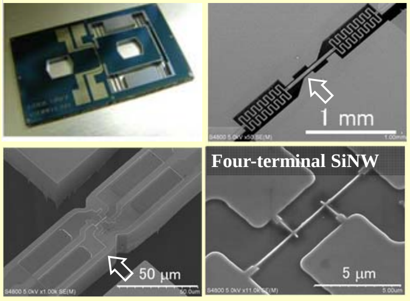




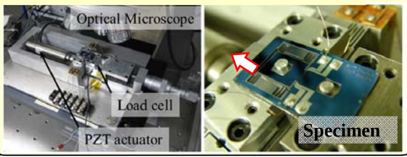
⇒ σ_{11} and σ_{22} were negligible. The equation $V_1 \cong \rho J_1 L_1$ is appropriate.

Fabrication results and Experimental setup

Specimen fabrication results



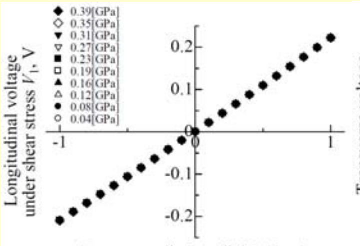
Shear loading tester and specimen



Experimental results of voltage under shear stress

- Applying a constant current to the SiNW in the longitudinal direction, voltages of V_1 and V_2 are measured under several shear stresses.

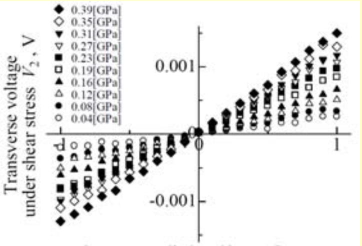
Longitudinal voltage, V_1



(a) V_1-I_1 characteristic

⇒ The ratio of V_1 to I_1 did not depend on shear stresses.

Transverse voltage, V_2

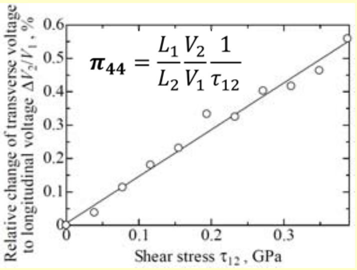


(b) V_2-I_1 characteristic

⇒ The ratio of V_2 to I_1 depended on the shear stress.

Evaluation of the shear piezoresistance coefficient, π_{44}

- π_{44} was directly determined from the relationship between the relative change of $\Delta V_2/V_1$ and the shear stress.



- Under consideration of *the stress transmission ratio of 0.2* at an impurity concentration of 7.3 × 10^{18} cm^{-3}

  π_{44} = 32.3 × 10^{-11} Pa^{-1}

- Under consideration of the effect of the *anisotropic electrical conductance* on the transverse voltage

  π_{44} = 203 × 10^{-11} Pa^{-1}

  $(\pi_{44} \cong 1.486 \tan(L_2/L_1)(V_2/V_1)/\tau_{12})$

⇒ 2.1 times larger than that of *p*-type piezoresistors.

This research has quantitatively evaluated the shear piezoresistance coefficient, π_{44}, of the single crystal SiNW by our AFPB testing method.