Supplementary Materials: Design of MEMS Tensile Testing Device

Toshiyuki Tsuchiya, Tetsuya Hemmi, Jun-ya Suzuki, Yoshikazu Hirai and Osamu Tabata

S1.1. Principle

Figure S1 shows a schematic of the MEMS tensile testing device. The device consists of a parallel plate actuator for loading force, differential parallel plate capacitive displacement sensor and seven support beams of two types. The force F_s applied on the specimen was calculated as;

$$F_s = F - k_b d \tag{S1}$$

where F is the force generated on the specimen and k_b is total stiffness of the support beams. In this research the force F_s was calculated using theoretical formulas described below and by measuring the displacement d of moving part using the displacement sensor, the tensile force on the specimen is obtained using Equation S1.

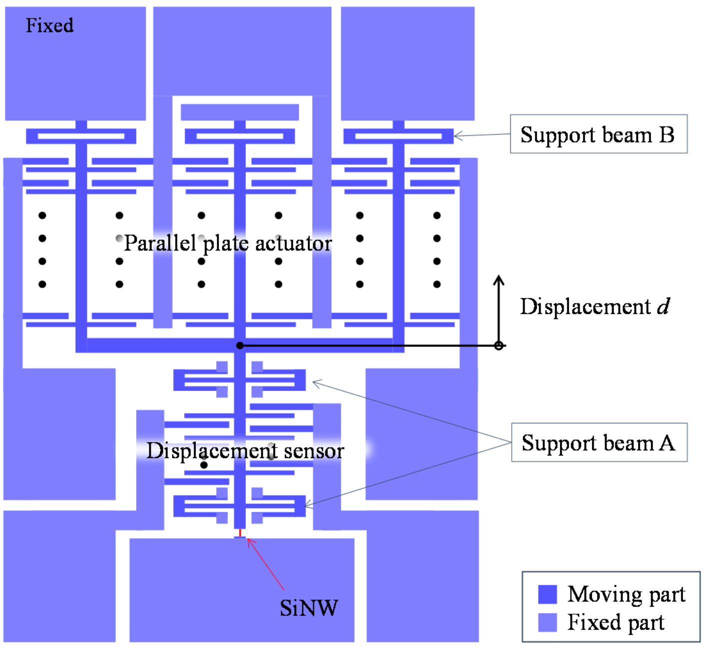

Figure S1. Schematic of tensile testing device.

The specifications of the device is listed in Table S1. The stiffness of specimen is calculated with the Young's modulus of Silicon of 168.9 GPa and the dimensions of SiNW of 100 nm in diameter and 5 µm long. The tensile strength was estimated to 3 GPa.

Table S1. Design target values and specifications.

Specimen stiffness: k_s [N/m]	265
Thickness: h [µm]	5
Maximum applied voltage: V_{max} [V]	30
Capacitance detection circuit resolution: [fF]	0.1
Fracture strength: [µN]	30
Fracture displacement: [nm]	90
Required force for actuator: [µN]	45
Displacement resolution: [nm]	1

Force resolution: [nN]	300

S1.2. Parallel Plate Electrostatic Actuator

Figure S2 shows the schematic design of one unit of parallel plate electrostatic actuator.

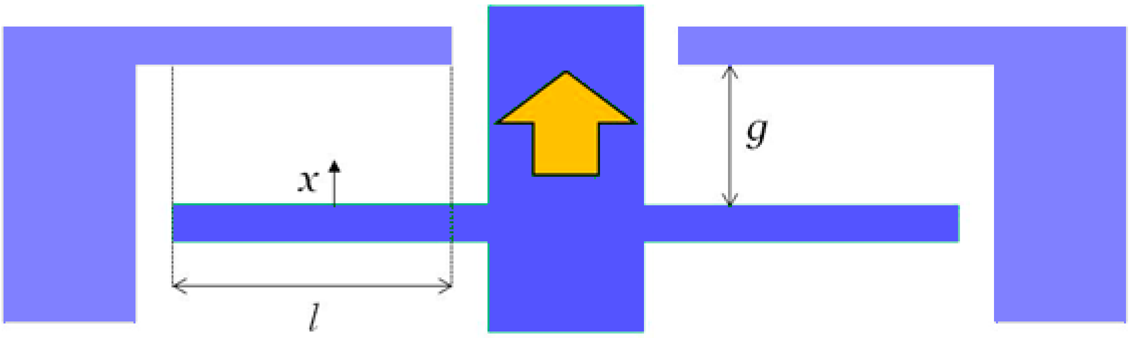

Figure S2. Unit design of parallel plate electrostatic actuator.

Electrostatic force F as a function of the displacement x of moving part is described as,

$$F = \frac{1}{2}\frac{N\varepsilon_0 hl}{(g-x)^2}V^2 \qquad \text{(S2)}$$

where N is the number of gaps, ε_0 is the permittivity, V is the applied voltage, h is the thickness and l is the overlapping length of parallel prate actuator. Table S2 shows the designed parameters. Fig. S3 is the plot showing the electrostatic force as a function of applied voltage. The force of 49.2 μN is generated at the voltage of 20 V.

Table S2. Design value of parallel drive actuator.

Overlap length of parallel drive actuator: l [μm]	200
Gap between electrode: g [μm]	3
Number of parallel plate gap: N	93

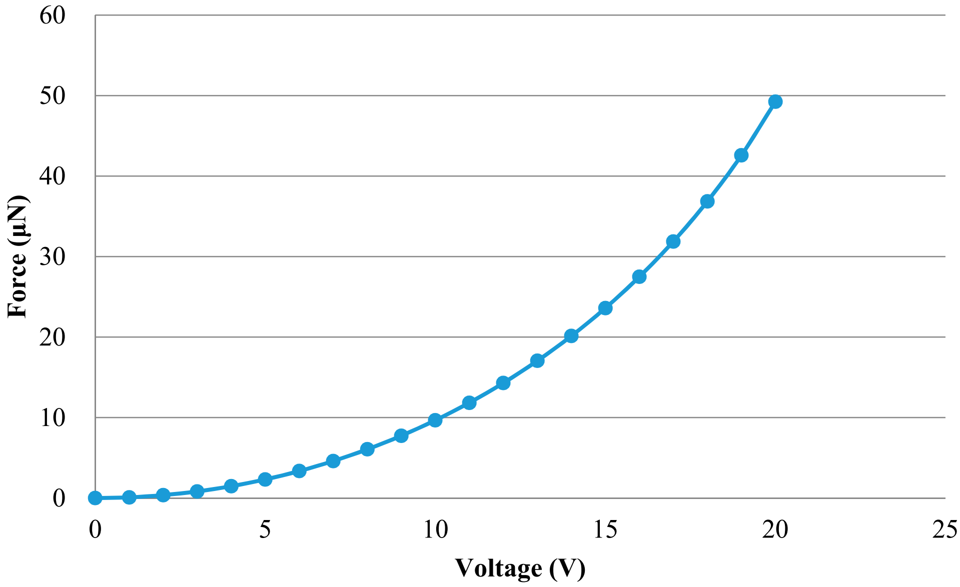

Figure S3. Calculation of parallel drive actuator.

S1.3. Parallel Plate Capacitive Displacement Sensor

Fig. S4 shows the schematics of a set of the parallel plate capacitive displacement sensor. The parallel plate capacitances C_1 and C_2 is formed between the fixed electrodes on the both (left and right) sides and the center moving part, respectively.

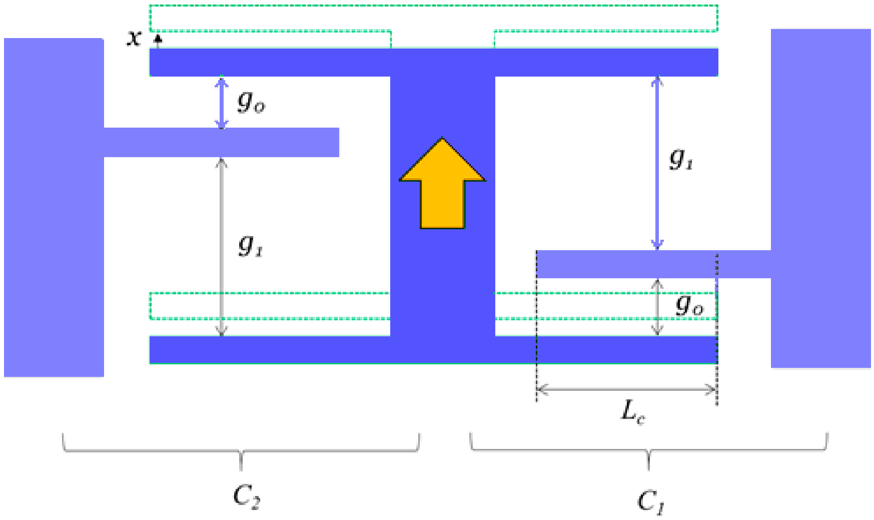

Figure S4. Unit design capacitive displacement sensor.

Assuming that the displacement x is much smaller than the gaps, the differential capacitance change ΔC is approximated as a following linear relationship,

$$\Delta C \cong 2\varepsilon_0 L_c h \left(\frac{m}{{g_0}^2} + \frac{n}{{g_1}^2}\right) x \quad \text{(S3)}$$

where g_0 and g_1 are the narrower and wider gaps of parallel plate, and m, n are the numbers of them on each side, respectively. The overlapping length is L_c.

The required displacement resolution of the device is 1 nm to realize tensile testing of SiNW. The resolution of capacitance readout circuit was measured in our previous research and was 0.1 fF/nm. Table S3 is the calculated parameter with this condition. The calculated plot of capacitance change against the displacement of moving part is shown in Fig. S5. The sensitivity of the voltage output of readout circuit is 18 mV/nm. The measurement resolution of the tensile force is 120 nN, sufficiently small for tensile testing of SiNW.

Table S3. Design value of displacement sensor.

Electrode length: $L_{electrode}$ [μm]	310
Overlap length of electrode: L_c [μm]	300
Electrode width: w [μm]	3
Gap between electrode: g_0 [μm]	2
Gap between electrode: g_1 [μm]	6
number of gap g_0: m	17
number of gap g_1: n	16

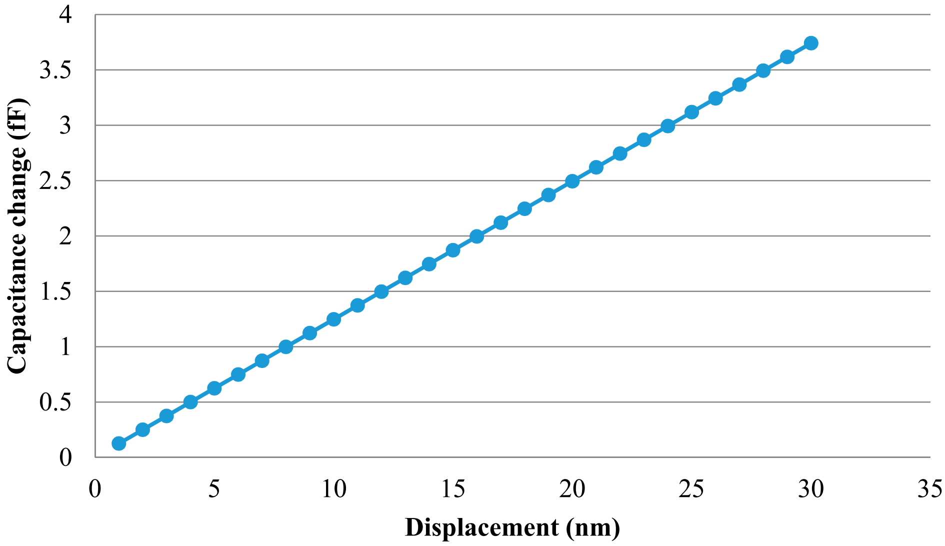

Figure S5. Differential capacitance change of displacement sensor.

The capacitive displace sensor also generates the electrostatic force F_{Sensor}, which is given by,

$$F_{Sensor} = 2\varepsilon_0 L_c h \left(\frac{m g_0}{({g_0}^2 - x^2)^2} + \frac{n g_1}{({g_1}^2 - x^2)^2} \right) x V^2 \quad \text{(S4)}$$

The input bias voltage of the capacitance readout circuit is 2.5 V, which is applied on the sensor. The electrostatic force as a function of moving part displacement is shown in Fig. S6. The force is small compared to the force by the actuator..

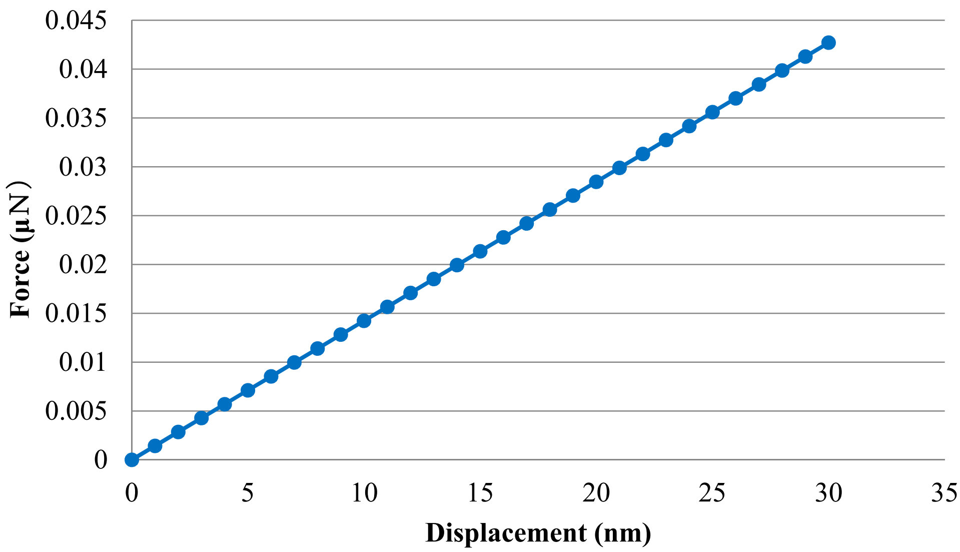

Figure S6. Electrostatic differential force generated by displacement senor.

S1.4 Supporting Beam

The tensile testing device has two types of supporting beams as shown in Fig. S1. Four type A springs near the displacement sensor and three type B springs are connected in parallel to support the moving part. The total stiffness along the tensile (moving) axis is designed as 120 N/m and 60 N/m, so as to have same with the SiNW specimens. In addition, the out of plane stiffness is designed as high as 200 N/m to avoid stiction of the moving part to substrate.

(1) Type A

The in-plane and out-of-plane stiffnesses of Type A spring are calculated by using an equivalent lumped parameter model, as shown in Fig. S7, consisting of two identical springs in parallel and the other spring connected in serial to them.

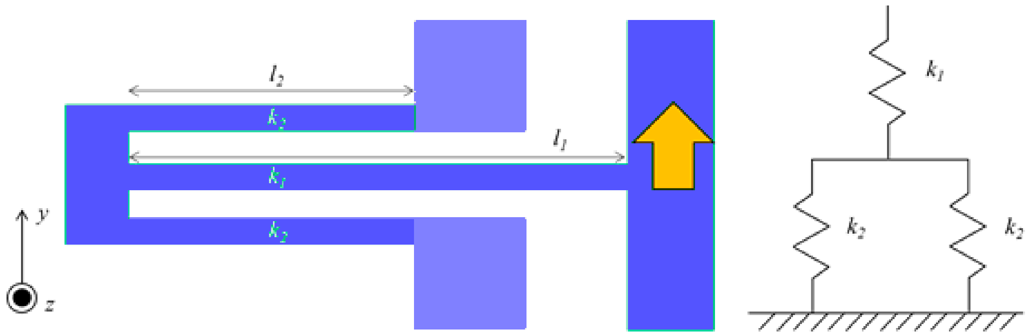

Figure S7. Type A spring.

The in-plane (along *y*-axis) stiffness k_{iy} of each cantilever beam spring is given by

$$k_{iy} = \frac{E_{Si} h w^3}{{l_i}^3} \qquad (i = 1,2) \qquad \text{(S5)}$$

and out-of-plane (*z*-axis) stiffness is given by

$$k_{iz} = \frac{E_{Si} w h^3}{{l_i}^3} \qquad (\mathrm{i} = 1,2) \qquad \text{(S6)}$$

where E_{Si} is the Young's modulus of silicon and *w* is the width of beam springs.

The total stiffness of y and z directions K_y, K_z is calculated as,

$$K_y = \left(\frac{2\ k_{1y}\ k_{2y}}{2\ k_{2y} + k_{1y}}\right), K_z = \left(\frac{2\ k_{1z}\ k_{2z}}{2\ k_{2z} + k_{1z}}\right) \qquad \text{(S7)}$$

Table S4 shows the designed parameters of the type A spring.

Table S4. Parameters of designed spring (Type A).

Target spring constant: *k* [N/m]	60	120
beam height: *h* [μm]	5	5
beam width: *w* [μm]	5	5
beam length: l_1 [μm]	220	175
beam length: l_2 [μm]	185	150
Spring constant: k_1 [N/m]	9.9	19.7
Spring constant: k_2 [N/m]	16.68	31.3
Spring constant: *K* [N/m]	7.6	14.9

(2) Type B

The schematics of type B spring is shown in Figure S8.

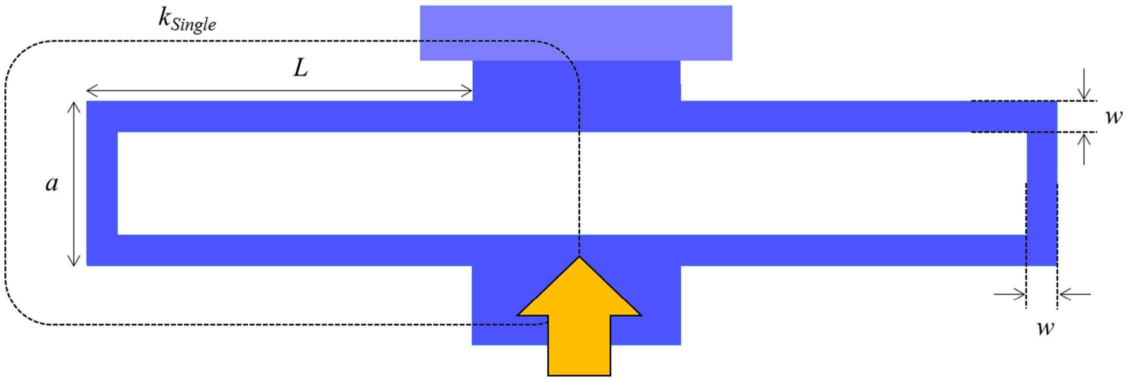

Figure S8. Type B spring.

The in-plane (y-axis) stiffness k_y of the o-shaped spring is,

$$k_y = 2k_{single} = \frac{E_{Si}w^3h(2L+a)}{2L^3(L+2a)} \tag{S8}$$

and, the out-of-plane (z-axis) stiffness k_z is.

$$k_z = 2\frac{E_{Si}h^3w}{L^3} \tag{S9}$$

Table S5 shows the designed parameters of the type B spring. The total stiffness of parallel connections of the three type A springs and four type B springs is shown in Table S6. The devices are indicated the nominal target spring constant *k*.

Table S5. Parameters of designed spring (Type B).

Target spring constant: *k* [N/m]	**60**	**120**
Beam length: *L* [μm]	170	134
Beam length: *a* [μm]	12	12
Beam length: *b* [μm]	4	4
Spring constant: k_y [N/m]	9.9	19.9
Spring constant: k_z [N/m]	68.4	140

Table S6. Spring constants.

Target spring constant: *k* [N/m]	60	120
Spring constant: k_y [N/m]	60.5	119.7
Spring constant for z direction: k_z [N/m]	162.6	329.6