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Supplementary Information

Electrical properties of Flexible Multi-channel Si Nanowire Field-Effect Transistors Depending on the Number of Si Nanowires

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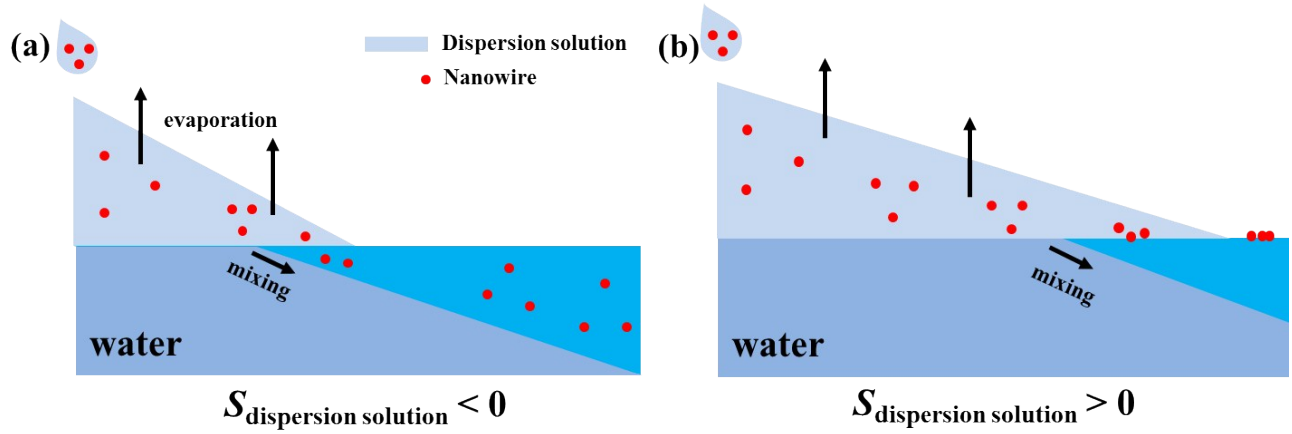


Fig. S1. Schematic illustration showing the formation of uni-directional nanowires on water surface base on spreading coefficient.

When the dispersion solution (alcohol) is dropped on a water surface, it quickly spreads on the water surface and generates a temporary alcohol-water bilayer. Some fraction of the alcohol evaporates, and the other is gradually mixed in the water. Once the alcohol is dropped on water, the NWs in alcohol spread on the water surface along the alcohol flow. Here, the spreading coefficient (S) is defined as follows: $S = \gamma_{w,a} - (\gamma_{alc,w} + \gamma_{alc,a}) = (\gamma_{w,a} - \gamma_{alc,w}) - \gamma_{alc,a}$, where $\gamma_{w,a}$, $\gamma_{alc,w}$, and $\gamma_{alc,a}$ are the interfacial tensions between water-air, alcohol-water, and alcohol-air, respectively. The NWs themselves do not have sufficient affinity to be

able to spread on the water surface because of the hydrophobic part of Si molecules. However, alcohol can spread itself because alcohol renders the surface hydrophilic and have the positive *S*. Therefore, the NWs diluted in alcohol can spread on the water surface.

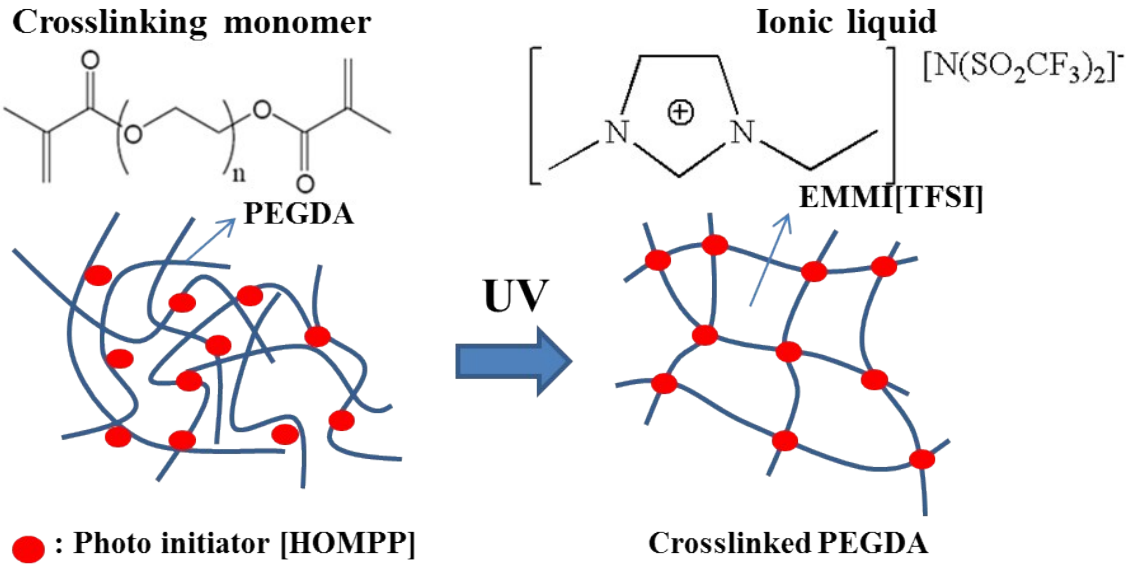


Fig. S2. Chemical structures of the ionic liquid and UV crosslinkable monomer exhibiting a mechanism of ion-gel polymerization.

To apply the ion-gel gate dielectric, a photo patternable solution consisting of poly(ethylene glycol) diacrylate [PEGDA] crosslinking monomer, 2-hydroxy-2-methylpropiophenone [HOMPP] photo initiator, and 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl) imide [EMIM][TFSI] ionic liquid is drop-casted onto Au electrodes/Si NWs/PI structure and a square-patterned film mask was placed on the solution. Then, UV exposure on the solution generated free radicals from [HOMPP] that initiated polymerization of acrylate end groups on PEG derivatives. Furthermore, since the patterned ion-gel was covalently bonded to the PI substrate during the UV crosslinking, the Si NWs were protected from external damages and bending stress.

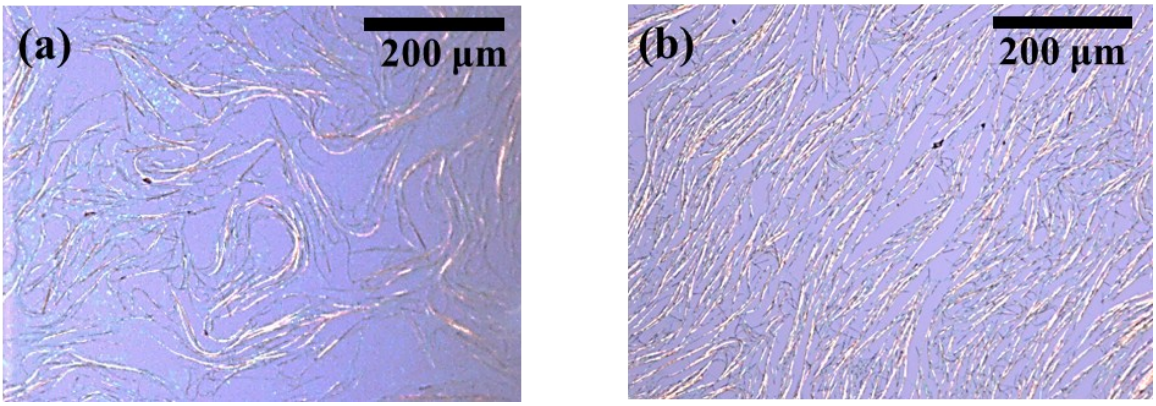


Fig. S3. The OM images of (a) randomly aligned Si NWs with 40 μm in the average length and (b) directionally aligned Si NWs with 20 μm in the average length.

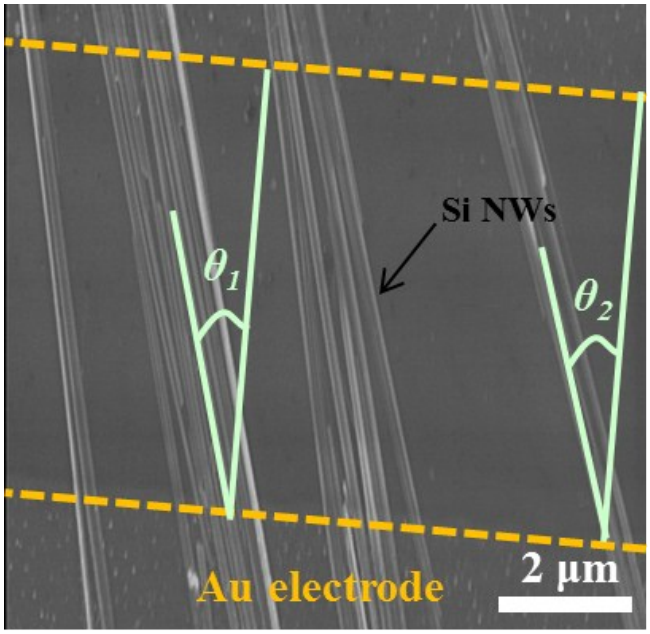


Fig. S4. The SEM image of the multi-channel FET with 37 Si NWs exhibiting tilted angles of Si NWs from a perpendicular line between electrodes.

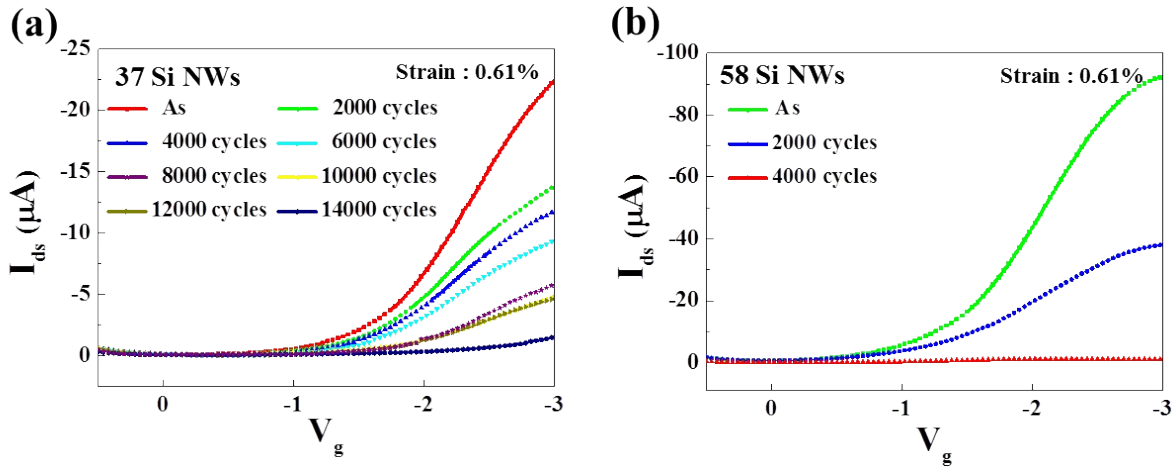
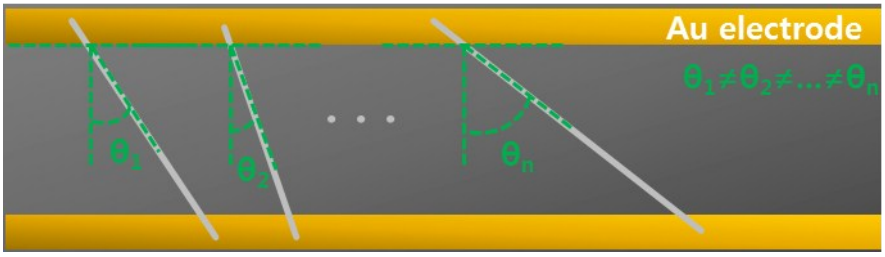


Fig. S5. The transfer curves of flexible Si NWs FETs as a function of bending cycle; the aligned number of Si NWs were (a) 37 and (b) 58, respectively.

Definition 1. Total correction factor (*k*)

Even though the Si NWs were aligned uni-directionally, the θ (tilted angles of Si NWs from a perpendicular line between electrodes) of Si NWs are not identical each other. When θ is not 90˚, the channel length (=the length of Si NWs linked source and drain electrodes) is not same as the distance between source and drain electrodes. So, the correction factor of $cos\theta_i$, where θ_i is the tilted angle of i_{th} Si NW, needs to be considered to calculate electrical properties of the FETs.

If NWs are located between electrodes and NWs have different tilted angles to electrodes ($\theta_1 \neq \theta_2 \neq \ldots \neq \theta_n$), the lengths of NWs are different and equation for calculating the mobility of FET should be complicatedly modified.



$$\mu_h = L/(W \times C_d \times V_{ds}) \times g_m \times k$$

$$= L/((d \times n) \times C_d \times V_{ds}) \times g_m \times \frac{\sum_i^n cos\theta_i}{n}$$

Where, d= mean diameter of Si NWs,

n= the number of Si nanowires located between electrodes,

k= total correction factor ($\frac{\sum_i^n cos\theta_i}{n}$)

To simply solve this problem, it is assumed that the lengths of NWs are equal (set a standard channel length to gap distance of electrodes, 10 μm, in this study) and the losses in lengths are compensated by the correction factor. If a NW located between electrodes is tilted about θ_1° from standard line, the ratio of real length of NW and standard length is equal to

$\cos\theta_1$. When n of NWs with different tilted angles are hanged, the total correction factor (k) can be indicated as '$\frac{\sum_i^n cos\theta_i}{n}$'. In this paper, the correction factor was applied to calculate the electrical property of the Flexible Multi-Channel Si NW FETs.

Experimental section

Preparation of Si NWs monolayer: The p-type Si NWs with 122 nm in the average diameter and 20 μm in the average length were synthesized by a MCE process from a boron-doped p-type Si wafer (< 100 >, 1-10 Ω·cm) following our previous work[23] and the stepwise reaction is described below:

- Cathode reaction

The noble metal acts as cathodic reaction site and H_2O_2 is reduced by noble metal.

$$H_2O_2 + 2Ag + 2H^+ \rightarrow 2H_2O + 2Ag^+ \quad [1]$$

- Anode reaction

When Si is in the tetravalent state,

$$Si + 4Ag^+ + 4HF \rightarrow SiF_4 + 4Ag + 4H^+ \quad [2]$$

$$SiF_4 + 2HF \rightarrow H_2SiF_6 \quad [3]$$

When Si is in the divalent state,

$$Si + 4HF_2^- \rightarrow SiF_6^{2-} + 2HF + H_2\uparrow + 2e^- \quad [4]$$

The mixed reaction of tetravalent and divalent dissolution is as follows:

$$Si + 6HF + nh^+ \rightarrow H_2SiF_6 + nH^+ + \frac{4-n}{2}H_2\uparrow \quad [5]$$

- The overall reactions are as follows:

$$\frac{n}{2}H_2O_2 + nAg + nH^+ \rightarrow nH_2O + nAg^+ \quad [6]$$

+

$$Si + 6HF + nAg^+ \rightarrow H_2SiF_6 + nH^+ + nAg + \frac{4-n}{2}H_2\uparrow \quad [7]$$

=

$$Si + \frac{n}{2}H_2O_2 + 6HF \rightarrow nH_2O + H_2SiF_6 + \frac{4-n}{2}H_2\uparrow \quad [8]$$

At the interface between Ag and etchant, Ag is oxidized by H_2O_2 (cathode reaction) and forms Ag^+ ion in the vicinity of the Ag film. This Ag^+ ion is subsequently reduced back to Ag (anode reaction) preferably onto the surface of Ag film instead of Si, since Ag is more electronegative than Si. Meanwhile, Si is oxidized by HF resulting in the formation of Si NWs.[1]

Prepared Si NWs were dispersed in isopropyl alcohol (IPA) with 0.05% dilute hydrazine hydrate (N_2H_4). To align the Si NWs on a 15 μm-thick PI substrate, the LB alignment method was applied. The Si NWs in IPA were dropped on DI water in a square dish and the monolayer of Si NWs with the uni-direction was formed on the water surface. In this process, the number of Si NWs was controlled by adjusting the density of Si NWs in a dispersion solution. A dispersion solution with the density of 9.8×10^9 NWs/mL was used for the devices linked by 15, 22, and 29 Si NWs, while the solution with the density of 2.45×10^{10} NWs/mL was used for the devices linked by 37, 46, and 58 Si NWs. The PI, cleaned with acetone, methanol, and DI water for 10 min each, was put into the square dish and Si NWs monolayer floated on Di water was dipped up and transferred on the PI substrate.

Drop cast method for the sparsely distributed Si NWs alignment : The Si NWs-dispersed solution flowed on a 30°-tilted PI substrate in order for Si NWs to be aligned in parallel and dried at room temperature to eliminate IPA solvent and residual DI water.

Deposition of Au electrodes and positioning an ion-gel: 100 nm-thick Au layer was deposited on the aligned Si NWs as source and drain electrodes using a stencil mask with a 10 μm gap by e-beam evaporation. To form a flexible GI on the Au electrodes and Si NWs structure, 1-Ethyl-3-methylimidazolium bis(trifluoromethylsulgonyl) imide [EMIM][TFSI] ionic liquid, poly(ethylene glycol) diacrylate [PEGDA] monomer, and 2-hydroxy-2-methylpropiophenone [HOMPP] UV cross-linking initiator were mixed up at a ratio of 10:1:1 (w/w) and the mixture was dropped on the Au/Si NWs/PI structure. After dropping the mixture, a patterned mask was located on it and UV light (365 nm, 100 mW/cm^2) shone on the structure for 8 s, followed by rinsing with IPA to remove an uncured mixture. The morphologies of Si NWs and the structure of the device were investigated by using a scanning electron microscope (SEM, S-5000 HITACHI) and an optical microscope. The crystallographic characteristics of the synthesized Si NWs were analyzed by using a scanning transmission electron microscope (STEM, JEM-ARM 200F). The I-V characteristics of the multi-channel Si NWs FETs were measured by using an Agilent semiconductor parameter analyzer (Agilent B1500A Agilent Technologies). The flexibility of the device was verified

by using a bending machine (Flexible Materials Tester, Hansung Systems Inc).

References

1. Z. P. Huang, N. Geyer, P. Werner, J. D. Boor and U. Gösele, *Adv. Mater*., 2011, **23**, 285.