

Facile Fabrication of C 60 Fullerene Nanowhisker Gas Sensors Based on Electric-Dipole Mediated Gas Sensing

Kunichi Miyazawa

miyakuni@rs.tus.ac.jp

Nano Alloy Technology Inc.

Yumi Tanaka

Tokyo University of Science

Research Article

Keywords: fullerene nanowhisker, C60 , FET, gas sensor, electric dipole moment

Posted Date: June 29th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10146813/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

This paper presents a simple fabrication process of C_{60} fullerene nanowhisker (C_{60} FNW) gas sensors, and discusses a novel sensing mechanism based on dipole-induced dipole interactions between polar gas molecules and C_{60} p-electron systems at room temperature. Two-electrode and FET (field-effect transistor)-based three-electrode gas sensors were fabricated, where slit-gap-type C_{60} FNW-based FET gas sensors with graphite electrodes and circular-gap-type C_{60} FNW-based FET gas sensors with bamboo charcoal cloth electrodes were fabricated. Seebeck effect experiments showed the C_{60} FNWs synthesized using the liquid-liquid interfacial precipitation method exhibited p-type semiconducting properties, which was consistent with the measured semiconducting properties of the FET gas sensors. Polar gases like methanol demonstrated distinct sensor currents, whereas the non-polar gases, such as CCl_4 , exhibited no sensor response. An increase in electrical conductivity due to the reduction of the HOMO-LUMO gap of C_{60} molecules caused by the adsorption of polar molecules, along with an increase in the adsorption probability via the dipole-induced dipole moment interactions between the polar molecules and C_{60} molecules, produces a pronounced sensor response for polar gases. The FET sensors exhibited linear relationships between the source-drain voltage and source-drain current, as well as between the gate voltage and source-drain current.

1. Introduction

Among multiple types of gas sensors, including resistive, optical, electrochemical, and FET (field-effect transistor) sensors, chemiresistive gas sensors have been widely investigated due to their low cost and ease of fabrication [1]. Various semiconducting metal oxides, carbon-based materials, and transition metal dichalcogenides have been used as the sensing materials in chemiresistive gas sensors. In particular, a wide range of carbon-based materials such as graphene, graphene oxide (GO), reduced GO (rGO), and carbon nanotubes (CNTs) have been intensively investigated for the fabrication of high-performance chemiresistive gas sensors [2, 3].

Chemiresistive CNT-based sensors have been widely studied to detect various gases such as methane, ethanol, NO_2 , H_2S , H_2 , Cl_2 , SO_2 , NH_3 , H_2 , CO_2 , isopropanol, CO, ethylene, benzene, water, acetone, chloroform, isoprene, and others. CNT composites with various metals and oxides, such as Pd, Au, Rh, Co, Pt, ZnO, SnO_2 , TiO_2 , In_2O_3 , Cr_2O_3 , WO_3 , Cu_2O , and NiO, have been tested as sensing materials. Similarly, composites of graphene, rGO, and GO with various metal oxides, like TiO_2 , Co_3O_4 , Fe_2O_3 , SnO_2 , ZnO, WO_3 , In_2O_3 , NiO, and others, have also been investigated for chemiresistive sensing applications [2].

In addition to carbon-based chemiresistive sensors, quartz crystal microbalance (QCM) sensors using carbon-based materials have been developed. Ethanol, butanol, isopropanol (IPA), and acetone were detected using QCM sensors coated with graphene flakes, whereas trimethylamine, ethanol, CO_2 and NO_2 were detected using QCM sensors based on GO or rGO [2].

Although fullerenes are totally composed of carbon atoms, the sensor applications of fullerenes are limited compared to CNT, graphene, GO and rGO. C_{60} molecules have been tested as chemiresistive gas sensing materials by modifying the surface of the C_{60} nanoparticles with metal oxides such as SnO_2 for the detection of H_2S gas [4]. QCM sensors using C_{60} and C_{60} -aluminum composite films have been tested for water and ethanol gas sensing applications [5]. Bairi et al. synthesized hierarchically structured fullerene C_{70} cubes (HFC) to detect volatile aromatic solvent vapors using a QCM sensor [6]. Similarly, Wei et al. synthesized cornhusk-shaped C_{60} fullerene crystals and fabricated a QCM sensor for acetic acid vapor detection [7].

On the other hand, fullerene nanowhiskers (FNWs) are thin needle-like crystals of fullerene molecules that have diameters less than 1000 nm. Among various FNWs, C_{60} fullerene nanowhiskers (C_{60} FNWs) have been widely studied for applications in catalysis, electronics, energy, environmental, and biomedical fields [8, 9]. C_{60} fullerene nanotubes, i.e., tubular C_{60} FNWs, were investigated for the application of chemical sensor by forming complexes with DNA on the surface of a glassy carbon electrode, for dopamine detection in highly concentrated ascorbic acid in a neutral buffer solution [10].

The first application of C_{60} FNWs in electronic devices was a back-gate-type field effect transistor, where the authors proposed to use C_{60} FNWs for gas sensing [11]. Recently, Nobuoka et al. reported FET gas sensors employing polymerized C_{60} nanowires for nitrobenzene detection via change of electrical conductivity [12].

In contrast to C_{60} nanowires that were produced using the irradiation of high-energy $^{129}Xe^{23+}$ ions (450 MeV) [12], C_{60} FNWs can be mass produced via the liquid-liquid interfacial precipitation (LLIP) method using common tools such as glass containers and refrigerators [8, 13]. Although the electrical resistivity of C_{60} FNWs decreases with diameter [14, 15], they exhibit a high electrical resistivity in air owing to the formation of a surface oxidation layer [16], which hinders their chemiresistive gas sensor application in the ambient atmosphere. However, in this study, we demonstrate that the C_{60} FNWs sensor current can be monitored through a high-resistance resistor connected in series with the sensing part of the C_{60} FNWs at room temperature.

We fabricate a slit-gap-type FET C_{60} FNW gas sensor containing a narrow linear gap filled with C_{60} FNWs and graphite electrodes. Similarly, a circular-gap-type FET C_{60} FNW gas sensor was fabricated with a narrow circular gap filled with C_{60} FNWs and bamboo charcoal cloth electrodes. The sensors studied herein can be easily fabricated by using pieces of graphite foil, bamboo charcoal cloth, double-sided adhesive tape, Scotch tape, polyimide tape, glass, or silicon substrates. No surface treatment was required for the C_{60} FNWs which was used as sensing material.

The present study focuses on

(1) Electric current changes observed in the slit-gap-type two-electrode C_{60} FNW sensors exposed to various organic gasses with different electric dipole moments.

(2) Electric current changes observed in the slit-gap-type and circular-gap-type C_{60} FNW FET sensors measured as functions of the source-gate and source-drain voltages when exposed to methanol and water vapors.

The circular-gap-type C_{60} FNW FET sensor is a carbon-based, flexible, and environment-friendly device with wide applications in monitoring the atmosphere, as it can be freely attached to the surface of various test objects. We will demonstrate the sensing of water vapor, as humidity sensing plays a critical role across a wide range of industrial and environmental applications, including food storage, agriculture, breath analysis, and so forth.

2. Experimental Section

2.1 Synthesis of C_{60} FNWs and the chemicals used in sensor experiments

The C_{60} FNWs were synthesized using the LLIP method combined with manual mixing, as described previously, using a toluene solution saturated with C_{60} and isopropanol [17]. C_{60} powder (99.5% purity, BBS Chemicals) was purchased from ATR Company (Japan). Toluene ($\geq 99.0\%$ pure) and isopropanol (IPA, $\geq 99.0\%$ pure) were purchased from Nacalai Tesque, Inc. (Japan) and used without further purification in preparing C_{60} FNWs. The synthesized C_{60} FNWs were vacuum-dried at room temperature and used in the sensor experiments.

In addition to toluene and IPA, other chemicals were purchased from commercial sources and used without further purification for the sensor experiments: ethanol (99.5% purity), methanol (99.8% purity), benzene (99.5% purity), acetone (99.5% purity), diethyl ether (99.5% purity), m-xylene (99% purity) (Nacalai Tesque, Inc., Japan), carbon tetrachloride (99.5% purity, Kanto Chemical Co., Inc., Japan), and methyl ethyl ketone ($\geq 99\%$ purity, SK KAKEN Co., Ltd., Japan).

2.2 Structural characterization of the synthesized C_{60} FNWs and the materials used as electrodes

The crystal structure of the synthesized C_{60} FNWs was characterized using x-ray diffraction (XRD, Cu K_{α} , Rigaku RINT-2200 HF X-ray diffractometer, Japan). The morphology of the C_{60} FNWs and bamboo charcoal cloth (thickness of 140 μm) used as electrodes was observed using scanning electron microscopy (SEM, HITACHI TM4000PlusII, Japan). The specific surface area of the synthesized C_{60} FNW was measured using Brunauer-Emmett-Teller (BET) method with N_2 adsorption-desorption isotherms recorded at 77 K (autosorb-iQ, Anton Paar GmbH).

2.3 Seebeck effect measurement of C₆₀FNWs

The semiconductor nature of C₆₀FNWs was examined via the Seebeck effect [18], using the schematic shown in Fig. 1. As depicted in Fig. 1 (a), a p-type Si crystal (resistivity < 0.0085Ωcm, 15×4×0.3 mm) with a SiO₂ layer of 300 nm in thickness was used as a reference. The temperature gradient between the two electrodes was applied by placing small ice particles near the electrodes. The change in the potential difference between the two electrodes was measured using a digital multimeter (PC7000, Sanwa, Tokyo, Japan).

As shown in Fig. 1 (b), C₆₀FNWs was filled into a glass capillary tube with an outer diameter of 1.6 mm and an inner diameter of 1.0 mm. The temperature gradient was applied using two glass rods (6.0 mm in diameter), A and B, connected to the capillary tube, by changing the temperature using hot water (70 °C) and iced water (5 °C). Because of the higher electrical resistivity of the C₆₀FNWs, the change in potential difference between electrodes 1 and 2 was monitored by measuring the potential difference through a 100 MΩ resistor connected in series with the filled C₆₀FNWs powder, using a digital multimeter. A DC voltage of 30 V was applied using a constant-voltage power supply (PS30V5A01, AS ONE Corporation, Japan).

2.4 Fabrication of C₆₀FNW gas sensors

Figures 2 (a) and (b) schematically shows a slit-gap-type two-electrode gas sensor consisting of a C₆₀FNW-filled narrow gap (55 μm in width and 3 mm in length) between graphite foil electrodes (thickness of 50 μm, PATIKIL), and a polyimide spacer. The electrodes were attached to a glass substrate of thickness 1.3 mm using double-sided adhesive tape of thickness 240 μm. A resistor of 100 MΩ was connected in series to one of the sensor electrodes, and a voltage of 30 V was applied to the sensor through the resistor. The sensor current was calculated from the potential difference across the 100 MΩ resistor. The organic solvent was poured into a cylindrical plastic container with an inner diameter of 27 mm and a depth of 12 mm. The complete setup was enclosed within a plastic box (85×120×35 mm) fitted with a vacuum pump, as depicted in Fig. 2 (a).

Figures 2 (c) and (d) schematically shows the slit-gap-type C₆₀FNW FET gas sensor with a p-type Si back-gate electrode, similar to Fig. 2 (a). The synthesized C₆₀FNW powder was filled into the slit gap formed between the graphite foil electrodes as depicted in Fig. 2 (a). The source-drain voltage (V_{SD}) ranging from 10 to 30 V was applied between the source-drain electrodes through the 100 MΩ resistor connected in series. The V_{SD} and gate voltage (V_G) were applied independently, using two constant-voltage DC power supplies, as described above. The source-drain current (I_{SD}) was calculated by measuring the potential difference across the 100 MΩ resistor.

A circular-gap-type C₆₀FNW FET sensor using the C₆₀FNW and bamboo charcoal cloth was fabricated as shown in Figs. 2 (e) and (f). The SEM image of the bamboo charcoal cloth is shown in Fig. 2 (g),

revealing that it is composed of carbon fibers with a mean diameter of $7.7 \pm 1.4 \mu\text{m}$. The synthesized C_{60}FNW powder was packed into a circular hole of diameter 4 mm, which was sealed with a charcoal cloth acting as the drain electrode. Gas molecules can be exposed to C_{60}FNW through the charcoal cloth drain electrode. A gate electrode was placed between the source and drain electrodes, similar to a gate-all-around (GAA) FET [19]. I_{SD} was calculated by measuring the potential difference across the 100 M Ω resistor connected in series. The sensor placement and electrical measurement apparatus remained similar to Fig. 2 (c). The sensor experiments were conducted at room temperature.

3. Results and Discussion

3.1 Structural characterization of the synthesized C_{60}FNWs

Figure 3 (a) shows the SEM image of C_{60}FNWs synthesized using the LLIP method. The particle size distribution was measured from SEM images, as shown in Figs. 3 (b), (c) and (d). The synthesized C_{60}FNWs exhibit a mean length of $4.3 \pm 2.2 \mu\text{m}$, a mean diameter of $630 \pm 180 \text{ nm}$, and a mean aspect ratio of 6.8 ± 2.7 . Figure 3 (e) shows the XRD profile for the synthesized C_{60}FNW , revealing a FCC crystal structure with a lattice constant of $a = 1.43 \text{ nm}$. This value is 0.9% greater than that of the pristine FCC C_{60} crystals ($a = 1.4166 \text{ nm}$, JCPDS no. 44–558). The specific surface area of the C_{60}FNW powder calculated from BET studies was $24 \text{ m}^2/\text{g}$.

3.2 Analysis of Seebeck effect measurement

The result of the Seebeck effect measurement is shown in Fig. 4. In Fig. 4 (a), peak A of positive electromotive force was observed when electrode 2 was cooled by placing an ice particle, whereas peak B of negative electromotive force was obtained when electrode 1 was cooled by placing an ice particle. Additionally, no electromotive forces were observed at room temperature (RT). This establishes that the sample was a p-type semiconductor as holes move from the higher temperature (HT) region to the lower temperature (LT) region, resulting in a positive potential at electrode 2 during peak A, and at electrode 1 during peak B [18]. In Fig. 4 (b), during peak A, electrode 1 was heated to 70°C , while electrode 2 was cooled to 5°C using the glass rods, which increased the potential difference. During peak B, electrode 1 was cooled to 5°C , while electrode 2 was heated to 70°C using the glass rods, which decreased the potential difference. This can be explained by the p-type semiconducting nature of the C_{60}FNWs present in the glass capillary tube, as inferred from Fig. 4 (a). Further, peaks C and D confirm the repeatability of the experiment. Ng et al. demonstrated that C_{60} crystals undergo a p-type doping upon exposure to oxygen molecules [20]. Thus, the p-type semiconducting nature of the synthesized C_{60}FNWs was attributed to the surface oxidization of the C_{60}FNWs .

3.3 Results for the slit-gap-type C_{60}FNW gas sensor exposed to organic gases

The responses of the two-electrode slit-gap-type C_{60} FNW gas sensors (depicted in Fig. 2 (a)) to organic gases such as ethanol, methanol, CCl_4 , etc., were investigated. New sensors were prepared for each experiment.

Figure 5 (a) shows the background current of approximately 10 pA from a control experiment conducted without any adsorbate gas molecules. Figure 5 (b) shows the sensor current after exposure to ethanol, followed by CCl_4 . Table 1 lists the electric dipole moments of the gases tested. Although a clear increase in current from the background level was observed for exposure to ethanol (1.69 D), no clear peak was detected upon exposure to CCl_4 (0 D). The sensor current decreased rapidly when the ethanol gas was evacuated.

As shown in Fig. 6, the sensor current was measured repeatedly for various combinations such as methanol and ethanol (Fig. 6 (a)), methyl ethyl ketone and methanol (Fig. 6 (b)), methanol and diethyl ether (Fig. 6 (c)), methanol and benzene (Fig. 6 (d)), methanol and m-xylene (Fig. 6 (e)), toluene and methanol (Fig. 6 (f)), and IPA and 1-propanol (Fig. 6 (g)). Clear peaks are observed for methanol (1.70 D), ethanol (1.69 D), methyl ethyl ketone (2.779 D), IPA (1.58 D), 1-propanol (1.55–1.58 D), and acetone (2.88 D, Fig. 6 (h)). In contrast, no clear peaks are observed in diethyl ether (1.098 D), benzene (0 D), m-xylene (0.33–0.37 D), or toluene (0.375 D).

With reference to Table 1, organic gasses with dipole moments greater than 1.5 D exhibited a distinct response to the C_{60} FNW sensors, while the organic gasses with smaller or no dipole moment showed ambiguous or no peaks. It is to be noted that CCl_4 and benzene did not show any peaks although they have higher or similar vapor pressures than ethanol and methanol which gave the clear peaks.

The electrical conductivity (σ) of a C_{60} crystal can be calculated using the following equation,

$$\sigma = AT^{3/2}\exp(-HLG/2KT), (1)$$

with A representing the Richardson constant ($6 \times 10^5 \text{ A m}^{-2}$), K being the Boltzmann constant, and T being the absolute temperature, and HLG is the HOMO-LUMO gap of a C_{60} molecule [21]. Using density functional theory (DFT), Alamri et al. showed that the HLG of a C_{60} molecule decreased from 1.68 eV to 0.65 eV upon the adsorption of acetone molecules on the C_{60} surface, increasing its electrical conductivity[21]. Similarly, Morad et al. used DFT to show that the adsorption of 5,6-dihydroxyindole-2-carboxylic acid (DHICA) molecules decreased the HLG of C_{60} molecules, resulting in enhanced conductivity [22]. As acetone and DHICA molecules are polar [23], the above observation strongly implies that the electrical conductivity of C_{60} crystals increases due to the reduction of HLG value upon the adsorption of polar molecules.

The intrinsic electric dipole moment of the C_{60} molecules is zero [24]. However, as C_{60} molecules are enveloped by the π electron cloud, they develop a non-zero electric dipole moment due to dipole-induced dipole interaction with the polar gas molecules [25, 26, 27]. This interaction generates an attractive force

that increases the adsorption probability of polar gas molecules on the C₆₀ surface. Therefore, the peaks observed in Fig. 6 can be attributed to the combined effects of increased electrical conductivity arising from the reduction of *HLG* values of C₆₀ molecules and increased adsorption probability of polar gas molecules onto the C₆₀ surface.

Table 1. Electric dipole moment and vapor pressure for tested gasses.

Chemical species	Chemical formula	Electric dipole moment (D, debye)	Vapor pressure (Pa) at 298 K
Methanol	CH ₃ OH	1.70 [28]	1.68×10 ⁴ [29]
Ethanol	C ₂ H ₅ OH	1.69 [28]	7.80×10 ³ [29]
1-propanol	CH ₃ CH ₂ CH ₂ OH	1.55 - 1.58 [28]	2.79×10 ³ [29]
Isopropanol (IPA)	(CH ₃) ₂ CHOH	1.58 [28]	6.05×10 ³ [30]
Methyl ethyl ketone	CH ₃ COC ₂ H ₅	2.779 [28]	1.33×10 ⁴ [30]
Diethyl ether	(CH ₃ CH ₂) ₂ O	1.098 [28]	6.65×10 ⁴ [29]
Benzene	C ₆ H ₆	0 [31]	1.20×10 ⁴ [29]
Carbon tetrachloride	CCl ₄	0 [32]	1.51×10 ⁴ [29]
Toluene	C ₆ H ₅ CH ₃	0.375 [28]	3.78×10 ³ [29]
Acetone	(CH ₃) ₂ CO	2.88 [28]	3.04×10 ⁴ [29]
Water	H ₂ O	1.8546 [28]	3.14×10 ³ [29]
m-xylene	C ₆ H ₄ (CH ₃) ₂	0.33 - 0.37 [33]	1.10×10 ³ [29]

3.4 Responses of the slit-gap-type FET C₆₀ FNW gas sensors prepared using Si substrates for methanol gas

Two slit-gap-type FET C₆₀FNW gas sensors, as depicted in Fig. 2 (c), were tested for the methanol gas sensing at a V_{SD} of 30 V.

As shown in Fig. 7, the initial I_{SD} after methanol exposure was less than 40 pA. The I_{SD} value gradually increased, stabilizing at 88 pA at 65 min of exposure, on reaching steady state. The I_{SD} decreased stepwise when V_G increased in the positive direction (V_G = 0–20 V), while it increased stepwise when V_G increased in the negative direction (V_G = 0 – -30 V). This indicates that the sensor behaved like a p-type

FET, which is consistent with the Seebeck measurements. The I_{SD} decreased rapidly beyond an exposure time of ~ 100 min owing to the evacuation of methanol gas.

Figure 8 compares the current response of another sensor with and without methanol exposure at a V_{SD} of 30 V after reaching steady state. Figure 8 (a) shows the stepwise decrease in I_{SD} for V_G values varying between 0 and + 30 V, and the stepwise increase in I_{SD} for V_G values varying between 0 and – 30 V before methanol exposure. Upon methanol exposure, high I_{SD} values were observed, as shown in Fig. 8 (b), while maintaining the stepwise dependence on V_G values, similar to that in Fig. 8 (a). Figure 8 (c) compares the sensor currents with and without methanol exposure, represented by the red and blue lines, respectively, where R^2 is the COD. The I_{SD} increased remarkably upon methanol exposure. Both fitted curves demonstrate a linear relationship between I_{SD} and V_G . The transconductance, defined as the slope of the fitted curve, was calculated to be -5.96 pS [34], which increased significantly when the sensor was exposed to methanol as compared with ambient air without methanol.

The methanol sensing experiment was further conducted, as shown in Fig. 9 (a), which shows the change in I_{SD} with respect to exposure time after reaching steady state. The data was obtained by changing V_G for each V_{SD} .

Figure 9 (b) shows the relationship between the I_{SD} and V_{SD} for each V_G obtained by analyzing Fig. 9 (a). Linear relationships are observed between I_{SD} and V_{SD} , showing similar output conductance values of ranging from 6.29 to 7.21 pS, where the output conductance is defined as the slope of the fitted curves [34].

FIGURE 9. (a) Change in I_{SD} (pA) with respect to methanol exposure time (min) obtained by changing V_G (V) for each V_{SD} (V). Marked points were used for analyses. (b) Change in I_{SD} measured as a function of V_{SD} for each V_G upon methanol exposure. (c) Change in I_{SD} as a function of V_G for each V_{SD} upon methanol exposure.

3.5 Responses of the circular-gap-type C₆₀ FNW FET gas sensor prepared using the bamboo charcoal cloth for water vapor sensing

A circular-gap-type C₆₀FNW FET gas sensor, as shown in Fig. 2 (e), was used for water vapor sensing. Figure 10 shows the change in I_{SD} with respect to exposure time for each V_G with V_{SD} varying from 15–30 V during the water vapor exposure. The I_{SD} reached a steady state after 110 minutes of exposure.

By analyzing Fig. 10 (a), the relationships between V_{SD} and I_{SD} for each V_G (Fig. 10 (b)), and the relationships between V_G and I_{SD} for each V_{SD} (Fig. 10 (c)) were obtained. Although the obtained relationships are linear, the output conductance increased from 0.458 to 1.05 nS with the downward shift of V_G in Fig. 10 (b), and the absolute transconductance increased from 0.230 to 0.563 nS with the upward shift of V_{SD} in Fig. 10 (c).

However, the observed linearity of curves suggests that the circular-gap-type C₆₀FNW FET sensor also possesses a favorable transistor behavior for reading gas responses as linear changes in drain current like the slit-gap-type C₆₀FNW FET sensor. Thus, the slit-gap-type and circular-gap-type C₆₀FNW FET sensors will be positioned as the prototype models for chemiresistive gas sensors that can be operated at room temperature and fabricated at low cost, which will be widely used in the environmental, medical and food industry fields in the future.

4. Conclusions

- (1) The slit-gap-type two-electrode C₆₀FNW sensors exhibited clear responses for polar gas molecules with dipole moments greater than 1.5 D. The sensor current increases due to the reduction of HOMO-LUMO gap of the C₆₀ molecules caused by the adsorption of polar molecules onto the C₆₀ molecules and the attractive forces generated thereby due to the dipole-induced dipole interactions that further increase the adsorption probability of the polar molecules onto the surface of the C₆₀ molecules.
- (2) The slit-gap-type and circular-gap-type C₆₀FNW FET sensors demonstrated linear relationships between V_G and I_{SD} , and V_{SD} and I_{SD} for methanol sensing or water sensing.
- (3) I_{SD} decreased on increasing V_G value in the positive direction, whereas it increased on increasing V_G value in the negative direction in both the slit-gap-type and circular-gap-type C₆₀FNW FET sensors. These observations corroborate the p-type semiconducting property of the synthesized C₆₀FNWs, as suggested by Seebeck effect measurements.

Declarations

Author Contribution

Kun'ichi Miyazawa: conceptualization, experiment, writing original manuscript. Yumi Tanaka: discussion, reviewing original manuscript.

Acknowledgements

The authors are grateful to NAKATSUYAMA NETSUSHORI.co., Ltd. (Nagaoka, Japan) for providing the bamboo charcoal cloth and to Dr. Mariko Kinoshita (Tokyo Metropolitan Industrial Technology Research Institute, Tokyo, Japan) for the measurement of the specific surface area of C₆₀FNWs, and to Dr. Takatsugu Wakahara (NIMS, Japan) for supplying Si substrates and fruitful discussions on our research.

Funding

No funding was received for conducting this study.

References

1. Hong S, Wu M, Hong Y, Jeong Y, Jung G, Shin W, Park J, Kim D, Jang D, Lee J-H. FET-Type Gas Sensors: A Review. *Sens Actuators: B Chem.* 2021;330:129240. <https://doi.org/10.1016/j.snb.2020.129240>.
2. Hejazi M-A, Eksik O, Taşdelen-Yücedağ Ç, Ünlü5 C, Trabzon L. Carbon-Based Nanomaterials in Gas Sensing Applications. *Emergent Mater.* 2023;6:45–77. <https://doi.org/10.1007/s42247-023-00454-7>.
3. Yang L, Zheng G, Cao Y, Meng C, Li Y, Ji H, Chen X, Niu G, Yan J, Xue Y, Cheng H. Moisture-Resistant, Stretchable NO_x Gas Sensors Based on Laser-Induced Graphene for Environmental Monitoring and Breath Analysis. *Microsystems Nanoengineering.* 2022;8:78. <https://doi.org/10.1038/s41378-022-00414-x>.
4. Keshtkar S, Rashidi A, Kooti M, Askarieh M, Pourhashem S, Ghasemy E, Izadi N. A Novel Highly Sensitive and Selective H₂S Gas Sensor at Low Temperatures Based on SnO₂ Quantum Dots-C₆₀ Nanohybrid: Experimental and Theory Study, *Talanta* 188, (2018): 531–539. <https://doi.org/10.1016/j.talanta.2018.05.099>
5. Grynko D, Burlachenko J, Kukla O, Kruglenko I, Belyaev O. Fullerene and Fullerene-Aluminum Nanostructured Films as Sensitive Layers for Gas Sensors. *Semicond Phys Quantum Electron Optoelectron.* 2009;12:287–9. <https://nasplib.isofts.kiev.ua/handle/123456789/118877>.
6. Bairi P, Minami K, Nakanishi W, Hill JP, Ariga K. L. K. Shrestha, Hierarchically Structured Fullerene C₇₀ Cube for Sensing Volatile Aromatic Solvent Vapors, *ACS Nano* 10, (2016): 6631 – 6637. [10.1021/acsnano.6b01544](https://doi.org/10.1021/acsnano.6b01544)
7. Wei Z, Song J, Ma R, Ariga K, Shrestha LK. Self-Assembled Corn-Husk-Shaped Fullerene Crystals as Excellent Acid Vapor Sensors, *Chemosensors* 10, (2022): 16. <https://doi.org/10.3390/chemosensors10010016>
8. Miyazawa K, Kuwasaki Y, Obayashi A, Kuwabara M. C₆₀ Nanowhiskers Formed by the Liquid-Liquid Interfacial Precipitation Method. *J Mater Res.* 2002;17:83–8. [10.1557/JMR.2002.0014](https://doi.org/10.1557/JMR.2002.0014).
9. Ko SW, Chung H. Synthesis of a Bimetallic Co/Zn Zeolitic Imidazolate Framework-C₆₀ Fullerene Nanowhiskey Composite and its Photocatalytic Degradation of Tetracycline Hydrochloride under LED Light Condition. *Eurasian Chem -Technol J.* 2025;27:191198. <https://doi.org/10.18321/ectj1666>.
10. Zhang X, Qu Y, Piao G, Zhao J, Jiao K. Reduced Working Electrode Based on Fullerene C₆₀ Nanotubes@DNA: Characterization and Application. *Mater Sci Eng B.* 2010;175:159. [10.1016/j.mseb.2010.07.020](https://doi.org/10.1016/j.mseb.2010.07.020).
11. Ogawa K, Kato T, Ikegami A, Tsuji H, Aoki N, Ochiai Y. Electrical Properties of Field-Effect Transistors Based on C₆₀ Nanowhiskers. *Appl Phys Lett.* 2006;88:112109. [10.1063/1.2186519](https://doi.org/10.1063/1.2186519).

12. Nobuoka M, Sakaguchi S, Kawata M, Taguchi A, Kishida K, Tsutsui Y, Suda M, Inoue H, Idesaki A, Yamaki T, Seki S. High Electrical Conductivity in Directionally Polymerized C₆₀ Nanowires by Grazing Incidence Single Particle. *Nanoscale Horiz.* 2025. 10.1039/D5NH00228A.
13. Miyazawa K. Synthesis and Properties of Fullerene Nanowhiskers and Fullerene Nanotubes. *J Nanosci Nanotechnol.* 2009;9:41–50. 10.1166/jnn.2009.J013.
14. Miyazawa K, Kuwasaki Y, Hamamoto K, Nagata S, Obayashi A, Kuwabara M. Structural Characterization of C₆₀ Nanowhiskers Formed by the Liquid/liquid Interfacial Precipitation Method. *Surf Interface Anal.* 2003;35:117–20. 10.1002/sia.1506.
15. Larsson MP, Kjølstrup-Hansen J, Lucyszyn S. DC Characterisation of C₆₀ Whiskers and Nanowhiskers. *ECS Trans.* 2007;2:27–38. 10.1149/1.2408950.
16. Xu MS, Pathak Y, Fujita D, Ringor C, Miyazawa K. Covered Conduction of Individual C₆₀ Nanowhiskers. *Nanotechnology* 19, (2008): 075712, 10.1088/0957-4484/19/7/075712
17. Miyazawa K, Hirata C, Wakahara T. Influence of the Solution Volume on the Growth of C₆₀ Nanowhiskers. *J Cryst Growth* 405, (2014): 68, 10.1016/j.jcrysgro.2014.07.036
18. Zhou Y, Wang J, Luo D, Hu D, Min Y, Xue Q. Recent Progress of Halide Perovskites for Thermoelectric Application. *Nano Energy.* 2022;94:106949. <https://doi.org/10.1016/j.nanoen.2022.106949>.
19. Naime NH, Akhi AA, Hossain M. Negative Capacitance Gate-All-Around Nanowire FETs for Highly Sensitive Catalytic Metal Gate Gas Sensors. *IEEE Sens J.* 2025;25:17342. 10.1109/JSEN.2025.3556303.
20. Ng TW, Lo MF, Zhou YC, Liu ZT, Lee CS, Kwon O, Lee ST. Ambient Effects on Fullerene/Copper Phthalocyanine Photovoltaic Interface. *Appl Phys Lett* 94, (2009): 193304, 10.1063/1.3118580
21. Alamri A, Alafnan A. Computational study on B, N, and Si-Doped C₆₀ Nanocages for Acetone Detection in Heart Failure Diagnosis and Environmental Remediation. *Sci Rep.* 2025;15:44298. <https://doi.org/10.1038/s41598-025-27880-3>.
22. Morad R, Maaza M. First-Principles Study on the Electronic and Optical Properties of Melanin-Fullerene C₆₀ Nanocomplexes for Light-Harvesting Applications. *J Mater Res.* 2026;41:259. 10.1557/s43578-025-01750-0.
23. Matta M, Pezzella A, Troisi A. Relation between Local Structure, Electric Dipole, and Charge Carrier Dynamics in DHICA Melanin: A Model for Biocompatible Semiconductors. *J Phys Chem Lett.* 2020;11:1045–51. <https://dx.doi.org/10.1021/acs.jpcclett.9b03696>.
24. Calculated electric dipole moments for (Buckminsterfullerene). <https://cccbdb.nist.gov/dipole2x.asp>
25. Israelachvili JN. *Intermolecular and Surface Forces*, Third Edition, Elsevier, 2011.
26. Mezour MA, Voznyy O, Sargent EH, Lennox RB, Perepichka DF. Controlling C₆₀ Organization through Dipole-Induced Band Alignment at Self-Assembled Monolayer Interfaces, *Chem. Mater.* 28,(2016): 8322 – 8329. 10.1021/acs.chemmater.6b03527

27. Solov'yov IA, Geng J, Solov'yov AV, Johnson BFG. On the Possibility of the Electron Polarization to be the Driving force for the C_{60} -TMB Nanowire Growth. Chem Phys Lett. 2009;472:166–70. 10.1016/j.cplett.2009.03.006.
28. CRC Handbook of Chemistry and Physics, 97th Edition, CRC Press, Taylor & Francis Group, FL, USA. (2017).
29. Chemistry NIST, WebBook. SRD69, <https://webbook.nist.gov>
30. National Library of Medicine. <https://pubchem.ncbi.nlm.nih.gov>
31. Rai KB, Ghimire RR, Dhakal C, Pudasainee K, Siwakoti B. Structural Equilibrium Configuration of Benzene and Aniline: A First-Principles Study. J Nepal Chem Soc Febr. 2024;44:1–15. <https://doi.org/10.3126/jncs.v44i1.62675>.
32. Minkin VI, Osipov OA, Zhdanov YA. Dipole Moments in Organic Chemistry. New York: Plenum; 1970.
33. Dean JA. *Lange's Handbook of Chemistry*, Fifteenth Edition, McGraw-Hill, Inc., (1999).
34. Babbar D, Garg N, Kabra S. Capacitance Modeling, Simulation and RF Characterization of Horizontal Floating Gate Field Effect Transistor (H-FGFET) for Gas Sensing Application. Eng Res Express. 2024;6:025351. <https://doi.org/10.1088/2631-8695/ad51d2>.

Figures

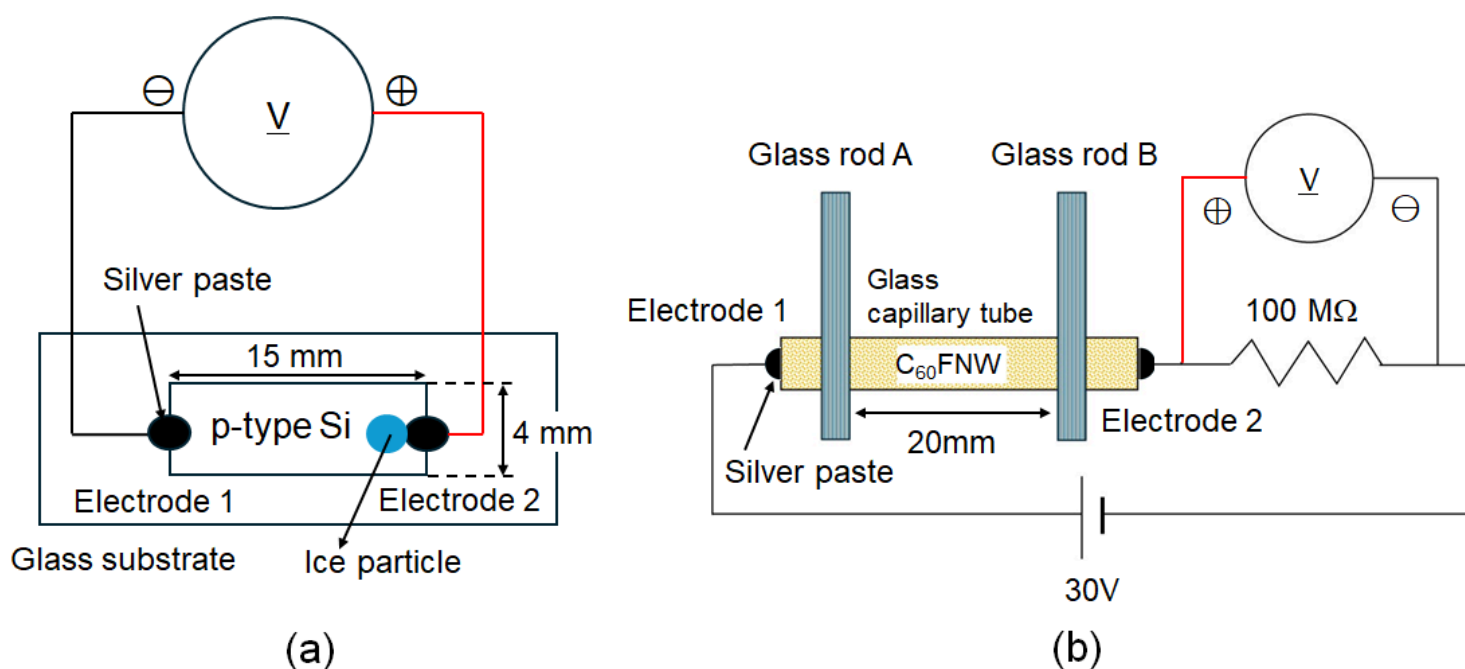


Figure 1

Schematic of the Seebeck effect measurement using (a) a p-type Si crystal, and (b) a glass capillary tube filled with powder of C_{60} FNWs.

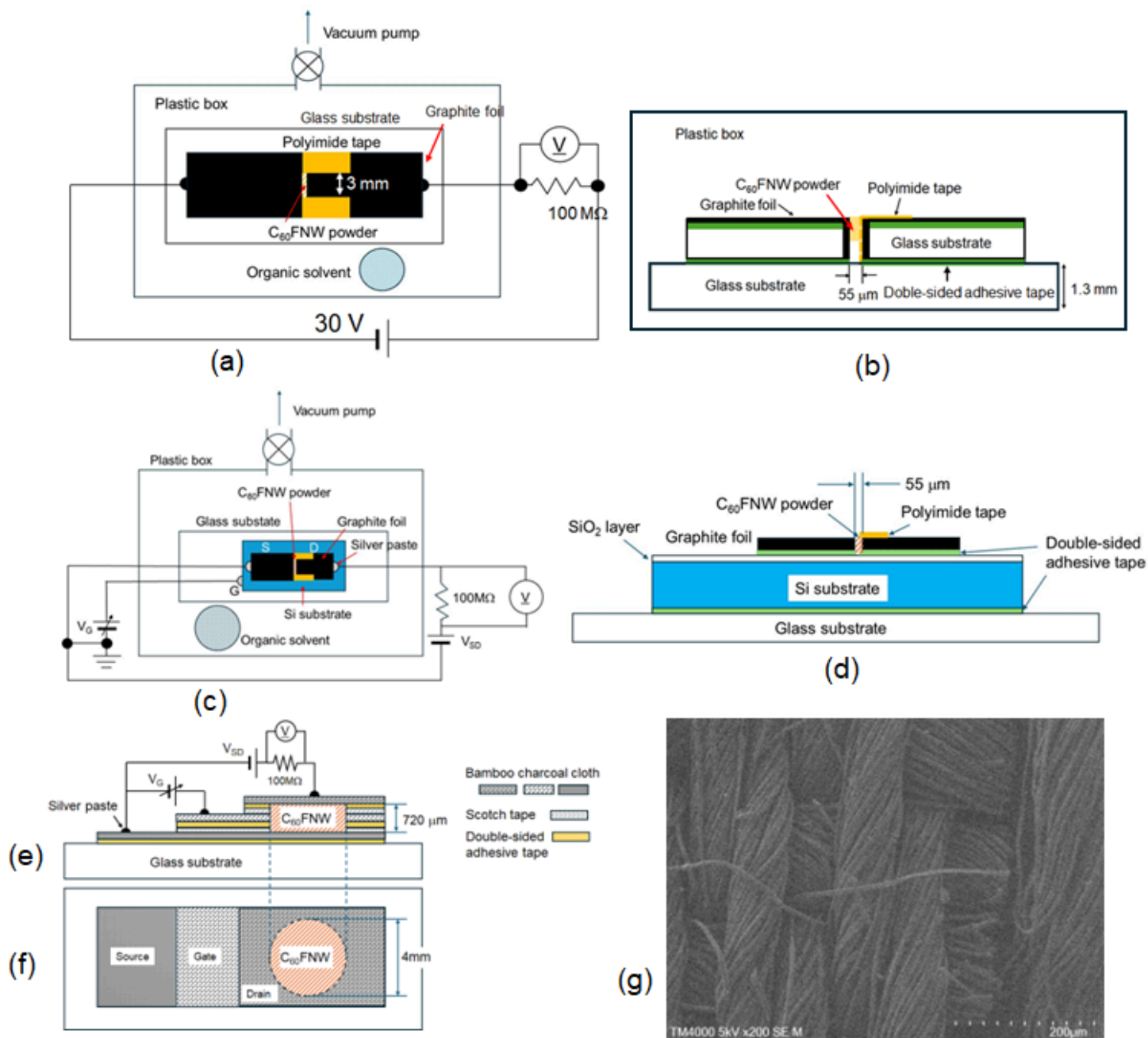


Figure 2

(a) Plan view and (b) side view of the slit-gap-type two-electrode $C_{60}FNW$ gas sensor with graphite foil electrodes. (c) Plan view and (d) side view of the slit-gap-type $C_{60}FNW$ FET gas sensor with a p-type Si back gate electrode. (e) Side view and (f) plan view of the circular-gap-type $C_{60}FNW$ FET gas sensor fabricated using the $C_{60}FNW$ and bamboo charcoal cloth. (g) SEM image of the bamboo charcoal cloth.

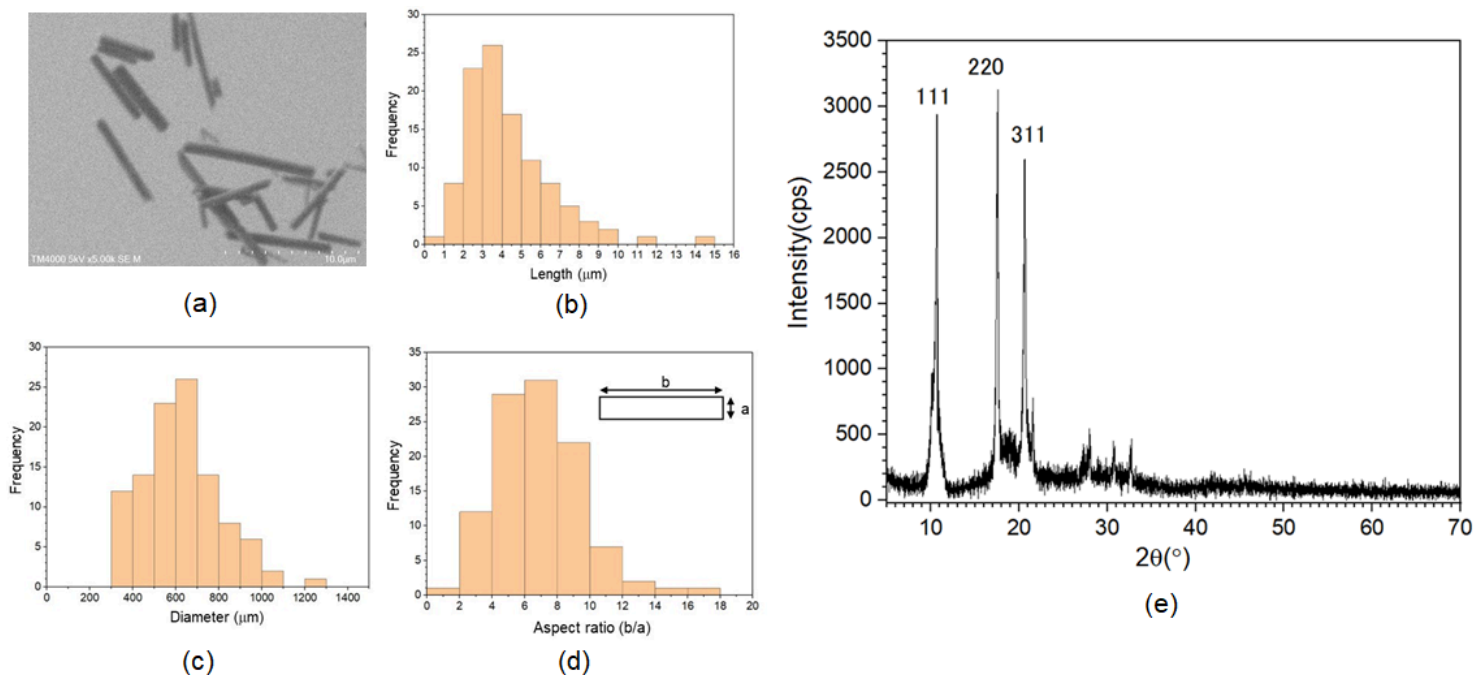


Figure 3

(a) SEM image of the C_{60} FNWs prepared using the LLIP method. Distributions of (b) length, (c) diameter, and (d) aspect ratio (b/a) for the synthesized C_{60} FNWs. (e) XRD profile of the synthesized C_{60} FNW powder.

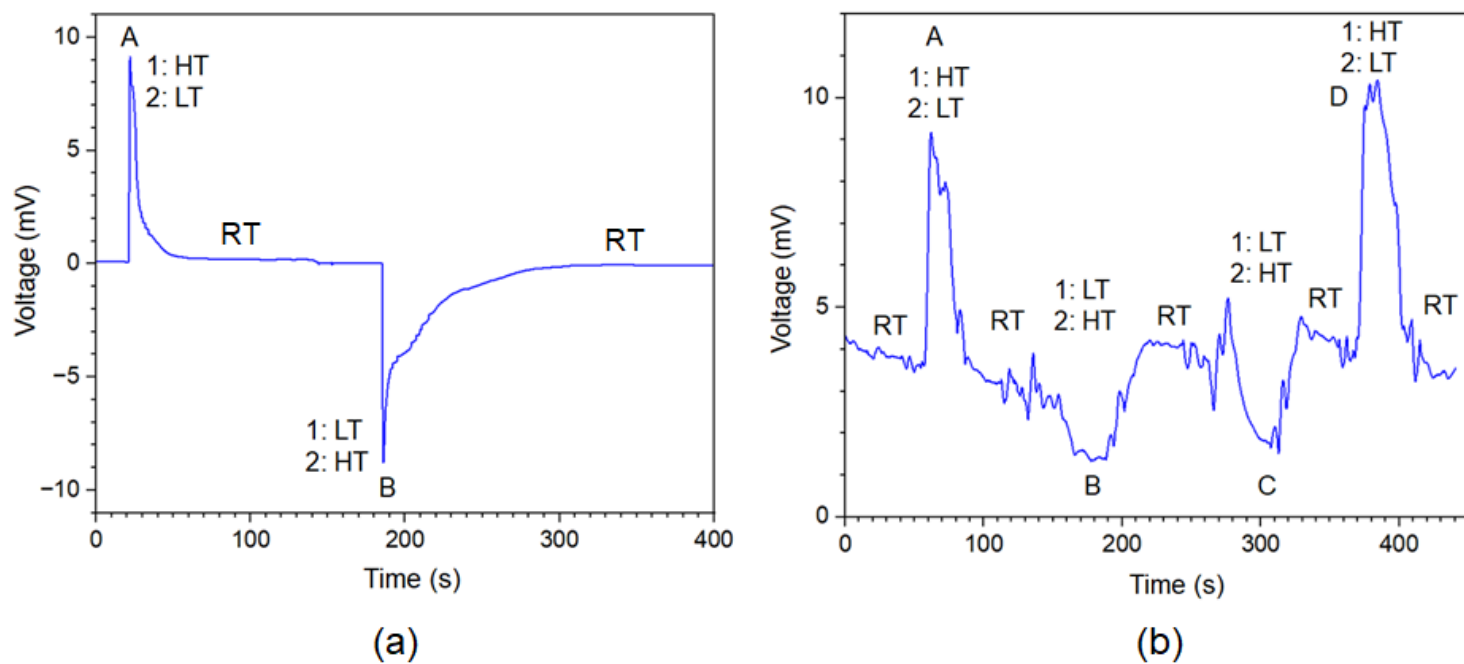
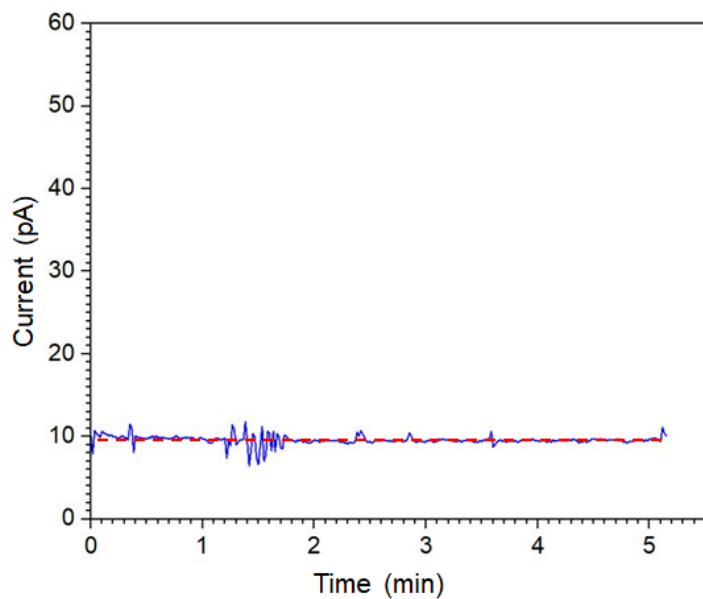
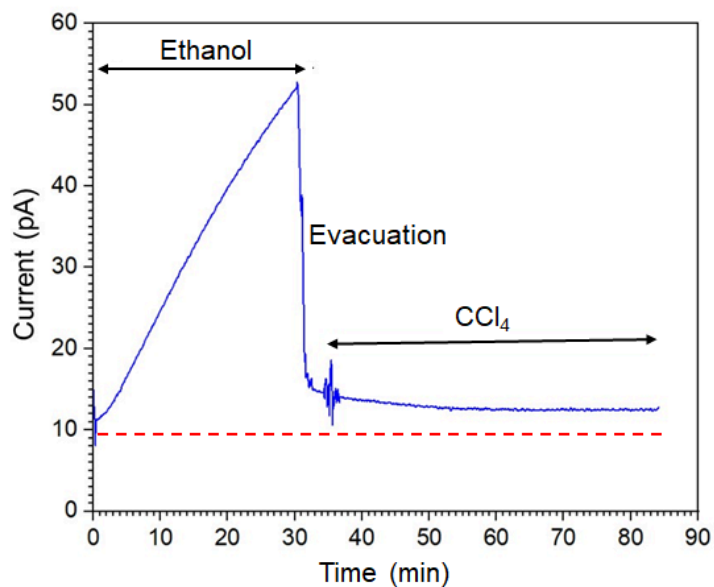


Figure 4

(a) Change in the electromotive force generated by the temperature difference between electrodes 1 and 2 of (a) the p-type Si crystal, and (b) the C_{60} FNW-filled glass capillary tube.



(a)



(b)

Figure 5

Variation of sensor currents with respect to exposure time for (a) control experiment for the two-electrode slit-type-gap C_{60}FNW sensor in the ambient air without adsorbate gas molecules, and (b) exposure to an ethanol gas followed by a CCl_4 gas.

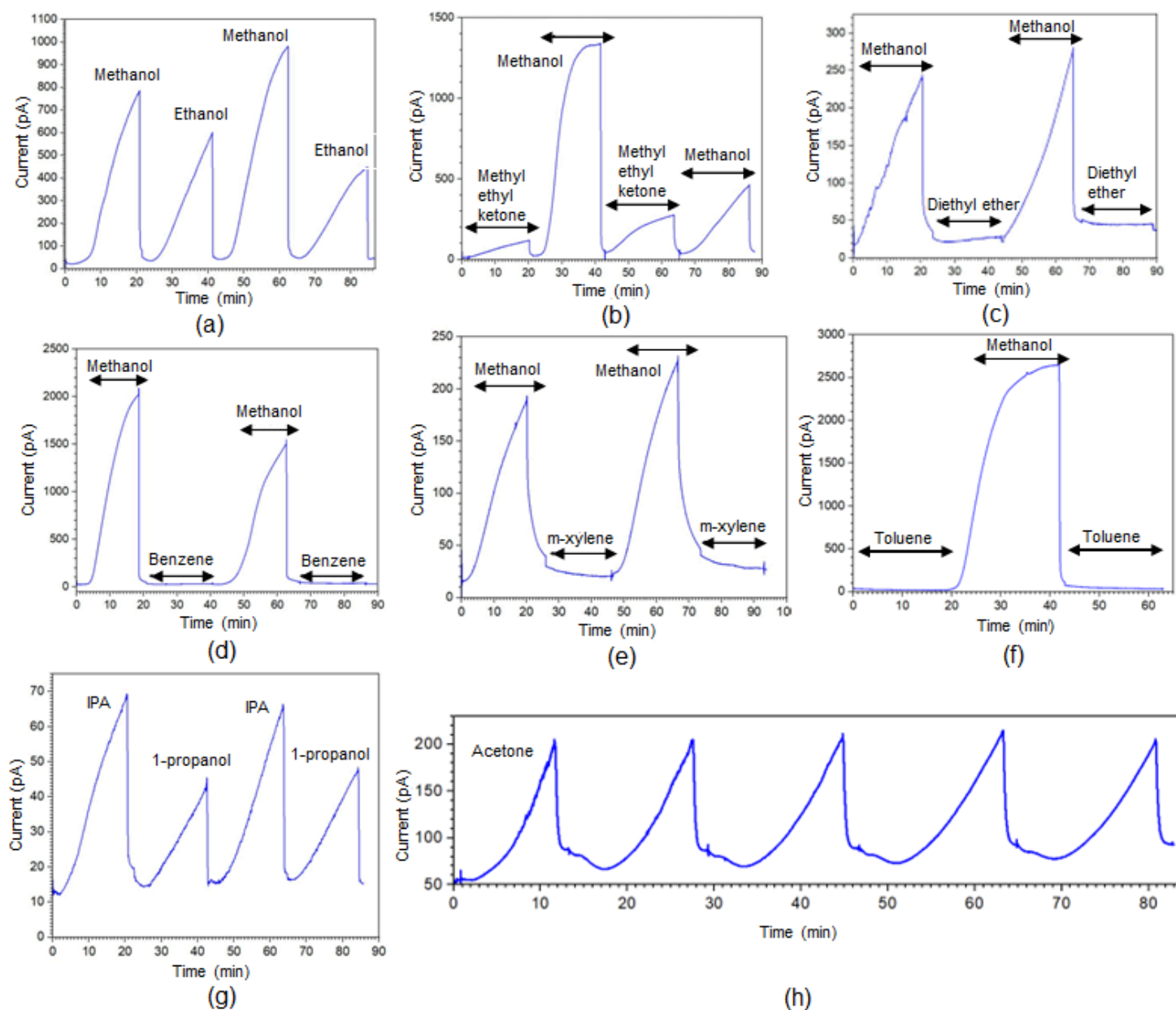


Figure 6

Measured sensor currents with time for repeated exposure for (a) methanol and ethanol, (b) methyl ethyl ketone and methanol, (c) methanol and diethyl ether, (d) methanol and benzene, (e) methanol and m-xylene, (f) toluene and methanol, (g) IPA and 1-propanol, and (h) acetone.

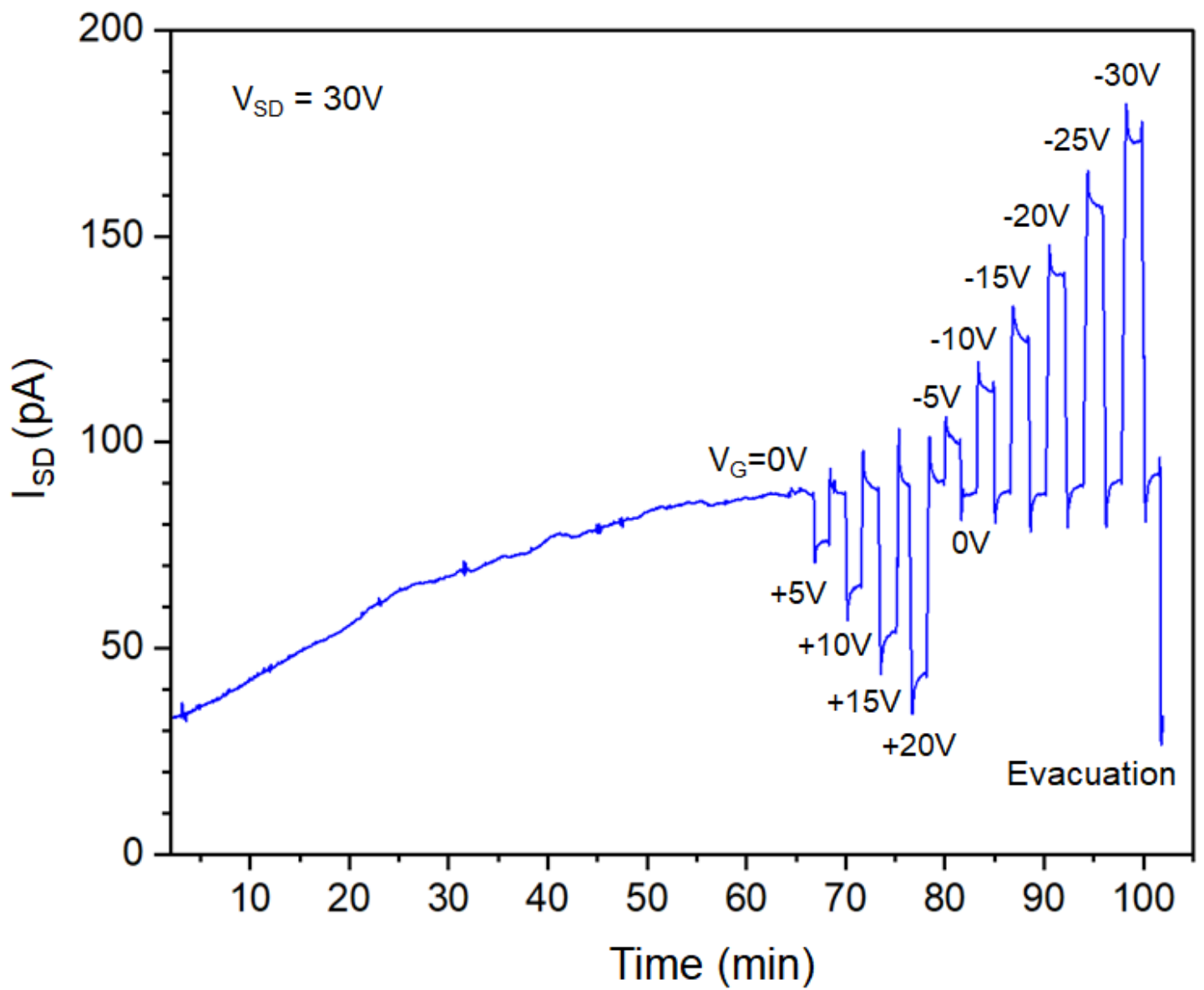


Figure 7

Change in I_{SD} of the slit-gap-type FET $C_{60}FNW$ sensor as a function of time upon methanol exposure.

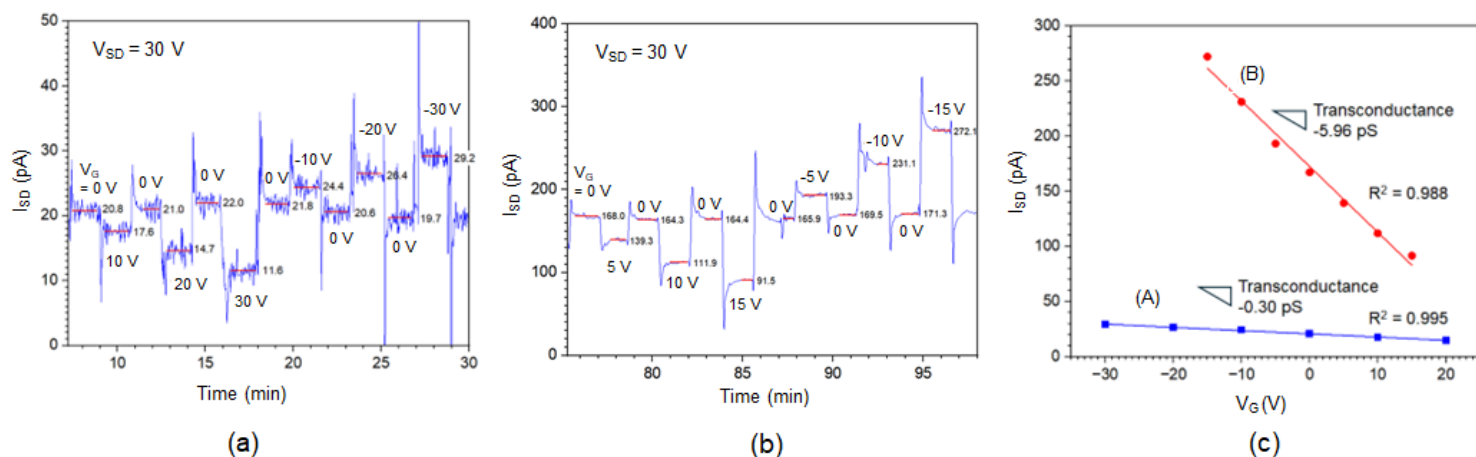


Figure 8

Change in I_{SD} (pA) of a slit-gap-type C_{60} FNW FET sensor with time (min) (a) before the methanol exposure, and (b) after the methanol exposure, measured by changing V_G (V). Averaged sensor currents indicated by the red lines were used for analyses. (c) I_{SD} measured as a function of V_G (A) without and (B) with methanol exposure for $V_{SD} = 30$ V.

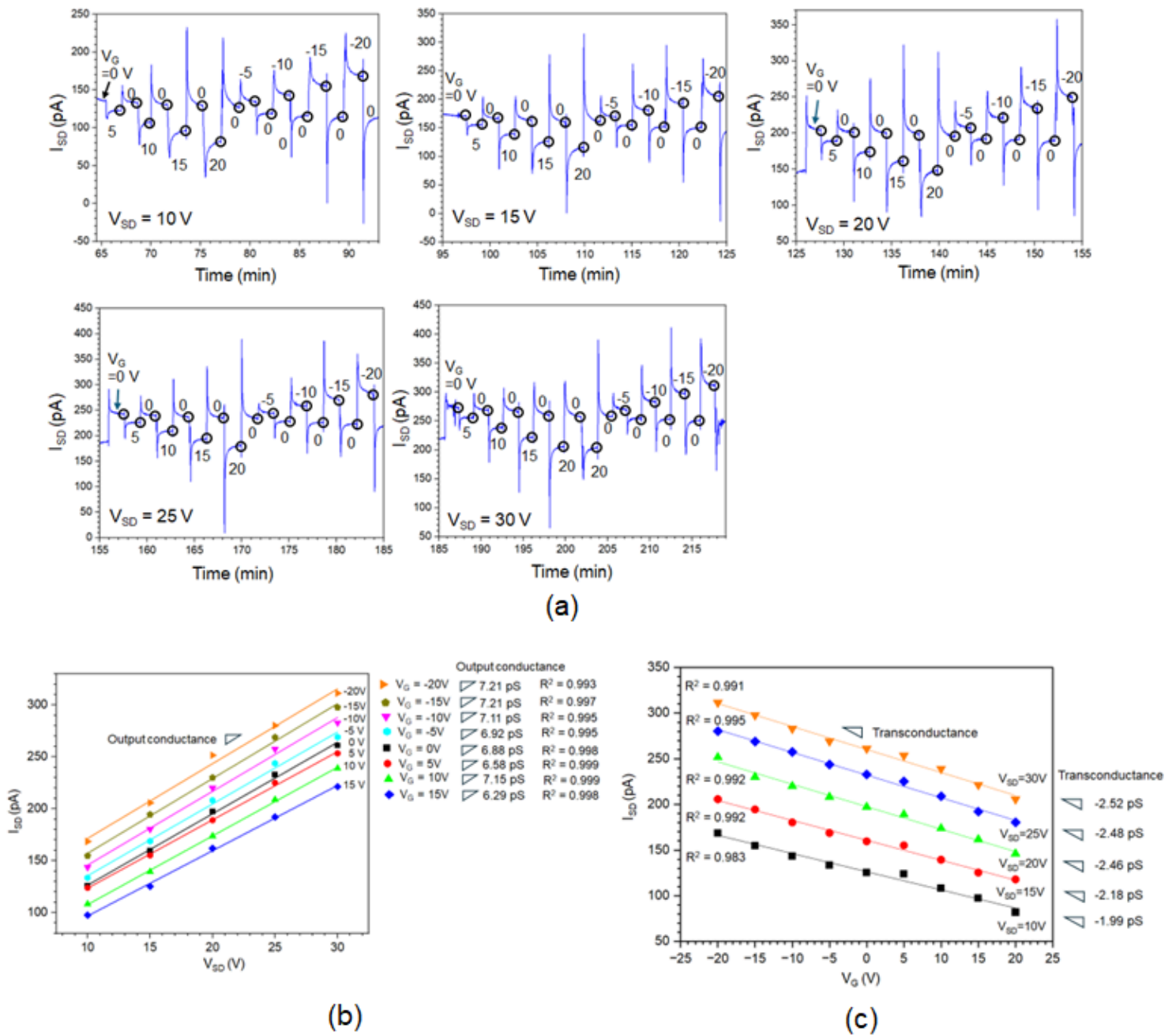
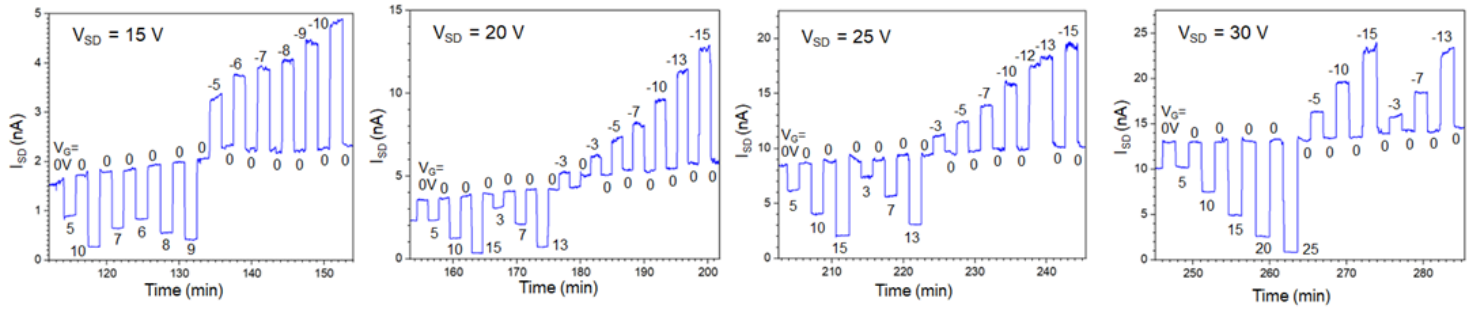
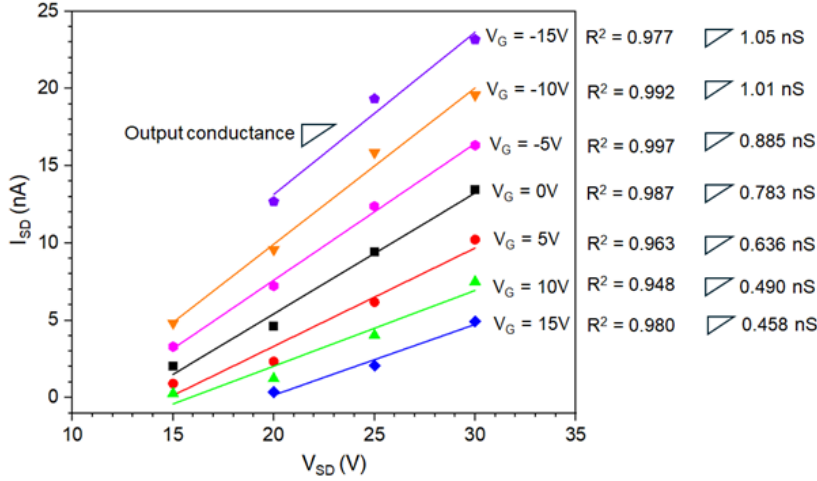


Figure 9

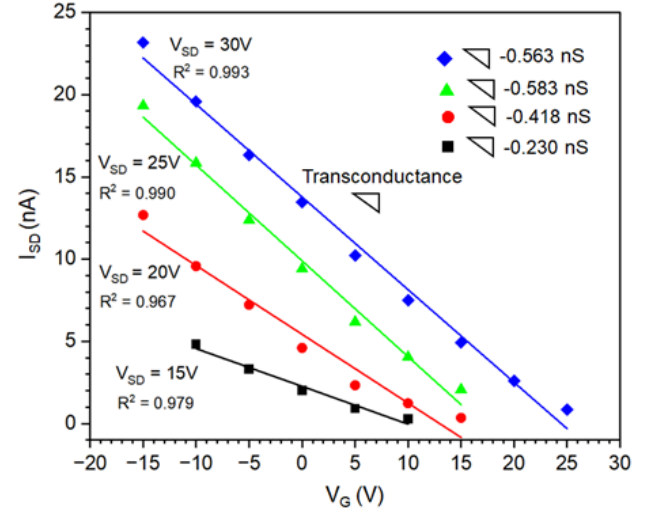
(a) Change in I_{SD} (pA) with respect to methanol exposure time (min) obtained by changing V_G (V) for each V_{SD} (V). Marked points were used for analyses. (b) Change in I_{SD} measured as a function of V_{SD} for each V_G upon methanol exposure. (c) Change in I_{SD} as a function of V_G for each V_{SD} upon methanol exposure.



(a)



(b)



(c)

Figure 10

(a) Change in I_{SD} (nA) with respect to exposure time for each V_G (V) measured under V_{SD} (V) varying from 15 to 30 V during the water vapor exposure. The peak values were obtained for individual steps by trapezoidal approximation. (b) Change in I_{SD} as a function of V_{SD} for each V_G upon the water vapor exposure. (c) Change in I_{SD} as a function of V_G for each V_{SD} upon water vapor exposure.