Ultra-Flexible Proximity Sensor Array Using Printed Organic Transistors

Hiroyuki Matsui[1,2], Itsuki Shoji[1,2], Hideki Wada[1,2], Kodai Uto[1,2], Yasunori Takeda[1], Toshiyuki Sugimoto[2]

h-matsui@yz.yamagata-u.ac.jp
[1]Research Center for Organic Electronics, Yamagata University, Jonan 4-3-16, Yonezawa, Yamagata, 992-8510, Japan
[2]Faculty of Engineering, Yamagata University, Jonan 4-3-16, Yonezawa, Yamagata, 992-8510, Japan
Keywords: organic semiconductors, inkjet printing, flexible electronics, organic electronics, static electricity

ABSTRACT

Here we show a novel proximity sensor array based on floating extended gate organic field-effect transistors, which is sensitive, ultra-flexible (2 μm thick), and digitally printable. The sensor can detect the proximity to the human hands with low static electricity at tens of centimeters.

1 Introduction

The demand for non-contact sensors is increasing for the post-COVID-19 society. Although a wide range of electromagnetic waves such as radio waves, infrared-visible-ultraviolet lights, and X-rays have been utilized for non-contact sensing, quasi-static electric fields with frequencies below tens of Hz have rarely been utilized [1-4]. Here we show an organic field-effect transistor (OFET) with a floating extended gate (FEG) can detect the quasi-static electric fields with a high sensitivity [5]. In addition, the FEG-OFET array integrated on a 2-μm-thick ultra-flexible substrate can visualize the position and the size of nearby objects such as human hands as long as they have static electricity.

The operation principle of the FEG-OFET proximity sensor can be understood in terms of electrostatic induction as shown in Fig. 1a. According to the Gauss's law, the charge density at the semiconductor layer, Q, and the electric field in the OFET, E_2, are given by

$$Q = \epsilon E_2, \qquad E_2 = \frac{1}{S_2}\int_{\mathrm{EG}} \mathbf{E}_1 \cdot \mathrm{d}\mathbf{S} = \frac{S_1}{S_2} E_{1,\mathrm{ave}}, \qquad (1)$$

where the integral is on the surface of the extended gate, S_1 is the area of the extended gate, S_2 is the overlap area of the gate and semiconductor, and $E_{1,\mathrm{ave}}$ is the average electric field at the extended gate. The second formula indicates that the electric field is enhanced by the factor of S_1/S_2, which is typically between 100 and 1,000 in our experiments. Thus, the FEG-OFET can detect electric field sensitively.

2 Experiment

Either 125-μm-thick polyethylene naphthalate (PEN, Teonex Q65, DuPont de Nemours, Inc.) films or 500-μm-thick glass substrates were used as substrates. Insulating layers of parylene derivative was deposited in vacuum using diX-SR (KISCO) as source material. All electrodes and interconnections were inkjet-printed using silver nanoparticle ink (NPS-JL, Harima Kasei) and annealed at 120 °C for 30 minutes. The surfaces of the silver source and drain electrodes were covered with self-assembly monolayers of pentafluorobenzenethiol (PFBT, Sigma-Aldrich) by immersing the substrates in a solution of PFBT (30 mM in 2-propanol) for 5 minutes. This treatment increases the work function of the electrodes from 4.8 eV to 5.3 eV and improves the injection of hole carriers to the p-type organic semiconductors. The solution of the organic semiconductor, 2,7-dihexyl-dithieno[2,3-*d*;2',3'-*d*']benzo-[1,2-*b*;4,5-*b*']dithiophene (DTBDT-C6, Tosoh Corporation, 0.9 wt%, Fig. 1c), in toluene was printed using a syringe dispenser, and annealed at 100 °C for 15 minutes [6].

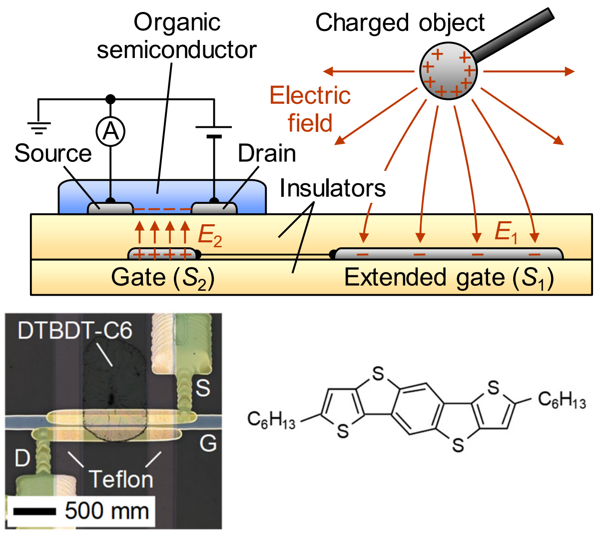

Fig. 1 (a) Schematic and (b) optical microscope image of floating extended gate organic field-effect transistors (FEG-OFET). (c) Structure of DTBDT-C6. Reproduced from [5] with permission of John Wiley & Sons.

For fabricating an ultra-flexible device, a glass substrate was coated with Teflon, and subsequently with a 1-μm-thick parylene layer (Fig. 2). Then, the FEG-OFETs were fabricated in the same procedure above and encapsulated with a 1-μm-thick parylene layer. Finally, the device was delaminated at the Teflon/ parylene interface [7].

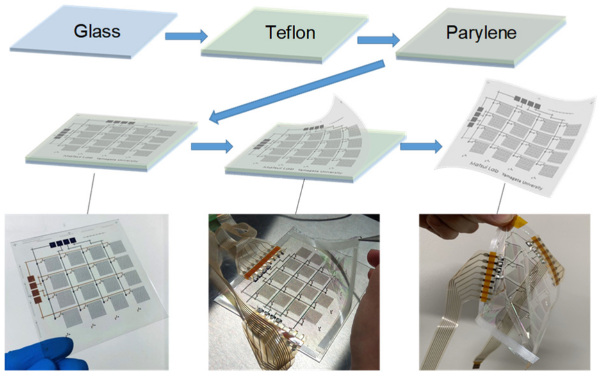

Fig. 2 Fabrication process of ultra-flexible proximity sensor array. Reproduced from [5] with permission of John Wiley & Sons.

3 Results and Discussion

3.1 Device Characteristics

Transfer characteristics of the FEG-OFET with an extended gate of 24 mm x 24 mm in size were evaluated in contact and non-contact modes. In contact mode, input voltage was directly applied to the extended gate with a metal probe needle. This mode is equivalent to the standard way of measurement for OFETs. In non-contact mode, on the other hand, input voltage was applied to an aluminum foil below a 1-mm-thick glass plate, and the FEG-OFET was placed on top of the glass plate (Fig. 3a). Fig. 3b shows the transfer characteristics in contact and non-contact modes at a drain voltage of -0.1 V. The contact mode characteristics exhibited typical p-type transistor operation in linear regime. The mobility was 0.12 ± 0.06 cm^2/Vs, threshold voltage was -0.5 V, on/off ratio was more than 10^4, and subthreshold swing was 0.2 V/dec. The non-contact mode characteristics also exhibited a p-type transistor operation because of a large capacitive coupling between the aluminum foil and the extended gate. This result demonstrates that a direct contact is not mandatory to modulate the current in the FEG-OFET.

Frequency characteristics were measured in the non-contact mode with a sinusoidal voltage input. The results in Fig. 3c and 3d indicate that the FEG-OFET has a constant gain and negligible phase delay up to 1 kHz. This bandwidth is wide enough for proximity sensing.

3.2 Proximity Sensing for Metal Sphere

For proximity sensing, we prepared four types of extended gates, A: 24 mm x 24 mm solid, B: 24 mm x 24 mm mesh, C: 12 mm x 12 mm solid, D: 12 mm x 12 mm mesh, as shown in Fig. 4a. The capability of proximity sensing was demonstrated first with a biased metal sphere to define the experimental setup exactly (Fig. 4b). The source current (almost same as drain current) was measured at a constant drain voltage of -1 V. Fig. 4c-e show the dependence of current on the potential, V_O, and distance, d, of the metal sphere. The variation in current was found almost proportional to the potential, and delays with the distance, following an empirical equation, $\Delta I_S \propto d^{-\alpha}$ (α = 1.3 - 1.5). Larger and solid extended gates exhibited larger signal than smaller and mesh extended gates. These results are consistent with Equation (1).

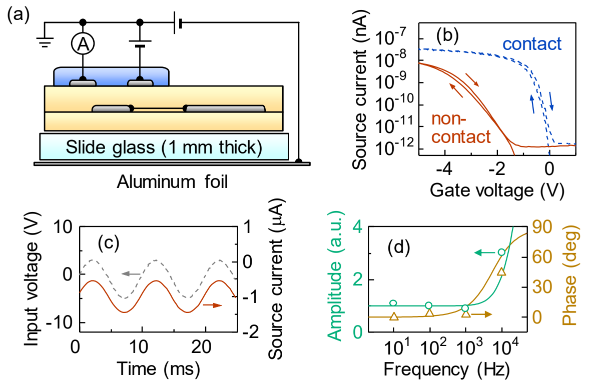

Fig. 3 Device characteristics. (a) Non-contact mode. (b) Transfer characteristics in contact and non-contact modes. (c) Response to sinusoidal input at 100 Hz. (d) Frequency characteristics. Reproduced from [5] with permission of John Wiley & Sons.

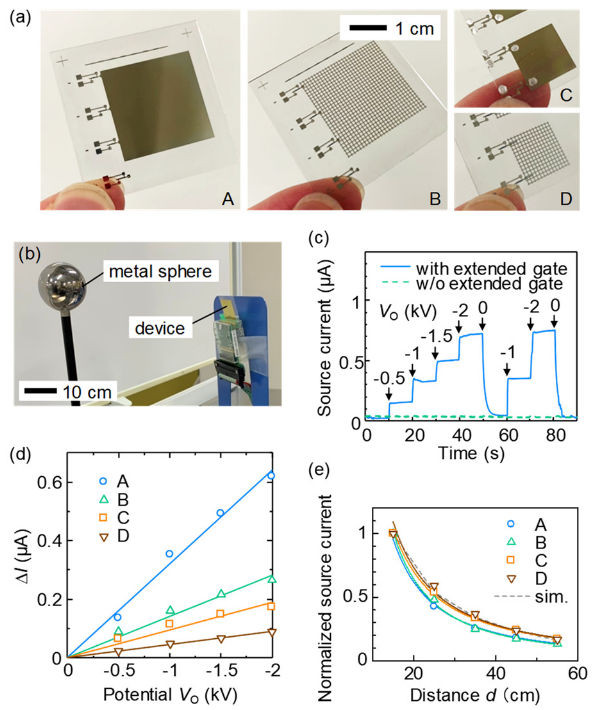

Fig. 4 (a) Photographs of FEG-OFETs. (b) Experimental setup. (c)(d) Dependence of current on potential at *d* = 15 cm, and (e) on distance at V_O = -2 kV. Reproduced from [5] with permission of John Wiley & Sons.

3.3 Proximity Sensing for Human Hand with Ultra-Flexible Array

Finally, we demonstrate the proximity sensing for human hands with an FEG-OFET array integrated on an ultra-flexible substrate. 4 x 4 passive matrix of FEG-OFETs were used for resolving the position and size of the target objects (Fig. 5a). Fig. 5b shows the distribution of the variation in current for 4 x 4 FEG-OFET matrix when a human hand approached to the device. The human hand had a static electricity of ~1 kV, which is lower than the static electricity we can percept as a static electric shock.

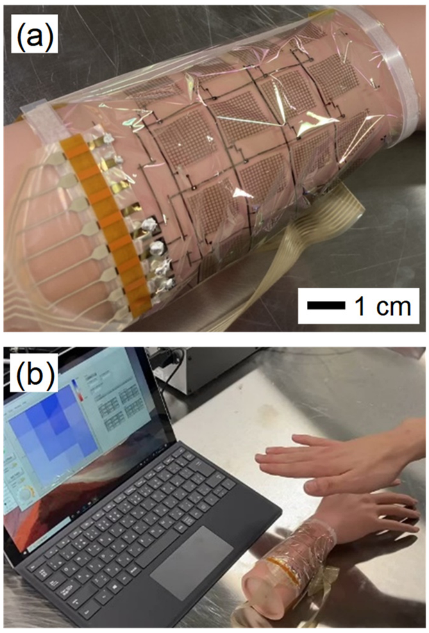

Fig. 5 Proximity sensing with ultra-flexible array. Reproduced from [5] with permission of John Wiley & Sons.

4 Conclusions

We demonstrated that an OFET with a floating extended gate can detect quasi-static electric field with a high sensitivity owing to the amplification effect in Equation (1). Its response to the potential of nearby objects was found linear and reversible and had a bandwidth up to 1 kHz. The passive matrix array integrated on an ultra-flexible substate successfully detected the proximity of human hands.

Acknowledgements

This work was partly supported by JSPS KAKENHI Grant Number 18H01855, MEXT Leading Initiative for Excellent Young Researchers, JST CREST Grant Number JPMJCR18J2, JST OPERA, and JST TI-FRIS. Organic semiconductor material DTBDT-C6 was provided by Tosoh Corporation.

References

[1] H. Wang, Q. Tang, X. Zhao, Y. Tong, Y. Liu, "Ultrasensitive Flexible Proximity Sensor Based on Organic Crystal for Location Detection", ACS Applied Materials & Interfaces, Vol. 10, No. 3, pp. 2785-2792 (2018).

[2] W. Liu, Y. Niu, Q. Chen, H. Jiang, F. Xu, G. Zhu, "High-Performance Proximity Sensors with Nanogroove-Template-Enhanced Extended-Gate Field-Effect Transistor Configuration", Advanced Electronic Materials, Vol. 5, No. 12, pp. 1900586 (2019).

[3] W. Liu, D. Lin, Q. Chen, Q. Zhang, X. Zhang, G. Zhu, "Ferroelectric Polarization Enhancement of Proximity Sensing Performance in Oxide Semiconductor Field-Effect Transistors", ACS Applied Electronic Materials Vol. 2, No. 10, pp. 3443-3453 (2020).

[4] G. Lv, H. Wang, Y. Tong, L. Dong, X. Zhao, P. Zhao, Q. Tang, Y. Liu, "Flexible, Conformable Organic Semiconductor Proximity Sensor Array for Electronic Skin", Advanced Materials Interfaces, Vol. 7, No. 16, pp. 2000306 (2020).

[5] I. Shoji, H. Wada, K. Uto, Y. Takeda, T. Sugimoto, H. Matsui, "Visualizing Quasi-Static Electric Fields with Flexible and Printed Organic Transistors", Advanced Materials Technologies, DOI: 10.1002/admt.202100723 (2021).

[6] H. Matsui, Y. Takeda, S. Tokito, "Flexible and printed organic transistors: From materials to integrated circuits", Organic Electronics, Vol. 75, pp. 105432 (2019).

[7] K. Fukuda, Y. Takeda, Y. Yoshimura, R. Shiwaku, L. T. Tran, T. Sekine, M. Mizukami, D. Kumaki, S. Tokito, "Fully-printed high-performance organic thin-film transistors and circuitry on one-micron-thick polymer films", Nature Communications, Vol. 5, pp. 4147 (2014).