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# Studies on Low-voltage Dual-gate Organic Transistor based Pressure-sensing Devices

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## Part 1: Research Content

### Background

An unprecedented drive to create a smart society based on the connectivity of electronic sensors to improve safety and quality of life has led to research into low-cost, flexible, and printable transistors. Billions of sensors are required to achieve this goal. Therefore, organic materials are good candidates to meet this demand of transistor switches for sensing applications because they require solution-processing methods to fabricate these devices known today as organic field-effect transistors (OFETs) at temperatures less or equal to 100°C on a wide range of substrates. Some of the advantages of using OFETs as readout elements for pressing sensing applications include monitoring of environmental pressure, electronic skin, human-machine interaction, monitoring of the footprints of the elderly in care homes [1-4]. Prototypes of organic pressure sensors reported operate in high voltages usually above 10 V; therefore, a need to develop organic pressure sensors that can be powered by portable battery cells is necessary. The operation voltage of the sensor is strongly dependent on the drive voltage of the OFET. Recently, our group demonstrated a pressure-sensing device using a piezoelectric copolymer film of Polyvinylidene Fluoride-Trifluoroethylene (P(VDF-TrFE)) as the sensing layer and a low-voltage OFET as the readout element [5]. The device configuration is such that pressure exerted on the sensing layer is assumed to induce the generation of charges from the piezoelectric layer, which transduces as threshold voltage and drain current changes observed in the electrical output of the OFET. However, the reason for the change in threshold voltage and drain current when pressure is applied to the sensing layer has not been quantitatively proved yet.

### Objective

The objective of this research is to clarify the operation mechanism of the device (dual-gate organic pressure sensor) by quantitative analysis to determine the piezoelectric constant,  $d_{33}$  of the sensing layer was carried out. First, by reproducing the dual-gate organic pressure sensor device already reported [5]. In addition, proposing a sensing mechanism to describe the operation of the device. Second, by quantifying charges per unit area generated by the sensing layer using a conventional dual-gate OFET with CYTOP as the top-gate dielectric layer. Third, by estimating  $d_{33}$  from results of the dual-gate OFET and dual-gate organic pressure sensor devices, then comparing the result with that obtained by direct measurement using a quasistatic (belincourt) method.

### Summary of results

Using dielectrics such as poly (vinyl cinnamate) (PVCN) and an environmentally friendly and degradable biopolyamide, low voltage OFET devices were fabricated and characterized in **chapter 2**. Photochemical crosslinking process was carried out to make PVCN insulator chemically resistant to chlorobenzene solvent while the biopolyamide material was characterized to confirm if it was chemically resistant to

chlorobenzene. Using these insulators, the OFETs operated in a low voltage range, 1 V to -5 V, because of the reduced interface traps the dielectrics formed with the TIPS-Pentacene/polystyrene semiconducting blend. The few trap states allowed for charge carriers to quickly fill up the sub-gap density of states thus leading to a small subthreshold slope of values 108 mV/decade for the biopolyamide based OFET and 110 mV/decade for the PVCN based OFET. Figure 2 (a) and (b) shows the transfer characteristics of the PVCN and biopolyamide based OFET. The mobility of the OFETs was  $0.27 \text{ cm}^2/\text{V.s}$  and  $0.18 \text{ cm}^2/\text{V.s}$  for the biopolyamide and PVCN respectively. The results obtained using the biopolyamide increases the prospects of eco-friendly organic transistors available for use in the nearest future.

**In chapter 3**, a dual-gate organic pressure sensor device was successfully fabricated using a polarized P(VDF-TrFE) layer. When the sensing layer (see Fig. 3(a)) is placed on the semiconducting layer of the low-voltage OFET, an initial shift in transfer characteristics is observed, thus confirming the polarization of the P(VDF-TrFE) layer. When pressure is applied on the piezoelectric layer, a corresponding shift in transfer characteristics to the left (see Fig. 3 (b)). Figure 3c shows the linear relation between pressures applied to the threshold voltage shift. The shift in transfer characteristics is similar to that of

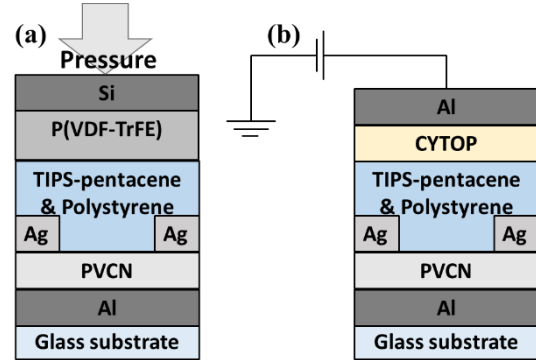


Fig. 1. Device structure of (a) low-voltage dual-gate organic pressure sensor (b) dual-gate OFET

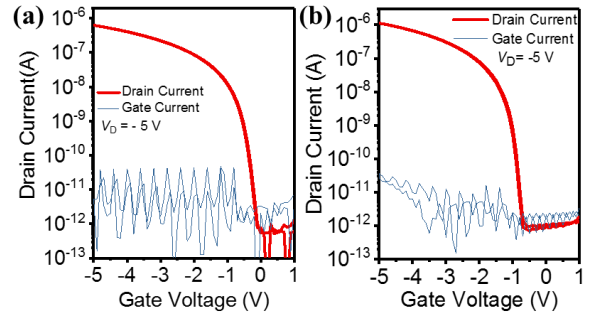


Fig. 2. Transfer characteristics of (a) PVCN based OFET (b) Biopolyamide based OFET

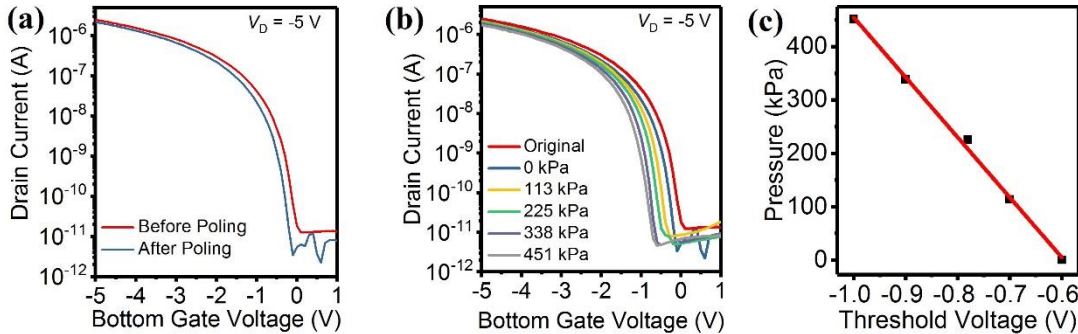


Fig. 3. (a) Threshold shift when polarized P(VDF-TrFE) was placed on the active layer (b) transfer curve shifts corresponding to pressure load (c) linear relationship between pressure and threshold voltage.

the conventional dual-gate OFET, just that in this case the sensing voltage generated by the deformed piezoelectric layer, induced the threshold voltage ( $V_{th}$ ) shift observed. Therefore, **in chapter 4**, a low-voltage dual-gate OFET using CYTOP as top-gate dielectric was successfully fabricated. The top-gate voltage controlled was used to control  $V_{th}$  of the bottom gate potential [6].

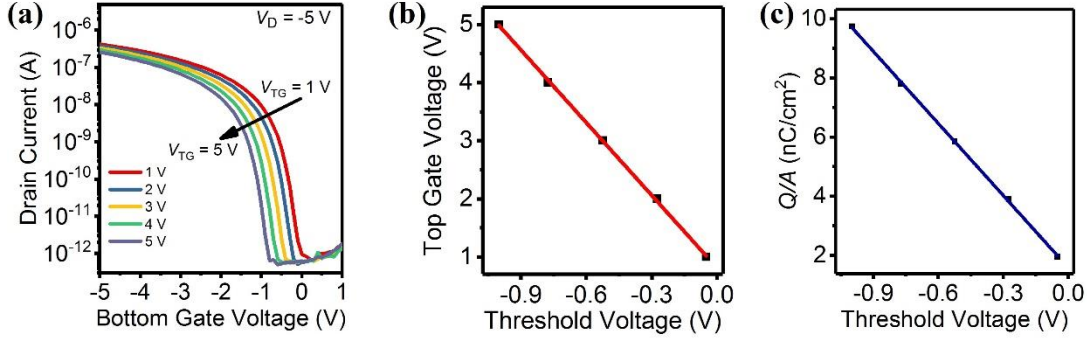


Fig. 4. (a) Threshold shift of the OFET corresponding to top-gate voltage (b) graph of top-gate voltage against threshold voltage (c) graph of charge per unit area against threshold voltage.

Figure 4 (a) shows the shift in transfer characteristics. This shift is consistent with that obtained by the dual-gate organic pressure sensor. In addition, the top-gate voltage relationship to  $V_{th}$  is linear (see Fig. 4b). From these results, the amount of charges generated by the piezoelectric P(VDF-TrFE) layer was estimated from the slope of Fig. 4c using equation (1)

**In Chapter 5**, By a quantitative analysis of results obtained from both the dual-gate pressure sensor and a conventional dual-gate OFET,  $d_{33}$  of the sensing layer was estimated. The amount of charges per unit area,  $Q$  depleted by the top-gate bias voltage,  $V_{top}$  from the equation (2) given below [6]. Fig. 4c shows the relation between  $Q$  and the threshold voltage shift.

$$Q = C_{top} V_{top} \dots \dots \dots (1)$$

Where  $C_{top}$  (2.065 nF/cm²) is the capacitance of the top gate dielectric. In order to determine the piezoelectric constant,  $d_{33}$ , equation (2) which states that the quantity of charges,  $Q$ , developed by the piezoelectric sensing layer is proportional to force applied,  $F$ , with the piezoelectric constant,  $d_{33}$ , as the proportionality constant was used [7].

$$Q = d_{33} F \dots \dots \dots (2)$$

Deducing  $F$  from the pressure applied on the 0.87 cm² sensing area ( $A$ ), equation (1) can be modified to this:

$$Q V = d_{33} F/A V \dots \dots \dots (3)$$

Both sides of equation (3) were extracted from the slope of Fig. 3b and Fig. 4c which are values c.a.  $11.2 \times 10^5$  Pa/V and 8.1 nC/cm²V, respectively. The absolute value of the piezoelectric constant  $d_{33}$  was calculated to be 72 pC/N.  $d_{33}$  of the piezoelectric layer was measured directly with a piezoelectric measurement system to be an average of 53 pC/N. These results conclude that the operation mechanism of the dual-gate pressure sensor was due to the piezoelectric behavior of the P(VDF-TrFE) layer used in the device. **In Chapter 6**, the surface charges on the polarized PVDF-TrFE layer required to cause the initial  $V_{th}$  shift, with respect to the magnitude of electric field used to polarize the P(VDF-TrFE) layer was quantified using results of a conventional dual-gate OFET. **Chapter 7** summarizes the results achieved in the previous chapters, future research as well as prospective applications of this work.

## Part 2: Research Purpose

The main results of this research give a quantitative description of the sensing mechanism of a novel low-voltage dual-gate organic transistor based pressure sensor [5]. Since solution processing methods were used to fabricate these devices, substrates such as polyethylene naphthalate (PEN) and polyethylene terephthalate (PET) could be used to fabricate flexible dual-gate organic pressure sensors the nearest future. In addition, a high-throughput production process can be implemented to commercialize the pressure sensors.

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## Part 3: Research Accomplishments

### Publications

1. Ogunleye Olamikunle Osinimu, Heisuke Sakai, Yuya Ishii, Hideyuki Murata. “Investigation of the sensing mechanism of dual-gate low-voltage organic transistor based pressure sensor,” *Organic Electronics* (accepted)
2. Ogunleye Olamikunle Osinimu, *et al.* A degradable biosynthesized polyamide as the gate dielectric for low-operating voltage solution-processable organic field-effect transistors. (Manuscript in preparation)

### Conferences

1. Ogunleye Olamikunle Osinimu, Yohei Yoshinaka, Heisuke Sakai, Tatsuo Kaneko, and Hideyuki Murata. “A Biodegradable Biopolymer as Dielectric for Low-Voltage Solution-Processed Organic Field-Effect Transistors”, International Symposium on Organic Electronic Molecular Electronics, Saga, Japan. May 31<sup>st</sup> – June 2<sup>nd</sup>, 2018.
2. Ogunleye Olamikunle Osinimu, Heisuke Sakai, Yuya Ishii, Hideyuki Murata. “Investigation of the Sensing Mechanism of the Dual-gate Low-voltage Organic Transistor based Pressure Sensor”, International thin-film transistor conference, Okinawa, Japan. Feb. 28<sup>th</sup> – Mar. 2<sup>nd</sup>, 2019.
3. Ogunleye Olamikunle Osinimu, Heisuke Sakai, Yuya Ishii, Hideyuki Murata. “Investigation of the Sensing Mechanism of the Dual-gate Low-voltage Organic Transistor for Pressure Sensing by Quantitative Analysis,” JSAP spring meeting, Tokyo, Japan. Mar. 9<sup>th</sup> – Mar.12<sup>th</sup>, 2019.

**Keywords:** Dual-gate pressure sensor; Dual-gate organic field-effect transistor; threshold voltage; P(VDF-TrFE); Piezoelectric constant.