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BRIEF PAPER *Special Section on Recent Progress in Organic Molecular Electronics*

Integration of a Low-Voltage Organic Field-Effect Transistor and a Sensing Capacitor for a Pressure-Sensing Device

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SUMMARY We integrate a pressure sensing capacitor and a low operation voltage OFET to develop a pressure sensor. The OFET was used as a readout device and an external pressure was loaded on the sensing capacitor. The OFET operates at less than 5 V and the change in the drain current in response to the pressure load (100 kPa) is two orders of magnitude.

key words: *low-voltage operation, pressure sensor, organic field-effect transistor, ferroelectric polymer*

1. Introduction

Recently, an organic pressure sensing devices have attracted much attention regarding the development of artificial skins, the health monitoring devices and the pressure sensing sheets, and several sensing devices such as capacitive sensors, piezoelectric sensors and transistor sensor have been reported [1]–[3]. Research-based development often focuses on the fabrication of the pressure sensors on flexible plastic substrates because devices flexibility is an essential factor for the artificial skin [4]. On the other hand, the reduction of the operation voltage and sensitivity improvement are necessary for practical applications. Pressure sensing with an organic field-effect transistor (OFET) as a readout device of the pressure load is promising owing to its advantages such as high sensitivity to the pressure load and lower susceptibility to electrical crosstalk. For example, a pressure sensor matrix of OFETs has been reported. The 32 × 32 array of sensor cells is fabricated on a plastic substrate, where a pressure image of a kiss mark on the sheet was obtained with a −20 V operating bias [5]. Y. Zang et al. reported an OFET with a suspended gate that exhibited ultra-sensitivity (192 kPa^{-1}) for the pressure detection, where the change in the drain current (I_D) in response to the pressure load (5 kPa) was more than three orders of magnitude with a −60 V operating bias [6]. Further reduction of operating voltage of the pressure sensing OFETs is necessary for practical applications. Thus, the development of a pressure sensing OFET that satisfies both low-voltage operation and high sensitivity is essential. A pressure-modulated OFET with an ultra-thin, hybrid organic/inorganic gate dielectric layer exhibits low operation voltage (2 V) [7]. Although the device operates with a low-voltage, the change in the I_D in response to the pressure load is limited to c.a. 5% of the initial value. In this study, we demonstrate an excellent pressure sensor with a low operation voltage and high pressure response by integrating a sensing capacitor using a piezoelectric polymer film and a low-voltage OFET as a readout device. Our pressure sensor operates at less than −6 V and the change in the I_D in response to the pressure load (100 kPa) is two orders of magnitude, where I_D of the OFET changes from 120 nA to 5 nA.

2. Experimental

The schematic structure of the organic pressure sensor is shown in Fig. 1 (a). The organic pressure sensor was prepared by integrating a sensing capacitor using a polarized copolymer of vinylidene fluoride (VDF) and trifluoroethylene (TrFE) with a VDF to TrFE ratio of 75 : 25 [P(VDF-TrFE), Fig. 1 (b)] film and a low-voltage operation OFET, where the bottom Al electrode acts as both an electrode of the sensing capacitor and the gate electrode of the OFET.

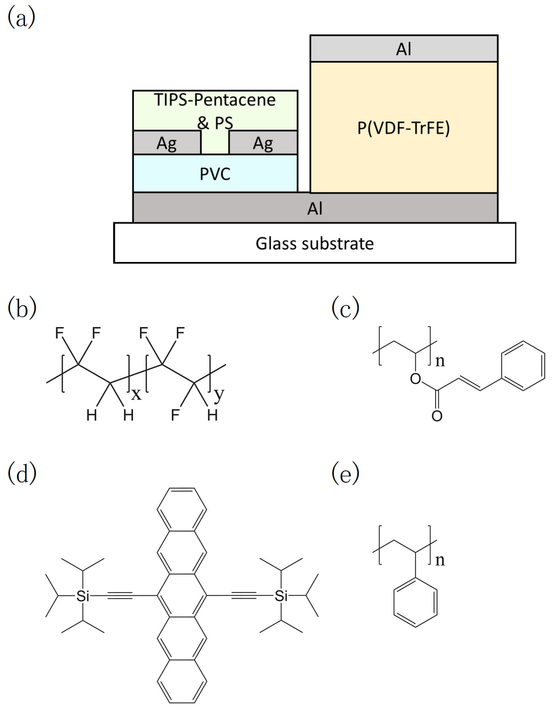

Fig. 1 (a) The schematic structure of the organic pressure sensor and molecular structures of (b) P(VDF-TrFE), (c) PVC, (d) TIPS-pentacene, and (e) PS.

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The Al bottom electrode (60 nm) was thermally evaporated onto a glass substrate. Prior to the fabrication of the OFET, the sensing capacitor was fabricated. As the pressure sensing material of the sensing capacitor, the P(VDF-TrFE) piezoelectric layer (8 μm) was blade coated on the Al bottom electrode. The Al top electrode (50 nm) was evaporated onto the P(VDF-TrFE) piezoelectric layer, followed by the polarization of the layer by a contact poling method. A poling voltage of 1 kV was applied to the Al top electrode and Al bottom electrode was grounded. As the gate dielectric layer of the OFET, poly(vinyl cinamate) [PVC, Fig. 1 (c)] (220 nm) was spin coated and cross linked by UV irradiation. Ag source/drain electrodes (50 nm) were evaporated with a shadow mask. The channel width (W) and channel length (L) of the electrodes were 2 mm and 50 μm, respectively. The electrodes were modified by immersion in a solution of pentafluorothiophenol in ethanol at a concentration of 5×10^{-3} mol/L. The semiconducting layer (100 nm) was then spin coated from a mixed solution consisting of 3 : 1 by weight blend of 6,13-bis(triisopropyl-silylethynyl) pentacene [TIPS-Pentacene, Fig. 1 (d)] and Polystyrene [PS, Fig. 1 (e)] at 0.01 g/mL concentration of solids. The pressure response of the device was measured as the change in the drain current (I_D) of the OFET at a certain drain voltage (V_D) by applying a pressure (100 kPa) to the P(VDF-TrFE) sensing capacitor. The pressure was loaded with a home-made pressure load system. Electrical measurements of the OFETs were carried out at room temperature (23°C) using a Keithley 4200 semiconductor characterization system in a dry nitrogen atmosphere.

The surface morphology of the PVC dielectric layer was measured with a HITACHI High-Tech Science AFM5000II, and a polarized optical microscope image of the active layer was obtained with a Nikon ECLIPSE E400POL.

For the Fourier-transform infrared (FT-IR) measurement of polarized P(VDF-TrFE) film, the film was prepared on an Si substrate. The conditions to prepare the film and to polarize the P(VDF-TrFE) film were the same as those used to prepare the sensing capacitor. The FT-IR absorption spectra were measured with a Thermo Nicolet 6700 FT-IR spectrometer. The resolution of the spectra was 4 cm^{-1}, and the number of scans collected was 128.

3. Results and Discussion

Figure 2 (a) shows an atomic force microscope (AFM) image of the PVC gate dielectric surface. The film was found to have a very smooth and pinhole-free surface, with a root-mean square roughness of 0.20 nm within a 5×5 μm^2 scan scale, which is much smoother than the value (0.67 nm) for the of PVC film previously reported [8]. Figure 2 (b) shows a polarized microscope image of the TIPS-pentacene/PS active layer. As can be seen, the high crystallinity of the active layer is confirmed. These results lead us to expect the low-voltage operation of the OFET as gate dielectric surface smoothness and high crystallinity of the active layer are key factors for the low-voltage OFET operation [9].

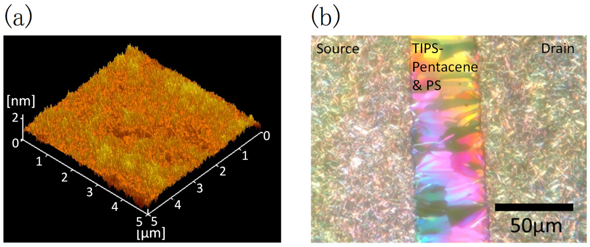

Fig. 2 (a) AFM image of the PVC surface. (b) Polarization microscope image of TIPS-pentacene and PS active layer.

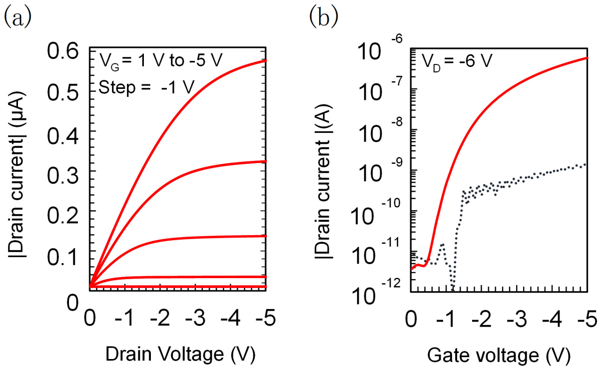

Fig. 3 (a) The output characteristics of the OFET (b) The transfer characteristics of the OFET.

Figures 3 (a) and 3 (b) show the output characteristics and the transfer characteristics of the OFET. In the output characteristics, the gate voltage (V_G) was swept from 0 to −5 V with a step voltage of 1 V. A clear increase in I_D as a function of V_G was observed despite the low V_G application. In addition, I_D was tended to saturate below V_G of −5 V as shown in Fig. 2 (b), where the ON/OFF ratio, mobility, threshold voltage (V_{th}) and threshold swing were 1.3×10^5, 0.29 cm^2/Vs, −1.25 V and 0.26 V/dec, respectively. From these results, we confirmed the low operation voltage of the OFET.

The pressure-sensing device was fabricated by integrating the low-voltage OFET and the sensing capacitor. Prior to the integration, the P(VDF-TrFE) film in the sensing capacitor is polarized by means of a contact poling method. While a poling voltage of 1 kV was applied to the Al top electrode, the Al bottom electrode was grounded. Thus, the direction of the polarization in the P(VDF-TrFE) film is from the bottom to the top. To confirm the electric field polarization in the P(VDF-TrFE) film induced by the change in the orientation of the P(VDF-TrFE) polymer chain, an FT-IR measurement of the film was conducted, where the orientation change of polar functional groups in the polymer chain can be observed as a change in the corresponding bands of the FT-IR spectra [10], [11]. In order to clarify the change in the spectra of the P(VDF-TrFE) after poling treatment, the difference spectrum was calculated by subtracting the spectrum of the polarized film from that of the pristine film. A clear difference in the bands before and after poling treat-

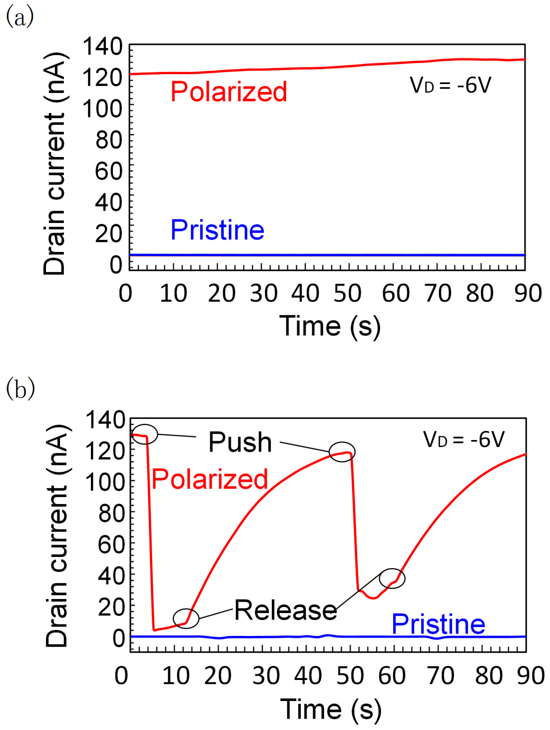

Fig. 4 (a) The I_D of the OFET integrated with the sensing capacitor using the pristine P(VDF-TrFE) film and the polarized P(VDF-TrFE) film at $V_D = -6$ V. (b) The the I_D response of the OFET integrated with the sensing capacitor using the pristine P(VDF-TrFE) film and the polarized P(VDF-TrFE) film at $V_D = -6$ V.

ment was observed, which is consistent with the previous reports [10], [11]. A detailed analysis on the FT-IR spectra will be reported elsewhere. The change in the bands indicates that the polar C-F bonds in the film are oriented along the direction of the external electric field during the poling treatment. In addition, the orientation of the bond is maintained after removal of the electric field. Thus, we concluded that the P(VDF-TrFE) film was successfully polarized by the contact poling treatment.

Figure 4 (a) shows the I_D at $V_D = -6$ V for the OFET. The I_D increased from 285 pA to 120 nA by integrating the sensing capacitor with the polarized P(VDF-TrFE). This suggests that the polarization in the P(VDF-TrFE) film induced the charge accumuration in the OFET channel. As the sensing capacitor and the OFET are integrated via the bottom electrode, the bottom electrode serve as the gate electrode of the OFET. Thus, the polarization of the film in the sensing capacitor applies an electric potential to the active layer of the OFET and consequently induces a change in the I_D. This is consistent with the changes observed in the device with similar structure [7], [12]. The change in the I_D induced by the polarization is produce shifts of the transfer curve and the V_{th} [13], [14]. In our device, however, the measurement of the transfer curve after integration was not succesful owing to electrical noise in the measurement, which was caused by the electrostatic charges in the polarized P(VDF-TrFE) layer. As can be seen in Fig. 4 (a), the typical I_D of our typical OFETs exceeded 100 nA after integration with the sensing capacitor, despite the measurement having been carried out without V_G application to the OFET. The value of I_D is consistent with that at approximately $V_G = -3$ V in Fig. 3 (a). Thus, we assume the effect of the polarization on the Vth shift would be c.a. 3 V in our integrated device. Figure 4 (b) shows the I_D response of the OFET integrated with the sensing capacitor using the pristine P(VDF-TrFE) film and the polarized P(VDF-TrFE) film. In the case of the sensor device with the polarized P(VDF-TrFE) film, I_D decreased from 120 nA to 5 nA by applying a pressure of 100 kPa. The variation of I_D was approximatly 16 times larger than that of a reported pressure sensor with a similar structure [1]. In addition, the change in the I_D caused by the pressure load is more than 95% of the initial value, which is significantly improved over the change (5%) for a pressure sensor using the low-voltage operation OFET [7]. After the release of the pressure, I_D slowly returned to the initial value, with a slow deformation of the P(VDF-TrFE) layer to its initial form. In contrast, in the case of the sensor device with the non-polarized (pristine) P(VDF-TrFE) film, no I_D difference against the pressure load was observed. This indicates that the polarization in the sensing capacitor is imperative for our sensor device. Furthermore, when the OFET of the sensor using the polarized P(VDF-TrFE) film was replaced by an OFET requiring high-voltage operation (60 V), the pressure response of the sensor was approximatly 10 times smaller than that of our device (data not shown). Thus, we concluded that the integration of the pressure sensing capacitors and the low operation voltage OFETs is critical to the development of high-performance pressure sensors. In particular, by using a low-voltage OFET with a sensing capacitor, we have succeeded in demonstratting a pressure sensing OFET that satisfies both low-voltage operation and high sensitivity.

4. Conclusion

In conclusion, we successfully achieved the pressure response at low operation voltage in our organic pressure sensor. The organic pressure sensor was prepared by integrating the sensing capacitor and the low-voltage operation OFET. The OFET was employed as the readout device of the pressure load and was operated below −6V. The sensing capacitor was prepared by using a polarized P(VDF-TrFE) film. I_D was changed from 120 nA to 5 nA by applying the pressure. The variation of I_D is approximately 10 times larger than that detected by a pressure sensor with a similar structure. We believe that the integration of the low-voltage OFETs and the sensing capasitors will be a one of the key technologies to develop the pressure sensor sheets.

Acknowledgments

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