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Title	Tunable Threshold Voltage of Organic CMOS Inverter Circuits by Electron Trapping in Bilayer Gate Dielectrics		
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Citation	IEICE TRANSACTIONS on Electronics, E98-C(5): 422- 428		
Issue Date	2015-05-01		
Туре	Journal Article		
Text version	publisher		
URL	http://hdl.handle.net/10119/12866		
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Description			



Japan Advanced Institute of Science and Technology

## PAPER Special Section on Fundamentals and Applications of Advanced Semiconductor Devices

# **Tunable Threshold Voltage of Organic CMOS Inverter Circuits by Electron Trapping in Bilayer Gate Dielectrics**

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SUMMARY We have demonstrated tunable *n*-channel fullerene and *p*channel pentacene OFETs and CMOS inverter circuit based on a bilayerdielectric structure of CYTOP (poly(perfluoroalkenyl vinyl ether)) electret and SiO<sub>2</sub>. For both OFET types, the  $V_{\rm th}$  can be electrically tuned thanks to the charge-trapping at the interface of CYTOP and SiO<sub>2</sub>. The stability of the shifted Vtth was investigated through monitoring a change in transistor current. The measured transistor current versus time after programming fitted very well with a stretched-exponential distribution with a long time constant up to 10<sup>6</sup> s. For organic CMOS inverter, after applying the program gate voltages for n-channel fullerene or p-channel pentacene elements, the voltage transfer characteristics were shifted toward more positive values, resulting in a modulation of the noise margin. We realized that at a program gate voltage of 60 V for p-channel OFET, the circuit switched at 4, 8 V, that is close to half supply voltage  $V_{DD}$ , leading to the maximum electrical noise immunity of the inverter circuit.

key words: controllable threshold voltage, stretch-exponential equation, noise margin enhancement, organic CMOS inverter

## 1. Introduction

In recent years, organic transistor circuits has been rapidly emerging since their attractive features including low-cost, low-temperature manufacturing, and mechanical flexibility, which are relatively difficult to be realized from Si-based counterparts [1]–[4]. In particular, tunable threshold voltage  $(V_{\rm th})$  of organic field-effect transistor (OFET) is very crucial for organic integrated circuit construction. This is due to the  $V_{\rm th}$  shifting to a lower value results in a decrease in power consumption of the transistor circuit while holding a high speed circuit operation [5]. On the other hand, controllable  $V_{\text{th}}$  allows the switching voltage of each OFET device to be modified, which can help to minimize manufacturing variation. Moreover, in complementary metal-oxidesemiconductor (CMOS) technology, due to a difference in the  $V_{\rm th}$  and the other electrical parameters between the pchannel and *n*-channel OFETs, the switching voltage of inverter may be close to either the ground voltage or the power supply. This results in a small noise margin, which in turn leads to the inverter is very susceptible to electrical noise. Thus, it is necessary to place the switching voltage of the

Manuscript received August 25, 2014.

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circuit at half power supply voltage by controlling the  $V_{\rm th}$  of the transistor elements in order to achieve the maximum noise immunity of the CMOS inverter [5], [6].

Several approaches have been recently introduced to tune the  $V_{\rm th}$  in organic transistor circuit. The  $V_{\rm th}$  tuning can be obtained by varying a doping concentration of Au nanoparticles (NPs) [7] or using polar self-assembled monolayers (SAMs) [8], [9] in a gate dielectric. Although the  $V_{\rm th}$ is well controlled with those techniques, the  $V_{\rm th}$  is only defined at manufacturing step [7]-[9]. To dynamically control the V<sub>th</sub> after fabrication, a number of methods have been developed. The tunability of the  $V_{\rm th}$  results from using space charge polarization [10] or charge-trapping polymer [11] or ferroelectric gate dielectrics [12], or Al floatinggate [13], [14]. However, the limitations of such methods are required long switching time and large switching voltage [10], [11] due to gradual formation of space charge polarization [10] or poor device performance resulting from the rough surface of ferroelectric materials [13] or instability of the shifted  $V_{\rm th}$  because the trapped charges easily leak through a SAM blocking-layer [13].

In our recent works [15], we have demonstrated highly stable transistor memories based on a double gate dielectric structure of poly(perfluoroalkenyl vinyl ether) (CYTOP) and SiO<sub>2</sub>. The  $V_{\text{th}}$  can be modulated thanks to electron trapping at the interface between CYTOP and SiO<sub>2</sub>. Taking the advantage of that, we have focused on the memory functionality by using the different levels of the  $V_{\text{th}}$  to present the binary values. The resulting memory transistors exhibit high performance with a large on/off ratio and excellent retention stability of data storage [15], [16].

In this work, we extend the findings to construct electrically tunable CMOS inverter circuits with a bilayerdielectric structure of CYTOP and SiO<sub>2</sub>. We firstly, in both n-channel fullerene and p-channel pentacene OFET elements, examined the tunability of  $V_{\rm th}$  and its stability after tuning through a current measurement. We found that a change in the drain current of the OFETs followed a stretched-exponential distribution with a long time constant of 10<sup>6</sup> s. In the latter part of this report, we describe additional experiments on control of the CMOS inverter circuit. The voltage transfer characteristic of the inverter was positively shifted after applying the program gate voltages for both transistor types. At a program gate voltage of 60 V for p-channel OFET, the inverting voltage of 4.8 V was realized, which approximates the half supply voltage. This brings about the maximum immunity of the circuits against

Manuscript revised December 12, 2014.

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DOI: 10.1587/transele.E98.C.422



Fig. 1 Illustration of OFET and CMOS inverter circuit layout and chemical structures of materials utilized in our experiments together with equivalent circuit of inverter.

the effect of electrical noise.

#### 2. Experimental Procedure

Figure 1 presents the schematic illustration of the inverter and the chemical structures of the used materials together with the equivalent circuit of the CMOS inverter. The transistor circuit was fabricated on a heavily doped Si (n+Si, resistivity:  $1-100 \,\Omega \,\text{cm}$ ) gate electrode coated with a SiO<sub>2</sub> (50 nm) dielectric layer. The silicon wafer was cleaned by ultrasonication (in acetone for 5 min, in detergent for 10 min, twice in pure water for 5 min, and in IPA for 10 min) and subjected to UV-O<sub>3</sub> treatment. A CYTOP electrontrapping layer (CTL-809 M, Asahi Glass) was spin-coated onto the gate dielectric at 2000 rpm for 60 s using a 0.5 wt% CYTOP solution (CT-Solv. 180) and dried at 100°C for 2 h. The CYTOP thickness of 10 nm was the optimized value as presented in our earlier work [15]. Fullerene ( $C_{60}$ , Nanom purple SUH, purity: 99.9%) and pentacene (Sigma-Aldrich Company) were thermally deposited through shadow masks onto the CYTOP layer to form the 40-nm-thick semiconductor layers for the *n*-channel and *p*-channel OFETs, respectively. To produce transistor configuration, 70-nm-thick Al and 50-nm-thick Au source-drain electrodes were formed on  $C_{60}$  and pentacene layers by thermal evaporation through shadow masks. The L and W of the OFETs were set at 75 and 5000  $\mu$ m, respectively. Finally, to complete the inverter circuit, a 100-nm-thick Ag interconnection line was vacuum-deposited through a shadow mask. The base pressure during the vacuum deposition was of  $2 \times 10^{-6}$  torr. Electrical characteristics of the OFETs and CMOS inverter were measured with a Keithley 4200 semiconductor parameter analyzer in a dry nitrogen atmosphere at room temperature in a dark probe station.

### 3. Results and Discussion

Figure 2 shows the output characteristics of the OFETs. The drain current  $(I_D)$  was monitored while the drain voltage



**Fig.2** Output characteristics of (a) *n*-channel and (b) *p*-channel OFET elements.

Table 1OFET parameters.

OFET type	$\mu (\text{cm}^2 \text{ V}^{-1} \text{ s}^{-1})$	$V_{\rm th}$ (V)	On/off ratio
n-channel	0.4	2.8	$5.5 \times 10^{4}$
p-channel	0.3	-4.4	$2.2 \times 10^{4}$

 $(V_{\rm D})$  was varied at the different gate voltage  $(V_{\rm G})$ . In a low  $V_{\rm D}$  region, a linear relationship between  $V_{\rm D}$  and  $I_{\rm D}$  was realized, suggesting efficient electron or hole injections at interfaces of C<sub>60</sub>/Al or pentacene/Au. The  $I_{\rm D}$  saturated at a high  $V_{\rm D}$  because the conducting channels were pinchedoff. These results indicate that the as-fabricated organic transistors exhibit standard *n/p*-channel field-effect operations. Table 1 presents the initial FET parameters in this study, where the field-effect mobility ( $\mu$ ) and the  $V_{\rm th}$  were extracted by fitting the curves with the standard equation for  $I_{\rm D}$  in the saturation regime. The estimated  $\mu$  and other parameters obtained in our experiments are typical values in OFETs using C<sub>60</sub> or pentacene as the semiconducting layers [11], [15], [16].

Figure 3 shows the transfer characteristics of OFETs recorded after application of a positive program gate voltage. In all processes, the pulse width of the program voltage is 1 s and the source-drain electrodes were grounded [16]. As can be seen in Fig. 3, the transfer curves positively shifted in both types of OFETs. Indeed, upon application of a high positive program voltage to a gate electrode, electrons are injected from the source-drain electrodes through the semiconducting and CYTOP layers and subsequently trapped at the interface of CYTOP and SiO<sub>2</sub>. The interfa-



**Fig. 3** Transfer characteristics of (a) *n*-channel and (b) *p*-channel OFETs measured after applying various program gate voltages.

cial trapping can be understood due to the electrets property of CYTOP material [17] and has been discussed in detail in our previous works [15], [16]. The trapped electrons then deplete electrons in the *n*-channel  $C_{60}$  or induce additional holes in p-channel pentacene, leading to the  $V_{\rm th}$  was shifted to more positive voltage. Note that, the trapped electrons at CYTOP/SiO<sub>2</sub> interface remain there without the need for any applied voltage, resulting in a built-in electric field. During the measurements of transfer characteristics, for nchannel C<sub>60</sub> OFET, when the applied electric field between the gate electrode and the semiconductor compensates the built-in electric field, the transistor operated similarly to the its initial state. Thus, the off-current of the device is almost unchanged (Fig. 3(a)). Meanwhile, in *p*-channel OFET, the built-in electric field leads to an increase in the number of holes accumulated in the pentacene channel that is the possible reason for an increase in the off-current (Fig. 3(b)).

We would like to confirm that the control of the  $V_{\rm th}$  is a reversible phenomenon. After applying a negative erase gate voltage, the trapped electrons were removed from the interface, the  $V_{\rm th}$  completely returns to the initial position. Figure 4 presents the characteristics of the reversible shifts in the  $V_{\rm th}$ . The change of the  $V_{\rm th}$  increased as the gate voltage pulse was increasing. Under applications of program/erase gate voltage pulses between 0 and  $\pm 55$  V (for the *n*-channel OFET device) and between 0 and  $\pm 90$  V (for the *p*-channel OFET device), the  $V_{\rm th}$  was reversely controlled, from +2.8 to +12.8 V for the *n*-channel OFET and from -4.4 to +4.6 V for the *p*-channel OFET. The required program voltage for *p*-channel device is larger than that for *n*-channel one (Fig. 4) because the facts that the larger injection barrier at the interfaces of Au/pentacene and electron



**Fig. 4** Relationships between  $V_{\text{th}}$  and gate voltage pulse in (a) *n*-channel and (b) *p*-channel OFET elements. OFETs were programmed/erased by changing magnitude of gate voltage pulse while source-drain electrodes were grounded. Width of each pulse was about 1 s.

transport through lower electron-mobility of pentacene [16].

Once the  $V_{\text{th}}$  can be controlled, its stability is the other important factor. In subsequent experiments, we studied the stability of the  $V_{\text{th}}$  after tuning to the new value. It was reported that an investigation of the change in the  $V_{\text{th}}$  of an OFET device can be converted to observation of the change in the  $I_{\text{D}}$ , and the relationship between the drain currents at initial  $I_{\text{D}}(0)$  and at the waiting time  $t I_{\text{D}}$  (t) can be expressed by a stretched-exponential equation [18]:

$$\frac{I_{\rm D}(t)}{I_{\rm D}(0)} = \exp\left[-\left(\frac{t}{\tau}\right)^{\beta}\right],\tag{1}$$

where  $\tau$  is the time constant and  $\beta$  is the dispersion parameter. To apply that knowledge for our devices, after programming,  $I_{\rm D}$  was continuously measured over 10<sup>5</sup> s at  $V_{\rm G}$  =  $\pm 10$  V and  $V_{\rm D} = \pm 4$  V for *n*-channel and *p*-channel OFETs (Inset of Fig. 5). The  $\mu$  was found to slightly decrease from 0.40 to  $0.35 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  for the *n*-channel OFET and from 0.30 to  $0.27 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  for the *p*-channel OFET, this is due to a decrease in the  $I_{\rm D}$ . Then, the  $I_{\rm D}(t)/I_{\rm D}(0)$  versus the waiting time were subsequently estimated. As can be seen in Fig. 5, the experimental data fit very well to the calculated results obtained with Eq. (1). The extracted  $\tau$  and  $\beta$  were shown in Table 2 where the  $\tau$  obtained from *p*-channel device is higher than that of *n*-channel OFET. This is probably due to, during bias process, the trapped electrons penetrate from the trap site through the pentacene layer slower than through the C<sub>60</sub> layer because of lower electron-mobility of pentacene material. Significantly, the obtained  $\tau$  is almost one order of the magnitude larger than that in a normal OFET [18], suggesting a highly stable  $V_{\rm th}$  obtained in our

 Table 2
 Parameters for stretched-exponential equation.





**Fig.5**  $I_D(t)/I_D(0)$  change as function of time during continuous bias voltages of (a) *n*-channel and (b) *p*-channel OFETs. Squares or circles represent experimental results, and solid curves represent calculated results obtained using stretched-exponential equation.



**Fig. 6** Voltage transfer characteristics and corresponding voltage gains (Inset) of CMOS inverter circuit at various  $V_{DD}$ . Dotted lines indicate  $V_{ins}$  positions.

devices even after tuning to the new value.

In organic CMOS technology, the changeable  $V_{\rm th}$  results in tunable switching voltage of inverter ( $V_{\rm ins}$ ), which in turn help to adjust the noise margin, avoiding the inadvertent switching of the circuit [5], [9]. To verify that hypothesis, we further studied on a CMOS inverter configuration constructed of *p*-channel pentacene and *n*-channel fullerene devices as discussed above. Figure 6 shows the voltage transfer characteristics and corresponding voltage gain of the organic CMOS inverter at various drain–drain voltages ( $V_{\rm DD}$ ).

For each curve, when an input voltage  $(V_{\text{In}})$  was varied from 0 to supply voltage  $V_{\text{DD}}$ , the output voltage  $(V_{\text{Out}})$  swings from  $V_{\text{DD}}$  to 0 V, indicating a typical inverting operation. The voltage gain, estimated by  $-dV_{\text{Out}}/dV_{\text{In}}$ , increased with increasing the  $V_{\text{DD}}$ . This trend is similar to that in other circuit systems [14], [19]. The obtained gain can be comparable to that of previous organic inverters [7], [8].

It knows that the  $V_{ins}$  occurs when both *n*-channel and *p*-channel devices are saturated and the  $V_{ins}$  can approximately be given by the following equation [19]:

$$V_{\rm ins} = \frac{V_{\rm DD} - |V_{\rm th,p}| + V_{\rm th,n} \sqrt{\frac{K_{\rm n}}{K_{\rm p}}}}{1 + \sqrt{\frac{K_{\rm n}}{K_{\rm p}}}},$$
(2)

where  $V_{\text{th,n}}$  and  $V_{\text{th,p}}$  are the threshold voltages for *n*-channel and *p*-channel OFETs, respectively;  $K_n = (W/L)\mu_n C_i$ ;  $K_p = (W/L)\mu_p C_i$ , in which  $C_i$  is the capacitance per unit area of the gate dielectric. Since the  $V_{\text{th}}$  and the  $\mu$  parameters of the *n*-channel device were different from those of the *p*channel one as presented in Table 1, our initial inverter did not switch at the theoretical point of  $1/2V_{\text{DD}}$  as evidently shown in Fig. 6. Thus, the voltage transfer characteristic should be relocated.

The controllable characteristics of the organic inverter circuit at  $V_{DD}$  of 10 V are shown in Fig. 7, where each  $V_{Out}$ - $V_{\rm In}$  relationship was taken after applying a program gate voltage for the n-channel or p-channel OFETs. The positive shift of  $V_{\rm th}$  in both transistor types caused the switching voltage of inverter  $V_{ins}$  tunes also to more positive voltage value. We would like to note that when applying a program voltage of 50 V for *n*-channel device (shifted  $V_{\text{th}} = \sim 10 \text{ V}$ , Fig. 4), the  $V_{ins}$  cannot be observed since it is actually larger than the  $V_{DD}$ . The changes in the  $V_{ins}$  as a function of the gate voltage pulse at  $V_{DD}=10$  V are shown in Fig. 8 (opened curves). The  $V_{ins}$  was tuned over a wide range, from 3.3 to more than 10 V after programming the *n*-channel OFET (Fig. 8(a)) and from 3.3 to 6.6 V after programming the pchannel OFET (Fig. 8(b)). Interestingly, we found that, at the program voltage of 60 V, the  $V_{\rm th}$  of *p*-channel OFET was placed at -2.9 V (Fig. 4(b)), nearly equal to that of the initial n-channel device (2.8 V). This leads to the inverter was switched at a voltage of 4.8 V, which is close to the ideal value  $(1/2 V_{DD})$ . On the other hand, to compare with the measured values, the  $V_{ins}$  of the organic CMOS inverter was theoretically calculated using Eq. (2) and plotted as filled curves in Fig. 8. As can be seen in Fig. 8(a) and (b), the experimental data tend to follow the calculated results with a relatively small error.

An electrical noise immunity of a digital CMOS circuit is quantified as the noise margin (NM) which is the maximum noise signal that can be superimposed on a digital signal without changing the function of the circuit [19]. In order to examine effect of the  $V_{\rm th}$  on the NM, in Fig. 9, we have estimated the NM at the high  $(NM_{\rm H})$  and low  $(NM_{\rm L})$ 



**Fig.7** Voltage transfer characteristics of CMOS inverter circuit measured after applying program gate voltage. pFET and nFET in figures are same definitions with *p*-channel OFET and *n*-channel OFET, respectively.



**Fig. 8** Change of  $V_{\text{ins}}$  as function of gate voltage pulse after programming (a) *n*-channel or (b) *p*-channel OFETs at  $V_{\text{DD}}=10$  V. Here, when OFET element of CMOS inverter was programmed, its complement was kept at initial state. Opened curves represent experimental results, and filled curves represent calculated results obtained using Eq. (2) with the  $V_{\text{th,n}}$  and  $V_{\text{th,p}}$  taken from Fig. 4.

logic levels from the selected voltage transfer characteristics at  $V_{DD}$ =10 V using the following equations [19]:

$$NM_{\rm H} = V_{\rm Out,H} - V_{\rm In,H} \tag{3}$$

$$NM_{\rm L} = V_{\rm In,L} - V_{\rm Out,L} \tag{4}$$

where  $V_{\text{In,L}}$  and  $V_{\text{In,H}}$  are the input low and high voltages,  $V_{\text{Out,H}}$  and  $V_{\text{Out,L}}$  are the output high and low voltages. The  $V_{\text{In,L}}$  and  $V_{\text{In,H}}$  are extracted at the points where the gain



**Fig.9** Noise margins of CMOS inverter estimated at (a) initial and after applications of program voltages of (b) 70 V and (c) 60 V for *p*-channel OFET. Gap between  $NM_L$  and  $NM_H$  is undefined region.

= -1 while the  $V_{\text{Out,H}}$  and  $V_{\text{Out,L}}$  are the output voltages for  $V_{\text{In}} = 0$  V and  $V_{\text{DD}}$ , respectively [20]. As can be seen in Fig. 9(a) and 9(b), there is no balance between the  $NM_{\text{L}}$ and the  $NM_{\text{H}}$ . The  $NM_{\text{L}}$  (2.5 V, obtained at initial state) and  $NM_{\text{H}}$  (2.7 V, obtained after applying the program voltage of 70 V for *p*-channel device) are both narrow and close to the ground potential and the supply voltage  $V_{\text{DD}}$ , respectively. This may cause a failure of the logic functionality since the inverter is quite susceptible to electrical noise. However, at the program gate voltage of 60 V for *p*-channel device, the balance between the  $NM_L$  (3.9 V) and the  $NM_H$  (4.1 V) is significantly improved as shown in Fig. 9(c). This results in a greater noise immunity [5], [9], i.e., the circuit can operate more reliably.

We would like to stress here that, to balance between the  $NM_L$  and the  $NM_H$  at a certain  $V_{DD}$ , it is necessary to choose a suitable program gate voltage for *n*-channel or *p*channel OFETs based on the tendency documented in Fig. 4 in order that results in a symmetrical  $V_{th}$  for both transistor types.

### 4. Conclusion

In summary, we have demonstrated tunable threshold voltage OFETs and CMOS inverter circuit based on pentacene/C<sub>60</sub> and a bilayer-dielectric structure of CYTOP and SiO<sub>2</sub>. The  $V_{\text{th}}$  of OFETs can be electrically switched thanks to electron trapping at the interface of CYTOP and  $SiO_2$  layers. The stability of the  $V_{th}$  after programming was examined through an investigation of the change in transistor current, which fitted very well with a stretchedexponential equation with a time constant up to  $10^6$  s. For organic CMOS inverter circuit, the voltage transfer characteristic was positively shifted after applying the program gate voltages for *n*-channel or *p*-channel elements. The noise margin NM of the inverter was found to be strongly depended on the  $V_{\rm th}$ . Significantly, at a program gate voltage of 60 V, the  $V_{\text{th}}$  of *p*-channel OFET was set to be nearly equal to that of the initial *n*-channel device, which provides an excellent balancing between the  $NM_{\rm L}$  and the  $NM_{\rm H}$  at supply voltage  $V_{DD}$  of 10 V. This in turn results in the maximum electrical noise immunity of the circuits. The experimental data suggest that the organic transistor and inverter based on a bilayer-dielectric structure of CYTOP and SiO<sub>2</sub> can be used to fabricate reconfigurable complex organic CMOS integrated circuits.

#### Acknowledgments

This research is funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number "103.99-2013.13".

#### References

- [1] K. Myny, E. van Veenendaal, G. H. Gelinck, J. Genoe, W. Dehaene, and P. Heremans, "An 8-Bit, 40-instructions-per-second organic microprocessor on plastic foil," IEEE J. Solid-State Circuits, vol.47, no.1, pp.284–291, Jan. 2012.
- [2] K. Kikuchi, F. Pu, H. Yamauchi, M. Iizuka, M. Nakamura, and K. Kudo, "CMOS circuits based on a stacked structure using siliconeresin as dielectric layers," IEICE Trans. Electron., vol.94-C, no.2, pp.136–140, Feb. 2011.
- [3] F. Kaneko, A. Baba, K. Shinbo, and K. Kato, "Nano-structured organic devises and biosensors utilizing evanescent waves and surface plasmon resonance," IEICE Trans. Electron., vol.E94-C, no.12, pp.1824–1831, Dec. 2011.
- [4] K. Kudo, S. Kuniyoshi, H. Yamauchi, M. Iizuka, and M. Sakai, "Vertical channel organic transistors for information tag applications,"

IEICE Trans. Electron., vol.E96-C, no.3, pp.340-343, Mar. 2013.

- [5] H. Etschmaier, P. Pacher, A. Lex, G. Trimmel, C. Slugovc, and E. Zojer, "Continuous tuning of the threshold voltage of organic thinfilm transistors by a chemically reactive interfacial layer," Appl. Phys. A, vol.95, no.1, pp.43–48, Apr. 2009.
- [6] M. Spijkman, E. C. P. Smits, P. W. M. Blom, D. M. de Leeuw, Y. Bon Saint Côme, S. Setayesh, and E. Cantatore, "Increasing the noise margin in organic circuits using dual gate field-effect transistors," Appl. Phys. Lett., vol.92, no.14, pp.143304, Apr. 2008.
- [7] S.-T. Han, Y. Zhou, Z.-X. Xu, and V. A. L. Roy, "Controllable threshold voltage shifts of polymer transistors and inverters by utilizing gold nanoparticles," Appl. Phys. Lett., vol.101, no.3, pp.033306, July 2012.
- [8] Q. Sun and S. Seo, "A tunable organic inverter based on groove patterned pentacene thin film transistors using soft-contact lamination," Org. Electron., vol.13, no.3, pp.384–387, Mar. 2012.
- [9] U. Zschieschang, F. Ante, M. Schlörholz, M. Schmidt, K. Kern, and H. Klauk, "Mixed self-assembled monolayer gate dielectrics for continuous threshold voltage control in organic transistors and circuits," Adv. Mater., vol.22, no.40, pp.4489–4493, Oct. 2010.
- [10] H. Sakai, K. Konno, and H. Murata, "Tuning of threshold voltage of organic field-effect transistors by space charge polarization," Appl. Phys. Lett., vol.94, no.7, pp.073304, Feb. 2009.
- [11] M. Marchl, M. Edler, A. Haase, A. Fian, G. Trimmel, T. Griesser, B. Stadlober, and E. Zojer, "Tuning the threshold voltage in organic thin-film transistors by local channel doping using photoreactive interfacial layers," Adv. Mater., vol.22, no.47, pp.5361–5365, Dec. 2010.
- [12] M.-H. Kim, G. J. Lee, C.-M. Keum, and S.-D. Lee, "Voltagereadable nonvolatile memory cell with programmable ferroelectric multistates in organic inverter configuration," Org. Electron., vol.14, no.5, pp.1231–1236, May 2013.
- [13] T. Sekitani, T. Yokota, U. Zschieschang, H. Klauk, S. Bauer, K. Takeuchi, M. Takamiya, T. Sakurai, and T. Someya, "Organic non-volatile memory transistors for flexible sensor arrays," Science, vol.326, no.5959, pp.1516–1519, Dec. 2009.
- [14] T. Yokota, T. Nakagawa, T. Sekitani, Y. Noguchi, K. Fukuda, U. Zschieschang, H. Klauk, K. Takeuchi, M. Takamiya, T. Sakurai, and T. Someya, "Control of threshold voltage in low-voltage organic complementary inverter circuits with floating gate structures," Appl. Phys. Lett., vol.98, no.19, pp.193302, May 2011.
- [15] T. T. Dao, T. Matsushima, and H. Murata, "Organic nonvolatile memory transistors based on fullerene and an electron-trapping polymer," Org. Electron., vol.13, no.11, pp.2709–2715, Nov. 2012.
- [16] T. T. Dao, T. Matsushima, R. Friedlein, and H. Murata, "Controllable threshold voltage of a pentacene field-effect transistor based on a double-dielectric structure," Org. Electron., vol.14, no.8, pp.2007– 2013, Aug. 2013.
- [17] Y. Sakane, Y. Suzuki, and N. Kasagi, "The development of a highperformance perfluorinated polymer electret and its application to micro power generation," J. Micromech. Microeng., vol.18, no.10, pp.104011, Oct. 2008.
- [18] H. H. Choi, W. H. Lee, and K. Cho, "Bias-stress-induced charge trapping at polymer chain ends of polymer gate-dielectrics in organic transistors," Adv. Funct. Mater., vol.22, no.22, pp.4833–4839, Nov. 2012.
- [19] K.-J. Baeg, M. Caironi, and Y.-Y. Noh, "Toward printed integrated circuits based on unipolar or ambipolar polymer semiconductors," Adv. Mater., vol.25, no.31, pp.4210–4244, Aug. 2013.
- [20] M. Guerin, A. Daami, S. Jacob, E. Bergeret, E. Benevent, P. Pannier, and R. Coppard, "High-gain fully printed organic complementary circuits on flexible plastic foils," IEEE Trans. Electron. Dev., vol.58, no.10, pp.3587–3593, Oct. 2011.



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