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Achieving Low-Program Voltage and High-Stability in Controllable Organic Complementary Logic Circuits by Photoactive Gate Dielectric

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Abstract

Control of threshold voltage is crucial for realizing robust organic digital circuit. So far, achievements of low-program voltage and high-stability of shifted state in organic circuit are still challenging. Here, we present controllable complementary organic circuits on PET substrate using a photoactive dielectric of DPA-CM:PMMA and electron-trapping site of Cytop. The threshold voltage of OTFTs and inverting voltage of circuits were reversibly controlled over a wide range under program voltage less than 10 V and UV light irradiation. At a program voltage of –2 V, excellent balance between the high and low noise margins was realized, resulting in the maximum noise immunity. Furthermore, the programmed circuit showed high stability such as a retention time of inverter switching voltage over 10^5 s.

1. Introduction

To construct organic electronic circuit, it is very important to adjust the transistor threshold voltage (V_{th}) after the device fabrication since it can minimize manufacturing variation. Also, tunable V_{th} leads to controllable switching voltage of inverter (V_{Ins}), which in turn adjusts the noise margin (*NM*), limiting the inadvertent logic switching [1,2]. In particular the V_{Ins} of organic circuit is required to tune with a voltage below 10 V [1,3]. But, such low-program voltage was realized with the expense of that the programmed V_{Ins} readily shifted back to its initial value because the stored charges in the floating-gate easily leaks through the capped AlO_x/SAM thin film [1].

In this work, we realize low-program voltage, highly stable and controllable complementary organic logic circuits on flexible PET substrate by introducing a photoactive gate dielectric layer composed of the layers of 6-[4'-(*N*,*N*-diphenylamino)phenyl]-3-ethoxycarbonylcoumarin (DPA-CM) doped into poly(methyl methacrylate) (PMMA) and Cytop. The characteristics of transistor circuits can be tuned over a wide range at a program voltage less than 10 V. The maximum noise immunity was observed at a program voltage of –2 V. The tuned V_{Ins} was stable even after 10^5 s.

2. Experimental procedure

The schematic layout of organic circuit and chemical structures of DPA-CM and Cytop are shown in Fig. 1(a). A DPA-CM:PMMA composite was spin-coated on the ITO/PET and dried at 70 °C for 60 min. Then, a Cytop (CTX-809AP2, Asahi Glass) layer was spin-coated and dried at 70 °C for 60 min. Subsequently, pentacene (for pOTFT) and fullerene (for nOTFT) were thermally deposited through shadow masks. Finally, Cu source-drain electrodes (L=50 μm,W=2000 μm) and interconnects were vacuum-deposited through a shadow mask. During programming/erasing, 365 nm UV light was irradiated from a PET substrate.

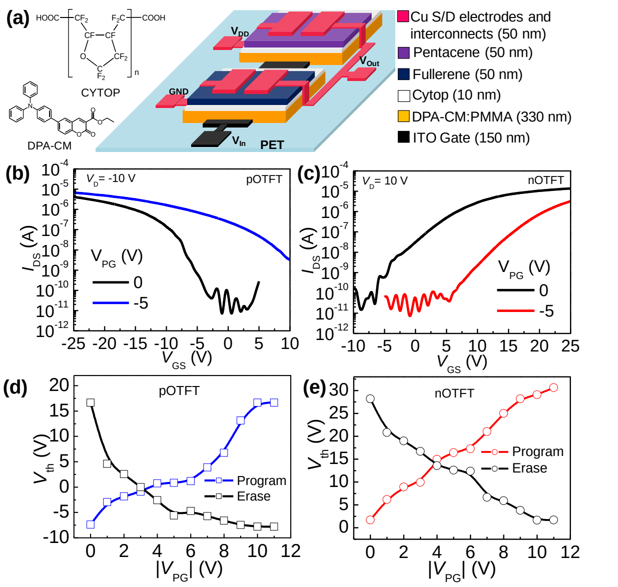

Fig. 1 a, Schematic layout of organic circuit and chemical structures of DPA-CM and Cytop. Transfer curves of pOTFT (b) or nOTFT (c) at initial and after programming. V_{th} versus V_{PG} of pOTFT (d) or nOTFT (e).

3. Results and discussion

The mobility values of initial pOTFT and nOTFT were estimated to be 0.18 and 0.73 cm^2 V^{-1} s^{-1}, respectively. Figures 1(b,c) show the transfer curves of OTFT elements after applying a program gate voltage (V_{PG}) of – 5 V for 1 s under UV light intensity of 3.94 mW/cm^2. When a negative gate voltage is applied, the charge-separation states of DPA-CM molecules are converted into free electrons and holes [4]. The free electrons internally provide for Cytop trap sites [2]. The trapped electrons subsequently induce additional holes in *p*-channel or deplete electrons in the *n*-channel, leading to the positive shifts of transfer curves. Figures 1(c,d) present the V_{th} change as a function of V_{PG}. Program or erase operations were done by applying negative or positive V_{PG} pulses to the gate for 1 s under UV light intensity of 3.94 mW/cm^2. Under V_{PG} between 0 and –/+10 V, the V_{th} was reversely controlled from – 7.4 to +16.7 V for the pOTFT and from + 1.7 to + 30.6 V for the nOTFT, respectively.

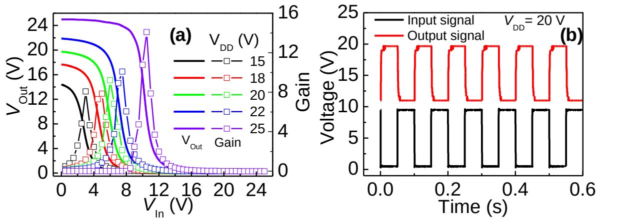

Fig. 2 *VTC* and corresponding gain (a) and dynamic response (b) of initial inverter.

Figure 2 shows the electrical characteristics of the initial complementary circuit. For each voltage transfer characteristic (VTC) curve (Fig. 2 (a)), when an input voltage (V_{In}) was varied from 0 to supply voltage V_{DD}, the output voltage (V_{Out}) swings from V_{DD} to 0 V. The dynamic response at 10 Hz is presented in Fig. 2(b). At any time point, the output signal inverted to the input signal. The static and dynamic behaviors indicate that the complementary inverter was well constructed from above-mentioned OTFTs.

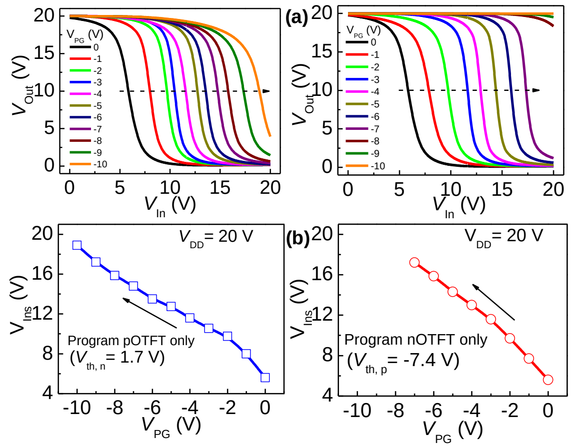

Fig. 3 Changes in *VTC* (a) and V_{Ins} (b) of circuit after programming pOTFT (left) or nOTFT (right).

The controllable behaviors of the organic inverter circuit at V_{DD} = 20 V are shown in Fig. 3. Each *VTC* curve was taken after applying a V_{PG} pulse for 1 s to the pOTFT or nOTFT under UV light intensity of 3.94 mW/cm^2. When one of the circuit devices was programmed, its complementary device was kept at initial. As shown in Fig. 3, the V_{Ins} was shifted over a wide range from 5.6 to 18.9 after programming the pOTFT and from 5.6 to more than 17.2 V after programming the nOTFT. By choosing V_{PG} of –2 V, we achieve V_{Ins} of 9.8 V, which is nearly ideal (½ V_{DD}). Figure 4 shows the analyses of the *NM* at the high (NM_H) and low (NM_L) logic levels from initial and programmed *VTC*s. In initial case, there is no balance between the NM_L and the NM_H. Also, the NM_L of 3.1 V (31% of ½ V_{DD}) is narrow and close to the ground potential. This may cause a failure of the logic functionality if the inverter works under electrical noise condition. After the programming, the balance between the NM_L (6.4 V=64% of ½ V_{DD}) and the NM_H (6.8 V=68% of ½ V_{DD}) is significantly improved, that leads to maximum immunity of the circuit against the effect of electrical noise [5].

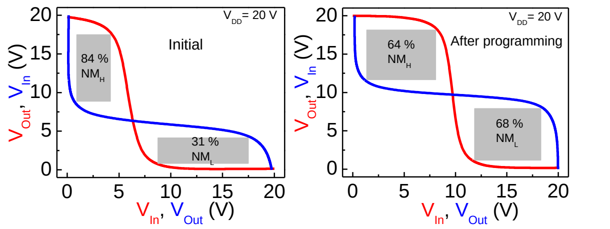

Fig. 4 *NM* analyses of circuit at initial (left) and after programming with V_{PG}= –2 V (right).

Besides the low-program voltage, stability of new circuit state is another important parameter. We measured the retention time of the V_{Ins} at 9.8 V. As shown in Fig. 5, the programmed V_{Ins} was almost unchanged after 10^5 s, which is the largest retention time ever reported in literatures [1]. The obtained such high-stability of V_{Ins} indicates that our circuit can work with good reliability even after programming.

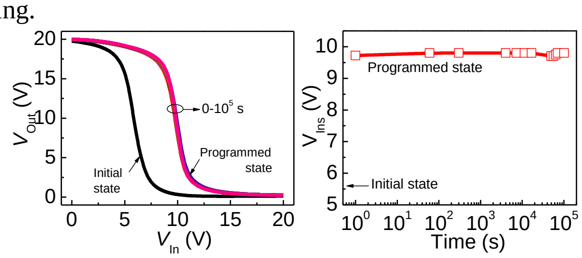

Fig. 5 *VTC* (left) and V_{Ins} (right) of circuit as function of time.

4. Conclusions

We have demonstrated the controllable complementary organic circuits with a photoactive gate dielectric of DPA-CM:PMMA and electron-trapping effect of Cytop. The V_{th} or V_{Ins} were tuned over a wide range under V_{PG} less than 10 V and UV light. At V_{DD} of 20 V, excellent balance between the NM_L and NM_H was realized under a V_{PG} of –2 V. In addition, the programmed circuit exhibited high stability with a retention time more than 10^5 s.

Acknowledgements

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References

[1] T. Yokota et al., IEEE Trans. Electron Dev. **59** (2012) 3434.
[2] T. Dao and H. Murata, IEICE Trans. Electron. **98** (2015) 422.
[3] T. Yokota et al., Appl. Phys. Lett. **98** (2011) 193302..
[4] T. Dao et al., Jpn. J. Appl. Phys. **53** (2014) 02BB03.
[5] H. Wang et al., Proc. Natl. Acad. Sci. USA **111** (2014) 4776.