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Letter

# Low-voltage complementary inverters employing organic vertical-type triodes

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ABSTRACT

In this study, we report the electrical characterization of complementary inverters fabricated using n- and p-channel organic vertical-type triodes (OVTs) on the same substrate. Because of the similar performance of the p-channel OVT (ON current: −229 μA; OFF current: −67.6 nA; turn-on voltage: −0.8 V) and n-channel OVT (ON current: 377 μA; OFF current: 86.9 nA; turn-on voltage: 0.4 V), the complementary inverter combining the n- and p-channel OVTs exhibited a voltage gain of ca. 9 at a low supply voltage of 4 V.


## 1. Introduction

Inverters employing complementary technologies – e.g., p- and n-channel transistors or two ambipolar transistors – are desirable for use in more complicated integrated circuits because of their low power dissipation, high noise margins, robust operation, and simple circuit design [1–6]. Earlier this decade, Bell Laboratories first fabricated large-area integrated circuits using organic complementary inverters; since then, organic complementary inverters have attracted considerable interest from academic and industrial researchers [1]. Their applications remain limited, however, to use in disposable electronics because of the low mobilities of organic semiconductors. Although the driving voltage and operation speed of organic inverters can be lowered by shortening the channel length of organic thin-film transistors down to the sub-micrometer regime, the resulting necessary complicated lithographic processes and the contact resistance of the semiconductor/metal would limit the performance of such devices [7]. Moreover, the formation of a transit time would delay the operating frequency when the structure employs the dielectric material as the insulator. Therefore, to overcome these drawbacks, recent research has focused on vertical-type transistors, which allow precise control over the channel length down to the sub-micrometer regime without the need to employ a dielectric material [8–12].

In a previous report, we investigated p-channel organic vertical-type triodes (OVTs) operated in the voltage-driving mode and fabricated organic inverters composed of the OVT connected with a resistance [12]. Although load-resistor inverters could be built into the logic gate, they are inappropriate for the realization of integrated circuits because the resistor would take up a larger area and be operated under “normally-on” conditions. The output voltage of the organic inverter would change gradually upon increasing input voltage, resulting in a lower transfer gain. In this Letter, we describe the fabrication of an organic complementary inverter integrating both p- and n-channel OVTs. To achieve high efficiency, we optimized the p- and n-channel OVTs so that they exhibited similar ON and OFF

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currents. Our vertical-type complementary organic inverter exhibited a transfer gain of up to −9 at a supply voltage ($V_{DD}$) of 4 V. To the best of our knowledge, this device is the first organic complementary inverter formed by integrating p- and n-channel OVTs.

## 2. Experimental

Fig. 1(a) and (b) display three-dimensional and circuit schematic representations, respectively, of the organic complementary inverter. Initially, a 30 nm-thick gold (Au) layer was deposited on a cleaned glass substrate to function as the collector electrode for the p- and n-channel OVTs. For the n-channel OVT, N,N′-dioctyl-3,4,9,10-perylenedicarboximide (PTCDI, ca. 98% purity, Sigma–Aldrich) was deposited on the Au layer to function as the collector layer. A 30 nm-thick aluminum (Al) strip was deposited on the collector layer to serve as the common-base electrode for the p- and n-channel OVTs. Next, a thin Al film (15 nm), to operate as the base electrode, was deposited on the strip. To decrease the OFF current, the sample was heated at 150 °C for 2 h [11]. A 100 nm-thick layer of $C_{60}$ was thermally evaporated onto the thin Al layer to function as the emitter layer. A 30 nm-thick silver (Ag) layer was deposited onto the emitter layer of the n-channel OVT to behave as the emitter electrode. For the p-channel OVT, a 50 nm-thick layer of copper phthalocyanine (CuPc, Luminescence Technology) was thermally deposited onto the Au layer to smooth the surface morphology and then a 270 nm-thick layer of pentacene (ca. 98% purity, Luminescence Technology) was thermally evaporated to function as the collector layer. A thin Al film (10 nm) was then deposited and a lithium fluoride (LiF) layer (0.4 nm) was thermally evaporated to function as a hole injection enhancement layer. Next, a 20 nm-thick layer of N,N′-bis(naphthalen-1-yl)-N,N′-bisphenylbenzidine (NPB) was thermally evaporated to enhance the carrier energy. Pentacene was then thermally evaporated to form the 100 nm-thick emitter layer. Finally, a film of $WO_3$ (10 nm)/Al (30 nm) was deposited onto the emitter layer of the p-channel OVT to function as the emitter electrode. All the organic materials were used as received; they were thermally evaporated at a base pressure of $10^{-6}$ torr. The devices were patterned using a metal mask; the active area for both the p- and n-channel triodes was 0.04 $cm^2$. The current–voltage ($I$–$V$) characteristics of the devices were measured in the dark under a nitrogen ($N_2$) atmosphere using a Keithley 4200-SCS semiconductor parameter analyzer.

## 3. Results and discussion

In previous reports describing the performance of p- and n- channel OVTs [11,12], a p-channel OVT employing Au as the emitter electrode could be operated through voltage-driving under an apparent saturation region, although the ON current was much less than that of an n-channel OVT. This behavior was attributed to the longer mean free path of electrons in metal films than that of holes [13]; electrons have a lower probability of recombining at the metal base than do holes and, thus, a greater number of electrons could diffuse through the metal base layer into the collector layer. Therefore, to enhance the ON current of the p-channel OVT, we inserted a $WO_3$ layer

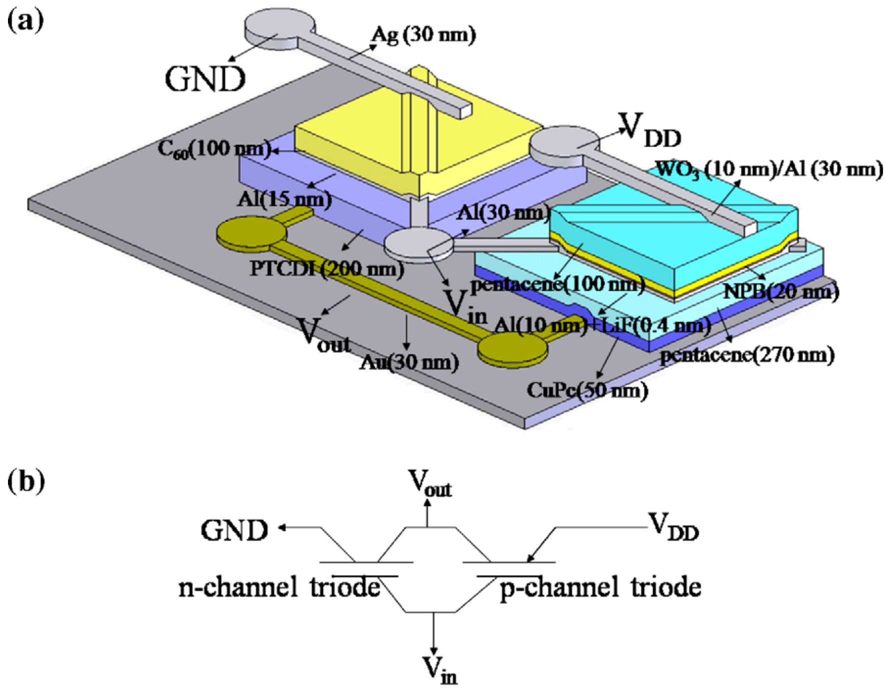


**Fig. 1.** (a) Three-dimensional and (b) circuit schematic representations of the organic complementary inverter.

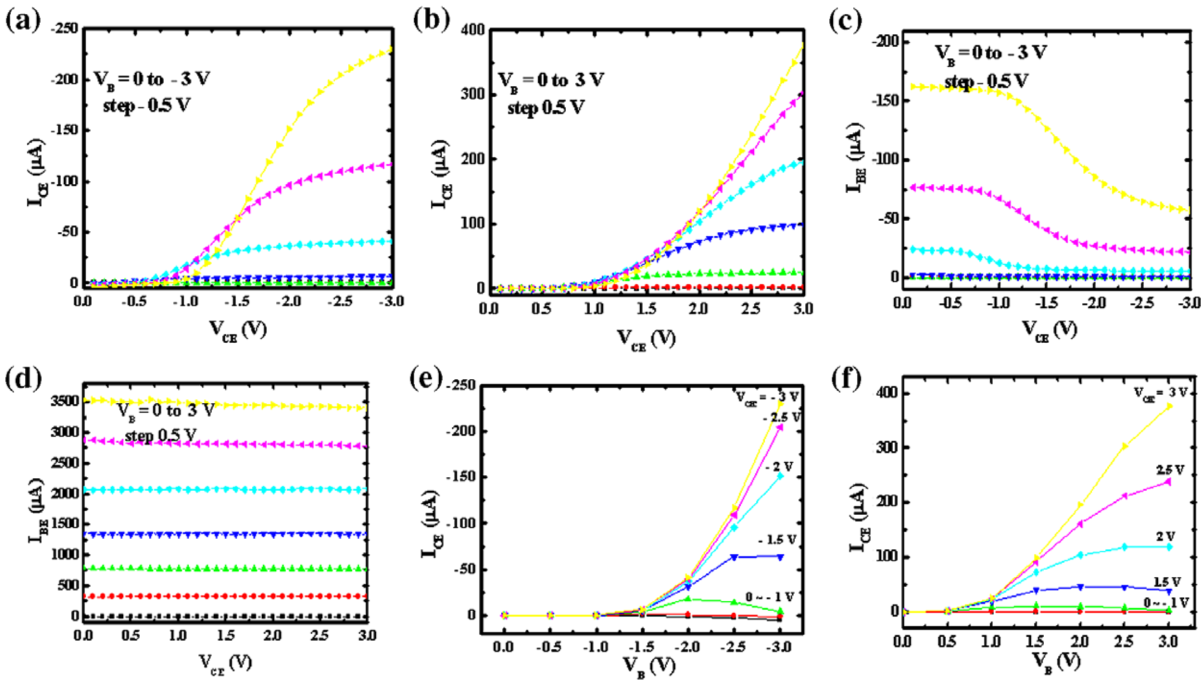


**Fig. 2.** (a) and (c) Collector-to-emitter current ($I_{CE}$) and the base current ($I_{BE}$) plotted with respect to the collector-to-emitter voltage ($V_{CE}$) for the p-channel organic triode at base voltages ($V_B$) ranging from 0 to −3 V at a step of −0.5 V. (b) and (d) $I_{CE}$ and $I_{BE}$ plotted with respect to $V_{CE}$ for the n-channel organic triode at values of $V_B$ ranging from 0 to 3 V at a step of 0.5 V. (e) and (f) the $I_{CE}$ versus $V_B$ characteristics of the p- and n-channel OVTs at $V_{CE}$ ranging from 0 to −3 V at a step of −0.5 V and ranging from 0 to 3 V at a step of 0.5 V, respectively.

at the Al–pentacene junction to lower the barrier between the electrode and organic semiconductor and prevent the reaction and/or diffusion of the metal into the active layer [14,15]. Current matching between p- and n-channel OVTs is important for an effective complementary inverter. Fig. 2(a) and (c) display the collector-to-emitter current ($I_{CE}$) and base current ($I_{BE}$) with respect to the collector-to-emitter voltage ($V_{CE}$) of the p-channel OVTs and Fig. 2(b) and (d) display the $I_{CE}$ and $I_{BE}$ with respect to the $V_{CE}$ of the n-channel OVTs. Fig. 2(e) and (f) display the $I_{CE}$ versus the base voltage ($V_B$) characteristics of the p- and n-channel OVTs, respectively. Due to the carriers without large enough energy, most of carriers would become recombination current at the base electrode, as result of the lower current gain [14]. To enhance the current gain, there are two possible ways to decrease the carrier recombination at based electrode. One is that increasing the tunneling current by optimizing LiF thickness [16]. The other is that the enhancing the carrier energy by replacing NPB layer with the material with higher HOMO level. For the p-channel OVT, the ON current ($V_B = -3$ V), OFF current ($V_B = 0$ V), and turn-on voltage were −229 μA, −67.6 nA, and −0.8 V, respectively; for the n-channel OVT, these values were 377 μA (at $V_B = 3$ V), 86.9 nA (at $V_B = 0$ V), and 0.4 V, respectively. Owning to the OVTs composed of the EB and the CB diode, while the $V_B$ was applied for zero, the most of the OFF current was caused by the leakage current of the CB diode. Therefore, the OFF current could be decreased by heating the device [11] or/and increasing the thickness of the CB diode. As the Fig. 1(e) and (f) shown, a leakage current exists at small $V_{CE}$ bias. It was observed in organic and inorganic vertical-type triodes due to the asymmetry of the CB diode and the EB diode and unideal transport factor [12,17,18]. As the $V_{CE}$ increasing, the $I_{CE}$ would be appropriately small current or near zero and this $V_{CE}$ was defined as the turn-on voltage. Although the ON current of the p-channel OVT could be increased by one order of magnitude, it remained somewhat less than that of the n-channel OVT. To further improve the performance of the p-channel OVT, we suspect that it would be necessary to insert a material possessing a higher energy level between the NPB layer and the thin Al layer to

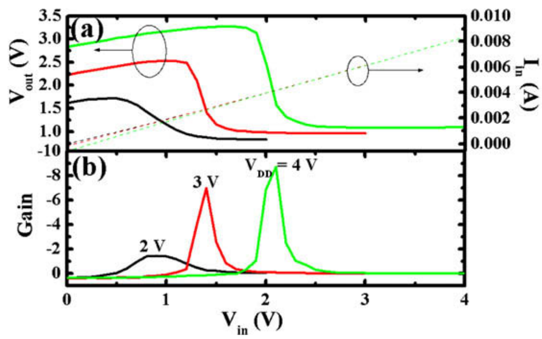


**Fig. 3.** (a) Measured transfer characteristics and input current ($I_{in}$) and (b) corresponding gain of an organic complementary inverter at supply voltages ($V_{DD}$) ranging from 2 to 4 V at a step of 1 V.

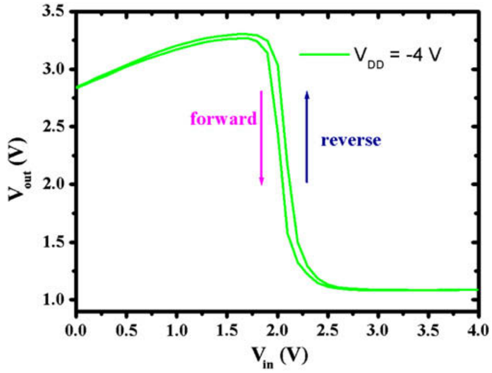


**Fig. 4.** Transfer characteristics in both forward and reverse directions for the complementary organic inverter at a value of $V_{DD}$ of 4 V.

raise the carrier energy; such studies are currently under investigation.

Fig. 3 displays the transfer characteristics, the input current and corresponding gain of the complementary vertical-type organic triode in the supply voltage ($V_{DD}$) range from 2 to 4 V at a step of 1 V. The larger input current was caused by the base current of the OVT. Although the complementary inverter could be operated by the lower voltage, larger input current may consume more power. Besides, it was not beneficial to drive the next device in the integrated circuit application. Therefore, enhancing tunneling current or/and increasing carrier energy could decrease the input current and improve the power dissipation. In addition, the electrical characteristics of the complementary inverter, corresponding gain, was also worth discussing. The corresponding gain, defined as $-dV_{out}/dV_{in}$, increased gradually upon increasing the value of $V_{DD}$, reaching its highest value of −8.75 when $V_{DD}$ was equal to 4 V. Relative to the corresponding resistance-load inverter [12], the complementary vertical-type organic triode exhibited an enhanced gain and a lower driving voltage. Fig. 4 displays the transfer characteristics for both the forward and reverse directions when $V_{DD}$ was 4 V. In the ideal case, the OVTs would not employ the insulator and the complementary inverter would not exhibit the hysteresis phenomenon. Fig. 4 reveals only minor hysteresis, which presumably resulted from the presence of impurities in the organic materials, thereby trapping some carriers within the active layers. In addition to hysteresis phenomena, the noise margin is another important electronic characteristic. Fig. 4 reveals values for the noise margin low ($N_{ML}$) and noise margin high ($N_{MH}$) of 0.97 and 0.82 V, respectively [19]. These measured values are less than the theoretical values ($N_{MH} = N_{ML} = V_{DD}/2$), presumably because of (i) the current mismatch and larger OFF current in the p- and n-channel OVTs and (ii) the gradual shift in the turn-on voltage upon increasing the base voltage. The p-channel OVT operated under the linear region at the lower value of $V_{in}$ of the inverter. A shift in the turn-on voltage would result in a change in the value of $V_{out}$ upon increasing $V_{in}$ and then a decrease in the values of $N_{ML}$ and $N_{MH}$. We suspect that the electrical characteristics of the vertical-type complementary organic inverter would be improved further upon lowering the base currents, OFF currents and turn-on voltages of both OVTs.

## 4. Conclusions

In summary, we have fabricated the first organic complementary organic inverter incorporating p- and n-channel OVTs that could be operated at a low-voltage of 4 V to provide a corresponding gain of −9. Our results suggest that these OVTs have the same electronic applications as planar-type OTFTs – while displaying the advantageous properties of lower driving voltages and a faster operating frequencies.

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