Organic Pseudo-CMOS Circuits for Low-Voltage Large-Gain High-Speed Operation

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***Abstract*—Pseudo-CMOS inverters operating at 2 V and comprising four p-type organic transistors with ultrahigh gain are fabricated using self-assembled monolayer gate dielectrics. The inverter gain is as large as 302 at an operation voltage of 2 V, whereas the minimum operation voltage is as small as 0.5 V. The oscillation frequency of a five-stage ring oscillator comprising pseudo-CMOS inverters is 4.27 kHz at 2 V, corresponding to 23.4 μs of propagation delay per stage. This is the fastest among organic circuits operating at low voltage. Pseudo-CMOS amplifier circuits show a large gain of 240 for a 3.0-mV input voltage.**

***Index Terms*—Design for manufacture, logic circuits, organic materials, organic thin-film transistors (TFTs).**

I. Introduction

ORGANIC THIN-FILM transistors (TFTs) and their integrated circuits have attracted much attention, since they are expected to play an important role in realizing large-area flexible electronics [1]–[4]. In order to characterize and to improve operation speeds in flexible devices, their frequency responses have been investigated intensively. Although the cutoff frequency is measured to examine frequency response in a stand-alone transistor [5], [6], propagation delay per stage in ring oscillators is a practical benchmark for frequency response in integrated circuits. Myny *et al.* reported propagation delay per stage of 0.4 μs in an organic-transistor-based 19-stage ring oscillator fabricated using photolithography [7], which is one of the fastest among organic circuits to date. Several groups reported propagation delay per stage of less than 1 μs; however, all these fast circuits require operation voltages larger than 10 V [7], [8]. In fact, the simultaneous achievement of low operation voltage and small propagation delay is very difficult for organic-transistor-based ring oscillators because almost all organic semiconductors have a low mobility of less than 1 $cm^2/V \cdot s$ and large parasitic capacitance and contact resistance. One of the fastest low-voltage organic ring oscillators was fabricated with ion-gel gate dielectric layers and exhibited propagation delay per stage larger than 100 μs at an operation voltage of a few volts [9], [10].

In this letter, we take full advantage of new technologies that combine single-molecule thin self-assembled monolayers (SAMs) [11], [12] and complementary circuit design to build low-voltage pseudo-CMOS inverters comprising four p-channel organic TFTs with ultrahigh gain [13]. The voltage gain of the inverter circuits exceeds 300 at a 2-V operation voltage. The oscillation frequency of a five-stage ring oscillator is 4.27 kHz at 2 V, which corresponds to 23.4 μs of propagation delay per stage. This is the fastest among the low-operation organic circuits of less than 2 V. Furthermore, the amplifier circuits comprising pseudo-CMOS show gain as large as 240 for a 3.0-mV input voltage.

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II. Experimental Results and Discussions

A. Manufacturing

Organic TFTs with SAM gate dielectrics were manufactured by vacuum evaporation and low-temperature solution processes. The cross section of organic TFTs with SAM gate dielectrics is shown in Fig. 1(a). A 20-nm-thick Al layer was deposited as the gate electrodes on a glass substrate through a shadow mask in a vacuum evaporator. An ultrathin AlO_x film with a large density of hydroxyl groups for molecular adsorption was formed by oxygen-plasma treatment (300 W, 30 min), and a SAM of n-tetradecylphosphonic acid was prepared from a 2-propanol solution at room temperature [11], [12]. A 30-nm-thick dinaphtho[2,3-b:2′,3′-f]thieno[3,2-b]thiophene (DNTT) [14] layer was deposited as channel layers on the AlO_x/SAM gate dielectric. Finally, a 50-nm-thick Au layer was evaporated through a shadow mask to form the source/drain contacts.

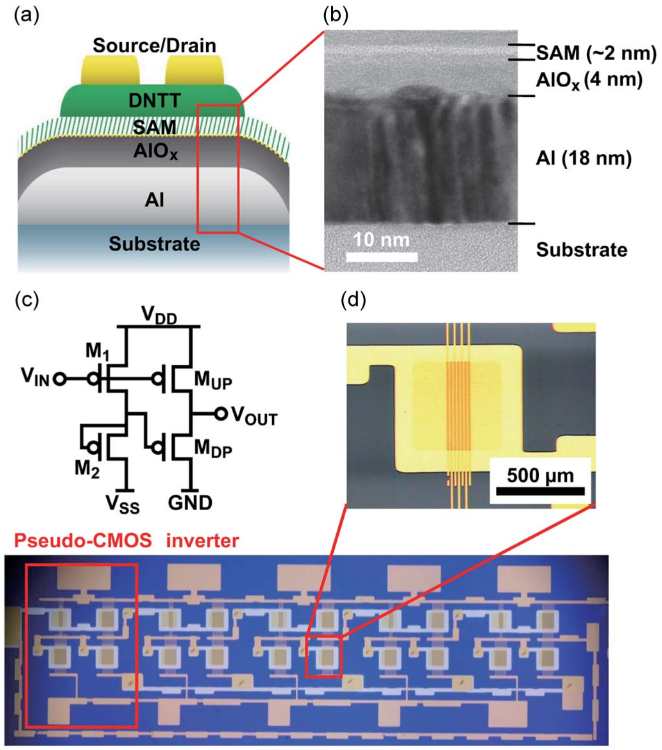

Fig. 1. (a) Cross section of organic TFT with SAM gate dielectrics. (b) TEM image of gate dielectrics. (c) Circuit diagram of pseudo-CMOS inverter. (d) Photograph of (right) a fabricated TFT and a five-stage pseudo-CMOS ring oscillator.

In order to allow access to the gate electrodes for electrical probing and to define vertical interconnects for integrated circuits, small pads of 20-nm-thick gold were evaporated through a second shadow mask in specific areas on the aluminum. After the gold deposition, SAM is not formed on the gold pads, thus leaving electrically conducting vias which are needed for probing and for interconnects.

The cross section of the manufactured device was observed by transmission electron microscopy (TEM) (HF-3300 Cold-FE TEM, 300 kV, Hitachi High-Technologies Corporation) [Fig. 1(b)]. The uniform SAM and, subsequently, the abrupt interface between the organic semiconductor layer and the SAM were observed unambiguously.

The pseudo-CMOS inverters comprise four p-channel organic TFTs [Fig. 1(c)]. The channel length of the fabricated TFTs was 7 μm, whereas the channel widths of M_1, M_2, M_{UP}, and M_{DP} were 1500, 4500, 4500, and 4500 μm, respectively. Photographs of the fabricated TFTs and five-stage ring oscillator are shown in Fig. 1(d).

B. Electrical Characteristics

All the electrical measurements were performed by a semiconductor parameter analyzer (Agilent, 4156C) and a digital oscilloscope (Agilent, DSO5032A) in ambient air. The fabricated TFTs show good contact characteristics despite having a very small channel length of 7 μm (Fig. 1). The on/off ratio exceeds 10^6, and the mobility at the saturation regime exceeds 1.8 $\mathrm{cm}^2/\mathrm{V}\cdot\mathrm{s}$ for all the four TFTs. The threshold voltages are approximately $+0.3$ V. The input–output characteristics

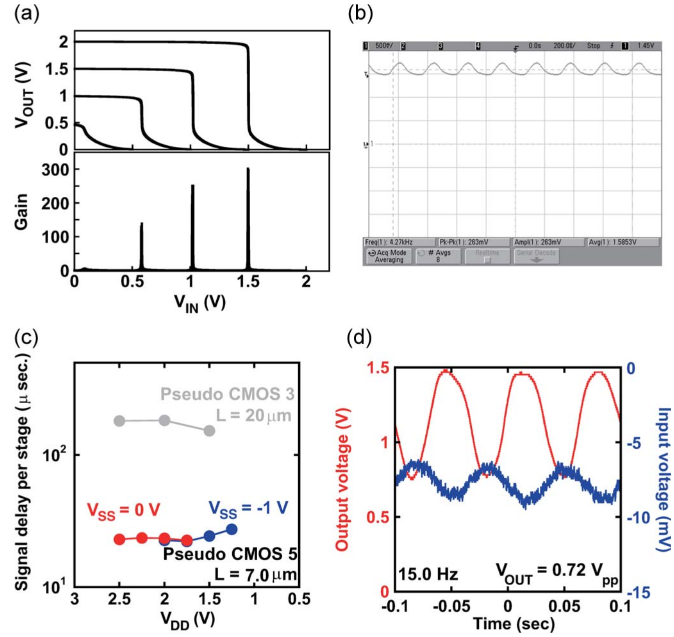

Fig. 2. (a) Input–output characteristics of pseudo-CMOS inverter. Output voltage and small-signal gain as a function of input voltage for supply voltages V_{DD} between 0.5 and 2 V at tuning voltage V_{SS} of 0 V. The small-signal gain is as large as 300. (b) Output voltage signal of a five-stage pseudo-CMOS ring oscillator with critical dimensions of 7.0 μm for a supply voltage of 2.0 V at a tuning voltage of 0 V, with a period of 4.27 kHz (corresponding to propagation delay per stage of 23.4 μs). (c) Signal propagation delay as a function of channel length and supply voltage. (d) Output voltage of a pseudoamplifier circuit as a function of time for an input voltage V_{IN} of 3 $\mathrm{mV_{pp}}$. The output voltage V_{OUT} is as large as 720 $\mathrm{mV_{pp}}$, so the amplifier gain is estimated to be 240.

of the pseudo-CMOS inverter are shown in Fig. 2(a). The output voltage and small-signal gain are a function of the input voltage at a supply voltage V_{DD} between 0.5 and 2 V and a tuning voltage V_{SS} of 0 V. The fabricated inverter showed negligibly small hysteresis. The gain was 5.2 at an operation voltage as small as 0.5 V. The voltage gain of the inverter circuits was 302 at 2 V; this gain is the highest, to the best of our knowledge, among organic inverters comprising p-channel organic transistor circuits at a 2-V operation voltage.

Fig. 2(b) shows the output voltage signal of a five-stage pseudo-CMOS ring oscillator with a channel length of 7 μm at a 2-V supply voltage and a tuning voltage of 0 V. The output wave shows a period of 4.27 kHz, which corresponds to a signal delay of 23.4 μs. The signal propagation delay per stage is shown in Fig. 2(c) as a function of the supply voltage. The minimum operational voltage is 1.25 V at V_{SS} of -1.0 V, and the propagation delay per stage is 27.4 μs.

Conventional organic CMOS circuits consist of p- and n-type organic transistors. Although p-type organic transistors on SAM gate dielectric layers exhibit mobility higher than 0.5 $\mathrm{cm}^2/\mathrm{V}\cdot\mathrm{s}$, n-type organic transistors on SAM exhibit mobility less than 0.02 $\mathrm{cm}^2/\mathrm{V}\cdot\mathrm{s}$ [11], [12]. As a result, frequency response (switching time) of the conventional CMOS circuits is determined by response of n-type organic transistors with lower mobility. In this letter, in order to obtain faster organic circuits (smaller propagation delay per stage), organic circuits have been fabricated with pseudo-CMOS inverters that comprise only four p-type organic transistors with very high mobility.

Furthermore, our p-type transistors have 7 μm in channel length and 7 μm in linewidths of source/drain electrodes, resulting in very small parasitic capacitance. These circuit design and high-mobility materials on SAM gate dielectrics lead to very small propagation delay per stage even in low-voltage operation.

Finally, we fabricated an amplifier circuit comprising pseudo-CMOS with a channel length of 20 μm. The output characteristics of the amplifier are shown in Fig. 2(d) as a function of time and input voltage $V_{\rm IN} = 3\ {\rm mV_{pp}}$ at a frequency of 15 Hz. Note that the output voltage $V_{\rm OUT}$ is amplified to be as large as 720 $\rm mV_{pp}$, which corresponds to an amplifier gain of 240. This value is consistent with the small-signal gain of the pseudo-CMOS inverter [Fig. 2(a)]. The amplifier gain was measured as a function of the frequency for two different input signal voltages $V_{\rm IN} = 10$ and 100 $\rm mV_{pp}$. With increasing the frequency of $V_{\rm IN}$ to 10 $\rm mV_{pp}$, the gain of the amplifier increases and reaches a maximum value of 123 at 20 Hz and then decreases. The cutoff frequency is 5 kHz when it is defined as a gain of unity.

III. Conclusion

In conclusion, we have demonstrated the feasibility of organic pseudo-CMOS circuits, which require no n-channel transistors, particularly at low voltage, and high-gain applications such as amplifiers. The gain of the inverter circuits is as large as 302 at a 2-V operation voltage, and the oscillation frequency of a five-stage ring oscillator comprising pseudo-CMOS inverters is 4.27 kHz at 2 V, which corresponds to 23.4 μs of propagation delay per stage. The pseudo-CMOS-based amplifier circuits show gain as large as 240 for an input voltage of 3.0 $\rm mV_{pp}$.

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