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Polymeric integrated AC follower circuit with a JFET as an active device

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Abstract

In this paper, successfully combining UV lithography and ink-jet printing techniques, we have fabricated a polymer-based AC follower circuit, including a polymer junction field-effect transistor (JFET) as the active device, and an ink-jet printed conductive polymer resistor. The polymer JFET, using poly (3,4-ethylenedioxythiophene) poly (styrenesulfonate) (PEDT/PSS) as the channel and poly (2,5-hexyloxy p-phenylene cyanovinylene) (CNPPV) as the gate, was fabricated by the conventional ultraviolet (UV) lithography techniques. As measured, the JFET's pinch-off voltage reaches 1 V that is in the applicable range, and the current is 13.8 μA at zero gate bias. By integrating the JFET and the polymer resistor, we tracked the frequency response of the follower circuit, and the circuit shows good frequency following features when the frequencies are higher than 10 kHz. Furthermore, the factors influencing the performance of the circuit, including the effects of load resistors, the JFET parameters, and the fabrication techniques, are discussed.

Keywords: Polymer; JFET; Integrated circuit

1. Introduction

Polymer materials are attracting more and more attention for their applications to microelectronic devices due to their flexibility, lightweight, and low cost. Due to the possibilities of processing electrically conducting polymers by coating techniques, this enabled researchers to fabricate various electronic devices such as thin film transistors (TFTs), diodes, LEDs, capacitors, organic integrated circuits, organic wires, and electro-luminescent devices [1–6]. Polymer thin films can be coated on substrates such as glass, plastic, silicon, wood, or paper.

It appears increasingly likely that organic TFTs will find applications not only to pixel access elements in low-cost active matrix displays [7–9], but also to integrated logic circuitry and memory arrays for low-cost electronic products such as smart cards, smart and inventory tags, and large-area sensor arrays [10,11]. Ink-jet printing, optical lithography, thermal evaporation, and reactive ion etching (RIE) are the main technologies utilized to fabricate polymer devices in this paper.

Active circuits can yield "gain", that is to provide greater power and/or voltage output than input. In most cases, more power can be delivered to a load by passing the signal through an amplifier than directly from a signal source. Obviously, the gained power has to come

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from somewhere, and this is generally from a DC voltage supply [12]. In this paper, we fabricated a polymer follower circuit by integrating a polymer transistor and an ink-jet printed resistor. The p-channel polymer JFET fabricated with ultraviolet (UV) lithography was presented, and its operation mechanism was discussed in detail. Secondly, we characterized the electrical properties of the circuit, such as the gain and phase difference. It shows that the output frequencies follow the input frequencies in phase when the input frequencies are higher than 10 kHz. For the voltage gain of the circuit, it was 0.3, which is relative low. Finally, the stability of the JFET was discussed.

2. Experiment

2.1. Fabrication

The polymer-based follower circuit with a JFET [13] as the active device was fabricated by UV lithography and ink-jet printing technologies. The follower circuit consists of a p-channel polymeric JFET and an ink-jet printed conductive polymer resistor.

First, a silicon dioxide or glass wafer covered with a layer of evaporated 0.15 μm aluminum (Al) was used as the substrate. Two layers of polymers, 1 μm PEDOT/PSS and 1 μm CNPPV, were spun on the substrate at the bottom and on the top, respectively. Each layer was baked at 100–105 °C for 5 min before the next layer was spun. Next, 0.15 μm Al was deposited on top of the CNPPV by thermal evaporation. Al, instead of photoresist (PR), was used as an etching mask layer because PR is difficult to remove selectively. After patterning of Al and Reactive Ion Etching (RIE) of CNPPV, a layer of PEDT/PSS was spun on top of the pattern to fill the channel region between two CNPPV gates, followed by another 0.15 μm thick Al film evaporated on top of the PEDT/PSS. Finally, the clean JFET structures, as shown in Fig. 1, were built after wet etching of Al and RIE of the polymer.

The PPy resistor, as shown in Fig. 1(b), was printed by ink-jet printer (Microdrop. Inc., Germany). For uniformly printed PPy films, we controlled the ink-jet printing nozzle temperature of 40 °C. *I–V* characteristic testing indicates that the resistance was about 550 kΩ.

2.2. Drain and transconductance characterization of JFET

The p-channel polymeric JFET was characterized in air ambient with Keithley Test and Measurement Instrument. The drain characteristics are shown in Fig. 2. Based on the testing curves, the polymer JFET was considered as a depletion-mode device, which is normally on when no reverse bias was applied onto the gate. The transconductance reaches 0.19 μS/mm at the gate voltage of 0.2 V.

The JFET makes use of the fact that a very strong electric field exists across a PN junction, and the electric field effectively removes carriers from the junction region. The gate electrodes shown in Fig. 1 are formed as PN junctions, with the channel forming between two junctions. Two identical positive voltages (V_{GS}) were applied onto the two gates. In the meantime, external voltages were applied between the source and the drain (V_{DS}). With the increasing V_{DS}, the currents between the source and the drain (I_{DS}) are going through the linear region and the saturation region. The width of the depletion region increases with increasing the

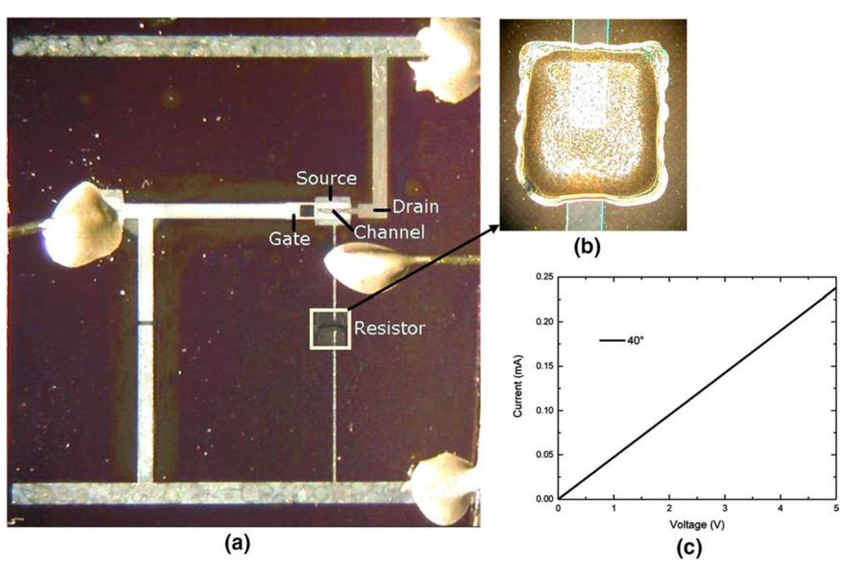

Fig. 1. (a) Fabricated follower circuit in the dimension of 0.8 cm × 0.8 cm. (b) Ink-jet printed PPy resistor with dimension of 0.5 mm × 0.5 mm (c) *I–V* characteristic of PPy resistor.

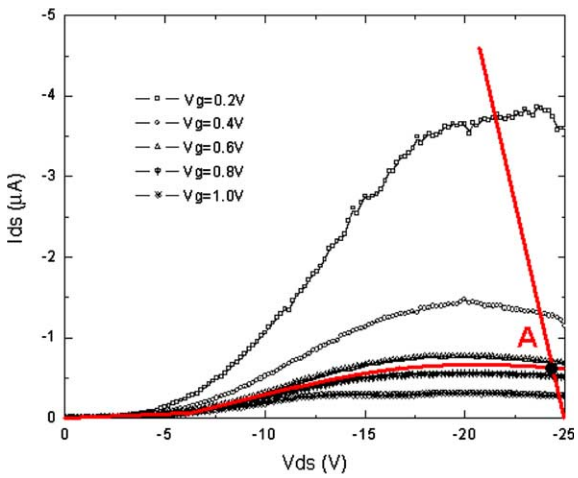

Fig. 2. Drain characteristics of a p-channel polymeric JFET with the operating point A. The red lines, the third line from the bottom and the straight line, indicated the calculated curves. (For interpretation of the references in color in this figure legend, the reader is referred to the web version of this article.)

reverse bias V_{GS}, thus extends into the channel, further increasing the channel resistance and shrinking the channel width. The resistance of JFET carrier-transport channel is modified by the electric field associated with the depletion region of a reverse-biased junction extended into the channel.

In linear region, we can obtain the relationship among I_{DS}, V_{DS} and V_{GS} as

$$I_{DS} = G_0\left(1 - \sqrt{\frac{\psi_0 - V_{GS}}{V_{PO}}}\right)V_{DS} \tag{1}$$

Here, G_0 is the channel conductance without any depletion, ψ_0 is the built-in potential, and V_{PO} is the sum of the pinch-off voltage V_P and the ψ_0.

$$G_0 = \frac{2qaWu_pN_a}{L} \tag{2}$$

where L is the channel length, W is the channel width, and a is the half of the channel height. The drain current is proportional to the drain voltage at small V_{DS} values.

In saturation region, the relationship between I_{DS} and V_{GS} can be expressed as

$$I_{DS} = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 \tag{3}$$

where V_P is the pinch-off voltage, and I_{DSS} denotes the drain saturation current at zero gate voltage. I_{DSS} was 13.8 μA from testing when V_{GS} is 0 V. At higher V_{DS}, the I_{DS} is independent of the V_{DS}, and it was determined by the V_{GS}. We can also obtain the V_P values at each V_{GS} condition.

One phenomenon illustrated in Fig. 2 is that the I–V characteristic has the trend of decreasing at higher V_{DS}. The conductivity of JFET carrier-transport channel is modified by the electric field associated with the depletion region of a reverse-biased junction extended into the channel. The saturation region occurs when the two depletion region meet each other at the pinch-off point at a certain V_{GS}. With further increasing V_{DS}, there were some small bubbles appearing at the interface of the Al layer and the polymer layer in some devices. Due to the poor adhesion between Al and polymer, heat may be generated in the channel region. This increases the channel resistance, and thus I_{DS} decreases. Improving the adhesion between Al and polymer layers and annealing the polymer layers before characterization are possible ways to improve the performance of the polymer devices.

2.3. Electrical properties of follower circuits

The work point and the load line of the depletion-mode JFET follower need to be decided. The output of this circuit, expressed in terms of the $v - i$ characteristics of the load, is given by

$$v_{OUT} = i_S R_S = i_D R_S \tag{4}$$

Here, v_{OUT} is the output voltage, R_S is the load resistance, and i_S and i_D are the source and drain current, respectively. v_{GS}, the gate-source voltage, is

$$v_{GS} = v_{IN} - v_{OUT} = v_{IN} - i_D R_S \tag{5}$$

Here, v_{IN} is the input voltage. Using graphical methods, we can find the operating point of the JFET, which is the point A as shown in Fig. 2.

It was found that

$$i_D = -0.55\ \mu A$$

$$v_{GS} = 0.7\ V$$

when the JFET operates at the work point A in the constant-current region.

In Fig. 3, the magnitude of gain and phase difference as a function of frequency was plotted on a logarithmic

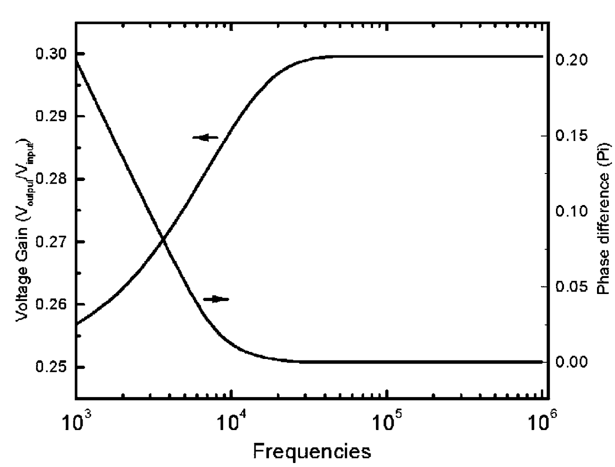

Fig. 3. Magnitude plot of gain and phase difference as a function of frequency on a logarithmic scale.

scale. It shows that the output signal can follow the phase of the input signal well when the frequencies are above 10 kHz. The maximum gain of the AC follower can reach 0.3. The lower value of the gain related to performance of the JFET and the load resistance.

At a lower frequency, the output amplitude was reduced as compared with those at higher frequencies. There exists phase shifts between the input and output signals. It is proved to be some redundant RC at the input of the circuit.

2.4. Device stability

The stability of the conducting polymers is one of the key issues related to the fabrication and performance of polymer devices.

One method reported is to observe the variations in resistance readings of each polymer sample when it is left open to air for a period of time [14]. Three different polymers have been investigated in the report, polypyrrole, polythiophene and PEDT/PSS. It was found that polypyrrole and PEDT/PSS have very good stability with a steady but slow increase in the resistance with time. The increase is due to the degradation of the polymer samples upon exposure to oxygen.

By retesting the polymer JFET after three months, we found the device was still in good working performance, compared with the testing curves of the fresh-made JFET. The reason is the polymer layers were covered by Al, and the polymer films were kept from contacting with oxygen and moisture. Obviously, Al-protected devices show similar transistor characteristics even after three months.

3. Conclusion

In this paper, we fabricated a polymer-based AC follower circuit in which the active device is a polymeric JFET. Ink-jet printing technique was utilized to print the load resistor. Electrical testing shows that the polymer JFET works in the depletion-mode. At higher frequencies, the output signal can follow the input AC signal in phase, and the resulted gain of the circuit is 0.3. At lower frequencies, the output amplitudes were decreased with reducing the frequencies of the input signals, companying by the phase shift between input and output signals. The optimization of the JFET characterization and IC fabrication are key points to improve the performance of the AC follower circuit.

Polymer electronic devices are currently in their infancy, like semiconductor devices when they just appeared. As a result, the current performance of these devices is hard to be comparable to the state-of-the-art semiconductor devices. Though it is difficult to make a comparison, we still found some similarities, such as the similarities in working mechanism and analyzing approach. The applications of polymer JFET are still limited due to the relative poor properties of materials. However, inorganic JFETs are fabricated by the state-of-the-art industry fabrication techniques, and they have good performance and a lot of commercial applications. With the improvement of polymer materials' properties, such as high conductivity and mobility, the performance of the polymer microelectronics devices could compete with the conventional ones in the future.

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