# Charge-Injection-Controlled Organic Transistor

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## Abstract

New-type organic transistors based on the charge injection process at organic/metal interface were proposed and demonstrated. The device was composed of an organic deposited film sandwiched by two metal electrodes and the third stripe-shaped electrode embedded in the organic film. The output current corresponding to collector current was modulated by the applied voltage of the third electrode corresponding to base electrode, and current amplification factor of $h_{FE}$ reached 20. The transistor operation was attributed to the electron injection caused by accumulation of holes supplied from the base electrode. The current amplification was observed up to about 100 Hz in the frequency response measurement.

## Introduction

Recently, organic transistors have been focused on as a next target after organic electroluminescent devices were put into practical use. They have many advantages such as low cost process by screen-printing or ink jet process, and ability to produce on a flexible substrate.[1,2] So far, organic transistors mostly mean field effect transistors (FET), which are composed of an organic film prepared on a gate electrode across an insulating layer with source and drain electrodes. In particular, pentacene shows remarkable performance of high mobility leading to the excellent current density and on/off ratio.[3,4] However, the device configuration of FET has a handicap to high-frequency operation because of coplanar electrodes with long channel length. From this viewpoint, an organic static induction transistor having a vertical structure was proposed.[5]

In this paper, we propose a novel organic transistor called charge-injection-controlled organic transistors. The principle of this device is based on the photocurrent multiplication phenomenon discovered in organic pigments.[6,7] Its mechanism can be explained by the energy diagram of organic/metal interface as shown in figure 1. Photogenerated holes accumulate at the organic/metal interface form high electric field. As a result, a large amount of electrons are injected from the metal electrode by tunneling process, resulting in photocurrent multiplication. Here, if the carriers triggering multiplication process are supplied from the third electrode embedded in the organic film, the small input current of holes can be amplified to a large output current of injected electrons. The amplified current can be controlled by the third electrode, therefore, this device is expected to act as a transistor. Based on this concept, we fabricated the three junction devices composed of an organic film indicating photocurrent multiplication sandwiched by two metal electrodes and the stripe-shaped third electrode embedded in the organic film.

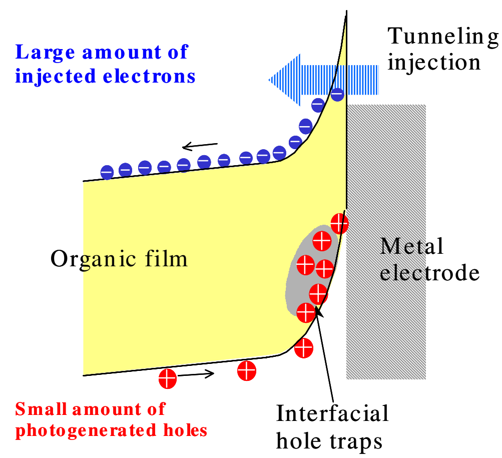


*Figure 1. Energy diagram of organic/metal interface during photocurrent multiplication. Chemical structures of organic pigment showing large multiplication are also shown.*

## Experimental

The device structure is shown in figure 2. Perylene pigment of 3,4,9,10-perylenetetracarboxylic 3,4:9,10-bis-methylimide (Me-PTC) was used as the organic semiconductor, which is known to exibit large photocurrent multiplication. Firstly, the perylene pigment was deposited on the cleaned ITO glass substrate with thickness of 500 nm. Then, the base electrode of Al was deposited through stripe-shaped mask with 100 µm pitch. Upper organic film (500nm) and the top electrode of Ag (20nm) were deposited. Since the multiplication occurs at the interface between the top electrode and the upper organic film, the upper organic film must be an organic pigment showing photocurrent multiplication. The active area where the three electrodes are overlapped was 0.02 $cm^2$.

The measurement system is illustrated in figure 3. Hereafter, we called the ITO the emitter electrode, the top Ag the collector electrode and the embedded Al the base electrode imitating bipolar transistors. The collector voltage ($V_c$) was applied between the collector and emitter electrodes constantly. The collector current ($I_c$) and the base current ($I_b$) were measured for various base voltage ($V_b$) applied between the base and collector electrodes. The measurements were performed by two source-measure units (Keithley 236) under vacuum condition.

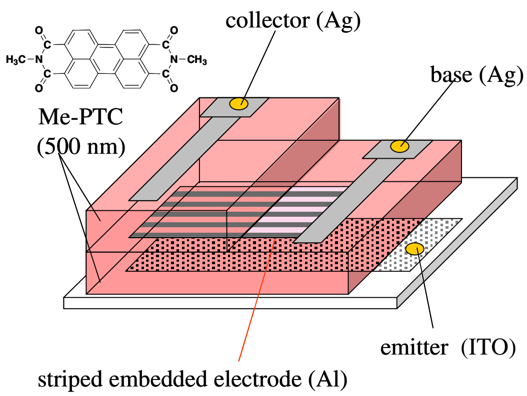


*Figure 2. Device structure of the charge-injection-controlled organic transistor.*

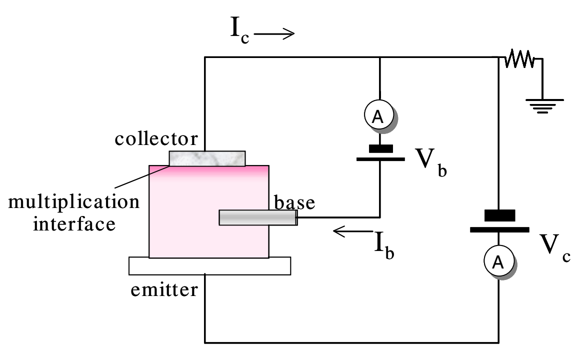


*Figure 3. Measurement system for evaluating the performance of the transistor. $I_c$ and $I_b$ were measured for various $V_b$ under a constant $V_c$.*

## Results and Discussion

Figure 4 shows the modulation characteristics of the three-terminal device. Figure 4(a) shows the base voltage dependence of the collector current under a constant collector voltage of 10 V. The collector current increases with increasing base voltage. Here, we evaluated the current amplification factor $h_{FE}$ used for evaluating performance of bipolar transistors, which is defined as a ratio of the collector current and base current change. As shown in figure 5, the $h_{FE}$ was found to reach about 25. This means that the change of the output current is larger than that of the input current, that is to say, current amplification occurs. Thus, it was confirmed that the three-terminal device acted as a transistor performing current amplification. The considerably large current modulation of 50 μA seems to reflect the advantage of this device having a vertical structure with short channel length.

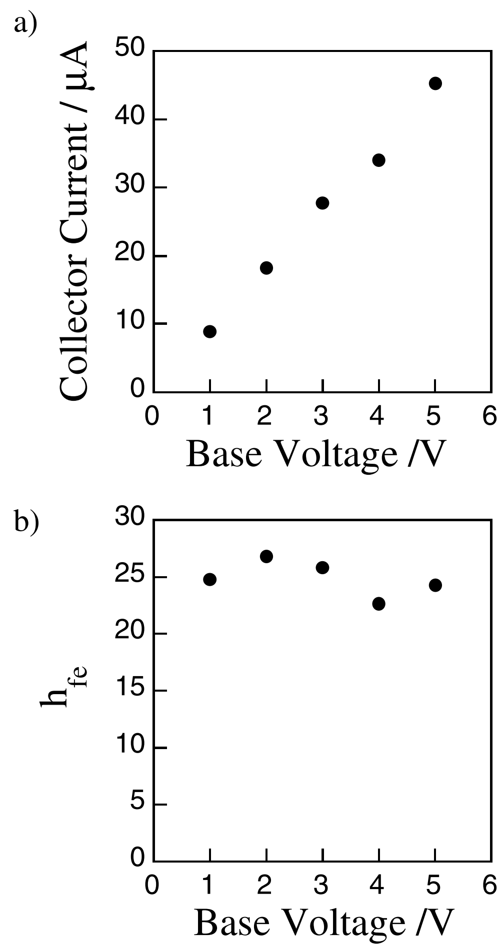


*Figure 4. Base voltage dependence of the collector current (a) and current amplification factor (b). The $V_c$ was 10 V. The base line of the collector current at $V_b$=0 was subtracted.*

To analyze the current amplification, we modeled the device as equivalent circuits composed of three electrodes and three resistances as shown in Fig. 5. If the part in which the base electrode exists and does not exist operate as an independent parallel circuit, the electrical property of the device can be determined by three resistances R1, R2 and R3 marked in Fig. 5. In this case, the input base current Ib and the output collector current Ic are depicted by simple Kirchhoff theory as follows.

$$I_c = \left(\frac{1}{R_3}\right)V_b - \left(\frac{1}{R_1}\right)V_c$$

$$I_b = \left(\frac{1}{R_2} + \frac{1}{R_3}\right)V_b - \left(\frac{1}{R_2}\right)V_c$$

These formulas prove that Ic can increase by positive Vb, however, the change magnitude of Ic is always smaller than that of $I_b$, in other words, hFE cannot exceed unity under this model. For current amplification, some mechanisms for the base voltage to enhance the current in which the striped electrodes do not exist are necessary. We believe that the current amplification occurs based on the same mechanism as the photocurrent multiplication phenomena. That is to say, supplied holes from the base electrode accumulate at the interface between the collector electrode and the upper organic film and cause tunneling injection of a large amount of electrons. A part of the injected electrons diffuse out to the part in which the base electrodes do not exist and contribute to enhancement of Ic leading to current amplification. In fact, current amplification is not observed in the organic film indicating no photocurrent multiplication.

One of the factors deteriorating hFE is leakage current in this device. As seen from Fig. 5, there are six components of carrier current. However, they are only two components that are essentially needed for the transistor operation, holes from the base to the collector and injected electrons from the collector to the emitter. All the other components are leakage current, in particular, any current is not needed between the base and emitter electrodes.

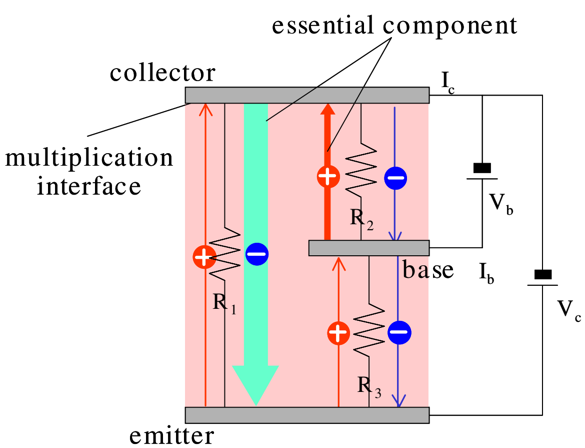


*Figure 5. Equivalent circuit model by a simple combination of three resistances, and six carrier components of holes and electrons in the charge-injection-controlled transistor.*

Therefore, to suppress the leakage current, we inserted a $SiO_2$ layer under the striped base electrode as an insulating layer. The $SiO_2$ (50 nm) was deposited through the same mask as the base electrode. Figure 6 shows the base voltage dependence of $h_{FE}$ in this device. The leakage current, to be concrete, the amount and the change of $I_b$ was successfully reduced. Consequently, the $h_{FE}$ became higher and reached about 80.

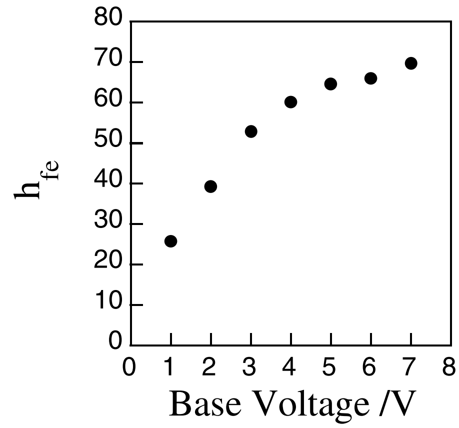


*Figure 6. Base voltage depdendence of $h_{FE}$ in the device with a insulating layer of $SiO_2$ under the base electrode. The $V_c$ was 10 V.*

Next, we measured the response speed and frequency characteristics in this device, which is another important performance of transistors. Considering the previous mechanism, we conjectured slow response speed in this device, for the photocurrent multiplication indicates slow response reaching several seconds, which is attributed to the charge accumulation process at the organic/metal interface. Contrary to our presumptions, however, the charge-injection-controlled transistor indicated considerably fast response. Figure 7 shows transient responses of the collector currents for the base voltage application. The collector current rises immediately within the time resolution limit of 250 ms. One explanation for the fast response is that the number of triggering holes from the base electrode is much larger than the photogenerated carriers in photocurrent multiplication phenomena. A large quantity of the supplied holes causes fast accumulation at the organic/metal interface, resulting in the fast response of the collector current.

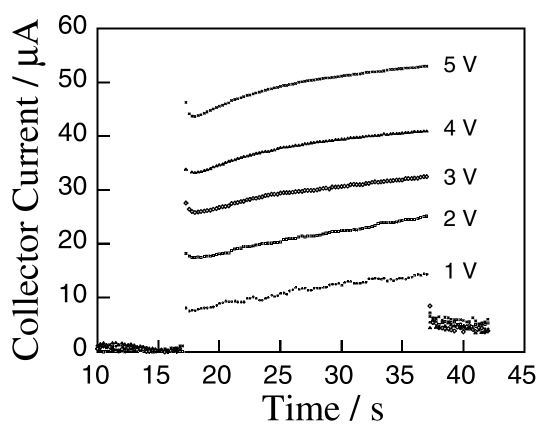


*Figure 7. Transient responses of the collector currents for the base voltage. Applied base voltage is shown in the figure. The $V_c$ was 10 V. The base line of the collector current at $V_b$=0 was subtracted.*

To investigate the response speed quantitatively, the output wave of the collector current was measured by an oscilloscope for the alternating base voltage. Figure 8 shows the frequency response of $h_{FE}$. The $h_{FE}$ decreases with an increasing frequency and reached unity at about 100 Hz. The cutoff frequency of –3 dB attenuation was estimated to be 60 Hz. In most organic FETs, the cutoff frequency remains several Hz because of its long channel length and low mobility of organic materials. Therefore, it is concluded that the charge-injection-controlled transistor has considerable high frequency response. This characteristic also reflects the advantage of a vertical structure device having shorter channel length than coplanar FET.

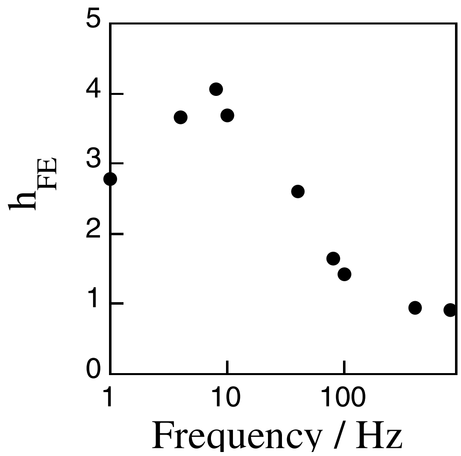


*Figure 8. Frequency characteristics of $h_{FE}$ in the transistor device. The $V_c$ and $V_b$ were 5 V and 3 V, respectively.*

## Conclusion

We proposed and demonstrated a new-type organic transistor called charge-injection-controlled organic transistor, which is fabricated by embedding the striped base electrode into the organic photocurrent multiplication device. This device achieved current amplification based on electron tunneling injection caused by accumulation of holes from the base electrode. The current amplification factor reached about 70 by suppressing the leakage current. The output current indicated considerably fast response and the cutoff frequency was estimated to be 60 Hz.

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## Biography

Ken-ichi Nakayama has worked as the research associate at Osaka University since 2000. He received the M. Eng. in 1997 and the Ph.D. Eng. in 2000 in Applied Chemistry from Osaka University. He is now investigating photo-electrical properties of organic semiconductors and their application. He is especially interested in structural and energetic properties of the organic/metal interface.