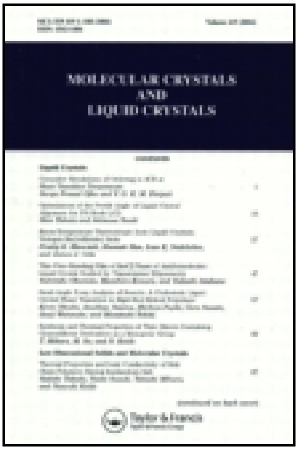

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CHARGE INJECTION CONTROLLED ORGANIC TRANSISTOR

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A novel type of organic transistor based on the charge injection at an organic/metal interface was proposed. The device was composed of an organic deposited film sandwiched between the emitter and collector electrodes and the third stripe-shaped base electrode embedded in the organic film. The output current was successfully modulated by an applied voltage on the third electrode, and the current amplification factor, h_{FE}, reached 25. The operation of the device was attributed to electron injection from an emitter electrode by the accumulation of holes supplied by the third electrode at the organic/metal interface. This device also worked as a photo transistor, in which the sensitivity can be modulated by the base bias.

Keywords: charge injection; organic transistor; photocurrent multiplication; phototransistor

INTRODUCTION

Recently, organic transistors have been focused as a next target of organic electronics following organic electroluminescent devices. Organic electronics have many advantages such as low cost process by screen-printing or ink jet process, and easy fabrication 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 disadvantage for 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 termed charge-injection-controlled organic transistor. The principle of this device is based on the photocurrent multiplication phenomenon discovered in organic pigments [6,7]. The mechanism of photocurrent multiplication can be explained by the energy diagram of the organic/metal interface as shown in Figure 1. Photogenerated holes accumulate at the organic/metal interface to form high electric field at the interface, which induces the injection of a large amount of electrons 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 Figure 1. Since the amplified current can be controlled by the third electrode, this device is expected to act as a transistor. Based on this concept, we fabricated the three terminal devices composed of two metal electrodes, emitter and collector, and a striped third electrode (base), which sandwich an organic film indicating photocurrent multiplication.

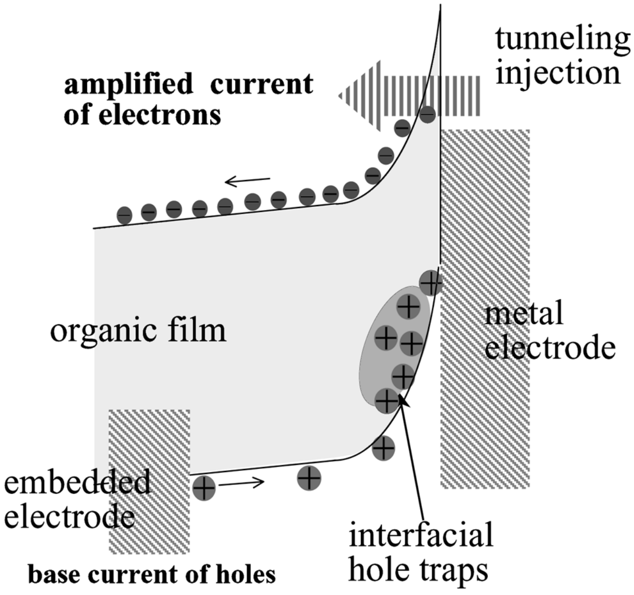

FIGURE 1 The energy diagram of the organic/metal interface indicating the operating mechanism of the charge injection controlled transistor.

EXPERIMENTAL

The device structure is shown in Figure 2. A 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 exhibit a large photocurrent multiplication effect. A 500-nm thick lower organic layer of perylene was deposited on a clean ITO glass substrate. The Al base electrode (30 nm) was deposited through a striped mask with 20-μm pitch. The upper perylene organic layer of 500 nm thick, and an Ag top electrode (20 nm) were then deposited. Since multiplication occurs at the interface between the top electrode and the upper organic film, the upper organic film must contain an organic pigment showing the photocurrent multiplication effect. The active area where the three electrodes overlapped was 0.02 cm^2.

The measurements were performed using two source-measure units (Keithley Instruments Inc., Model 236) as shown in Figure 3. Hereafter, we denote the ITO as the collector electrode, the top Ag layer as the emitter electrode, and the embedded Al layer as the base electrode. The collector voltage (V_c) for driving the device was applied between the collector and emitter electrodes using a negative bias on the emitter, because the photocurrent multiplication process is known to occur at the organic film with

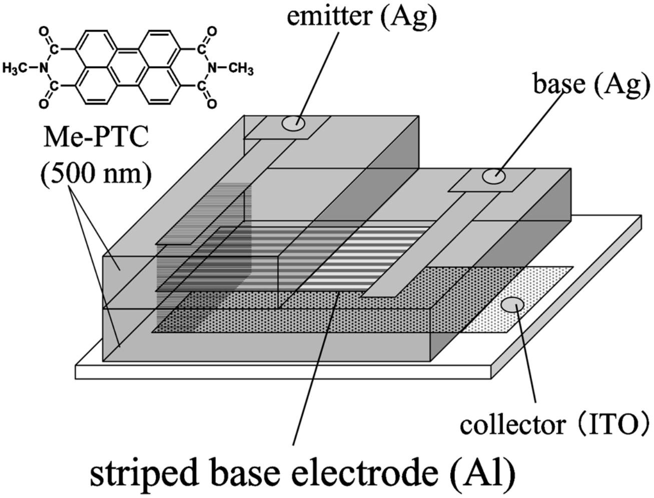

FIGURE 2 The device structure of the charge injection controlled organic transistor. Both the lower and upper organic films were deposited perylene pigment films with a thickness of 500 nm. The inserted Al base electrode was deposited through the striped shadow mask having a 20 μm pitch. The active area where the three electrodes overlap is shadowed.

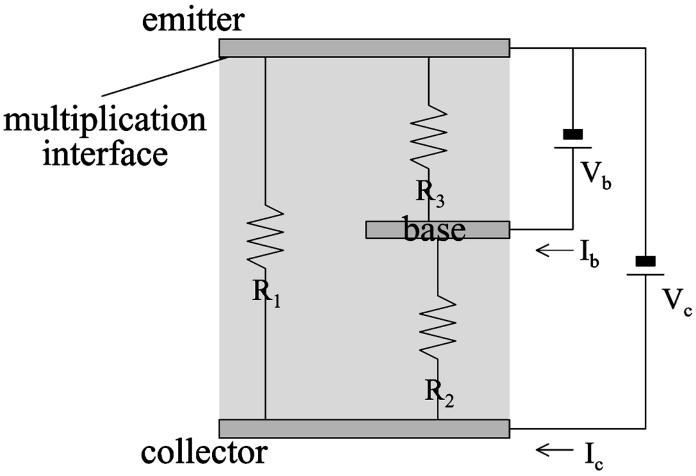

FIGURE 3 Measurement system for evaluating the performance of the transistor. I_c and I_b were measured for various V_b under a constant V_c. An equivalent circuit model of the charge injection controlled transistor using a simple combination of three resistances is also shown.

a negatively biased electrode. As an input signal, the base voltage (V_b) was applied between the emitter and base electrodes using the negative bias of the emitter. The output current from the collector (I_c) and the input current to the base (I_b) were measured for various values of V_b.

RESULTS AND DISCUSSION

The modulation characteristics of the three-terminal device were investigated. Figure 4(a) shows the dependence of I_c on V_b under a constant V_c of 10 V. The I_c was found to increase with increasing V_b, which means that in this device, the output current of I_c can be modulated by the input voltage of V_b. We also evaluated the current amplification factor, h_{FE}, which is commonly used for evaluating the performance of bipolar transistors, and defined as the ratio of I_c to I_b. As is shown in Figure 4(b), the h_{FE} was almost unchanged, having a steady value around $h_{FE} = 25$. This means that the change in the output current was always larger than the change in the input current, i.e., current amplification occurs. Thus, it was confirmed that the proposed device acts as a transistor in amplifying an input current.

The current modulation was analyzed using a simple model of equivalent circuit composed of three electrodes and three resistances, as illustrated in Figure 3. If the part of the circuit containing the base electrode and a part not containing the base electrode operates as separate parallel circuits,

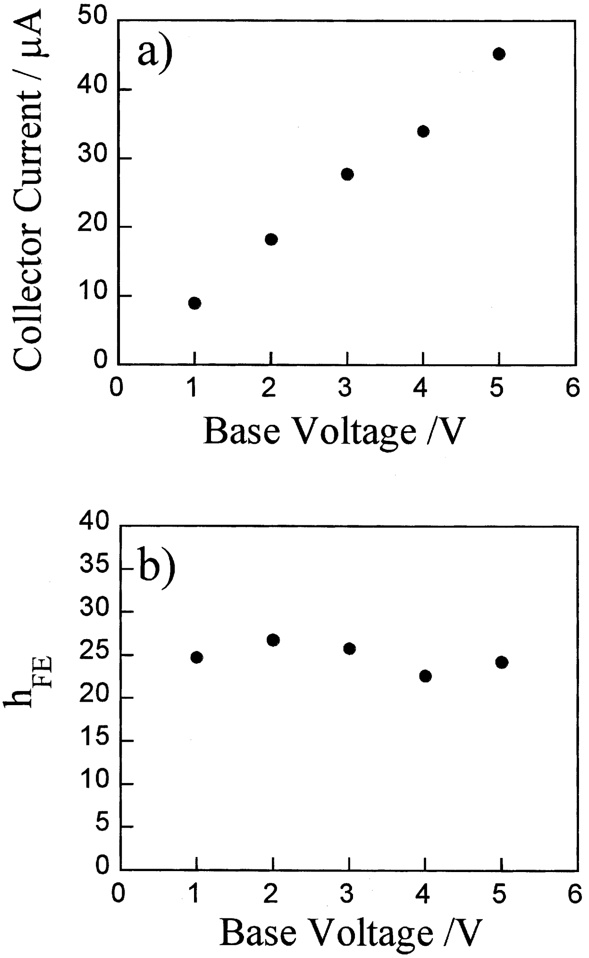

FIGURE 4(a) The dependence of the collector current on the base voltage, (b) the behavior of the current amplification factor, h_{FE}. The collector voltage was fixed at 10 V. The base line of the collector current at $V_b = 0$ was subtracted from the measured I_c values.

then the electrical properties of the device can be determined by the three resistances R_1, R_2, and R_3. In this case, the input current, I_b, and the output current, I_c, can be derived from Kirchhoff's theory as

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

and

$$I_c = -\left(\frac{1}{R_2}\right)V_b + \left(\frac{1}{R_1} + \frac{1}{R_2}\right)V_c$$

The above formulae tell us that I_c does not increase under a positive V_b. As shown in Figure 4, however, this is not the case because I_c increases apparently with increasing V_b toward positive. For increasing of I_c, *i.e.*, current amplification with V_b, some mechanisms for enhancing I_c current from emitter to collector must be essential. We believe that current amplification occurs based on the same mechanism as can be seen in the photocurrent multiplication phenomena. Namely, the holes supplied from the base electrode accumulate at the interface between the upper organic film and emitter electrode. Consequently, tunneling injection of a large number of electrons is caused due to the field concentration at the interface. Thus, it is thought that most of the injected electrons from the emitter electrode pass through the striped base electrodes toward the bottom collector electrode, and this current contributes to the enhancement of I_c, leading to current amplification.

The response speed is another important performance of transistors. Figure 5 shows the transient response of the collector currents for the various base voltages. Generally, the photocurrent multiplication based on

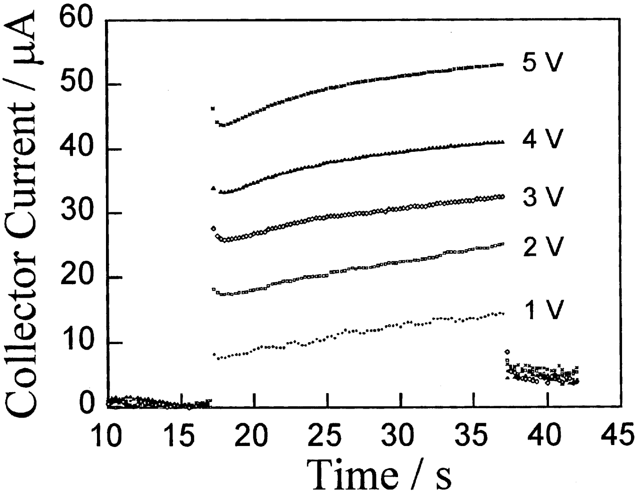

FIGURE 5 Transient responses of the collector currents for the base voltage. Applied base voltage is shown in the figure. The collector voltage was fixed at 10 V. The base line of the collector current at $V_b = 0$ was subtracted.

the similar mechanism showed slow response over several seconds for some cases, which is attributed to the charge accumulation process at the organic/metal interface. Contrary to our presumptions, however, the present transistor equipped with the base electrode exhibited considerably fast response within the time resolution limit of 250 ms. One explanation for the fast response is that the number of triggering holes supplied from the base electrode is much larger than the number of photogenerated carriers in photocurrent multiplication. A large quantity of the supplied holes can cause fast accumulation at the organic/metal interface and fast response of the collector current.

Another important feature of this device is to show large photo-response because this device is originally based on the photocurrent multiplication device. We tried to modulate the multiplied photocurrent by the base electrode in this device. Figure 6 shows the base voltage dependence of photocurrent multiplication rate, which is defined as a ratio of the number of carriers flowing through the device to the number of input photons. The multiplication rate increases with increasing base voltage from about 24,000 at $V_b = 0$ to 28,000 at $V_b = 3$ V. This photocurrent modulation with the base voltage is interpreted as a pre-charging effect. Namely, the injected holes from the base electrode accumulate at the organic/emitter interface before input light irradiation. Consequently, the number of photogenerated carriers required for causing the current multiplication is

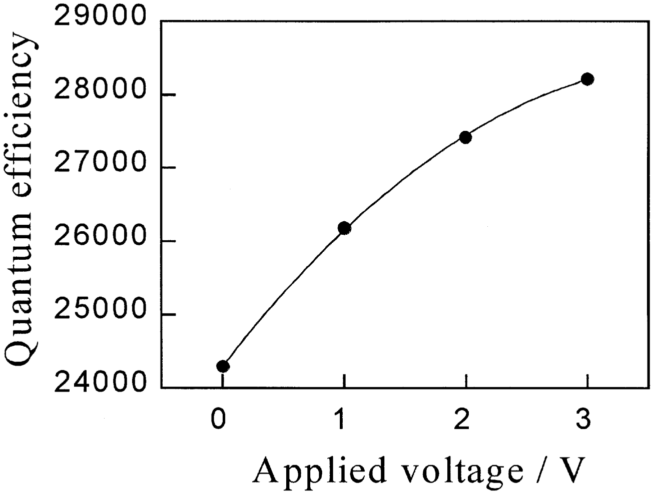

FIGURE 6 Dependence of photocurrent multiplication rate on the base voltage. The input light was incident from the emitter electrode side with a wavelength of 600 nm and an intensity of 40 μW cm^{-2}.

reduced, which leads to higher multiplication rate. Thus, this device can work as a phototransistor too, in which the sensitivity can be tuned with the base voltage.

CONCLUSION

In conclusion, we have proposed a novel organic transistor termed a charge injection controlled transistor. This device was fabricated by embedding a striped base electrode into an organic photocurrent multiplication device. This device achieved current amplification by electron tunneling injection caused by the accumulation of holes from the base electrode, and a large photo-response, which can be modulated by the base electrode.

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