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Current Enhancement in the Vertical-Type Metal-Base Organic Transistors

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The vertical-type metal-base organic transistors (MBOT) are high-performance transistors which have a simple layered structure of organic/metal/organic layers. In this study, we investigated various structures for the collector layer to enhance current modulation and reduce operation voltage. The device having collector layers composed of perylene derivatives/bathocuproine(BCP)/C_{60} and base electrode of LiF/Al showed very high current modulation of 165.1 mA/cm^2 at 2 V of collector voltage and 1 V of base voltage. We found that the LiF layer and BCP layer contribute to current enhancement, and the C_{60} layer contributes to suppression of leakage current, respectively.

Keywords: base electrode; low-voltage operation; metal-base organic transistors; on/off ratio

INTRODUCTION

Organic transistors utilizing molecules or polymers are expected to be used for flexible displays and printable electronics [1–4]. Most researchers of this field study organic field-effect transistors (OFETs), which have parallel source and drain electrodes separated by several microns, and a gate electrode isolated from the channel by an insulating layer. Recently, improvement of performances in OFETs has led to a high mobility greater than $1\,\mathrm{cm}^2 \cdot \mathrm{V}^{-1} \cdot \mathrm{s}^{-1}$ [5–6]. On the other hand, it is difficult to make the source-drain gap shorter than 10 microns, unless expensive lithography techniques are employed. Such a lateral-type FET structure is not necessarily the best way to achieve

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low voltage and high frequency operation for the organic semiconductor having relatively low mobility.

Several types of vertical organic transistors have been proposed [7–9]. In these devices, the channel carriers flow in the vertical direction to the film surface, and the channel length, which is defined as the thickness of the organic layer, can be easily reduced to less than 1 μm. We have recently reported a novel type of vertical organic transistor with a simple organic/metal/organic layered structure, termed as the metal-base organic transistor (MBOT) [10]. The MBOT has achieved very high current density modulation exceeding 100 mA/cm^2 with low voltage operation of several volts [11], when the emitter electrode was optimized.

The basic mechanism of the MBOT is interpreted by the electron transmission through the thin base electrode with high probability. However, the design principle has not been clarified, in particular, for the collector layer. So far, we have reported that heat treatment in air after deposition of base electrode is very effective to suppress the off current and observe clear current modulation. These methods, however, are difficult to be controlled and not desirable for practical application. In this study, we focused on the collector layer of the MBOT devices. Various structures for the collector layer were investigated without changing the emitter layer, and a significant current enhancement and voltage reduction were achieved without any treatment in air.

EXPERIMENT

The device structure and measurement system of MBOT are shown in Figure 1. A cleaned ITO glass substrate was used as the collector electrode. All the layers were prepared by thermal vacuum evaporation. The collector layers were composed of N,N′-dimethyl-3,4,9,10-perylene tetracarboxylic diimide (Me-PTC, Dainichiseika Color and Chemicals Manufacturing Co., Ltd.), bachocuproine (BCP, DojinDo Laboratories), and fullerene (C_{60}, Tokyo Chemical Industry Co., Ltd.). The base electrode was LiF and Al. The emitter layer was C_{60} again, and the emitter electrode was Ag. The base pressure for evaporation was 10^{-4} Pa for all the organic layers, and 10^{-3} Pa for LiF/Al base electrode and Ag emitter electrode. As reference devices, we also prepared MBOT devices having bottom layers composed of Me-PTC/LiF/Al and Me-PTC/BCP/LiF/Al. In this study, we did not employ any heat treatment in air, and the chamber was flushed by dry nitrogen gas to reduce the effect of atmospheric exposure. The active area where the three electrodes were overlapped was 0.04 cm^2.

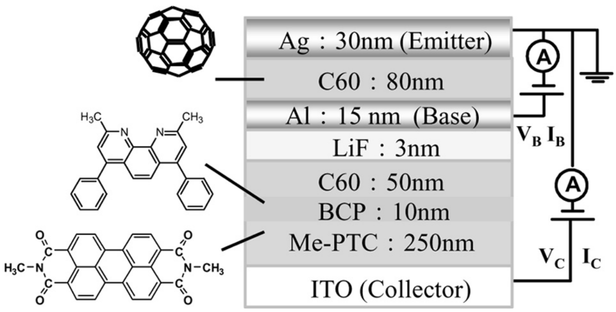

FIGURE 1 Device structure and measurement system of the metal-base organic transistor are illustrated. Chemical structures of organic materials used are also shown.

The current modulation of MBOT was measured by a semiconductor parameter analyzer (Agilent 4155C) in the glove box, where the concentration of oxygen and water were less than 1 ppm. The collector voltage (V_C) of an output voltage was applied between the collector and emitter electrodes using a negative bias on the emitter. The base voltage (V_B) of an input voltage was applied between the emitter and base electrodes; in this case also, a negative bias was applied on the emitter. Under a constant V_C, the output collector current (I_C) between the emitter and collector, and the input base current (I_B) between the emitter and base were measured.

RESULTS AND DISCUSSION

The MBOT device having bottom layers of Me-PTC/BCP/C_{60}/LiF/Al showed the best performance. Its modulation characteristics in common-emitter configuration are shown in Figure 2. Figure 2(a) shows the $I_C - V_B$ curves for various constant V_C. The collector current (I_C) was increased remarkably with increasing V_B, and finally, I_C exceeded 165.1 mA/cm^2. It should be noted that large current modulation was achieved in very low operation voltage, $V_B = 1\,V$ and $V_C = 2\,V$. On the other hand, the input base current (I_B) between the base and emitter electrodes showed smaller change than I_C, as shown in Figure 2(b). The current amplification factor (h_{FE}) is shown in Figure 2(c). The h_{FE} is defined as a ratio of the change in output current (I_C) to that in input current (I_B) for V_B application. The value of h_{FE} was increased by applying V_B, and reached 18.9 at $V_C = 2\,V$ and $V_B = 1\,V$. The h_{FE} exceeding unity indicates current amplification that is characteristic of transistors. Thus, the fabricated device worked as a transistor with low operation voltage and high current density.

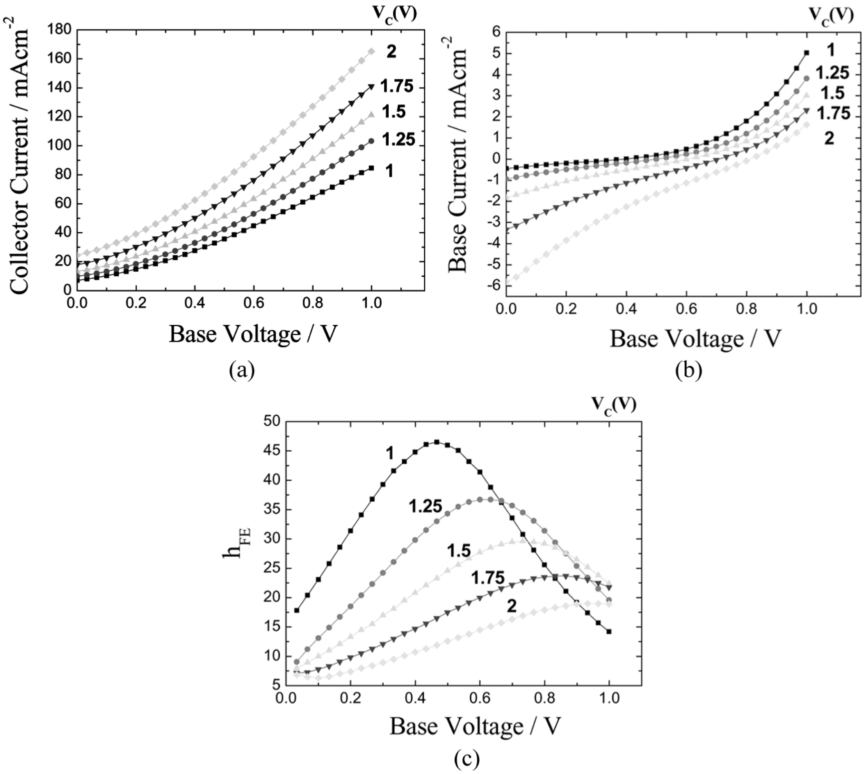

FIGURE 2 The current modulation characteristics of the MBOT having bottom layers composed of ITO/Me-PTC/BCP/C_{60}/LiF/Al, (a) output modulation characteristics ($I_C - V_B$ curves) for constant V_C, (b) input modulation characteristics ($I_B - V_B$ curves) for constant V_C, and (c) the current amplification factor (h_{FE}).

Table 1 summarizes obtained performance of the transistors investigated in this study. The on;off ratio was defined as the ratio of the I_C at $V_B = 1\,V$ to that at $V_B = 0\,V$. In the device having bottom layers of Me-PTC/LiF/Al, the off current was larger than the on current.

TABLE 1 Transistor Performances of the MBOT Having Various Structures of Bottom Layers ($V_B = 1\,V$, $V_C = 2\,V$)

Bottom layers	On current (mA/cm^2)	Off current (mA/cm^2)	h_{FE}	On/Off ratio
Me-PTC/LiF/Al	3.8	8.8	–	–
Me-PTC/BCP/LiF/Al	294.6	155.2	151.0	1.9
Me-PTC/BCP/C60/LiF/Al	165.1	24.4	18.9	6.8

This means that this device did not work as a transistor, and merely obeyed Kirchhoff's law of two resistors connected serially. This behavior is often observed in the MBOT without heat treatment in air. On the other hand, the device with Me-PTC/BCP/LiF/Al structure showed efficient current modulation, that is, collector current increased with increasing V_B, and very high current density of 294.6 mA/cm^2 was obtained. The device with Me-PTC/BCP/C_{60}/LiF/Al structure also indicated large current modulation of 165.1 mA/cm^2, but the off current became smaller. As a result, the on;off ratio was improved from 1.9 to 6.8. From these results, it was concluded that the BCP layer worked as the on current enhancement layer, and the C_{60} layer under the base electrode worked as the off current suppression layer.

The operation mechanism of the MBOT can be explained by the energy diagram as shown in Figure 3. In the on state ($V_B > 0$), electrons are injected from the emitter by the V_B between the emitter and base. These electrons can pass through the base electrode with high probability and plunge into the collector layer. Finally, they reach the collector electrode by the collector voltage, and are observed as output collector current. The transmission mechanism through the base electrode is the kernel of the operation mechanism, but has not been clarified in detail. For one plausible explanation, we have proposed the hot electron or ballistic electron mechanism. Based on these

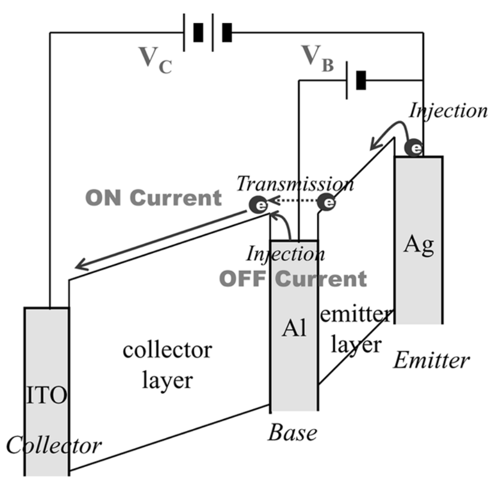

FIGURE 3 The energy diagram of MBOT during operation. The wiring diagram for emitter-common measurements are also indicated. The emitted electrons can pass through the base electrode with high probability, and are finally collected to the collector electrode.

considerations, it is concluded that the magnitude of on current is determined by injection efficiency at the emitter electrode and electron transportation from the emitter through the collector, assuming constant and high probability of electron transmission through the base. In the off state ($V_B = 0$), electrons are not injected from the emitter electrode, because there is no potential difference between the emitter and base electrode. This indicates that the off current is mainly composed of the current between the base and collector caused by the V_C.

The BCP in the collector layer remarkably enhanced the on and off current. From the above consideration on the operation mechanism, this result can be attributed to reduction of the bulk resistance of the collector layer. The current through all the layers, from the emitter electrode through the collector, can flow more easily when the resistance of the collector layer is reduced. This presumption is supported by the fact that two terminal measurements between the emitter and collector (open base condition) also showed obvious current enhancement. Unfortunately, this behavior cannot be explained by energy levels of highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) as shown in Figure 4. The higher LUMO level of BCP cannot account for reduction of the bulk resistance. The origin has not been clear, but enough thin BCP layer in the collector layer may cause some interfacial phenomena like charge generation at the Me-PTC/BCP interface.

We also discovered that C_{60} layer under the base electrode suppressed the off current. These results can be attributed to suppression of electron injection from the base electrode due to the higher LUMO level of C_{60} compared to that of Me-PTC. The insertion of C_{60} layer

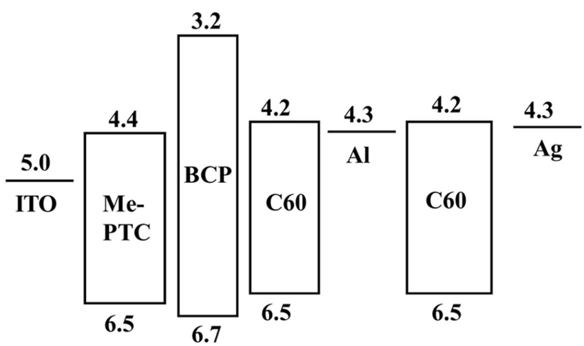

FIGURE 4 Energy levels of HOMO and LUMO, or work function of each material in this study. The energy level of LiF was omitted because precise value cannot be measured in our system.

blocked the electron injection and the main component of the off current was suppressed. The slight decrease of on current was attributed to the increase of bulk resistance of the collector layer. The LUMO level of BCP is much higher than that of C_{60}, but the BCP/LiF/Al interface is well-known preferable combination for electron injection and used for organic light-emitting diode generally, which resulted in a large off current. Thus, two additional layers in this study controlled the on and off current successfully, resulting in high current and low voltage operation without heat treatment in air.

CONCLUSION

In this study, we investigated various structures for the collector layer in the MBOT to enhance current modulation and reduce operation voltage without the heat treatment in air. We found that the collector layer composed of Me-PTC/BCP/C_{60} and the base electrode of LiF/Al showed very high current modulation of 165.1 mA/cm^2 at $V_C = 2$ V and $V_B = 1$ V. The LiF layer and BCP layer contribute to current enhancement. The C_{60} layer contributes to suppression of leakage current, respectively. These results suggest important guiding principles to design the MBOT devices.

REFERENCES

[1] Wang, J. Z., Gu, J., Zenhausern, F., & Sirringhaus, H. (2006). *Appl. Phys. Lett.*, *88*, 133502.

[2] Nikolai J. Kaihovirta, Daniel Tobjörk, Tapio Mäkelä, & Ronald Österbacka. (2008). *Appl. Phys. Lett.*, *93*, 053302.

[3] Seung H. Ko, Heng Pan, Costas P. Grigoropoulos, Christine K. Luscombe, Jean M. J. Fréchet, & Dimos Poulikakos. (2007). *Appl. Phys. Lett.*, *90*, 141103.

[4] Gelinck, G. H., Huitema, H. E. A., Van Veenendaal, E., Cantatore, E., Schrijnemakers, L., Van der Putten, J., Geuns, T. C. T., Beenhakkers, M., Giesbers, J. B., Huisman, B. H., Meijer, E. J., Benito, E. M., Touwslager, F. J., Marsman, A. W., Van Rens, B. J. E., & De Leeuw, D. M. (2004). *Nat. Mater.*, *3*, 106.

[5] Sundar, V. C., Zaumseil, J., Podzorov, V., Menard, E., Willett, R. L., Someya, T., Gershenson, M. E., & Rogers, J. A. (2004). *Science*, *303*, 1644.

[6] Kato, Y., Iba, S., Teramoto, R., Sekitani, T., & Someya, T. (2004). *Appl. Phys. Lett.*, *84*, 3789.

[7] Kiyoshi Fujimoto, Takaaki Hiroi, Kazuhiro Kudo, & Masakazu Nakamura. (2007). *Adv. Mater.*, *19*, 525.

[8] Sheng-Han Li, Zheng Xu, Liping Ma, Chih-Wei Chu, & Yang Yang. (2007). *Appl. Phys. Lett.*, *91*, 083507.

[9] Shiau-Shin Cheng, Chuan-Yi Yang, You-Che Chuang, Chun-Wei Ou, Meng-Chyi Wu, Shih-Yen Lin, & Yi-Jen Chan. (2007). *Appl. Phys. Lett.*, *90*, 153509.

[10] Fujimoto, S., Nakayama, K., & Yokoyama, M. (2005). *Appl. Phys. Lett.*, *87*, 133503.

[11] Nakayama, K., Fujimoto, S., & Yokoyama, M. (2006). *Appl. Phys. Lett.*, *88*, 153512.