Influence of thin metal base thickness on the performance of CuPc vertical organic triodes

Shiau-Shin Cheng, Chuan-Yi Yang, You-Che Chuang, Chun-Wei Ou, Meng-Chyi Wu, Shih-Yen Lin, and Yi-Jen Chan

Influence of thin metal base thickness on the performance of CuPc vertical organic triodes

Shiau-Shin Cheng, Chuan-Yi Yang, You-Che Chuang, Chun-Wei Ou, and Meng-Chyi Wu
Department of Electrical Engineering, National Tsing Hua University, Hsinchu, Taiwan 30013

Shih-Yen Lin[a)]
Research Center for Applied Sciences, Academia Sinica, Taipei, Taiwan 11529 and Department of Photonics, National Chiao-Tung University, Hsinchu, Taiwan 300

Yi-Jen Chan
Electronics and Optoelectronics Research Laboratories, Industrial Technology Research Institute, Hsinchu, Taiwan 310

In this letter, the characteristics of vertical organic triodes fabricated by using two copper phthalocyanine (CuPc) back-to-back Schottky diodes with different metal base thicknesses are reported. The vertical organic triodes exhibit pronounced saturation regions in the output current-voltage characteristics. The common-emitter current gain reduces with increasing the Al base thickness due to the increase of recombination current at the base end resulted from the reduction of opening voids in the Al metal film. The common-emitter current gain of the device with 4.5 nm thick Al base reaches 1.9 at $V_{CE}=-6$ V and $J_B=2.5$ mA/cm^2. © 2007 American Institute of Physics. [DOI: 10.1063/1.2722623]

Organic thin film transistors (OTFTs) have received considerable interest in recent years due to their potential applications as fundamental components for organic sensors, organic integrated circuits, flat panel displays, smart tags, electronic papers, and radio frequency identification.[1–6] Due to their low-cost, low-temperature fabrication procedure and the possibility of their fabrication onto the flexible substrates, many research groups have devoted to the development of OTFTs. Up to now, most of the reports on OTFTs are focused on the planar-type structure. Nevertheless, planar-type OTFTs are of disadvantages such as high operation voltages and low operation speed due to the limitation of channel length and low carrier mobility of the organic materials. As compared with the planar-type OTFTs, the vertical-type OTFTs have been reported to exhibit superiority such as a high current gain, a low operation voltage, and a high operation frequency due to their short channel length.[7–11] The channel length can be easily controlled by reducing the organic film thickness to a submicrometer range. Pronounced saturation regions with high current gain values are also observed for the pentacene-based vertical organic triodes.[10,11] Compared with the pentacene material, although the carrier mobility of copper phthalocyanine (CuPc) is lower, however, higher stability under ambient conditions and much lower price for this material have made CuPc-based organic transistors promising for practical applications.[12] In this letter, we fabricate the vertical organic triodes by using two CuPc back-to-back Schottky diodes with different metal base thicknesses. The common-emitter current gain reduces with increasing Al base thickness due to the increase of recombination current at the base end resulted from the opening void reduction of the Al metal film. The common-emitter current gain of the device with a 4.5 nm Al base can reach 1.9 at $V_{CE}=-6$ V and $J_B=2.5$ mA/cm^2.

The device structure of the vertical triodes is shown in Fig. 1. The devices were fabricated on Coning 1737 glass substrates. The glass substrates were precleaned by using acetone, isopropyl alcohol, and de-ionized water in an ultrasonic cleaner. All organic materials and metal electrodes were deposited in a thermal evaporation chamber at a base pressure of 10^{-6} torr. The deposition procedure of the vertical organic triodes was as following: (a) a 50 nm Au layer as the collector electrode, (b) a 70 nm CuPc layer as the collector, (c) a thin Al layer with different thicknesses of 0, 4.5, 9, and 13.5 nm as the base, (d) a 30 nm thick Al layer as the base electrode, (e) a LiF layer as the hole injection enhancement layer, (f) a 15 nm N'-di(naphthalen-1-yl)-N,N'-diphenylbenzidine layer as the kinetic-energy enhancement layer for holes injected from the emitter, (g) a 35 nm CuPc layer as the emitter, and (h) a 50 nm Au as the emitter electrode. The active area is 4×10^{-4} cm^2, which is defined by the intersection of emitter and collector electrodes. The current-voltage (I-V) characteristics of the devices were measured by HP 4156 semiconductor parameter analyzer in darkness under atmospheric environments.

Figure 2(a) shows the collector current density versus collector-to-base voltage (J_C-V_{CB}) characteristics of the de-
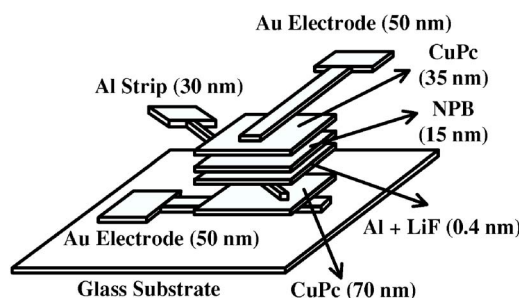

FIG. 1. Device structure of the CuPc-based vertical organic triodes with different Al base thicknesses of 0, 4.5, 9, and 13.5 nm.
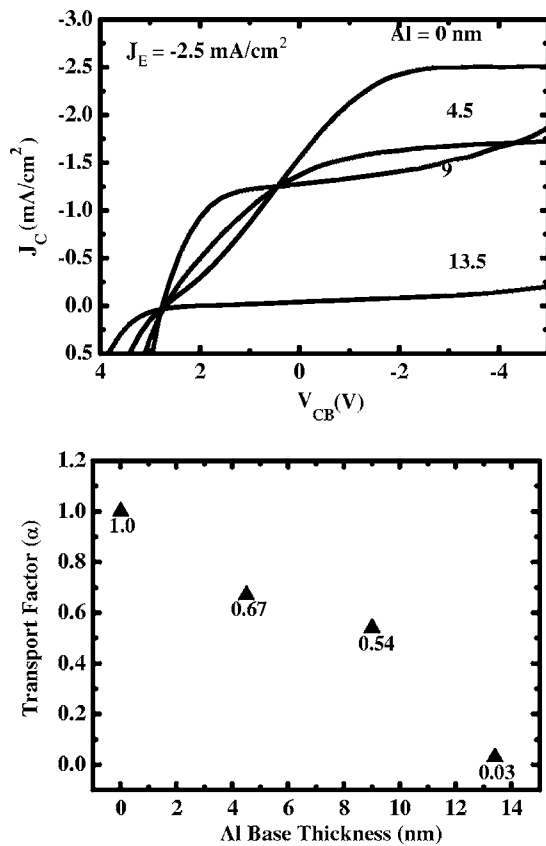
a)Electronic mail: shihyen@gate.sinica.edu.tw

FIG. 2. (a) Collector current density vs collector-to-base voltage (J_C-V_{CB}) characteristics for the devices with different Al base thicknesses of 0, 4.5, 9, and 13.5 nm operated at J_E=2.5 mA/cm². (b) The transport factor (α) of the devices with different Al base thicknesses under the saturation region.

FIG. 3. AFM images of the samples with (a) 4.5 and (b) 13.5 nm Al films deposited on the 70 nm CuPc.

vices with different Al base thicknesses of 0, 4.5, 9, and 13.5 nm at J_E=2.5 mA/cm² measured under the common-base mode. Inspection of Fig. 2(a) reveals that the pronounced saturation regions can be observed for all the organic triodes. For the device without an Al metal base, it is expected that the transport carriers would only experience a thick organic layer. Therefore, it is obvious that the transport factor α would reach 1 for the device at higher applied voltages. An increase of Al base thickness would lead to a decrease of transport factor. Figure 2(b) shows the transport factor values of the devices operated in the saturation region. The α values are 1, 0.67, 0.54, and 0.03 for the devices with Al base thicknesses of 0, 4.5, 9, and 13.5 nm, respectively. The phenomenon is attributed to the increase of recombination current at the thicker metal base thickness.

We further investigate the mechanisms responsible for the reduction of transport factor values with increasing Al thickness. Figures 3(a) and 3(b) show the images of atomic force microscopy (AFM) for the samples with 4.5 and 13.5 nm thick Al metals deposited onto the 70 nm CuPc, respectively. As shown in Fig. 3(a), a more rough surface morphology is observed for the sample with a 4.5 nm Al thickness, which implies that more opening voids are observed for the sample. Because the thickness difference between the two samples is only 9 nm, the diffusion current reduction should not result in such a huge reduction of transport factor value from 0.67 to 0.03. Therefore, assuming that most of the collector current flows through the opening voids instead of diffusing through the Al base, the α value reduction should be attributed to the decrease of opening voids
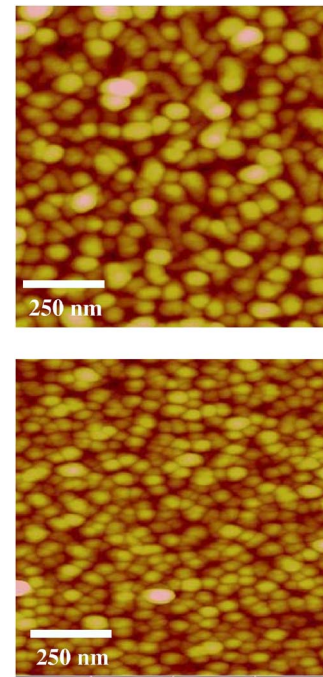
with increasing the Al thickness. Under this assumption, the role of the opening voids at the Al base would be similar to the grip structure in the static induction transistors (SITs).[9] The major difference is that the size of the grid structure in SITs is limited by the metal masks. The optimized linewidth is usually of several tens of micrometers. However, as shown in Fig. 3, the size of the opening voids at the Al base is down to less than 0.1 μm, which makes the thin metal base more effective in current modulation and also advantageous for carrier transport.

Figure 4 shows the J_C-V_{CE} characteristics of the device with a 4.5 nm thick Al base measured at different base current densities (J_B) under the common-emitter mode. Again, the pronounced saturation regions can be observed for the organic triode. The appearance of the saturation region is attributed to the almost constant base voltage at the region, which results in a constant emitter current (I_E or J_E). Part of emitter current contributes to base current (I_B or J_B), rest of the emitter current would flow through the thin Al base electrode and form the collector current.[10,11] The common-
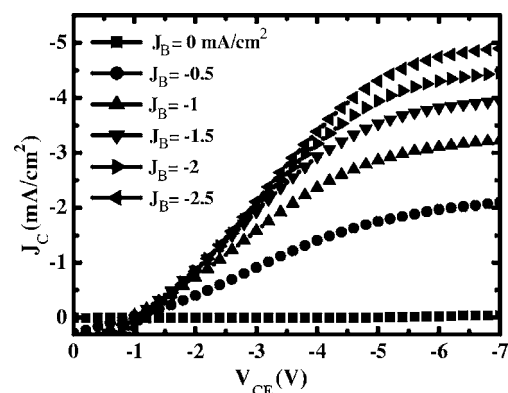

FIG. 4. Collector current density vs collector-to-emitter voltage (J_C-V_{CE}) characteristics at different base current densities (J_B) for the device with a 4.5 nm thick Al base.

emitter current gain β for the device reaches 1.9 at the flat saturation region with $V_{CE}=-6$ V and $J_B=2.5$ mA/cm^2. The measured current gain β is close to the calculated value of 2.03 derived through the transport factor ($\beta=\alpha/(1-\alpha)$). The result is different from the case for pentacene-based vertical organic triodes.[10,11] Because the surface morphology of CuPc is smoother than that of pentacene, it is expected that more opening voids would be available for the pentacene-based triodes. Therefore, the transport factor would be relatively high for the devices. However, when the device is operated under common-emitter mode, the less conductive metal base for the pentacene-based triodes would force more emitter current to flow through the thick Al strip. In this case, a large difference between the measured and derived current gain values would be observed for the pentacene-based triodes, while similar measured and derived current gain values are obtained for the CuPc-based devices.

In conclusion, we have investigated the characteristics of vertical organic triodes fabricated by using two CuPc back-to-back Schottky diodes with different metal base thicknesses. The reduced common-emitter current gain with increasing the Al base thickness is attributed to the increase of recombination current at the base end resulted from the reduction of opening voids in the Al metal film. The results suggest that most of the collector current flows through the opening voids instead of diffusing through the metal base.

The current gain of the device with 4.5 nm Al base has reached 1.9 at $V_{CE}=-6$ V and $J_B=2.5$ mA/cm^2. Compared with the pentacene-based triodes, the similar measured and derived current gain values are resulted from the smoother surface morphology of the CuPc material.

[1]D. J. Monsma, J. C. Lodder, T. J. A. Popma, and B. Dieny, Phys. Rev. Lett. **74**, 5260 (1995).

[2]H. Edzer, A. Huitema, G. H. Gelinck, J. Bas, P. H. van der Putten, K. E. Kuijk, K. M. Hart, E. Cantatore, and D. M. DeLeeuw, Adv. Mater. (Weinheim, Ger.) **14**, 1201 (2002).

[3]C. D. Sheraw, L. Zhou, J. R. Huang, D. J. Gundlach, and T. N. Jackson, Appl. Phys. Lett. **80**, 1088 (2002).

[4]C. J. Drury, C. M. J. Mutsaers, C. M. Hart, M. Matters, and D. M. deLeeuw, Appl. Phys. Lett. **73**, 108 (1998).

[5]F. Eder, H. Klauk, M. Halik, U. Zschieschang, G. Schmid, and C. Dehm, Appl. Phys. Lett. **84**, 2673 (2004).

[6]Y. Y. Lin, D. J. Gundlach, S. F. Nelson, and T. N. Jackson, IEEE Trans. Electron Devices **44**, 1325 (1997).

[7]Y. C. Chao, S. L. Yang, H. F. Meng, and S. F. Horng, Appl. Phys. Lett. **87**, 253508 (2005).

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

[9]K. Kudo, M. Iizuka, S. Kuniyoshi, and K. Tanaka, Thin Solid Films **393**, 362 (2001).

[10]T. M. Ou, S. S. Cheng, C. Y. Huang, M. C. Wu, I. M. Chan, S. Y. Lin, and Y. J. Chan, Appl. Phys. Lett. **89**, 183508 (2006).

[11]C. Y. Yang, T. M. Ou, S. S. Cheng, M. C. Wu, S. Y. Lin, I. M. Chan, and Y. J. Chan, Appl. Phys. Lett. **89**, 183511 (2006).

[12]R. Ye, M. Baba, and K. Mori, Jpn. J. Appl. Phys., Part 2 **44**, L581 (2005).