Enhanced performance of organic base-modulation triodes by nanoscale interfacial modification

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1. Introduction

The organic thin-film transistors (OTFTs), which have the advantages of low cost, low-temperature fabrication process, and the possibility of their fabrication onto the flexible substrates, have been studied widely in recent years, due to their applications such as pixel drivers of the display, radio frequency identifications (RFIDs), and organic sensors.[1-4] Compared with the two architectures of the OTFTs, namely, planar- and vertical-type OTFTs, the latter possesses offer advantage of lower driving voltages and faster operation frequencies owing to the precise control of their channel down to sub-micrometer. Although some research reports employed the high-k dielectrics and reduced the channel length, the devices suffered the drawback of the larger leakage current in the former case and larger contact resistance in the latter case. Therefore, recent research groups have further investigated the vertical-type OTFTs. However, the devices lacked the apparent saturation region which limits their development in electronic applications.

In our previous report, it has been demonstrated that a thin LiF layer inserted between the metal and the organic layer can enhance carrier injection.[5-8] While the appropriate LiF thickness was employed, the maximum current on/off ratio can be measured. However, the LiF-layer capacitance would be easily modified by the humidity and the output current of the device will be changed. Besides, the LiF layer will result in a larger off current. In this work, we fabricate the organic base-modulation triode (OBMT) by employing cesium carbonate (Cs₂CO₃) to replace the LiF layer. In accordance with the optimization of the Cs₂CO₃ thickness, the current on/off ratio can reach up to 10⁶ while both the V_B and V_CE are biased at -3 V.

2. Experimental

The device structure of the vertical organic triodes is shown in the inset of Fig. 1. The devices were fabricated on the glass substrates. The glass substrates were sequentially pre-cleaned by using acetone, isopropyl alcohol, and de-ionized water in an ultra sonic cleaner and treated with ultraviolet (UV) ozone cleaner for 20 min. All the organic materials and metal electrodes were deposited in a thermal evaporation chamber at a base pressure of 10⁻⁶ torr and patterned by a metal mask. The Au strip with a thickness of 30 nm was deposited on the glass substrate as collector electrode. Then, the CB diode, which is composed of the copper phthalocyanine (CuPc) layer with 50 nm and the pentacene layer with 270 nm, was deposited. The pentacene layer was thermally evaporated at a rate of 0.1 nm/sec and a thick Al strip with 30 nm as the base electrode was deposited onto the pentacene layer. The thin Al layer with 10 nm was deposited as the base layer and the Cs₂CO₃ layers with different thicknesses of 0, 0.5, 1.0, and 1.5 nm were thermally evaporated as the carrier injection enhancement layer. Afterwards, the 20 nm thick N, N'-di(naphthalene-1-yl)-N, N'- diphenyl-benzidine (NPB) layer and a 70 nm thick pentacene layer was thermally evaporated at the rate of 0.1 nm/sec as the emitter layer. Finally, the thick Au strip with 30 nm was deposited onto the pentacene layer as the emitter electrode. The active area of the device was 4.0 × 10⁻⁴ cm², as defined by the crossover area between the emitter and collector electrodes. The current-voltage (I-V) characteristics of the device were measured by Keithley 4200 semiconductor parameter analyzer. All the electrical characteristics of these devices were measured in dark under glove box environment.

3. Results and Discussion

The collector-to-emitter current (I_CE) versus the collector-to-emitter voltage (V_CE) characteristics of the OBMT, which employed a 1.0 nm Cs₂CO₃ layer as the interfacial-modification layer, is shown in Fig. 1. As shown in Fig. 1, different base-emitter voltages (V_BE) range from 0 to -3 V at a step of 0.5 V was applied. The I_CE can reach up to ~10.7 nA at V_CE = -3 V and V_BE = -3 V. The current on/off ratio which is defined as I_CE (V_BE = -3 V)/I_CE (V_BE = 0 V) at V_CE = -3 V is about 5.63 × 10² and the off current is 0.019 nA. It can be found the measured lower off current is attributed to the minimized leakage current in the presence of the interface modification. The increase of the temperature above 690 °C would lead to the formation of Cs₂O and CO₂.[9] The role of Cs₂O is similar as the insulator and the emitter current is composed of tunneling current and...
thermionic emission current. With a thinner Cs$_2$CO$_3$ layer, the energy barrier for carriers from NPB to collector layer through the thin Al layer could be greatly lowered by the larger potential drop. It would increase the electron injection via tunneling while decrease the thermionic emission current. On the other hand, a thicker Cs$_2$CO$_3$ layer would reduce the tunneling probability and thus block the carrier injection from the emitter layer into the collector layer. When the Cs$_2$CO$_3$ was thermal evaporated, Cs$_2$CO$_3$ might get decomposed to metallic Cs and there is a possibility of metallic Cs clusters incorporated into the Cs$_2$CO$_3$ film.$^{[10]}$ The presence of metallic Cs clusters would alter the band alignment at the interface between the thin Al and the NBP layer and thus increase the carrier injection efficiency. It can increase the recombination probability at $V_B = 0$ V and decrease the leakage current. With the negative bias applied at the base electrode, the holes will attain higher energies and thus reduce the recombination probability. Furthermore, to clarify the influence of Cs$_2$CO$_3$ thickness on the performance of OBMT, the current on/off ratio as a function of Cs$_2$CO$_3$ thickness of the devices operated at -3 V for both the $V_{BE}$ and $V_{CE}$ is shown in the Fig. 2. The maximum current on/off ratio of 563 occurs at the Cs$_2$CO$_3$ layer thickness of 1.0 nm. Although the maximum current on/off ratio is lower than the practical electronic applications, it can be further improved by modifying the interface between the emitter electrode and emitter layer because the output current is contributed from the current of EB diode under forward bias. These improved ways are under our current investigations.

4. Conclusions

In summary, we have demonstrated the fabrication of organic base-modulation triodes operated in the pronounced saturation region by inserting the Cs$_2$CO$_3$ layer between the thin Al and the pentacene layer. With the optimized Cs$_2$CO$_3$ thickness, the barrier between the thin Al and NBP will be aligned and results in a maximum current on/off ratio of 563. Overall, the interface modification seems to be able to enhance the device performance and can be considered as the necessary process parameter for the future nanoelectronics.

![Fig. 1. Collector-to-emitter current ($I_{CE}$) as a function of the collector-to-emitter voltage ($V_{CE}$) at various base voltages which range from 0 to -5 V at a step of -0.5 V. The schematic of the device structure is shown at the inset.](image)

![Fig. 2 Current on/off ratio as a function of Cs$_2$CO$_3$ layer thickness of the devices operated at -3 V for both the $V_{BE}$ and $V_{CE}$.](image)

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References