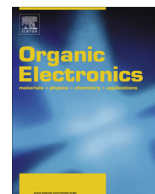




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A cascade energy band structure enhances the carrier energy in organic vertical-type triodes

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ABSTRACT

Organic vertical-type triodes (OVTs) based on the cascade energy band structure as emitter layer are studied. The electric characteristics were dramatically enhanced while incorporating the cascade energy under current driving and voltage driving modes. The improvement is attributed to that injection carriers can obtain higher energy through a stepwise energy level. When the device has a layered structure of F₁₆CuPC (10 nm)/PTCDI (10 nm)/pentacene (100 nm) in emitter, it exhibits a common-base transport factor of 0.99 and a common-emitter current gain of 225 under current driving mode and exhibits a high current modulation—exceeding $-520 \mu\text{A}$ for a low collector voltage of -5 V and a base voltage of -5 V and the current on/off ratio of 10^3 under voltage driving mode. Furthermore, we realized first organic current mirror that exhibited out/in current ratio of 0.75 and output resistance of $10^5 \Omega$ by using the OVTs.

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1. Introduction

The study of organic thin film transistors (OTFTs) has attracted much interest for their potential use in high-value, low-cost electronics, such as displays, sensors, radio frequency identifications, and e-papers [1–4]. Recently, organic semiconductors with mobilities comparable with that of amorphous silicon have been realized [5–8]; nevertheless, OTFTs possessing the typical metal–oxide–semiconductor field effect transistor structure exhibit low output currents and low frequencies of operation because of their high resistivities and low carrier mobilities, which restrict their practical applications. Although shortening

the channel length can further improve the device performance, this approach requires that state-of-art lithographic techniques, which are not practical for fabricating low-cost flexible electronics, be performed prior to organic semiconductor growth; in addition, the contact resistance between the source/drain electrodes and the organic semiconductor will dominate the device performance [9,10]. To realize the incorporation of OTFTs in most proposed applications, it will be necessary to improve not only the electrical properties of the organic materials but also the device structures. Organic vertical-type transistors are a promising technological option for improving device performance [11–16] because their channel lengths can be controlled precisely by varying the thickness of the active layer.

In the early days of inorganic semiconductor development, bipolar-junction transistors (BJTs)—the most important inorganic vertical-type transistors—were formed using n–p–n or p–n–p double homojunctions [17]. Due to their

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larger minority-carrier diffusion and base resistance, the operation speeds of BJTs are limited by the transition time [18]. To overcome this obstacle, unipolar hot-carrier transistors (HCTs) were developed, featuring a thin metallic base sandwiched between two semiconductors to serve as an emitter and a collector. If the depletion region at the metal–semiconductor junction of a Schottky diode is thinner than the junction capacitance of a pn diode, it results the lower resistance. To further improve their performance, cascade energy band structures, formed by the different element concentration ratios, have been incorporated in HCTs. Such structures enhance the carrier energy in emitter–base (EB) diodes; therefore, the carriers can be inhibited from contributing to the recombination current at the base electrode and effectively approach the collector electrode to increase the output current. To control the element concentration ratio accurately, the devices must be grown using expensive fabrication processes (e.g., molecular beam epitaxy, metal organic chemical vapor deposition). In addition, the carrier transport mechanism in such devices is based on band-type conduction and the carriers are affected by the acoustic phonons. Therefore, it is difficult to operate these devices at room temperature [19,20]. In contrast, organic thin films can be fabricated using simple processing techniques. In their corresponding devices, carrier transport occurs through tunneling between the localized states caused by defects and/or disorder states, with a conduction theory associated with phonon-activated hopping. Therefore, organic vertical transistors are readily operated at room-temperature and can be applied in low cost, flexible electronics [21,15,22]. Due to lower carrier mobility of the materials and the shorter mean free path in the base layer, the most of the carriers are recombined at the base electrode. Which lead to a lower common-emitter current gain and lack the apparent saturation region. Several approaches have been developed to improve these drawbacks (e.g.,) by inserting a hole injection enhancement layer (LiF or Al₂O₃) at the emitter–base junction or using a metal-grid base electrode [23–25]. When inserting a hole injection layer the tunneling barrier are formed, as a result of the emitter current being dominated by the tunneling current, with exhibiting a saturation region and enhanced current gain.

In this paper, we describe organic vertical triodes (OVTs) incorporating a cascade-type energy band structure that operate at pronounced saturation with high gain. The most injection carriers can obtain higher energy through a stepwise energy level, more carriers can surmount the thin metal base electrode and diffuse into the collector layer. Therefore, this device exhibits a larger transport factor and a current gain when operated in the current-driving mode. On the other hand, the device displays a larger current on/off ratio and a smaller offset voltage when operated in the voltage-driving mode. The device exhibits a sufficiently large current gain; a current mirror operated at a greater out/in current ratio (I_{out}/I_{in}) and a greater output resistance (r_o) is achieved by integrating two p-channel OVTs with a load resistor.

2. Experimental

Prior to deposition, the glass substrates were cleaned sequentially with detergent, acetone, and isopropyl alcohol

followed by treating in an ultraviolet (UV) ozone cleaner for 15 min. The gold (Au) (30 nm) layer was deposited on the glass substrate to serve as a collector electrode. The copper phthalocyanine (CuPC) (50 nm) layer (Luminescence Technology) was thermally deposited on the Au layer to smooth the surface morphology and then the pentacene (270 nm) layer (Luminescence Technology), serving as the collector of the p-channel triode, was thermally evaporated. The aluminum (Al) (10 nm) strip was thermally evaporated onto the pentacene layer to function as the base electrode. Next, a thin Al film (15 nm), operating as the base electrode, was deposited on the strip. To study the effects of the materials with different highest occupied molecular orbital (HOMO) energy levels on the device performance, different organic semiconductor layers were thermally evaporated onto the thin Al film as shown in Table 1. Finally, films of molybdenum(VI) oxide (MoO₃) (30 nm) and Al (30 nm) were deposited onto the emitter layers of the five OVTs mentioned above to function as emitter electrodes. This process was performed with patterning through a metal mask. All organic materials and metal electrodes were deposited in a thermal evaporation chamber at a base pressure of 10⁻⁶ torr. The active area of the device (0.04 cm²) was defined by the intersection of the emitter and collector electrodes. The current–voltage (*I*–*V*) characteristics of the devices were measured using a Keithley 4200 semiconductor parameter analyzer. All of the electrical characteristics of these devices were measured in dark environments.

3. Results and discussion

Fig. 1a and b presents the device configuration and the energy diagram of the emitter–base diodes, respectively [26–29]. The device, fabricated from two Schottky diodes, comprises a collector–base diode as the bottom diode and an emitter–base diode as the top diode. To form the Schottky diode, the active layer was sandwiched between Au and Al. To reduce the leakage current and the energy barrier between the metal and the organics, a CuPC film was used as the buffer layer in the collector–base diodes and MoO₃ was inserted as the carrier injection layer in the emitter–base diodes [30–33]. Several organic semiconductors—pentacene, *N,N'*-bis(naphth-1-yl)-*N,N'*-bis(phenyl)-benzidine (NPB), *N,N*8-dioctyl-3,4,9,10-perylene tetracarboxylic diimide (PTCDI), and copper(II) 1,2,3,4,8,9,10,11,15,16,17,18,22,23,24,25-hexadecafluoro-29H,31H-phthalocyanine (F₁₆CuPC)—with different energy levels were employed to form the cascade-type structure in the emitter–base diodes. To investigate the influence of the cascade-type energy structure in the emitter–base diodes, we fabricated five different devices by incorporating the various materials in the emitter–base diodes as shown in Table 1. All five different devices configuration were fabricated and characterized with same material in the collector–base diodes ((Au (30 nm)/CuPC (50 nm)/pentacene (270 nm)/Al (30 nm)/thin Al layer (10 nm)). Fig. 2a and c displays the common-base (CB) electrical characteristics of devices A and E, respectively; Fig. 2b and d present the common-emitter (CE) electrical characteristics of devices

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