

Bulk heterojunction ambipolar thin film transistors

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1. Introduction

Recently, the organic thin-film transistors (OTFTs), with advantages of low cost, solution processing, flexible, large area,¹ low-temperature processing, have been the most fundamental element for numerous applications including flat-panel displays, organic integrated circuits, physical-chemical sensors, and other electronic devices. For the further applications of OTFTs, such as inverters, CMOS circuits and ring oscillators, it has been demonstrated that it is essential to incorporate both n- and p-type transistors for achieving the organic complementary integrated circuits.^{2,3}

Numerous groups have reported the ambipolar transport in bilayer semiconductors made by evaporating with a standard OTFT geometry, and by using two different semiconductors, one for the electron injection and the other for hole injection.⁴ In such a case, both materials had to be deposited sequentially and the thickness is required to be optimized. Beside, it is difficult to use the solution processing. In this work, we report the easy and low-cost solution processing method to fabricate the ambipolar OTFTs by using a conjugate polymer of poly(3-hexylthiophene) with good solubility as p-type material, and a small-molecule fullerene with high mobility as n-type material. Both them are blended as the semiconductor layer. It could avoid different polymers assembled and also improve the small-molecule film uniformity. Then, the operation of ambipolar OTFTs can be realized in a single layer, while maintaining the attractiveness of easy solution processing.

2. Experimental

Typically, the bottom-gate OTFT structure employed in this study is shown in Fig. 1. The devices were fabricated on the indium tin oxide (ITO)-coated glass substrates (10-20 Ω/\square , sheet resistance), acting as gate electrode of the ambipolar transistors. Prior to the device fabrication, the ITO substrates were cleaned by TFD4 and deionized water in an ultrasonic bath and then were treated with UV-ozone for 15 min. After routine solvent cleaning, the polymer solution, which was prepared by containing 11 wt% poly-4-vinylphenol (PVP) and 4 wt% poly(melamineco-formaldehyde) dissolved in propylene glycol monomethyl ether acetate (PGMEA), were spun on ITO substrates at 1000 rpm for 60 s. The substrates were baked at 100°C for 5 min to remove the residual solvent, and

followed by baking at 200°C for 20 min to cross-link the polymer. The dielectric thickness, measured by α -step, is 660 nm and the resulting capacitance per unit area of the film is 5.47 nF/cm². A 1 wt%-ratio blended solution of poly(3-hexylthiophene) (P3HT) and fullerene (C₆₀) were dissolved in trichlorobenzeneboth (TCB), and followed by mixing at various ratios. The mixing active layers were deposited on CPVP-coated substrates by spin casting and then thermal annealing at 50°C on the stabilized hot plate for 30 min under N₂ atmosphere. Finally, the source and drain electrodes with 40 nm thickness were thermally evaporated onto the C₆₀/P3HT blended film through a shadow mask to define the S/D electrodes. The channel length (L) and width (W) were 250 and 2000 μ m, respectively. The current-voltage (I-V) characteristics of OTFTs were measured in N₂ by Keithley semiconductor analyzer (4200-SCS).

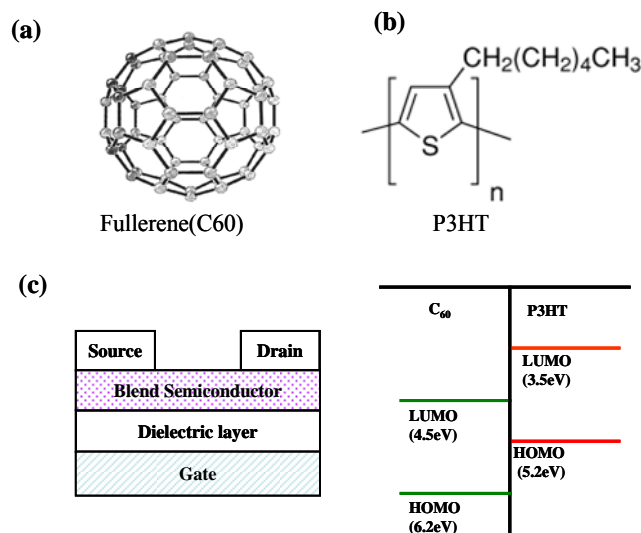


Fig. 1. Molecular structures of (a) the electron acceptor fullerene (C₆₀), (b) the electron donor poly(3-hexylthiophene) (P3HT), and (c) a schematic of the thin film transistor with their energy levels.

3. Results and Discussion

The charge transport of the OTFTs with C₆₀/P3HT blended films is further investigated. Fig. 2 shows the drain-source current versus drain-source voltage (I_{DS} vs. V_{DS}) for the OTFTs at different C₆₀ to P3HT ratios using Au as S/D electrodes with a channel length of 120 μ m. The device shows the hole-accumulation mode only at the C₆₀ concentration of 25%.

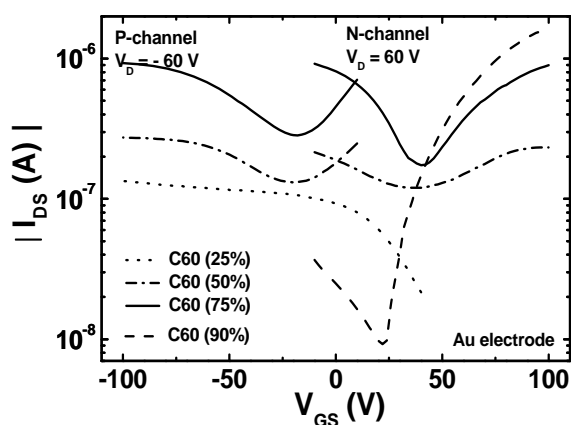


Fig. 2 Transfer characteristics for the OTFTs with different weight ratios of blended C₆₀/P3HT.

With further increasing the C₆₀ concentration, the n-channel operating characteristics are enhanced, leading to exhibit the ambipolar characteristics of both the hole accumulation and electron accumulation modes. The ambipolar carrier transport behavior can be observed in the blended range of the C₆₀:P3HT from 1:1 to 3:1 (C₆₀ concentration ~ 50%-75%). With the 3:1 blended ratio of C₆₀ to P3HT, the saturated drain currents of both n- and p-type operations are almost the same. Both would reach a higher drain current of about 10⁻⁶ A at |V_G| = 100 V. Therefore, it could get higher and balanced mobilities for electron and hole. The mobilities extracted from the saturation region are $\mu_h = 1.6 \times 10^{-3} \text{ cm}^2/\text{V-s}$ and $\mu_e = 2.8 \times 10^{-3} \text{ cm}^2/\text{V-s}$ for hole transport in P3HT and electron transport in C₆₀, respectively.

In spite that the energy barrier between the gold work function (~5.2 eV) and the lowest unoccupied molecular orbital (LUMO) level of C₆₀ (~4.5 eV) is as high as 0.7 eV, the N-type organic semiconductor still had higher-mobility electrons to overcome the barrier. It is possible for the mixed C₆₀ in the blended semiconductor layer to reduce the formation of interface dipoles between metal (Au) and semiconductor (P3HT), and thus to enhance the hole carrier transport. Hence, the balanced ambipolar transport in C₆₀/P3HT blended semiconductor layer has been demonstrated even by employing the high work function of gold electrodes. Furthermore, only the n-channel characteristics can be observed by increasing the C₆₀ concentration up to 90%. The results show that it is important to control the C₆₀ concentration for obtaining a balanced ambipolar transport.

Finally, we demonstrated the complementary-like voltage inverter circuits composed of two ambipolar FETs with the blended films by a C₆₀:P3HT ratio of 3:1. The typical transfer characteristic of the ambipolar inverter is shown in Fig. 3. At a supply voltage of 60 V, the calculated gain of the inverter is around 6.5 by differentiating the voltage transfer curve.

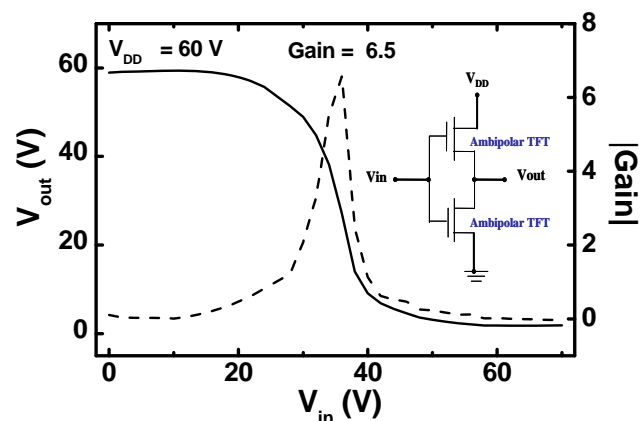


Fig. 3 Transfer characteristics of complementary-like ambipolar inverter with their corresponding gain.

4. Conclusions

In summary, the single blend-semiconducting polymer layer can exhibit ambipolar charge transporting, and using high work-function metal (Au) as source/drain electrodes for the balanced electron and hole mobility. It can provide not only a simple the fabrication process but also the reduction of the electron-trapping at the interface of organic semiconductor and insulator layer. Using this solution processing, the mixtures of p- and n-type semiconductors poly(3-hexylthiophene) and fullerene would provides the balanced ambipolar characteristics with high hole and electron mobilities of 0.0016 and 0.0028 cm²/V-s without any further treatments.

References

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