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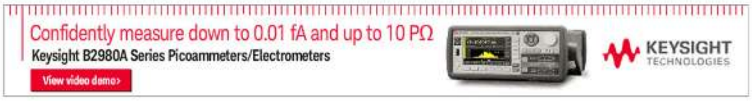

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Electrical characteristics of lateral heterostructure organic field-effect bipolar transistors

Samarendra P. Singh,[1] Prashant Sonar,[1] Alan Sellinger,[1,2] and Ananth Dodabalapur[1,3,a)]
[1]*Institute of Materials Research and Engineering (IMRE), Agency for Science, Technology and Research (A*STAR), 3 Research Link, Singapore 117602, Republic of Singapore*
[2]*Department of Materials Science and Engineering. Geballe Laboratory for Advanced Materials, Stanford University, 476 Lomita Mall, Stanford, California 94305, USA*
[3]*University of Texas at Austin, Austin, Texas 78758, USA*

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We describe and discuss the unique electrical characteristics of an organic field-effect transistor in which the active layer consists of a type II lateral heterojunction located approximately midway between the source and drain. The two active semiconductors on either side of the junction transport only one carrier type each, with the other becoming trapped, which leads to devices that operate in only the steady state when there is balanced electron and hole injections from the drain and source. We describe the unique transfer characteristics of such devices in two material systems. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3064160]

The unique properties of organic and polymeric semiconducting materials has led to many advances in device designs, performance characteristics, and applications of organic transistors.[1–11] Organic field-effect transistors (OFETs) are used in logic circuits,[5] displays drivers,[6,7] for light emission,[8] and as chemical[9,10] and biosensors.[10,11] Light emitting transistors are required to be ambipolar, meaning that the semiconductor supports sizable concentrations of both carrier species. One way to accomplish this is through the use of combinations of two materials, either in the vertical heterostructure geometry[12] or as a mixed phase.[13] The development of materials that are truly ambipolar has led to light emission from single component ambipolar transistors as well. This has often required the use of specific dielectrics that suppress the formation of interfacial traps for one of the carrier species.[14]

In this communication, we report on the transfer characteristics of the organic transistor, in which the active layer consists of a type II (Ref. 15) lateral heterojunction of two materials, each of which supports the transport of one carrier type with the other carrier being immobile. Such lateral heterostructure OFETs are more properly described as bipolar OFETs since each material transports one carrier type and recombination between electrons and holes occurs close to the heterointerface. There is always balanced electron and hole injections. Such balanced hole and electron injection is very reminiscent of organic light emitting diodes (OLEDs). However, an important difference is that, in OLEDs, balanced electron and hole injection is only achieved by careful design and is sometimes not achieved at all; whereas in the present device, it is always present. Similar devices have been reported recently[16] and their output characteristics explained, although the work in Ref. 16 did not involve type II heterostructures.[15] It must be emphasized that the actual barrier heights at the interface are influenced by interface dipoles, and a considerable amount of characterization work is necessary before an interface can be understood.[17] From the values of the highest occupied molecular orbital (HOMO)/lowest unoccupied molecular orbital (LUMO) levels for the two materials, we have a type II (Ref. 15) heterostructure. The data we present support this basic picture.

For lateral heterostructure OFETs, a modified nomenclature of electrodes as "anode" and "cathode" for electrodes in contact with the hole and electron transport layers, respectively, is employed and illustrated in Fig. 1. A pair of hole and electron channel materials has been used to fabricate lateral heterostructure OFETs. We have chosen dihexyl quarter thiophene (DH-α4T) (Ref. 18) and dihexyl-benzothiadiazole-quarter thiophene (DH-BTZ-4T) (Ref. 19) as hole transport materials in combination with naphthalene-tetracarboxylic-dianhydride (NTCDA) (Ref. 20) and *N*-ditridecylperylene tetracarboxylic diimide (PTCDI-$C_{13}H_{27}$) (Ref. 21) as electron transport materials. In-house synthesized DH-α4T and DH-BTZ-4T materials exhibited hole mobilities of 0.04 and 0.17 cm^2/V s, respectively. Electron transport material PTCDI-$C_{13}H_{27}$ was sourced from Sigma Aldrich and used without any further purification while NTCDA was received from FLUKA and purified by sublimation before usage in device fabrication.

The top contact lateral heterostructure OFETs are fabricated using n^+-Si/SiO$_2$ (200 nm) substrates in bottom gate geometry. Before organic layer deposition, Si/SiO$_2$ substrates were subjected to standard wafer cleaning using acetone, methanol, and de-ionized water, and exposed to UV ozone for 20 min after drying. The hole transport and electron transport organic layers are thermally evaporated in a vacuum chamber having $\sim 6\times10^{-6}$ mbar vacuum. For lateral heterostructure OFETs, 30 nm of hole and electron transport layers were deposited sequentially using shadow mask

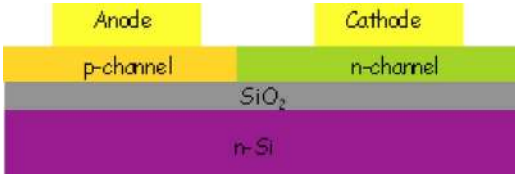

FIG. 1. (Color online) Cross-sectional view of the lateral organic heterostructure based organic thin film transistor device.

[a)] Electronic mail: ananth@mail.utexas.edu.

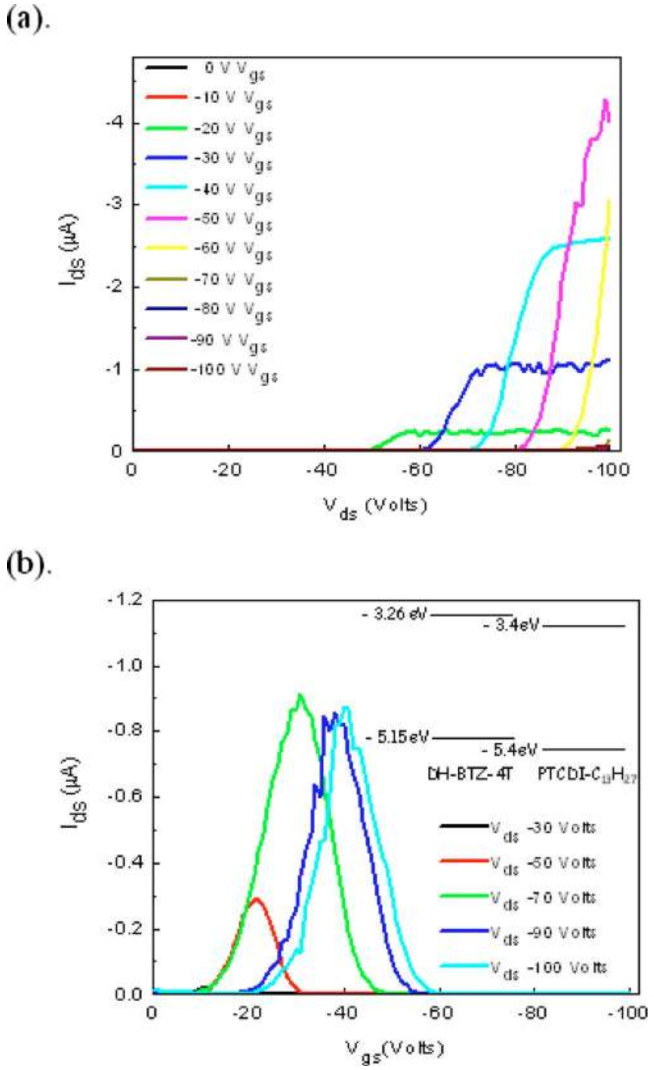

FIG. 2. (Color online) Current-voltage characteristic (a) I_{DS}-V_{DS} and (b) I_{DS}-V_{GS} of lateral heterostructure based OTFT, having DH-BTZ-4T:PTCDI-$C_{13}H_{27}$ as *p*-type and *n*-type organic semiconductors. The devices are operated in hole enhancement mode, i.e., V_{GS}:-ive and V_{DS}:-ive. The inset in (b) shows LUMO and HOMO energy levels of the DH-BTZ-4T:PTCDI-$C_{13}H_{27}$ heterostructure.

and alignment of masks ensuring overlap of both layers. 100 nm of gold (Au) source (S) and drain (D) (or anode and cathode) contacts were deposited on top of organic layer structure using shadow mask.

In lateral heterostructure devices, gold deposition shadow masks were aligned to ensure that the interface between hole and electron transport layers is located approximately midway between the electrodes. The channel length to width ratio (L/W) of lateral heterostructure devices is (200/3000). All devices were fabricated and measured in a glove box under nitrogen using a Keithley 4200 parameter analyzer.

The electrical characteristics of the lateral heterostructure OTFT devices of DH-BTZ-4T (hole transporting) and PTCDI-$C_{13}H_{27}$ (electron transporting) are shown in Figs. 2(a) and 2(b). The transfer characteristics are distinctive as shown in Fig. 2(b). For a given drain-source voltage, the drain current initially does not increase with gate voltage and then starts to increase. The increase is followed by a decrease after which the drain current goes to zero and the transfer curve looks like a Gaussian. The Gaussian-like transfer characteristic was also seen in DH-α4T: NTCDA based lateral heterostructure devices, shown in Fig. 3.

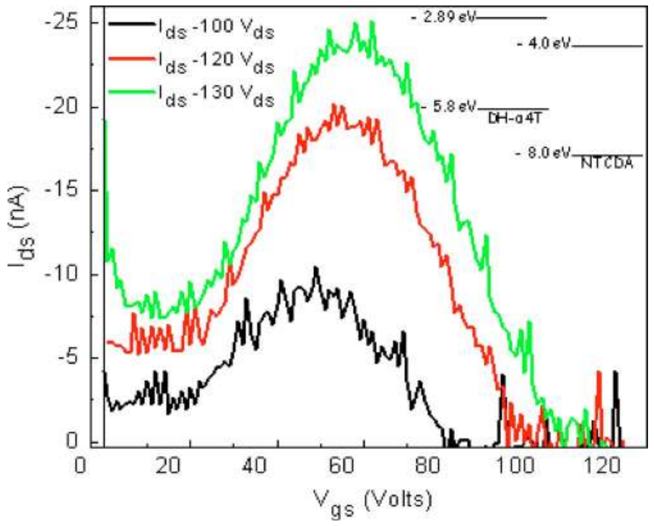

FIG. 3. (Color online) Transfer characteristic (I_{DS}-V_{GS}) of the lateral heterostructure based OTFT, having DH-α4T:NTCDA as *p*-type and *n*-type organic semiconductor. The devices are operated in hole enhancement mode, i.e., V_{GS}:-ive and V_{DS}:-ive. The inset shows LUMO and HOMO energy levels for DH-α4T and NTCDA.

The transfer characteristics reflect the electric-field driven carrier injection across the heterointerface. This lateral electric field is a maximum when the carrier populations of electrons and holes in the two sides of the heterojunction are equal, which corresponds to bias conditions in which the magnitude of V_{GS} is approximately half of the magnitude of V_{DS} (assuming threshold voltages are small). Figure 2(a) shows that when the magnitude of V_{DS} becomes larger than about twice V_{GS}, the drain current abruptly increases from near zero and saturates for higher V_{DS}. In contrast, when we sweep V_{GS}, the device current reaches a maximum and falls. This can be explained by the fact that when we sweep V_{DS} beyond twice V_{GS}, the extra voltage is dropped without increasing the maximum electric field significantly but by expanding the extent of the depletion regions. We note that our device configuration differs significantly from that in Ref. 16 and we have a type II heterojunction[15] with significant barriers for both electrons and holes, as illustrated in inset of Figs. 2(b). When we sweep V_{GS} with a fixed V_{DS}, the accumulated carrier concentrations are changing as is the lateral electric field. Maximum device current occurs when the field is a maximum, as explained above. Increasing the magnitude of both V_{DS} and V_{GS} (while maintaining their ratio), increases the device current as the electric field increases in the vicinity of the heterojunction.

We determined the threshold voltages (V_T) of unipolar *p*-channel and *n*-channel transistors with the same gate dielectric used in the lateral heterostructure devices. The threshold voltage for DH-BTZ-4T is −7 V. Preliminary evaluation of the threshold voltage for PTCDI-$C_{13}H_{27}$ is in the range of 8–12 V. This is reflected in the transfer characteristics. If the magnitude of V_T is too high, then V_{GS} (and V_{DS}) needed for device operations will be increased. If the magnitude of the threshold voltages of *p*-channel and *n*-channel materials is different, then there would be greater asymmetry in the voltages needed for current flow through the device.

Qualitatively very similar behavior is observed in lateral heterostructure FETs based on DH-α4T and NTCDA, shown in Fig. 3. The current levels are much lower, however, which is presumably due to the much larger energy barriers arising from the offsets at the heterojunction. This suggests that for obtaining high current densities in lateral heterostructure FETS, the barrier must be relatively small, as is the case for the DH-BTZ-4T and PTCDI-$C_{13}H_{27}$ devices described above. Scaling the channel length down will also increase the device current for a given set of voltages as the lateral electric fields will be high.

The detailed device physics of such type II (Ref. 15) lateral heterojunction FETs and the *p*-*n* junctions formed in them by biasing are an interesting domain of organic semiconductor device physics and are worth examining in more detail. The combined effects of drift, diffusion, and injection of charges across the heterointerface (by tunneling) need to be examined in detail both theoretically and experimentally.

The obvious application for lateral heterostructure FETs is light emission.[16] The balanced charge injections are very beneficial for this. However, since many of the organic transistor materials are not efficient light emitters, it may be necessary to dope one of the layers with a fluorescent or phosphorescent dye with an energy gap less than that of the host. This will permit efficient luminescence by charge transfer or energy transfer from the host material.

In summary, we discussed the output and transfer characteristics of lateral heterostructure [type II (Ref. 15)] OFETs. We showed that in such devices, under steady state conditions, there is always an exact balance between electron and hole injection. The shape of the transfer characteristic, which we described is very unusual with nothing similar reported for any transistor, organic or inorganic based.

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