AIP Applied Physics Letters

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Citation: Applied Physics Letters **98**, 073302 (2011); doi: 10.1063/1.3553191
View online: http://dx.doi.org/10.1063/1.3553191
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/98/7?ver=pdfcov
Published by the AIP Publishing

Electrical characteristics of zinc oxide-organic semiconductor lateral heterostructure based hybrid field-effect bipolar transistors

Samarendra P. Singh,[1,a)] Zi-En Ooi,[1] Serene Ng Lay Geok,[1] Gregory K. L. Goh,[1] and Ananth Dodabalapur[2,b)]
[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 Electrical and Computer Engineering, University of Texas at Austin, Austin, Texas 78758, USA*

(Received 28 October 2010; accepted 5 January 2011; published online 15 February 2011)

Zinc oxide-organic semiconductor lateral heterostructure based field-effect bipolar transistors (FEBTs) having heterointerfaces approximately midway between the source and drain electrodes are fabricated and characterized. These hybrid FEBTs comprise zinc oxide (ZnO) and *p*-channel organic semiconductors [Pentacene and α-sexithiophene (6T)] supporting electron transport and hole transport on either side of the heterojunction, respectively. Current flow in the transistor channel is established as a result of carrier injection across the heterointerface followed by recombination. In steady state, such devices possess significant populations of holes and electrons in the transistor channel and operate in bipolar mode.
[doi:10.1063/1.3553191]

The use of heterostructures is an effective way of manipulating the electronic and optoelectronic properties of semiconductor devices. Heterostructures enable technologically advantageous combinations of semiconductor materials with different properties, often resulting in properties that are not achievable with a single semiconductor. Beneficial properties of zinc oxide (ZnO) such as wide band gap, high charge carrier mobility, and environmental robustness have attracted significant interest for application in semiconductor devices.[1–5] Solution processed ZnO is an important *n*-type semiconductor material and exhibits mobilities in the range 4–6 cm^2/Vs.[3] Additionally, the tuneable and efficient light emission and absorption properties of organic semiconductors make them suitable for applications in light emitting devices (LEDs) and photovoltaics (PVs), respectively.[6,7] Inorganic oxide-organic semiconductor hybrid devices are a promising class of optoelectronic devices with enormous potential for applications in LEDs[2,8] and PVs.[9] Understanding charge transfer and energy transfer mechanisms at the heterostructure interface is an important step in realizing efficient organic-inorganic hybrid optoelectronic devices.

In this paper, we report the electrical characteristics of ZnO:Organic semiconductor lateral heterostructure based hybrid field-effect bipolar transistors (FEBTs) with a *p*-*n* junction formed between a *p*-channel organic semiconductor and *n*-channel ZnO within the transistor channel. In these devices, each constituent semiconducting layer favors the transport of only one type of charge carrier (ZnO thin films transport electrons while *p*-channel organic semiconductor layers transport holes) while efficiently trapping the opposite carrier type. Under suitable drain and gate bias conditions, conducting channels form in both semiconductors by injection of charges from the appropriate electrode. Charge carrier injection across the heterointerface and subsequent recombination enable steady state current flow. Under steady state conditions, lateral heterostructure FEBTs have significant concentrations of holes and electrons and operate as field-controlled bipolar transistors.[10] The observed electrical characteristics of such devices resemble closely the electrical characteristics of lateral heterostructure FEBTs based only on organic semiconductors.[10,11] In FEBTs, the electron and hole accumulation layers are separate, making the device laterally polarized.[12] It has only one junction, unlike a bipolar junction transistor (BJT) which has two junctions.

Inorganic-organic lateral heterostructure based hybrid FEBTs consists of a patterned electron transporting ZnO layer paired with a hole channel organic semiconductor to form the *p*-*n* interface inside the FEBT channel between the source and drain electrodes. Figure 1 shows a schematic of the samples fabricated for this work, which contains three different types of field-effect transistors (FETs) on a single substrate: A unipolar *p*-channel FET, a hybrid FEBT, and a unipolar *n*-channel FET. In this work, we have chosen Pentacene[13] and α-sexithiophene (α-6T) [13,14] sourced from Sigma Aldrich as hole channel organic materials and used without any further purification. Pentacene and α-6T have exhibited hole mobility >2.0 [15] and 0.02 cm^2/Vs,[13] respectively, and are widely used for charge transport studies in organic field-effect transistors (OFETs).

The top contact bottom gate lateral heterostructure FETs are fabricated using p^+-Si/SiO_2 (200 nm) substrates. Before deposition, the substrates were cleaned using acetone, methanol, and deionized water and exposed to UV-ozone for 20 min after 5 min of drying at 100 °C. ZnO thin films are prepared by two different methods. The first method involved deposition of a thin film of zinc acetate followed by calcination at 350 °C, which removed all organic residue

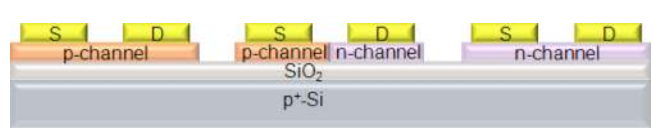

FIG. 1. (Color online) Schematic of *p*-channel, inorganic-organic lateral heterostructure and *n*-channel transistors.

a)Author to whom correspondence should be addressed. Electronic mail: samar-singh@imre.a-star.edu.sg.
b)Electronic mail: ananth.dodabalapur@engr.utexas.edu.

while leaving behind a film of ZnO. This was repeated five more times to obtain a roughly 60 nm thick polycrystalline ZnO film[16] consisting of 5–15 nm grains. The second method was to deposit ZnO by sputtering under 5 mTorr Argon at a power density of 1.3 W/cm^2. The sputtered ZnO thin film is polycrystalline in nature consisting of 100–300 nm grains with average height ~31 nm and roughness 15 nm. Subsequently, about half of the ZnO thin film was covered with Kapton® tape and the unprotected half was etched away in a dilute solution of acetic acid. The ZnO film was then washed under deionised water and isopropanol to remove the acid and trace adhesive to obtain a 35 nm thick film of ZnO covering half of the substrate with a clean edge where coverage ended. A *p*-channel organic semiconductor (35 nm) is thermally evaporated through a shadow mask to make a *p-n* heterointerface within the transistor channel, as defined by 100 nm of gold (Au) source and drain contacts. The source and drain contacts also defined unipolar *p*- and *n*-channel field-effect transistors on the same substrate (see Fig. 1). In lateral heterostructure hybrid FEBTs, gold deposition shadow masks were aligned to ensure that the interface between the hole and electron transport layers is located approximately midway between the electrodes. Acetate-derived ZnO was paired with Pentacene and sputtered ZnO was paired with α-6T. The channel length to width ratio (L/W) of lateral heterostructure devices are (200/3000) and (200/5000). After the ZnO etching process, all fabrication steps and measurements were carried out in a glove box under nitrogen. The electrical characteristics of FEBT devices are measured using a Keithley 4200 parameter analyzer.

The output and transfer characteristics of the ZnO-Pentacene lateral heterostructure hybrid FET are shown in Figs. 2(a) and 2(b), respectively. For a negative gate bias, the device operates in hole accumulation mode and hole injection across the heterointerface become favorable. In Fig. 2(b), at a given drain-source voltage (V_{DS}), the drain current initially does not increase with gate voltage but then starts to increase once past a particular onset voltage. The drain current then reaches a maximum followed by a decrease approaching zero, which results in a Gaussian-like transfer curve that appears skewed to the left, as shown in Fig. 2(b). With increasing V_{DS}, the peak current increases while peak position shifts toward higher V_{GS}.

The transfer characteristics reflect the electric field driven carrier injection across the heterointerface. This lateral electric field depends on the concentration of the charge carriers on each side of the heterojunction and becomes 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 and both charge carriers have similar mobility). In our unipolar FETs, the threshold voltages and charge carrier mobility for *p*-channel ($V_T=-6.5$ V, $\mu_h=0.15$ cm^2/Vs) and *n*-channel material ($V_T=12.5$ V, $\mu_e=0.05$ cm^2/Vs) are different, which would presumably affect the I_{DS} peak position to some extent.

Figure 2(a) shows that at appropriate V_{DS} (~−13 V), the drain current starts increasing from near zero and tends to saturate for higher V_{DS}. This can be explained by the fact that when we sweep V_{DS} in a near saturation region of I_{DS}, the extra voltage is dropped without increasing the maximum electric field significantly but by expanding the extent of the depletion regions. On the other hand, 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 lateral field is a maximum. Increasing the magnitude of both V_{DS} and V_{GS} (while maintaining their ratio), increases the device current as the lateral electric field increases in the vicinity of the heterojunction.

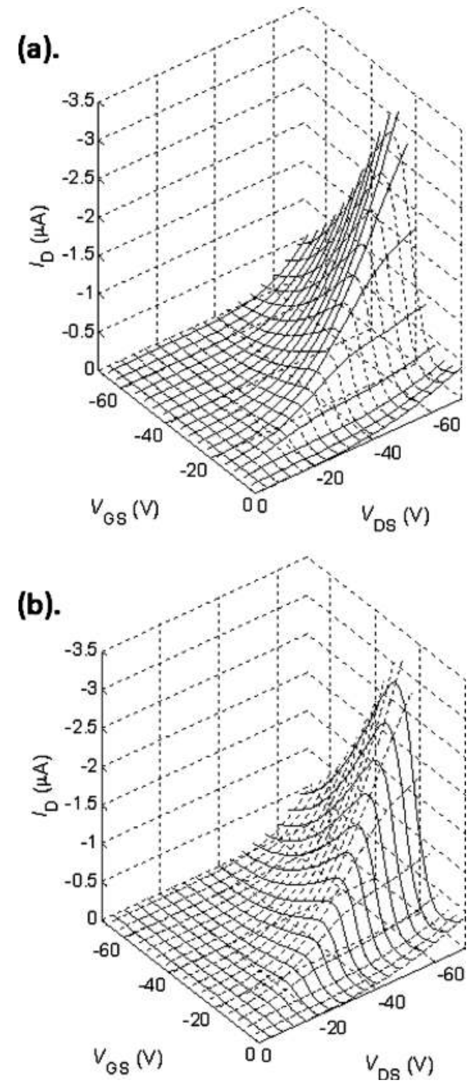

FIG. 2. Output (a) and transfer (b) characteristics of ZnO:Pentacene inorganic-organic hybrid lateral heterostructure FETs.

Qualitatively, a very similar behavior is observed in the ZnO-α-6T lateral heterostructure based hybrid FET, shown in Figs. 3(a) and 3(b). The current level is one order of magnitude lower than that of the ZnO:Pentacene based hybrid FEBT, presumably due to significantly lower hole and electron mobilities observed in the constituent *p*-type (α-6T, 0.001 cm^2/Vs) and *n*-type (sputtered ZnO, 0.19 cm^2/Vs) thin films, respectively. We note that the energy band offset at the heterojunction between Pentacene-ZnO and α-6T-ZnO are roughly the same (Fig. 4), and, in principle, should not affect injection rates (and hence currents) drastically. This indicates that high hole and electron mobilities are necessary for obtaining high current densities in lateral heterostructure FEBTs. Interestingly, the shape of the transfer characteristics is changed from a left-skewed Gaussian (for ZnO:Pentacene) to a right-skewed Gaussian

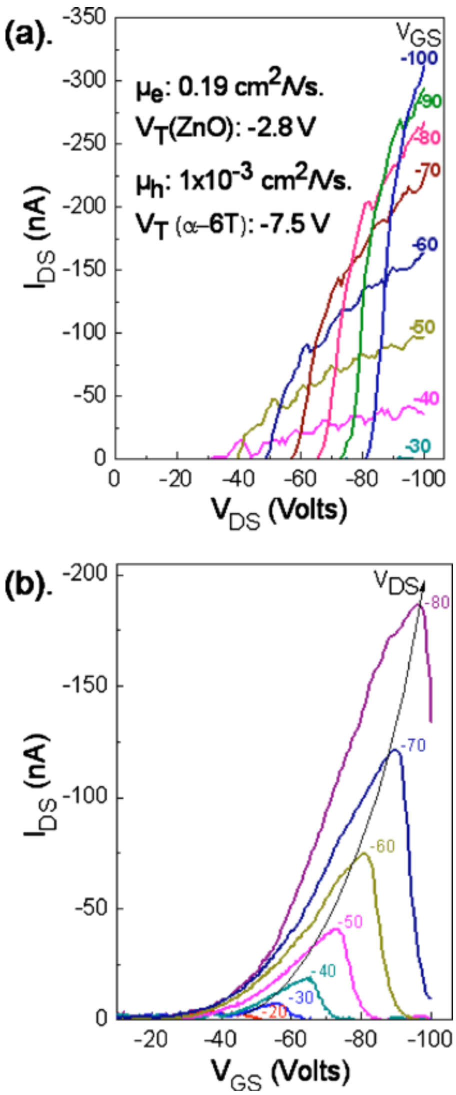

FIG. 3. (Color online) Output (a) and transfer (b) characteristics of ZnO-α-6T inorganic-organic hybrid lateral heterostructure FETs.

for α-6T:ZnO, which can be partly attributed to a significantly lower hole-to-electron mobility ratio (1/190) α-6T-ZnO as compared to that of Pentacene-ZnO (3). In the hole accumulation mode (large V_{GS} magnitude) the device current becomes effectively limited by the hole mobility and the overall device performance will largely depend on the efficiency of hole transport in *p*-channel material.

We have determined the threshold voltages (V_T) of unipolar *p*-channel and *n*-channel transistors fabricated on the same Si/SiO_2 substrates (as shown in Fig. 1) used in the lateral heterostructure devices. The threshold voltages for Pentacene and ZnO FETs are −6.5 and −12.5 V, respectively. For α-6T and ZnO FETs, the threshold voltages are −7.5 and −2.8 V, respectively. If the magnitudes of the threshold voltages of *p*-channel and *n*-channel materials are different, then there would be a greater asymmetry in the voltages needed for current flow through the device.

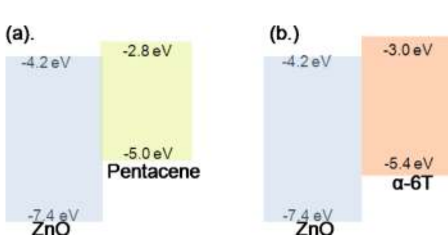

FIG. 4. (Color online) Energy level scheme of (a) ZnO-Pentacene, and (b) ZnO-α-6T inorganic-organic hybrid heterostructure.

The two material systems used in our devices (Fig. 4) have a significant injection barrier for electrons and holes at the heterointerface (type-II heterojunction).[17] The device physics of such lateral heterostructure FEBTs involves electric field assisted charge carrier injection across the heterointerface, drift, and recombination of charge carriers, which are presently being studied analytically. A better understanding of underlying device physics of lateral heterostructure FEBTs would be helpful in realizing potential applications in light emitting transistors and chemical sensors.

In summary, we have discussed the output and transfer characteristics of ZnO-Organic semiconductor lateral heterostructure hybrid field-effect transistors and our results show good electrical continuity at the ZnO-Organic semiconductor heterointerface. These devices operate under steady state with significant populations of hole and electrons inside the transistor channel, which makes them bipolar in nature and suitable for applications in light emitting devices.

The authors acknowledge the Visiting Investigatorship Programme (VIP) of the Agency for Science, Technology and Research (A*STAR), Republic of Singapore for their financial support.

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[12]A bipolar transistor is a semiconductor device in which there are separate regions of different types (i.e, *n*-type or *p*-type). These transistors are bipolar in that the electron and hole accumulation layers are separate, making the device laterally polarized. It has only one junction, unlike a bipolar junction transistor which has two junctions. Nevertheless, it is a transistor due to its three-terminal nature, the ability of the gate to control the current between source and drain, and the ability to achieve amplifications of the signals.
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