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Ambipolar Organic Permeable Base Transistors

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ABSTRACT

Organic transistors with vertical current transport like the Permeable Base Transistor (PBT) show a high performance while allowing for an easy fabrication on the device level. For a simple implementation on a circuit level, ambipolar transistors, providing the functionality of n-type as well as p-type devices, have a benefit for complementary logic. This requires transistors where electrons and holes are present. Here, we investigate a potential concept of bipolar current transport in PBTs. In our device structure, we use the base electrode to control the current flow, but also to investigate the charge carrier transport. The ambipolar organic PBT achieves a charge carrier transmission of 88 % and a current density above 200 mA/cm². Additionally, we show that recombination near the base is required in an ambipolar PBT for a good performance.

Keywords: Vertical Organic Transistor, Permeable Base Transistor, Ambipolar, Hetero-Structure

1. INTRODUCTION

Organic transistors like conventional organic field-effect transistors (OFETs) are usually unipolar devices, where charge carriers of one type form a channel at the gate. However, OFETs can also be built as ambipolar devices.¹ They allow for a simplification in fabrication, as they enable the use of one single type of transistor to create complementary logic, thus reducing the required effort for processing large circuits.² Beside the conventional OFET, there are other transistor structures as well, like the Permeable Base Transistor (PBT), where the current flows in a vertical direction, perpendicular to the substrate.³⁻⁸ This concept of a vertical current transport also simplifies fabrication, as no high-resolution structuring is required for short channels and thus high performance devices. Additionally, the vertical structure allows for an easy stacking and circuit integration with other elements, like Organic Light Emitting Diodes.

For the PBT structure, an ambipolar transport would be interesting as well in order to get the best performance while using very simple fabrication techniques. Therefore we take the PBT structure consisting of three parallel electrodes, with the base in the middle, and use the p-type semiconductor pentacene in the bottom part, while the n-type semiconductor C₆₀ is used in the upper part of the device, as shown in Figure 1. In order to allow charge carriers to be transmitted through the base in the on-state, the base needs to be permeable, which is realized by openings in the base layer, so the base can be understood as a grid-like electrode.⁸⁻¹⁰

The working mechanism for unipolar PBTs using one organic semiconductor material can be shown in the energy diagrams Figure 2a and 2b for n-type and p-type PBTs, respectively. The injection of one type of charge carrier is preferred due to a lower energy barrier at the injecting contact. Injection can be further enhanced by inserting a p- or n-doped layer at the emitter. By changing the base potential, the energy barrier for the charge carriers can be adjusted, thus controlling the current that flows in the device. High base potentials allow electron transport and block holes, which means that n-type PBTs are in the on-state while p-type devices are in the off-state. The opposite applies for low base potentials.

The energy diagram for the ambipolar PBT from Figure 1 with p-type semiconductor (bottom layer) and n-type (top layer) is shown in Figure 2c. Holes can be injected at the bottom electrode, while electrons can be injected at the top electrode. This circumstance makes the use of the terms emitter and collector ambiguous. Therefore the electrodes are referred to as top and bottom, while the middle electrode remains the base.

By omitting one of the doped layers, the injection at the corresponding contact can be significantly reduced. That way electron-only or hole-only devices can be fabricated, which allows to study the current transport more

Figure 1: Schematic structure of the Ambipolar Organic Permeable Base Transistor. The bottom part of p-type semiconductor (Pentacene) and the top part of n-type semiconductor (C_{60}) are separated by the base electrode. For enhancement of the charge carrier injection, properly doped layers are inserted at the bottom and top electrode.

Figure 2: Energy diagram for different PBT types. The injection barriers at top and bottom contact define the type of charge carrier. An n-type PBT is in the on state for a high Base potential, while low base potentials represent a high energy barrier to electrons leading to the off-state. On- and off-state for p-type PBTs are opposite to the n-type behavior. The charge carrier type contributing to the current can be controlled by the base potential, high base potentials favor electrons while low base potentials favor holes. Doped layers are not shown in the figures.

in detail. However, if both doped layers are present, the base controls whether electrons or holes are allowed to be transmitted, but on and off state cannot be assigned to a high or low base potential. The resulting current of the device will depend on how well electrons and holes can be transported in the opposite region and where recombination processes occur.

In this work, the transport mechanisms in the ambipolar PBT structure will be investigated. As holes and electrons react adversatively on a change of the base potential, the charge carrier type that contributes to the current can be identified. Therefore, the base electrode and its potential based charge carrier selectivity act as a probing grid that is implemented within the hetero-structure.

2. EXPERIMENTAL

The samples are processed by thermal vapor deposition under high vacuum conditions with a pressure below $2 \cdot 10^{-7}$ mbar. Deposition onto a cleaned glass substrate is done layer-by-layer according to the structure shown in Figure 1. The active area of 4 mm^2 results from the overlap of all three electrodes which are structured using shadow masks.¹⁰ The size of the base is designed to be slightly larger in order to avoid leakage currents between top and bottom electrodes in case a misalignment is present.

The bottom electrode consists of 100 nm aluminum (evaporated at 2 Å/s) and 20 nm (0.3 Å/s) gold. The following 50 nm thick pentacene layer is p-doped by co-evaporating F_6TCNNQ , the doping concentration is 1 wt%, evaporation rate 1 Å/s . The intrinsic pentacene layer (2 Å/s) has a thickness of 200 nm. A 15 nm aluminum layer (1 Å/s) is deposited on top of the pentacene. Due to a network-like structure of pentacene on gold,^{11,12} openings are formed in this thin aluminum layer.⁸ That way a grid-like permeable base is created. Although no additional structuring inside the active area is required, this opening formation is essential for the device, as otherwise only two separate Schottky diodes connected by the base at their rectifying contacts would result, not showing any transistor behavior.

After processing of the base, the device is exposed to ambient air for 15 min in the dark. During this air exposure step, a native aluminum oxide film forms around the base, acting as an insulator which reduces the base leakage currents.¹³ For the top part of the device, 200 nm intrinsic C_{60} (1 Å/s) is used, and 50 nm C_{60} doped with 1 wt% $\text{W}_2(\text{hpp})_4$ (0.6 Å/s). The top electrode also consists of 20 nm gold and 100 nm aluminum. In order to restrict the current transport to either electron or hole only, we simply omit the doped layer at the bottom or top electrode, respectively.

The samples are characterized using a Keithley 4200-SCS semiconductor characterization system with three SMUs. Between top and bottom electrode, a constant voltage is applied. The polarity complies with the given doped layer configuration, i. e. the bottom electrode has a higher potential than the top electrode. The potential at the middle electrode, the base, is varied.

3. RESULTS

3.1 Electron-only PBT

If only the n-doped layer at the top electrode is present, without a p-doped layer at the bottom, the device becomes mainly n-type, where electrons are injected at the top electrode. The corresponding base sweep is shown in Figure 3. It can be seen as an n-type PBT where the emitter is at the top electrode and the collector at the bottom. The operation voltage is 3 V, i. e. the potential of the top electrode is 0 V, and bottom 3 V. An increase of the base potential – which means the voltage between emitter and base is increasing – leads to a higher emitter current due to more electrons being injected at the emitter contact.

An increase of the base potential leads to a reduced voltage between base and collector. So one would expect the collector current (bottom electrode) to decrease, which is the behavior obtained for a separate measurement of the IV characteristic between base and bottom (dashed line in Fig. 3). In contrast, the collector current is rising, because a small fraction of the increasing electron flow from the emitter is transmitted through the base. Those increasingly transmitted electrons are responsible for the higher collector current.

In principle, two mechanisms could apply, as shown in Figure 2c. After being transmitted through the base, electrons are transported through the pentacene layer until they reach the collector at the bottom (1). Alternatively, they recombine in the base region at the interface between Pentacene and C_{60} with holes that have been injected from the bottom (2). We exclude the latter as the corresponding collector current (red line) is higher than the current of the single undoped bottom element (dashed line), but the number of recombining electrons cannot be higher than the number of holes available. Additionally, at a base-top voltage of 3 V or above, holes cannot flow towards the base region.

Therefore, the observed behavior must result from electrons diffusing to the bottom electrode. However, even at a high base potential, when electrons are energetically allowed to pass the base, the transmission current is still lower by two to three orders of magnitude. Because of the barrier for electron injection from C_{60} into pentacene of 0.64 eV,¹⁴ the electrons are more likely to flow into the base through the aluminum oxide.

Figure 3: Base sweep showing the current densities at different base voltages for electron-only PBT. The potential of the top electrode (electron emitter) is 0 V, the bottom electrode (electron collector) is at 3 V. Only a small transmission can be observed. The dashed line shows the current when only the bottom part is used, i. e. a voltage between base and bottom electrode is applied (top electrode floating).

3.2 Hole-only PBT

Figure 4 shows the base sweep corresponding to a device with a opposite configuration. Here, only the p-doped layer at the bottom electrode is present, without any n-doped layer. Consequently, for low base potentials a large voltage drops across the bottom part of the device and a high hole current is injected at the emitter (bottom electrode). At higher base potentials, this current decreases. The collector currents (top contact),

Figure 4: Base sweep for a device without an n-doped layer. The potential of the top electrode (hole collector) is 0 V, the bottom electrode (hole emitter) is at 3 V. The resulting behavior is a series connection of independent bottom and top element.

in contrast, decrease with lower base potentials. No clear transmission of holes or electrons can be identified, as the top electrode current is monotonically increasing, while the bottom electrode current is monotonically decreasing. Injected charge carriers, either holes at the bottom or electrons at the top contact that flow into the base represent only leakage currents. The same behavior would be seen for independent p- and n-type diodes which are externally connected. However, a very small transmission current flowing from emitter (bottom) to collector (top) below 1 mA/cm^2 cannot be excluded completely, as this would be overlaid by the quite high leakage currents between base and top contact.

3.3 Ambipolar PBT

When doped layers at both sides are used, electrons as well as holes can provide a high current. As shown in Figure 5, the electron current injected at the top contact is increasing with higher base potentials. At least in a certain range between 0 V and 0.5 V, also the bottom electrode current follows these characteristics. Similar to the case shown in Figure 3, this can be identified as an electron transmission current, as a higher base potential means a low energy barrier only for electrons and thus an increasing current that passes the base can only be explained by an electron transport. This time, however, the transmitted current is much larger, reaching 222 mA/cm^2 and exceeding the base leakage currents. In this device, the current between top and bottom electrode can be controlled by the base potential, and additionally the required base current is smaller than the output current. Therefore, this transistor is showing current amplification. The differential transmission, which is defined as the derivative of collector current with respect to emitter current, reaches a value of 88%, with everything above 50% corresponding to a current gain > 1 .

Due to the additional p-doped layer at the bottom electrode, electrons which were able to pass the base do not need to travel towards the bottom electrode any longer, which showed an inferior current transport as discussed in Fig. 3. Instead, holes can now be injected at the bottom electrode easily, which flow towards the base electrode, where electrons and holes recombine.

As can be seen in Figure 5, this only works efficiently in a certain range with a base-top voltage between 0 V and 0.5 V. If the base potential is increased further, the voltage across the bottom part of the device gets lower and therefore the number of injected holes decreases. At a certain point, between 0.5 V and 1 V, not enough holes

Figure 5: Left: Base sweep for an ambipolar PBT. Implementing both, p-type and n-type doped layers allows for injection of holes as well as electrons. Nevertheless an n-type PBT behavior can be observed, as currents increase for higher base potentials. Right: Differential transmission of current reaches 88%, current amplification is present. The operation voltage is 2 V.

are available at the base for recombination and electrons flow into the base, through the imperfect insulator. This leads to an increase of the base currents of course, but also the transmission decreases, until finally the bottom current decreases as well. In principle, this could result in an ambipolar characteristic, where the current decreases after reaching the on-state, i. e. the transistor is switched on for a medium base potential, and is in the off-state for low and high base potentials. This behavior would be exactly the opposite of ambipolar OFETs, which are in the on-state if electrons or holes are present, while the ambipolar PBT is in the on-state only when electrons and holes are present at the same time. This new characteristics could open up new possibilities for applications. Unfortunately, the base leakage currents are very high in our samples, thus making the observation of this ambipolar behavior difficult.

Both devices incorporating an n-doped layer showed an n-type PBT behavior, in case of doped layers at top and bottom even a current amplification was possible due to charge carrier recombination behind the base. However, no p-type behavior could be observed. This would have required holes to flow through the openings in the base layer, which did not happen, even at low base potentials. This can be explained by the high energy barrier for holes between pentacene and C₆₀ of 1.04 eV¹⁴ and is also related to the processing details: The openings in the base layer are already present directly after the base evaporation. Upon evaporation of the following C₆₀ layer, those are filled with C₆₀ (Fig. 1), resulting in devices which exhibit n-type PBT behavior.

4. CONCLUSION

By placing a grid-like base electrode into a p-i-n like structure, we realize a PBT which reaches an output current density of more than 200 mA/cm² and shows a differential current transmission of 88 %. As the base potential can control the charge carrier type that passes the base, it allows for an experimentally simple investigation of the basic charge transport. We observe, that electrons from C₆₀ can be injected and transported in pentacene, but a good performance and high currents are possible only with recombination behind the base electrode, where electrons and holes stay at the energy barrier of the interface of pentacene and C₆₀. While indeed electrons and holes are required to contribute to the transport, we could not observe that holes from pentacene are injected into C₆₀ and the transistor using the material combination C₆₀ and pentacene only shows an electron transmission behavior. However this could also be due to a resolution limitation of the method because of a high base leakage current. When the rather technical problem of improving the native aluminum oxide can be solved and therefore leakage currents are reduced, also the ambipolar behavior should emerge, which has, in contrast to ambipolar OFETs, an on-state between two off-states.

5. ACKNOWLEDGMENTS

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