Electrically Stable Organic Permeable Base Transistors for Display Applications

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Vertical organic permeable base transistors (OPBT) can drive large current densities of kA cm\(^{-2}\) and achieve record-high transition frequencies of up to 40 MHz. They are therefore an interesting candidate for numerous applications, including the use in active-matrix organic light emitting display (AMOLED) backplanes. However, the transistor characteristics are required to be stable against electrical stress. Here, the threshold voltage shifts under current- and voltage-stress conditions over various temperatures and illumination conditions are investigated. OPBTs show excellent stability under the probed conditions, even at extended exposure to large on-state currents of 3 A cm\(^{-2}\). The strongest shifts are observed at elevated temperatures, suggesting a temperature activation of the stress effect. On-state current stress scales linearly with the current density, while off-state stress is induced by the applied voltage. The effects of both kinds of stress are complementary and can compensate each other. It is found that the OPBT is perfectly suitable as a switching transistor in AMOLED displays.

1. Introduction

Organic thin-film transistors (TFT) have seen a tremendous increase in their performance in recent years. Particularly in their switching speed, measured by the transition frequency, which has increased into the tens of MHz regime.[1–3] This progress has mainly been enabled by a steady improvement in the charge carrier mobility. A more direct way to increase the transition frequency is by the reduction of the channel length, which can be achieved by an adequate structuring method, is the most effective path to increasing the transition frequency.

Unfortunately, high-resolution patterning techniques operating in the nanometer regime are costly and currently incompatible with the promise of low-cost flexible electronics. Hence, new device concepts need to be conceived which allow for an ultra-short channel length in conjunction with low fabrication costs. In this regard, vertical organic transistors with a channel length of ≈100 nm have generated significant interest in recent years,[4–10] as the vertical dimensions of an organic transistor can be easily controlled over the nanometer regime. The organic permeable base transistor (OPBT) is a truly vertical device with a semiconductor thickness in the order of 100 nm. Due to the extraordinarily short channel and a reduced influence of the contact resistance,[11] the OPBT can drive very large current densities above 1 kA cm\(^{-2}\)[12] and reaches record-high transition frequencies of 40 MHz,[3] making it the fastest organic transistor to date. The transistor consists of a vertical stack of three electrodes separated by organic semiconductor layers. The outer electrodes constitute emitter and collector, while the central electrode is the base. It has native nano-sized holes, making it permeable for electrons. Current leakage into the base is prevented by a native oxide film around the electrode. In the on-state, a charge-accumulation channel at the oxide interface is formed, ensuring efficient charge transport through the base, while in the off-state the base potential hinders the charge conduction through the pinholes. Figure 1 shows a cross-sectional transmission electron microscopy (TEM) image of an OPBT with C\(_{60}\) semiconductor layers and the ultra-thin permeable base electrode of aluminum.

These advances enable a broad range of possible applications for OPBTs, including display driver circuits where high currents and fast switching are needed,[13] and radio-frequency identification (RFID) systems with MHz operation.[14,15] Real-world applications, however, require a number of other properties like integrateability, low power consumption, and stability. OPBTs operate on low voltages, generally enabling facile integration into electronic circuits. The static power consumption of OPBTs was recently dramatically reduced by the introduction of a controlled base oxidation technique.[16] Stability, though, has not yet been studied for OPBTs and there is little research regarding the behavior of short-channel vertical organic transistors under continued electrical stress.
High current operation is one of the main advantages of OPBTs, but at the same time puts the device in a strong stress condition. While extremely large current densities in the order of kA cm$^{-2}$ are only reached in pulsed operation, continuous current in OPBTs is regularly of the order of several A cm$^{-2}$. We find that the threshold voltage shifts ranging from several volts after an hour of bias-stress, though, it becomes dependent on the magnitude of the supply voltage, hindering any analytical modeling.

In this work, a suitable technical definition of the threshold voltage for short-channel vertical OPBTs was conceived and it was shown that its value can be used as an indicator for electrical stress. The threshold voltage was derived from the voltage-axis crossing using a linear fit of the transfer curve and a value was obtained that provides a basis for the evaluation of shifts in the transistor characteristics. Alternatively, a quadratic fit was investigated with qualitatively very similar results. A more detailed assessment of the $V_{th}$ definition as a figure of merit for transistor stability is given in the Supporting Information.

### 2. Experimental Section

Electrical stress conditions are applied to OPBTs in this work by setting a constant supply voltage of $V_{CE} = 1$ V between the emitter and collector electrodes and adjusting the base potential to drive the device in the high or low current regime, labeled as on- or off-stress in the following sections. Before the stress condition is applied and at set intervals during the stress test, a transfer curve is recorded by sweeping the base-emitter voltage from $-0.5$ to $1.5$ V, in order to determine the threshold voltage $V_{th}$, as can be seen on a logarithmic timescale in Figure 2a,b. Measurements are conducted with a Keithley 4200-SCS Parameter Analyzer and a custom built Peltier cryostat (Peltier element by Peltron GmbH and controller HAT Control by BelektroGmbH, Germany). The equipment is controlled and measurement data are recorded using the software SweepMe! (sweep-me.net). Figure 2c shows how the emitter current level follows the base-emitter voltage. It is large during on-stress (2 mA, corresponding to a current density of 3 A cm$^{-2}$) and more than five orders of magnitude lower during off-stress. Hence, during on-stress conditions the device is exposed to large current, potentially leading to trap-filling and/or material degradation, while the off-stress condition represents a strain solely by an electrical potential. With a layer thickness of 100 nm, the electric field strength at 1 V amounts to $0.1$ MV cm$^{-1}$ between base and emitter in the off-state. OPBTs drive a space-charge limited current through both the upper and lower semiconductor layers in the on-state. At the base electrode an accumulation channel is formed and all charge carriers pass through nanometer-sized holes in the thin aluminum film. Consequently the charge carrier density at the interface between the semiconductor and the base oxide is several orders of magnitude larger than in the bulk semicon-
It can thus be assumed that any effects of on-stress predominantly occur in the base electrode region. Effects that could be caused by the self-heating of devices under large currents are reduced by regulating the sample temperature in a Peltier cryostat during all measurements.

4. Results and Discussion

Figure 2d shows the development of the threshold voltage under on- and off-stress at room temperature. A \( V_{th} \) shift to higher voltages is observed during on-stress, while off-stress creates the opposite effect at a slightly reduced magnitude. The shift is small for short stress intervals and increases monotonically with stress duration. For each data point the stress condition is interrupted to record a transfer curve and to evaluate \( V_{th} \). Since the transfer curve measurement involves brief on- and off-state conditions, it can be assumed that the measurement partly levels the stress effect for short stress times leading to a stable \( V_{th} \) value at the beginning of the measurement. At longer uninterrupted stress times, the stress effect is too large for the transfer curve measurement to fully recover the device. In order to understand the threshold voltage shifts during on- and off-stress, a more detailed look should be taken at the evolution of transfer curves, as shown in Figure 3. While a clear shift of the threshold voltage position can be observed in either case (toward higher voltages with on-stress and toward lower voltages with off-stress), there is a decisive difference in the sub-threshold behavior of the curves. Off-stress shifts the entire transfer curve, leaving the sub-threshold slope and the on-current level unchanged. Conversely, with on-stress the sub-threshold curve shifts only for the very first data-point. The later shift in \( V_{th} \) is then caused by a decrease of the on-current and the steepness of the slope. Even though this behavior might indicate a destructive degradation, the experiment proves that is reversible, since the sample returns to its original on-current level after a period of rest or off-stress. In the insets in Figure 3a,b, the threshold voltage positions are marked on a section of the transfer curve using a linear plot. It can be clearly seen how the turn-on point of the device shifts to higher voltages and lower currents under on-stress and undergoes the opposite development under off-stress. In many realistic cases, a different behavior is observed.
application scenarios, for example in an oscillator circuit with a duty cycle of 50%, on-stress situations occur alternately with longer times of off-stress. In such an application the on- and off-stress effects in an OPBT may cancel each other out, leading to a particularly stable device operation.

Stress mechanisms in organic transistors may be temperature activated, hence it is of interest to investigate stress effect at various temperatures. Figure 4 shows the threshold voltage shifts measured at room temperature and at 30 K above and below room temperature under the same measurement conditions as detailed above. At low temperatures, hardly any stress effect can be seen, suggesting that both the on- and off-stress are in some way temperature activated. This is different for higher temperatures though, since off-stress effects are very similar for room temperature and for 54 °C, while on-stress is significantly increased in magnitude.

It has to be underlined that the temperature activation of the on-stress is not due to an increase in the on-stress current at the elevated temperature. In contrast, the stress-current observed at 54 °C is not significantly larger than at room temperature. Figure 5 provides the threshold voltage shift data after 1 h for different stress current levels. The on-stress effect scales perfectly linearly with the stress current, indicating that the dominating physical origin of the on-stress effect is the current driven through the device, while the inverse off-stress effect is caused by a potential applied to the transistor without significant current flow. This result also means that an OPBT that is used in an application with lower on-current densities, will experience a proportionally reduced threshold voltage shift.

Threshold voltage shifts can become problematic in an electronic circuit, since the transistor’s response to an input signal is altered. This problem is detrimental to the commercialization of organic thin-film transistors, as well as amorphous

![Figure 3](image_url) Evolution of transfer curves under extended a) on-stress and b) off-stress. The on-stress in sub-figure a) corresponds to a current of 2 mA (3 mA cm⁻²). Even after a cumulative stress time of several hours, the V₉₀ shift does not exceed 150 mV.

![Figure 4](image_url) Threshold voltage shift under on- and off-stress at temperatures varied from –6 to 54 °C. At low temperatures, V₉₀ is stable with marginal changes below 50 mV. Elevated temperatures activate a larger on-stress.

![Figure 5](image_url) The threshold voltage shift after 1 h of stress with dependence on the stress current. The stress effect scales linearly with the applied current.
silicon devices. Inorganic oxide transistors, that are commonly used in inorganic active matrix displays, and microcrystalline silicon devices exhibit comparably low threshold voltage shifts of 50 to 100 mV after 1 h at 50 °C.[25] While the shifts in OPBTs are slightly larger than that at a high temperature, we find that they show excellent stability at room temperature or in applications that operate with a reduced duty-cycle.

An important example application with a short duty-cycle is the switching transistor in an activate matrix display backplane. There, a transistor has to drive a very high current during a short pixel-addressing time, typically below 1 µs, in order to program the desired brightness information onto the storage capacitor. The $V_{th}$ stability is highly significant, because the current level at a given voltage relates to the pixel brightness. In a display, additionally to current and temperature, intense illumination is present as a third stress source. 

Figure 6 shows the behavior of OPBTs under stress with additional very strong illumination by white light (1.5 kW m$^{-2}$), which is comfortably above the levels reached even in bright displays or OLED lighting applications. The changes in $V_{th}$ are almost identical both with and without illumination, but at a slightly different absolute level. This apparent deviation in threshold voltage can be regarded as an artifact related to a change in the form of the transfer curve, as can be seen in the insets of Figure 6. It originates from an increase in the off-current at a current level approximately two orders of magnitude below the on-current and is related to the charge carrier generation by absorption of interface states. The form and magnitude of the threshold voltage shift, though, are not affected by illumination.

The fact that the threshold voltage shift is not changed under illumination gives some insight into the physical origin of the stress effect. If the main reason for threshold voltage shifts with on-stress was the filling of trap states, the off-stress shift would be expected to be reduced under illumination, because the trapped charge carriers would absorb photons and be released from the traps. Another possible reason for the observed threshold voltage shifts is some form of electromigration in the device, as observed in OFETs by Bobbert et al.[26] Such a process would not be influenced by illumination and would thus be in agreement with our observation. Migrating moieties may be ions from residual water molecules in the device. These are inevitably present in OPBTs, because the devices have to be exposed to an oxidizing agent in order to form the native base oxide layer. This explanation is in line with our finding that no stress-effect can be observed at a temperature below the freezing point of water, as was previously proposed by Kettner et al.[27]

5. Conclusion and Outlook

We investigate the stability of vertical short-channel organic permeable base transistors and find competing effects of on-stress and off-stress on the threshold voltage of the device. $V_{th}$ shifts are below 100 mV for extended stress-times of several hours and can be reverted by opposite stress. The stability of the device at room temperature is comparable that of inorganic oxide-TFTs and microcrystalline silicone devices.

The effect of the on-stress is found to be significantly temperature activated and the threshold-voltage shift does not change under strong illumination. These observations hint toward an electromigration process as the source of the stress effect. Consequently, mitigation of electromigration can further enhance stability of the OPBT. The critical layers in the device are the base electrode and its oxide, as very high current densities in the base region are expected to be responsible for the on-stress effect. Hence, a hydrophobic treatment of the central base electrode is a promising path for future research.[28]

Since OPBTs, in comparison to other organic transistors, can drive very large current densities, have excellent on-/off-ratio and achieve short switching times, they are ideal candidates for use in organic display backplanes. Excellent stability during short-term on-stress and under strong illumination, comparable to devices already used in display industry, further highlights their suitability for this application.
Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
Dr. Axel Fischer is founder of “Axel Fischer und Felix Kaschura GbR” that provides the measurement software mentioned in this work.

Keywords
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