High Performance Organic Transistors

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ABSTRACT

We summarize recent progress on vertical organic transistors, allowing nanometer channels controlled by layer thickness. We have achieved devices with the highest operation speed for organics. Vertical organic transistors with two independent control electrodes allow to easily tune the threshold voltages, of key importance for applications such as display driving.

1 INTRODUCTION

Organic field-effect transistors (OFET) [1, 2] have so far not achieved major commercial impact, despite their many attractive properties such as low-cost, low-temperature processing, and flexibility, which would be especially useful for display applications. The key problems are low operating speed [3, 4], stability, and manufacturing issues.

In the past few years, we have undertaken several steps to improve organic transistors. One key approach is to introduce controlled electrical doping into OFET structures, allowing better injection and novel operation principles such as inversion operation [5].

Furthermore, we realize vertical transistor structures [6-8] which have very short channel length without micropatterning. These structures allow much higher current densities than the lateral OFET despite rather simple processing technology. These devices are e.g. well suited to drive organic light emitting diodes (OLED), allowing all-organic flexible OLED displays.

Recently, we have achieved current densities as high as kA/cm^2 [9] which will allow to use these devices for applications where higher power is required, such as bright OLED displays.

These devices also show very interesting nonlinear properties such as negative differential resistance (NDR) due to the heating-induced improvement of mobility [10]. They have also shown record operating frequencies for organic transistors, above 40 MHz [11]. Recent studies prove excellent stability, sufficient for broad applications [12].

Finally, we will discuss dual-base transistors which will enable high operation frequency as well as adjustable device characteristics (i.e. threshold voltage). Organic transistors with two independent control electrodes are perfectly suited to realize complex logic circuits while keeping the main benefit of vertical transistors devices, namely the high switching frequency.

2 EXPERIMENT

Important figures of vertical organic transistors we have developed will be introduced in this section, such as current densities, S-NDR properties, operating frequencies, and electrical stabilities. Finally, a new device concept of dual-base vertical organic transistors is presented.

2.1 Towards kA/cm^2

We present here vertical organic permeable base transistors (OPBT using a metal grid as base contact. In Ref. [9], we have realized c_{60} based vertical devices using a base electrode which spontanously foms a grid when annealed.. As seen in Fig. 1a, at collector-emitter voltage (V_{CE}) of 7 V, we achieve current densities above 1 kA/cm^2, which is a performance beyond what has so far been possible using organic semiconductors, despite extremely simple processing without any high-resolution structuring [9].

At a current density j of 40 A/cm^2 and a V_{CE} of about 3.6 V, the transistors amplifies signals up to 11.8 MHz (cf. Fig. 1b). The frequency-current dependence predicts a f_T in the range of 100 MHz if a current density of 1 kA/cm^2 would be applied. However, the f_T-measurement is limited to current densities the device can withstand at steady-state conditions.

The performance can even be further enhanced when the latest achievements for lateral field-effect mobilities can be transferred to vertical bulk mobilities. Thus, in future even much better vertical organic transistors could be realized with our approach.

2.2 S-shaped NDR (S-NDR)

As mentioned above, our transistors can be driven at very high current densities at which effects can be observed which usually do not occur in other organic transistors. One of these effects is the Joule heating of the devices during operation at high current densities, leading to bistable IV-curves. Joule heating leads to an increasing device temperature during operation and be easily observed, e.g., by a thermal camera (cf. Fig. 2a). However, as we will see, the temperature increase is highly dynamic during a measurement and it can severely affect important transistor performance parameters such as frequency, which is usually thought to be a static property [10].

The effect of self-heating can be seen in Fig. 2b where output characteristics of the transistors are shown for various base-emitter voltage. At moderate base-emitter voltage (V_{BE}), the heating effect is small and the device reaches a static temperature during a current-voltage measurement at each point (the power is sufficiently dissipated). At high V_{BE}, the heating dissipation via the substrate limits the heat flow and the device starts to show the self-heating effect. The self-heating causes the current and device temperature to run away for a fixed voltage, which manifests itself in a so-called S-shaped NDR. A more detailed view on the self-heating also describing the dynamics of heating is given by Fischer et al. [13, 14].

2.3 Enabling speeds of 40 MHz

Kheradmand-Boroujeni and co-workers measured the small- and large-signal properties of high-performance organic transistors reported by Klinger et al. [9] almost free of bias-stress and self-heating. As can be seen in Fig. 3, a new speed record for the operation of organic transistors of 40 MHz was reached, more than 10 MHz above the previous record [11].

In general, intrinsic gain decreases with scaling down the channel length. However, our transistors provide a good gain of 35 dB at low currents and a fairly acceptable gain of 16 dB at the f_T = 40 MHz bias point, i.e. 200 mA, with a short physical L = 200 nm. With intrinsic gain of 16 dB, one can make an amplifier with a gain of 10 dB per stage by means of the bootstrapping technique [15].

2.4 Electrical stability

The huge potential for our transistors to be used in high-power and high-frequency applications has very recently been underlined by Dollinger et al. reporting for the first time on the electrical stability under high-power stress conditions [12].

As shown in Fig. 4, even at a continuous current stress for 10^4 s, the threshold voltage shift remain below 100 mV. Only at elevated temperature, a stronger thermal activation of the stress has been observed. However, in any case, the threshold voltage shift under stress is found to be reversible when the device is switched from on- to off-state or vice versa.

2.5 Dual-base transistors

The main advantage of organic transistors with dual gates/bases is that the threshold voltage can be set as a function of the applied second gate/base bias, which is crucial for the application in logic gates and integrated circuits. Based on this transistor structure, we have now succeeded in realizing such novel devices [16].

The vertical organic transistors with two independent control electrodes are characterized by a high switching frequency (a few nanoseconds) and an adjustable threshold voltage (cf. Fig. 5). Based on these developments, even single transistors can be used to represent different logical states (AND, NOT, NAND). Furthermore, the adjustable threshold voltage ensures signal integrity and low power consumption.

3 CONCLUSIONS

In conclusion, we have shown that vertical organic transistors can provide excellent parameters. In particular due to the short channels of a few hundred nm, higher operation frequencies become possible. In the future, these transistors could make it possible to realize even sophisticated electronic functions or high-resolution flexible displays completely with organic components.

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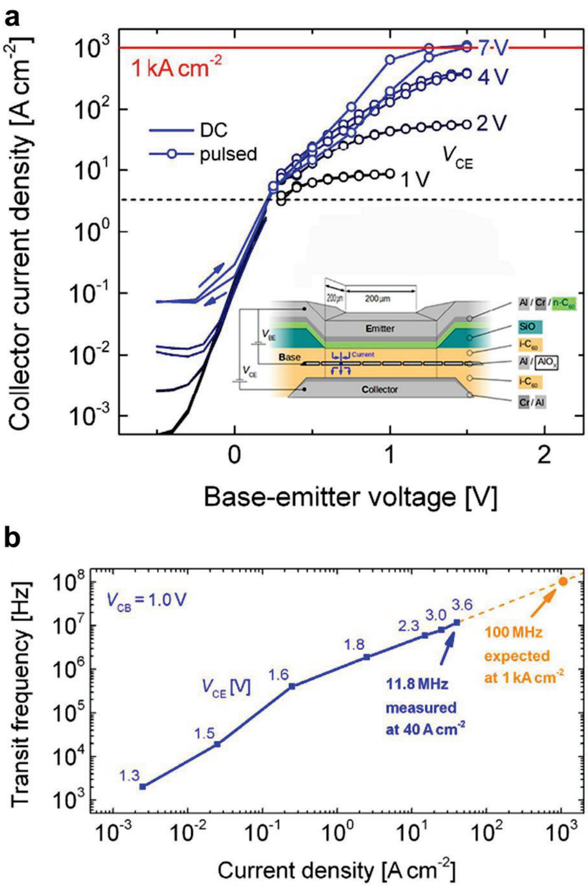

Fig. 1. a) Transfer curves of a device measured at different operation voltages V_{CE}. Applying a V_{CE} of 7 V leads to current densities in excess of 1 kA/cm^2 (red line). Inset: Device cross-section and electric circuit in common-emitter configuration. b) Transfer measured transit frequencies f_T at different current densities. A f_T up to 11.8 MHz is reached at a current density of 40 A/cm^2. [9]

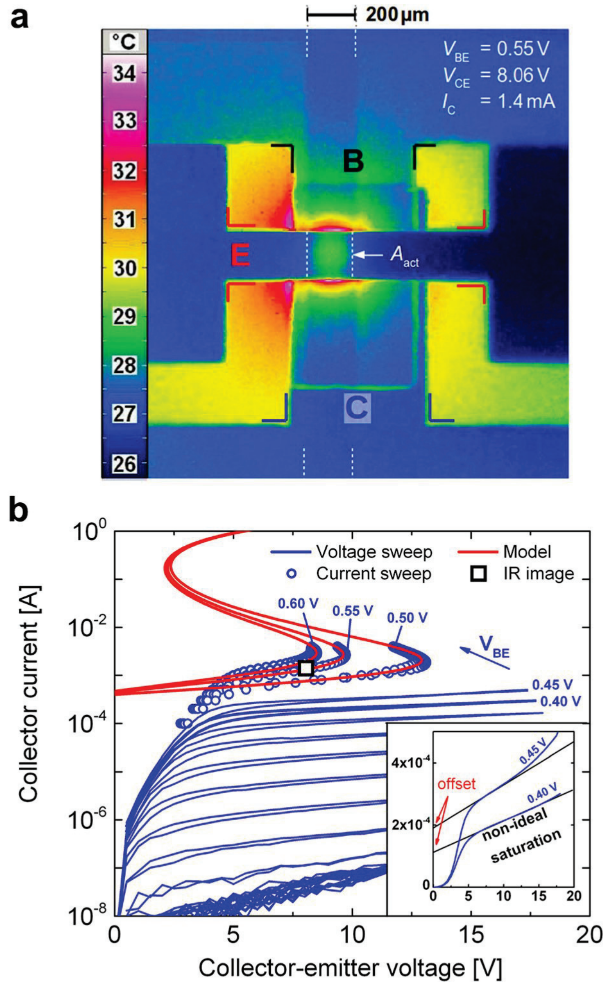

Fig. 2. a) The thermal imaging during the S-NDR measurement confirms the increased temperature in the active area A_{act} of the device. b) Output characteristic of a transistor revealing S-NDR behavior. At low base-emitter voltages, a voltage sweep (blue lines) is used. In order to stabilize the NDR at base-emitter voltages starting from V_{BE} = 0.5 V, a current controlled measurement (blue circles) is used. The model (red lines), assuming an Arrhenius-like temperature activation of the conductivity, leads to a reasonable agreement with the experimental data. The black squared point indicates where the thermal image is taken. Inset: The transistor shows a nonideal saturation behavior. It can be described by a linear curve with an additional offset. [10]

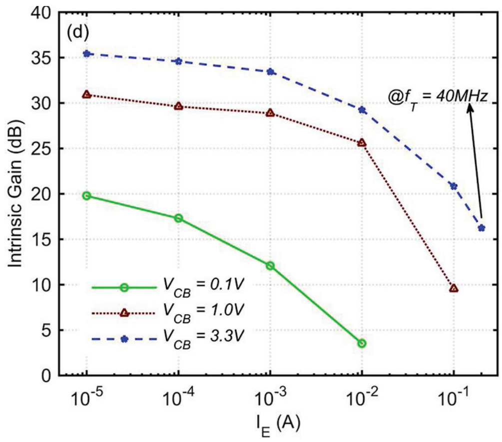

Fig. 3. Transfer intrinsic voltage gain versus pulse-biased emitter current for devices. [11]

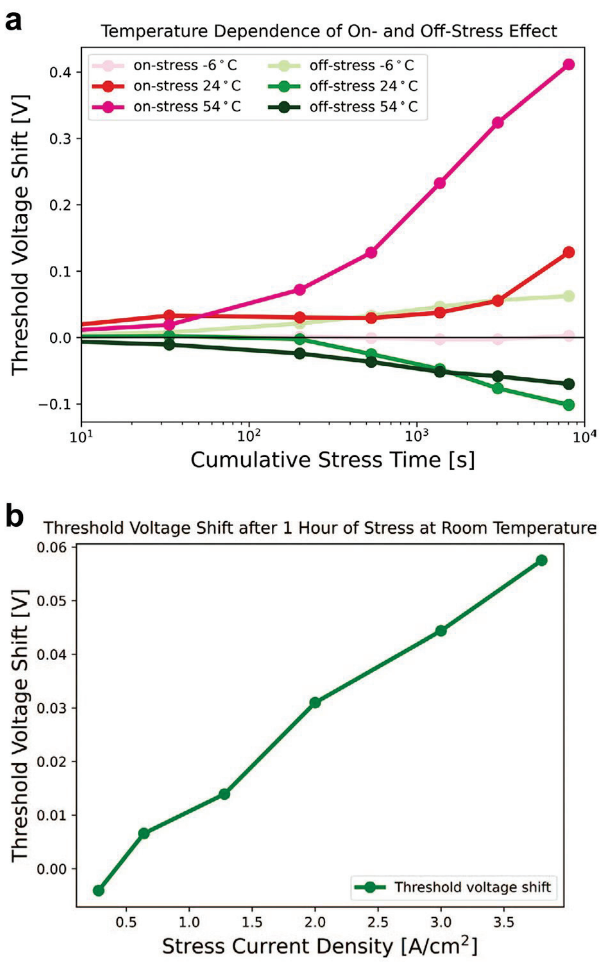

Fig. 4. a) Threshold voltage shift under on- and off-stress at temperatures varied from −6 to 54 °C. At low temperatures, the threshold voltage is stable with marginal changes below 50 mV. Elevated temperatures activate a larger off stress. b) The threshold voltage shift after 1 h of stress with dependence on the stress current. The stress effect scales linearly with the applied current. [12]

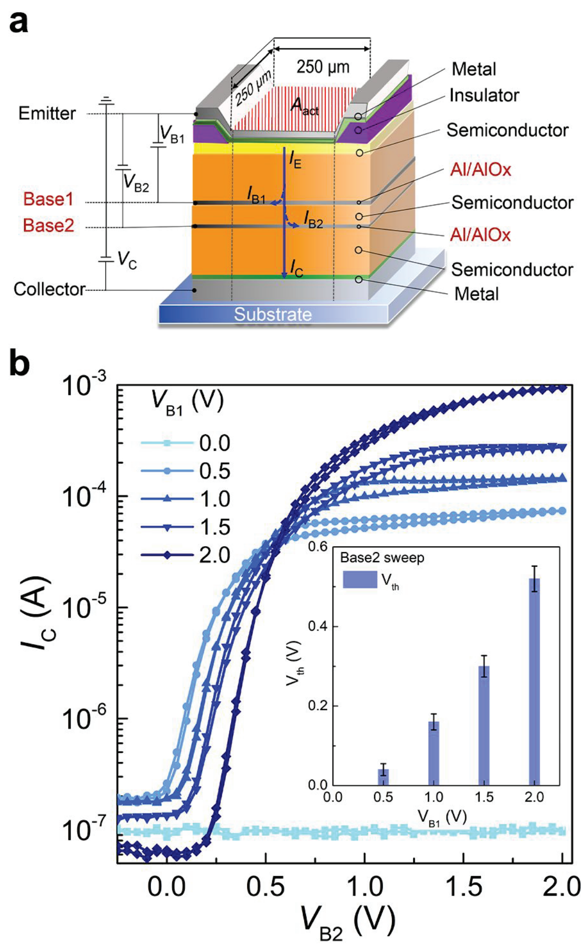

Fig. 5. a) Structure schematic view of a dual-base organic transistors measured using common-emitter configuration. b) Transfer curves as a function of base2-emitter voltage (V_{B2}) at different base1-emitter voltage (V_{B1}) of 0, 0.5, 1.0, 1.5 and 2.0 V, respectively. Inset: Threshold voltage shifts. The threshold voltages are dependent on the base1 bias during base2 sweep, error bars indicate the slight device-to-device variations measured over 61 devices. [16]