High Performance Organic Transistors based on Organic Doping

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Organic transistors hold the promise of enabling the field of flexible electronics. However, despite significant progress in the past [1], the performance and reliability of organic transistors has to be improved further to turn the dream of flexible electronics into reality and to make applications such as smart textiles, flexible displays, or RFID tags commercially available.

Two approaches to make organic transistors more reliable and to improve their performance are discussed here: *doping* and *vertical organic transistors*.

1. Doping Organic Transistors: Depletion and Inversion FETs

Doping of organic semiconductors led to several breakthroughs in the design of highly efficient optoelectronic devices such as OLEDs and organic solar cells [2]. As for inorganic semiconductors, a small percentage of an impurity is added to the matrix material. If the LUMO of the impurity is below the HOMO of the matrix, an electron is transferred from matrix to dopant generating a free hole on the matrix. (p-doping). On the other hand, if the HOMO of the impurity is above the LUMO of the matrix material, an electron is transferred to the matrix (n-doping). In effect, the density of free charge carriers is increased and, depending on the doping concentration, the conductivity of the matrix material rises by several orders of magnitude (cf. **Fig. 1**).

Doping has mainly been studied for their use in organic LEDs or organic solar cells. In particular p-doping of MeO-TPD[1] with the acceptor type molecules F6-TCNNQ[2] and $C_{60}F_{36}$ was studied in detail, e.g. by Ultraviolet Photoelectron Spectroscopy (UPS) [3,4]. By UPS, the energetic distance between the Fermi-Level in the matrix material and the corresponding HOMO density of states is determined. As expected from classical semiconductor theory, the Fermi-Level shifts towards the HOMO level upon doping (cf. **Fig. 2**). However, the steep increase visible in **Fig. 2** cannot be explained by the standard theory developed for inorganic semiconductors and it turns out that trap states have to be included in the model. At low doping concentrations, the Fermi-Level is pinned at these trap states. Only once the trap states are completely filled, the Fermi-Level moves past the trap states and free holes are generated.

[1] N,N,N',N'-tetrakis(4-Methoxy-phenyl)benzidine
[2] 2,2'-(perfluoronaphthalene-2,6-diylidene)dimalononitrile

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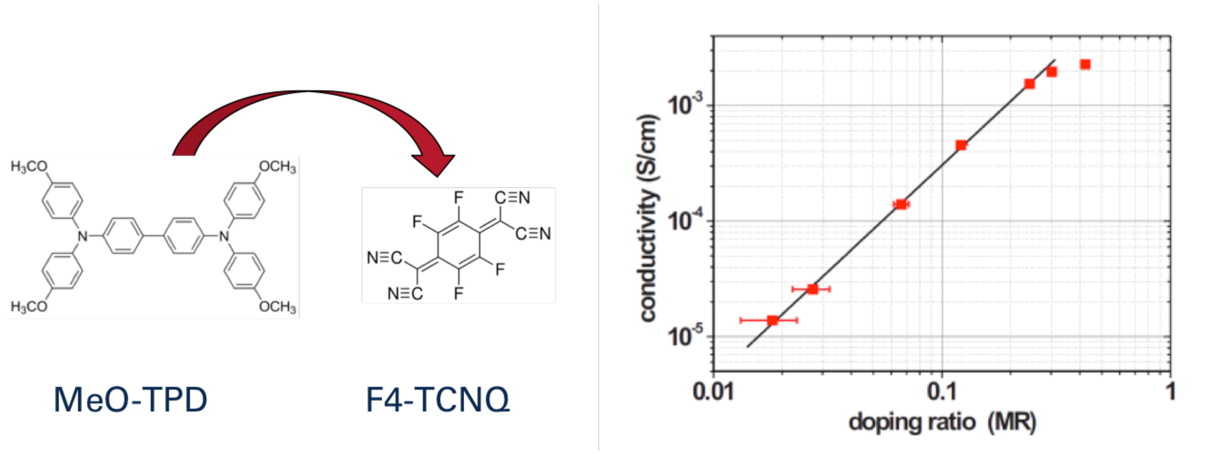

Fig. 1: Molecular Doping. Impurities are added to the organic matrix material to generate free charge carriers. For p-doping, strong electron acceptors (such as F4-TCNQ) are used, which attract an electron from the matrix (MeO-TPD) and generate a free hole. In effect, the conductivity of the doped layer increases with doping concentration.

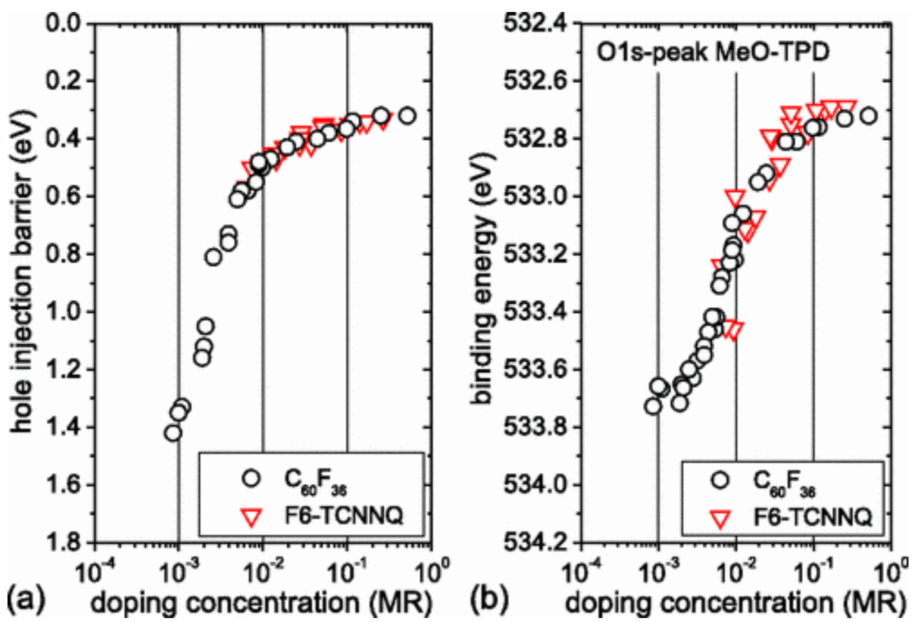

Fig. 2: Doping induced shift of the Fermi-Level. Part (a) shows a representative example of a doping induced Fermi-Level shift using the standard combination MeO-TPD doped by F_6TCNNQ or $C_{60}F_{36}$ as p-dopants. In part (b) the shift of the O1s core level is shown for comparison. Reprinted with permission of the American Physical Society from [4].

Doping can be used to control the threshold voltage of organic FETs [7] and to reduce gate-bias stress effects [8]. The setup of these devices is shown in Fig. 3a. The transistors consist of pentacene as organic semiconductor, which can be p-doped by the dopant F6-TCNNQ and n-doped by the dopant $W_2(hpp)_4$[3]. To ensure optimized injection at the source and drain contacts, the contact area is highly p-doped. In the channel region, only a very thin layer of pentacene is lightly doped (2-8nm). In effect, these structures are depletion (using p-doping in the channel) and inversion (using n-doping) transistors.

If the doped channel layer is kept thin, the transistors behave almost identical to intrinsic transistors but with a shifted threshold voltage (cf. **Fig. 3** (b) and (c)). Whereas p-doping shifts the transfer characteristic to positive voltages, n-doping shifts the characteristic to more negative values.

(a)

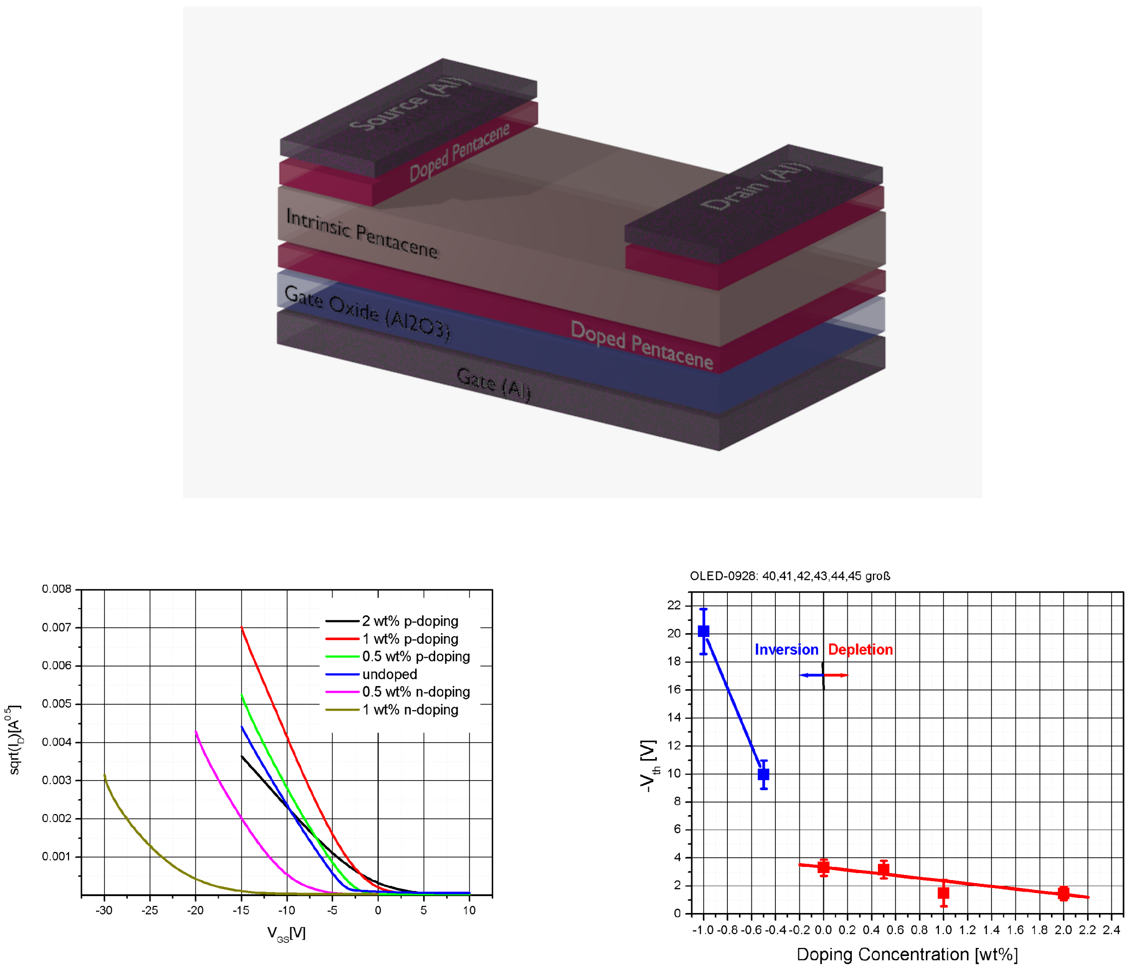

Fig 3: Doped organic transistors. Part (a) shows the setup of the doped transistors discussed here. A thin doped layer is added close to the organic/oxide interface. The doped layer shifts the threshold voltage of the transistors ((b) and (c)).

[3] tetrakis(1,3,4,6,7,8-hexahydro-2H-pyrimido[1,2-a]pyrimidinato)ditungsten (II)

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Furthermore, besides providing a possibility to fine tune the threshold voltage of organic transistors, p-doped organic transistors show a significantly improved stability. As shown recently [8], doping is a promising tool to reduce gate bias stress effect. Whereas in p-doped transistors gate bias stress effects are reduced by an order of magnitude, n-doping leads to a worsening of the gate bias stress behaviour.

2. Vertical Organic Transistors

Doping can be used to control and stabilize transistor behaviour. To improve the performance of organic transistors as well, a second concept can be used: *vertical organic transistors.*

The transit frequency f_T of organic transistors can be approximated by

$$f_T \approx \frac{\mu_{eff}(V_{GS}-V_{th})}{2\pi L} \qquad \textbf{(Eq. 1)}$$

with μ_{eff}: the effective mobility of the organic semiconductor and L the channel length. **Eq. 1** shows that the transit frequency is limited by the low mobility usually observed in organic semiconductors.

However, as seen in **Eq. 1** as well, the speed of the transistors can alternatively be increased by scaling down the channel length. To keep the cost advantage of organic electronics, cost intensive structuring techniques have to be avoided and novel structuring techniques for scaling the channel length have to be found.

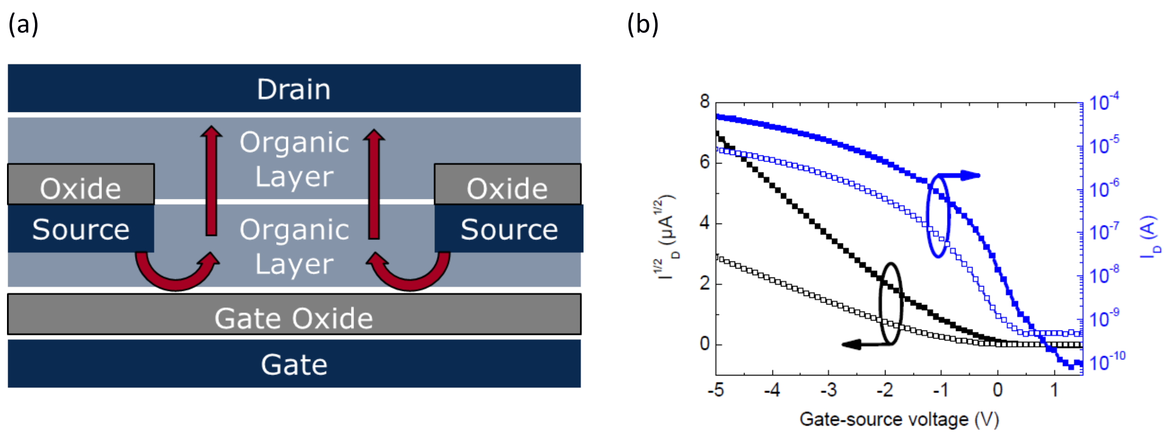

Fig 4: Vertical Organic Transistors. In vertical transistors the channel length is defined by the thickness of the organic layers and can be easily scaled into the sub-100nm regime (a). The saturation current increases by an order of magnitude compared to conventional transistors ((b), open symbols correspond to horizontal transistors, filled symbols to the vertical transistor) [10].

In vertical transistors the normal arrangement of source, drain and gate contacts is rotated by 90°. Thus, the transistor channel is built in vertical direction and the channel length is defined by the layer thickness, which can thus be controlled with nanometer precision.

One example of a vertical field effect transistor is shown in **Fig.4**. The drain contact is structured above the source contact, i.e. the channel length is given by the thickness of the second organic layer.

Both, n-type and p-type vertical OFETs have been realized [10], showing significant performance improvement in comparison to the classical horizontal OFET. The p-type vertical transistors boosts the saturation current by one order of magnitude, which relates to a 10 fold increase in the transconductance of the devices and should facilitate an increase in the transit frequency.

3. Summary

Novel device concepts have to be found to facilitate further growth in the field of organic transistors. Two examples are presented here: Organic depletion/inversion transistors and vertical transistor concepts. Both technologies improve the classical organic transistor technology in stability and/or performance.

In particular the depletion/inversion transistors show that molecular doping can become a key technology in the design of improved organic transistors and present a rewarding and challenging field for further studies.

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