Ambipolar Organic Field Effect Transistors

Transistors that are able to conduct both electrons and holes

Introduction

Complementary technology

Both n-type and p-type transistors

- low power dissipation
- good noise margins
- high operational stability

Two possible ways:

- connection of separate n- and p-type transistors
- ambipolar transport in a single transistor

Operation Principle

Unipolar Transistor NMOS

V_D

V_G NMOS

V_S

$\mathbf{V_{GS} > V_{TN}}$ → **ON**

$\mathbf{V_{DS} < V_{GS} - V_{TN}}$ → **LINEAR**

$\mathbf{V_{DS} > V_{GS} - V_{TN}}$ → **SATURATION**

A unipolar channel of electron is formed when the gate voltage becomes more positive than the terminal with the lowest voltage of almost one threshold voltage $\mathbf{V_{TN}}$

Operation Principle (cont'd)

Ambipolar Transistor

V_D

V_G

V_S

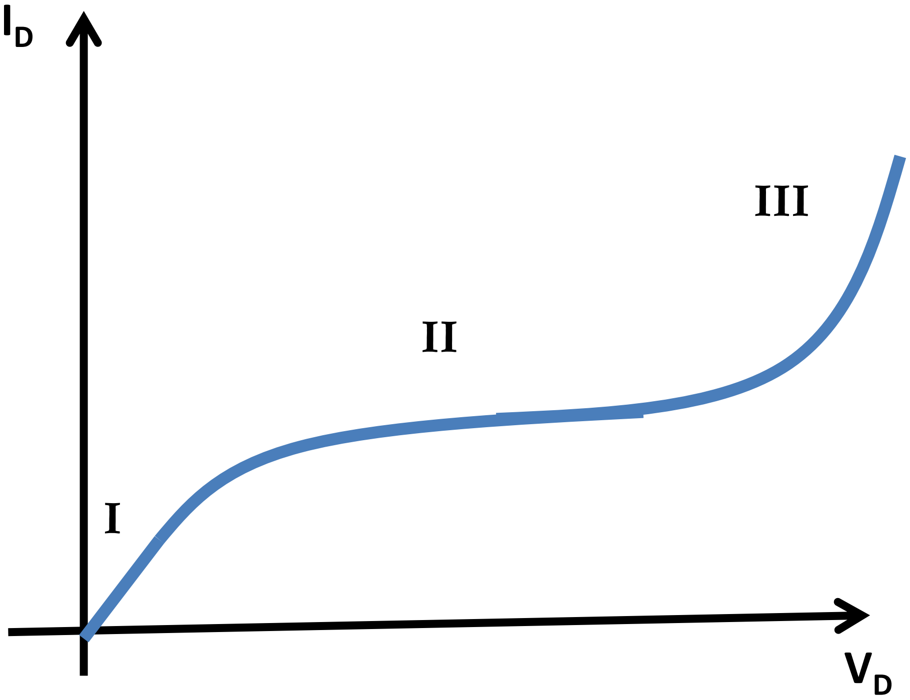
$V_G > V_S + V_{TN}$ → n–channel formed

$V_D > V_G + |V_{TP}|$ → p–channel formed

In an ambipolar transistor two different channels can be formed:

- an n-channel is formed when the gate voltage become greater of the source voltage of at least one threshold voltage **V_{TN}**
- A p-channel is formed when the drain voltage become greater of the gate voltage of at least one threshold voltage **V_{TP}**

Output characteristic



$V_G > V_{TN}$

$V_G - V_{TN} < V_D < V_G - V_{TP}$

$V_D < V_G - V_{TN} < V_G - V_{TP}$

$V_D > V_G - V_{TP}$

I – TRIODE

II – SATURATION

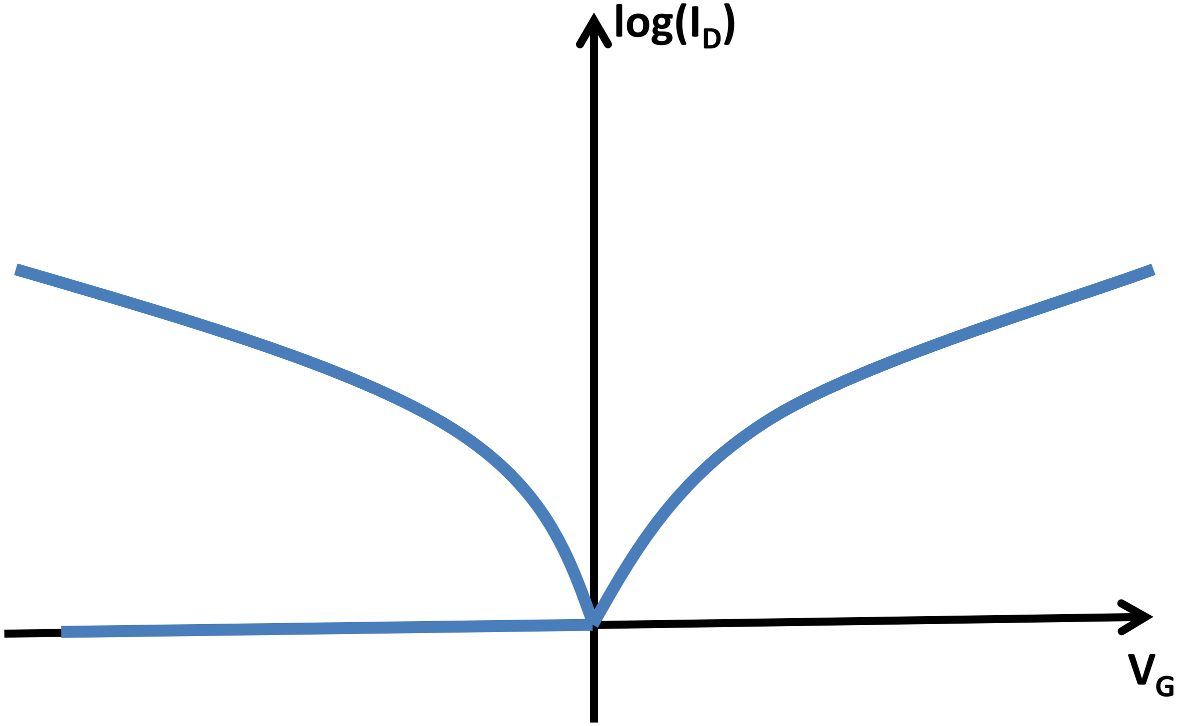
III – AMBIPOLAR

$$I_D = \frac{W}{L} \cdot C_G \cdot \mu_n \cdot V_D \cdot \left(V_G - V_{TN} - \frac{V_D}{2}\right)$$

$$I_D = \frac{W}{2L} \cdot C_G \cdot \mu_n \cdot (V_G - V_{TN})^2$$

$$I_D = \frac{W}{2L} \cdot C_G \cdot \left(\underbrace{\mu_n \cdot (V_G - V_{TN})^2}_{\text{electrons current}} + \underbrace{\mu_p \cdot (V_D - (V_G - V_{TP}))^2}_{\text{holes current}}\right)$$

Transfer characteristic



A unipolar NMOS transistor operates only when Vg > 0

Ambipolar tranistor conducts for every value of Vg. When Vg < 0 a p-channel is formed as soon as the voltage drop V_{DG} exceeds a threshold voltage V_{TP}. The current in this region is equal to:

$$I_D = \frac{W}{2L} \cdot C_G \cdot \mu_p \cdot (V_D - (V_G - V_{TP}))^2$$

Carrier Injection

To realize an ambipolar transistor we must be able to efficiently inject both electrons and holes

Organic transistors (OFET) are not intrinsically defined as n- or p- type. The dominant carriers inside an OFET are the one that are injected more easily by the electrodes.

Optimal hole injection happens if the work function of the metal electrode lines up with the highest occupied molecular orbital (HOMO) level of the semiconductor, whereas for efficient electron injection, the work function of the metal should be close to the lowest unoccupied molecular orbital (LUMO) level.

Realize an ambipolar transistor

i) single layers architectures with **asymmetric source and drain** electrodes, with high and low work function respectively in order to allow both kind of charge carriers injection within the channel

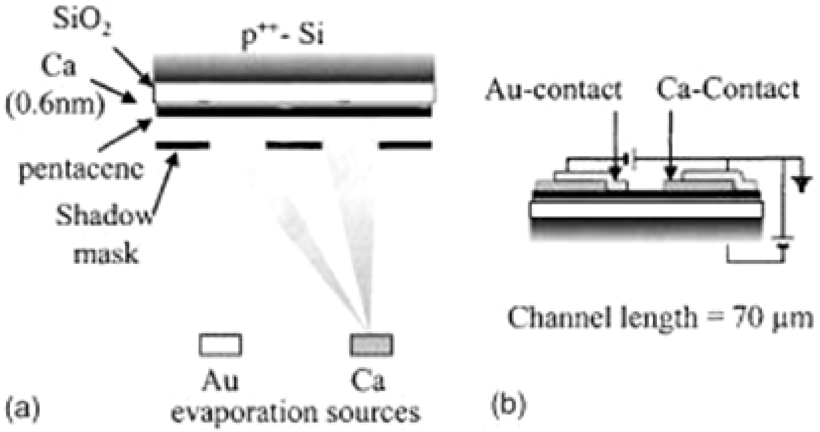
ii) single layer architectures with **low band-gap** organic semiconductors in order to have lower injection barriers for both kind of charge carriers

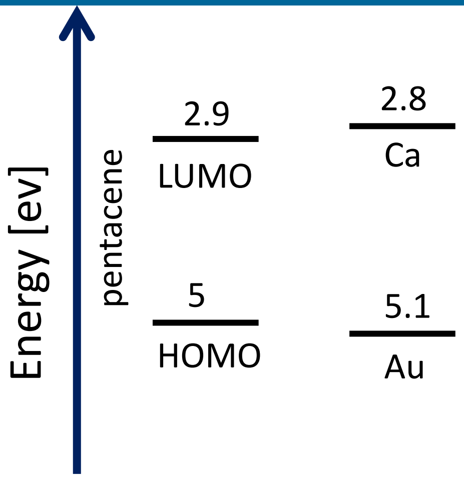
iii) double layer structures, with **planar heterojunctions** of two different organic small molecules

iv) single layer structures with **co-deposited** organic **small molecules**

v) single layer structures of solution-processable **blends** of two different **polymers**

Asymmetric source and drain





Energy [ev]

pentacene

2.9
LUMO

5
HOMO

2.8
Ca

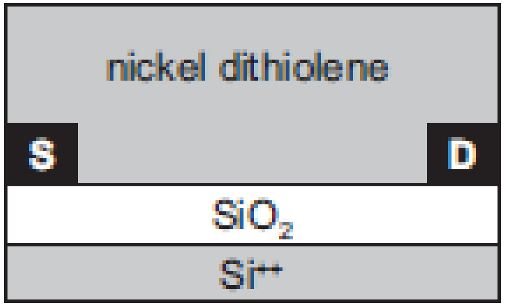
5.1
Au

The work function of Ca (2.8 eV) is well adapted to the lowest unoccupied molecular orbital (LUMO) of pentacene (2.9 eV), allowing for a good electron injection. The work function of Au (5.1 eV) fits the highest occupied molecular orbital (HOMO) of pentacene (5.0 eV).

An Ohmic-like contact was realized for both electrons and holes.

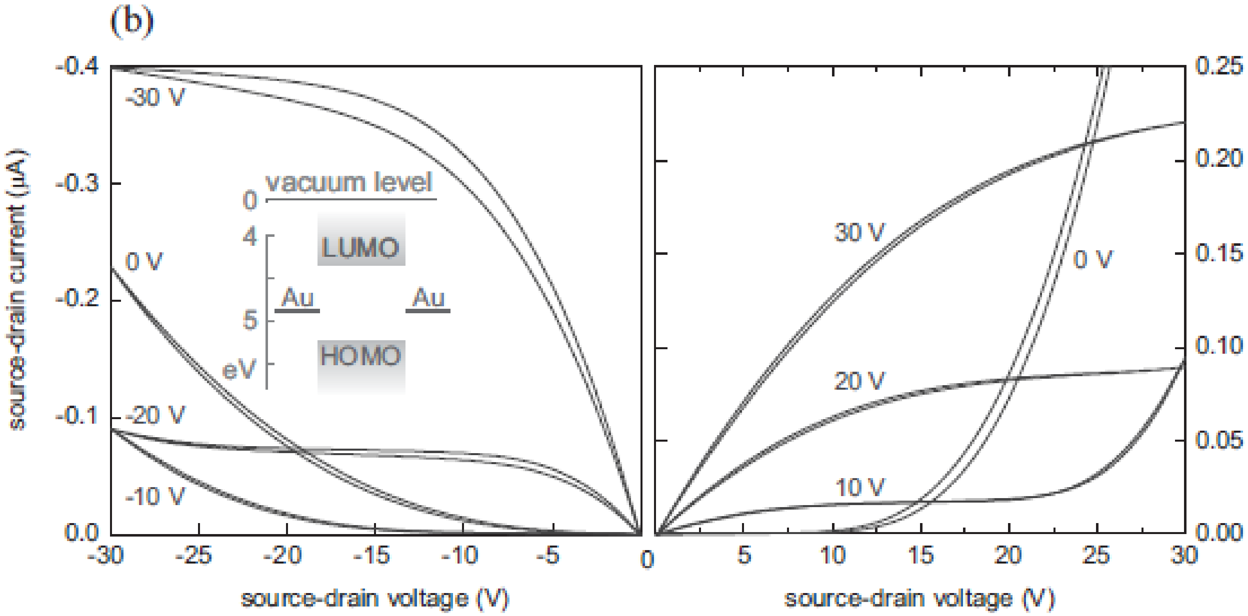
A pentacene ambipolar transistor: Experiment and theory, Schmechel, Roland and Ahles, Marcus and von Seggern, Heinz, Journal of Applied Physics, 98, 084511 (2005)

Low band-gap semiconductors



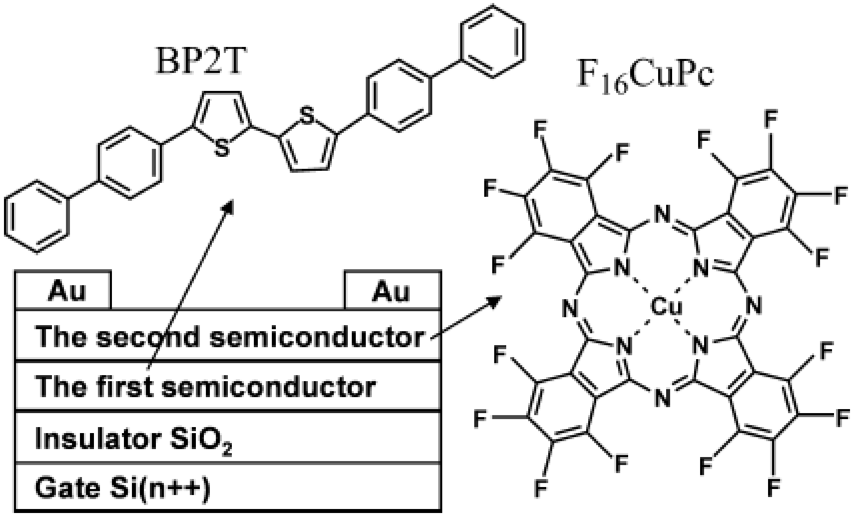
Nickel dithiolene has a bandgap of only 0.9 eV with the HOMO – LUMO levels at 5.2 and 4.3 ev. Using **Au** for electrodes (work function 5.1 eV) we are able to realize an ambipolar transistor.

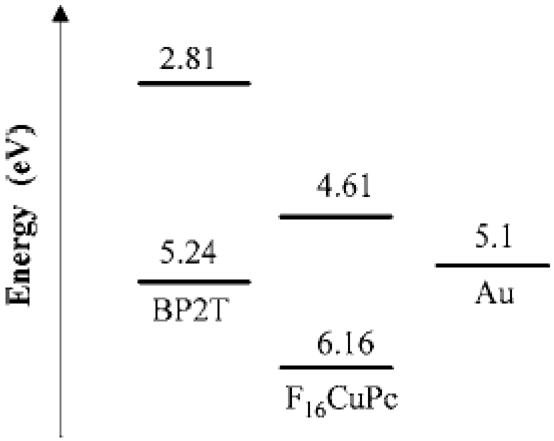
Nickel dithiolene is also higly stable in air so as measurements were performed under ambient conditions.



Anthopoulos, T. D., Setayesh, S., Smits, E., Colle, M., Cantatore, E., de Boer, B., Blom, P. W. M. and de Leeuw, D. M. (2006), Air-Stable Complementary-like Circuits Based on Organic Ambipolar Transistors. Adv. Mater.

Planar heterojunctions

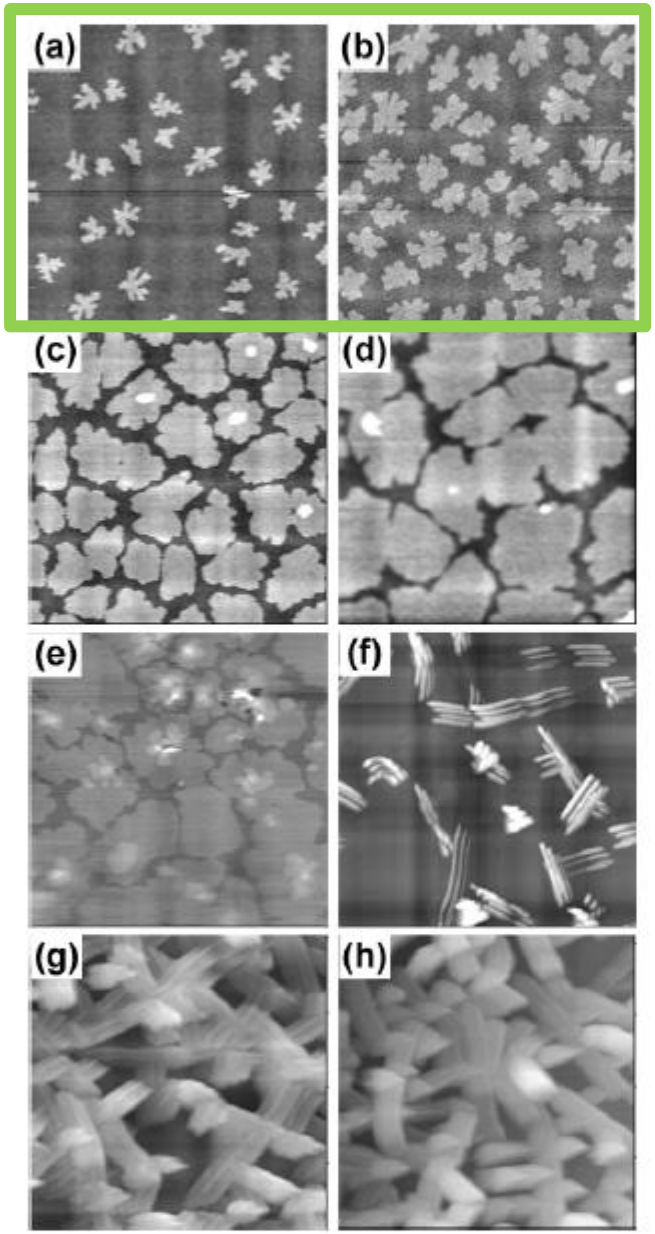




An ambipolar device could be realized also using at the same time two different semiconductors. In the Figure above a planar heterejunction of two different semiconductors was shown, one that shows good n-type ($F_{16}CuPc$) behavior and the other with good p-type (BP2T) performances. The behavior of the device for different BP2T thicknesses while keeping the $F_{16}CuPc$ thickness costant was analyzed.

Shi, J. W., Wang, H. B., Song, D., Tian, H. K., Geng, Y. H. and Yan, D. H. (2007), n-Channel, Ambipolar, and p-Channel Organic Heterojunction Transistors Fabricated with Various Film Morphologies. Adv. Funct. Mater

Planar heterojunctions (cont'd)

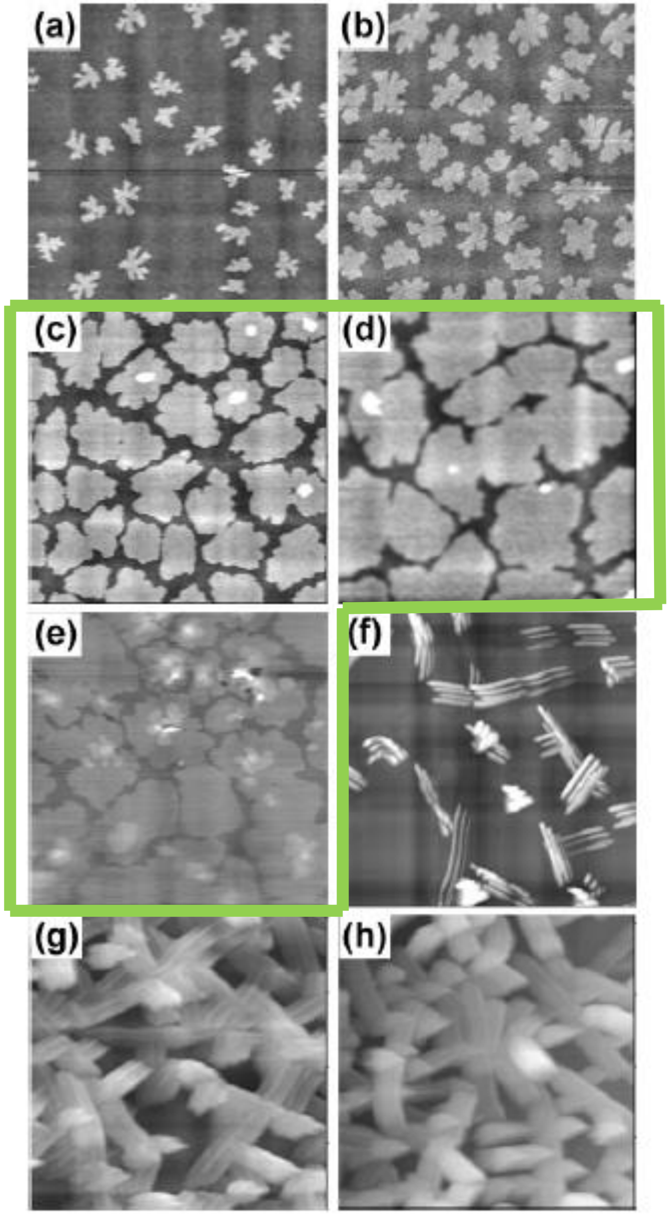


The BP2T films showed three morphology types:

- discontinuous islands (Fig. 4.a and 4.b),
- lamellar crystals (Fig. 4.c–e),
- and rod-like crystals (Fig. 4.f–h).

At film thicknesses **below 2 nm** the films were composed of discontinuous islands, as shown in **Fig. 4.a and Fig. 4.b**. Therefore, no p-channel can be formed and no ambipolar behavior was measured.

Planar heterojunctions (cont'd)



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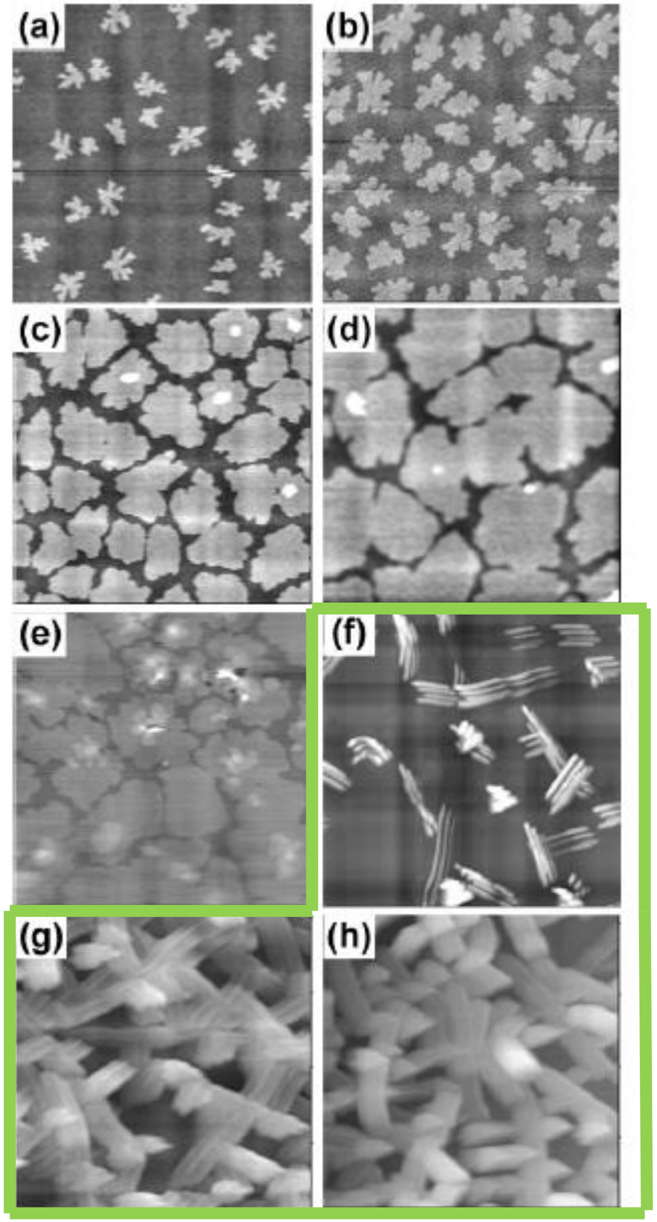
- discontinuous islands (Fig. 4.a and 4.b),
- lamellar crystals (Fig. 4.c–e),
- and rod-like crystals (Fig. 4.f–h).

At film thicknesses **between 2 and 5 nm** the films showed a layered structure with lamellar crystals, as shown in **Figure 4.c–e**. An ambipolar behavior is possible with BP2T film thicknesses in this regime as a result of this continuous structure

Planar heterojunctions (cont'd)



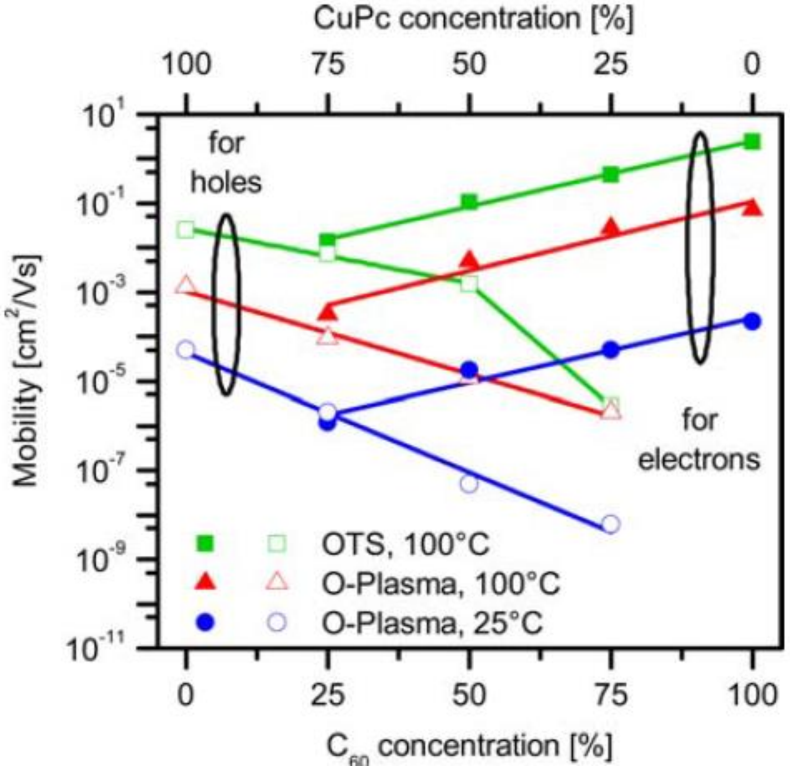
The BP2T films showed three morphology types:

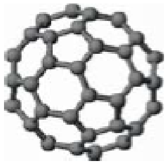
- discontinuous islands (Fig. 4.a and 4.b),
- lamellar crystals (Fig. 4.c–e),
- and rod-like crystals (Fig. 4.f–h).

At thicknesses **above 5 nm** rodlike crystals emerged in the films, as shown in **Figure 4.f–h**. These rodlike crystals cause a rough surface which enhances the carrier scattering and causes a bumpy electron channel in the F16CuPc layer. As a result the electron mobility decreases dramatically.

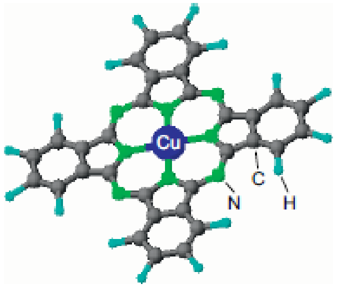
Co-deposited small molecules

Other than build up an heterostructure of two different materials we can think of co-deposit two different molecules on the same substrate. Acting on the concentrations of the two different species we can tune the electrical properties of the resulting semiconductor.





Buckminster-Fullerene
C_{60}

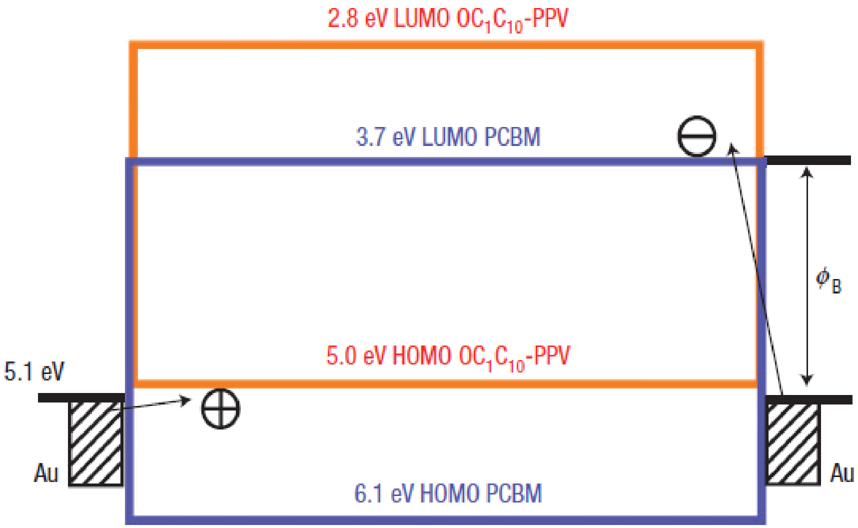


Copper-Phthalocyanine
CuPc

Bronner, M., Opitz, A. and Brutting, W. (2008), Ambipolar charge carrier transport in organic semiconductor blends of phthalocyanine and fullerene. Phys. Status Solidi A, 205: 549–563.

Blends of two polymers

To fully exploit the advantageous properties of organic molecules, such as ease of processing solution processing is preferable. Ambipolar transistors using heterogeneous blends, consisting of interpenetrating networks of p-type (OC_1C_{10}-PPV) and n-type (PCBM) were realized.



The alignment of the gold work function with the LUMO level of the PCBM is not as good, and the mismatch in energy levels results in an injection barrier ϕB of 1.4 eV for electron injection into the PCBM network. However, this injection barrier can be significantly reduced to 0.76 eV, due to the formation of a strong interface dipole layer at the Au/PCBM interface

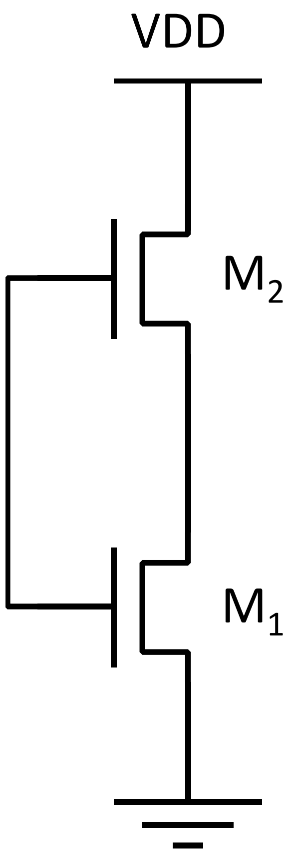
E. J. Meijer, D. M. De Leeuw, S. Setayesh, E. Van Veenendaal, B.-H. Huisman, P. W. M. Blom, J. C. Hummelen, U. Scherf and T. M. Klapwijk (2003), Solution-processed ambipolar organic field-effect transistors and inverters. Nature Materials

Ambipolar OFET applications

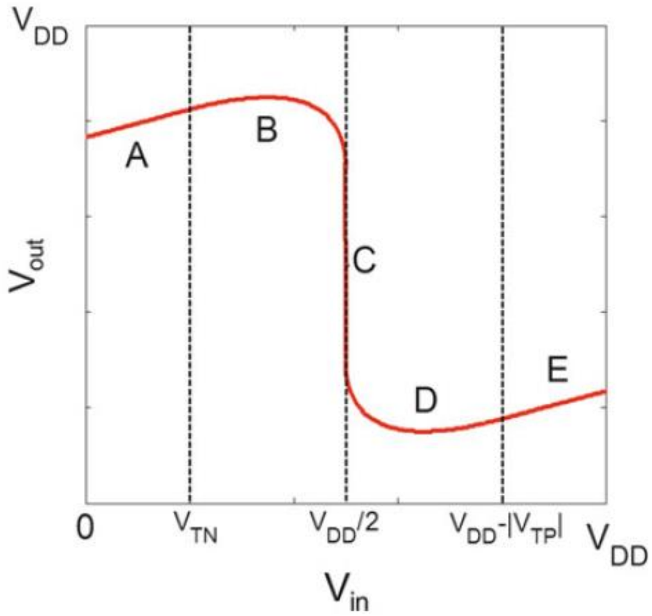
Inverter

Light Emitting Transistor

Inverter



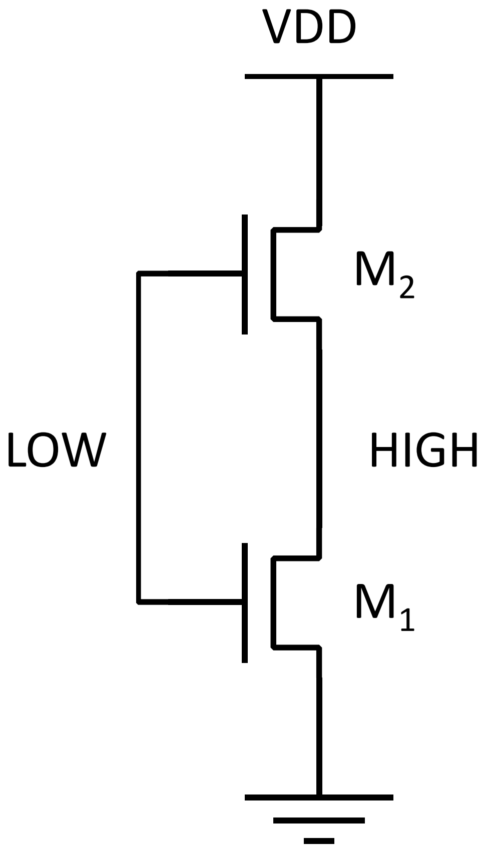
An inverter could be realized in ambipolar technology without requiring two different process for realizing N-MOS and P-MOS. The Figure shows a typical VTC for an ambipolar inverter with a “Z-shape”.



Inverter (cont’d)

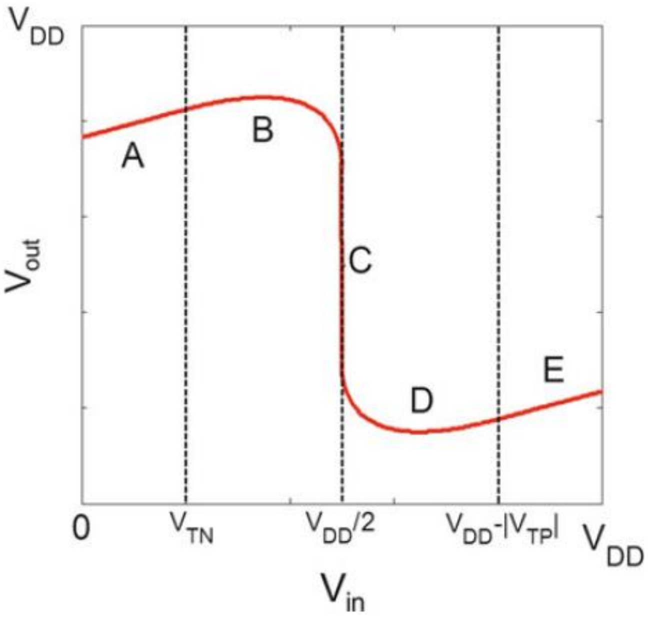
REGION A

$V_{in} < V_{TN}$ and $V_{out} \approx V_{DD}$



M1 operates in saturation with an unipolar current due to holes

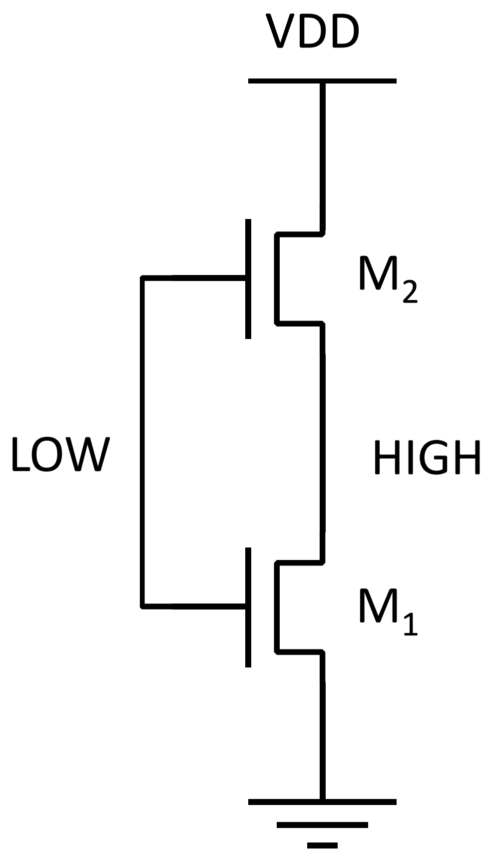
M2 operates in the linear region and only holes contribute to the current



Inverter (cont'd)

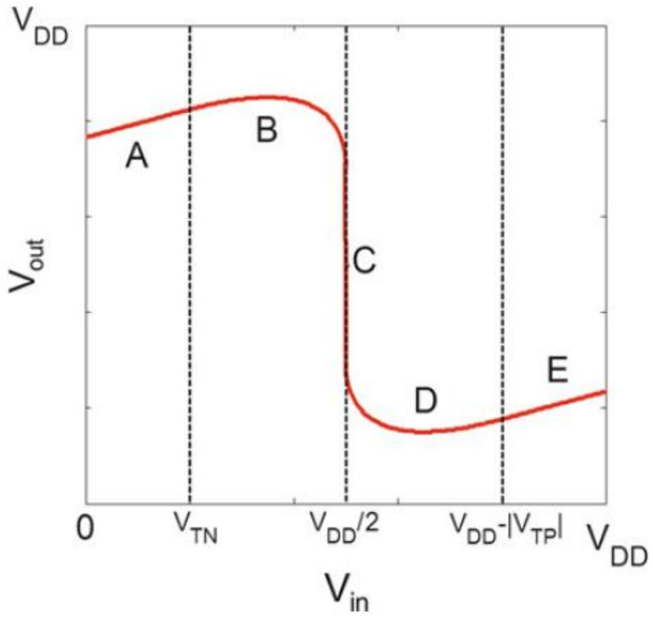
REGION B

$V_{TN} < V_{in} < V_{DD}/2$ and $V_{out} \approx V_{DD}$



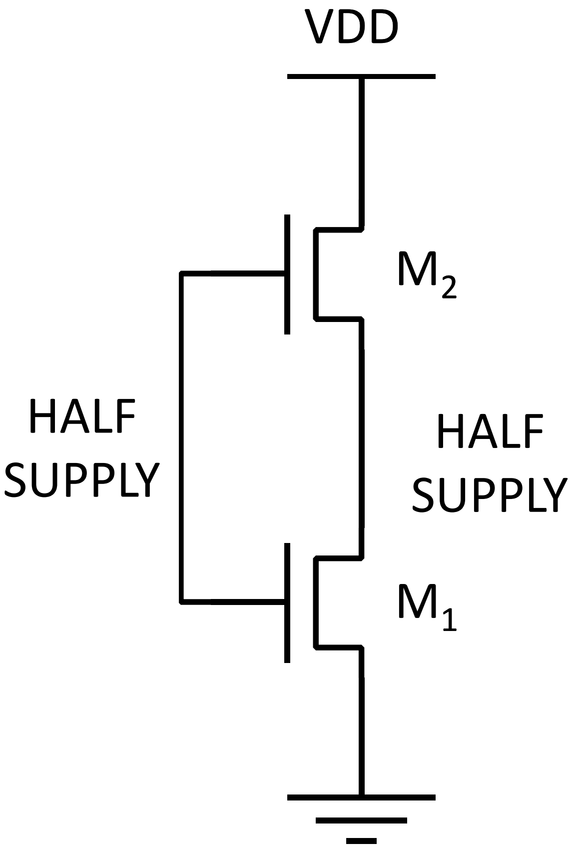
M1 operates in saturation with an ambipolar current

M2 operates still in the linear region and only holes contribute to the current



Inverter (cont’d)

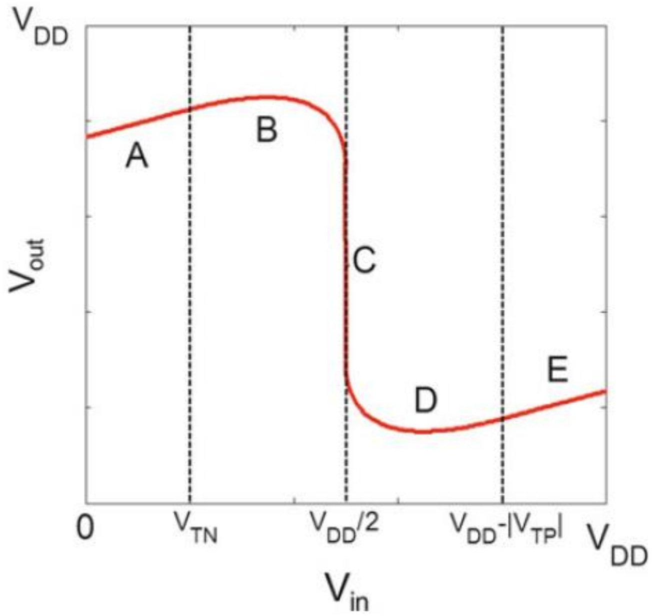
REGION C



$V_{in} = V_{DD}/2$ **and** $V_{out} \approx V_{DD}/2$

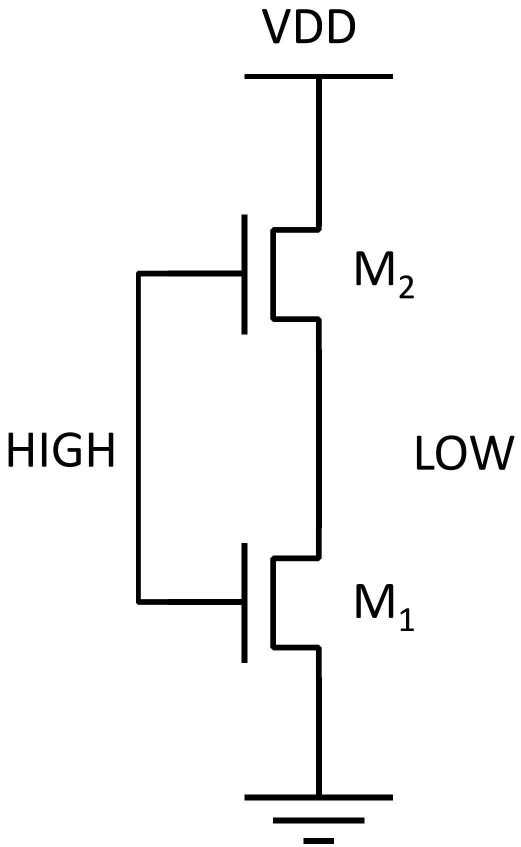
M1 operates in saturation with an unipolar current due to electrons

M2 operates in saturation with an unipolar current due to holes



Inverter (cont'd)

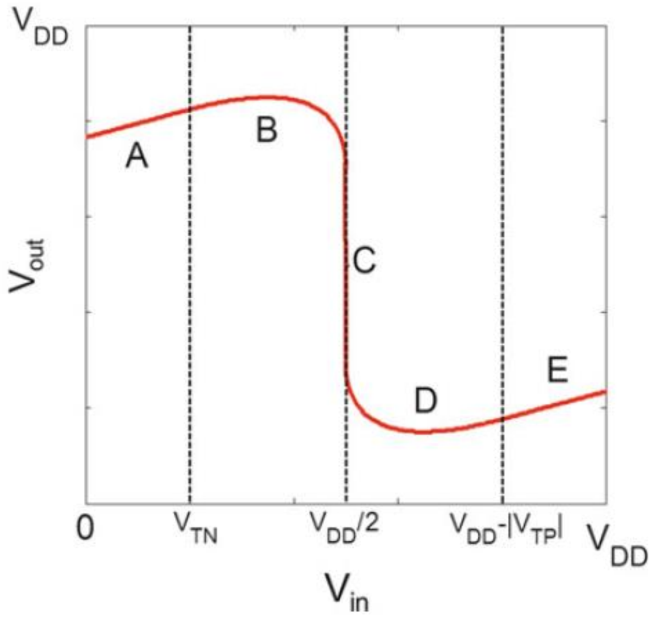
REGION D



$V_{DD} < V_{in} < V_{DD}+V_{TP}$ and $V_{out} \approx 0$

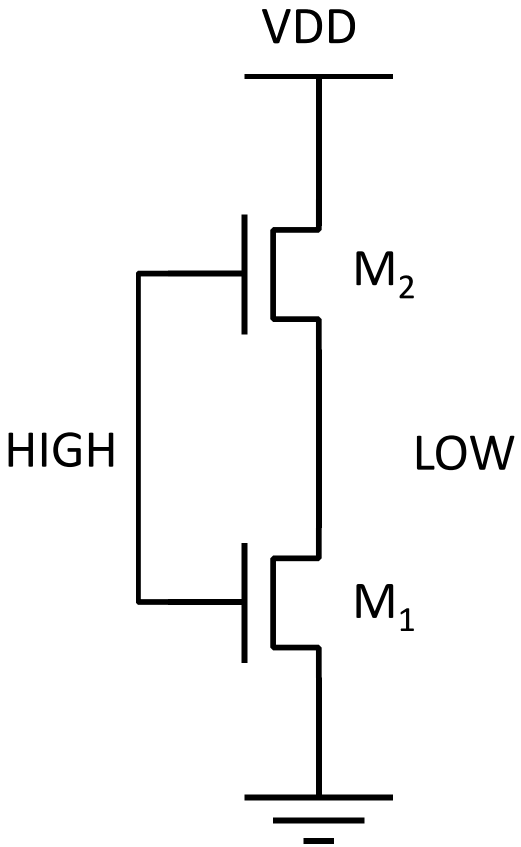
M1 operates in triode with an unipolar current due to electrons

M2 operates in saturation with an ambipolar current



Inverter (cont’d)

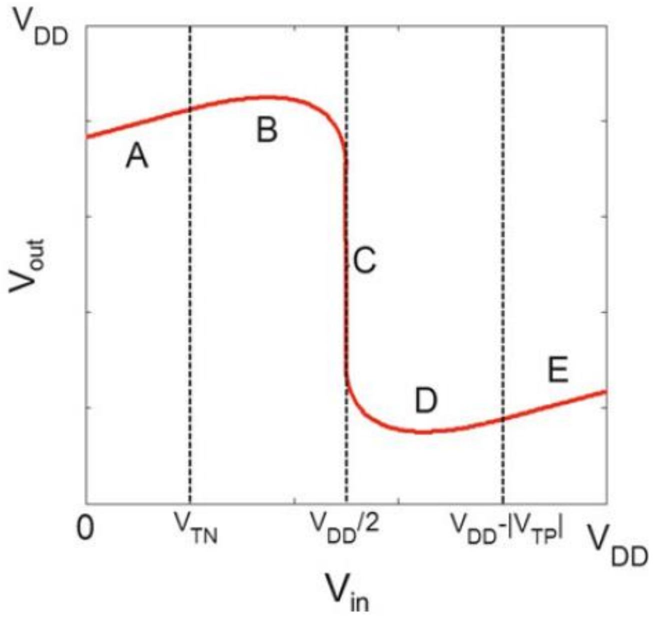
REGION E



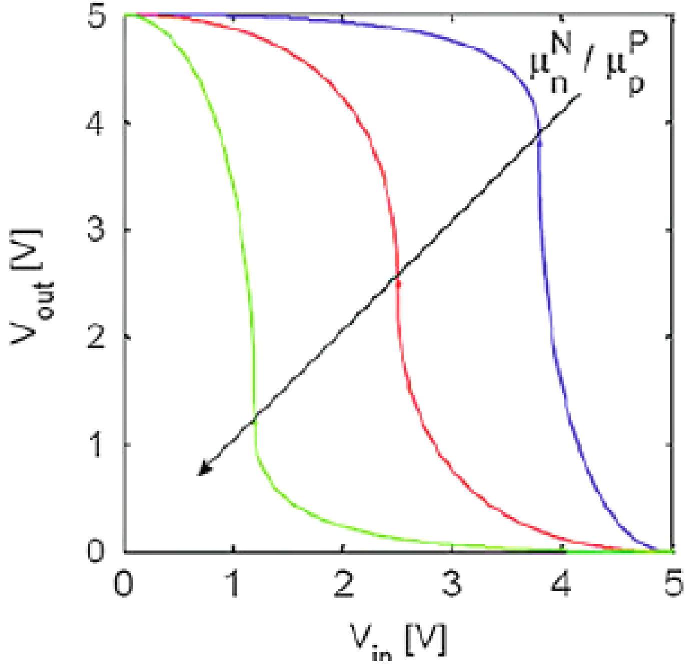
$V_{DD}+V_{TP} < V_{in} < V_{DD}$ and $V_{out} \approx 0$

M1 operates in triode with an unipolar current due to electrons

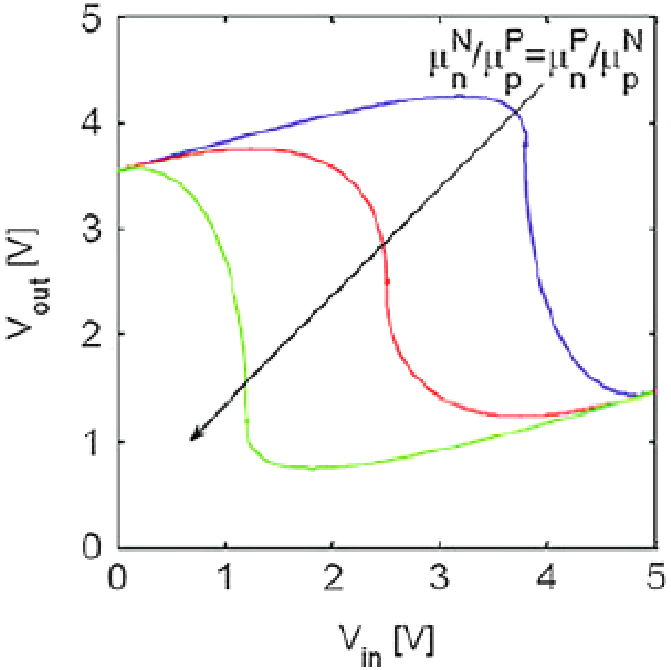
M2 operates in saturation with an unipolar current due to electrons



Inverter (cont’d)



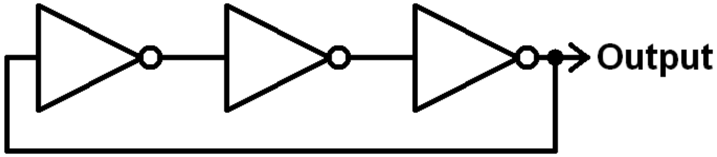
CMOS

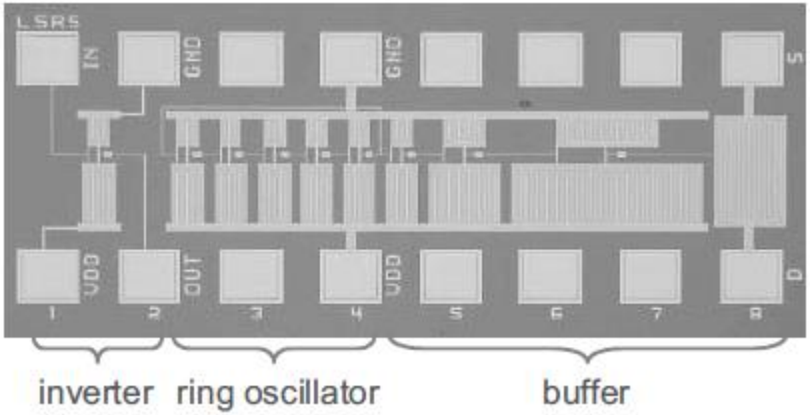


AMBIPOLAR

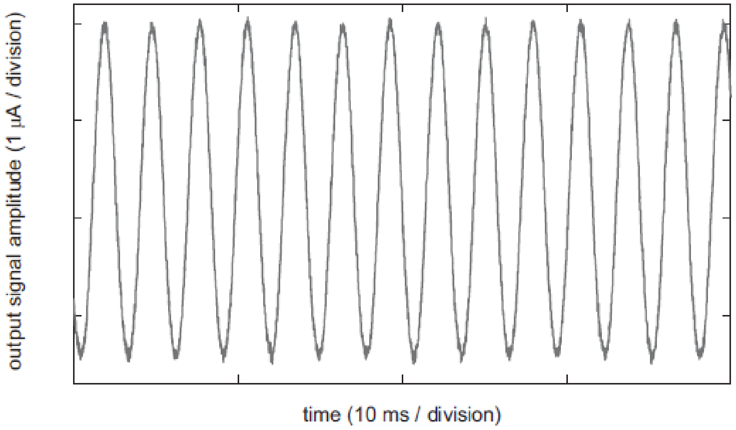
In a CMOS inverter at each logical state, one of the transistors is turned off and the current flow is insignificant therefore, the output voltage reaches either 0 V or V_{DD} and the static power consumption is negligible. On the other hand, for an ambipolar inverter, since both the n-type and the p-type transistors cannot be switched off at low and high input voltages, respectively, the VTC shows a “Z-shape”.

Ring Oscillator



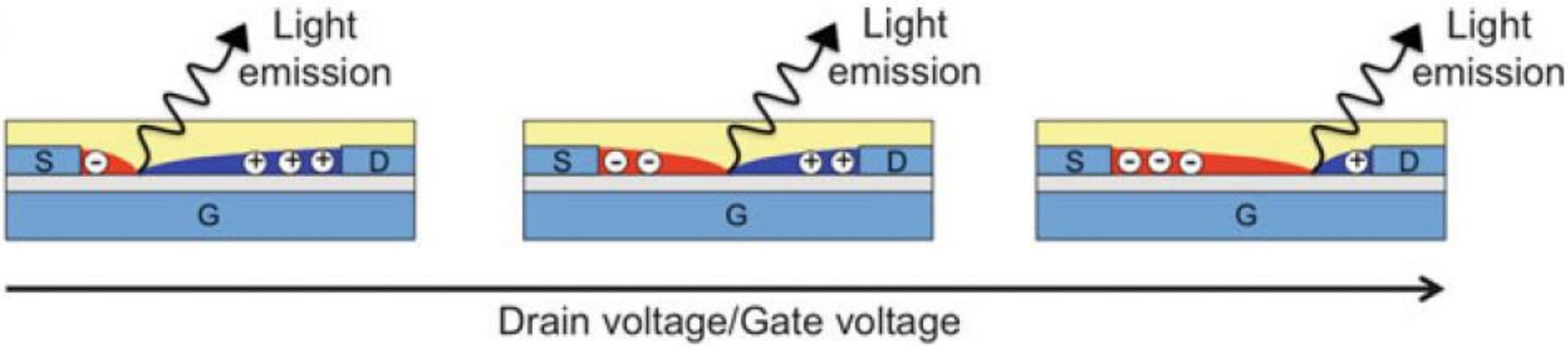


Combinig more inverters in series it is also possible to build up a ring oscillator. In [1] a five-stage ring oscillator, fabricated and tested in air was realized. The maximum oscillation frequency measured is 710 Hz, which corresponds to a stage delay (s) of 140 us for the single inverter



[1] Anthopoulos, T. D., Setayesh, S., Smits, E., Colle, M., Cantatore, E., de Boer, B., Blom, P. W. M. and de Leeuw, D. M. (2006), Air-Stable Complementary-like Circuits Based on Organic Ambipolar Transistors. Adv. Mater., 18: 1900–1904.

Light Emitting Transistor



An ambipolar transistor allows to have both electrons and holes inside the channel that is a good properties for light emitting devices.

Moreover ambipolar transistors unlike classical optical device provide the interesting properties of controlling the position of the emission point simply by changing the bias voltages.

In unipolar light-emitting transistors, the recombination happens in the vicinity of the electrode making it inefficient as most of the majority charge carriers can escape in the contact without recombining.

Conclusions

- Ambipolar transistors are a promising technology as they allows to embed in an unique device both n- and p-type transistors
- However up to now there is not yet a definitive processing solution that makes convenient to use ambipolar transitors instead of two different unipolar transistors patterned on the same substrate
- Performances of digital logic builds up in ambipolar technology are inerhently lower due to the inability to turn completely off the device
- Light Emitting Transistor realized in ambipolar technology has the great advantage of allowing to tune the emitting point