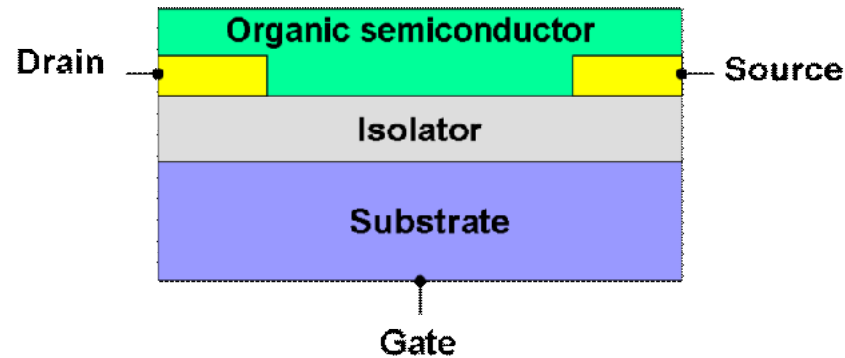


Transistor Organik – OFET
(Organic Field Effect Transistor)

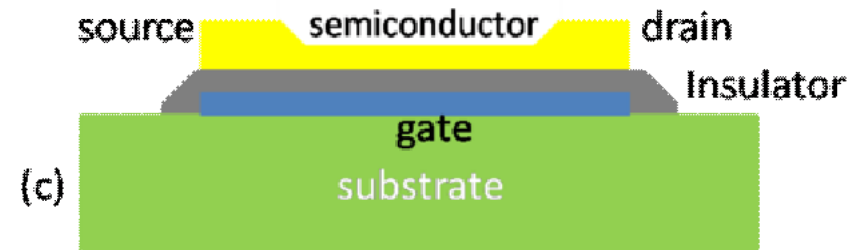
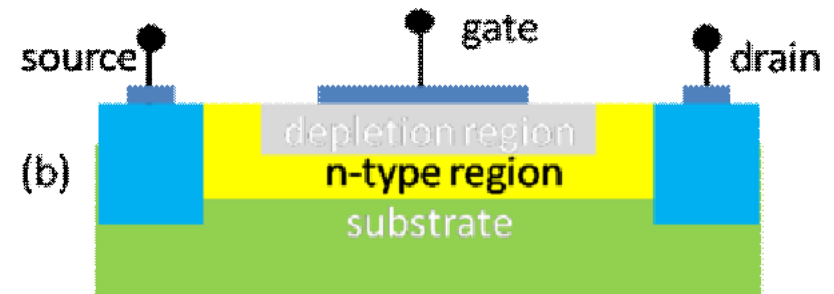
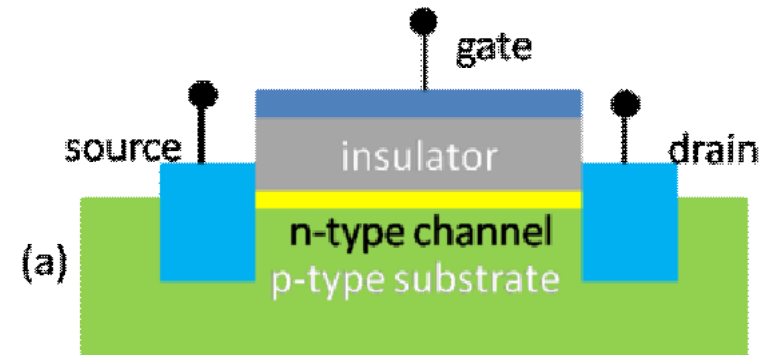
Elektronika Organik

maulana.lecture.ub.ac.id

Basic Structure of OFET

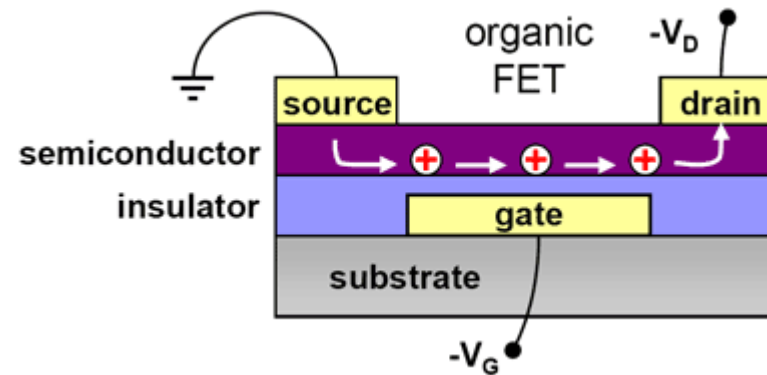
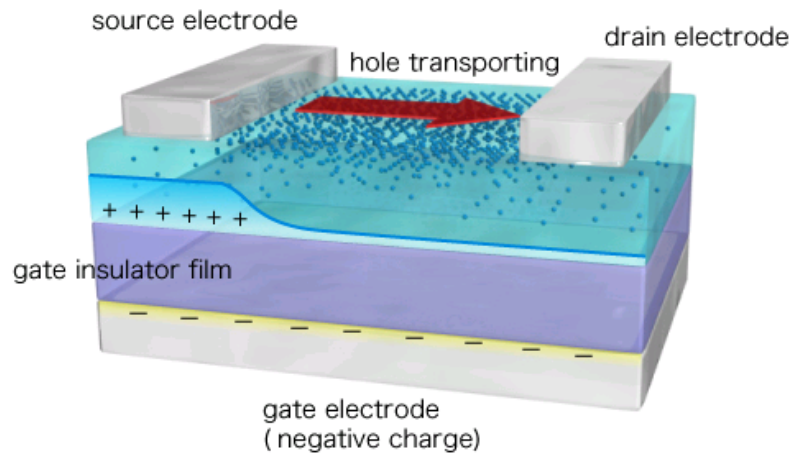
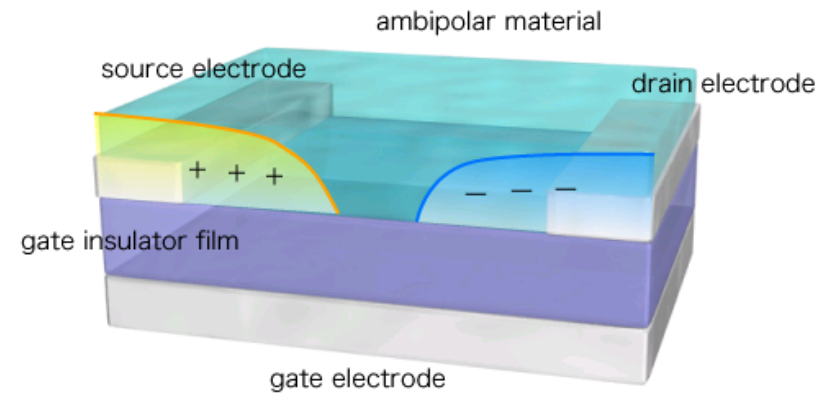
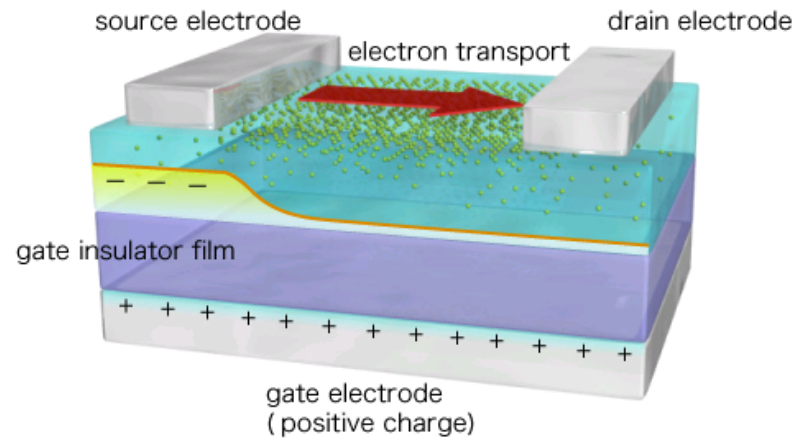


Skematik OFET



- (a) metal-insulator-semiconductor FET (MISFET);
- (b) metal-semiconductor FET (MESFET);
- (c) thin-film transistor (TFT).

Struktur dan Mekanisme OFET



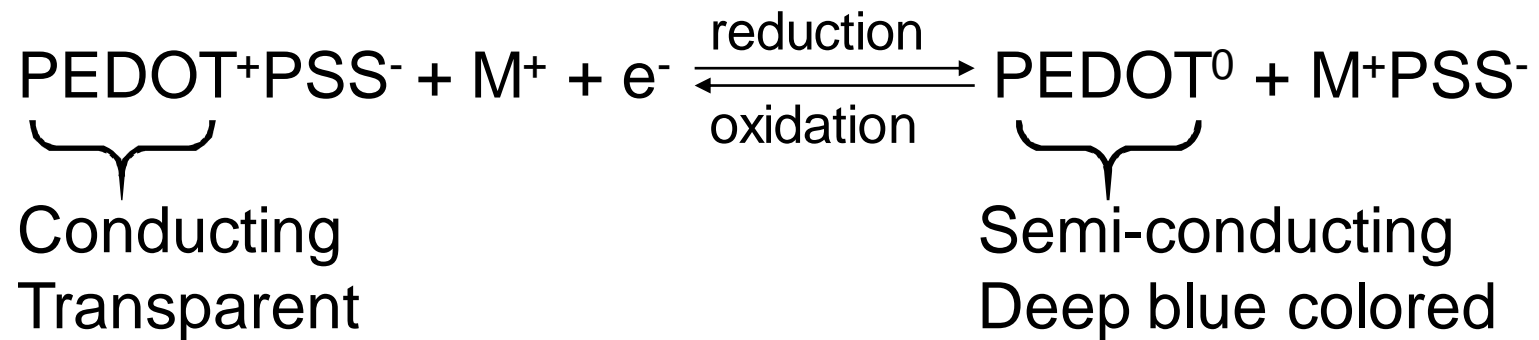
Organic Transistors

OFET

- 1. Organic electrochemical transistors (OECTs)**
- 2. Organic field effect transistors (OFETs)**
- 3. Electrolyte-gated OFETs**
- 4. Sensors Application based on OFET**

1. Organic Electrochemical Transistors (OECTs)

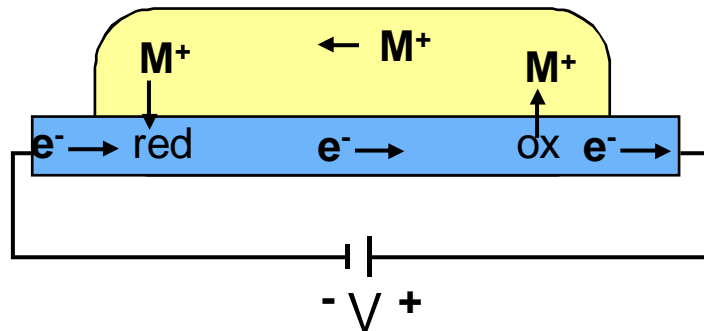
- Reversible oxidation and reduction switching
- Electrochemical devices uses both electrons and ions as charge carriers



1.1.The dynamic configuration

Structure 1 (one area of conducting polymer)

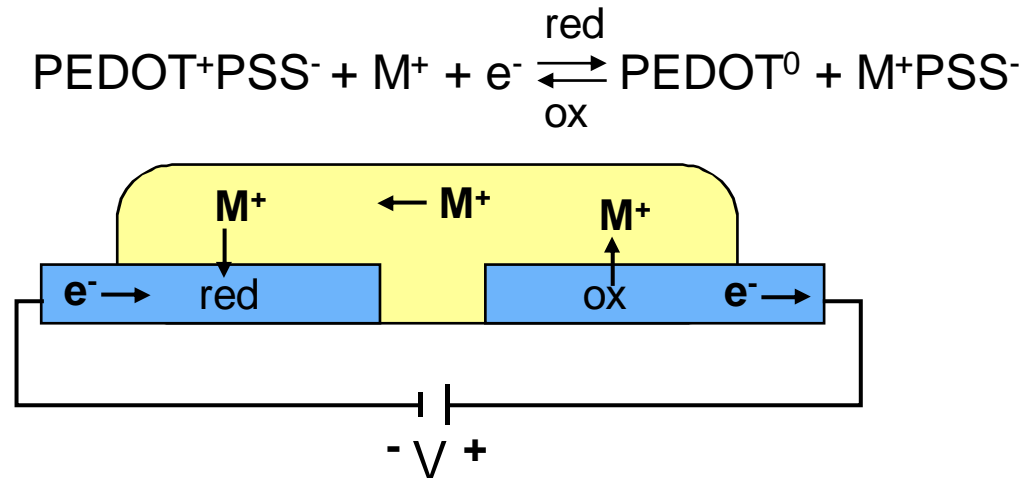
- Reduction at the negatively biased side of electrode
- oxidation at the positively biased side of electrode
- Dynamic behavior



1.2 The bi-stable configuration

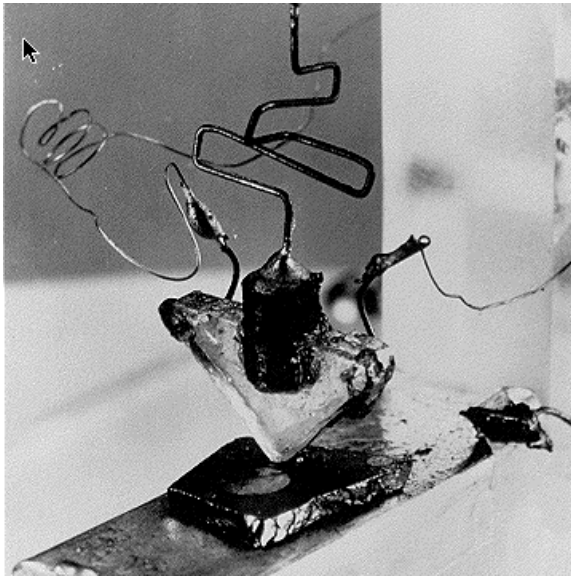
Structure 2 (two areas of conducting polymer)

- Reduction at the negatively biased electrode
- Oxidation at the positively biased electrode
- Bi-stable behavior

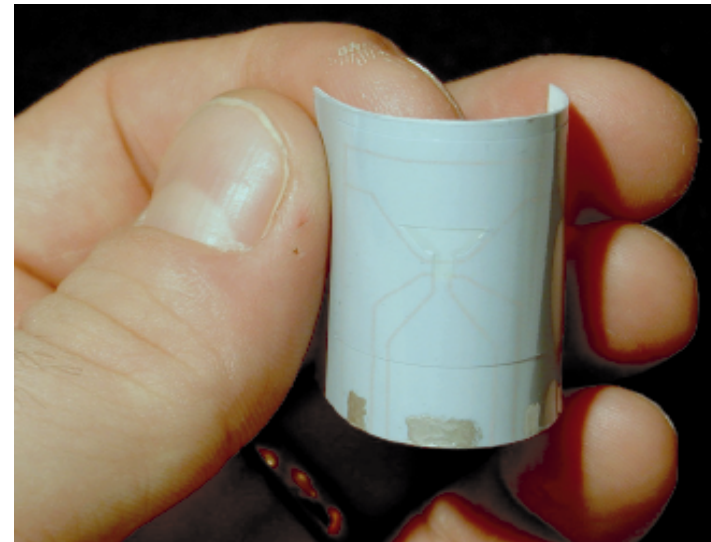


Flexible substrates

The first transistor (1947)
Size: 2.5cm

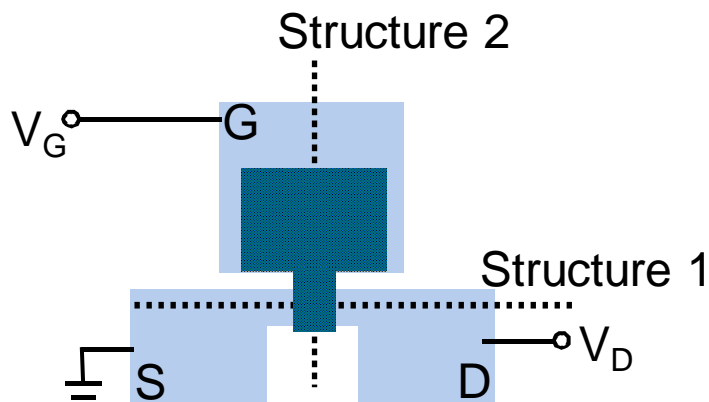


A flexible organic
electrochemical transistor



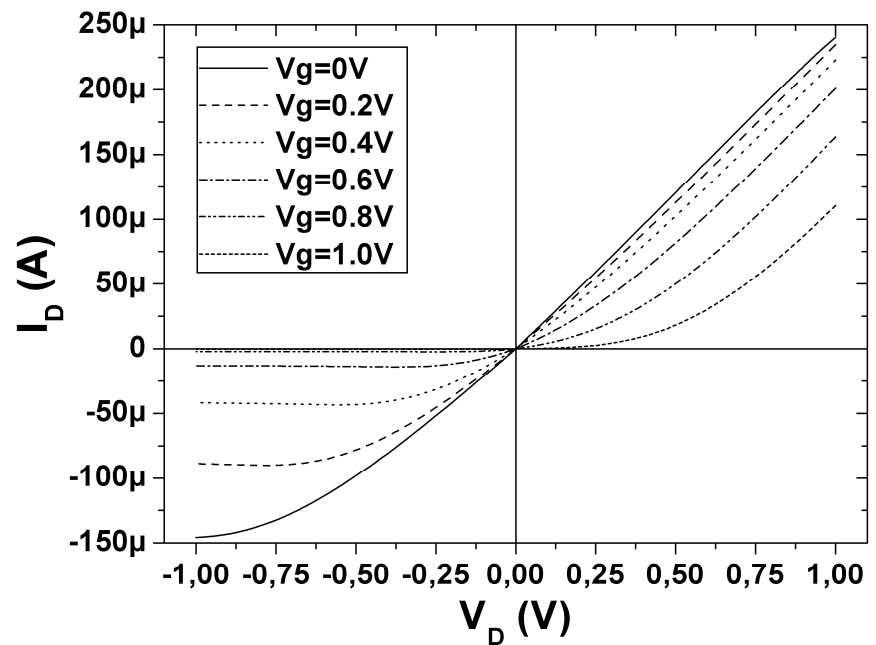
1.3 The three-terminal transistor

Common ground



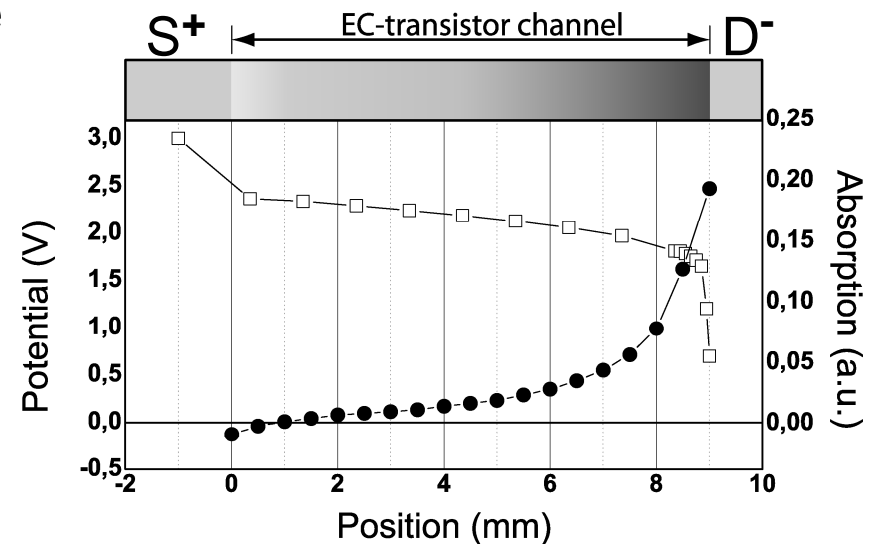
PEDOT:PSS

Electrolyte



Pinch-off

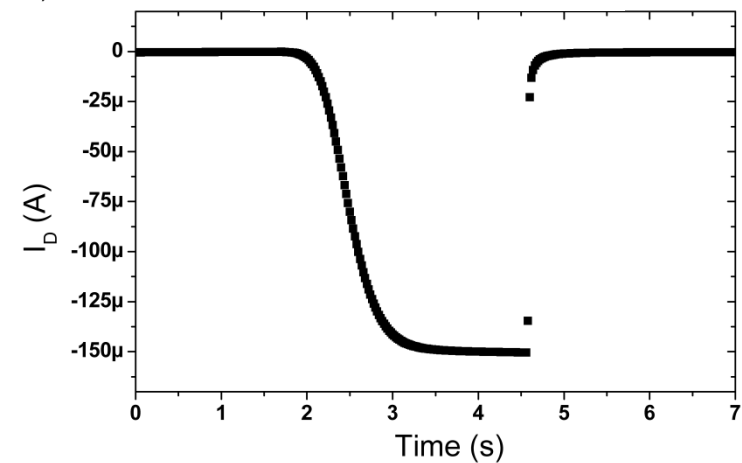
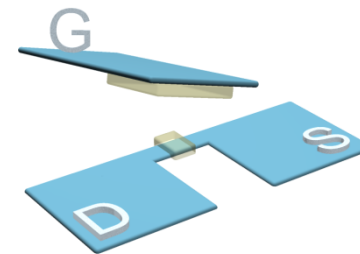
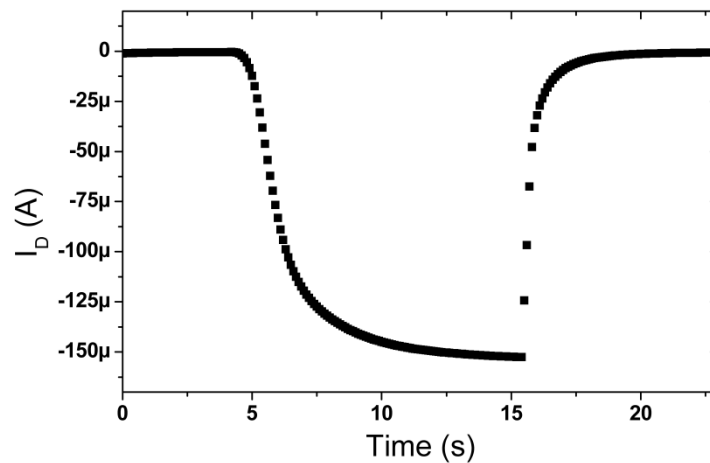
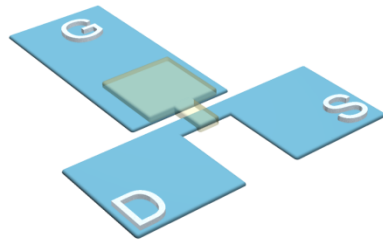
- Pinch-off due to the decrease of charge carriers at the drain side of the channel
- Almost all resistance is located within 100 μm of the channel edge
- Effect of structure 1



□ Potential ● Absorption

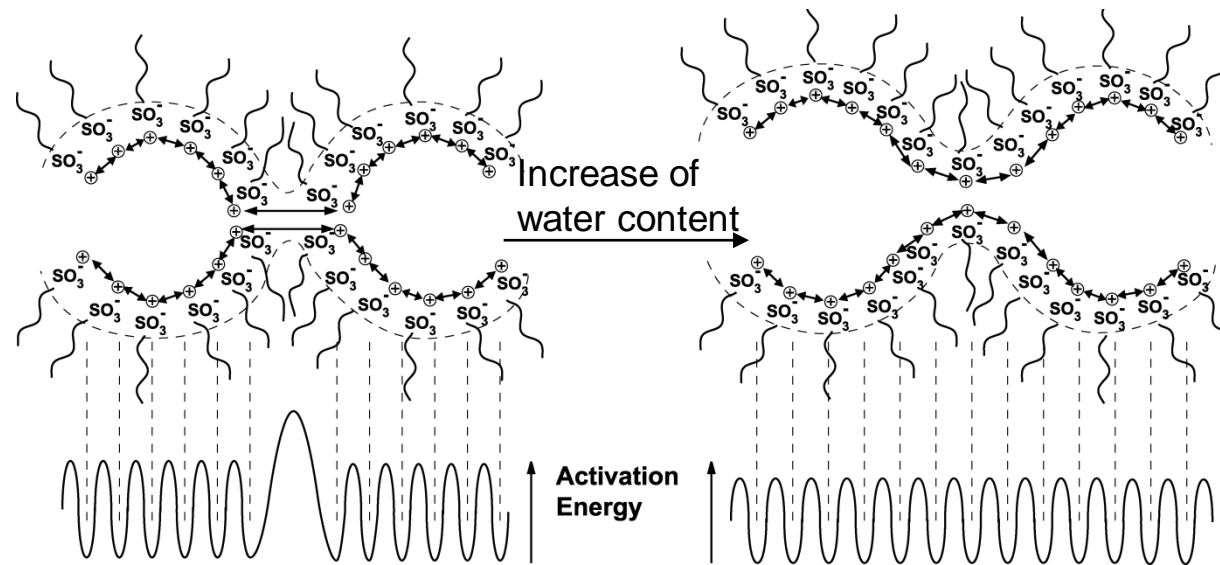
Chronoamperometric response

- Comparison between lateral and vertical design



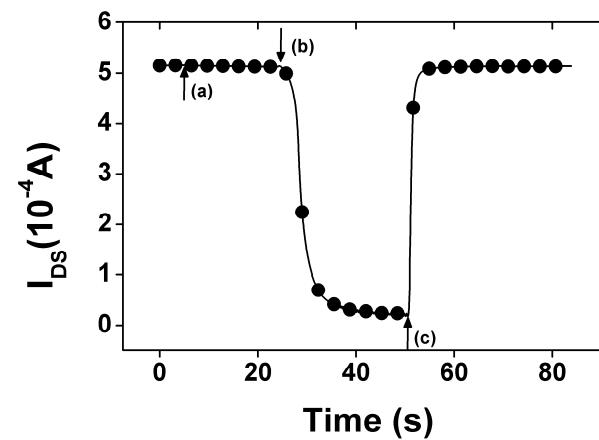
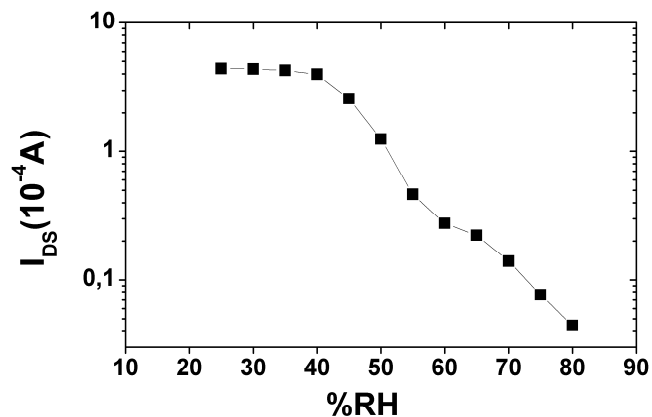
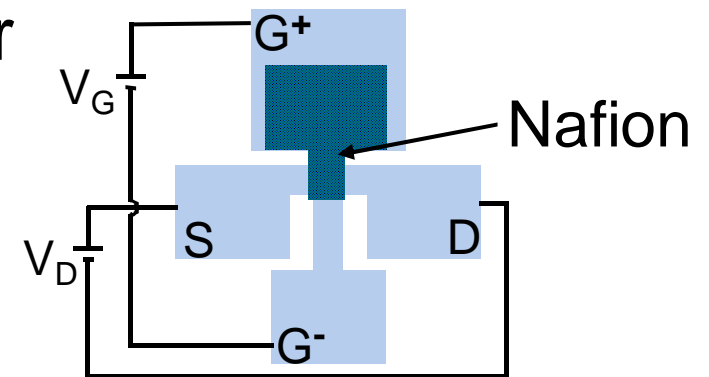
Nafion

- Cation conductor, mainly protons.
- Forms inverted micelle clusters with sulphonic acid groups on the inner surface
- The micelles are joined through canals.
- Charge transport by cations wandering between $-\text{SO}_3^-$ groups.
- Ion conduction increases with water content due to swelling and dissociation of ions.



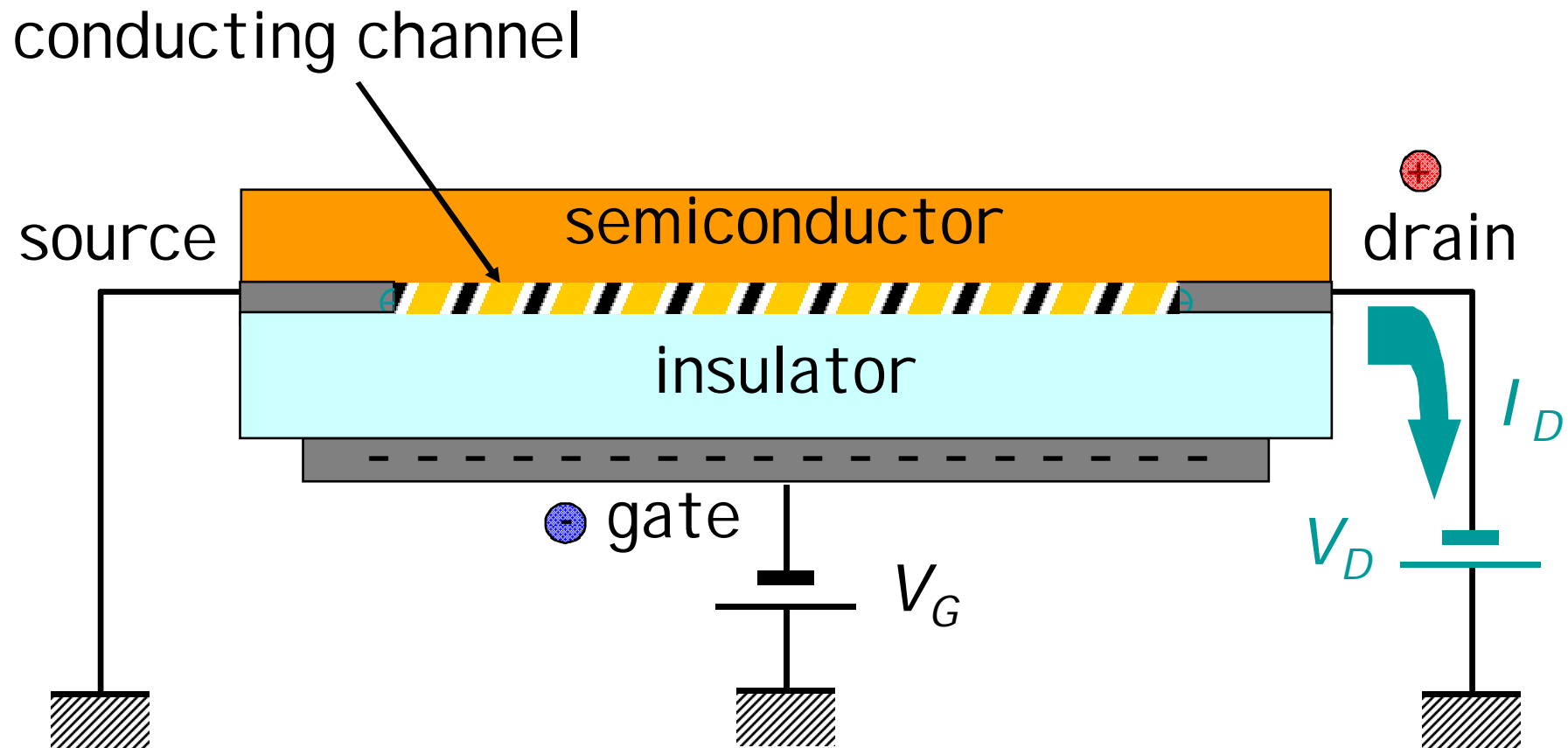
Humidity sensor

- Transducer part: EC-transistor
- Sensitive part: Nafion



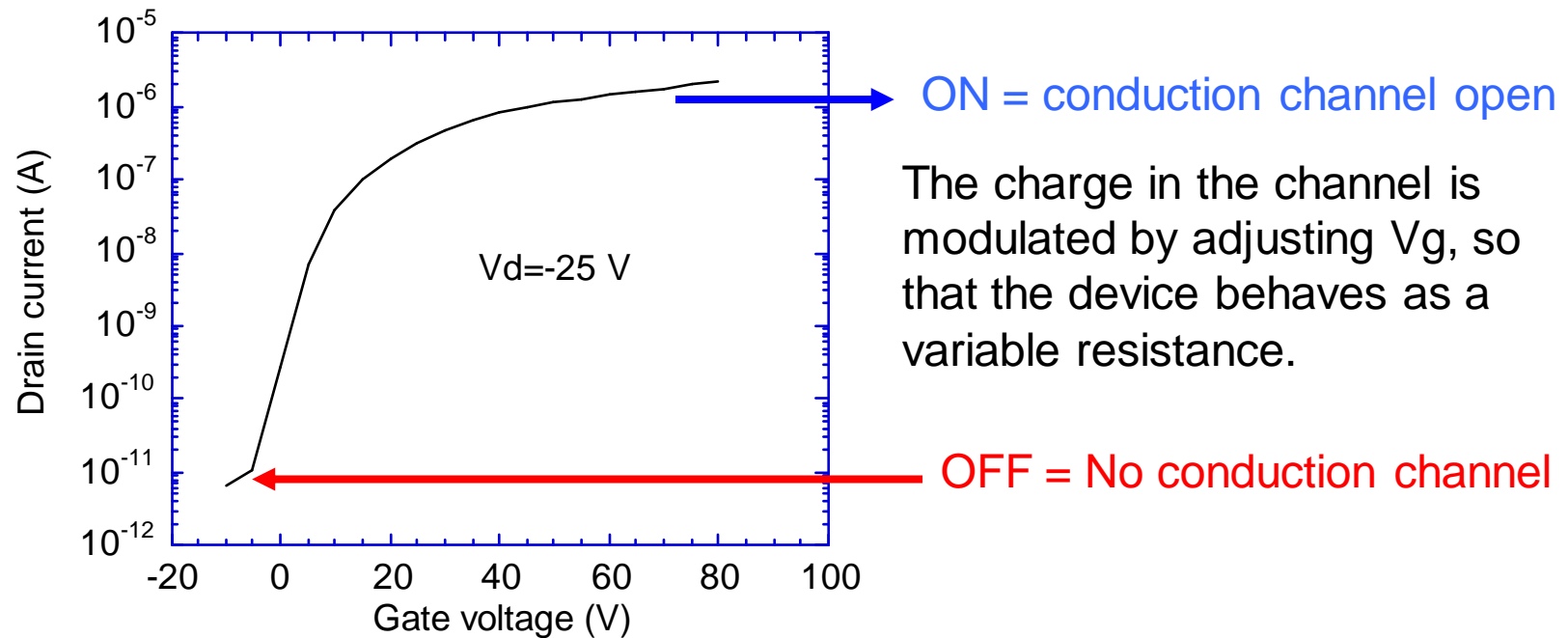
2. Organic Field-Effect Transistors (OFETs)

Structure of an Organic Thin Film Transistor



2.1. Current-voltage characteristics

2.1.1. Transfer characteristic



A FET is basically a capacitor, where one plate is constituted by the gate electrode, and the other one by the semiconductor film. When a voltage V_g is applied between source and gate, majority carriers accumulate at the insulator-semiconductor interface, leading to the formation of a conduction channel between source and drain.

→ A potential signal V_g is transformed in a current signal I_d

2.1.2. Current-voltage

$$I_D = \frac{W}{L} \int_0^{V_D} C_i \mu (V_G - V_T) dV$$

No analytical solution, unless the **mobility is assumed to be constant**.

If V_D small, the charge is nearly constant over the channel and the drain current is :

Linear

$$I_D = \frac{W}{L} C_i \mu (V_G - V_T) V_D$$

If $V_D > V_G$, the channel is pinched-off:

Saturation

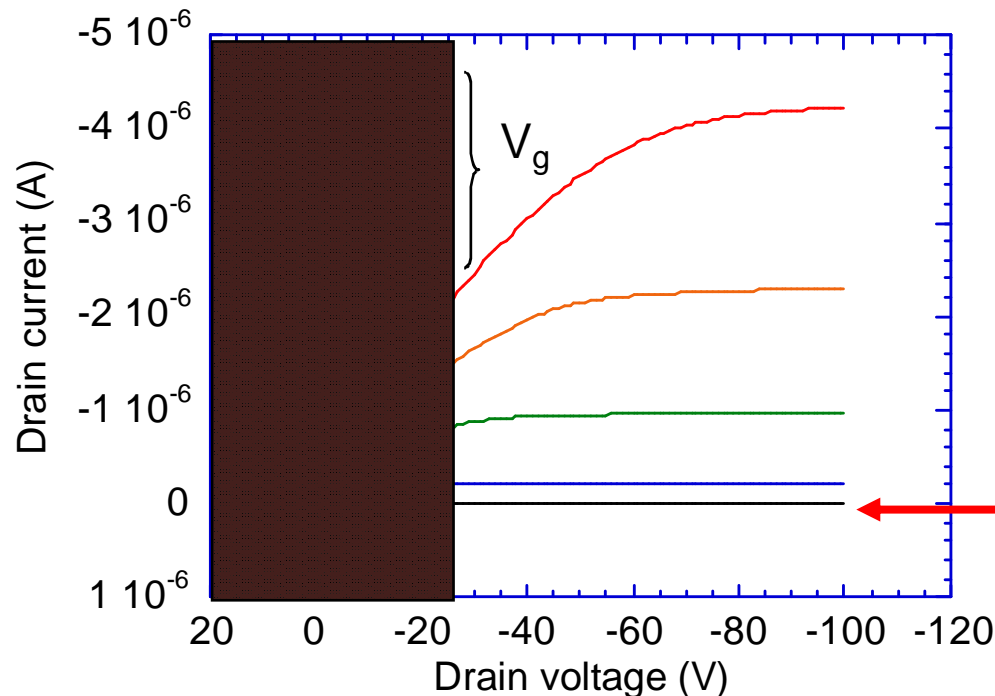
$$I_{D,sat} = \frac{W}{2L} C_i \mu (V_G - V_T)^2$$

2.1.3. Output characteristic

Linear regime:

For a given $V_g > 0$, the current provided by the conduction channel increases with V_d . The drain electrode injects the charge carriers passing through the channel, the channel lets pass as many charges as the drain electrode injects.

V_g controls the doping level N in the conduction channel: large $V_g \rightarrow$ large current I_d

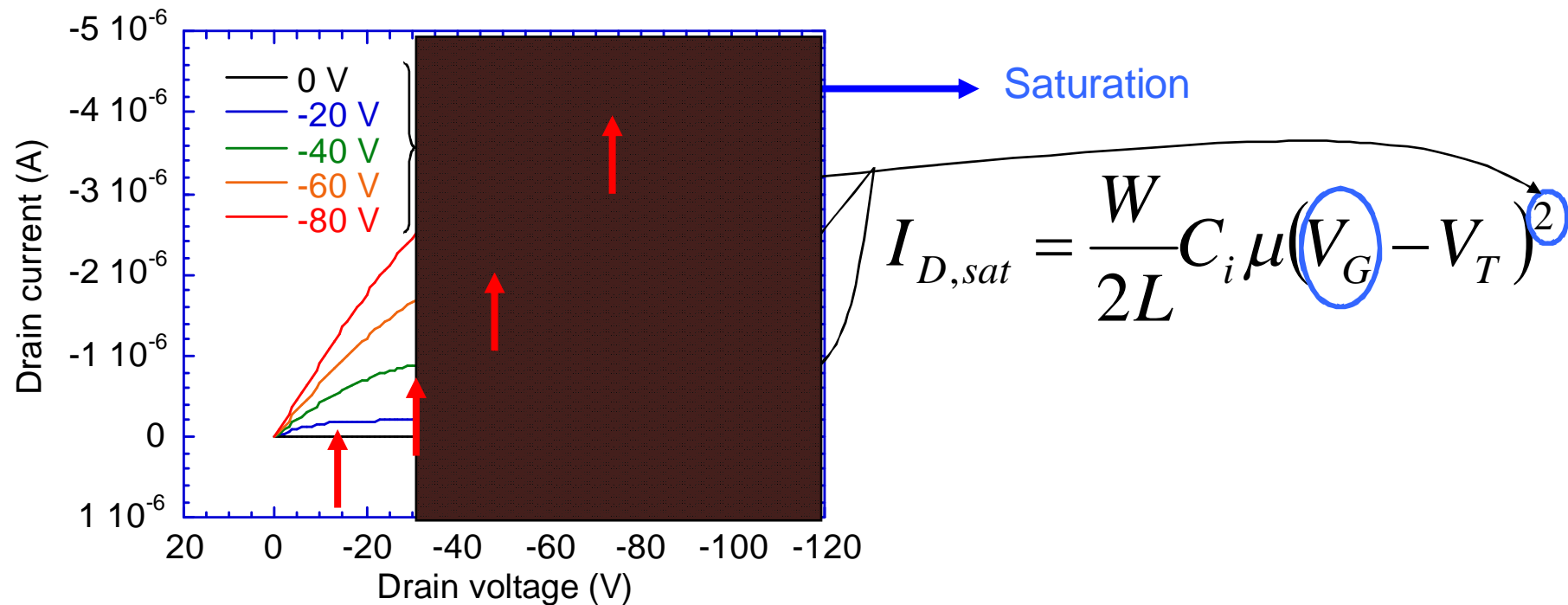


W and L = channel width and length
 C_i = capacitance of the insulator layer
 μ = field-effect mobility
 V_T = threshold voltage (accounts for voltage drops of various origin across the insulator-semiconductor interface)

$$I_D = \frac{W}{L} C_i \mu (V_G - V_T) V_D$$

Saturation regime:

For a given V_g , when $V_d = V_g$, the electrical potential between drain and gate is zero. This destroys the capacitor created between the doped channel and the gate : pinch off. The channel is then interrupted close to the drain.



Output characteristic

2.1.4. How to get the field effect mobility?

1) If V_d small, the charge is nearly constant over the channel and the drain current is :

Z =channel width

Linear

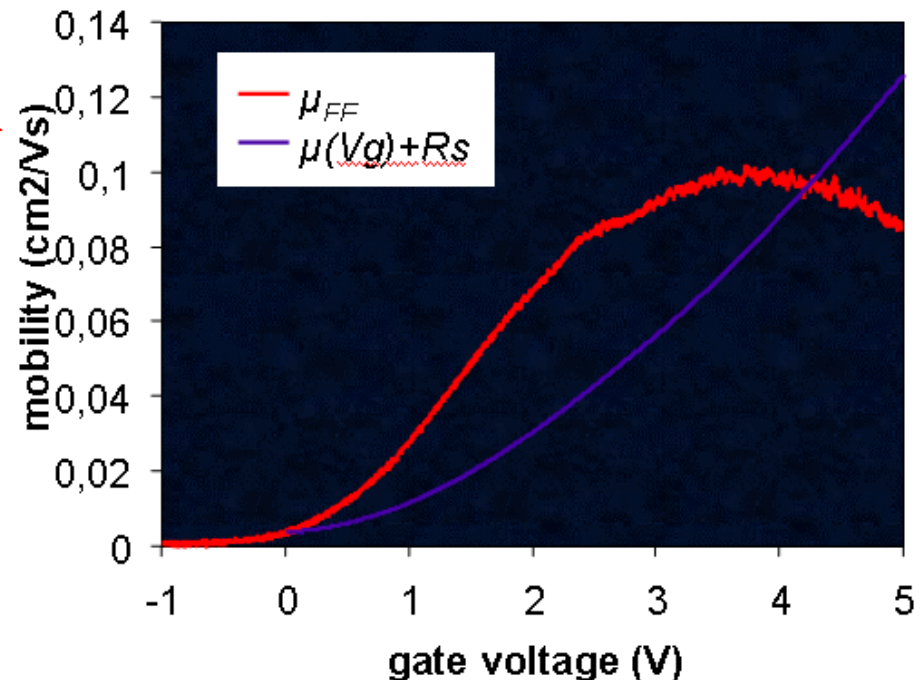
$$I_D = \frac{Z}{L} C_i \mu (V_G - V_T) V_D$$

•The channel conductance g_d can be expanded to first order:

$$g_d = \frac{\partial I_d}{\partial V_d} = \frac{Z}{L} \mu C_i (V_g - V_0)$$

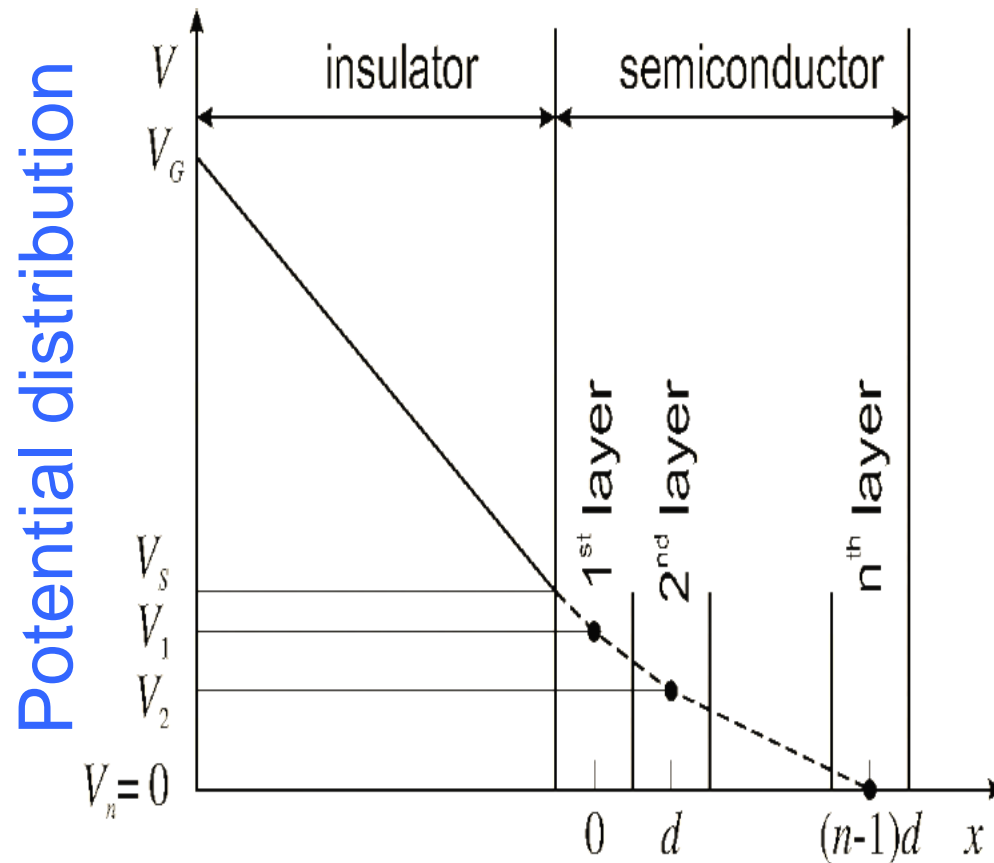
2) A further step of the method consists of introducing a contact series resistance R_s , which leads to

$$g_d = \left(\frac{\frac{Z}{L} \mu C_i (V_g - V_0)}{1} + R_s \right)^{-1}$$



2.2. Film morphology versus field-effect mobility

The mobility measured with a FET is characteristic for the whole film. It is thus expected to depend on the quality of the organic film; especially the quality of the first mono-layers deposited on the insulator

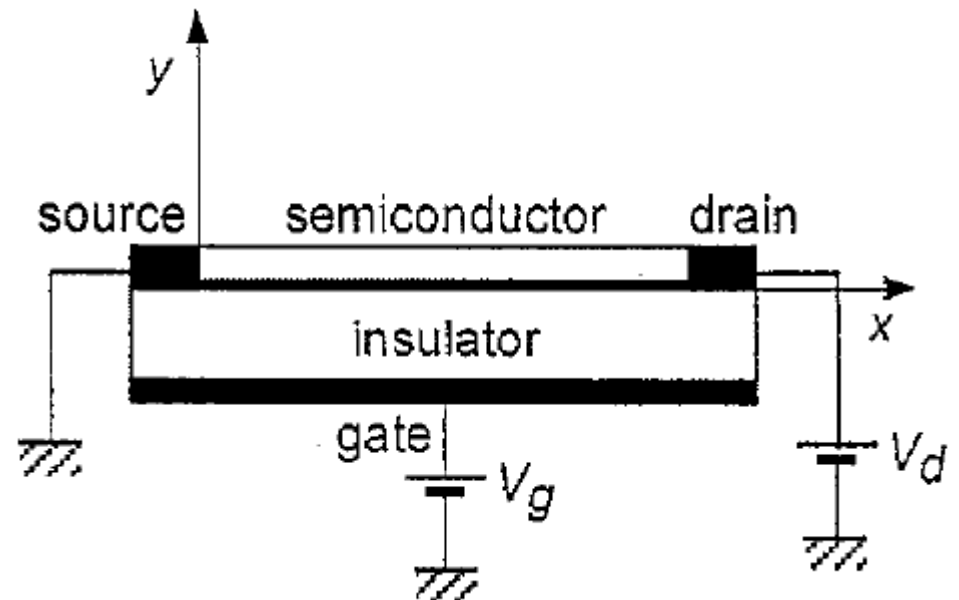
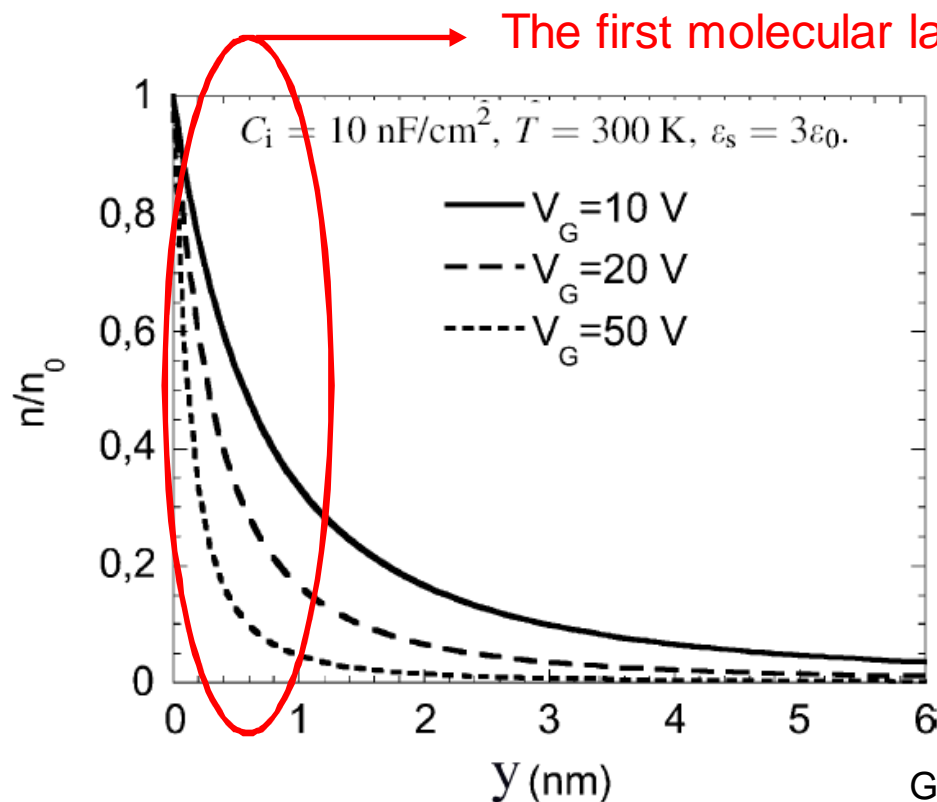


2.2.1. The distribution of charge in the channel

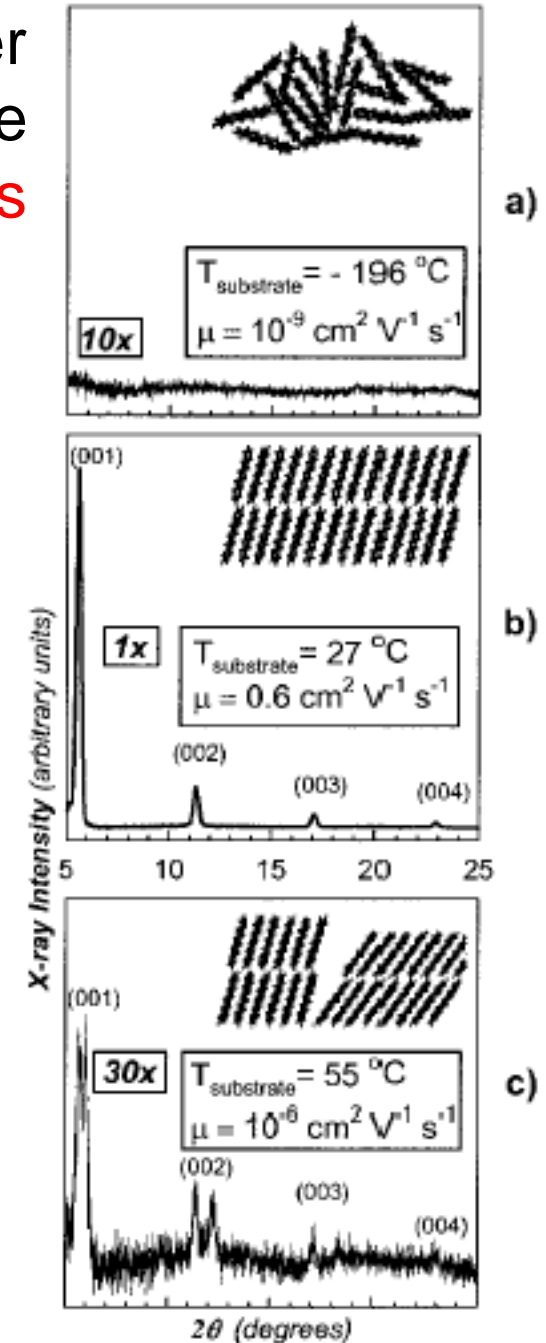
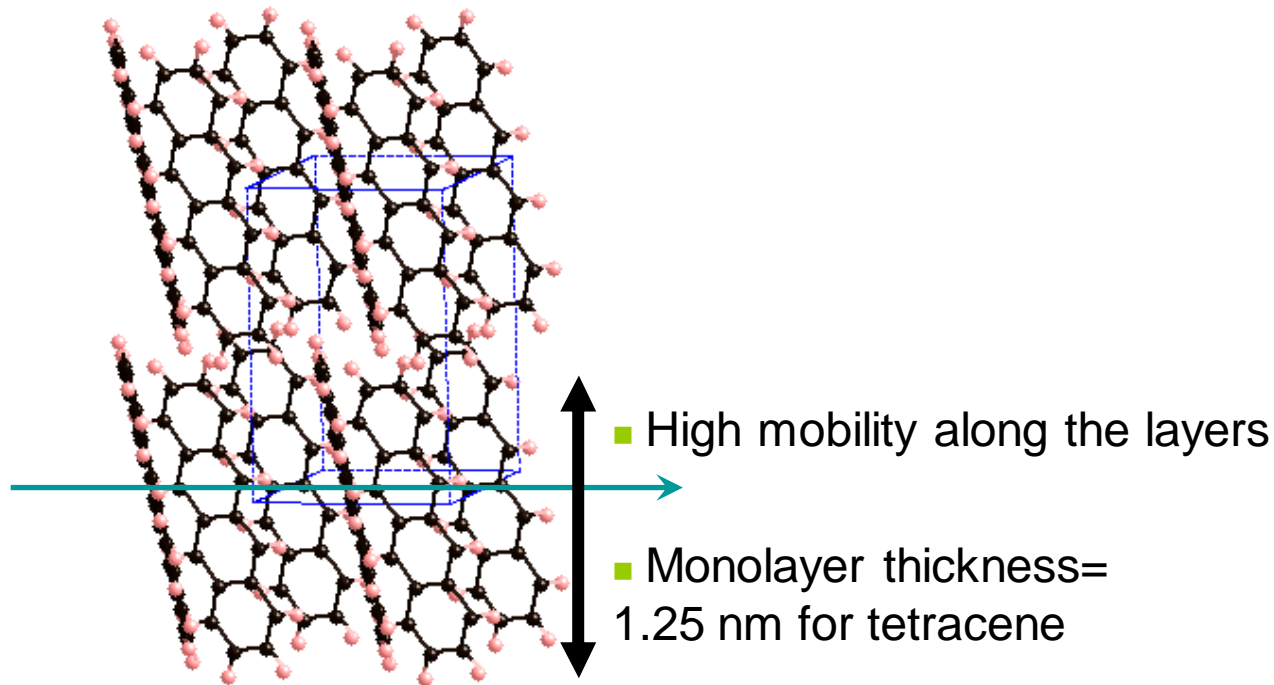
(from Poisson's equation):

$$n(y) = \frac{2kT\epsilon_s}{q^2(y + y_0)^2}, \quad y_0 = \frac{2kT\epsilon_s}{qC_iV_G}$$

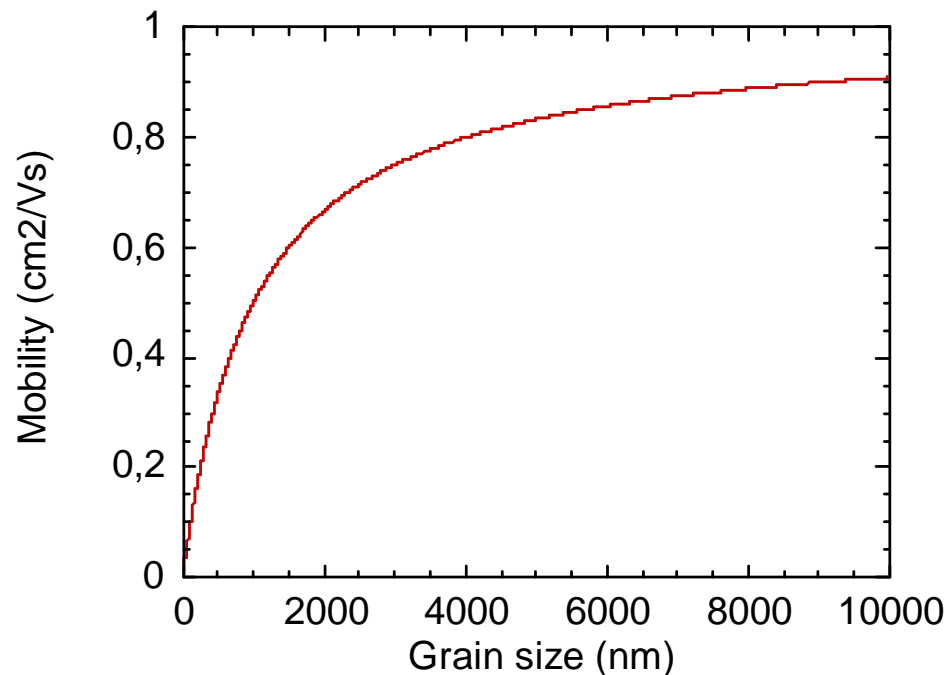
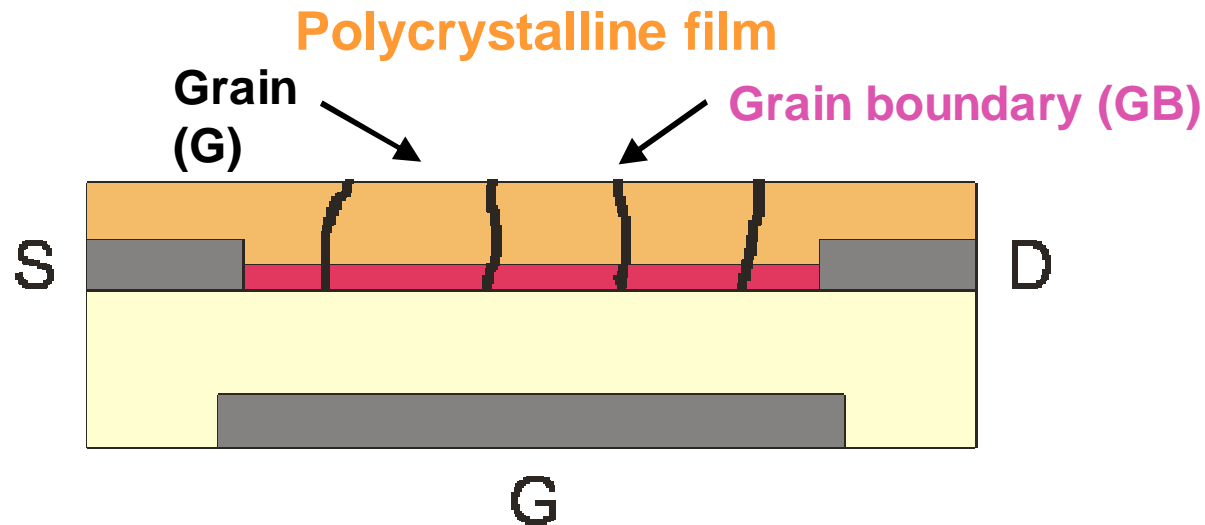
ϵ_s = permittivity of the organic semiconductor
 q = electron charge
 C_i = capacitance (per unit area) of the insulator



The channel reduces to the first monolayer
→ The organic TFT is a 2D device
→ Structural order in the first monolayer is crucial



2.2.2. Grain size dependence mobility



$$\mu_G = 1 \text{ cm}^2/\text{Vs}$$

$$\mu_{GB} = 0.01 \text{ cm}^2/\text{Vs}$$

Length of the GB $L_{GB} = 10 \text{ nm}$

Charge transport in polycrystalline media

→ divide the material into high (crystal grains) and low (grain boundaries) conductivity region.

As grains and grain boundaries are connected in series: $R_{\text{tot}} = R_G + R_{GB}$

□ $R = \rho L / S$ (ρ =resistivity)

→ for the same surface $S_G = S_{GB}$ (active thickness in the FET), we can write
 $\rho L = \rho_G L_G + \rho_{GB} L_{GB}$

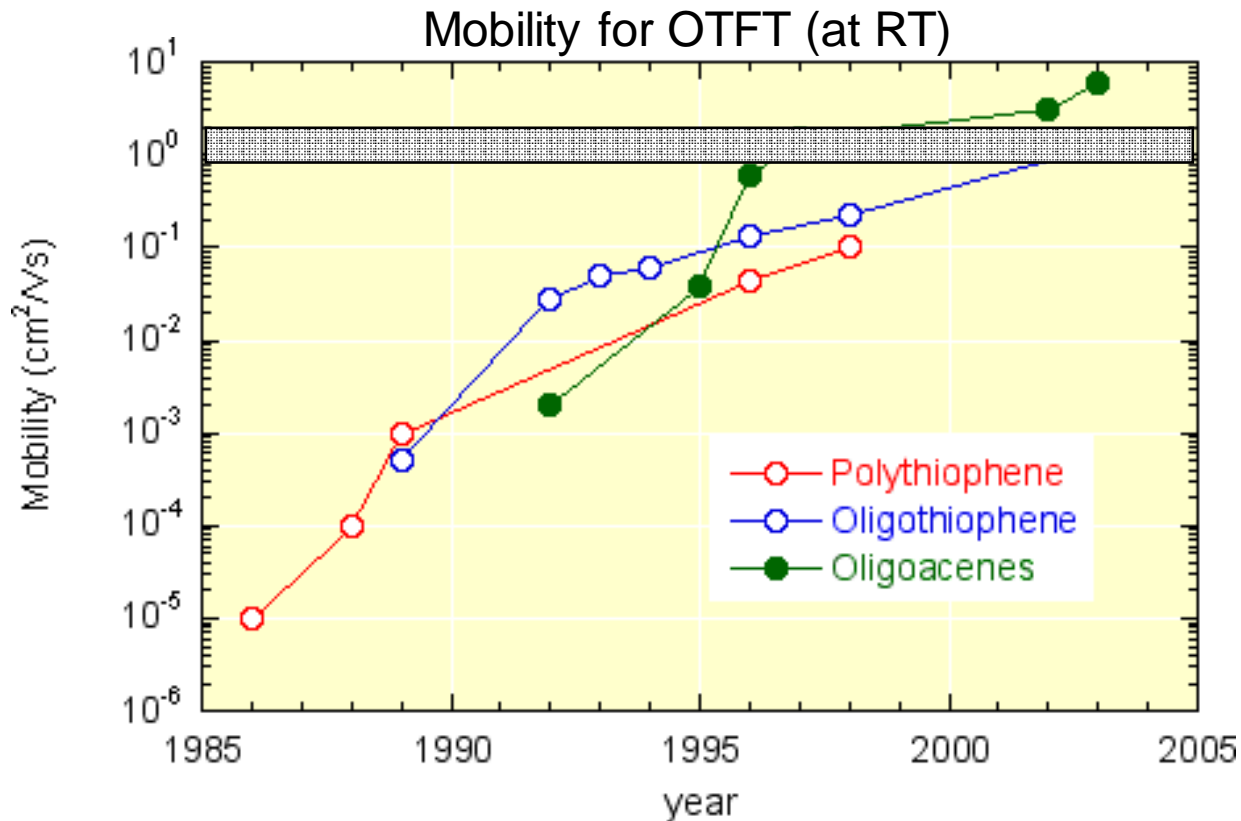
□ Conductivity $\sigma = 1/\rho \div p\mu$

→ if the concentration in charge carrier "p" is similar in both regions, the effective mobility of the medium is given by

$$\frac{L_G + L_{GB}}{\mu} = \frac{L_G}{\mu_G} + \frac{L_{GB}}{\mu_{GB}}$$

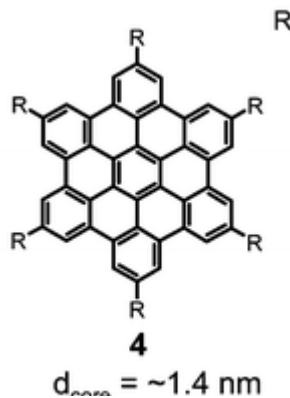
2.3. Mobility and architecture evolution

- ❑ Organic material can have a mobility larger than amorphous silicon
- ❑ Saturation with oligoacene
➔ maybe with another molecule, mobility will go higher...

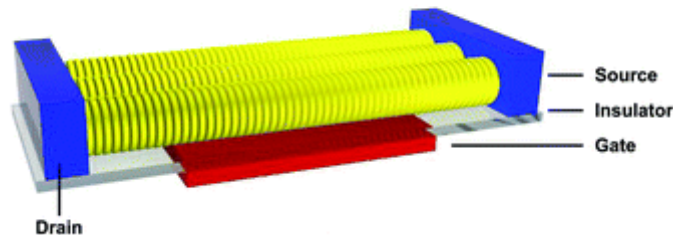


Discotic liquid crystals

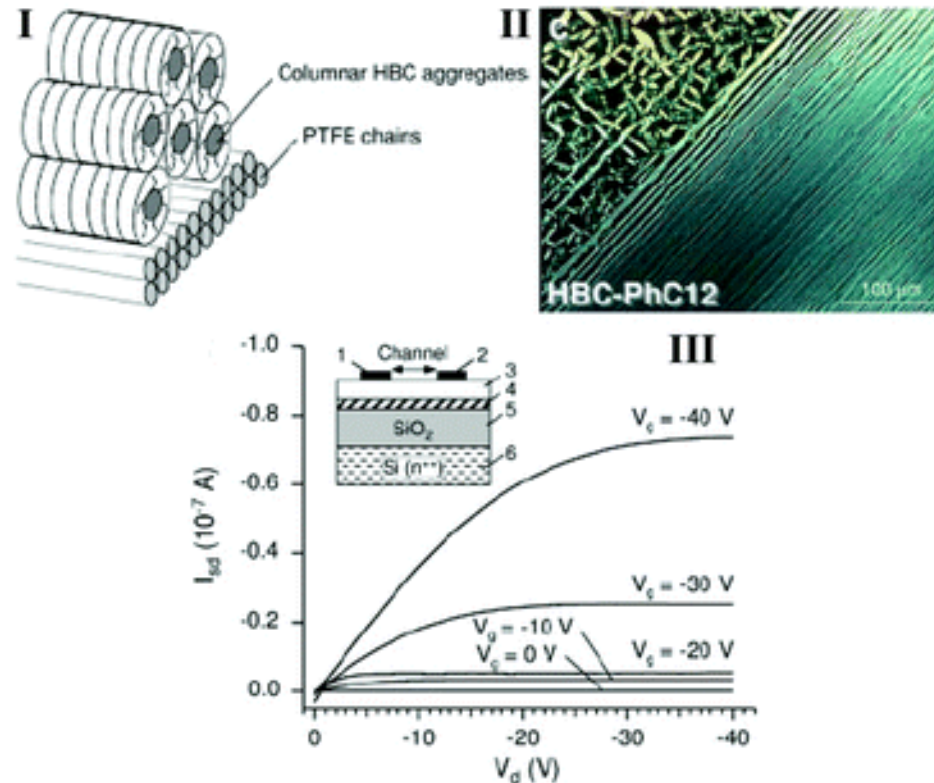
hexa-*peri*-hexabenzocoronene (HBC)



Field Effect Transistor: “edge-on”

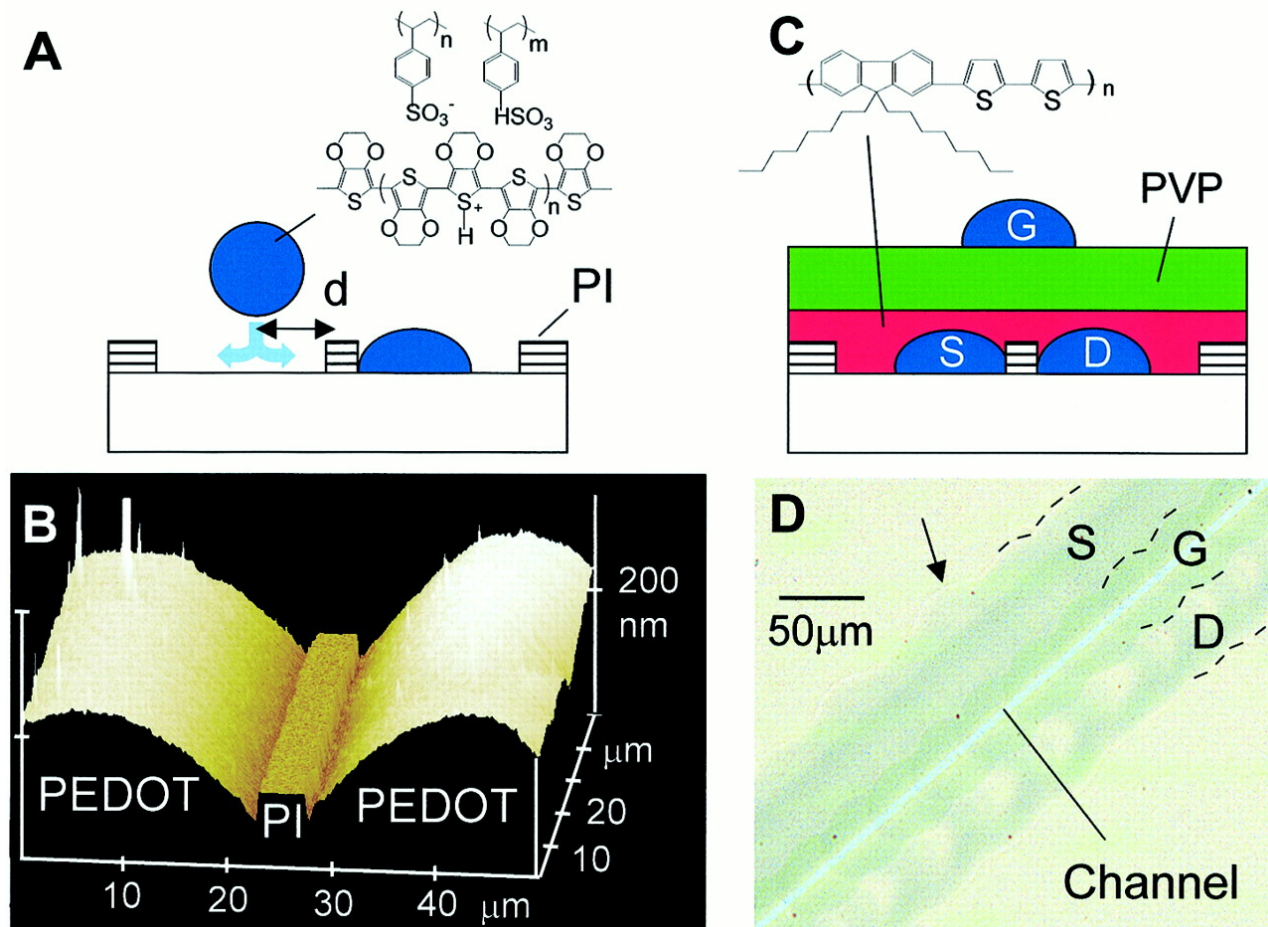


vs.



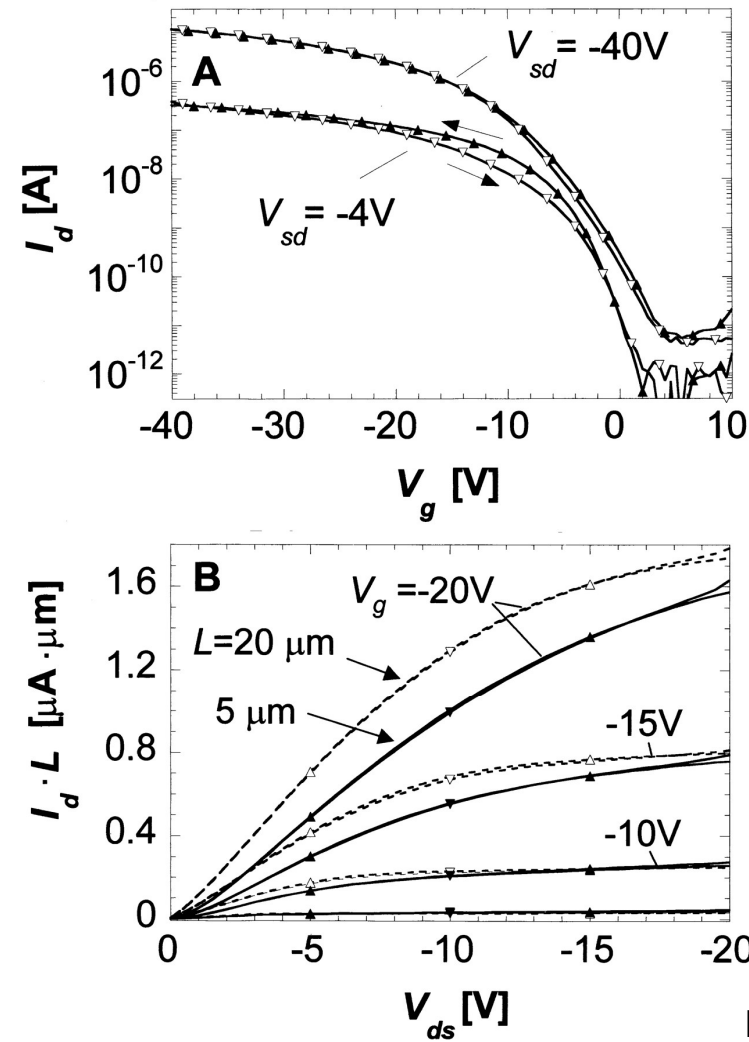
I) Schematic representation of the columnar HBC stacks lying edge-on and parallel with respect to the underlying PTFE chain. **(II)** Optical micrograph under crossed polarisers of **4e** showing glass areas with (lower right) and without (upper left) alignment layer. **(III)** FET device characteristics of an aligned HBC film.

Ink-jet Printed OFET's



H. Sirringhaus, Science, 290 (2000)

Fig. 1. (A) Schematic diagram of high-resolution IJP onto a prepatterned substrate. (B) AFM showing accurate alignment of inkjet-printed PEDOT/PSS source and drain electrodes separated by a repelling polyimide (PI) line with $L = 5 \mu\text{m}$. (C) Schematic diagram of the top-gate IJP TFT configuration with an F8T2 semiconducting layer (S, source; D, drain; and G, gate). (D) Optical micrograph of an IJP TFT ($L = 5 \mu\text{m}$). The image was taken under crossed polarizers so that the TFT channel appears bright blue because of the uniaxial monodomain alignment of the F8T2 polymer on top of rubbed polyimide. Unpolarized background illumination is used to make the contrast in the remaining areas visible, where the F8T2 film is in an isotropic multidomain configuration. The arrow indicates pronounced roughness of the unconfined PEDOT boundary.

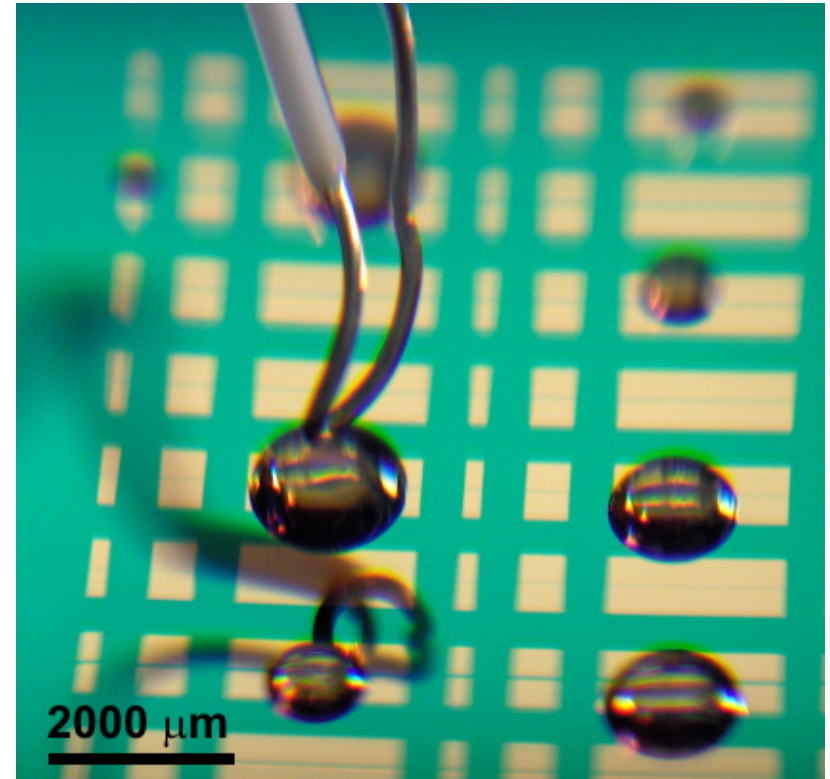


H. Sirringhaus, Science, 290 (2000)

A) Transfer characteristics of an IJP TFT with F8T2 aligned uniaxially parallel to the current flow ($L = 5 \mu m$, $W = 3000 \mu m$) measured under an N₂ atmosphere. Subsequent measurements with increasing (solid symbols) and decreasing (open symbols) gate voltage are shown. **(B)** Scaling of the output characteristics of IJP F8T2 TFTs normalized by multiplying the drain current by the channel length (dashed lines with open symbols, $L = 20 \mu m$; solid lines with solid symbols, $L = 5 \mu m$). Subsequent measurements with increasing (upward triangles) and decreasing (downward triangles) gate voltage are shown.

3. Electrolyte-gated OFETs

The use of a polyelectrolyte allows combining the advantages of the electrochemical transistors (**low-voltage** $<1V$, **robustness**, **less sensitive to thickness**) and the advantage of the OFETs (**fast response** $< 0.3ms$).



Low-cost plastic transistors

- 1) For portable applications: compatible with printable batteries ($\sim 1.5\text{V}$)

→ Low voltage

- 2) For “one-use” applications: compatible with roll-to-roll printing techniques

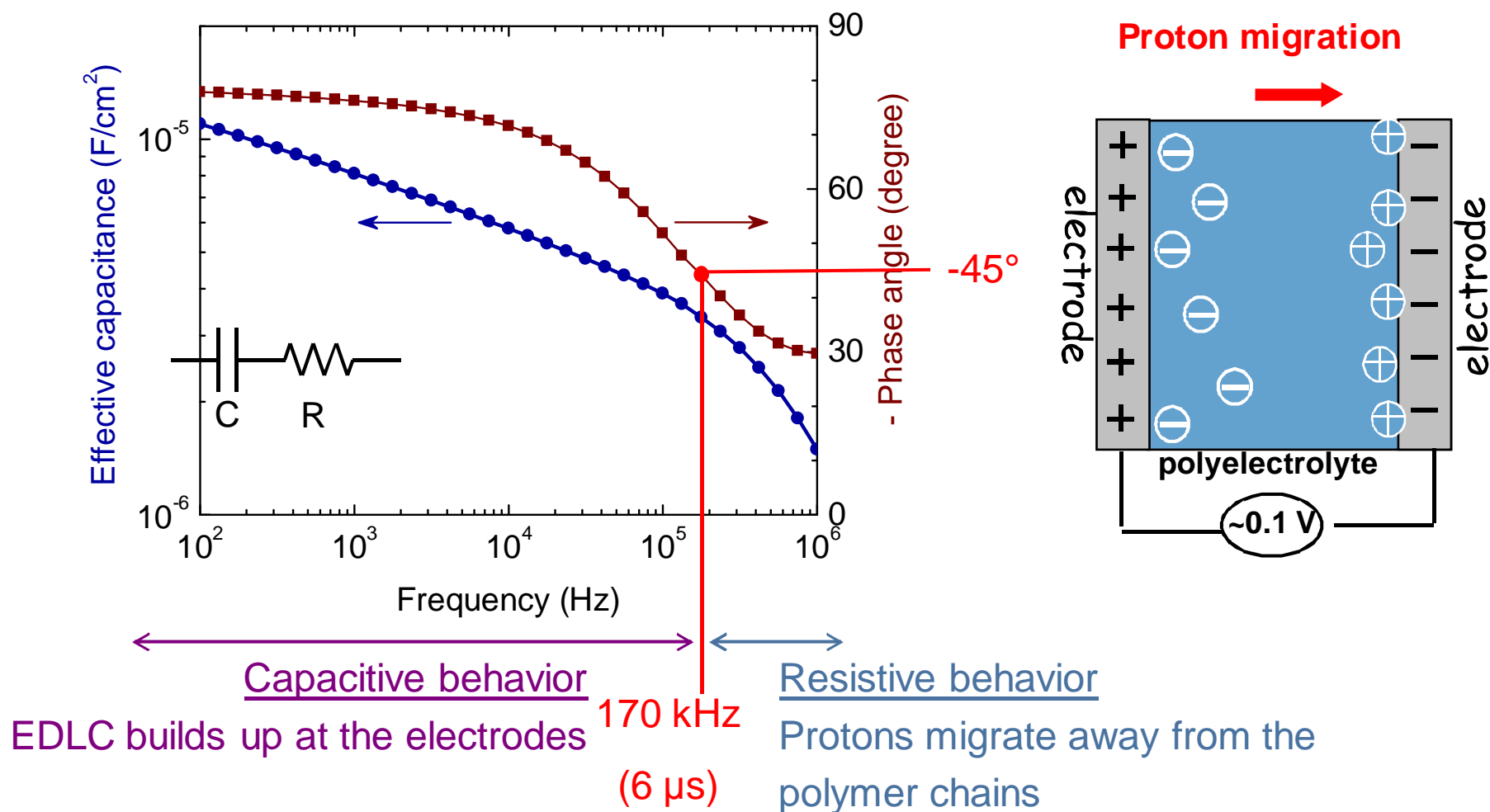
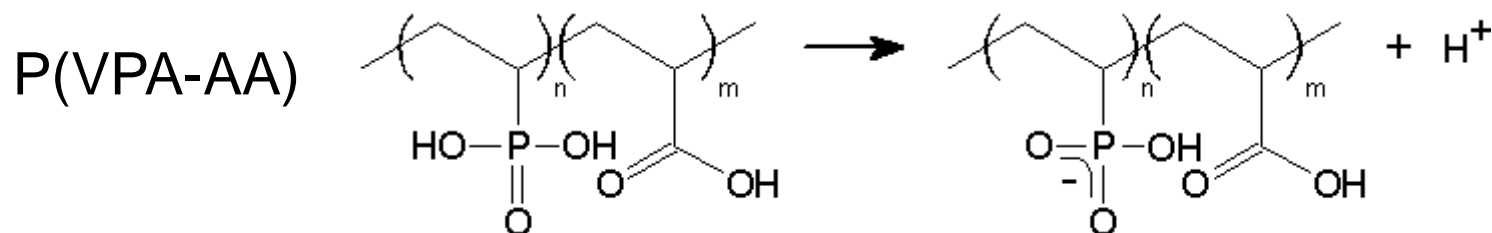
→ Robustness, printable electrodes, thicker layers

- 3) For logic applications:

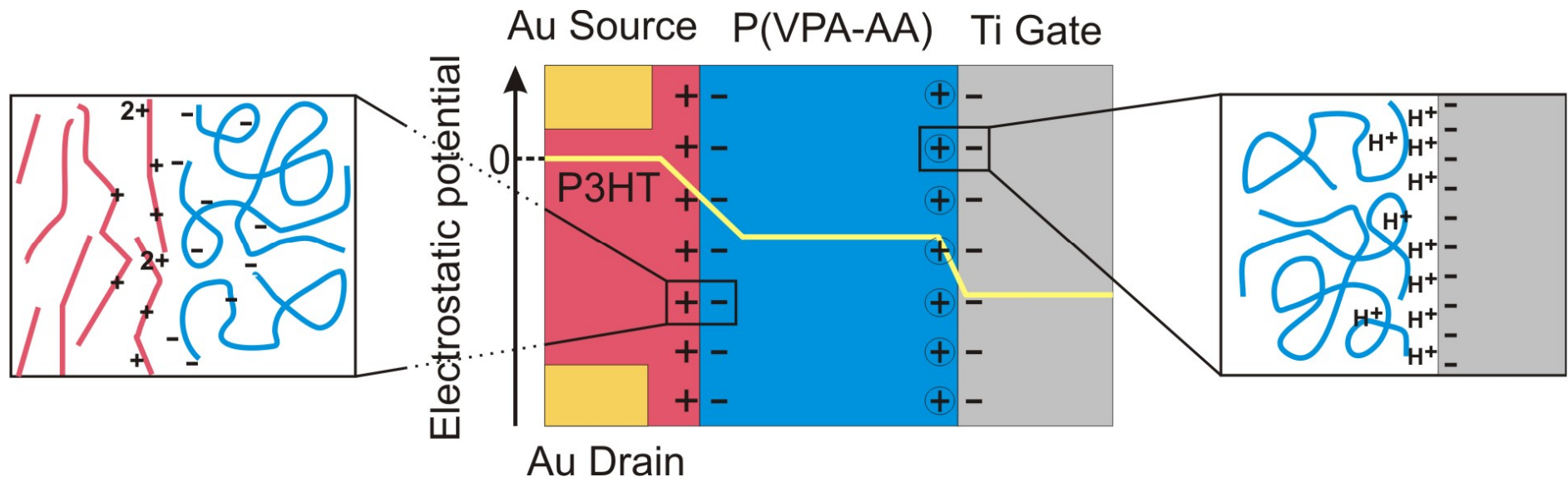
→ Fast response, low capacitive currents

The Challenge: To combine those properties

Electric double layer capacitors (EDLCs)

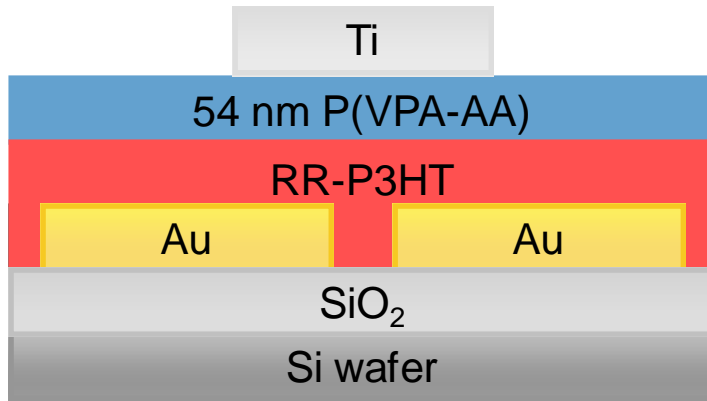


Electric double layer capacitor gated OFETs

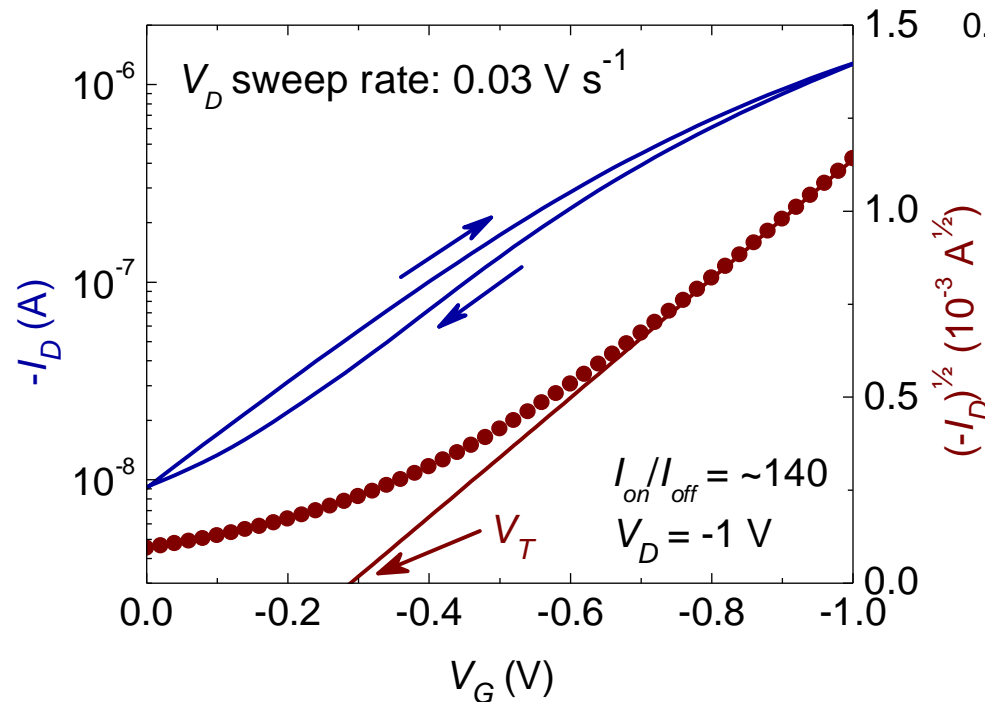
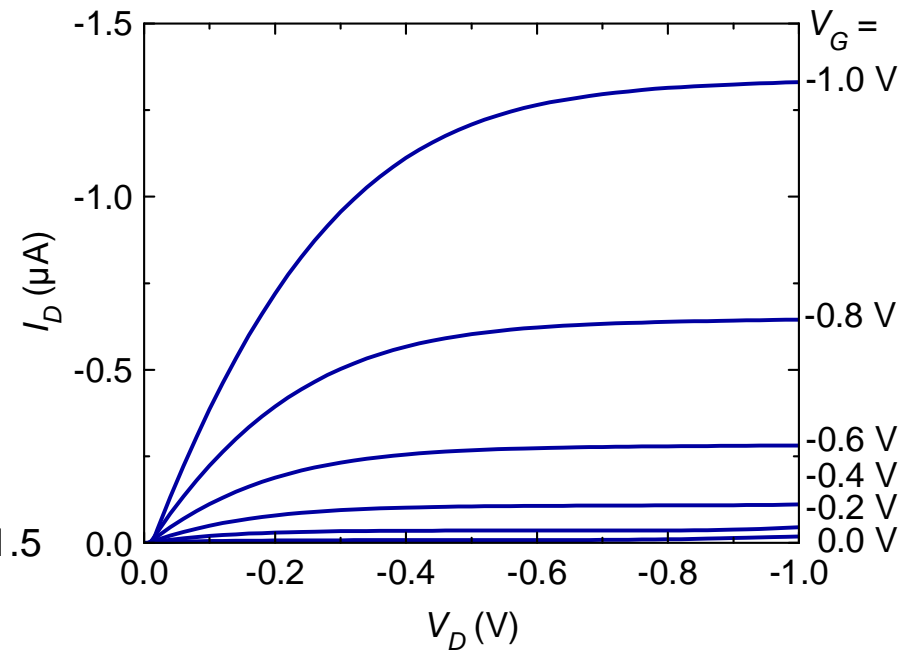


1. Protons migrate to the gate and form an EDLC
2. Simultaneously, holes injection at Au/P3HT contact and formation of an EDLC at the P3HT-polyanion interface
3. ➔ The channel is open

Transistor characteristics



$L = 9 \mu\text{m}$, $W = 200 \mu\text{m}$

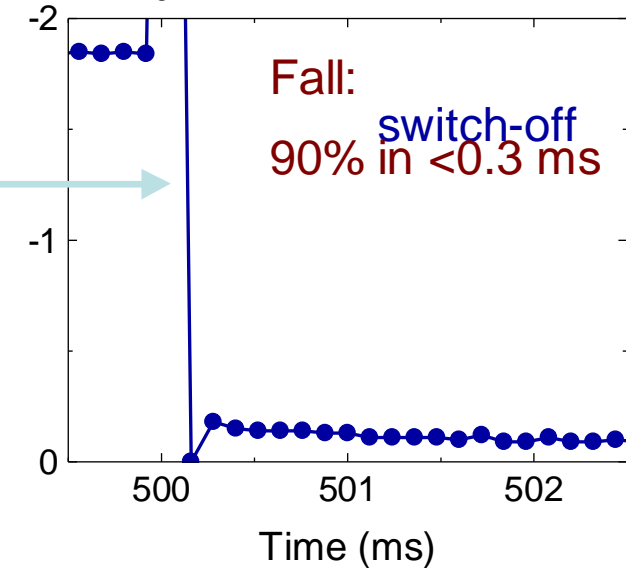
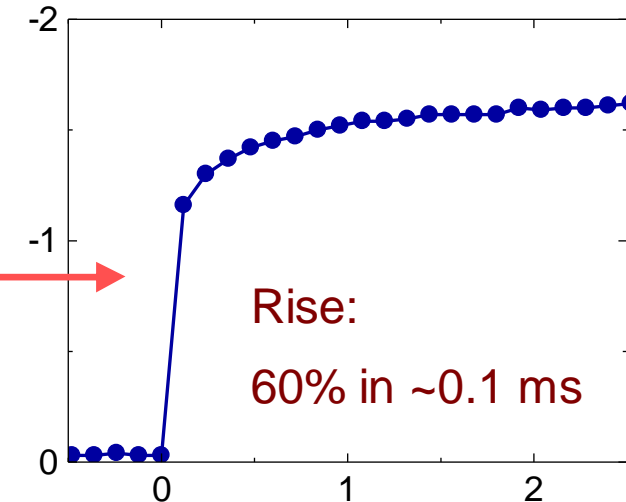
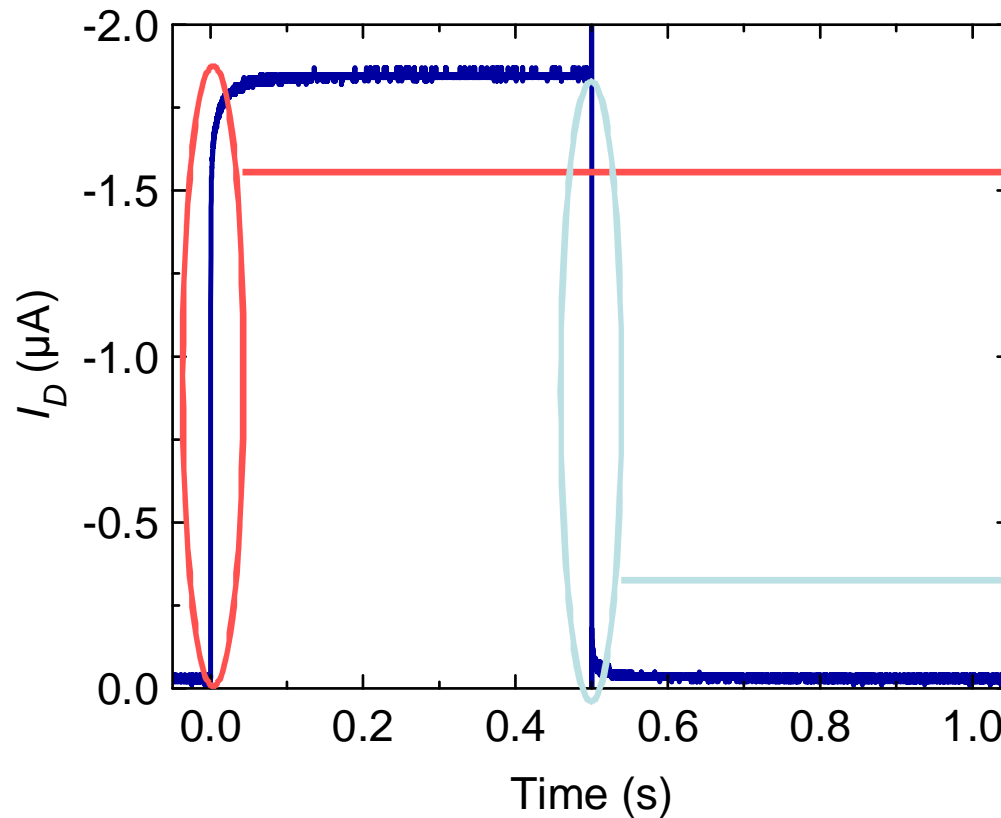


$$I_D^{sat} = \frac{W}{2L} \mu C_i (V_G - V_T)^2$$

Extracted mobility:
 $\sim 0.012 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$

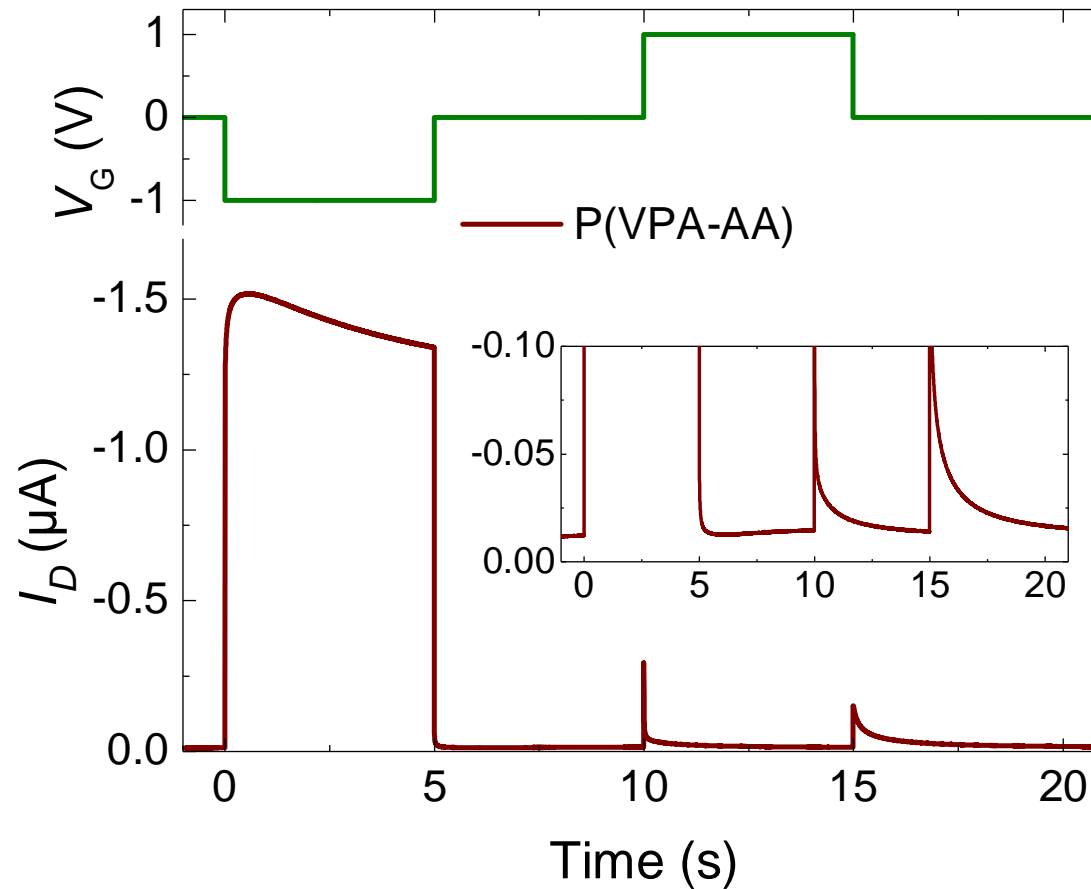
Response Time

$$V_D = -1 \text{ V}; V_G = \begin{cases} -1 \text{ V} & \text{when } 0 \text{ s} \leq t \leq 0.5 \text{ s} \\ 0 \text{ V} & \text{otherwise} \end{cases}$$

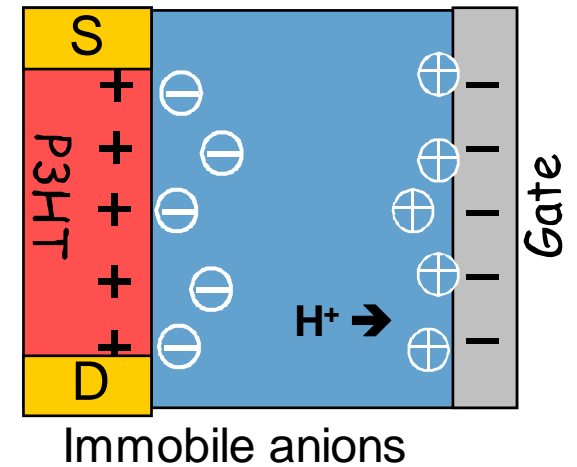


Towards the mechanism

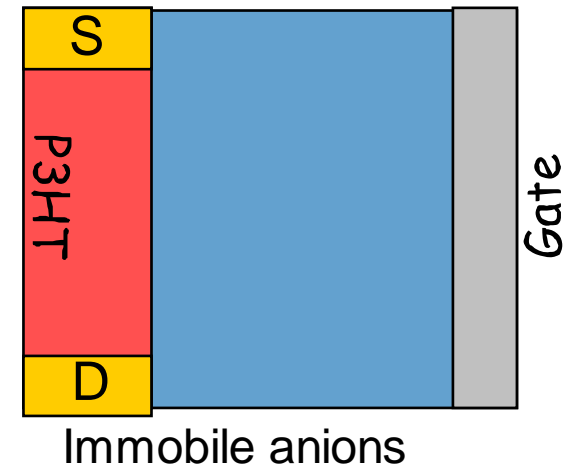
A. Field-effect vs. Electrochemistry



OFET is ON

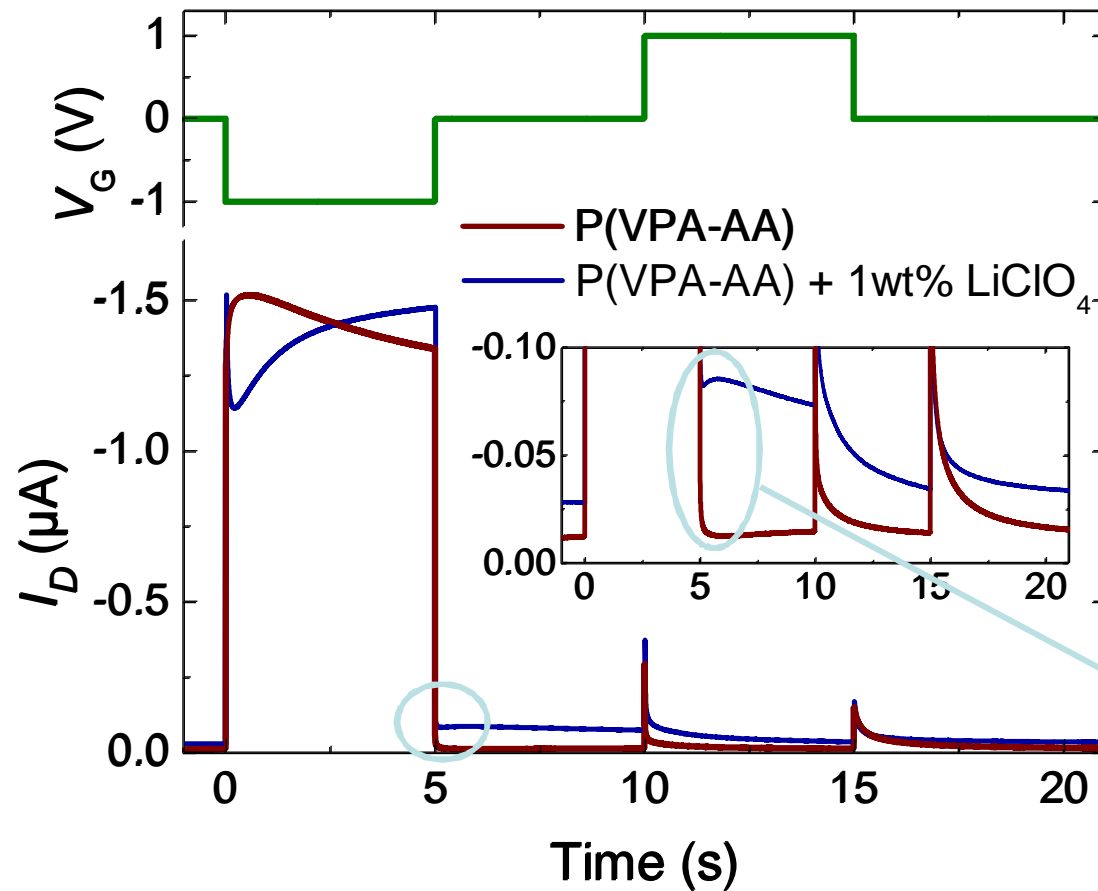


OFET is OFF

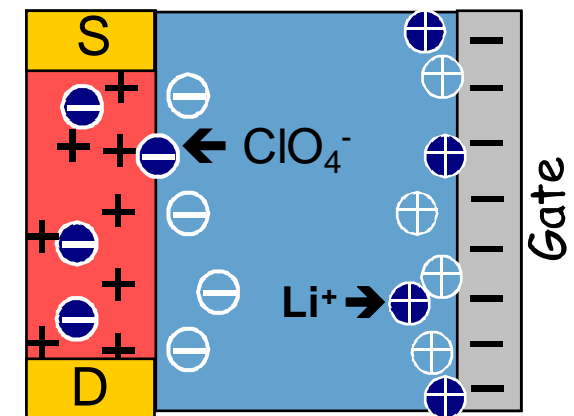


Towards the mechanism

A. Field-effect vs. Electrochemistry

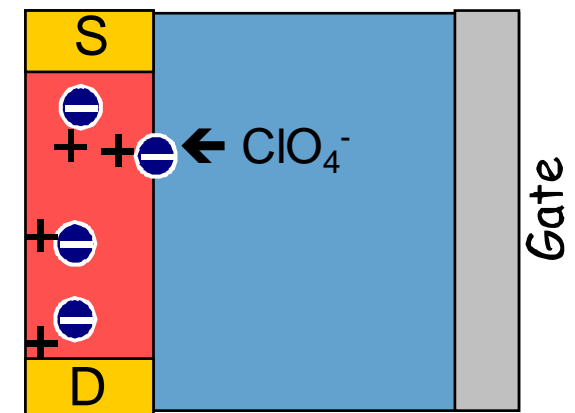


Electrochemical transistor is ON



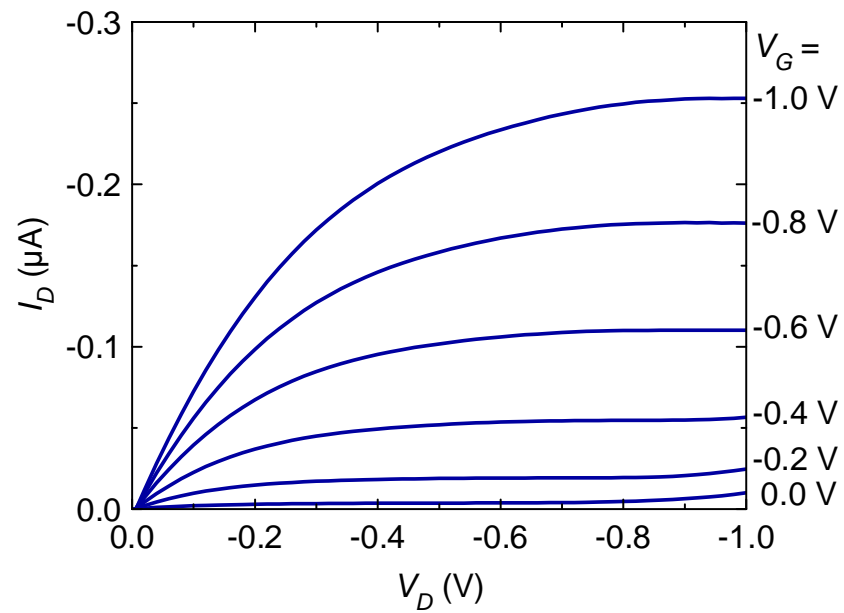
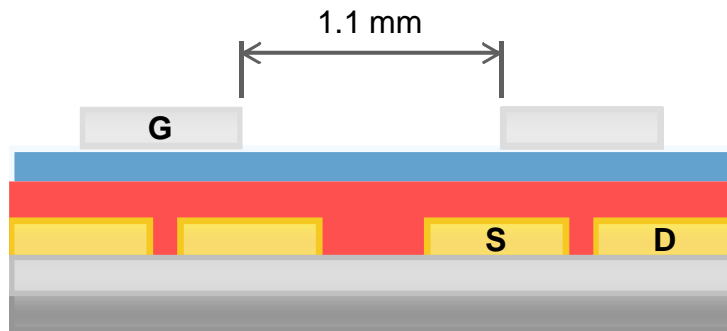
Penetration of anions

$V_G = 0$, but not completely OFF

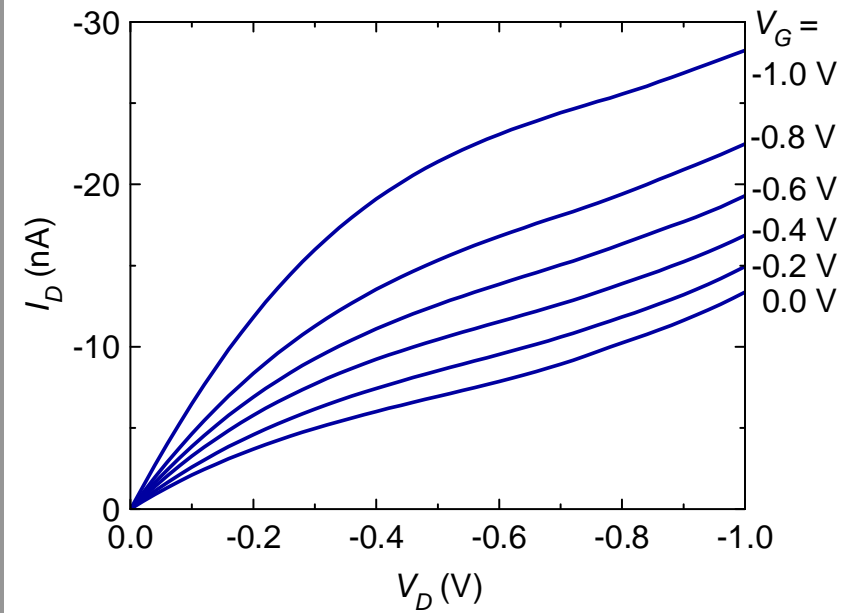
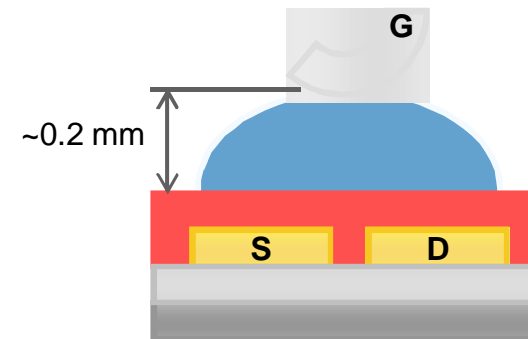


B. EDLC builds independently of the channel-gate distance

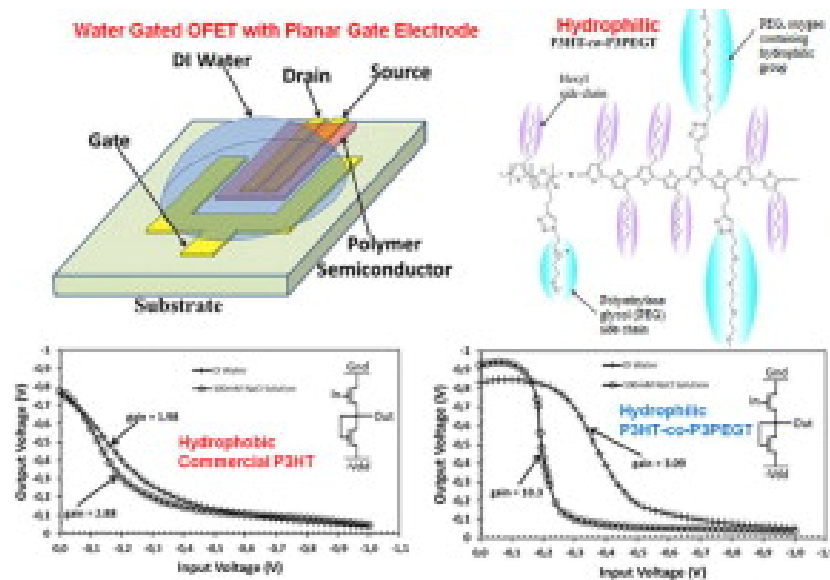
Laterally gated OFET



Hemispherical PE

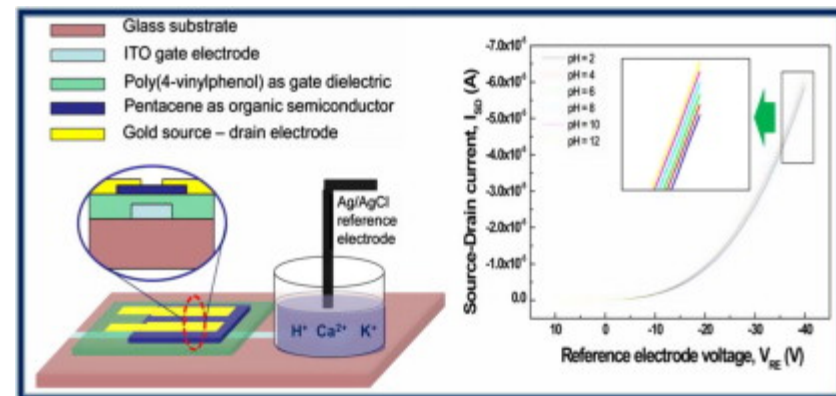


Planar water gated organic field effect transistor



*Organic Electronics, Volume 15,
Issue 3, March 2014, Pages 646-653*

Organic field-effect transistor with extended indium tin oxide gate structure for selective pH sensing



*Organic Electronics, Volume 12,
Issue 11, November 2011, Pages 1815-1821*

Fabrication Method

Planar water gated Organic Field Effect Transistor

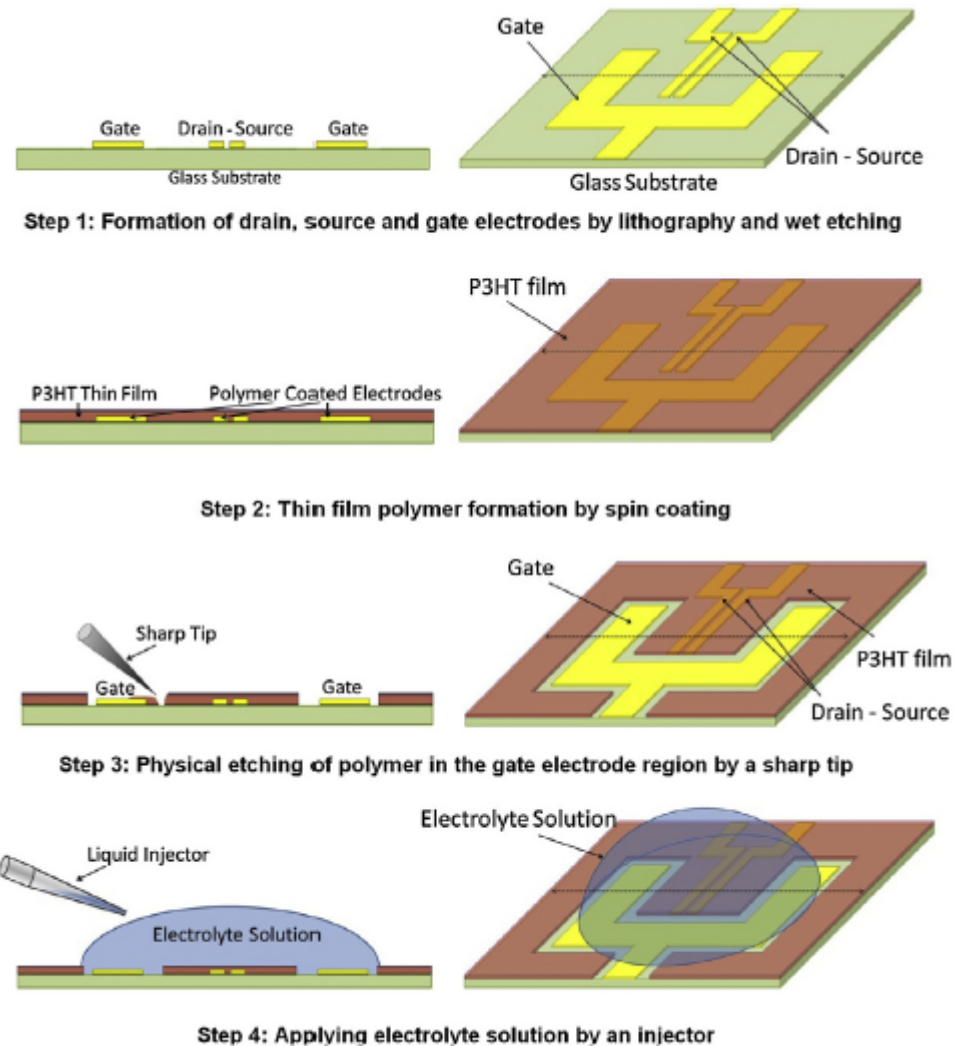


Fig. 2. Fabrication process flow of planar WG-OFET.

Design and Fabrication

Planar Water Gated Organic Field Effect Transistor

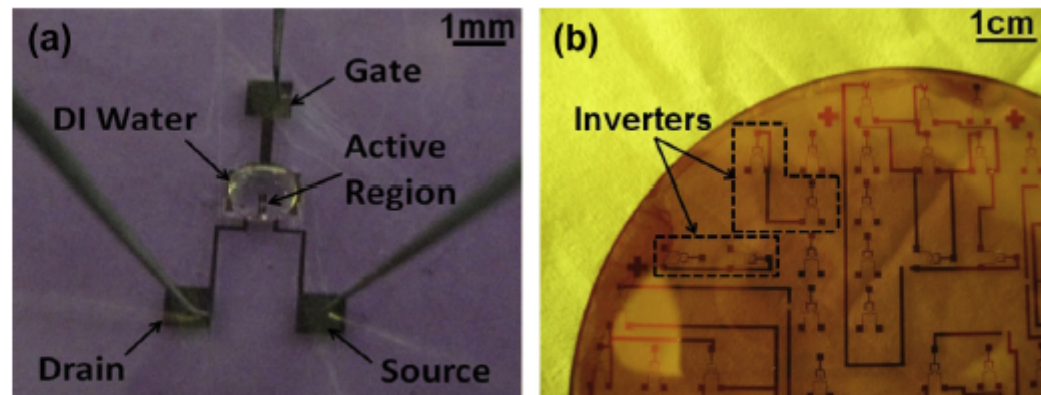
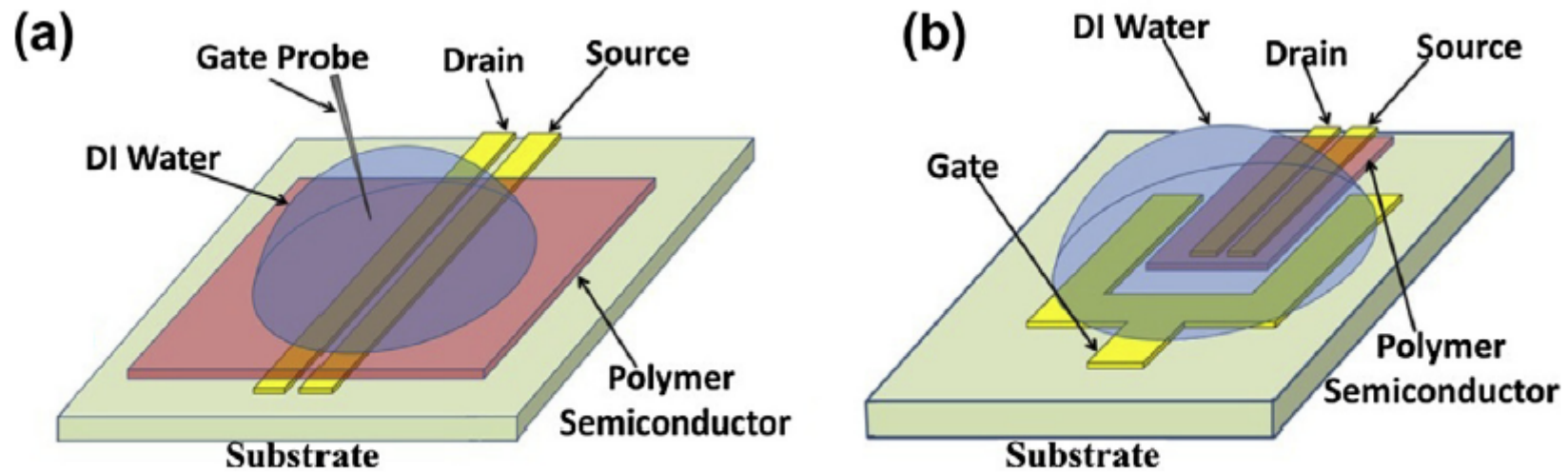
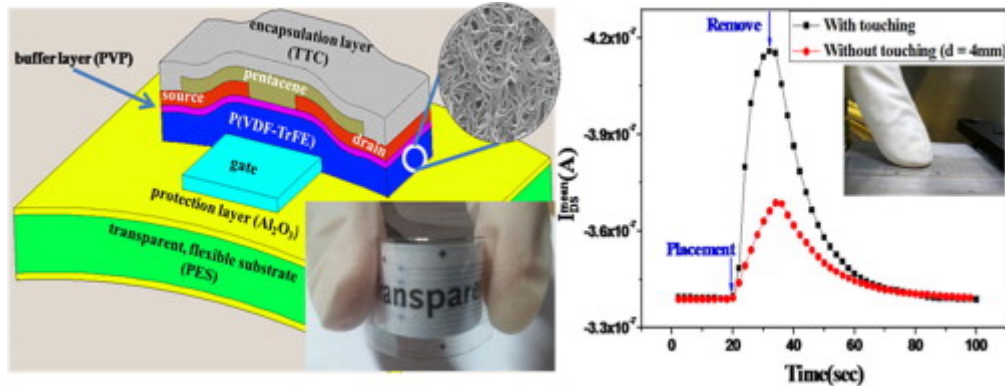


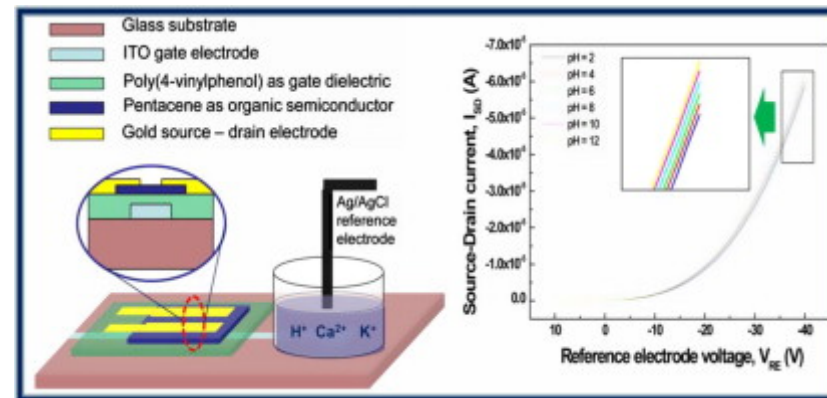
Fig. 3. (a) Photograph of a fabricated planar WG-OFET. Background color is purple due to spin-coated polymer film and (b) fabricated inverters

Transparent and flexible organic field-effect transistor for multi-modal sensing



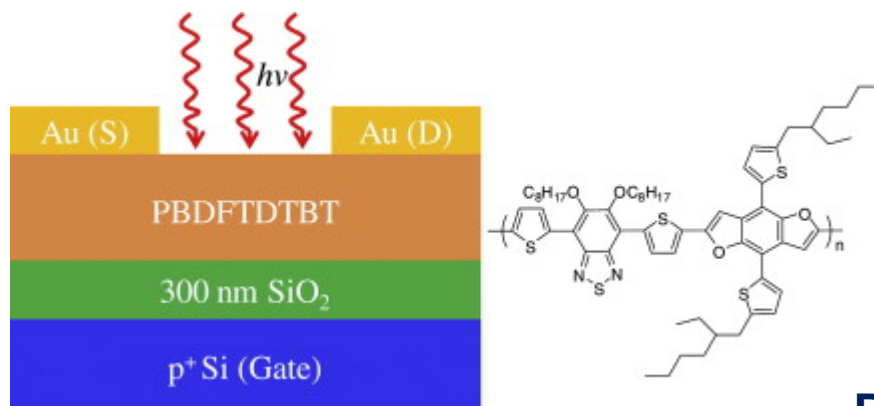
Organic Electronics, Volume 13, Issue 4, April 2012, Pages 533-540

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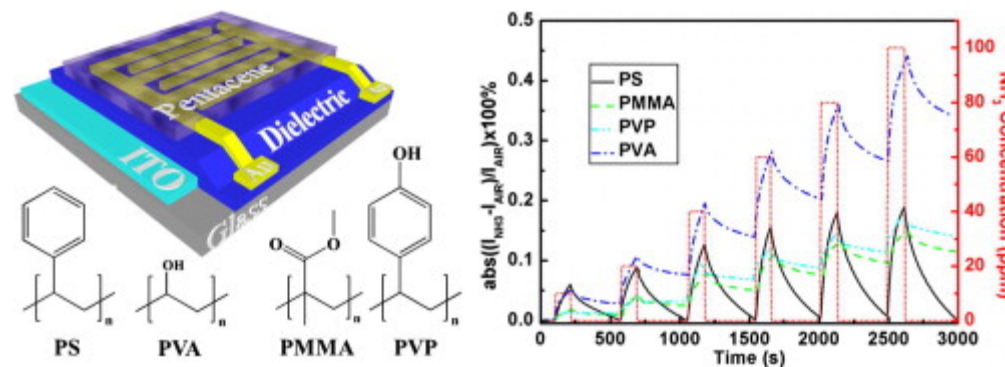
Organic Electronics, Volume 12, Issue 11, November 2011, Pages 1815-1821

Organic field-effect transistor and its photoresponse



*Organic Electronics, Volume 15,
Issue 5, May 2014, Pages 1050-1055*

Polymer dielectric layer functionality in organic field-effect transistor based ammonia gas sensor



*Organic Electronics, Volume 14,
Issue 12, December 2013, Pages 3453-3459*