Shenyang-2008

Device Physics and Applications of Organic Thin Film Transistors

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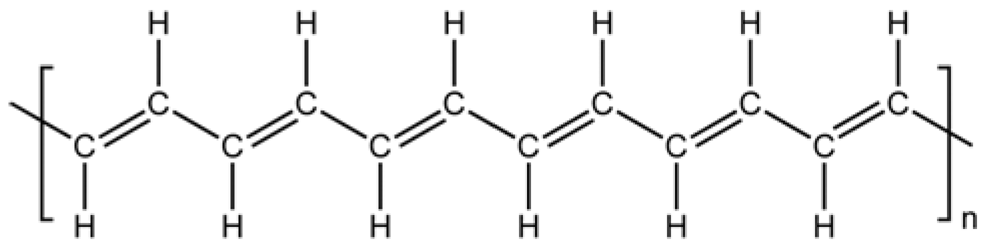
Contents

- Conduction mechanism of organic semiconductors
- Application of organic devices
- Organic thin film transistor
- Organic phototransistor
- DNA sensor based on OTFTs

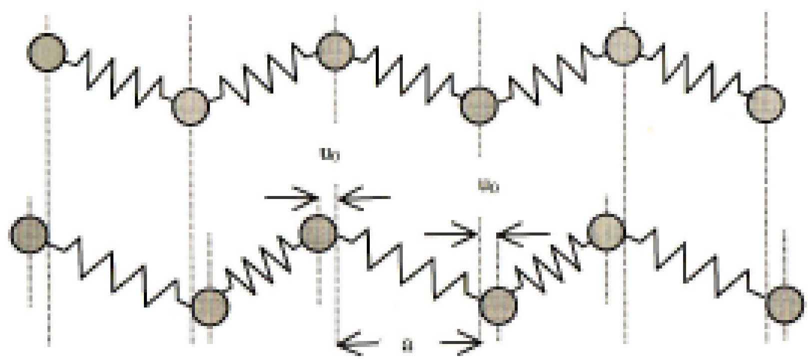
I. Conduction mechanism of organic semiconductors

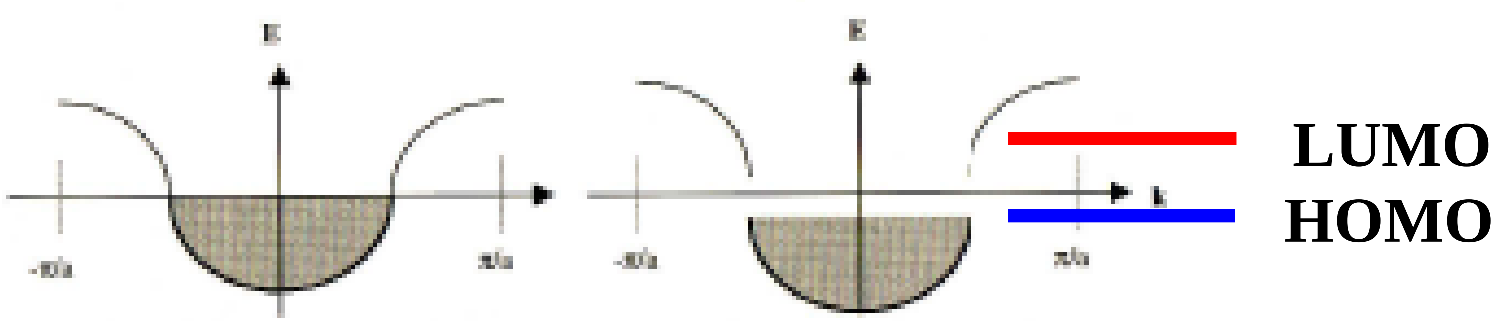
1.1 Semiconducting polymers



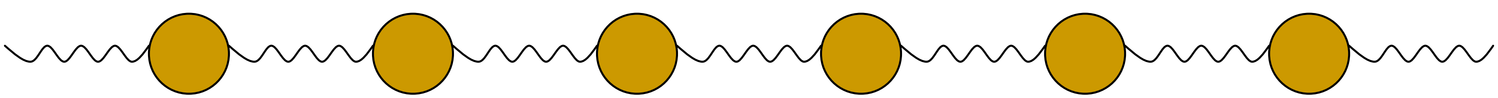
polyacetylene

Peierls transition





Transition from metallic to semiconductor due to Peierls distortion



2n states for ***n*** C atoms,

1.2 Conduction mechanism

1. Small polaron hopping (Holstein's model)

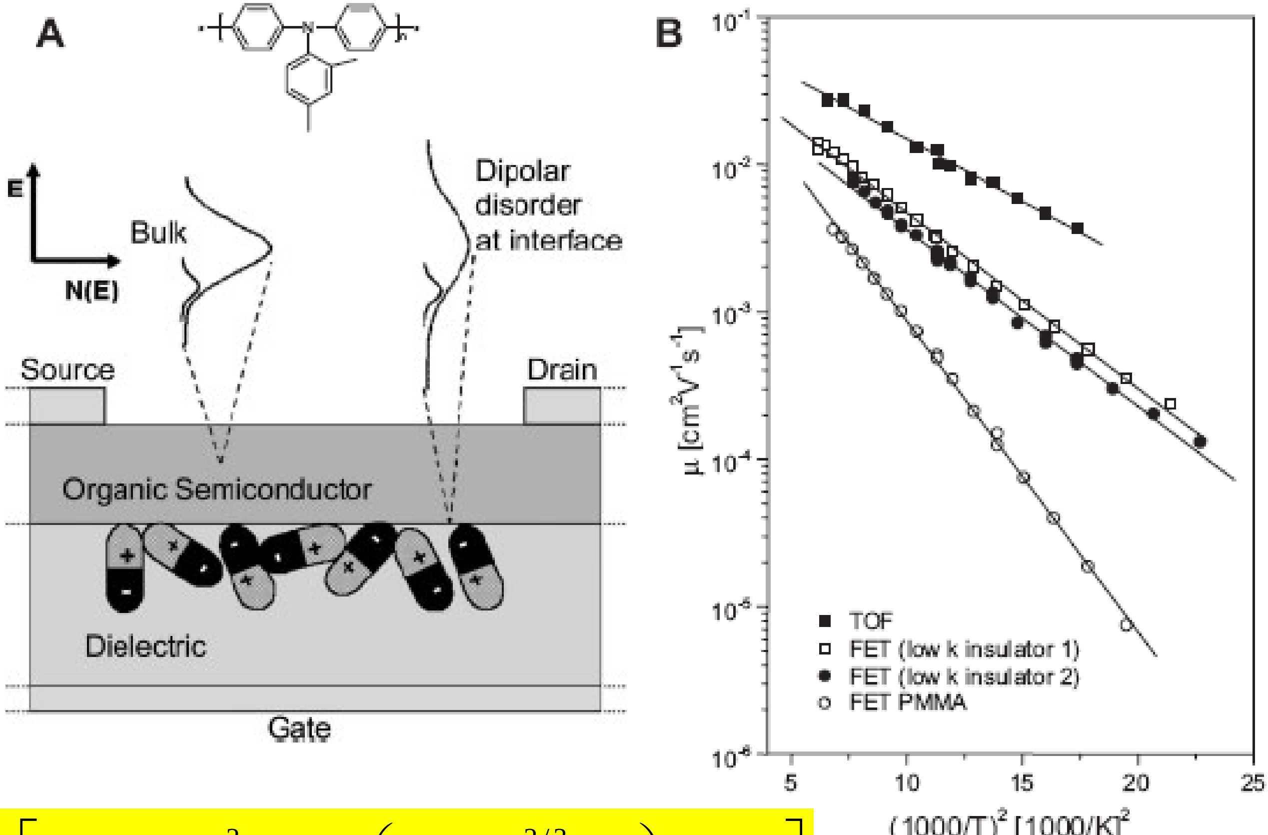
$$\mu = \sqrt{\frac{\pi}{2}}\frac{ea^2}{\hbar}\frac{J^2}{\sqrt{E_b}}(kT)^{-3/2}\exp(-\frac{E_b}{2kT})$$

E_b: polaron binding energy

J : nearest-neighbor interaction energy

Strong Interaction with photon
high effective mass
hole transport is associated with lattice distortion

2. Hopping model (Bässler,1993, Novikov 1998)



PTAA

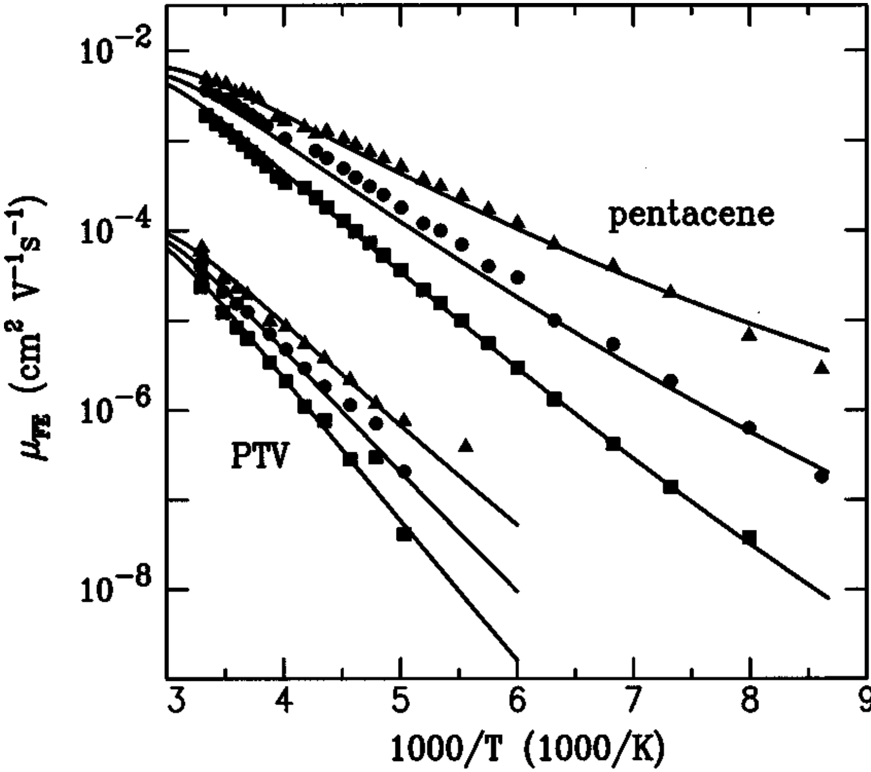
$$\log \mu \propto 1/T^2$$

$$\mu = \mu_0 \exp\left[-\left(\frac{3\sigma}{5k_BT}\right)^2 + 0.78\left(\left(\frac{\sigma}{k_BT}\right)^{2/3} - 2\right)\sqrt{\frac{eaE}{\sigma}}\right]$$

3. variable-range hopping transport (Vissenberg 1998)

$$g(\in) = \frac{N_t}{k_B T_0} \exp\left(\frac{\in}{k_B T_0}\right) \qquad (-\infty < \in \leq 0)$$

$$\mu_{\text{FE}} = \frac{\sigma_0}{e} \left[\frac{\left(\frac{T_0}{T}\right)^4 \sin\left(\pi \frac{T}{T_0}\right)}{(2a)^3 B_c} \right]^{T_0/T} p^{T_0/T-1}$$

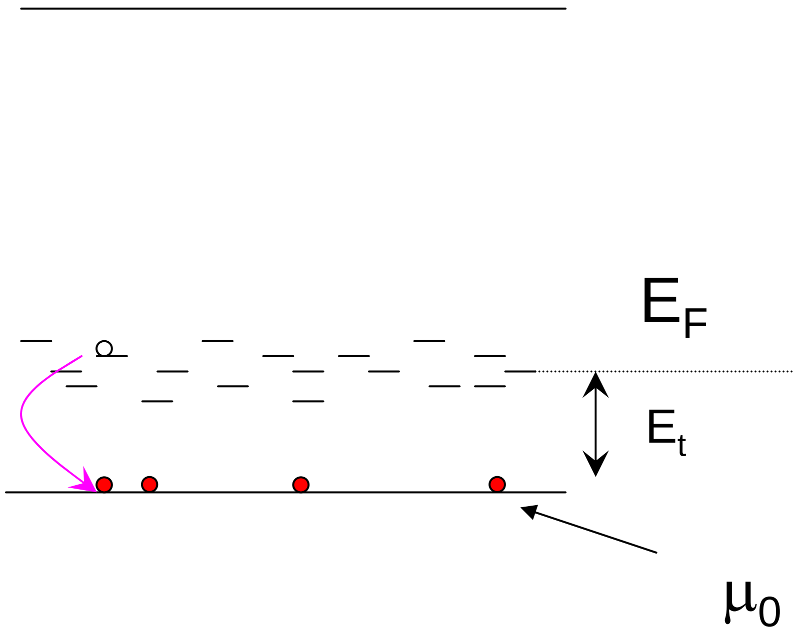


V_G =-20 V (triangles),-10 V (circles), and -5 V (squares).

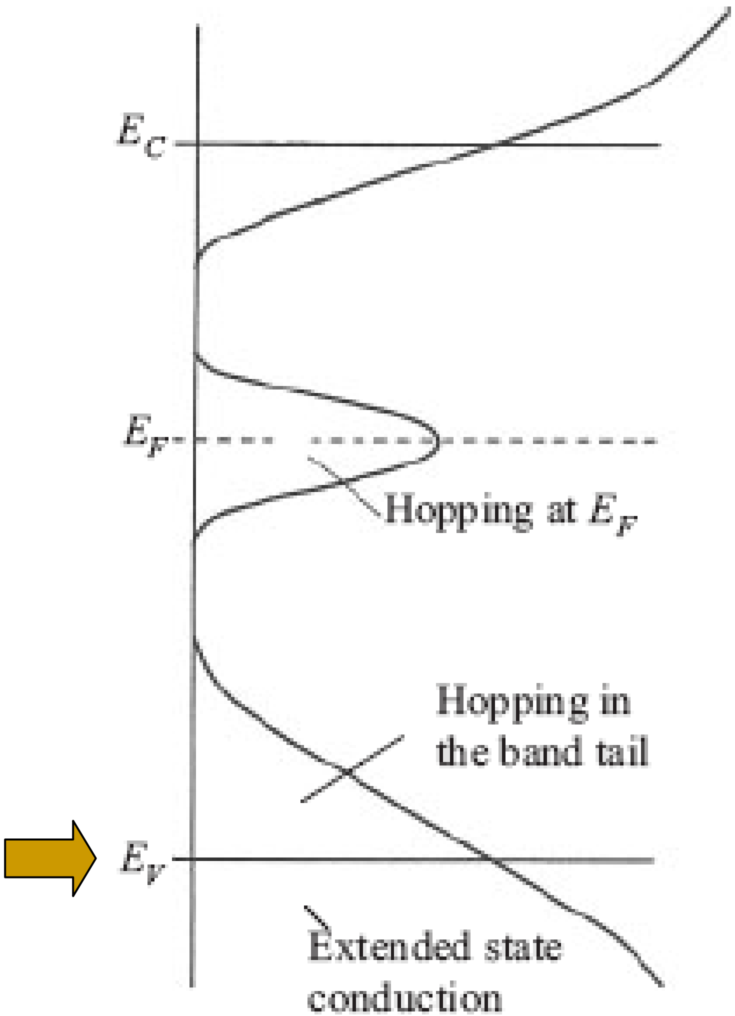
4. multiple-trapping model (for a-Si)

$$\mu_D = \mu_0 \alpha \exp(-\frac{E_t}{kT})$$

μ_D :drift mobility,
μ_0 :mobility of carriers in valence band
E_t :the distance between Fermi level and valence band energy
T :temperature
$\alpha = N_V/N_T$



mobility edge



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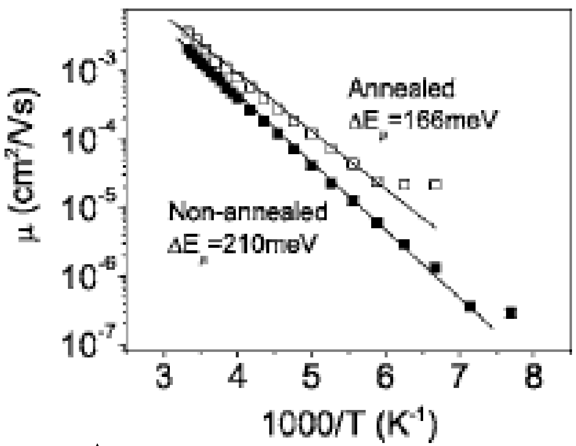
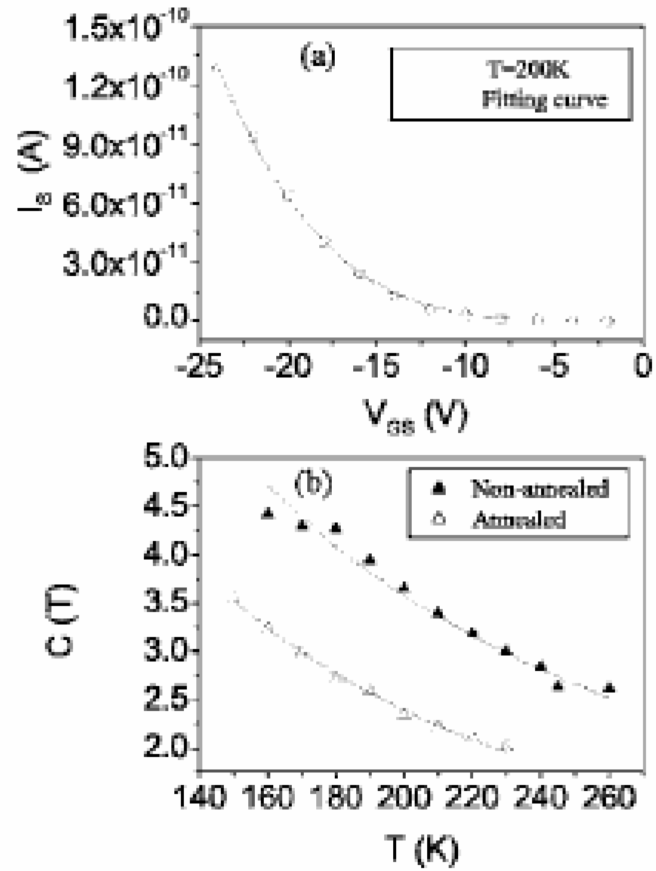
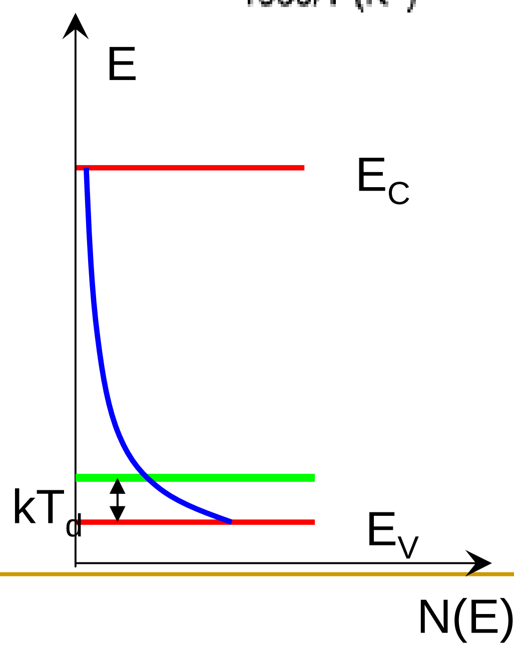




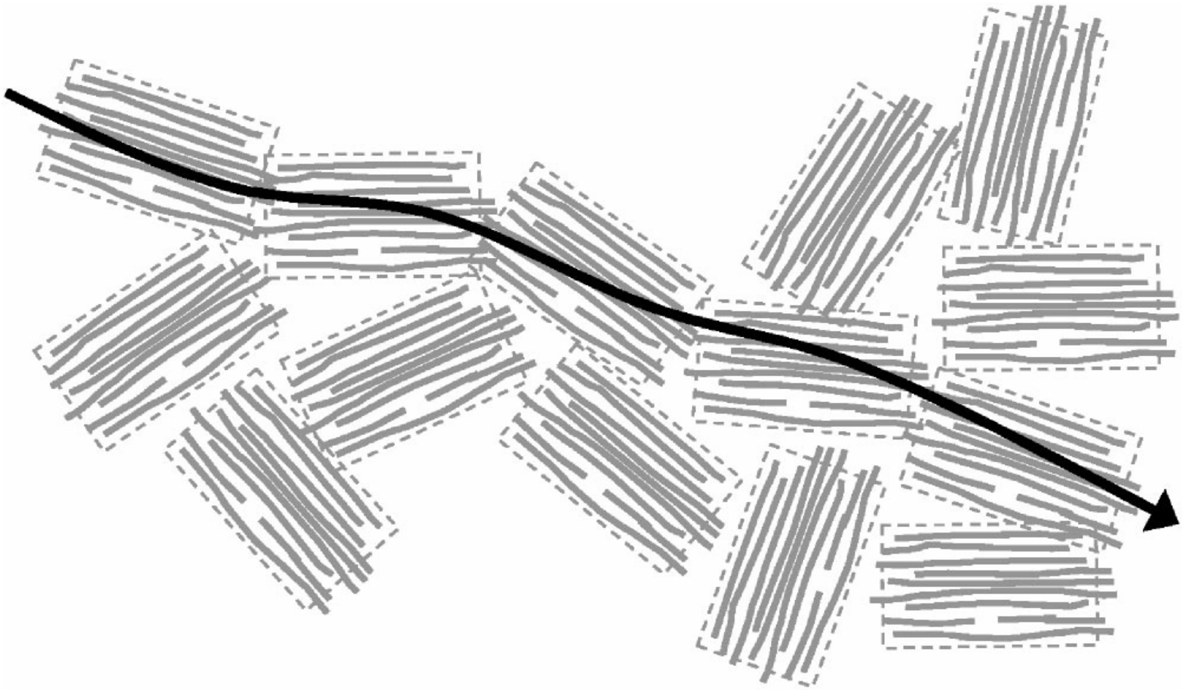


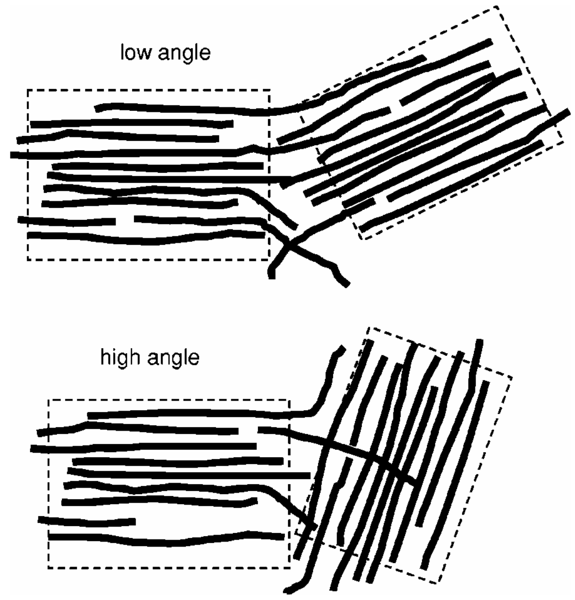
$$N(E) = N_d \exp[(E_V - E)/kT_d]$$

$$T_d = 458K$$

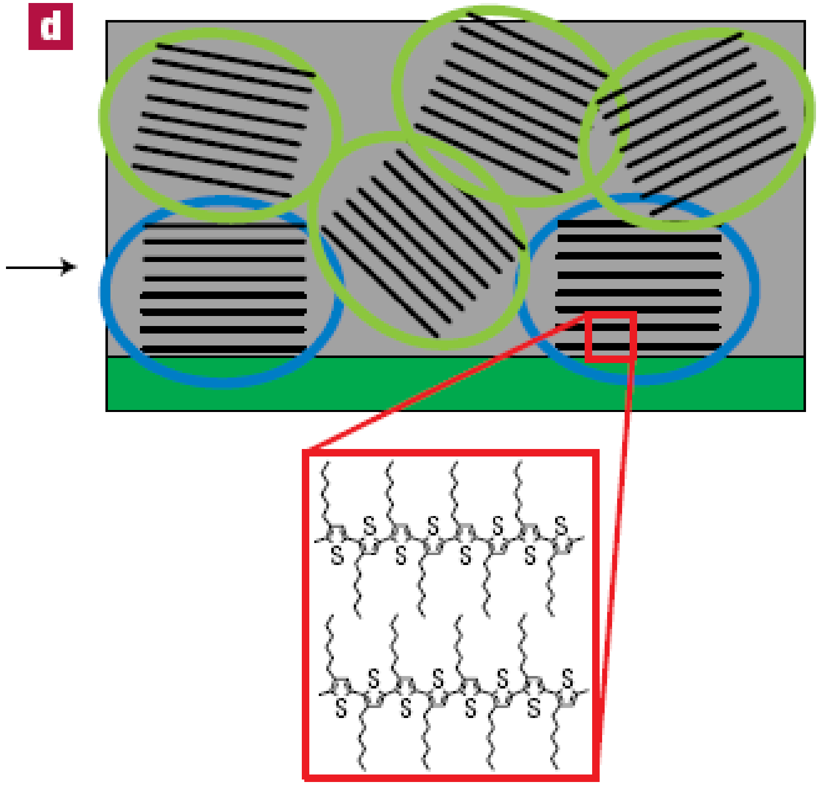
F8T2, JAP, 101, 064501 (2007)

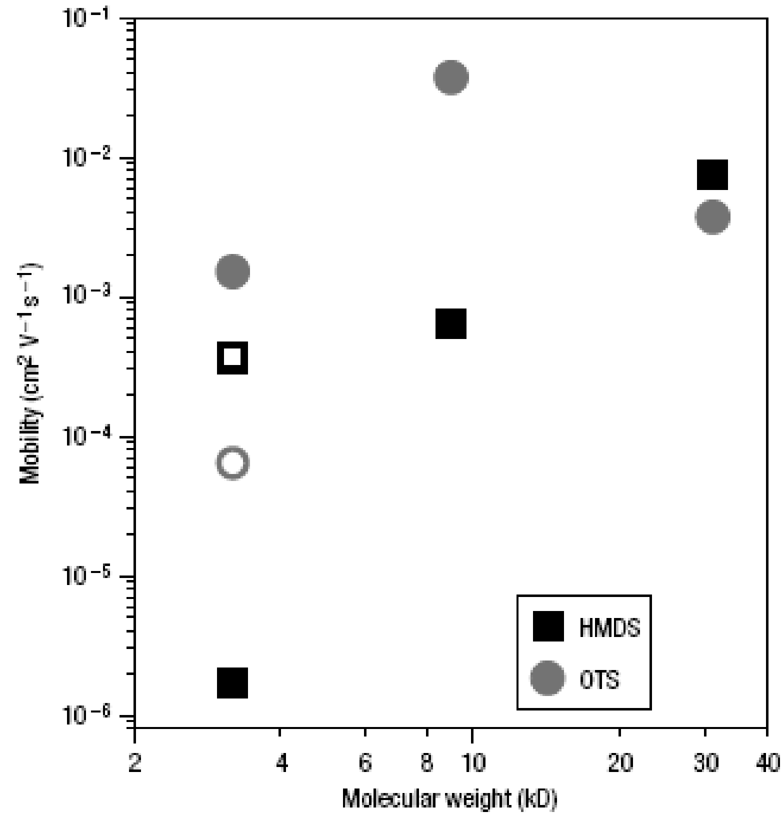
5. Effect of microstructure





PRB, 71, 165202 (2005)

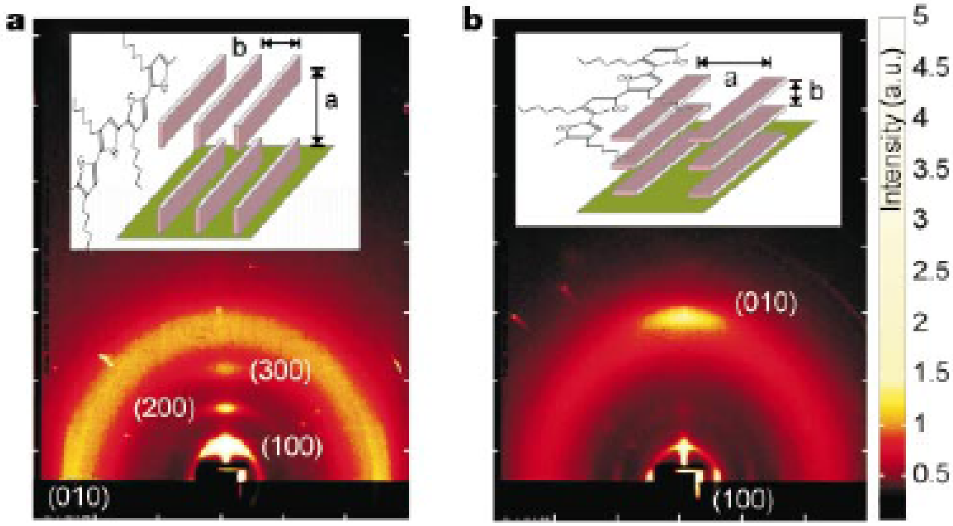


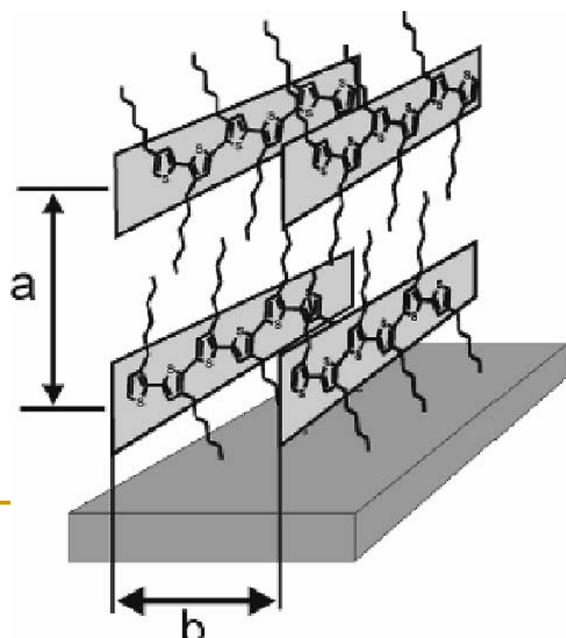


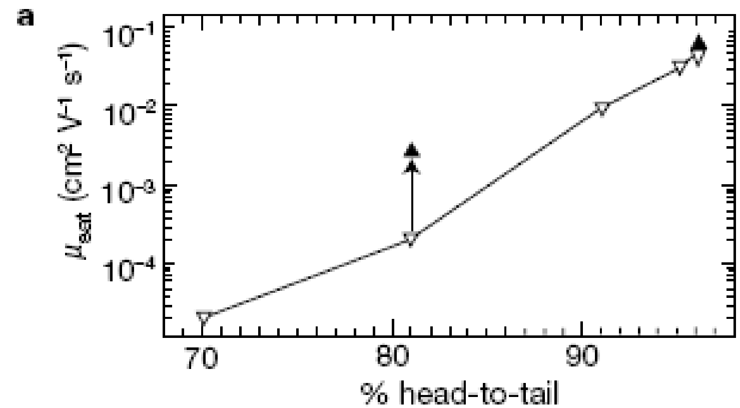
- Annealing condition
- Molecular weight
- substrate

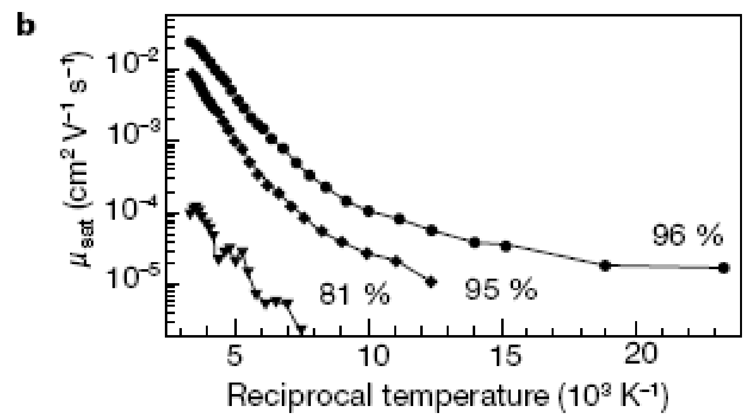
Nat.Mat. 2006

Shenyang-2008

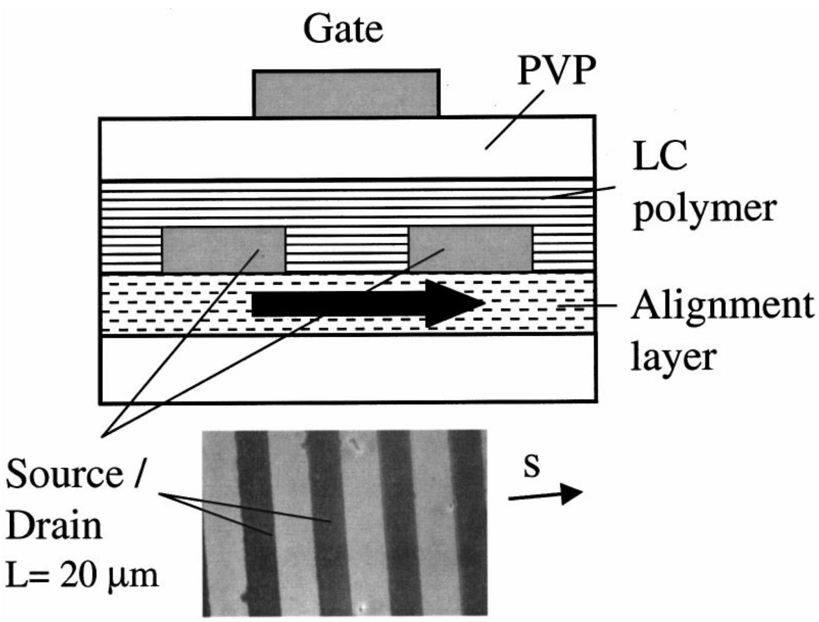


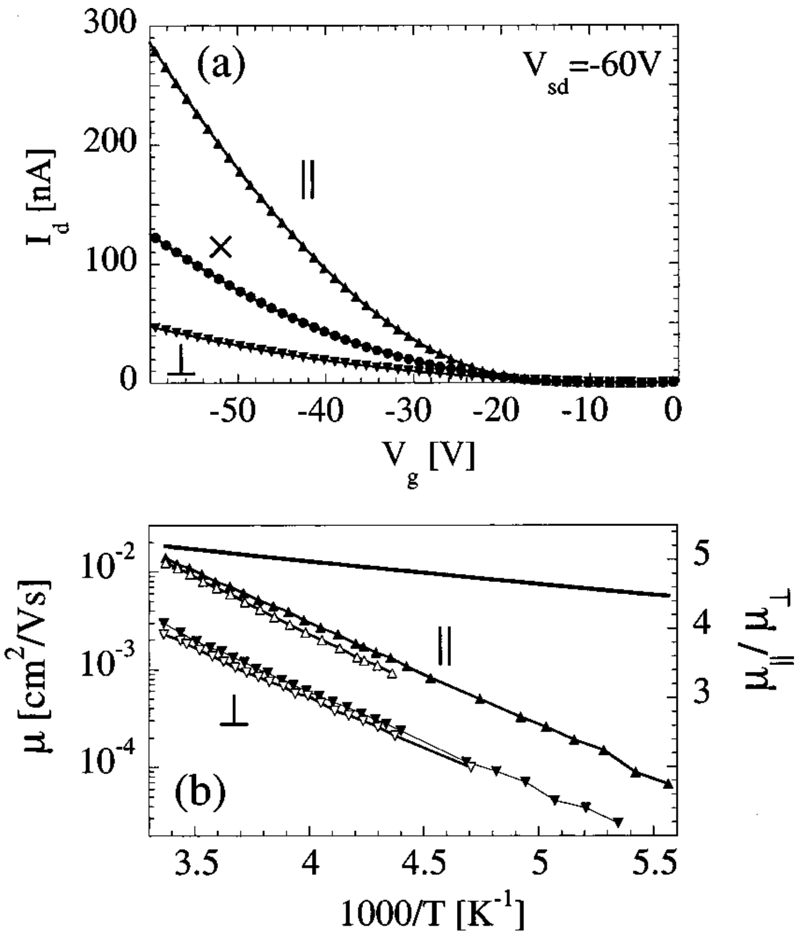






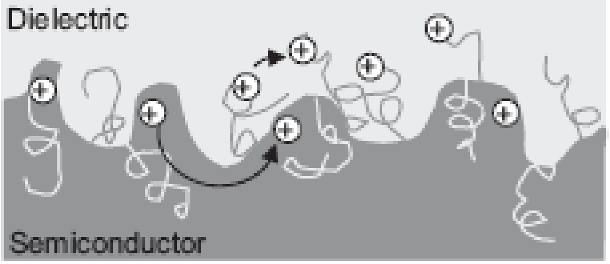
Nature, 401, 485 (1999)

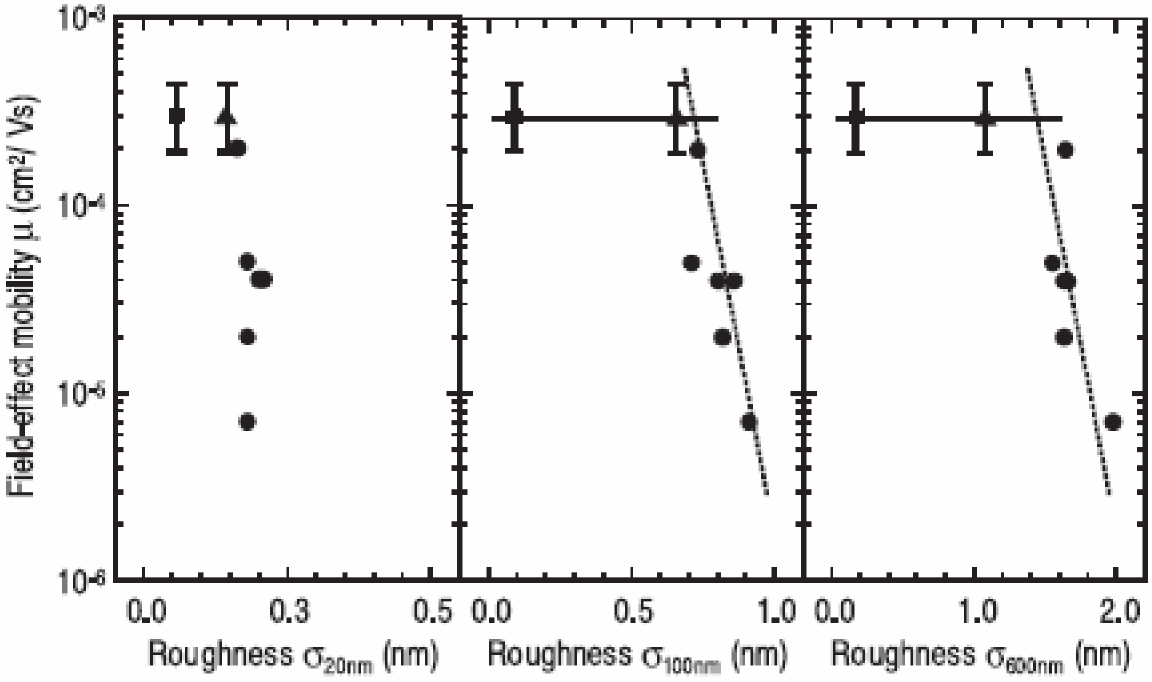




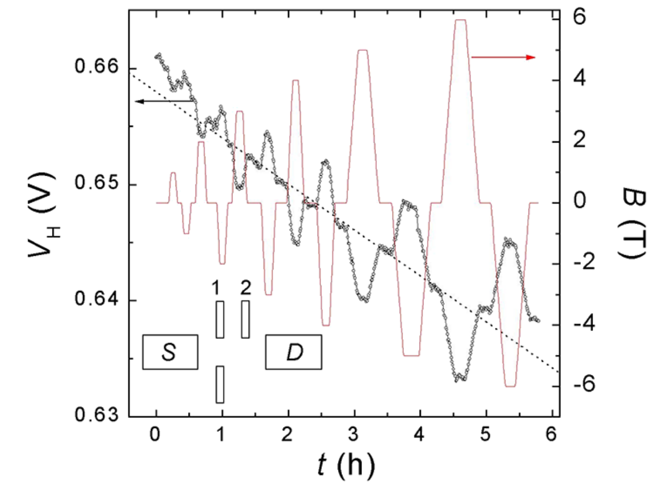
APL, 77. 406 (2000)

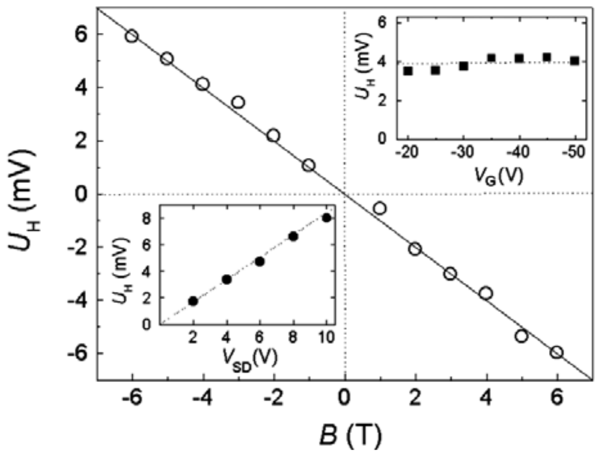
6. Effect of interface

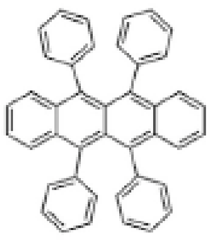




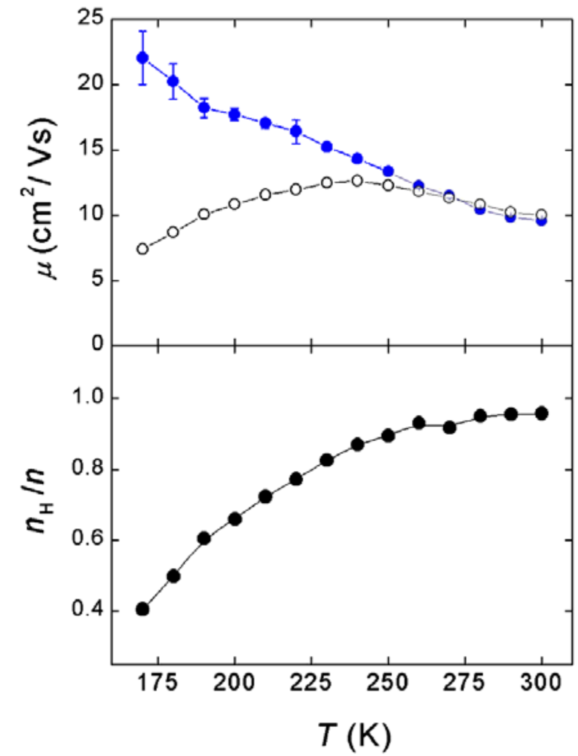
1.3 Small molecule organic semiconductors







Rubrene



rubrene single-crystal

V. Podzorov, PRL, 95, 226601 (2005)

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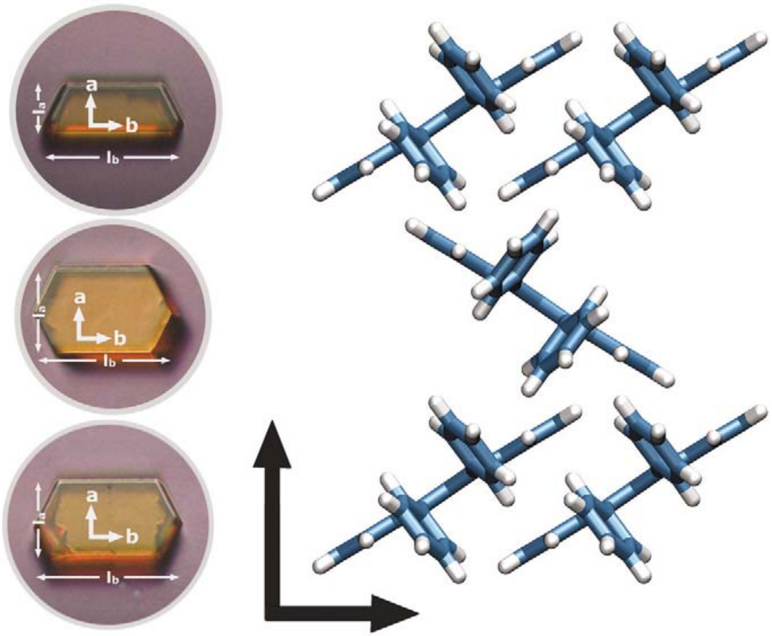
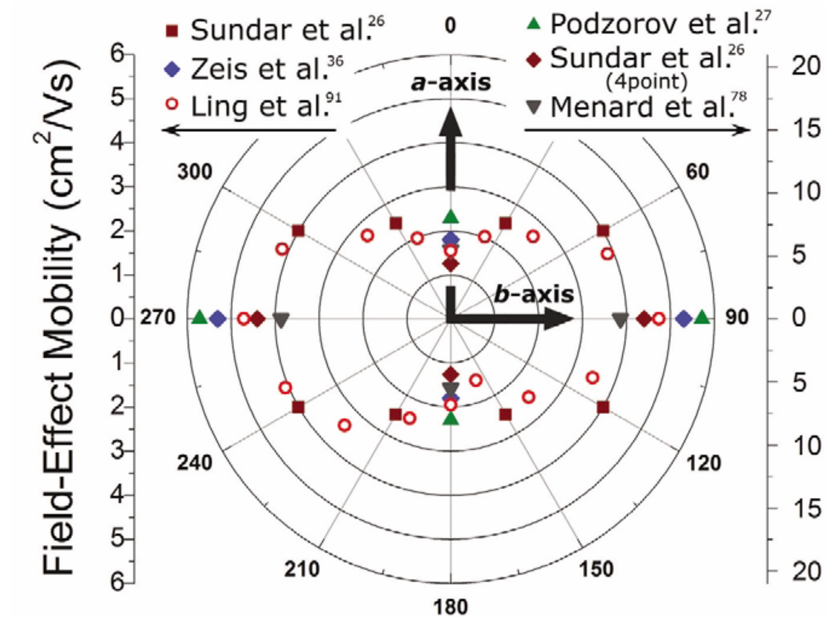
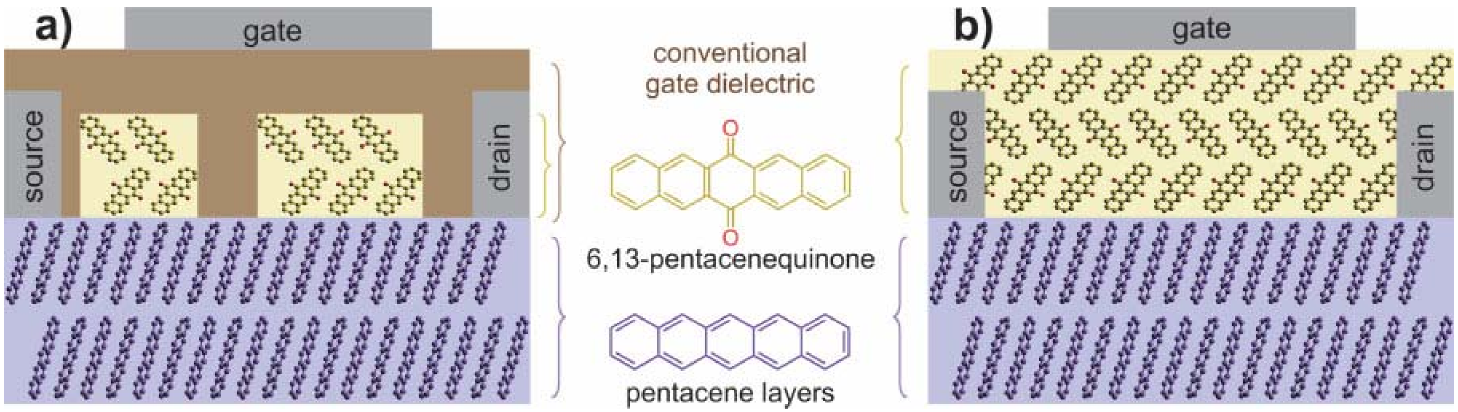
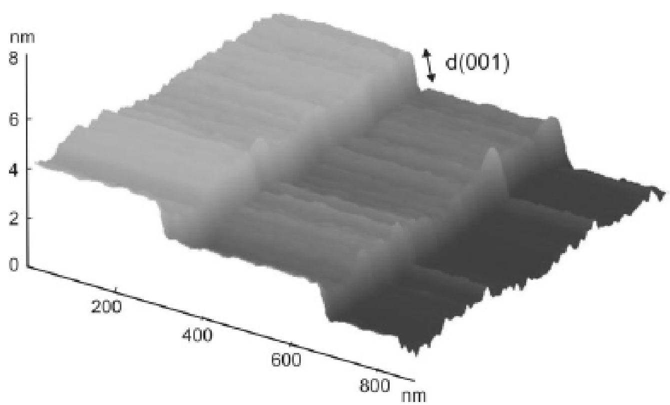
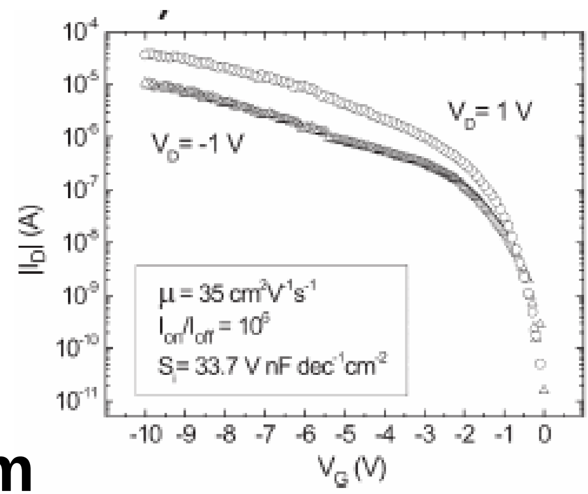




Sundar, V. C., *et al.*, *Science* (2004) **303**, 1644







Pentacene single crystal film

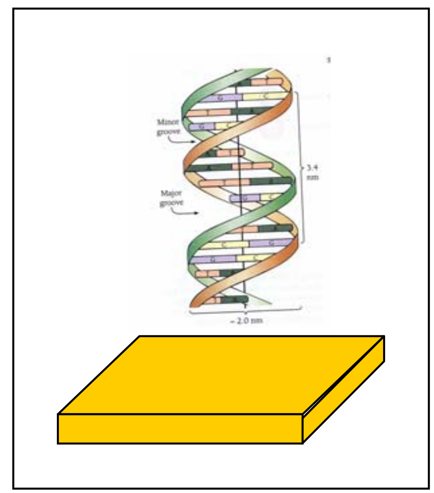
Adv. Mat. 19, 688 (2007)

2. Application of organic devices

2.1 Why is important?

The potential market of organic electronics

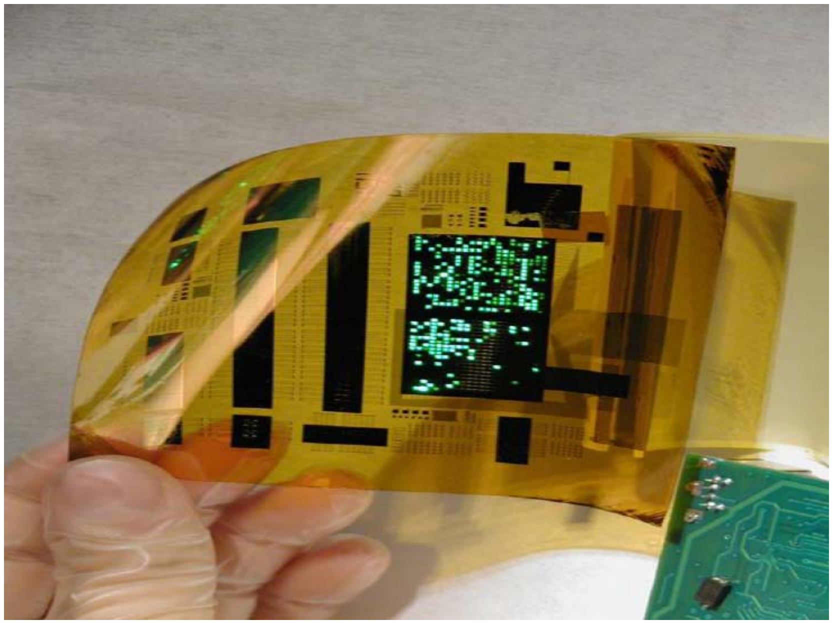
- flexible display
- OLED
- Solar cells
- sensors
- electronic labels (RFID tags)
- Wearable electronics
- Smart package

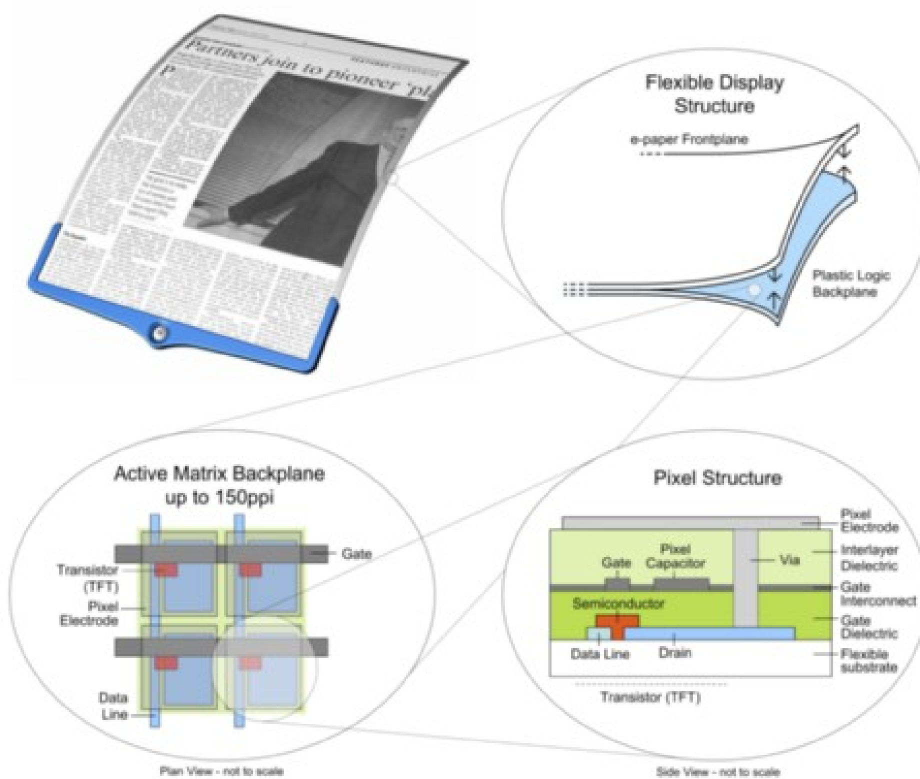


Advantages

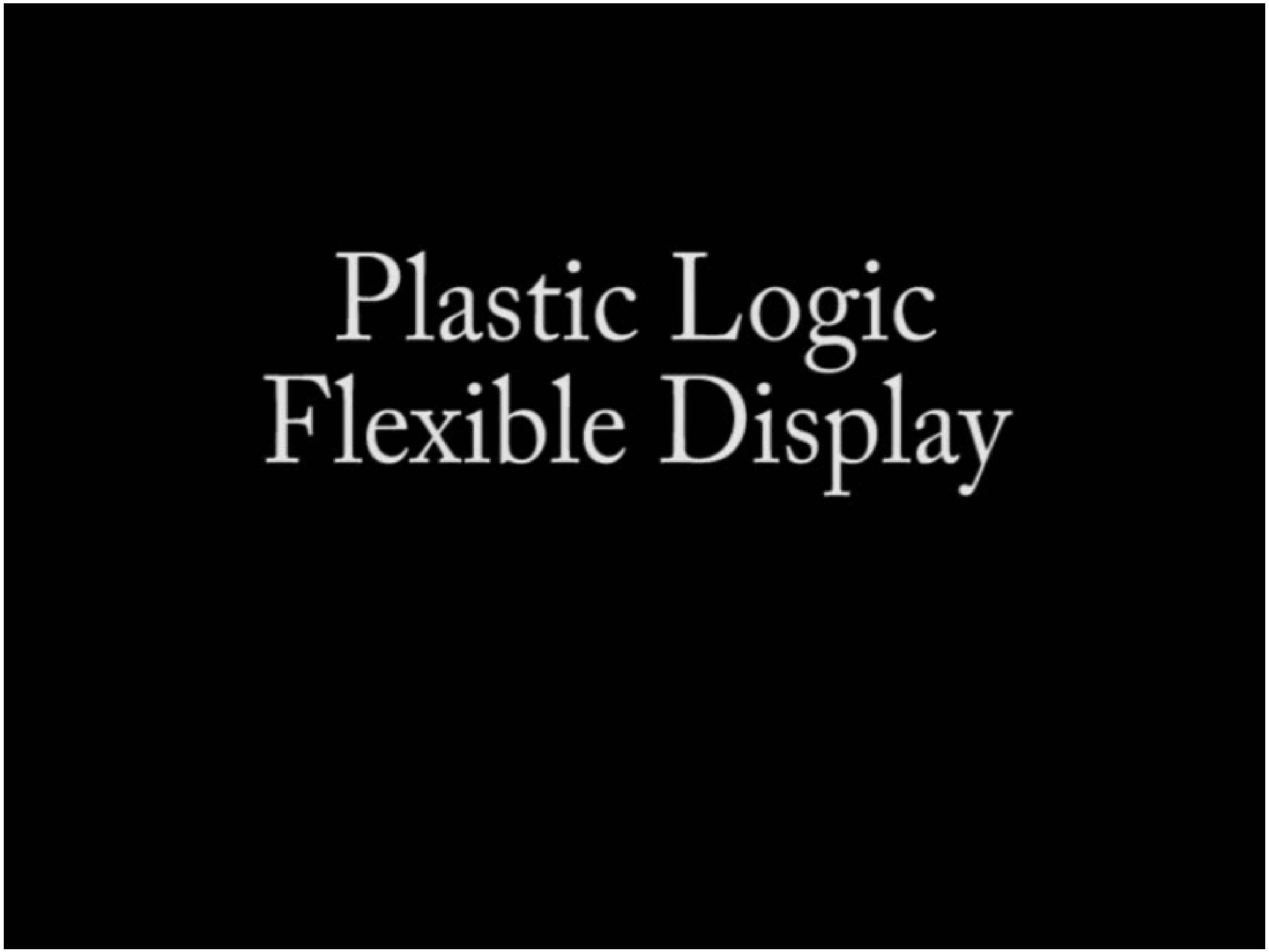
- Solution processable, feasible for :
  1. low temperature process
  2. large area applications(display, smart package, wearable electronics)
  3. mass-production (low cost, disposable)
- Flexible (display, e-paper, etc.)
- Light
- Compatible with bio-materials
- Environment friendly

2.2 Application of PTFTs in displays

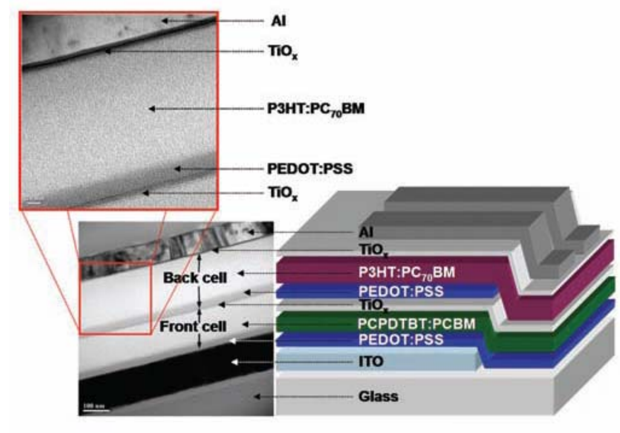




Active Matrix display


Plastic Logic
Flexible Display

2.3 Organic Solar cells



Power-conversion efficiencies > 6%

Science, 317, 5838, 2007

2.4 Fabrication of organic devices

- Spin coating (small size)
- Printing process (R2R)
  1. Inkjet printing
  2. Contact printing

Inkjet printer

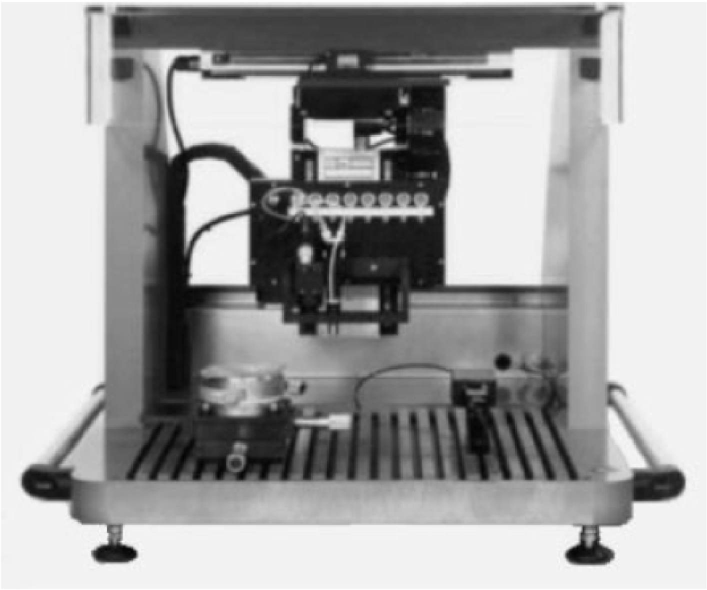
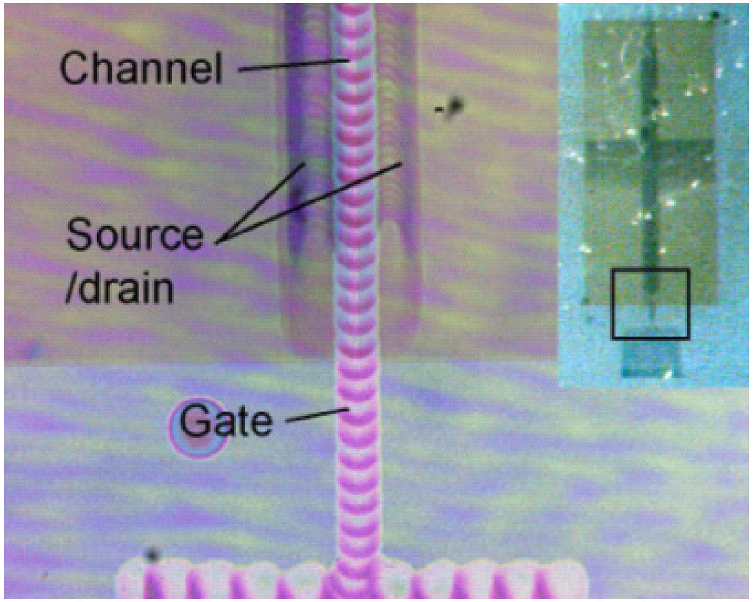
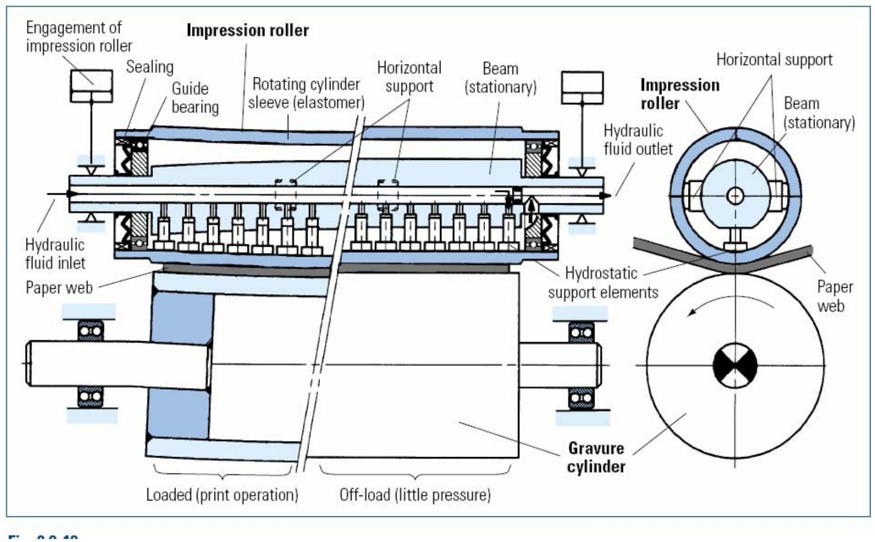


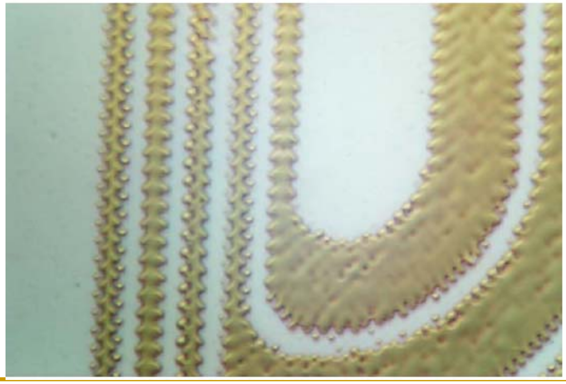
Figure 1. Microdrop Autodrop Platform (courtesy Microdrop GmbH, Germany).



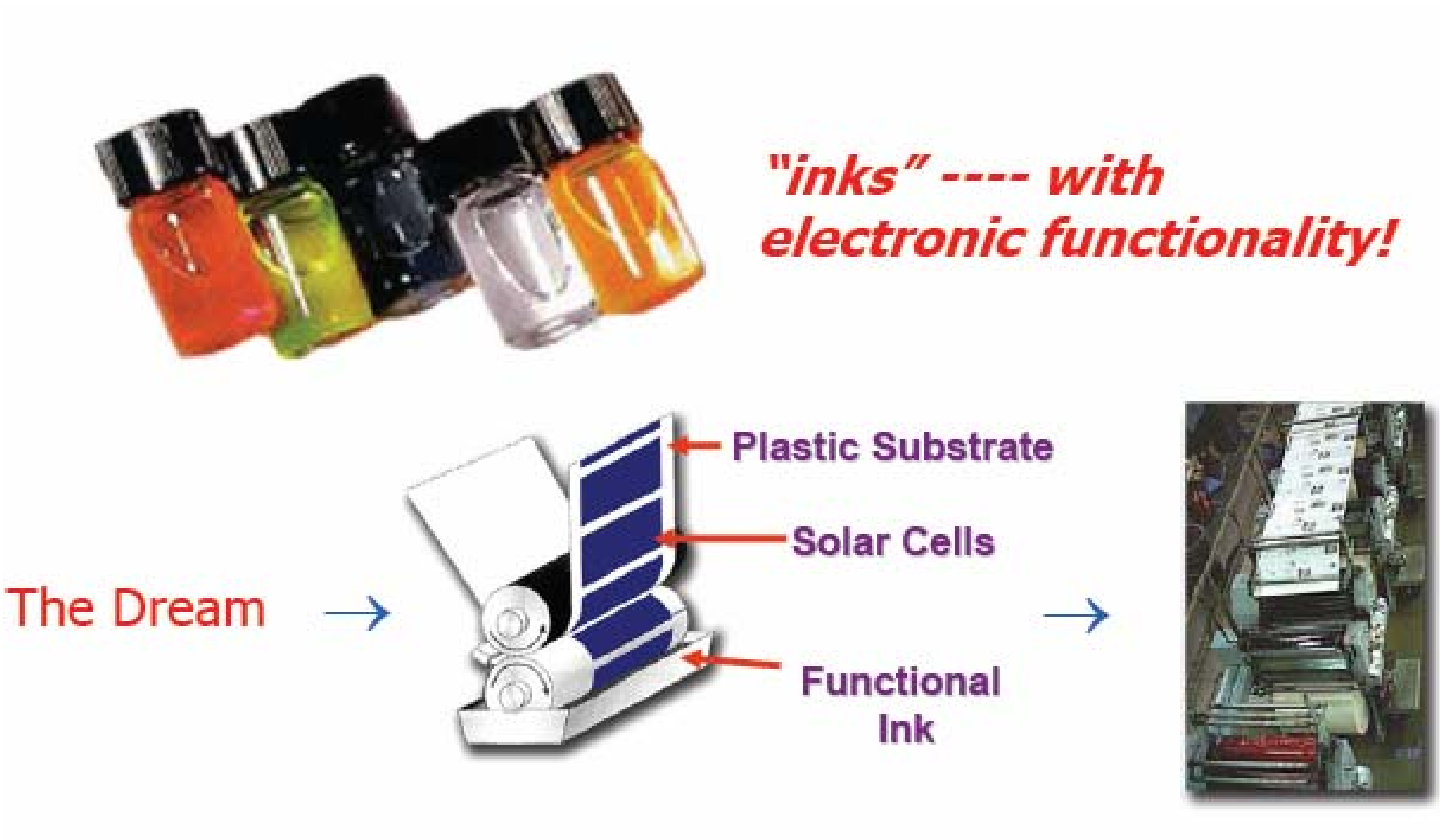
Injet printed polymer TFT

Gravure printer

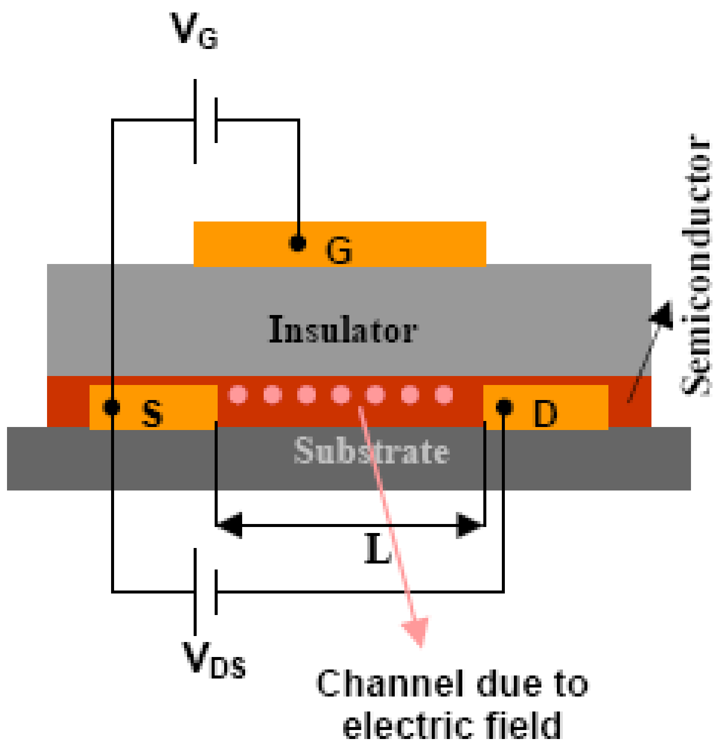


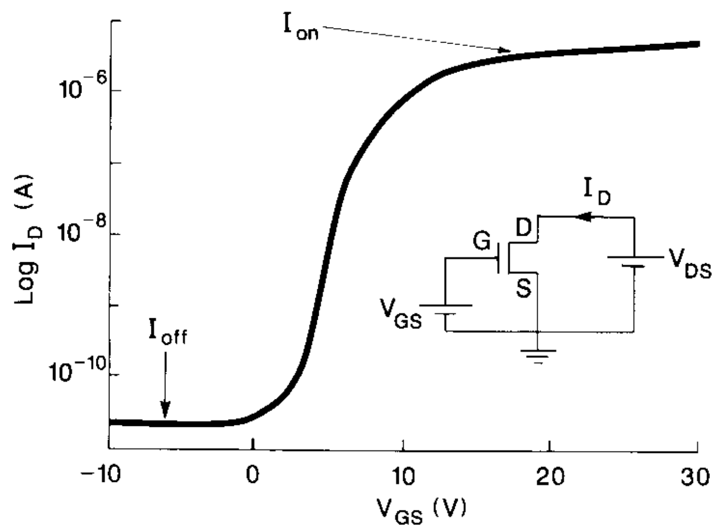


Gravure printed film


"inks" ---- with
electronic functionality!
Plastic Substrate
Solar Cells
The Dream
Functional
Ink

3. Organic thin film transistor





$$I_D = \left(\frac{W}{L}\right)\mu_h C_i (V_G - V_T) V_D \qquad \text{(linear region)}$$

$$I_{DS} \propto W/L$$

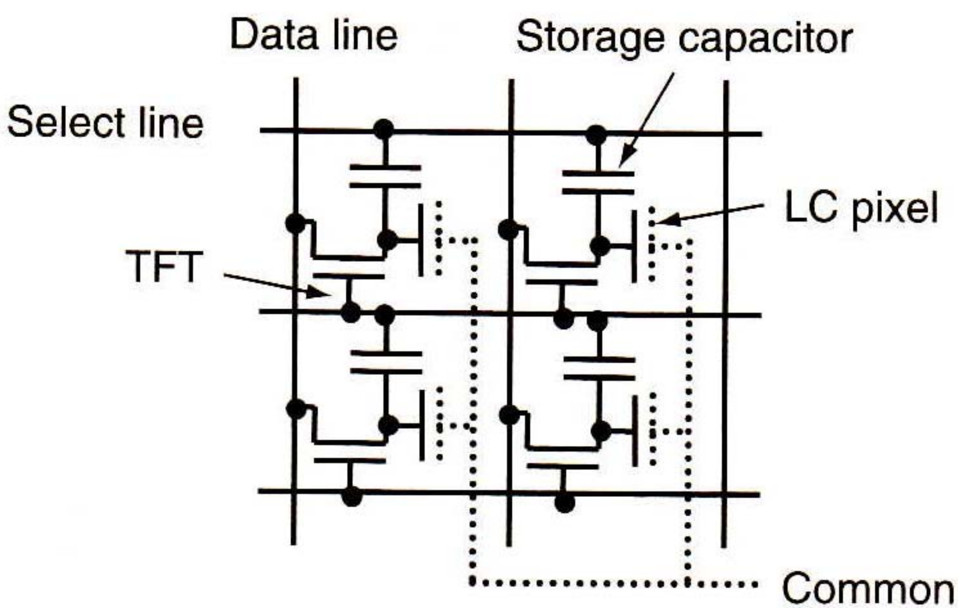
$$V_T = V_{FB} + 2\psi_B + \frac{\sqrt{4 \in_s qN_A(-\psi_B)}}{C_i} = V_{FB} + 2\psi_B + 2K\sqrt{-\psi_B}$$

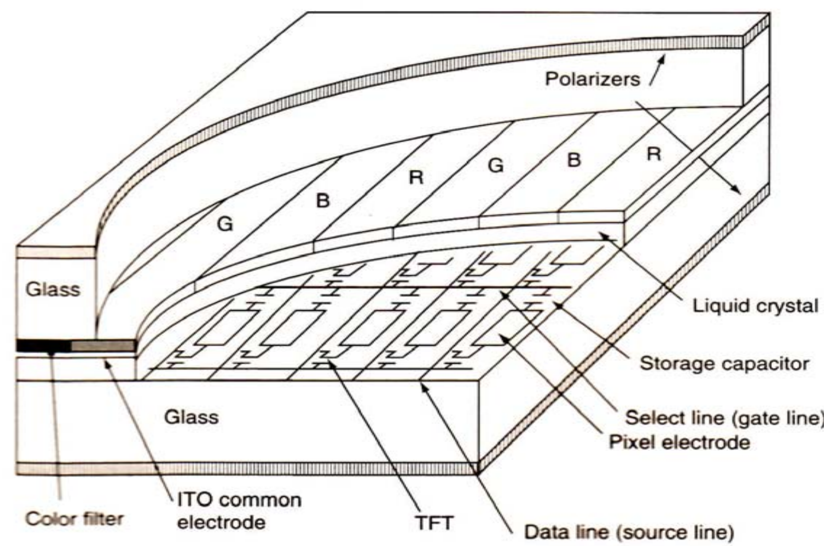
The device can be miniturized without losing signal to noise ratio

Application of TFT

- Active matrix flexible display (switch)
- sensors
- electronic labels (RFID tags)
- Wearable electronics
- Smart package
- Organic memory
- Spin valves

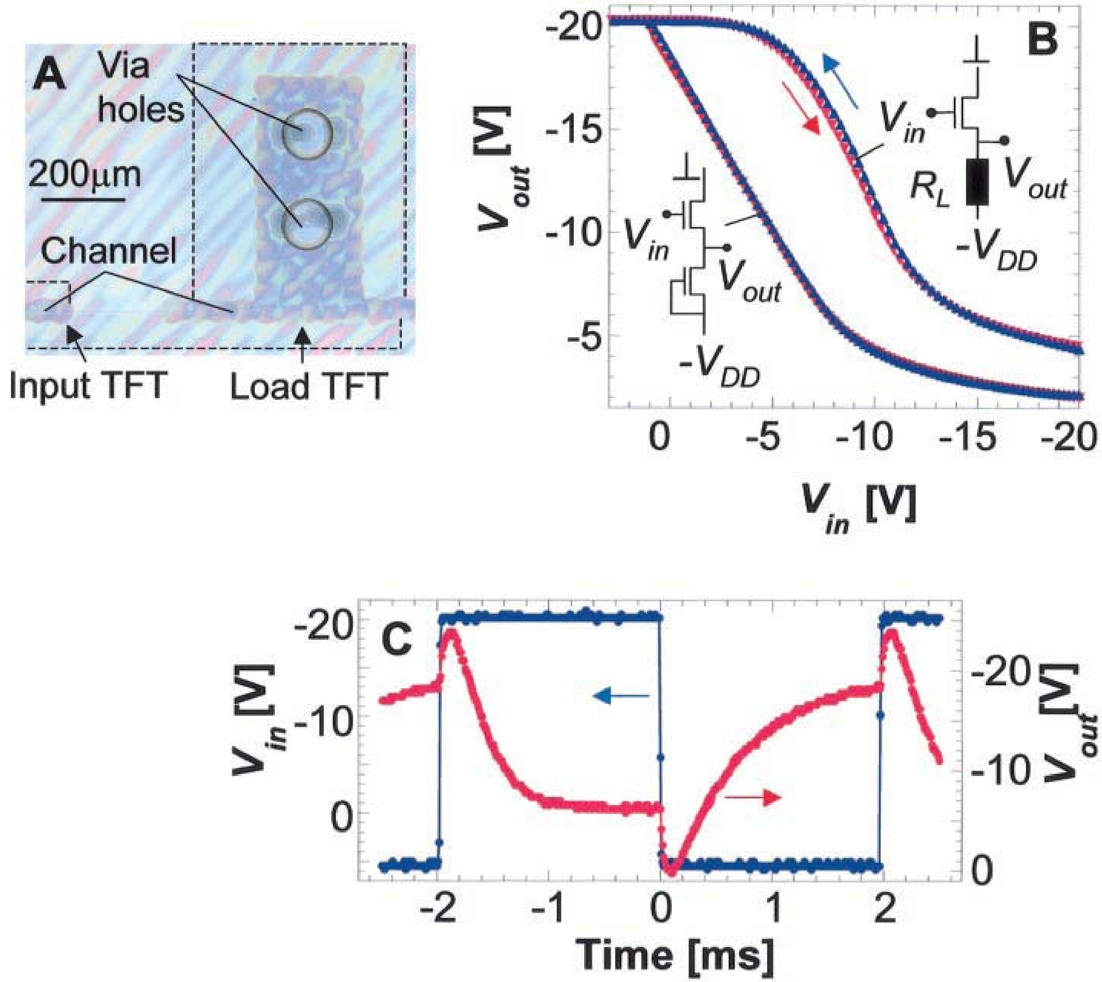
Circuit of active matrix display





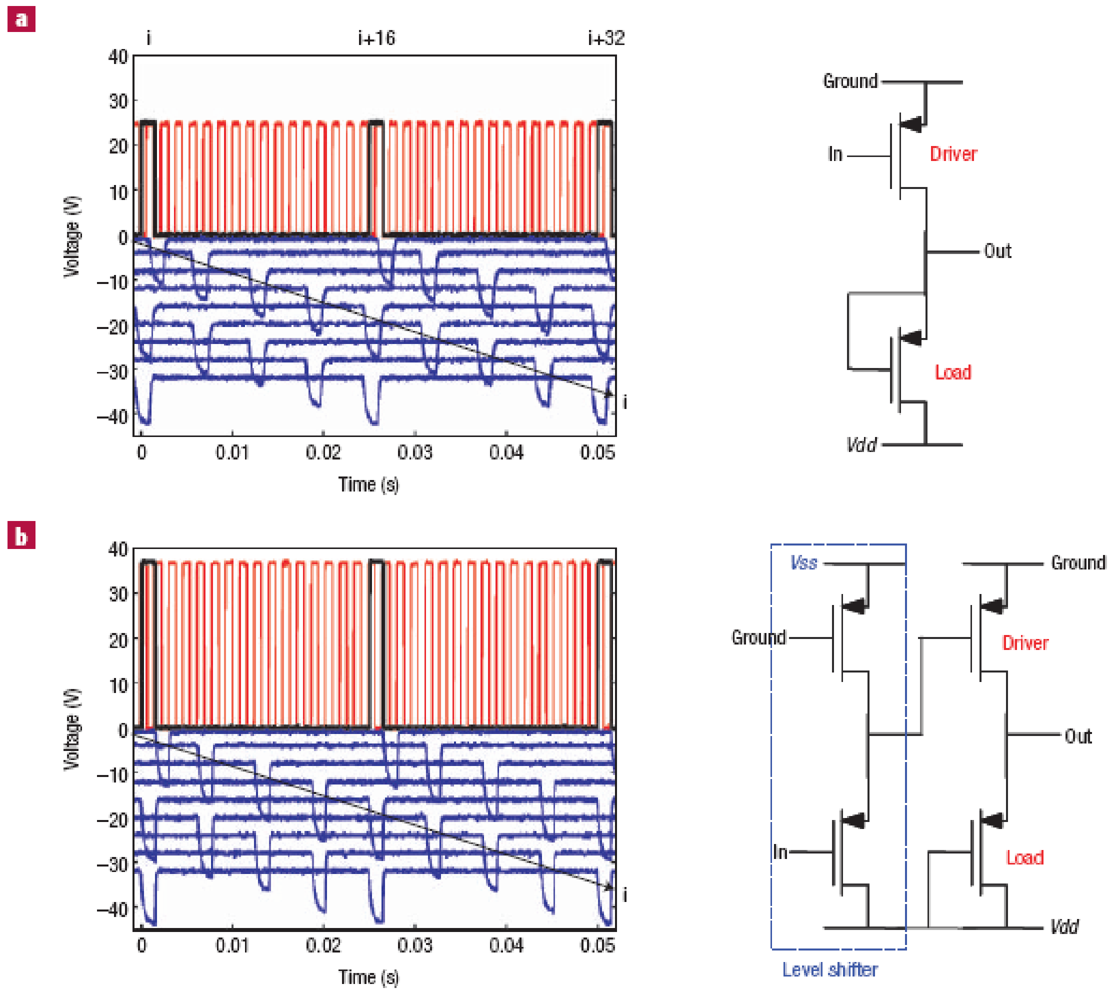
Active matrix

Resistance load inverter



Science, 290, 2123 (2000)

Shift register based on organic TFTs (Philips)

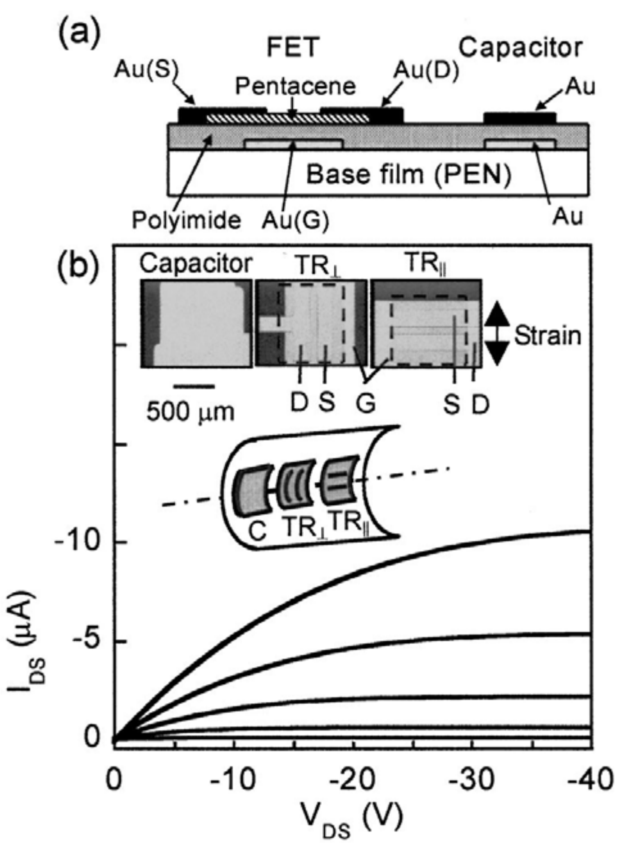


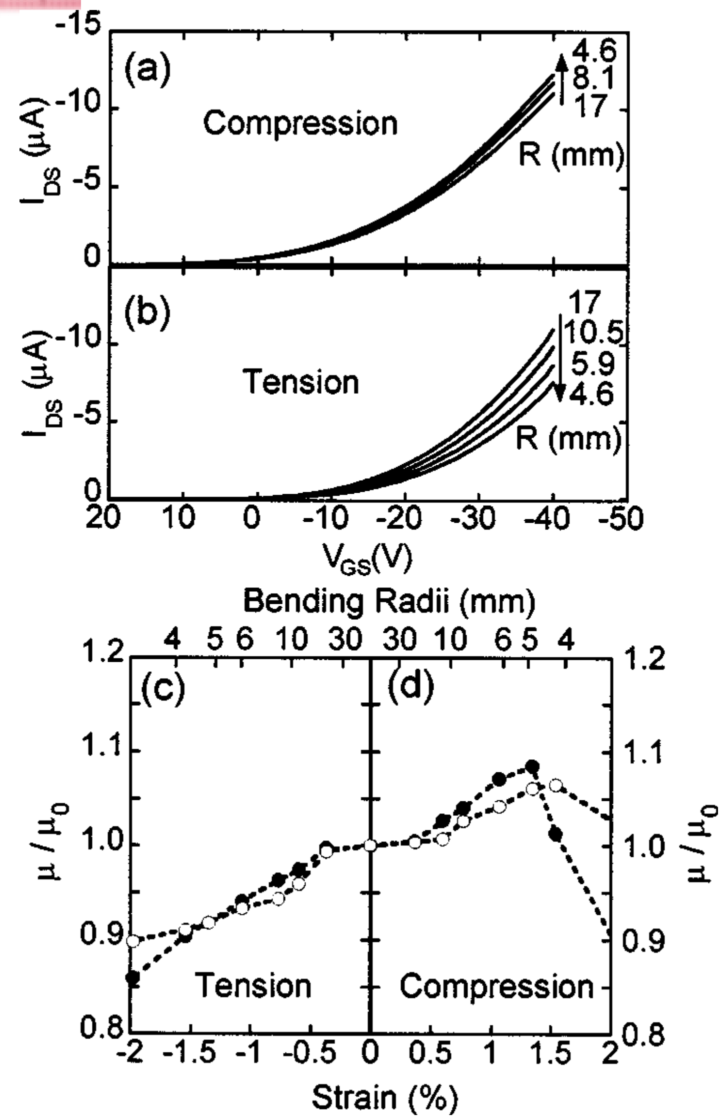
Nat. Mat. 3, 106 (2004)

Application on sensors

1. Gas sensor
2. Stress sensor
3. light sensor
4. biosensor

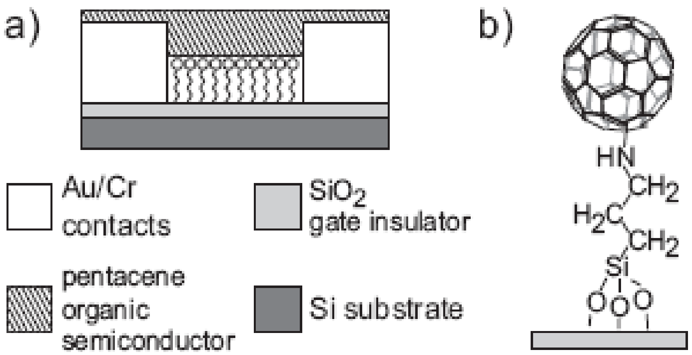
Stress sensor

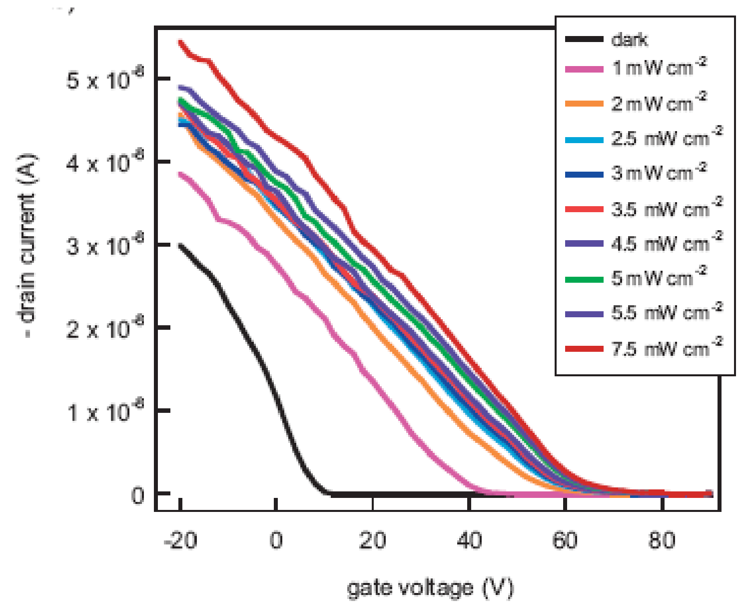




APL, 86, 073511 (2005)

Light sensor





B. Park, Adv. Mat. 19 (2007), 4353

pH sensor based on organic TFT

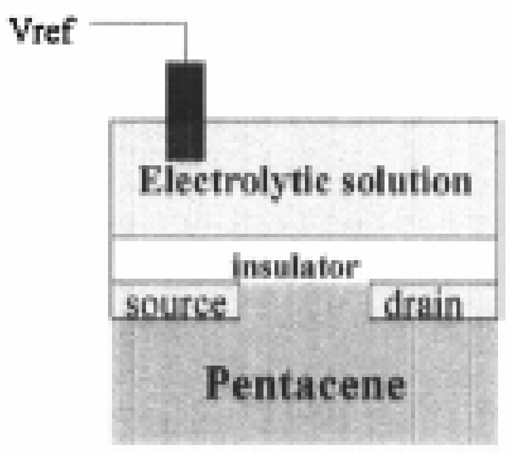
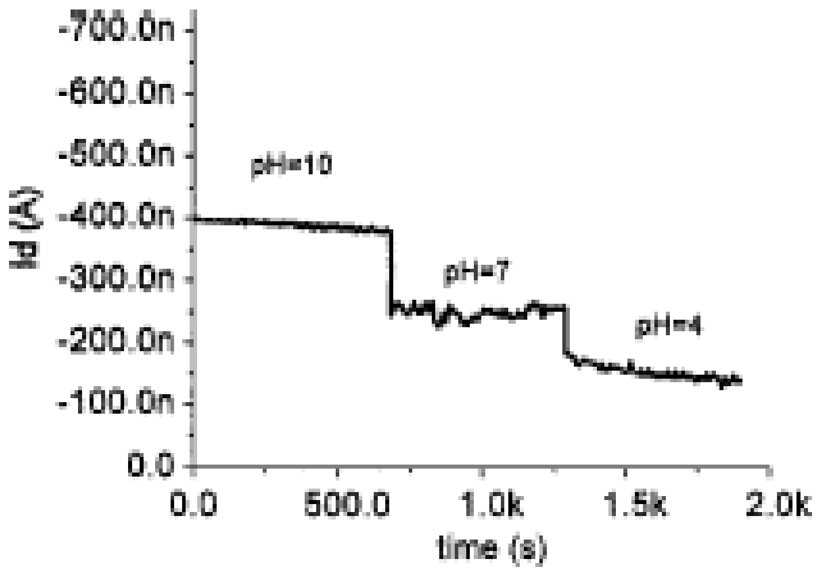


FIG. 1. Structure of the device.



Substrate: 900-nm-thick Mylar™ sheet (Du Pont)

A. Loi, et al. *APL*, **86**, (2005) 103512.

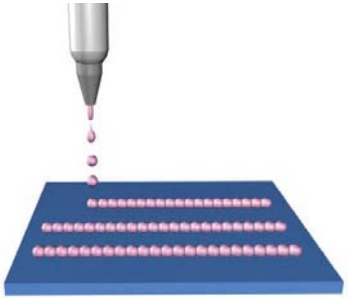
4. Organic phototransistor based on P3HT/TiO2 nanoparticle composite

4.1 Introduction

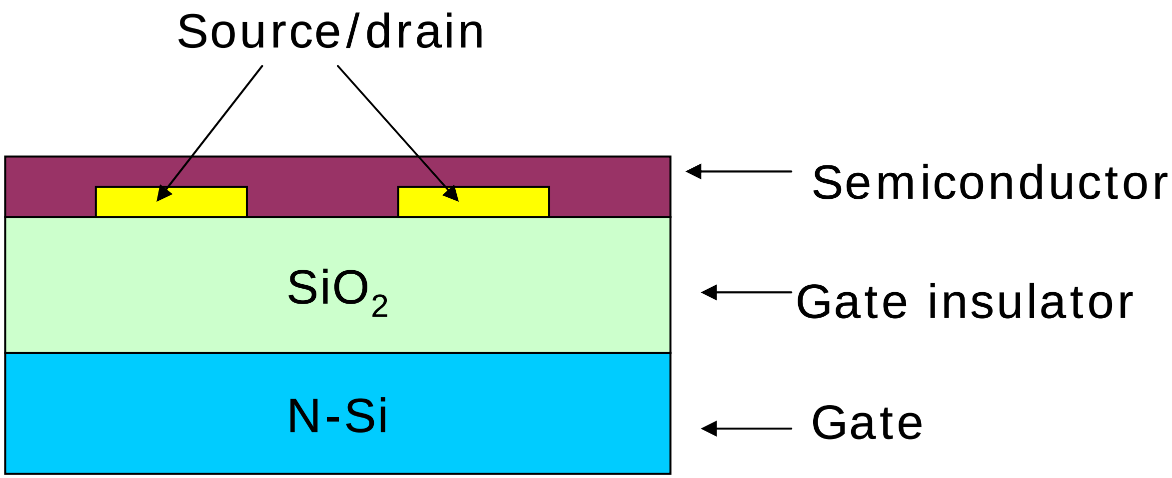
Potential applications OPT:

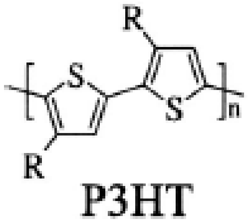
- Phototransistors are a type of optical transducer in which light detection and signal amplification are combined in a single device.
- Organic phototransistors (OPTs) are considered to be one of the feasible application of organic thin film transistor (OTFT) because of their large adsorption properties in ultraviolet (UV) and visible light and the excellent photo current generation efficiency of organic semiconductors.
- More importantly, some OPTs can be fabricated by solution process, such as printing or spin coating, at room temperature and therefore can be easily integrated in smart clothes, packages, and biological systems as light sensors, biosensors and multifunctional sensors.

- Photo detector
- Imaging array
- biosensors



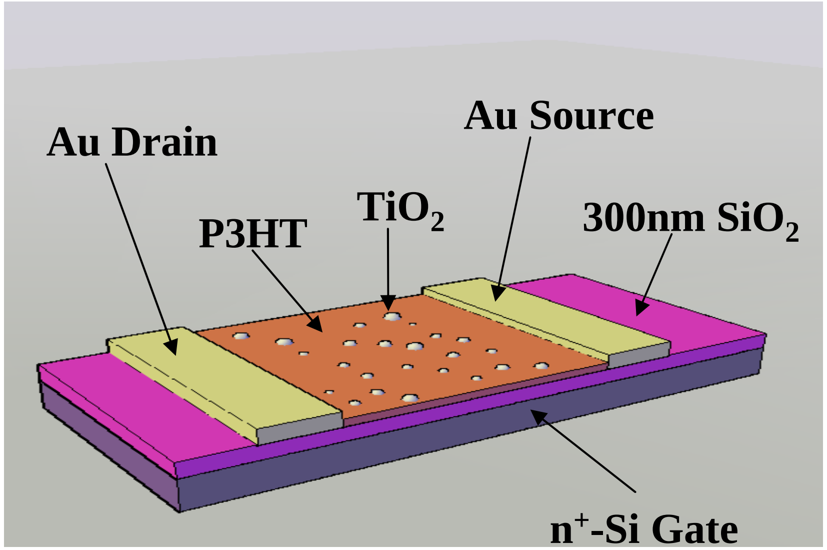
4.2. Device fabrication

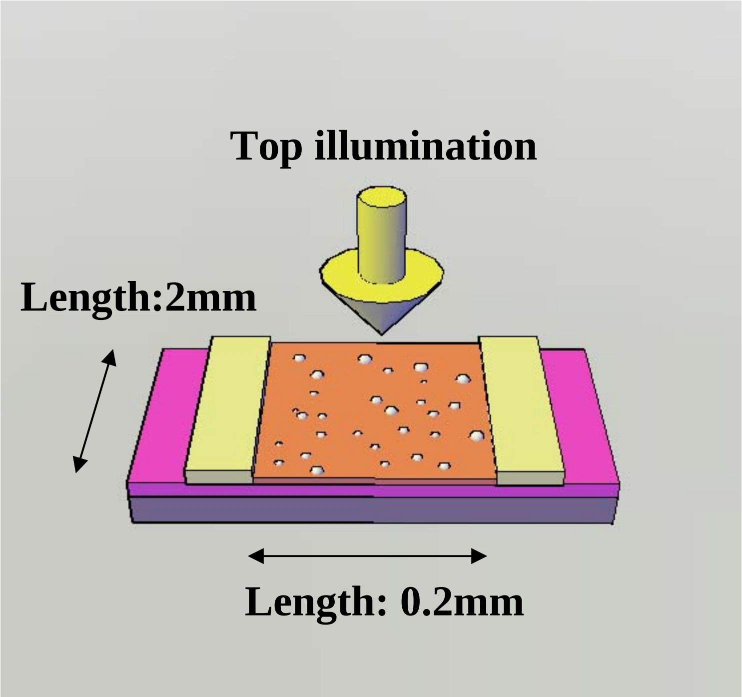




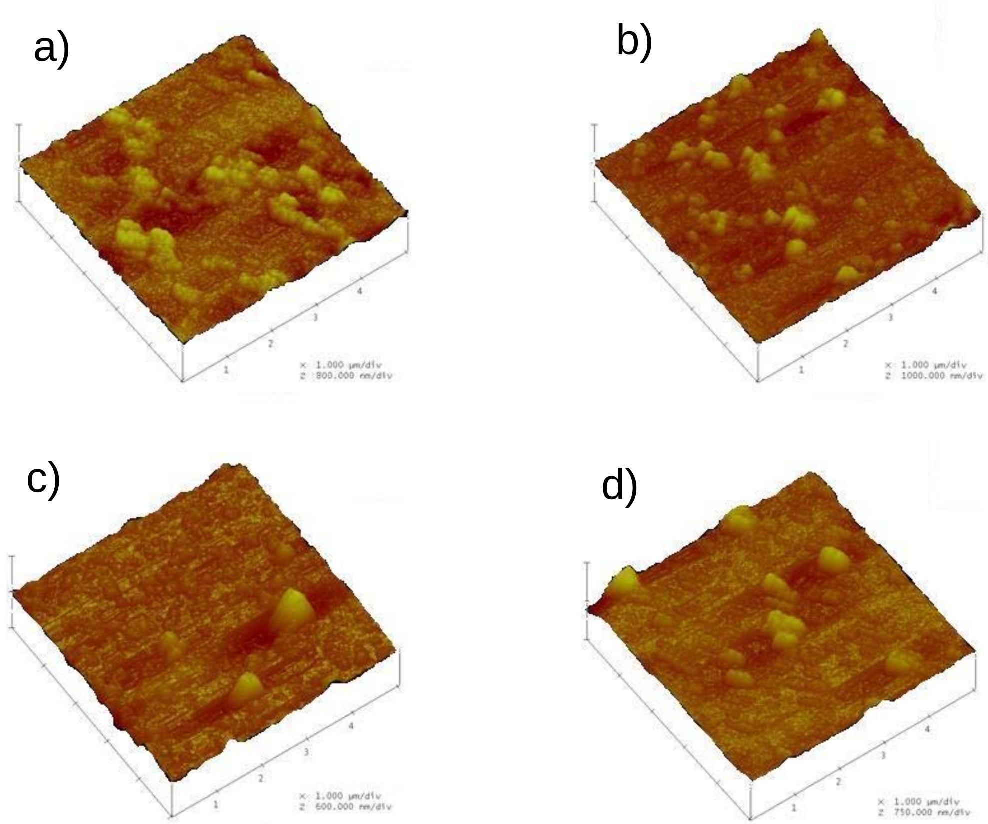
Bottom gate device

P3HT/TiO_2 composite


Au Drain
Au Source
P3HT
TiO_2
300nm SiO_2
n^+-Si Gate

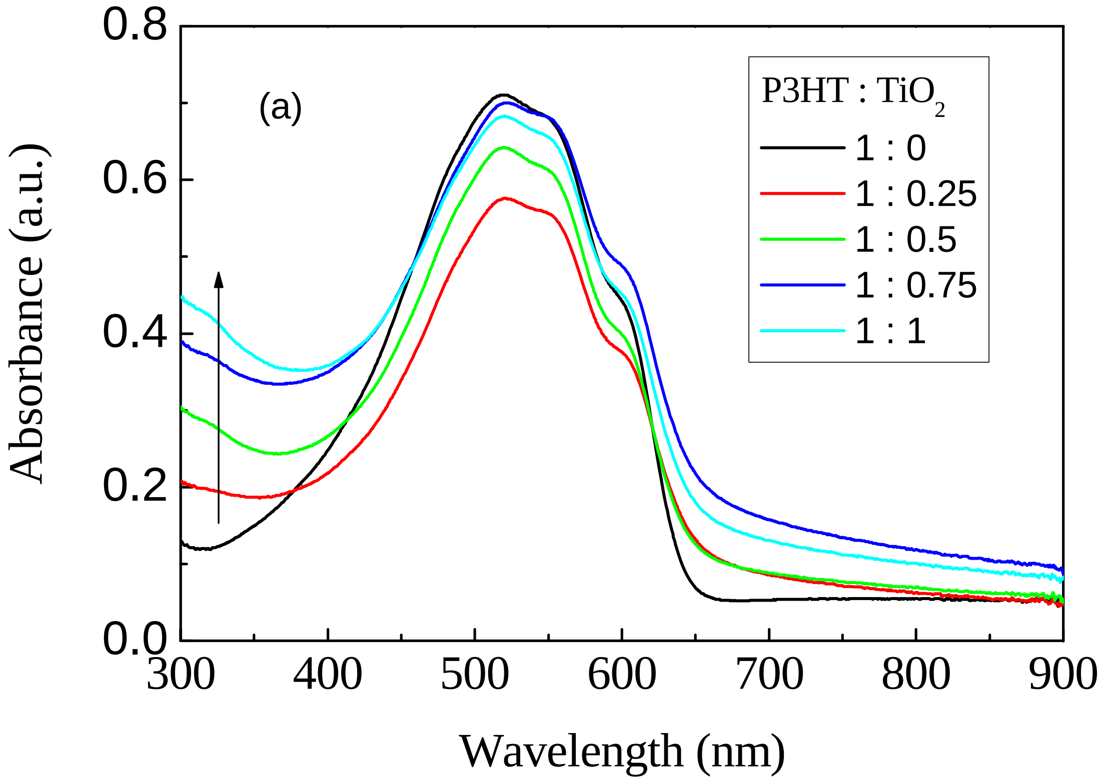

Top illumination
Length:2mm
Length: 0.2mm

P3HT/TiO_2 composite



The P3HT:TiO2 weight ratio are a)1:1. b)1:0.75, c)1:0.5 and d)1:0.25

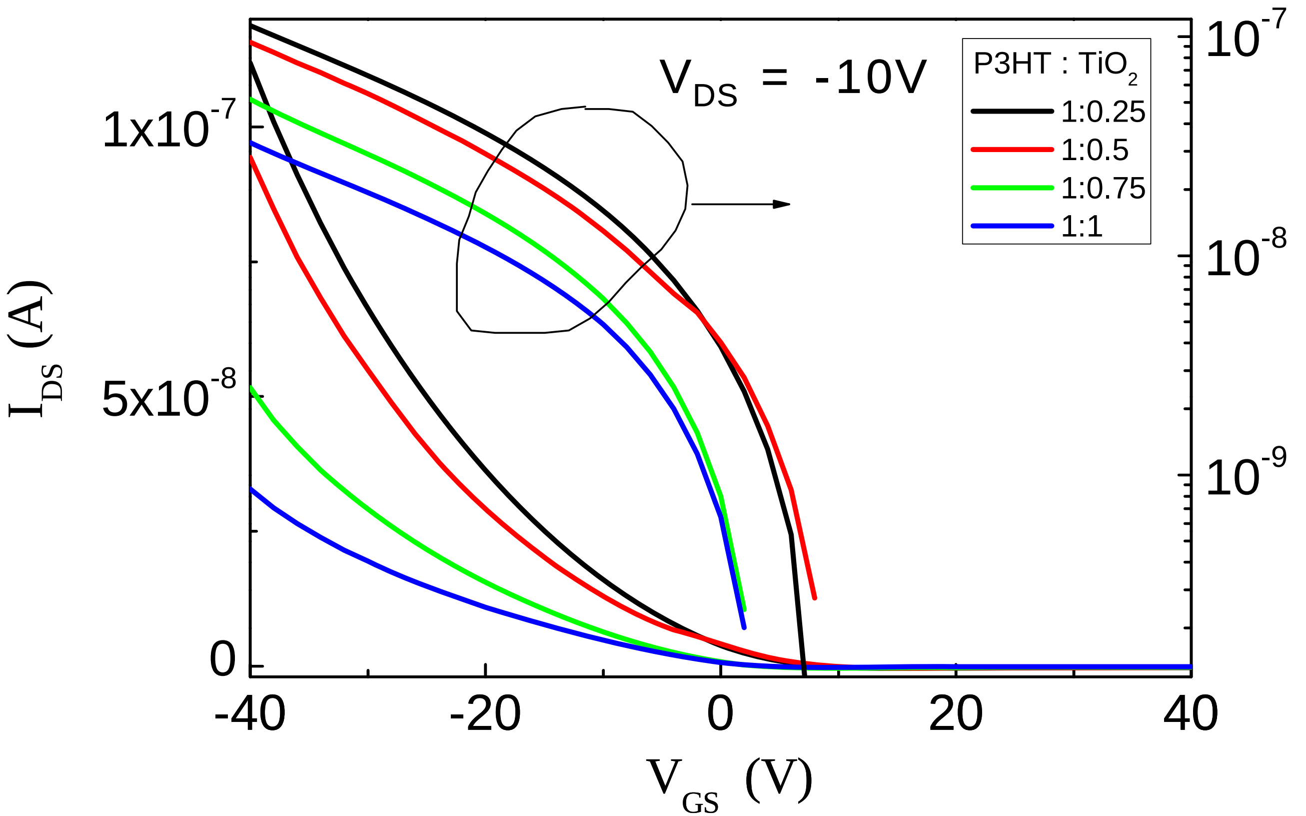
Mixture of Anatase and rutile phases, 100nm



Light absorption of the composite films

4.3. Experimental results

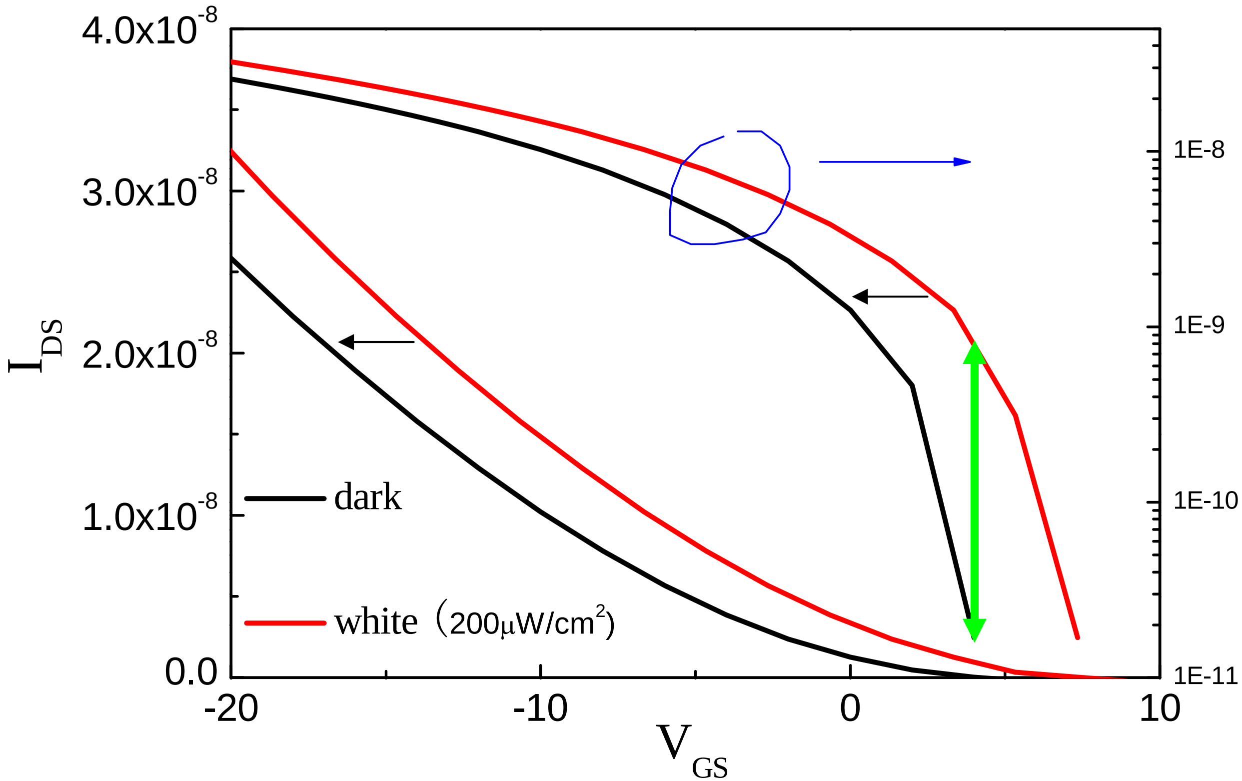
4.3.1 Influence of TiO_2 nano-particles on channel current



Mixture of Anatase and rutile phases, 50-100nm

TiO_2 prohibit charge transfer in the channel

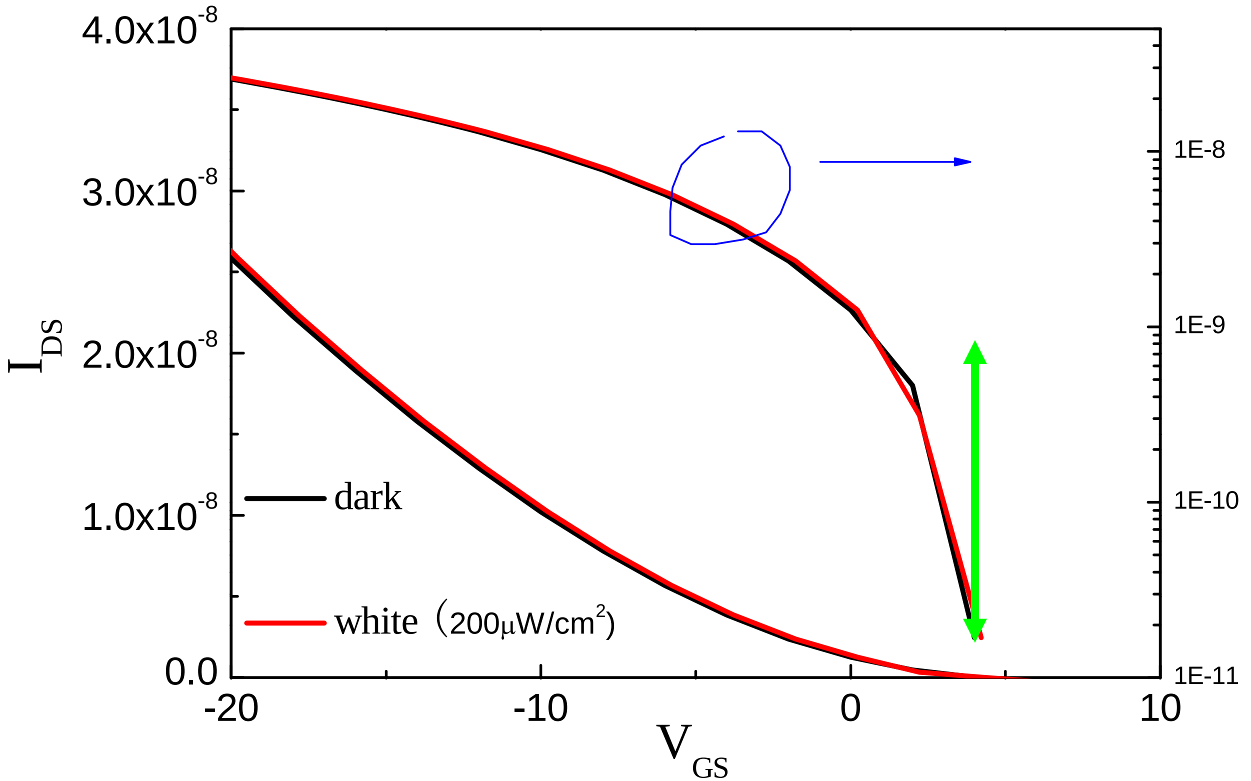
4.3.2 Photosensitive OTFT



V_{DS}= -10V; P3HT:TiO_2 is 1:0.75

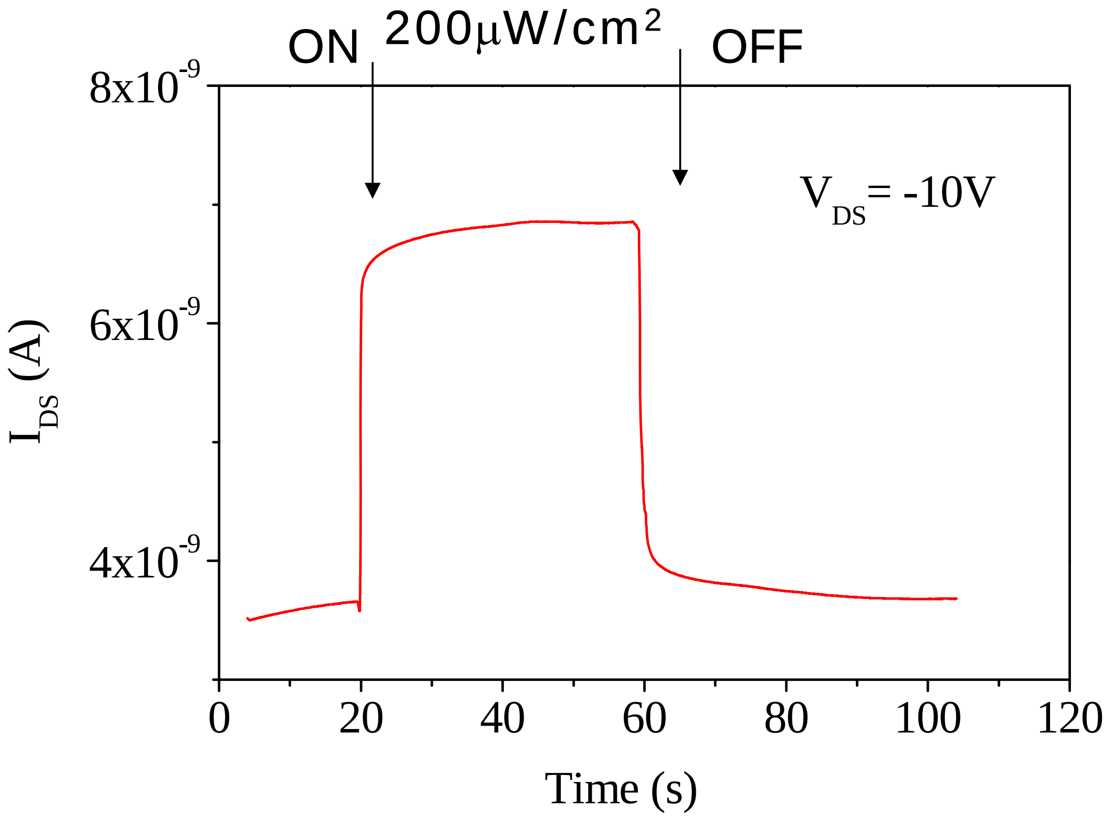
Mixture of Anatase and rutile phases, 50-100nm

Mixture of Anatase and rutile phases, 50-100nm



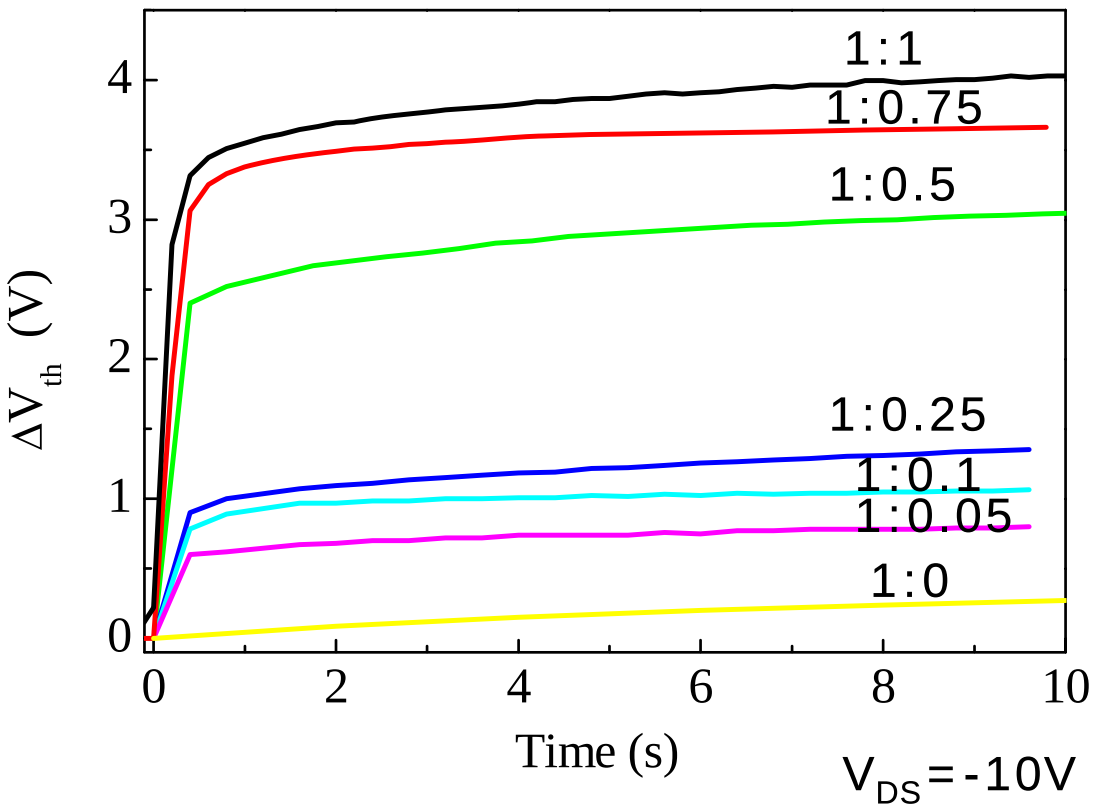
V_{DS}= -10V; P3HT:TiO_2 is 1:0.75

Mixture of Anatase and rutile phases, 50-100nm



V_{DS}= -10V; P3HT:TiO_2 is 1:0.75

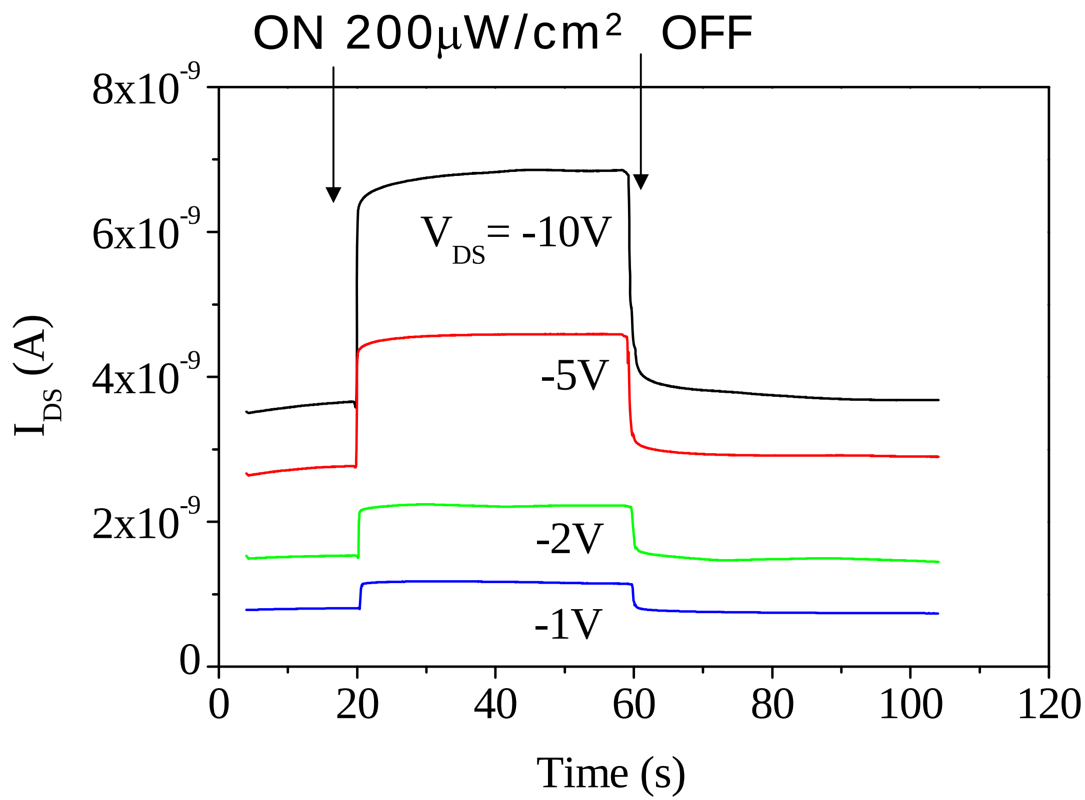
Mixture of Anatase and rutile phases, 50-100nm



TiO_2 nano-particles induce photo sensitive behavior

Different ratio between P3HT and TiO_2

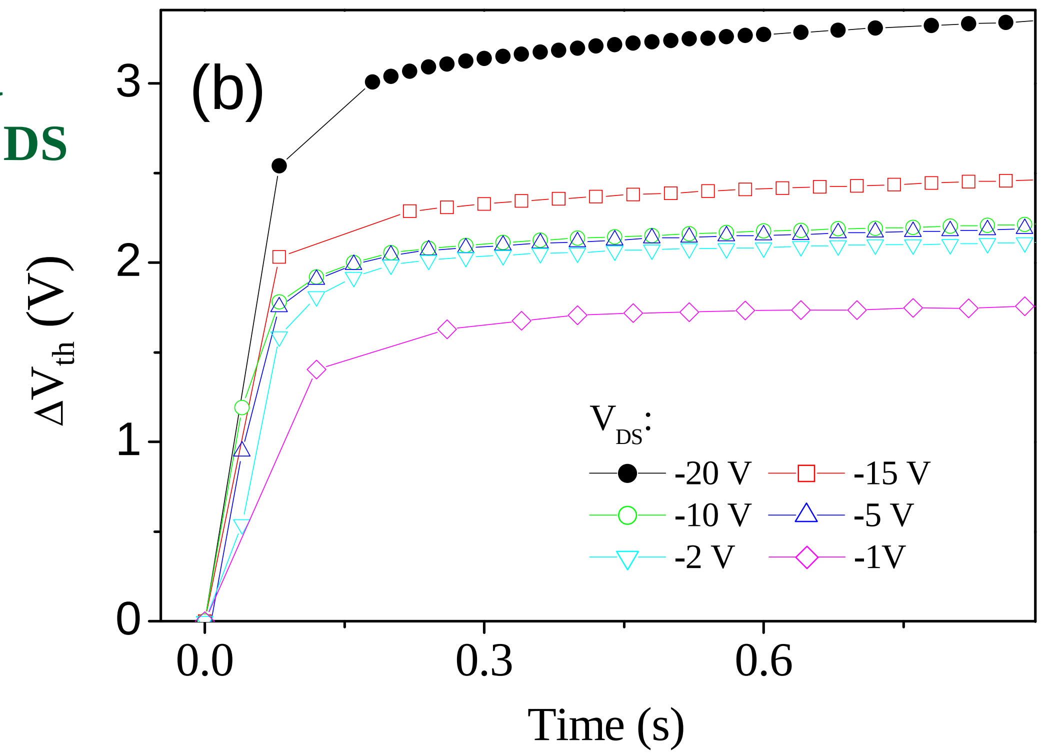
Mixture of Anatase and rutile phases, 50-100nm



V_{DS}= -10V; P3HT:TiO_2 is 1:0.75

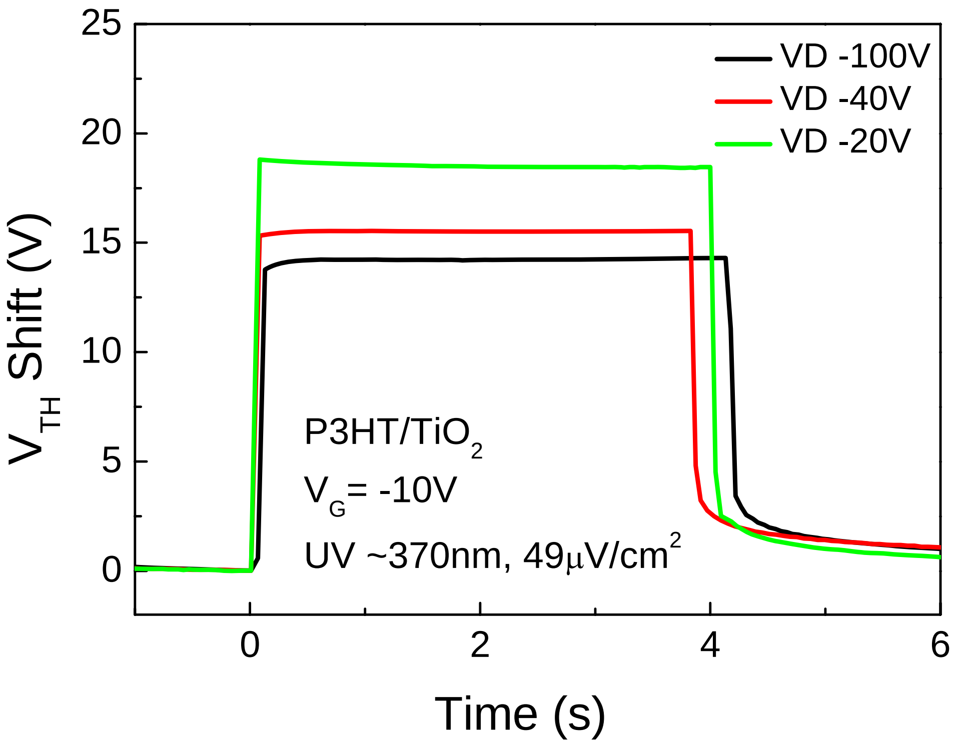
Mixture of Anatase and rutile phases, 50-100nm

Different V_{DS}



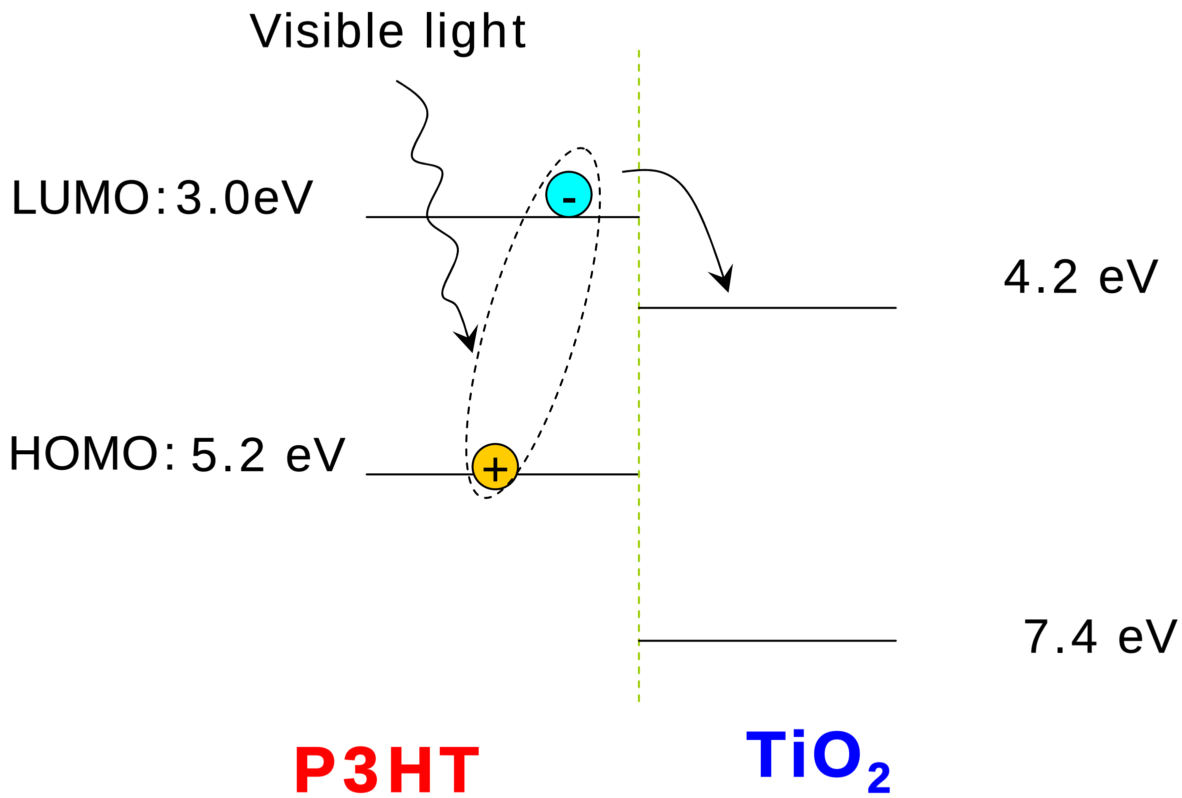
Field enhances charge separation at the P3HT/TiO_2 interface

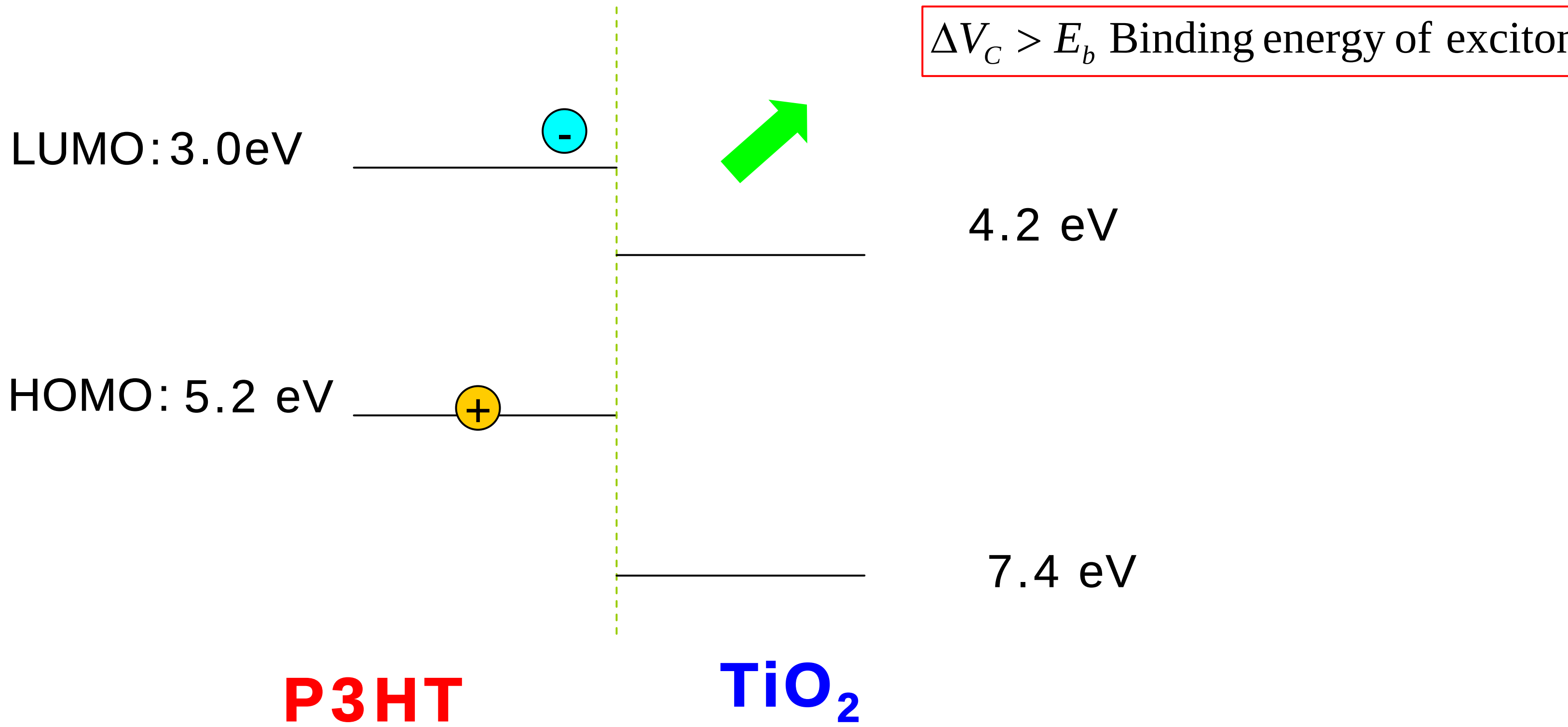
UV sensitivity



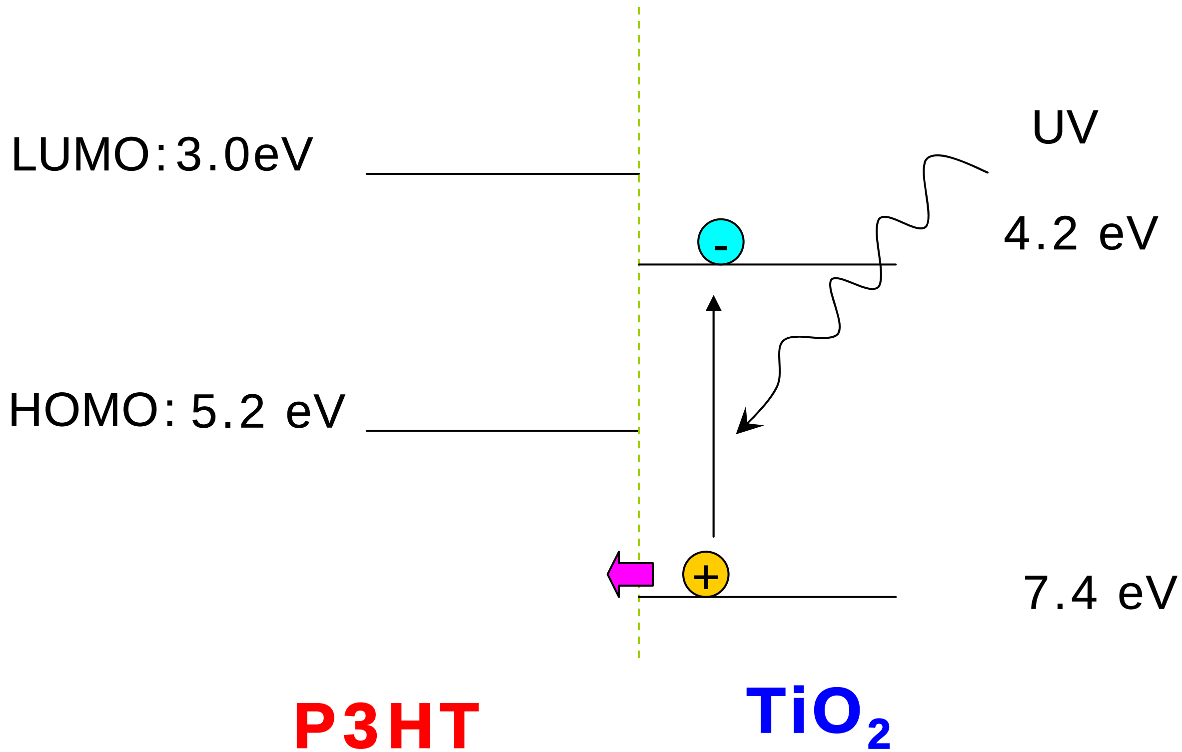
4.4. Theoretical explanation

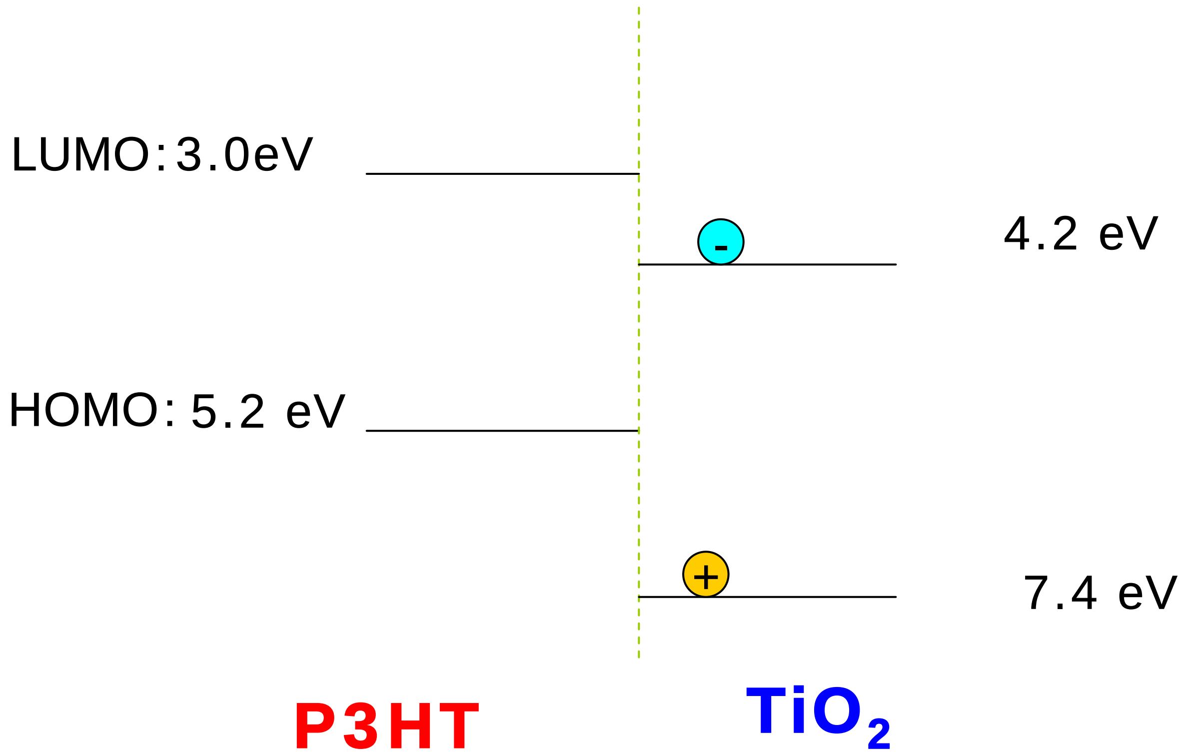
4.1 Why it is photosensitive



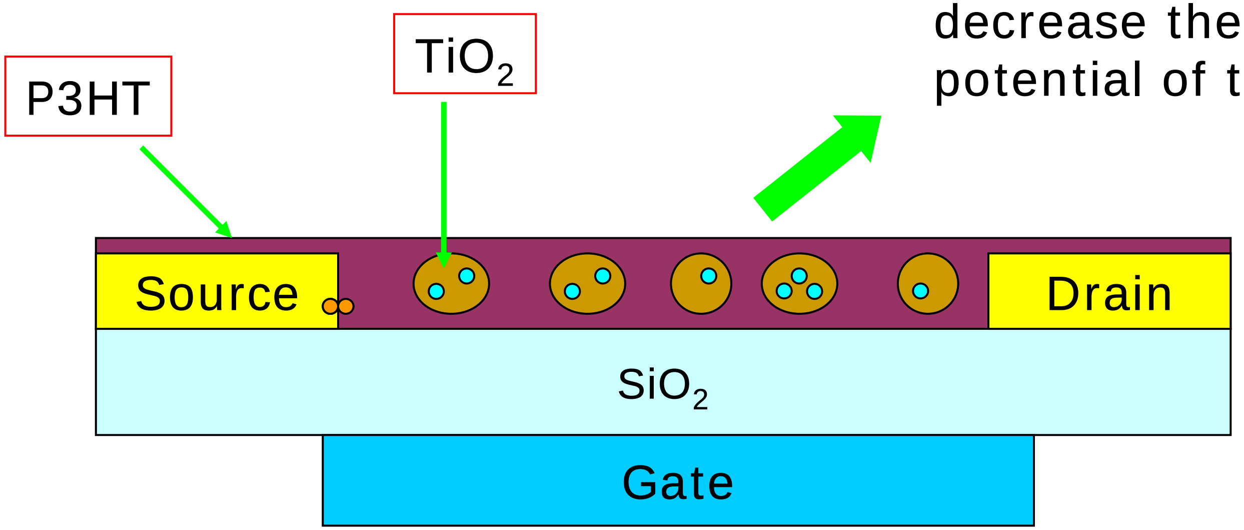


Electric field can enhance exciton-dissociation


UV
LUMO:3.0eV
4.2 eV
-
HOMO: 5.2 eV
+
7.4 eV
P3HT
TiO2


LUMO:3.0eV
4.2 eV
HOMO: 5.2 eV
7.4 eV
P3HT
TiO2

decrease the electrostatic potential of the channel



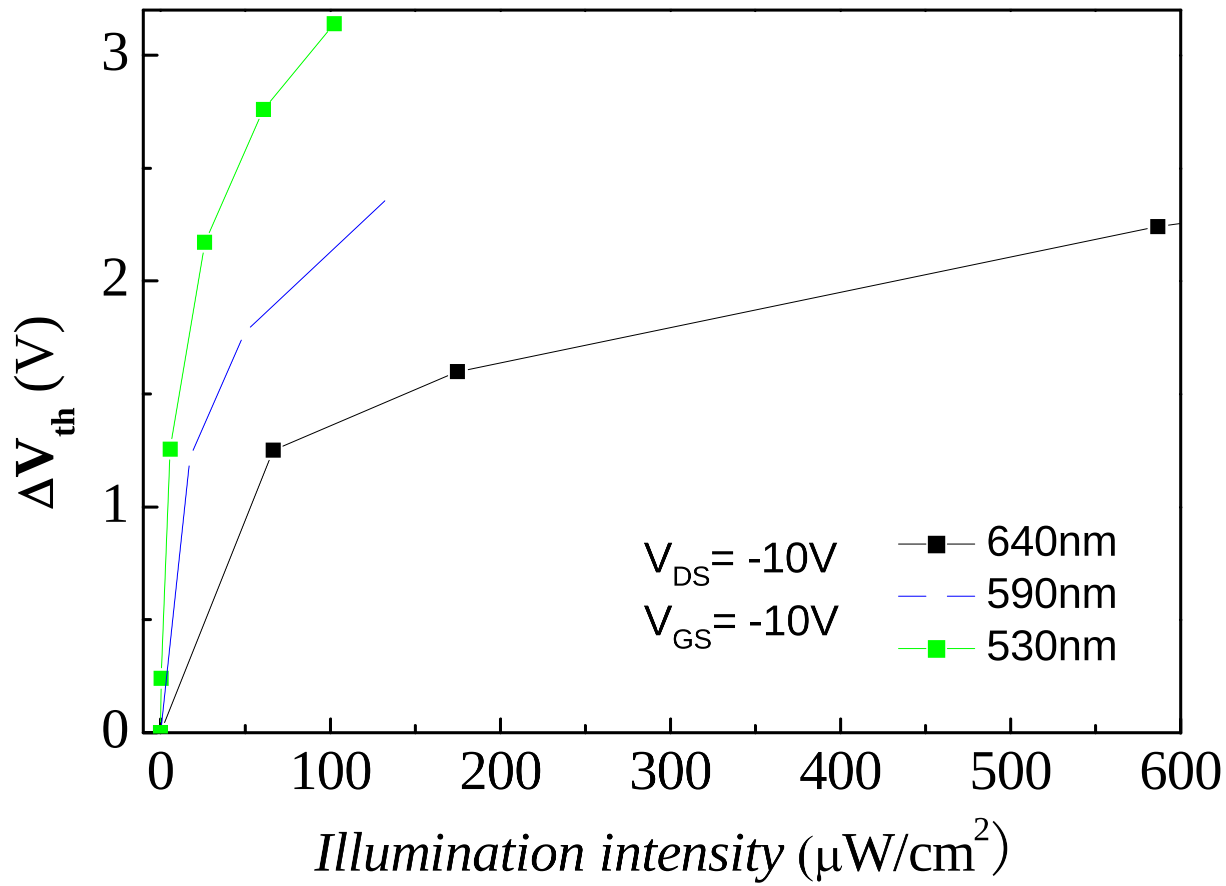
$$I_D = \left(\frac{W}{L}\right)\mu_h C_i (V_G - V_T) V_D \qquad \text{(linear region)}$$

$$V_T = V_{FB} + 2\psi_B + \frac{\sqrt{4 \in_s qN_A(-\psi_B)}}{C_i} = V_{FB} + 2\psi_B + 2K\sqrt{-\psi_B}$$

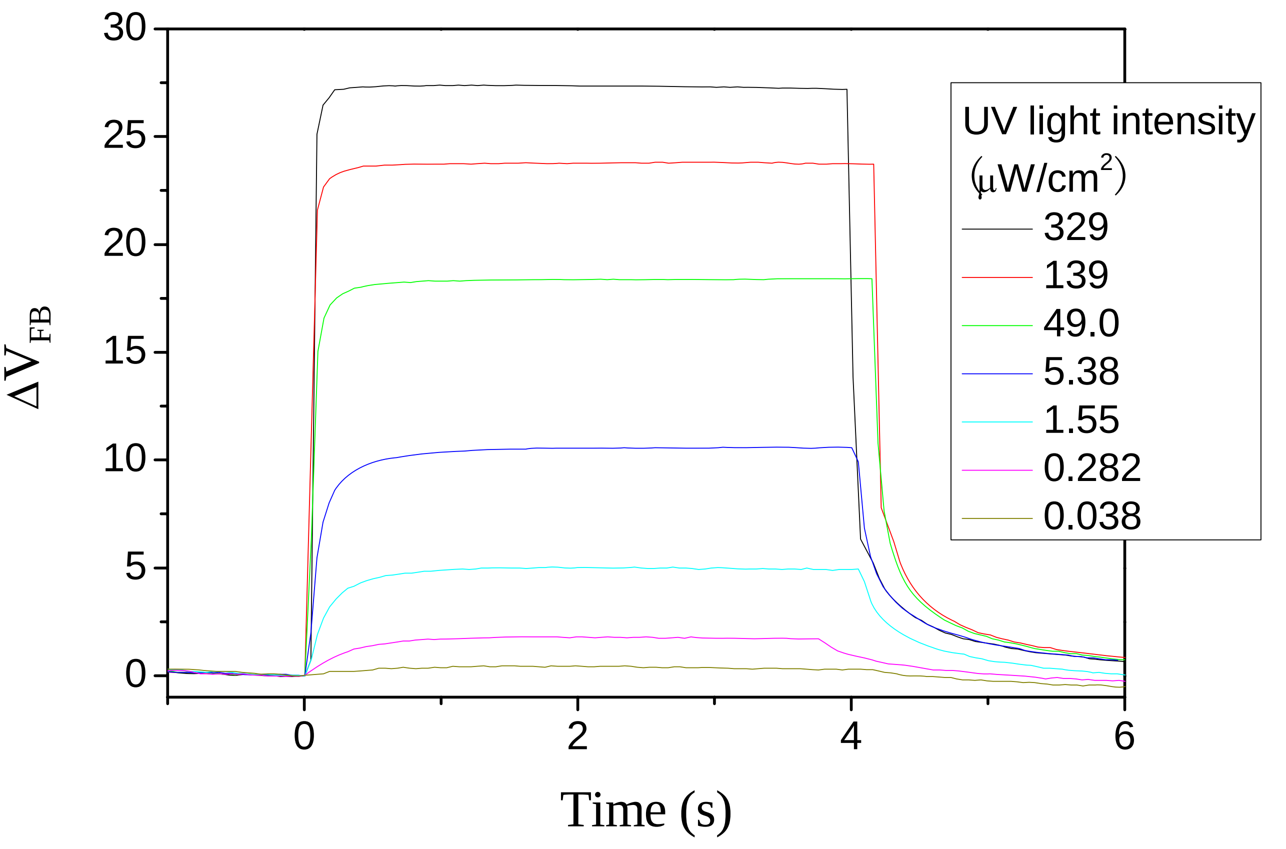
$$K = \frac{\sqrt{\in_s qN_A}}{C_i}$$

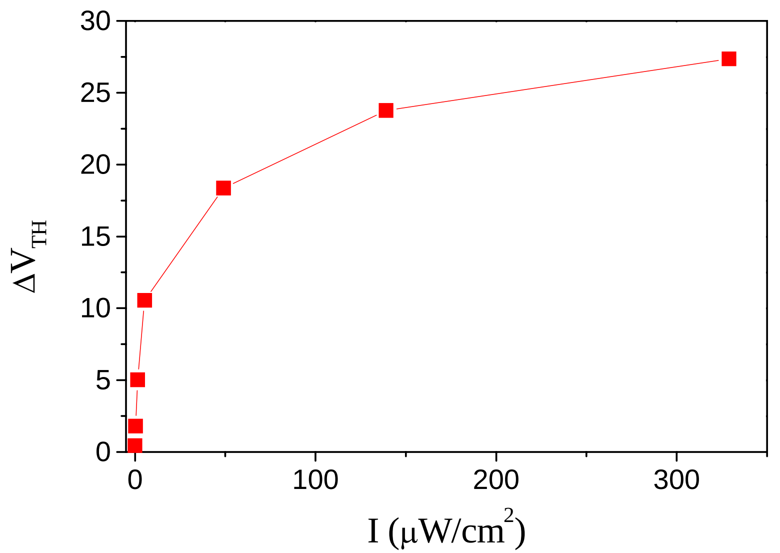
ψ_B is the electrostatic potential in the active layer

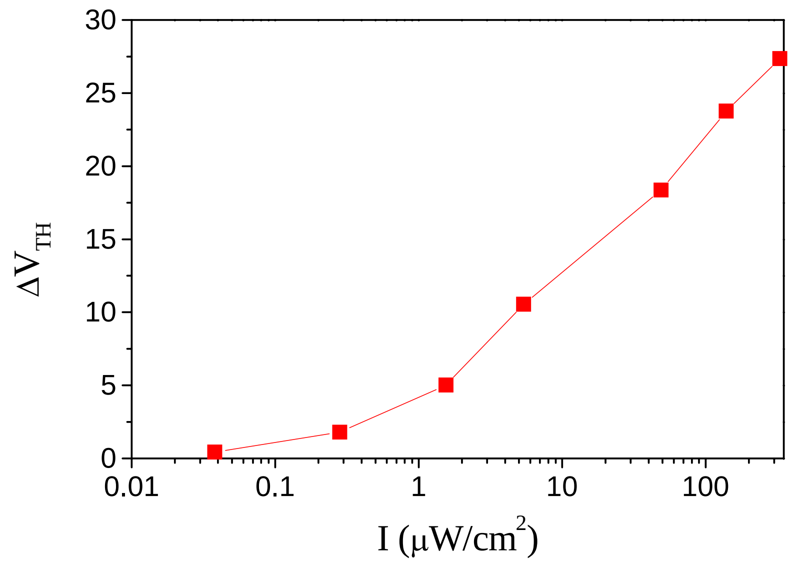
Different wavelength and light intensity



UV sensitivity

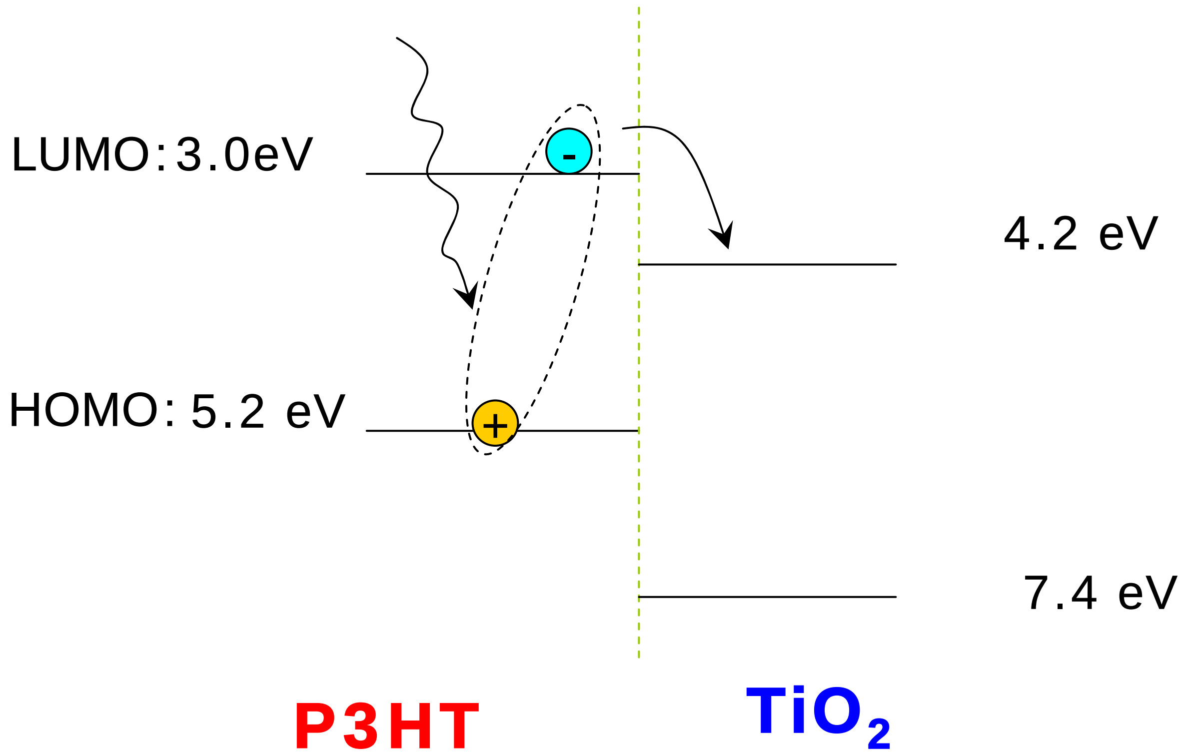


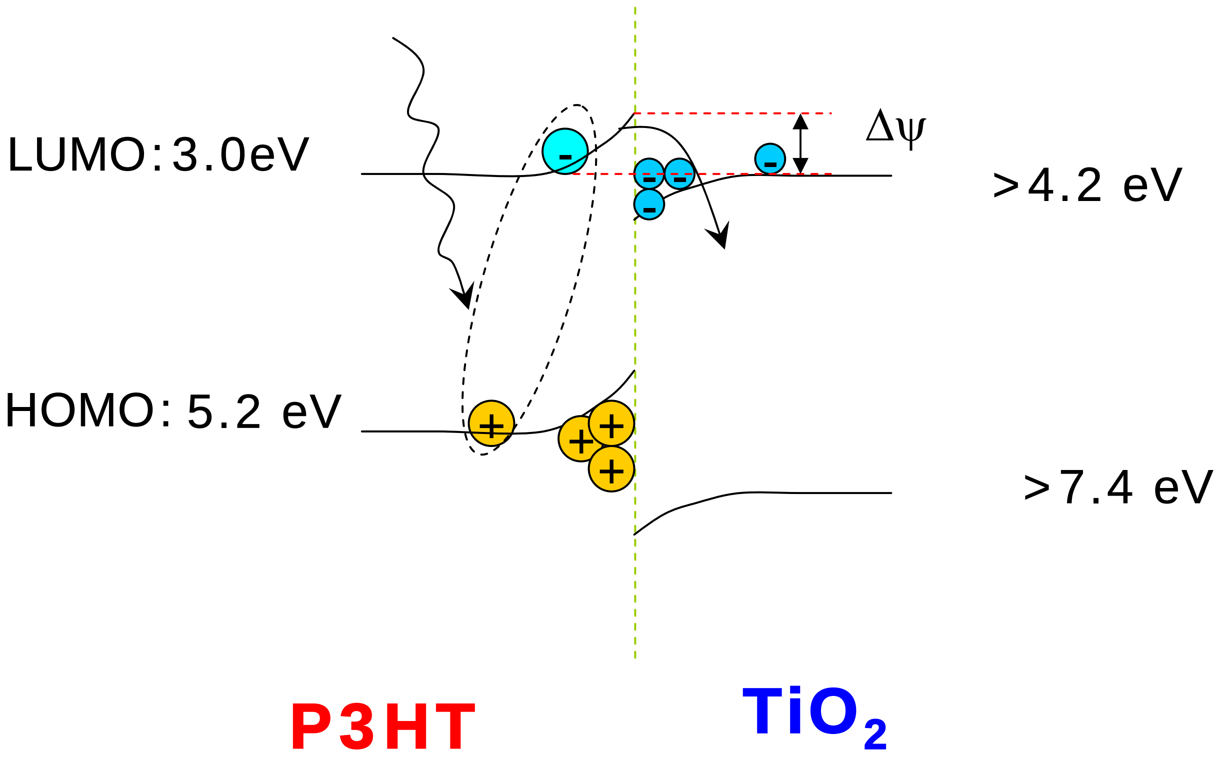

30
25
20
15
10
5
0
ΔV_TH
0
100
200
300
I (μW/cm²)


30
25
20
15
10
5
0
ΔV_TH
0.01
0.1
1
10
100
I (μW/cm²)

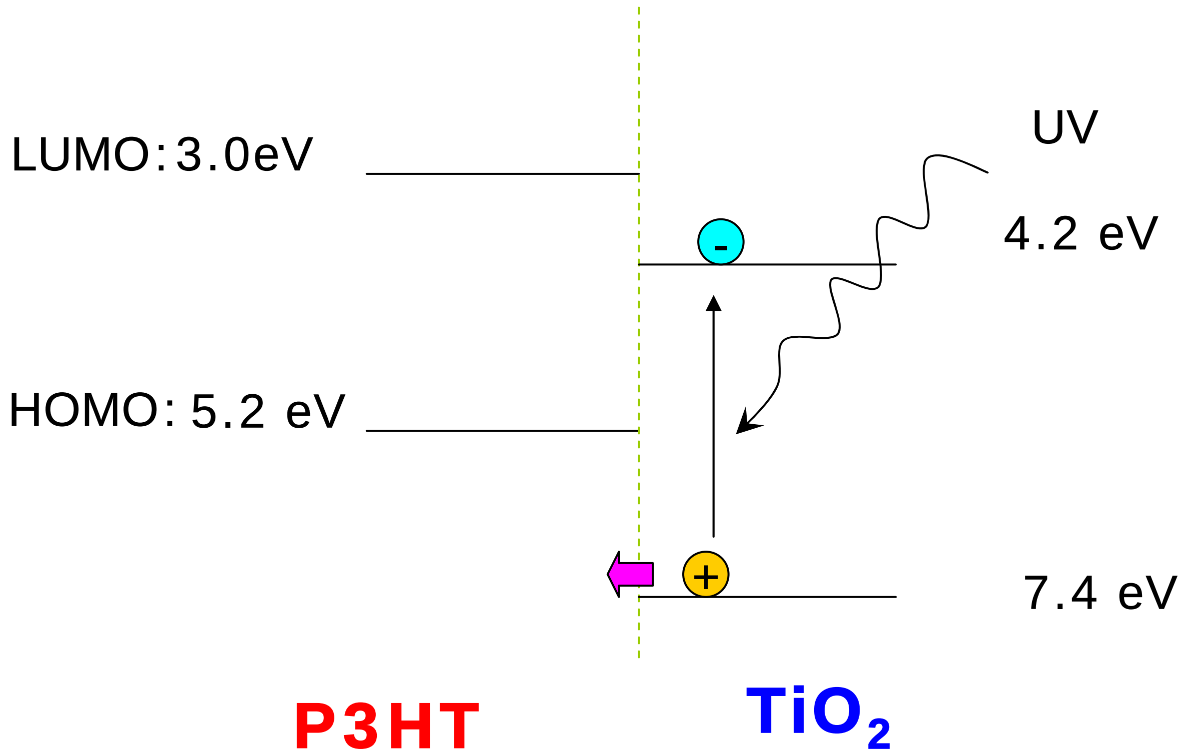
4.4.2 Mechanism for non-linear sensitivity

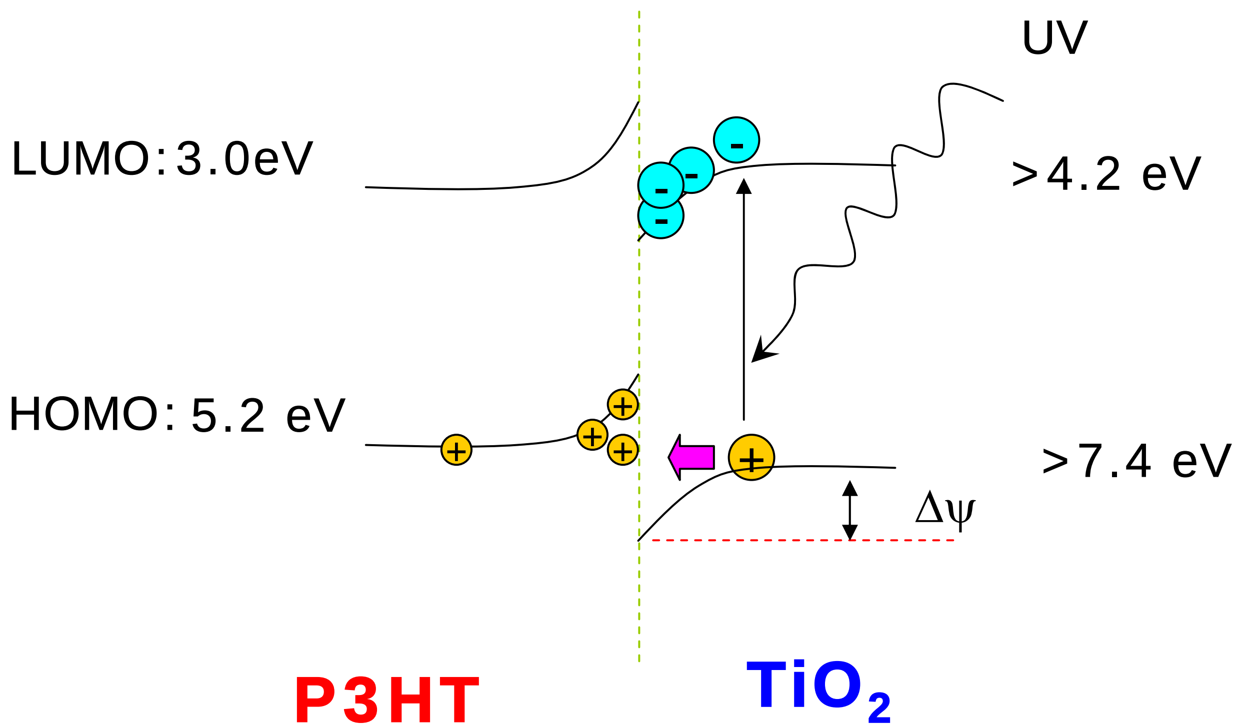
Visible light:




LUMO: 3.0eV
HOMO: 5.2 eV
Δψ
>4.2 eV
>7.4 eV
P3HT
TiO_2

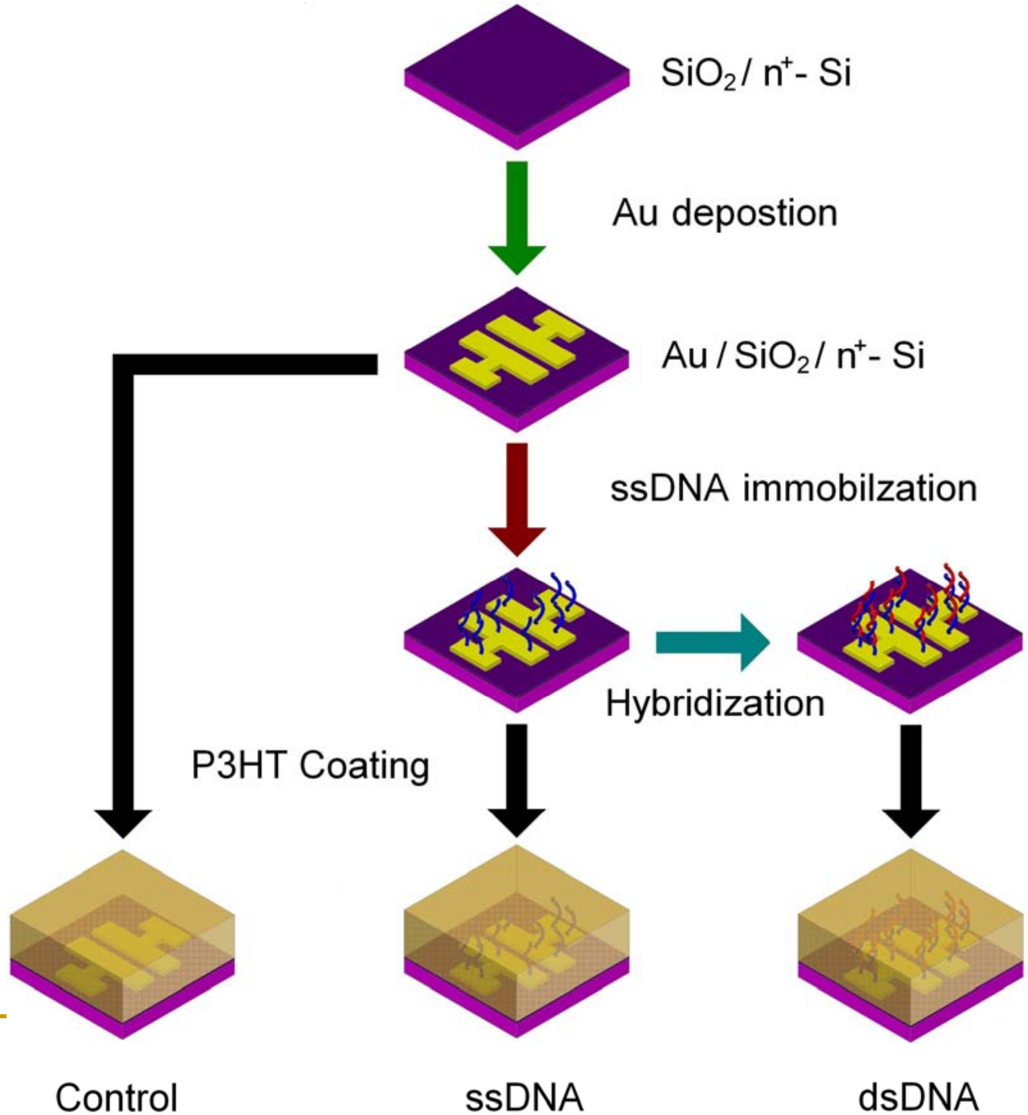
UV light:

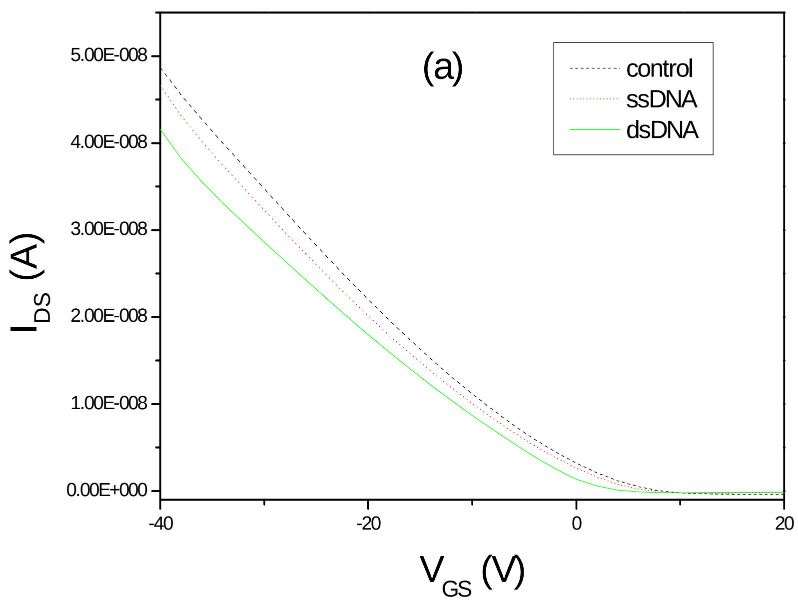


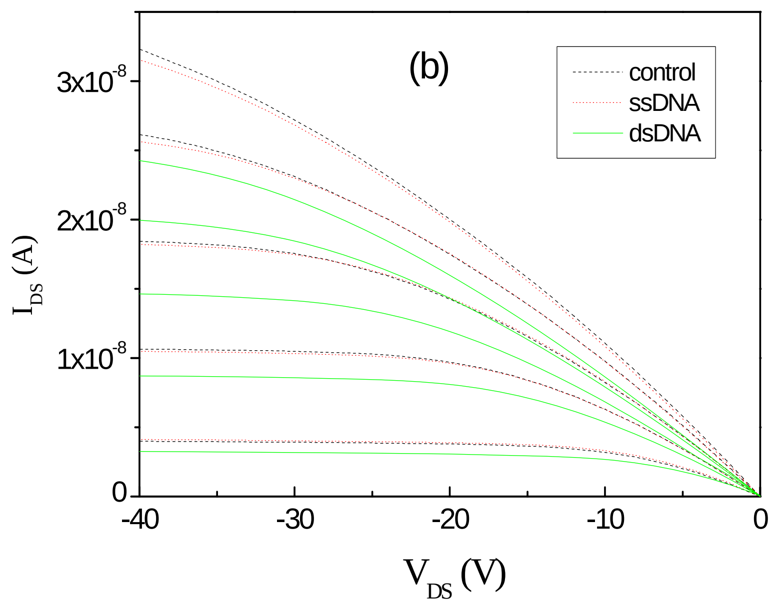

UV
LUMO:3.0eV
>4.2 eV
HOMO: 5.2 eV
>7.4 eV
Δψ
P3HT
TiO_2

5. Organic DNA sensor

Device fabrication

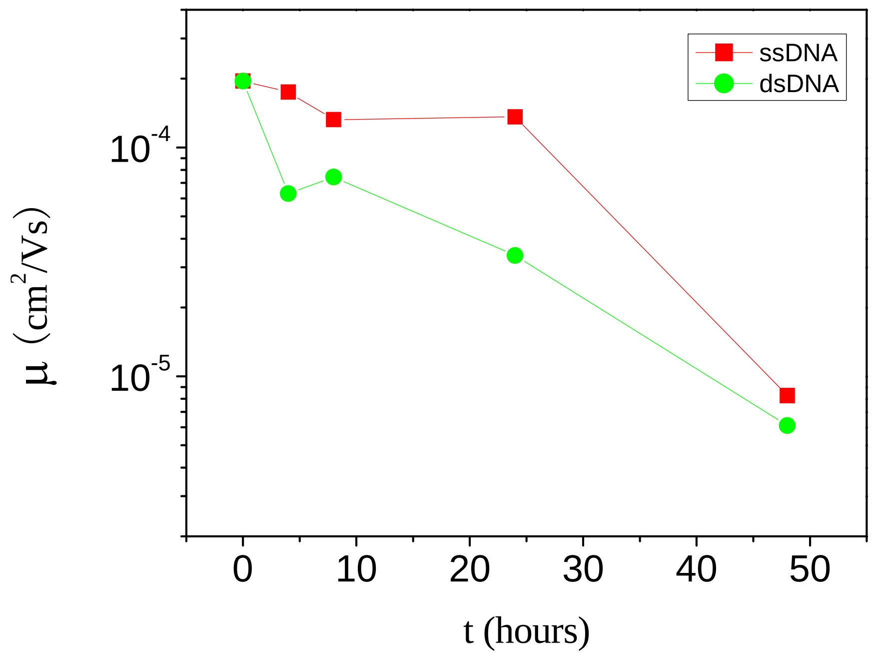






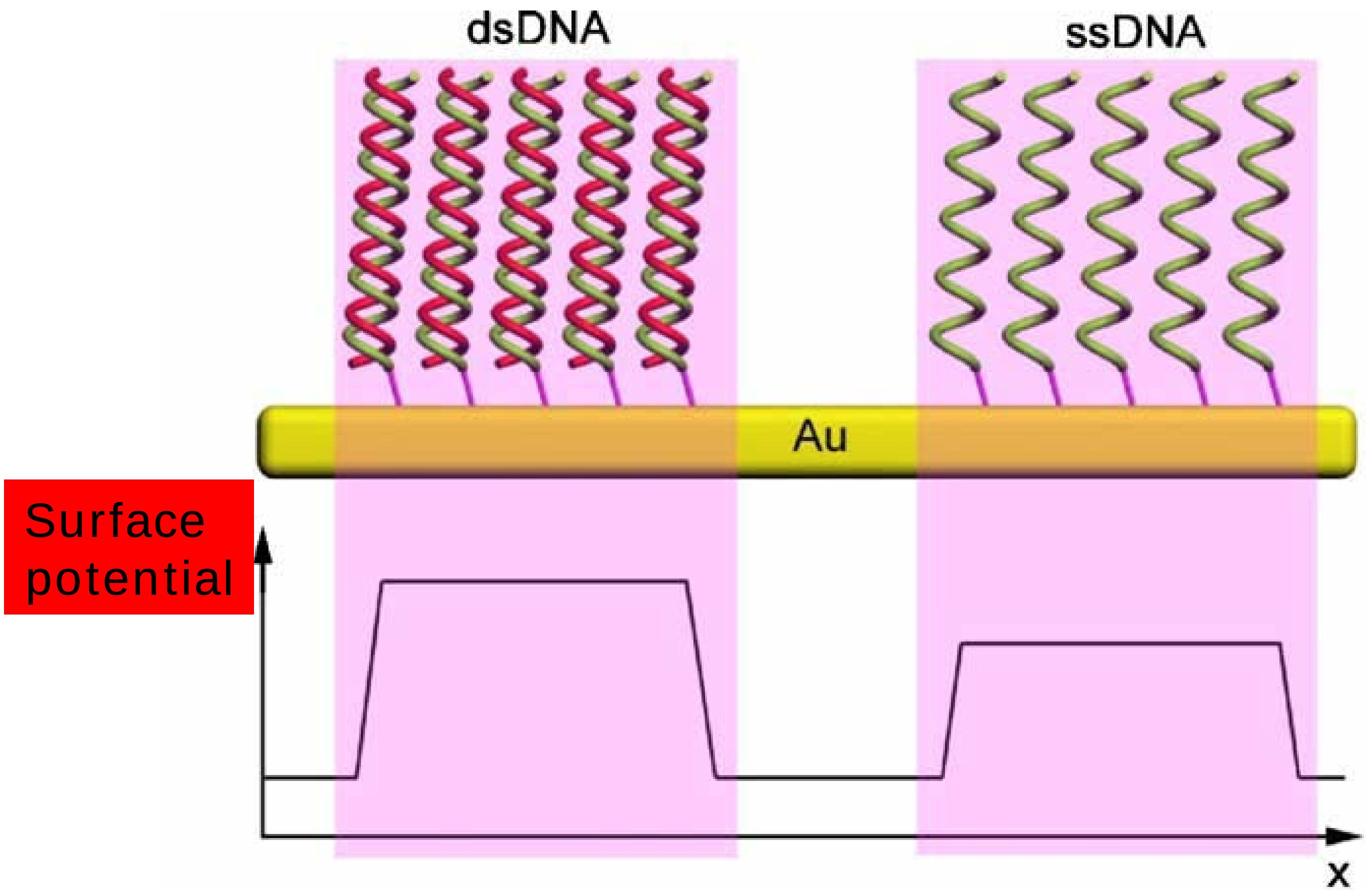
Performance of OTFTs with DNA probe immobilized on Au source/drain electrodes for 4 hours.

Shenyang-2008

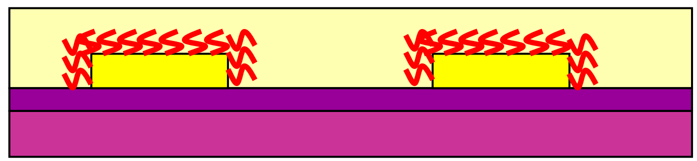


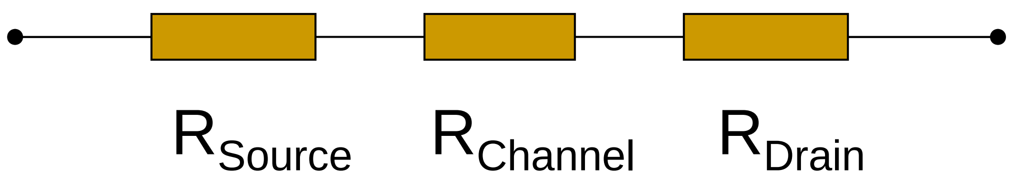
The field effect mobilities of OTFTs with ssDNA and dsDNA layers immobilized on Au source/drain electrodes as a function of immobilization time t (t = 4, 8, 24, 48 hours) of DNA.

Surface potential change



Contact resistance





DNA layer can increase contact resistances (R_{Source} and R_{Drain}) of OTFT, which can be attributed to the decrease of work function of Au electrodes.

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- Dr. Mo Yang
- Mr. Jinjiang Yu

Thanks for your attention