Low Voltage OFETs

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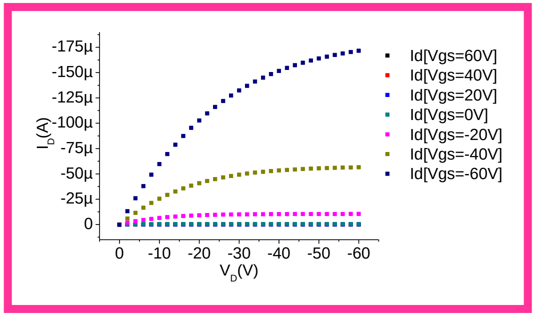
Why Organic Materials?

- Low temperatures
- Large areas
- Easy and low cost processes

  Inkjet Printing

- Plastic materials are flexible
- **Wide range of applications: wearable electronics and/or robotics (e-skin)**

Drawbacks



- High operating voltages

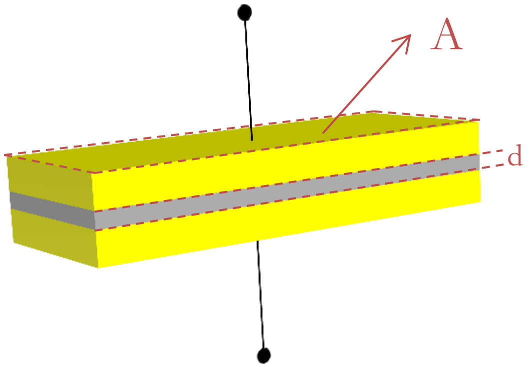
very low portability, step-up conversion needed for battery-operating devices, high power consumption

- Flexible structure doesn't mean flexible electronics

Electrical behavior is severely affected by mechanical deformation

Towards low voltage OTFTs

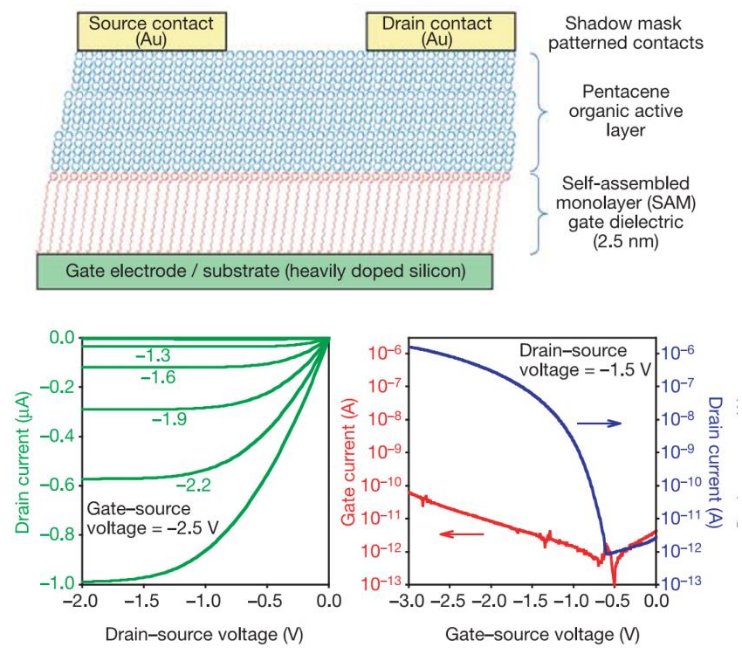
Is it possible to scale down the operational voltages in OTFTs?



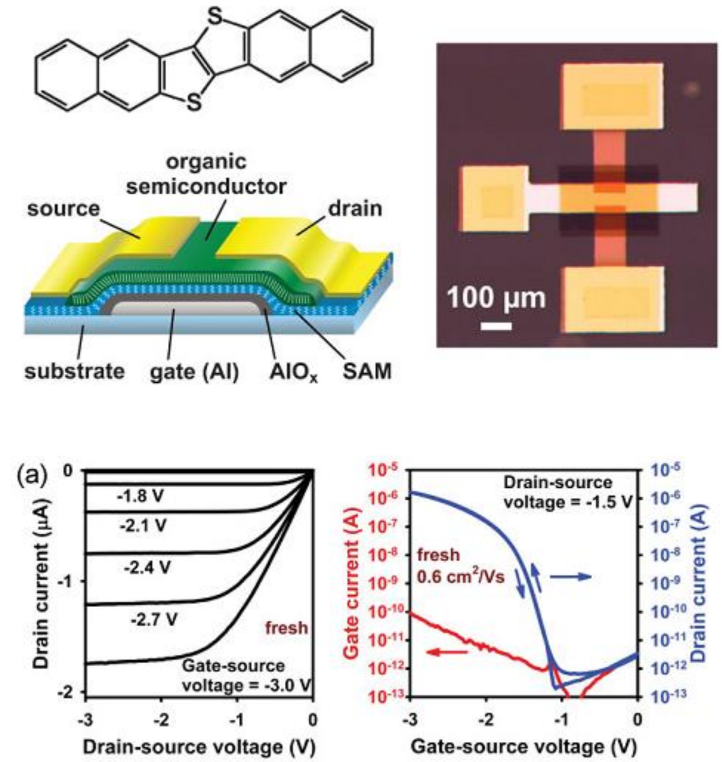
$$C_{ins} = \frac{\varepsilon_0 \varepsilon_r \uparrow}{d \downarrow} A$$

Increasing gate capacitance is the key factor for realizing low-voltage OFETs

State of the art – SAMs and Polymers



Halik et al., Nature, 2004, 431



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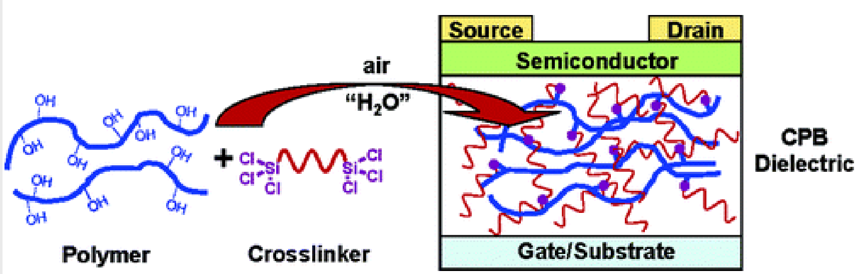

Young-geun Ha, et al. JACS, 2010, 132, 17426

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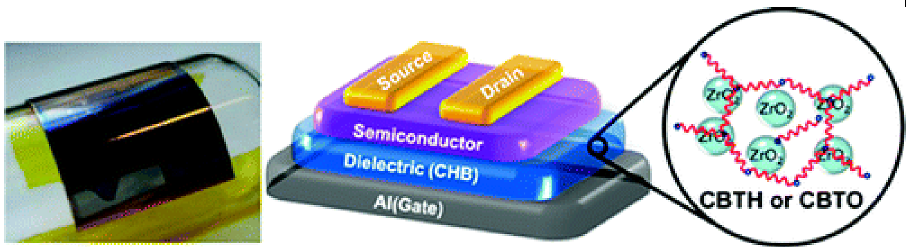
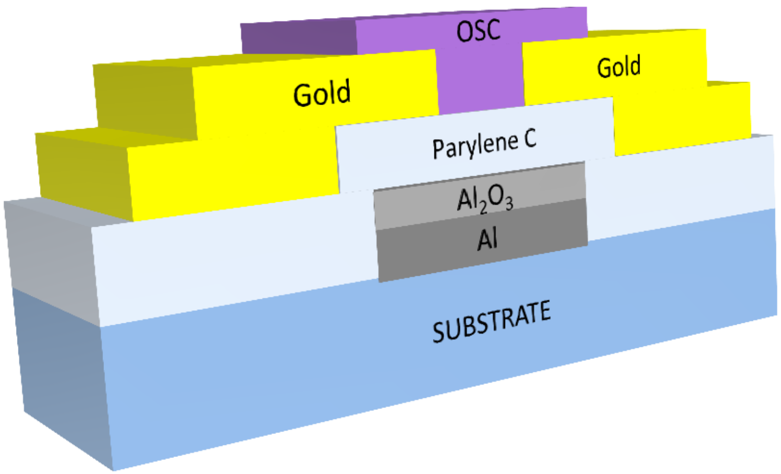


Low voltage OTFTs

Bottom gate, bottom contact structure on flexible PET substrate

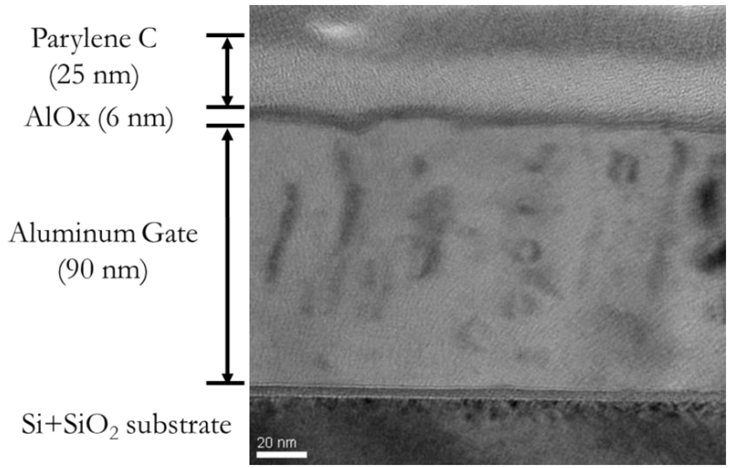


- **Gate: Aluminum**
- **Gate Dielectric:**

AlOx ***[UV-Ozone treatment at room temperature]***

Parylene C ***[deposited by CVD]***

[air-stable, robust, biocompatible and resistant to solvents; can be deposited in very thin films]

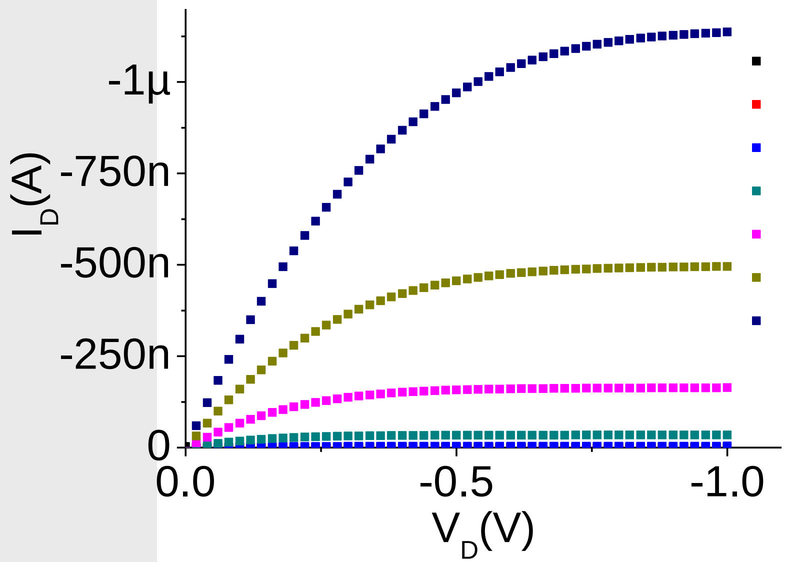


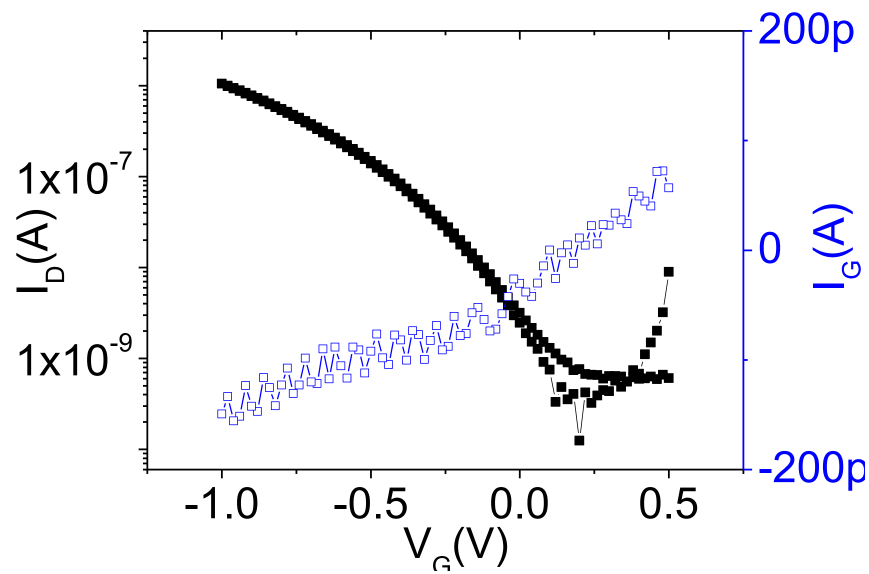
P. Cosseddu, et al. Appl. Phys. Lett. 100, 093305 (2012)

AlOx/Parylene C Double-Layer

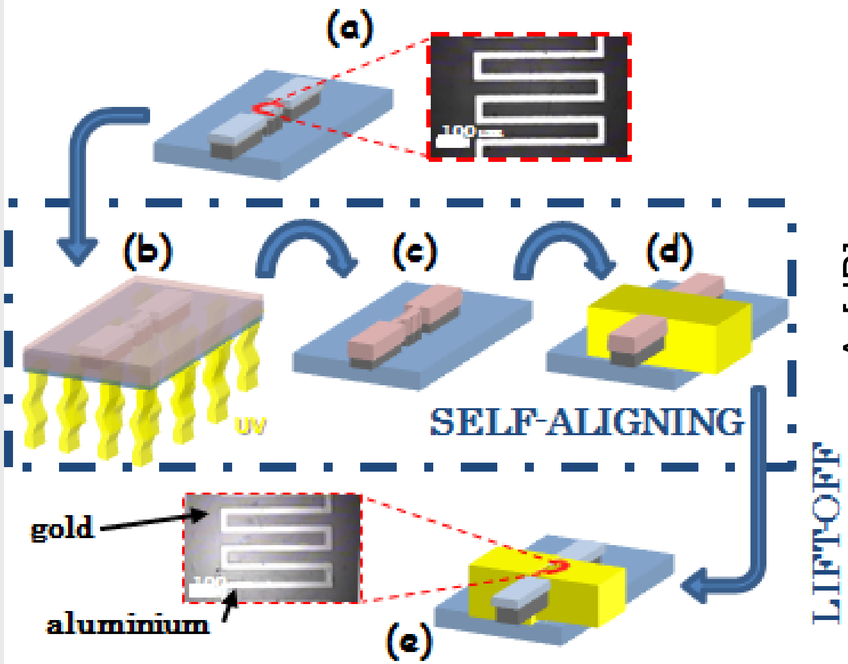
Thermally evaporated pentacene as OS

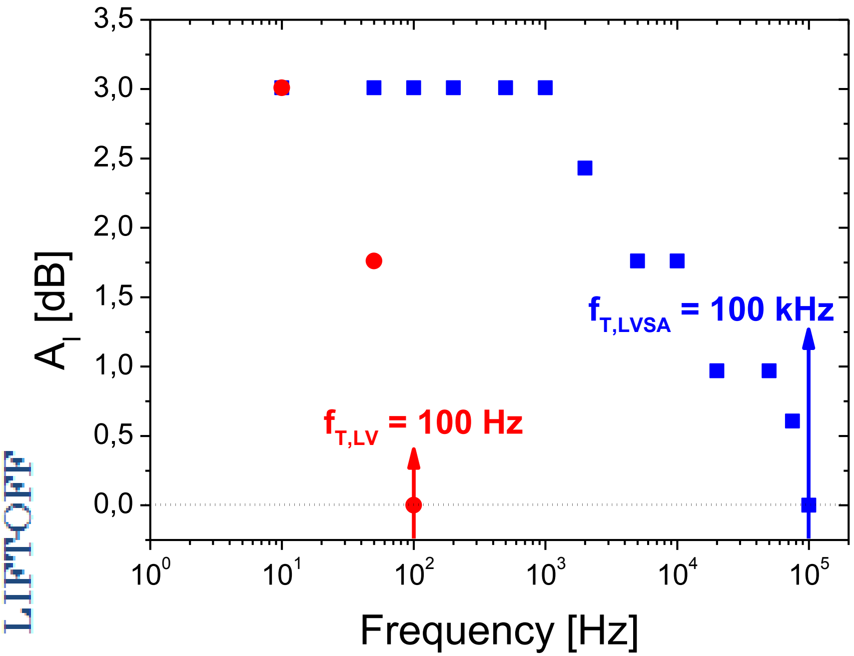
Insulating Structure	Capacitance [F/cm²]	I_G [A] J_G[A/cm²]	Vt [V]	μ [cm²/Vs]	S [mV/dec]	Nt [cm⁻²eV⁻¹]	OTFTs Yield [%]
AlOx	3.5 E-6	6 E-6 2.9 E-5	-1.2	3.3 E-3	360	1.1 E14	15%
AlOx + 25nm Parylene	1.3 E-7	4 E-10 1.9 E-9	-0.5	6 E-2	350	4 E12	95%

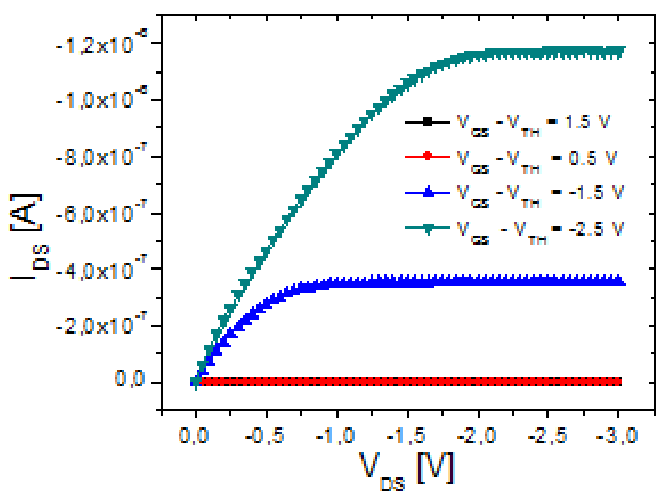


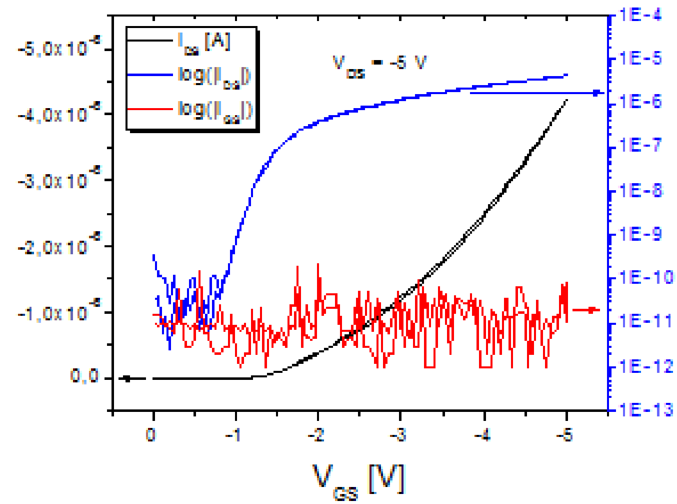


Towards high frequency: self-alignment





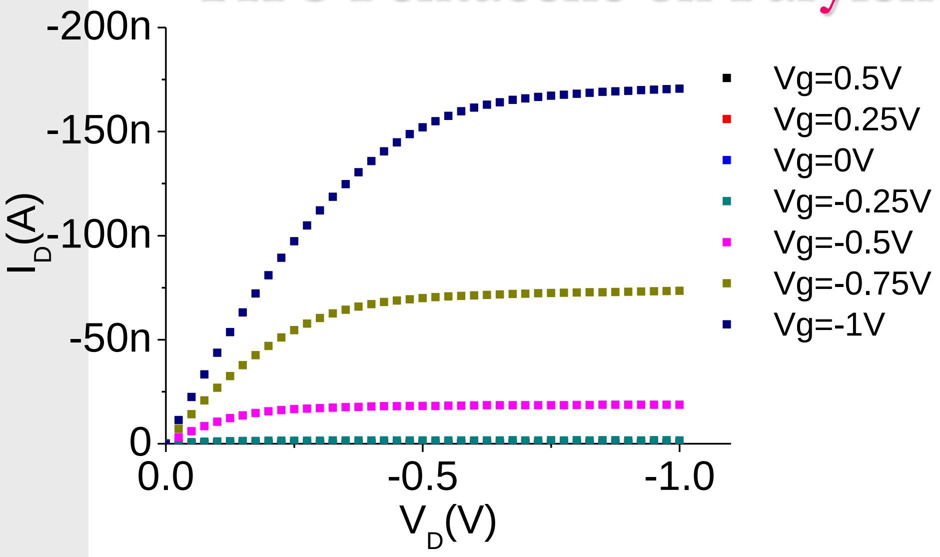


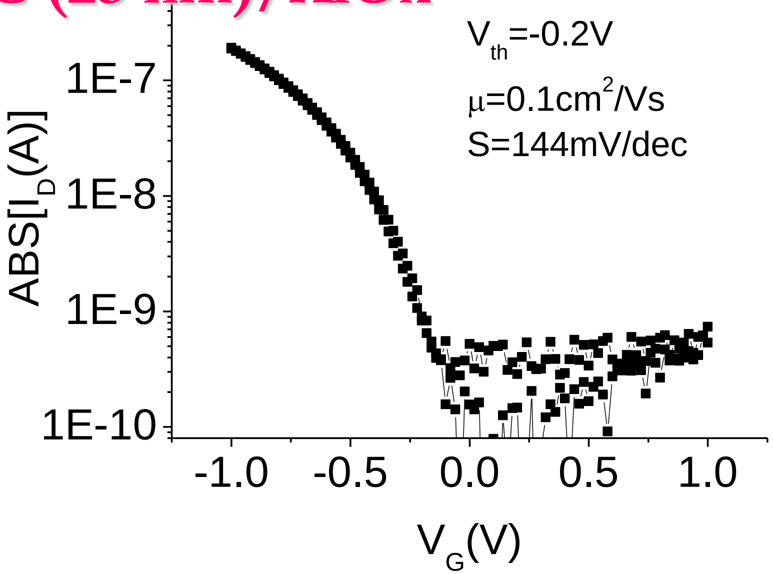


S. Lai, P. Cosseddu, G.C. Gazzadi, M. Barbaro e A. Bonfiglio, Org. Electr. 14, 754-761 (2013)

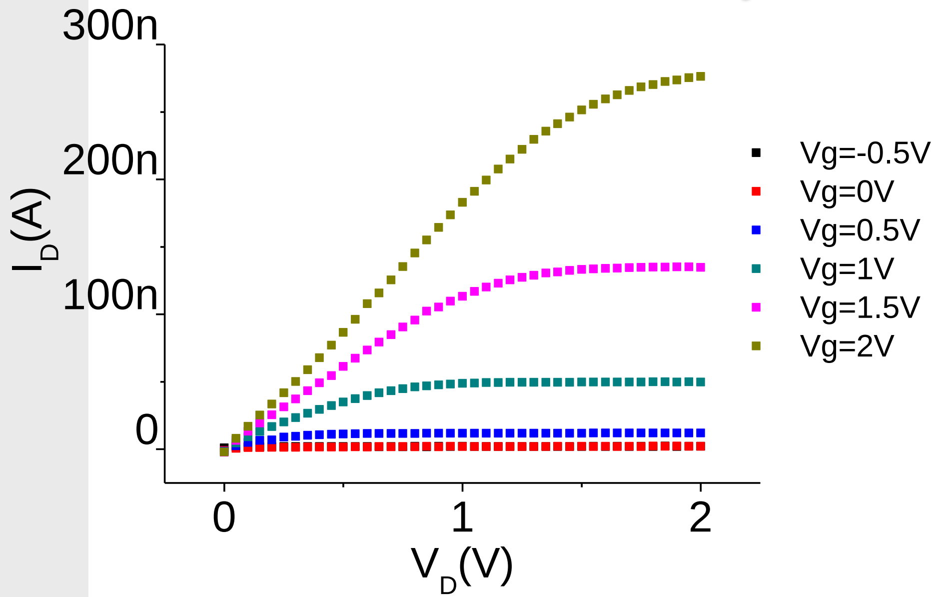
Low Voltage OFETs: Solution-Processable OSC

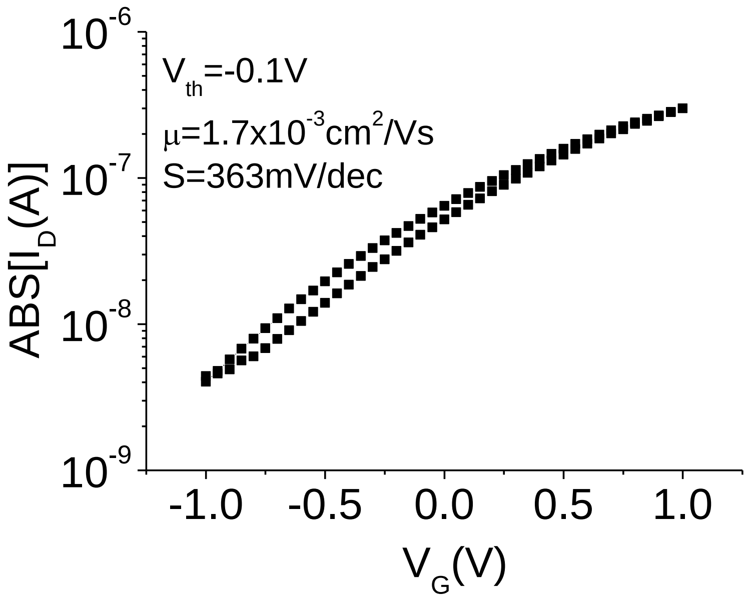
TIPS Pentacene on Parylene C (25 nm)/AlOx



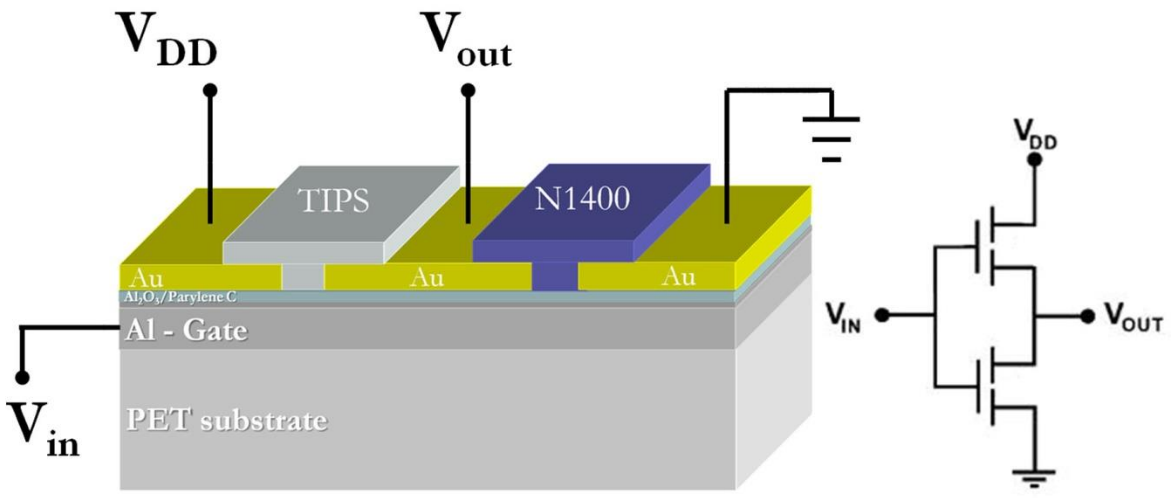


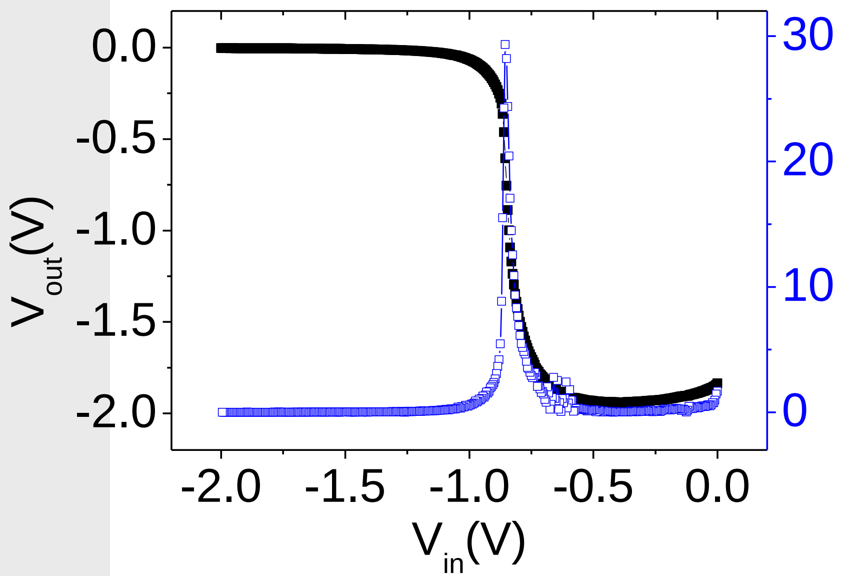
N1400 on Parylene C (25 nm)/AlOx

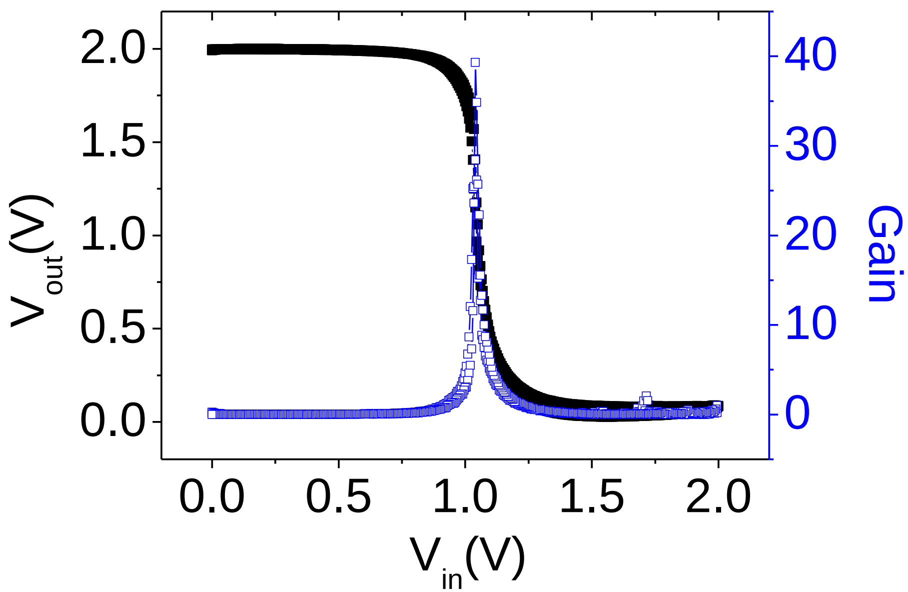




Low Voltage Complementary inverters







paper to be submitted

Electrolyte Gated Organic Field Effect Transistor EGOFET

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Elettrolita

Un elettrolita è una sostanza che contiene ioni liberi, per cui è in grado di condurre elettricità

Un elettrolita può essere in forma liquida, solida o in forma di gel

In genere è costituito da un sale (soluto) e un solvente che fa si che il sale si dissoci in uno ione positivo (catione) e uno negativo (anione)

Possono essere classificati in forti o deboli a seconda del grado di dissociazione (ionizzazione)

Elettrolita

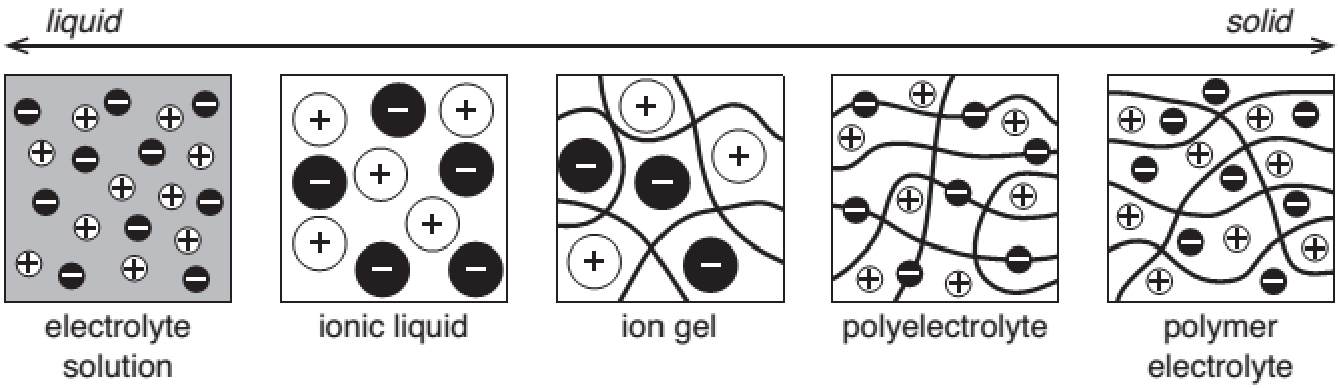


Figure 3.1 Schematic illustrations of different types of electrolytes, ordered from left to right by their physical appearance.

- Electrolitic solutions
- Ionic liquids
- Ion gels
- Polyelettroliti
- Polymer electrolites

Elettrolita

Electrolitic solutions

Sale disciolto in un liquido, generalmente un solvente polare

Acetonitrile, molto più stabile, non da luogo a reazioni chimiche non volute

Anche l'acqua di per se è un elettrolita, ioni H+ e OH- anche se molto debole

Elettrolita

Ionic liquids

È semplicemente un **sale in forma liquida**

Ha una temperatura di fusione inferiore ai 100°C

Possono dare luogo a **conducibilità molto elevate**

Sono tra gli elettroliti più utilizzati

Elettrolita

Ion gels

I precedenti non sono però molto utili per realizzare dispositivi allo stato solido, per cui vengono generalmente **trattati** in modo da essere immobilizzati, per esempio **con degli opportuni co-polimeri o polielettroliti**

In genere questi polimeri hanno una bassa concentrazione e **la conducibilità risultante degli ion gels non è elevatissima**

Elettrolita

Polyelettroliti

Sono polimeri che hanno un gruppo elettrolita nella loro catena

Questi gruppi si possono dissociare quando in contatto con dei solventi polari

Il polimero si ionizza e rimangono i controioni in soluzione

Elettrolita

Polymer electrolites

Elettrolita solido non in soluzione!

Sale distribuito in una matrice polimerica

Il più noto è il PEO polyethileneoxide

Hanno basse conducibilità, ma possono essere utilizzati in numerose applicazioni allo stato solido

Es. batterie flessibili

Elettrolita

Trasporto ionico

- Diffusione (gradiente di concentrazione)
- Elettromigrazione (campo elettrico)

Gli ioni che si muovono in un liquido risentono di forze d'attrito che dipendono dalla viscosità del liquido → bassa mobilità

Nei polimeri elettrolitici, effetto polaronico, gli ioni interagiscono con la catena, basse mobilità

I protoni in genere si muovono in un mezzo acquoso polare seguendo un meccanismo differente.

Riarrangiamento dei legami ad idrogeno → mobilità elevate

Elettrolita

Formazione del doppio strato

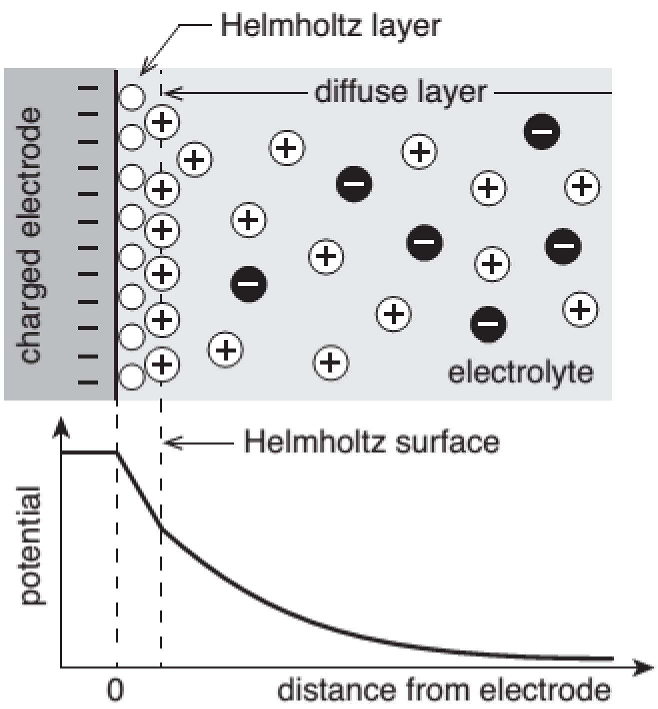
La differenza di potenziale tra un elettrodo e l'elettrolita porta alla formazione di un layer di interfaccia carico

Un layer carico di segno opposto si andrà a formare all'interfaccia nell'elettrolita (Electric Double Layer EDL)

Il layer più vicino all'interfaccia viene chiamato Helmholtz layer

L'Helmholtz layer e le cariche superficiale nell'elettrodo formano una sorta di capacitore

Elettrolita



Proprio per questo motivo questi materiali vengono generalmente utilizzati per fare dei capacitori

Elettrolita

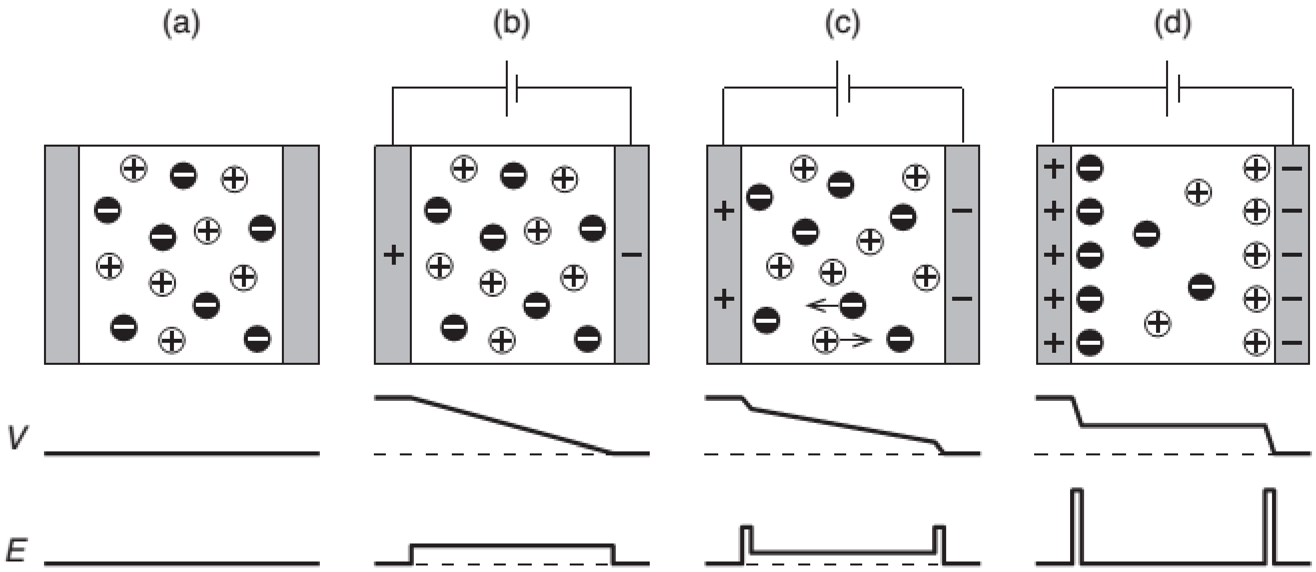


Figure 3.4 Schematic illustrations of the charge distribution, electric potential (*V*) and electric field (*E*) in the electrolyte layer of an electrolytic capacitor during charging. (a) The ions are evenly distributed when no voltage is applied. An applied voltage will induce a redistribution of the charges in the electrolyte. The situation in the electrolyte (b) before, (c) during and (d) after ionic relaxation is shown.

L'EGOFET

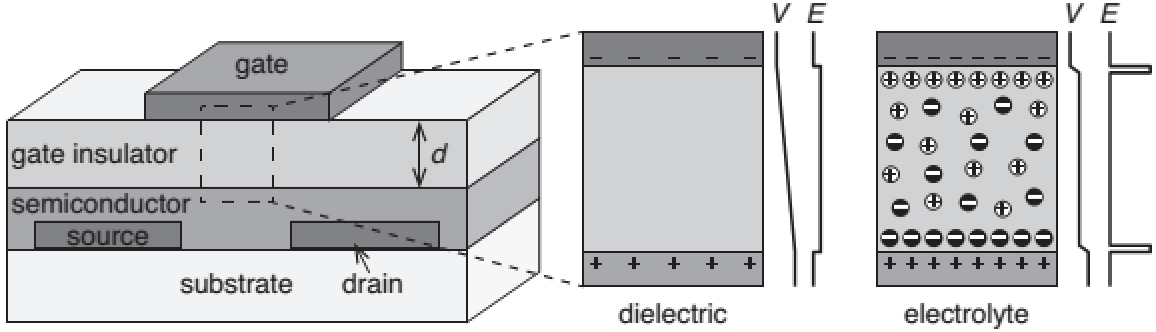


Figure 4.6 Schematic cross section of an organic thin-film transistor and illustrations of the voltage (*V*) and electric field (*E*) distributions in a dielectric and an electrolytic gate insulator when a negative gate voltage is applied.

Nel caso di un dielettrico normale, il campo varia linearmente all'interno del dielettrico.

Nel caso di un elettrolita, la ridistribuzione e il rilassamento fa si che il campo all'interfaccia sia molto più intenso

L'EGOFET

L'applicazione di un potenziale di gate fa si che gli ioni mobili migrino all'interno dell'elettrolita per formare il doppio layer alle due interfacce

Non ho caduta nel dielettrico, tutta la tensione viene applicata al semiconduttore

Accoppiamento capacitivo molto pronunciato

Formazione del canale

Basse tensioni operative

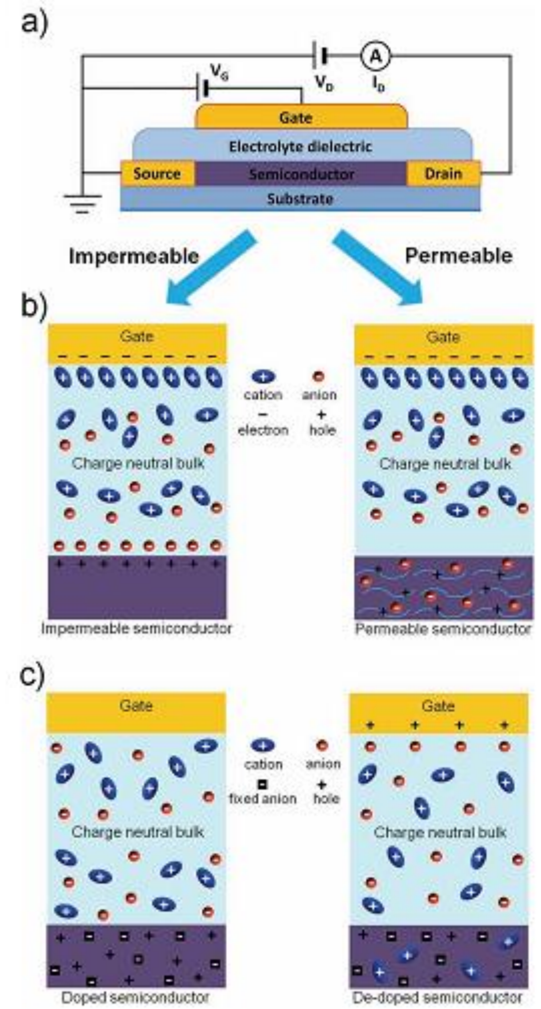
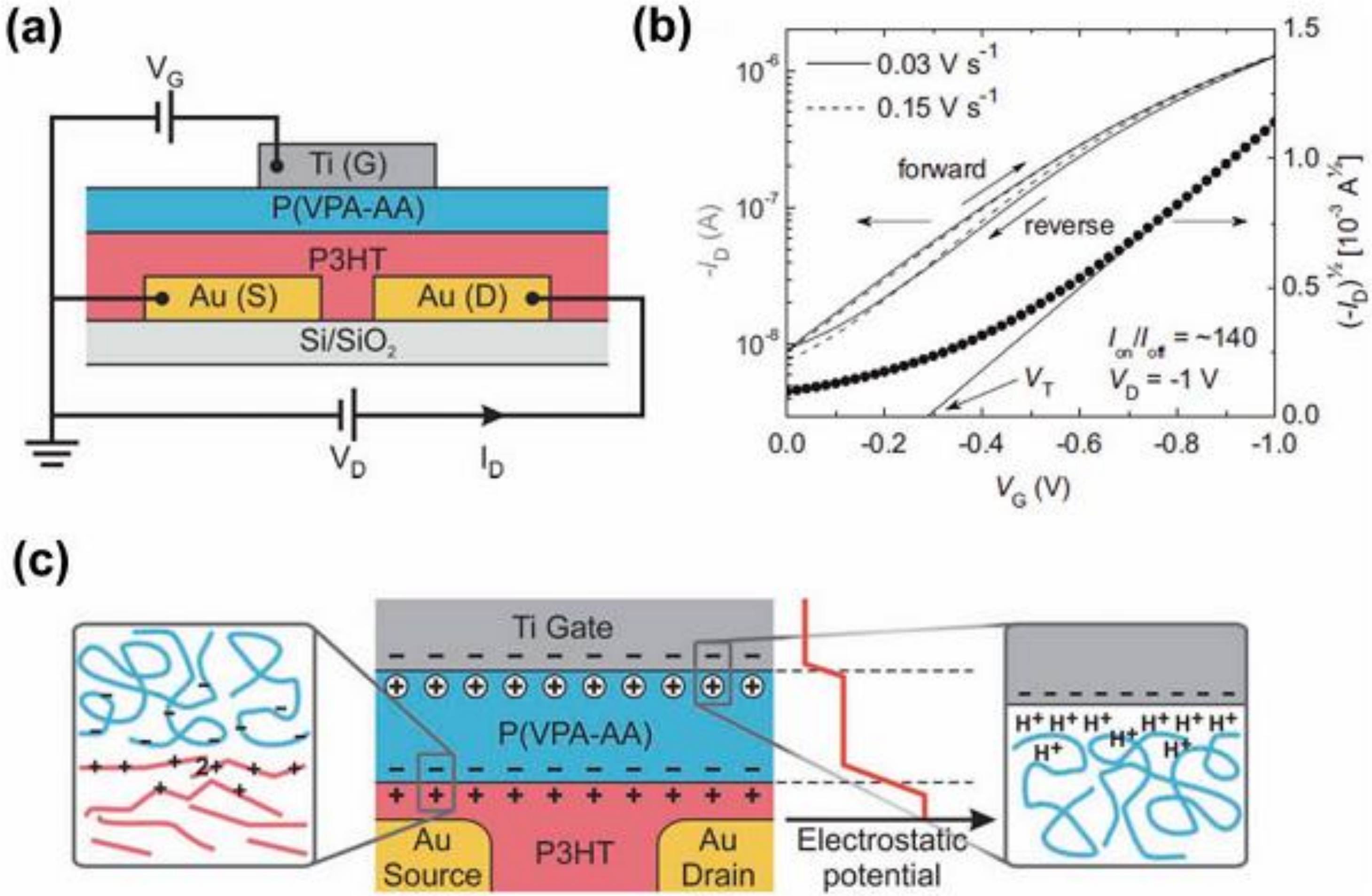


Figure 1. (a) Cross-section of an EGT. (b) Carrier accumulation-mode operation of an EGT for un-doped ion-impermeable (left) and permeable semiconductors (right) and (c) depletion-mode operation for degenerately doped semiconductors without (left) and with (right) a gate voltage.

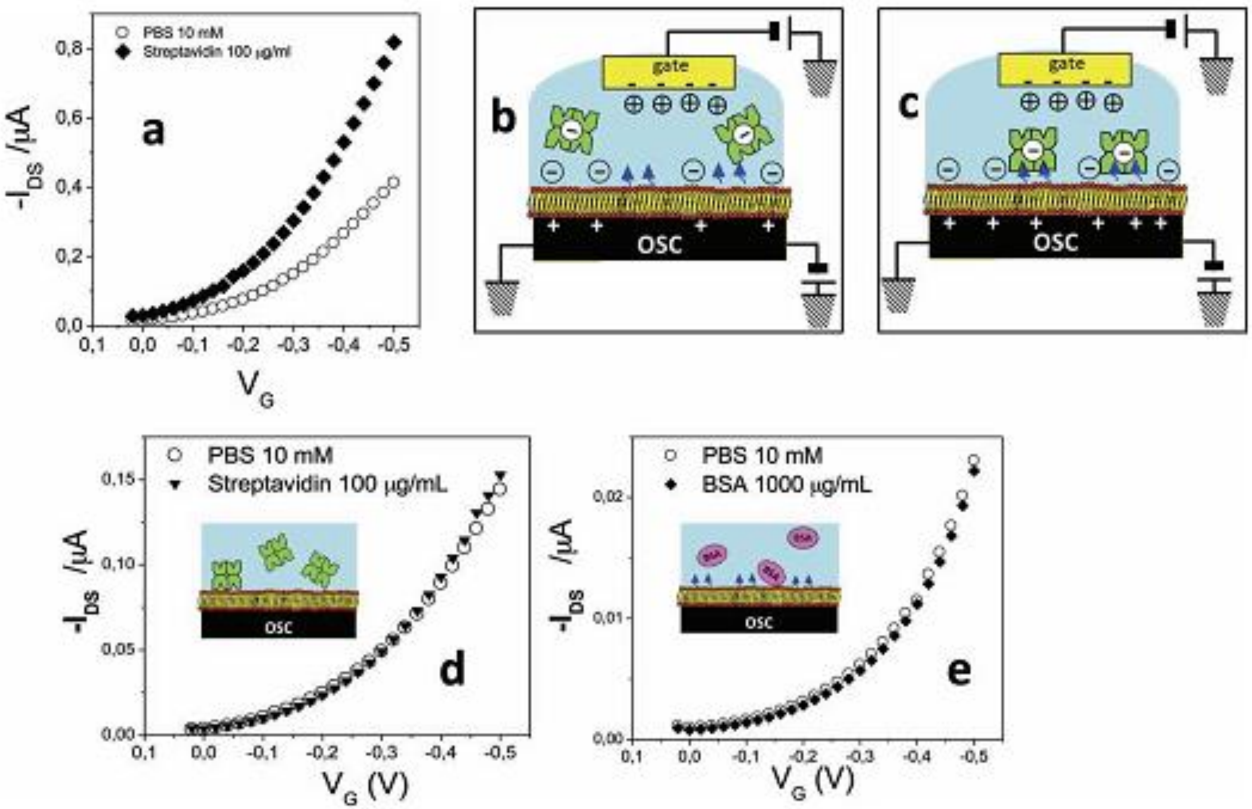
L'EGOFET



(a)
V_G
Ti (G)
P(VPA-AA)
P3HT
Au (S)
Au (D)
Si/SiO₂
V_D
I_D
(b)
0.03 V s⁻¹
0.15 V s⁻¹
forward
reverse
-I_D (A)
(-I_D)^½ [10⁻³ A^½]
I_on/I_off = ~140
V_D = -1 V
V_T
V_G (V)
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
1.5
1.0
0.5
(c)
Ti Gate
P(VPA-AA)
Au Source
P3HT
Au Drain
Electrostatic potential
H⁺
2+

L'EGOFET come bio-sensore

È possibile modificare la carica all'interno dell'elettrolita tramite l'aggiunta di specie cariche. Tali specie genereranno un potenziale interno che modula la tensione di soglia del transistor



Organic Electro-Chemical Transistors (OECTs)

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Tecnologie e Dispositivi Elettronici Avanzati
A.A. 2015/2016

OCET: Introduzione

È possibile modificare la conduttività di alcuni polimeri conduttori semplicemente utilizzando una cella elettrochimica.

Tramite un processo di ossido-riduzione (reversibile) è possibile passare da uno stato ad elevata resistività ad uno a bassa resistività

Tale approccio è stato utilizzato per la fabbricazione di veri e propri transistor, chiamati:

Organic Electro-Chemical Transistors

OCET: Introduzione

- Possono essere fabbricati su larga area
- Da fase liquida
- Tecniche a basso costo → Printing
- Materiali a basso costo → all plastic
- Basse tensioni di pilotaggio
- Basse Temperature di processing → substrati plastici
- Effetto elettrocromico → Display
- Se opportunamente modificati → sensing

OCET: Introduzione

L'OECT è basato sull'utilizzo di polimeri conduttori in cui il trasporto di carica è dovuto sia ad elettroni che a ioni.

Tra i vari materiali ricordiamo il PEDOT:PSS

Questi materiali possono subire, in maniera reversibile, un processo di ossido-riduzione

Tale processo favorisce un doping o dedoping del materiale, introducendo nuovi livelli elettronici e di conseguenza un numero maggiore di portatori di carica liberi, nel polimero

OCET: Introduzione

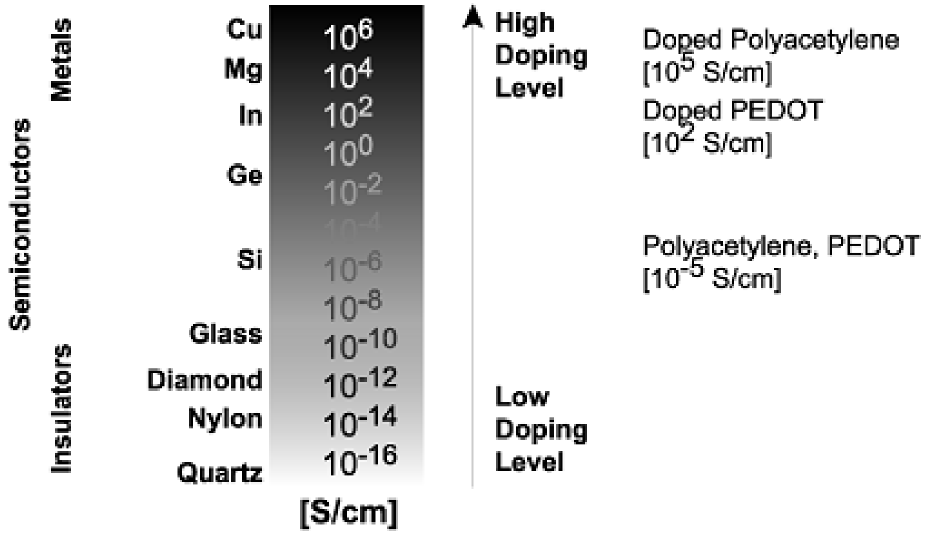


Figure 2. Conductivity levels of polyacetylene and PEDOT. In comparison, conductivity of some other materials is given, from very good insulators to metallic conductors.

OCET: Introduzione

Il doping in realtà può essere fatto in differenti maniere:

- Chemical doping
- Electrochemical doping
- Photo-induced doping
- Charge injection doping

I primi due metodi sono di gran lunga quelli più utilizzati

I polimeri possono essere dopati sia p che n

L'ossidazione induce un doping di tipo p

OCET: Introduzione

Il processo di doping di tipo p è dovuto alla «rimozione» di un elettrone dalla sistema π lungo la catena polimerica

Se questo avviene, si crea uno sbilanciamento di carica che porta alla creazione di una lacuna libera che può muoversi lungo la catena coniugata

Il polimero, depositato sotto forma di film sottile, viene interfacciato con una soluzione elettrolita

La neutralità di carica è garantita dagli ioni e contro-ioni dell'elettrolita, che penetrano o escono dal film polimerico

In alcuni casi gli ioni possono essere mobili, in altri immobili

Riconsideriamo il caso del PEDOT:PSS

PEDOT:PSS doping

Il PEDOT è un polimero semiconduttore!

Se dopato con il PSS diventa un ottimo conduttore

Il PEDOT:PSS può essere ossidato o ridotto tramite un processo elettro-chimico, e può passare da uno stato conduttivo → $PEDOT^+$ ad uno stato semiconduttivo → $PEDOT^0$

L'elettrolita

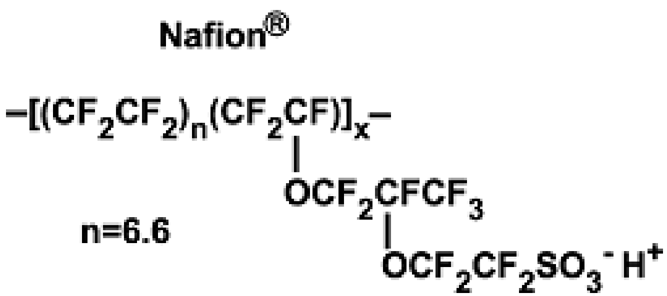
Per realizzare un transistor elettrochimico è però necessario utilizzare degli elettroliti, che possono essere solidi o liquidi

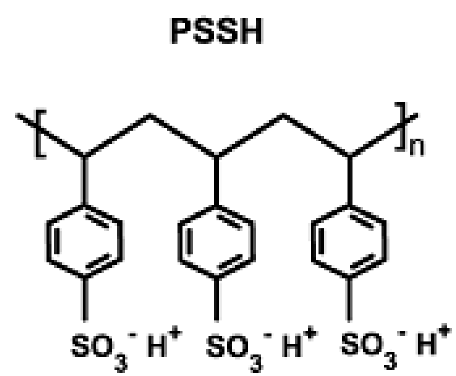
Nafion

Polys(tyrene sulfonic)acid (PSSH)

Poly(etylene oxide) (PEO)

Poly(vinyl alcohol) (PVA)





Il transistor elettrochimico

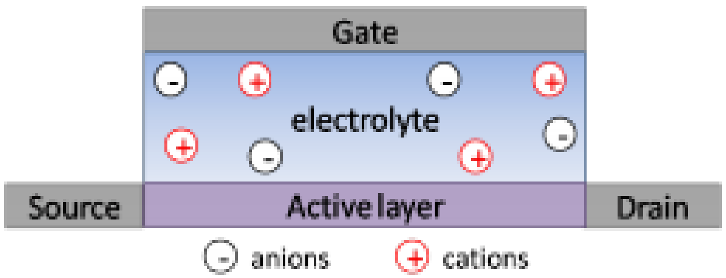
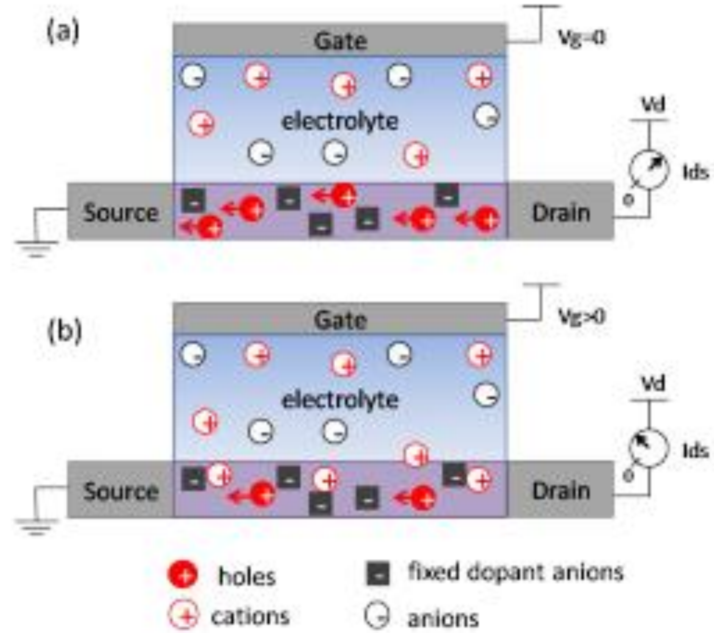


Figure 3.1: Schematic view of an OECT.



Il PEDOT:PSS è, come già detto drogato di tipo p, (lacune mobili e ioni fissi negativi). Per convenzione mettiamo il source a massa e applichiamo una tensione al drain (*V*d).

Se non applico tensione con il gate, misuro la conducibilità intrinseca del PEDOT:PSS

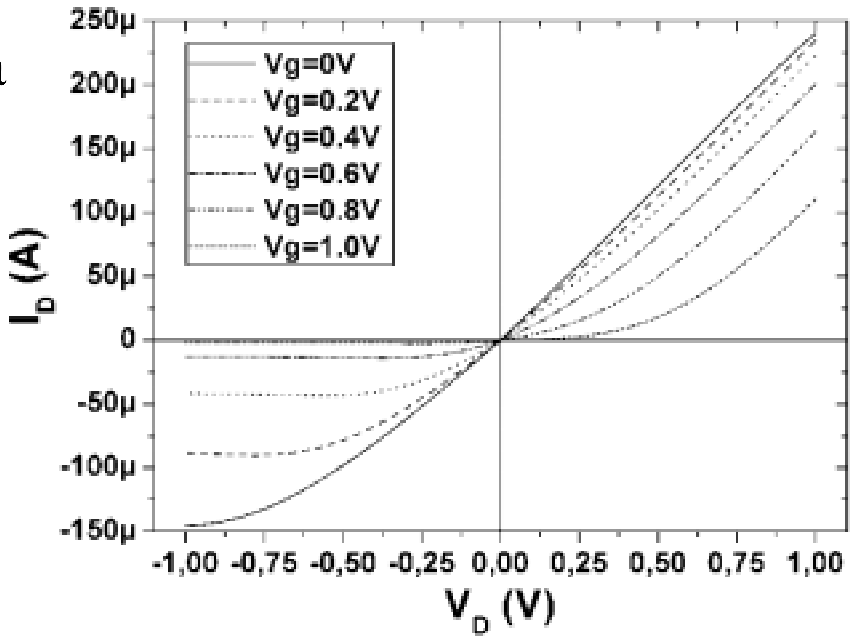
La corrente che scorre nel semiconduttore può essere modulata tramite la tensione applicata con il gate.

Il transistor elettrochimico

Se applico una Vgs positiva, i cationi M^+ dell'elettrolita vengono iniettati nel semiconduttore

Tali ioni inducono un de-doping (riduzione) dello stesso, e di conseguenza, una diminuzione della corrente di uscita.

- Effetto di campo dovuto alla modulazione della conducibilità di canale
- OECT funziona in spegnimento!
- Basse tensioni operative

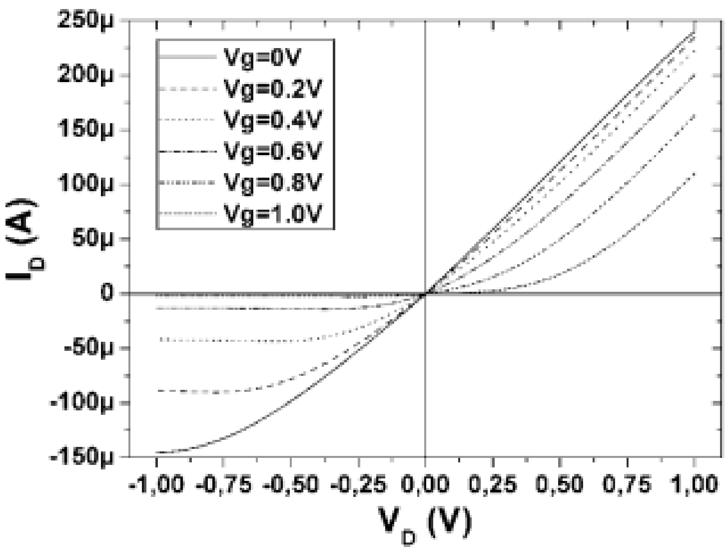


Il transistor elettrochimico

Quando V*d* <0 una porzione del canale può essere interamente dedpopata quando la concentrazione intrinseca di dopanti è uguale alla concentrazione dei cationi iniettati

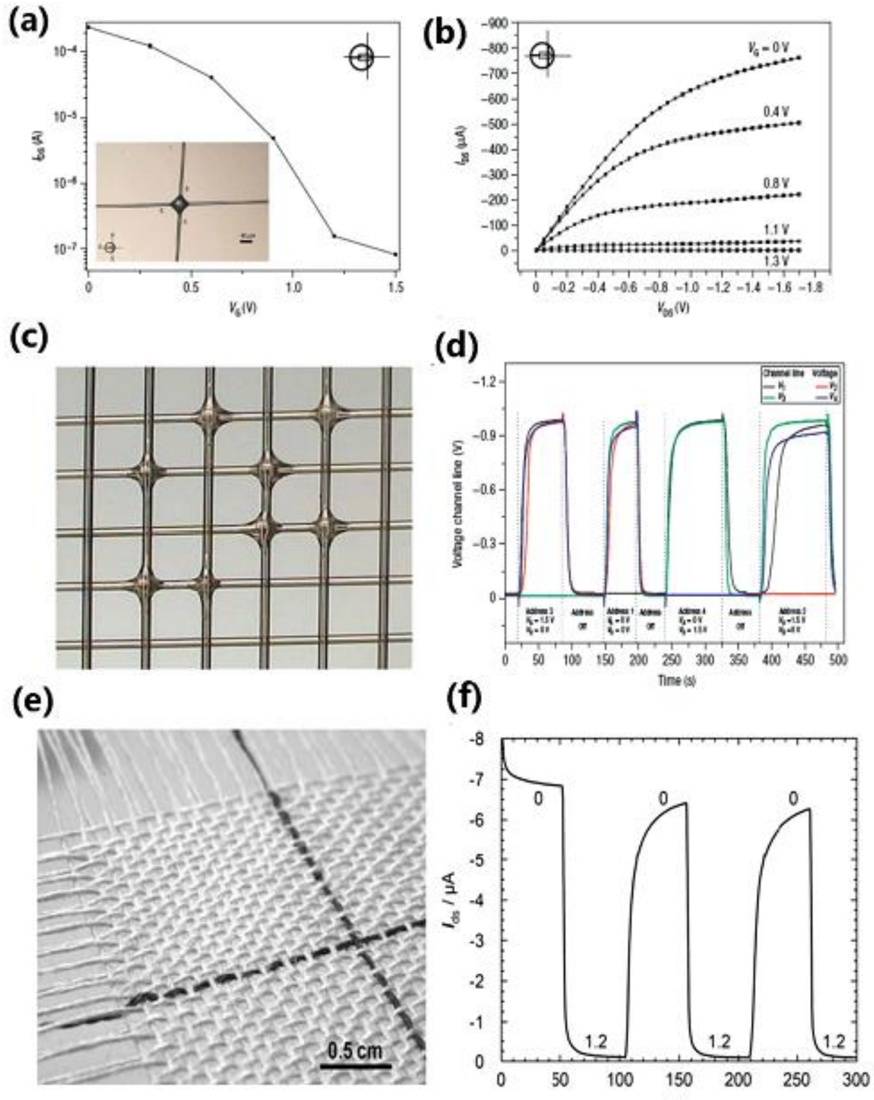
Per cui, se si aumenta ulteriormente la tensione di drain, la corrente tende a saturare perchè il canale raggiunge il pinch-off

Se l'elettrodo di gate è a massa o polarizzato negativamente, il canale di PEDOT:PSS viene ossidato di nuovo, e la corrente aumenta



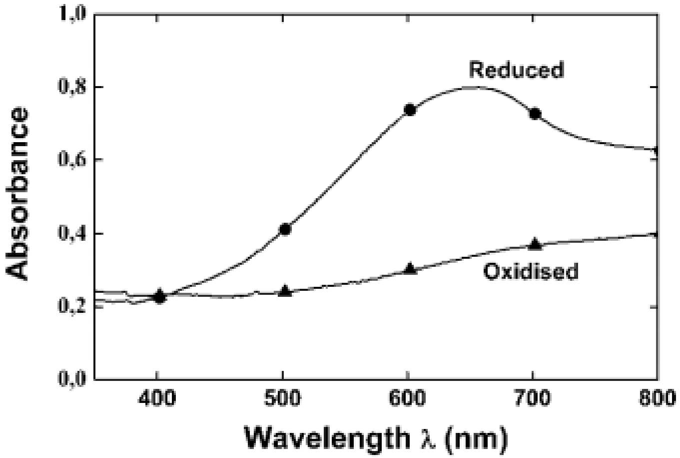
Il transistor elettrochimico

Transistor elettrochimici su fili

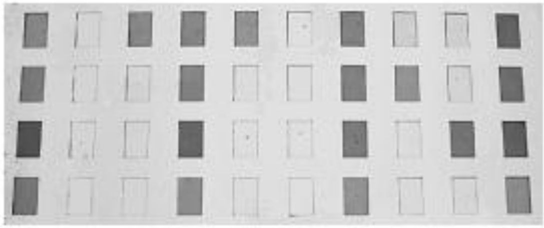


Il transistor elettrochimico: effetto elettrocromico

- Dopare un polimero significa creare polaroni all'interno della catena
- Stati localizzati dentro il band gap che modificano l'assorbimento ed emissione ottica del materiale
- Saranno possibili assorbimenti ad energie minori
- Il picco nello spettro di assorbimento si sposta verso lunghezze d'onda maggiori
- Il film diventa semitrasparente
- Cambiamento di colore!



a)



b)

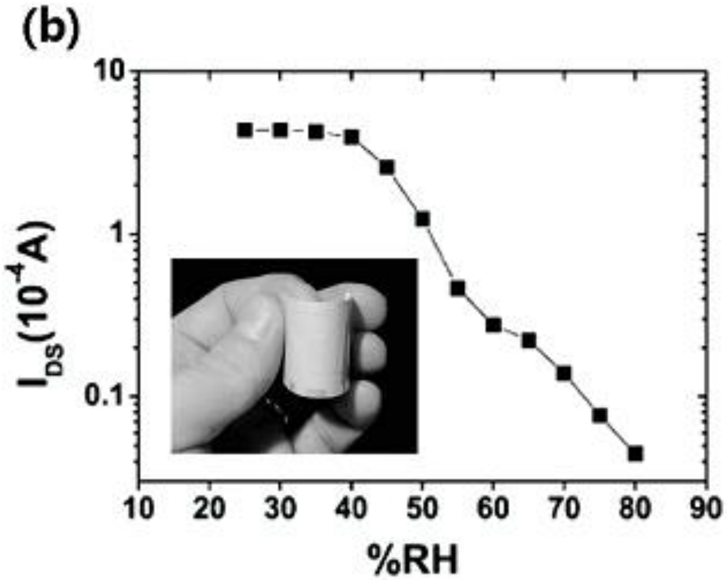
OECT: sensori di umidità

In questo caso i dispositivi sono stati realizzati su Nafion

Il Nafion è un elettrolita solido che cambia la sua conducibilità al variare dell'umidità relativa

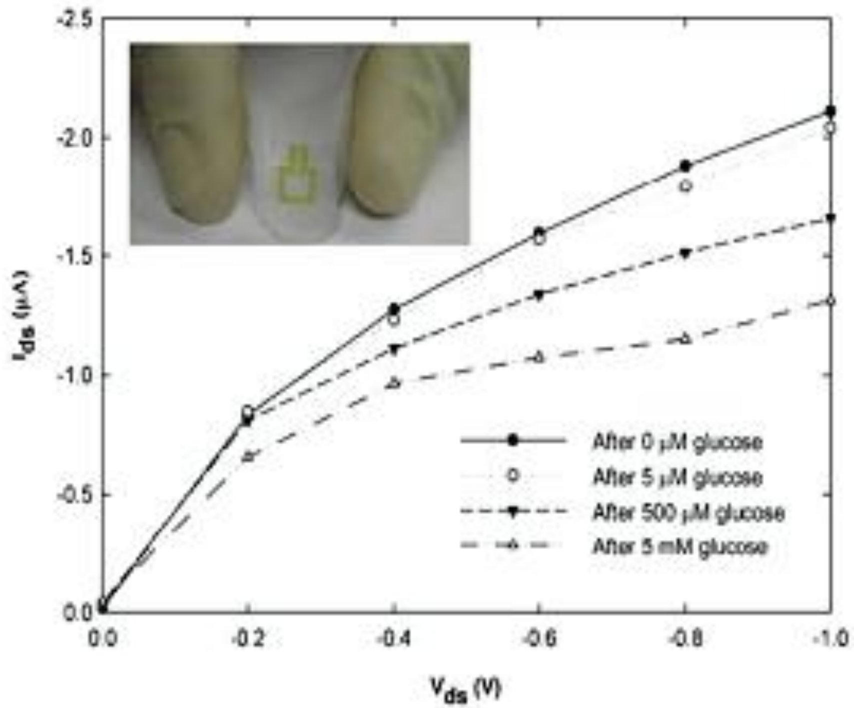
Aumento di umidità fa si che i protoni generati nel Nafion entrino all'interno del film di PEDOT:PSS de-dopandolo (neutralizzano il PSS^-)

Riduzione della corrente di uscita proporzionale all'umidità relativa



OECT: sensori di glucosio

L'area di canale viene ricoperta da una soluzione salina all'interno della quale può essere variata la concentrazione di glucosio (de-doping del PEDOT)



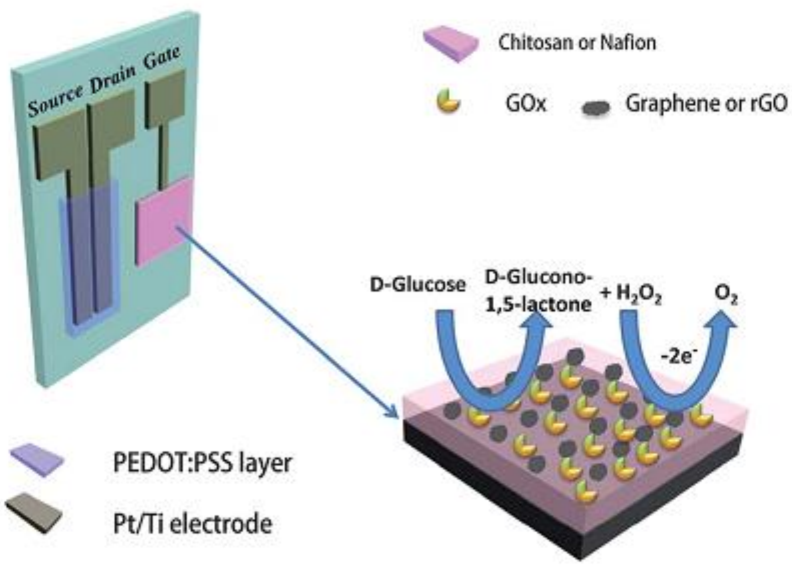
OECT: sensori di glucosio

In questo caso l'area dell'elettrodo di gate viene funzionalizzata con glucose oxidase oppure con graphene, che fungono da catalizzatori per il glucosio

L'aggiunta in soluzione di glucosio genera la reazione seguente

$$\text{D-Glucose} \xrightarrow{\text{Enzyme(GOx)}} \text{D-glucono-1, 5-lactone} + H_2O_2$$

$$2H_2O_2 \xrightarrow{-2e^-} O_2 + 2H_2O$$



OFET-based sensors

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Corso di Tecnologie e Dispositivi Elettronici Avanzati
A.A. 2015-16

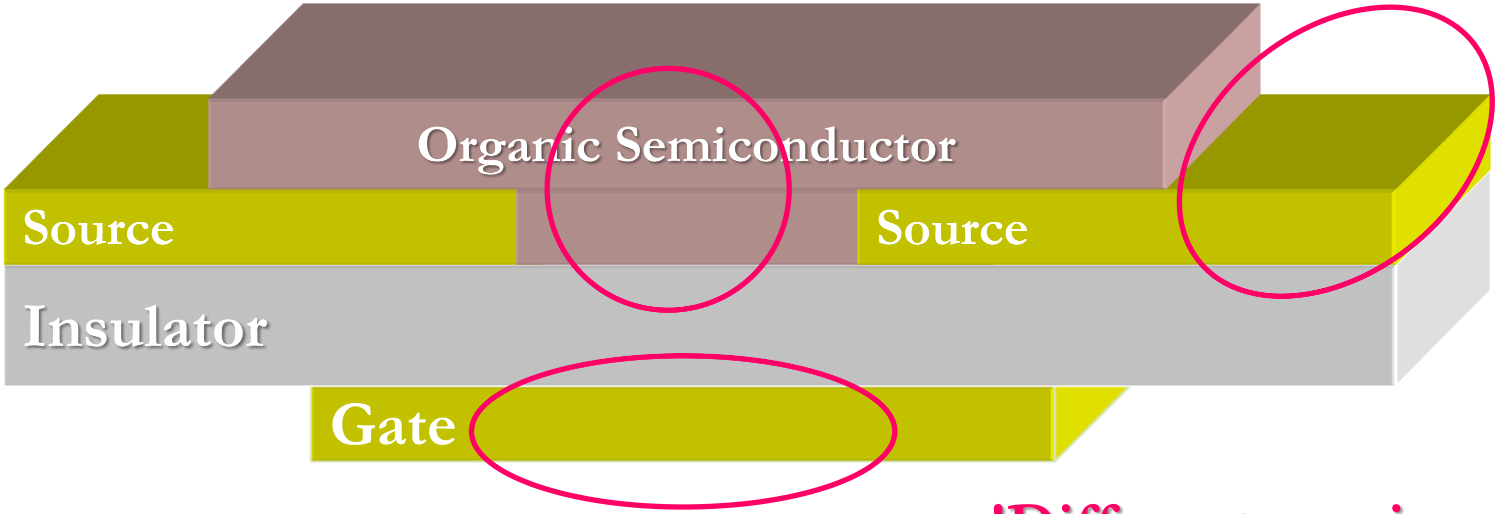
FET based sensors

How an OFET can be used as a sensor?

Change of its electrical behaviour (in a reversible way!) when exposed to an external stimulus

- *Bio-Chemical agent*
- *Mechanical stimulus*

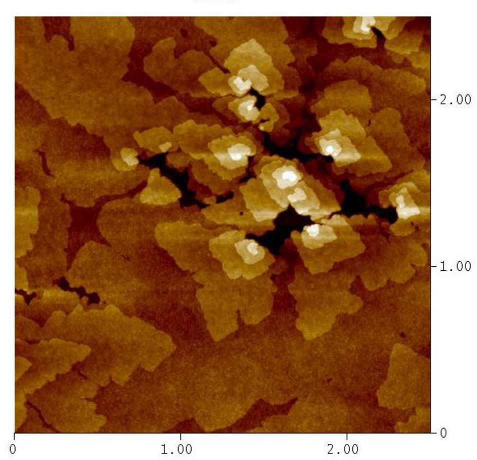
- FET Amplification
- Sensing + switching
- Multiple parameters
    - *Mobility*
    - *Off Current*
    - *Threshold voltage*

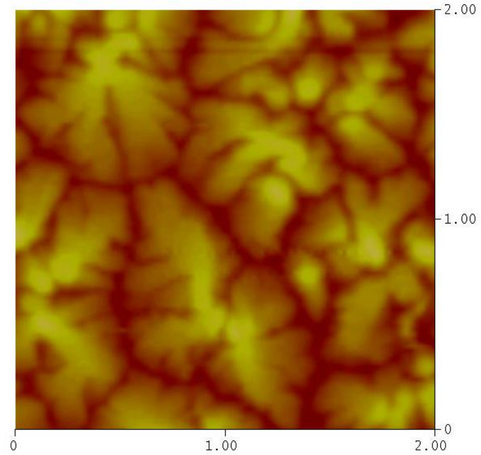


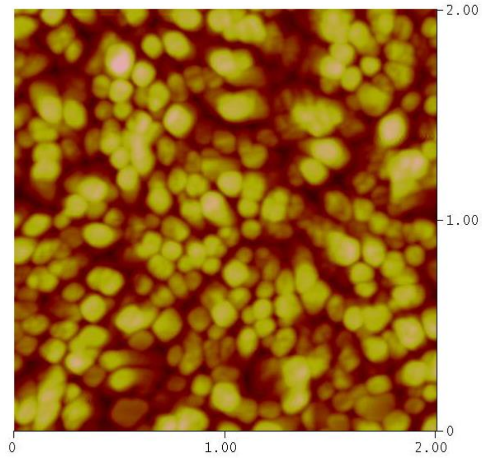
!Different sensing areas!

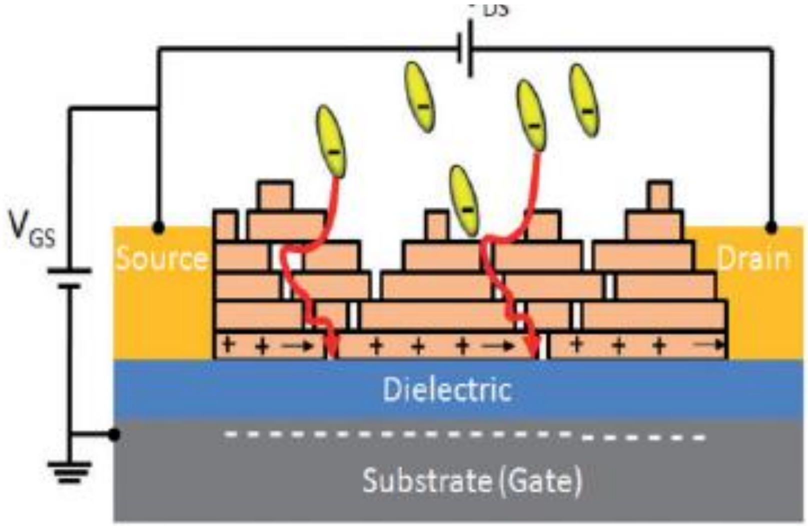
OFET for chemical sensing

Organic semiconductor thin film are generally polycrystalline films



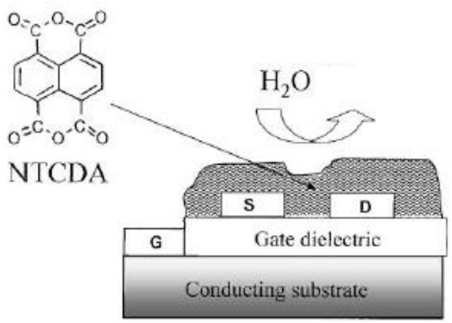


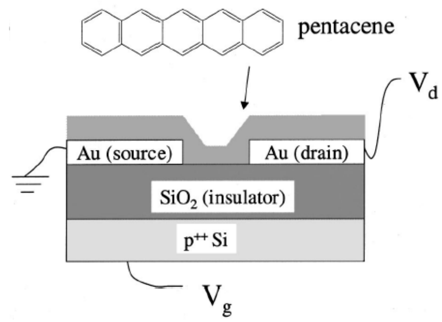


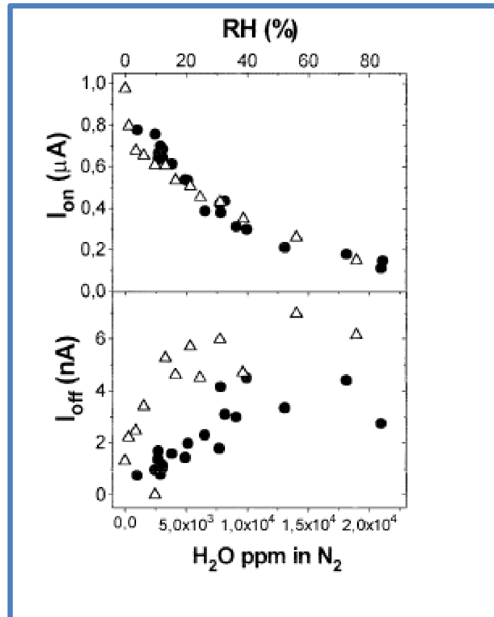


- **Strong interaction with external ambient**
- **Oxygen, moisture, chemical agents can diffuse into the active layer and change the electrical behavior**

OFET for chemical sensing



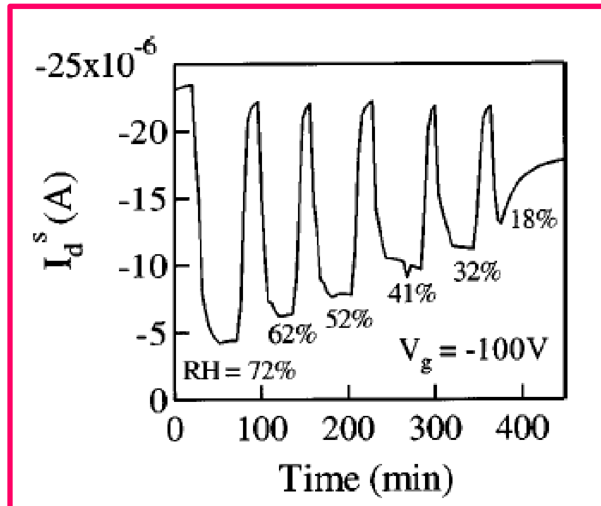




NTCDA highly ordered films
High concentration of grain boundaries
High sensitivity

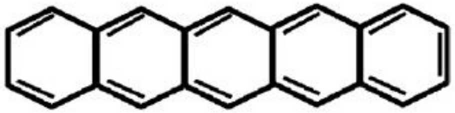
Pentacene open morphology
H_2O molecules diffuse into crevices altering the electric field at the grain boundaries

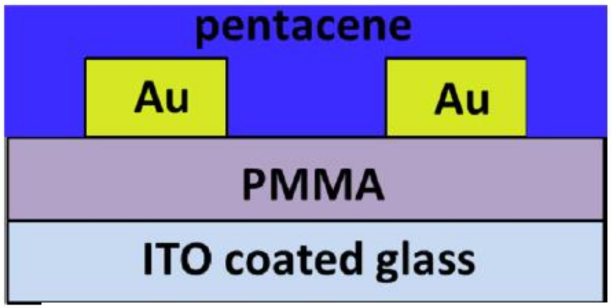
Ion and mobility decrease for high H_2O concentration
No hysteresis can be observed, fully recoverable
Ioff increases for high H_2O concentration
Significant hysteresis, fully recoverable
Vt shifts towards negative values
Significant hysteresis, fully racoverable

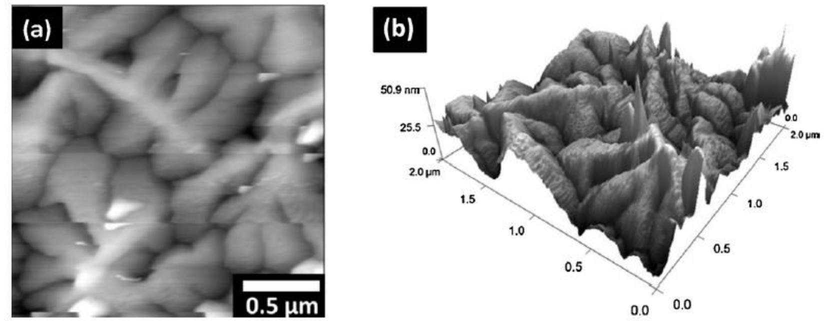


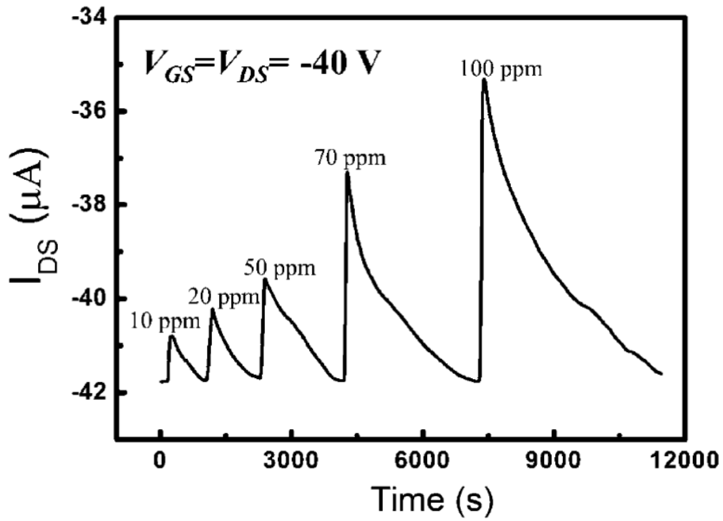
L. Torsi et al. Sensors and Actuators B 77, 7 (2001)
Zheng-Tao Zhu et al. Appl. Phys. Lett. 81, 4643 (2002)

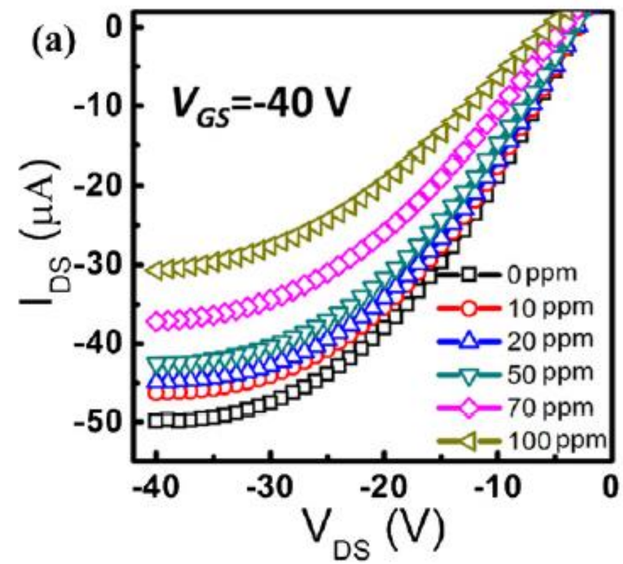
OFET NH_3 sensing







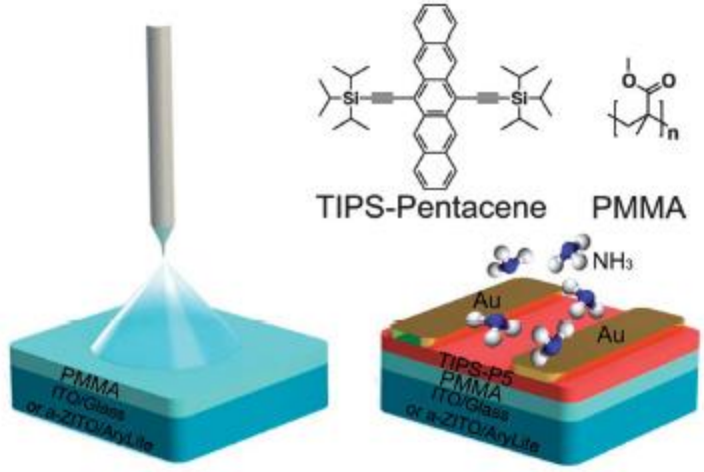


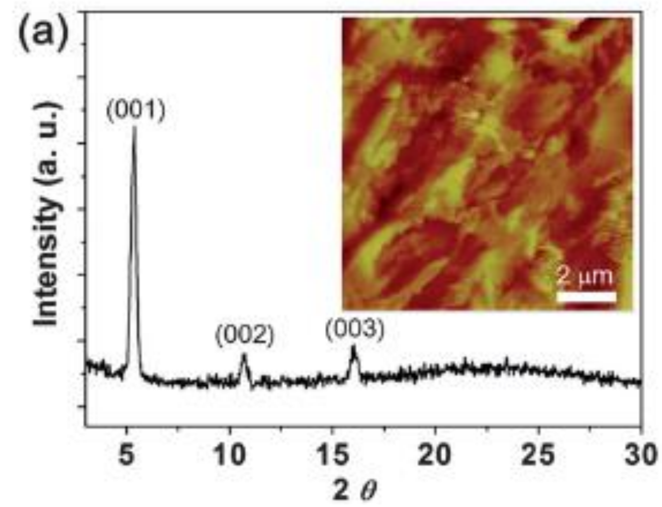


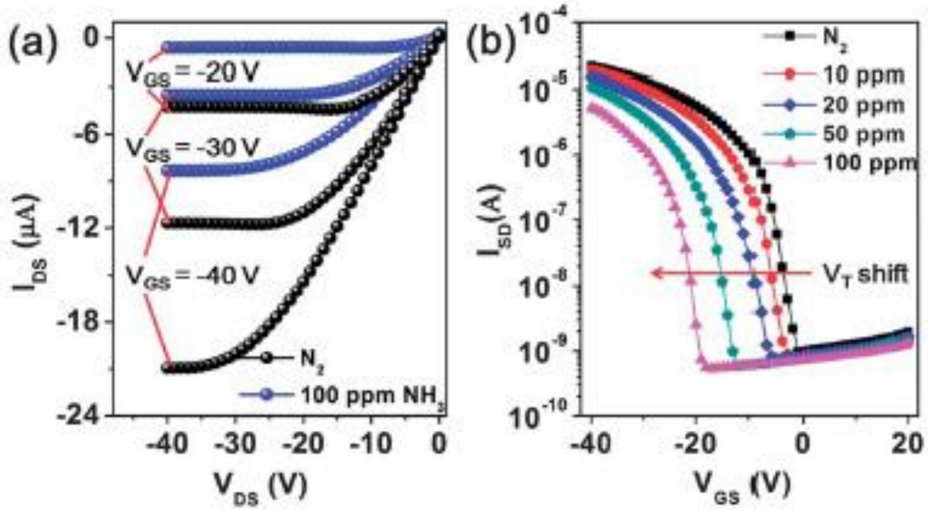
- Grain boudaries allows NH_3 molecules to diffuse into the active layer
- Polar molecules create disorder → lower transport efficiency → reduction of the mobility
- Create trapping sites → higher Vt

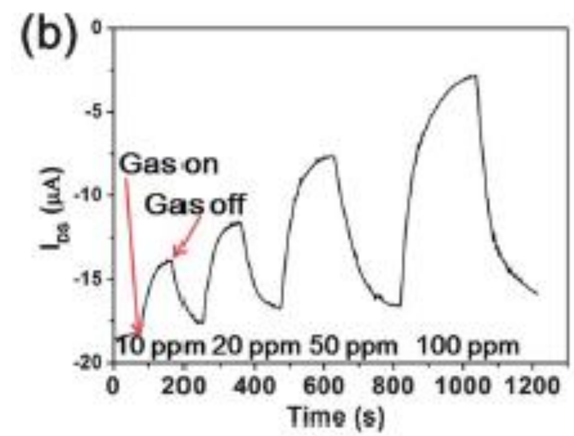
J. Yu et al. / Sensors and Actuators B 173 (2012) 133– 138

OFET NH_3 sensing









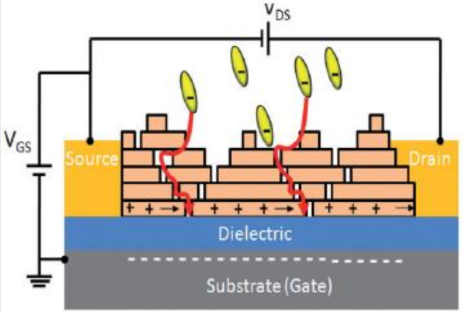
X. Yu et al. J. Mater. Chem. C, 2013, 1, 6532–6535

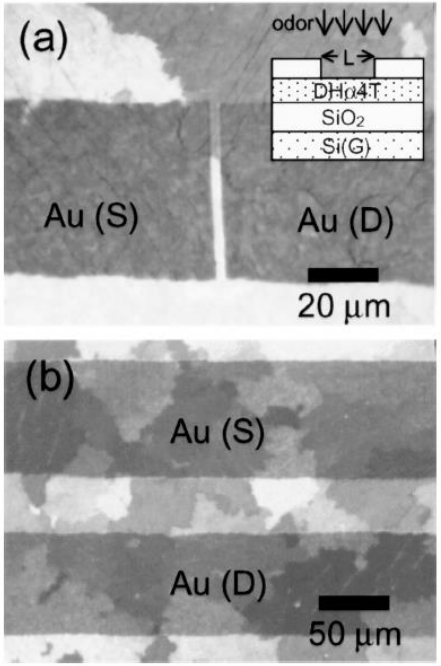
OFET for chemical sensing

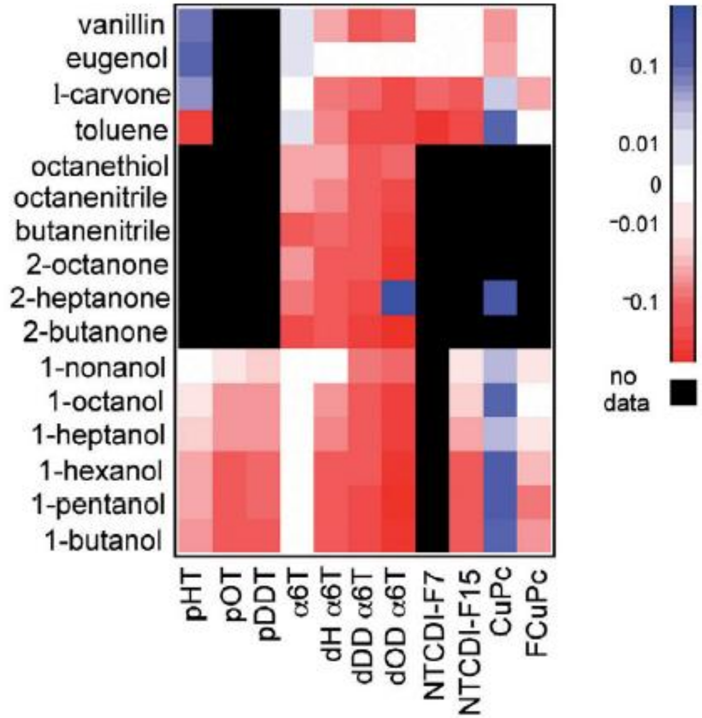
Correlation to grain size (morphology)

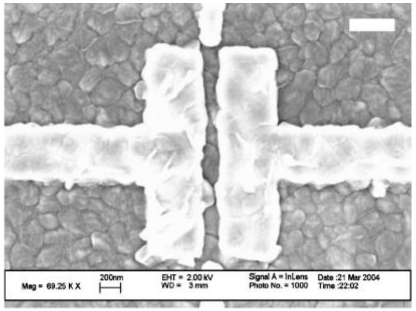
Many garin boundaries → high sensitivity!

Few grain boundaries → different sensing mechanism









T. Someya et al. Appl. Phys. Lett. 81, 3079 (2002)

Wang et al. Appl. Phys. Lett., 85, 6386(2004)

Crone, B., et al., App. Phys. Lett. (2001) 78, 2229.

Torsi L et al. J. Phys. Chem. B 106, 12563 (2002), Anal. Chem. 77, 380A (2005)

Poor Selectivity!

OFET for chemical sensing

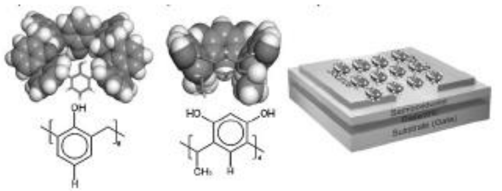
Bilayer OTFT with calixarene container molecules deposited on the assembled device:

OS first layer:

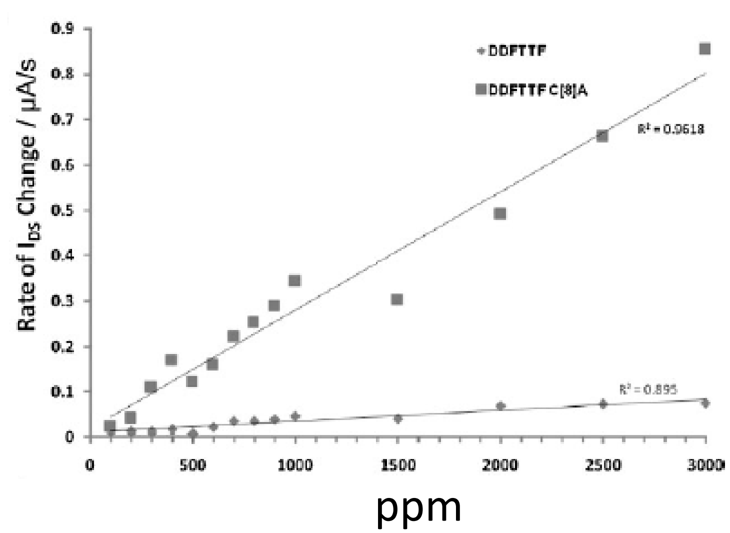
5,50-bis-(7-dodecyl-9H-fluoren-2-yl)-2,20-bithiophene (DDFTTF)

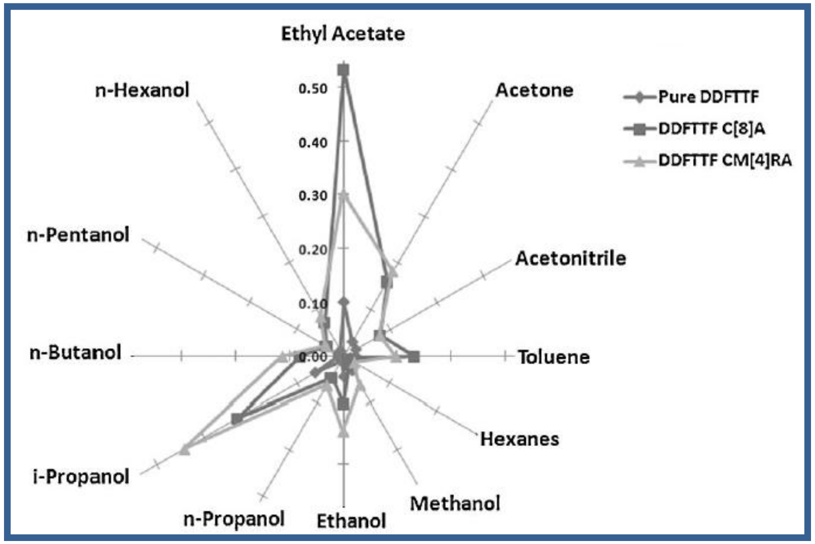
Container molecules:

calix[8]arene (C[8]A) and C-methylcalix[4]-resorcinarene (CM[4]RA)



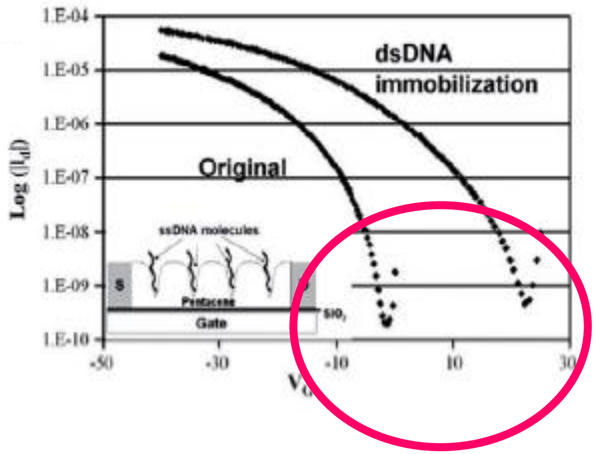
Selective molecular uptake!

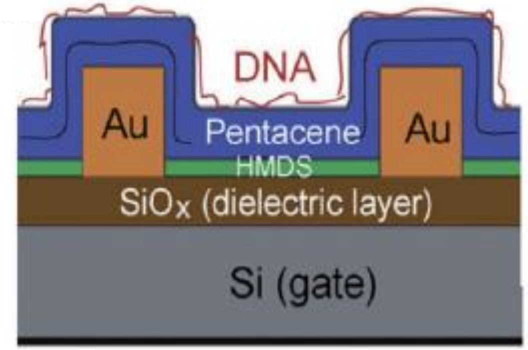




A. N. Sokolov, et al. Adv. Mater. 2010, 22, 2349–2353

OFET DNA detection

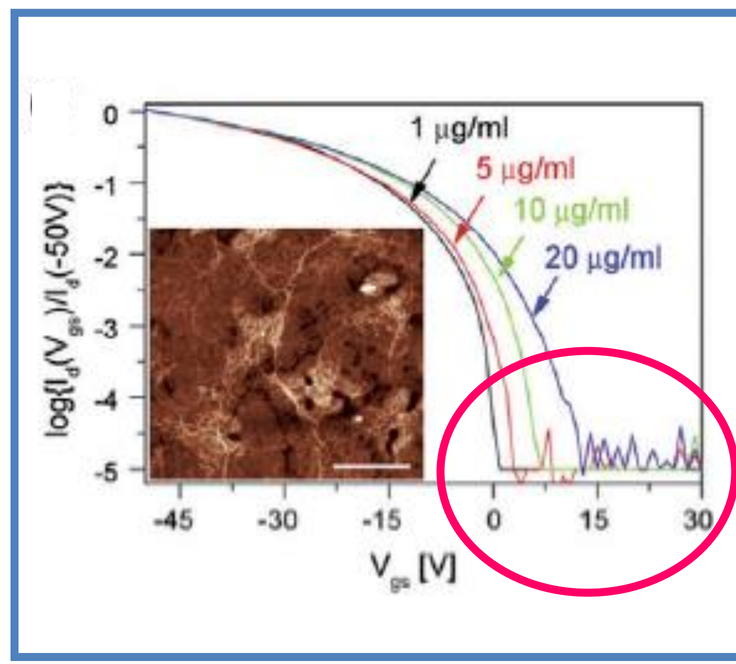




DNA molecules are directly immobilized by physical adsorption in the pentacene film

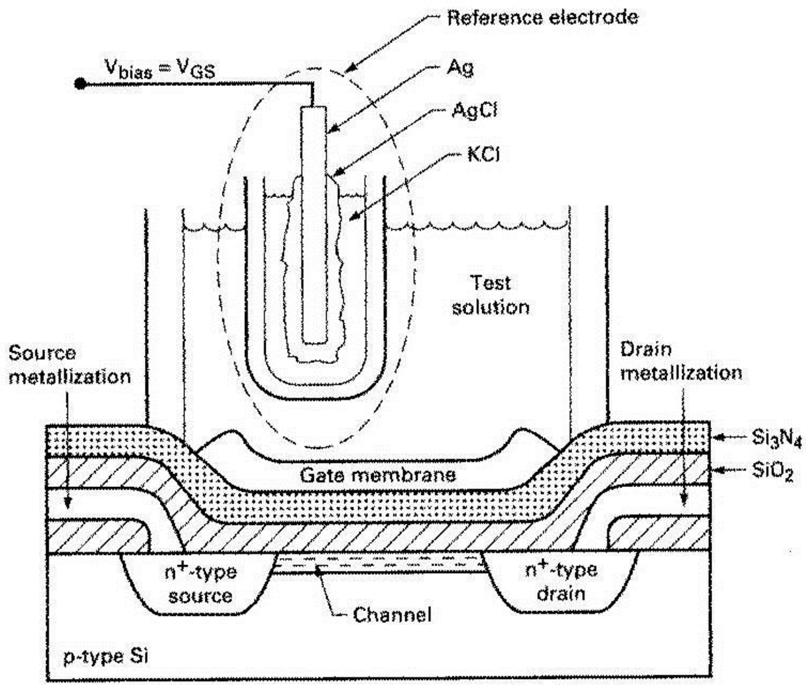
The immobilization can be optimized according to the sizes of DNA molecules by controlling morphology of pentacene films

phosphate groups on the DNA backbone are known to be able to attract electrons, leaving more holes than before DNA immobilization → Vt shift



Q. Zhang, et al. Biosens. Bioelectr. 22, 3182 (2007)

Ion Sensitive FET (ISFET)



(a)

The interface potential at the gate oxide-electrolyte interface is determined by the surface **dipole potential of the solution χ_{sol}**, which is a constant,

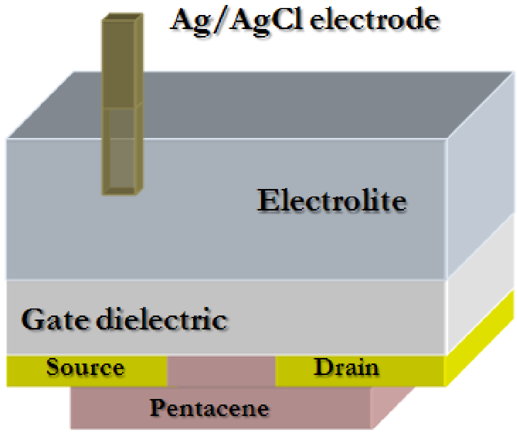
surface potential ψ_o, which results from a chemical reaction, usually governed by the **dissociation of oxide surface groups**. The resulting equation for the flatband voltage of an ISFET is thus given by:

$$V_{FB} = E_{ref} - \Psi_0 + \chi_{sol} - \frac{\Phi_{Si}}{q} - \frac{Q_{ss} + Q_{ox}}{C_{ox}}$$

All terms are constant except ψ_o

it is this term which makes the ISFET sensitive to the electrolyte pH, which is controlling the dissociation of the oxide surface groups

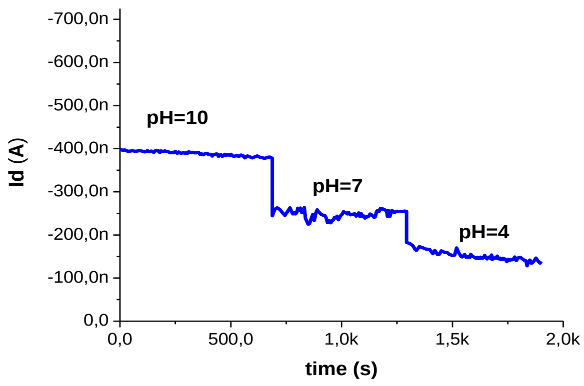
ISOFET

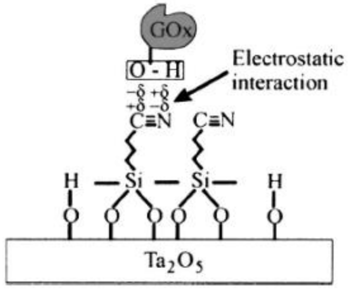


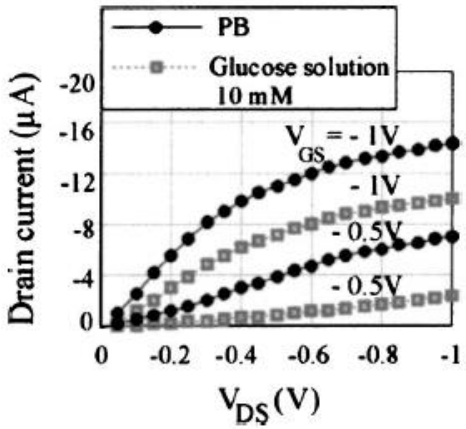
Free standing PET (Mylar ®) film
Fully flexible structure
Mylar® acts at the same time as gate dielectric and as support for the final device

Protonation/deprotonation of the polar surface of the gate dielectric (Mylar, TaO5, SiH:N)
Potential drop at the solution/dielectric interface → Vt shift

Different ions → proper functionalization of the dielectric



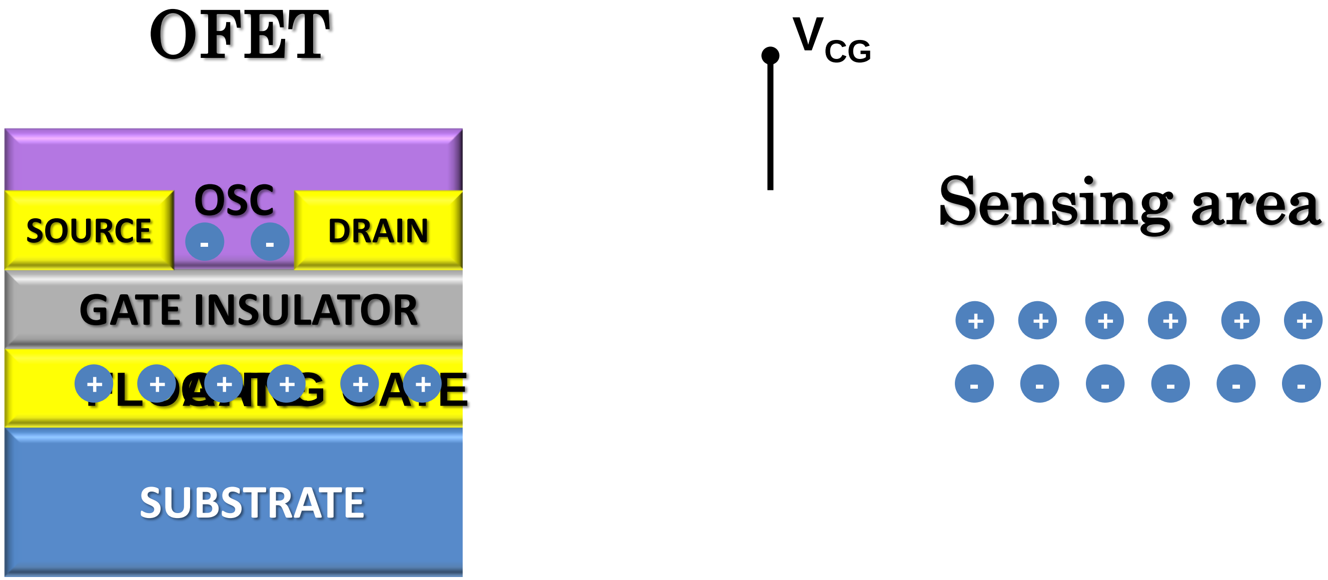




Bartic et al. Appl. Phys. Lett. 82, 475 (2003)
Loi et al. Appl. Phys. Lett. 86, 103512 (2005)
K. Diallo et al. Appl. Phys. Lett. 93, 183305 (2008)

Organic Charge-Modulated Field-Effect Transistor

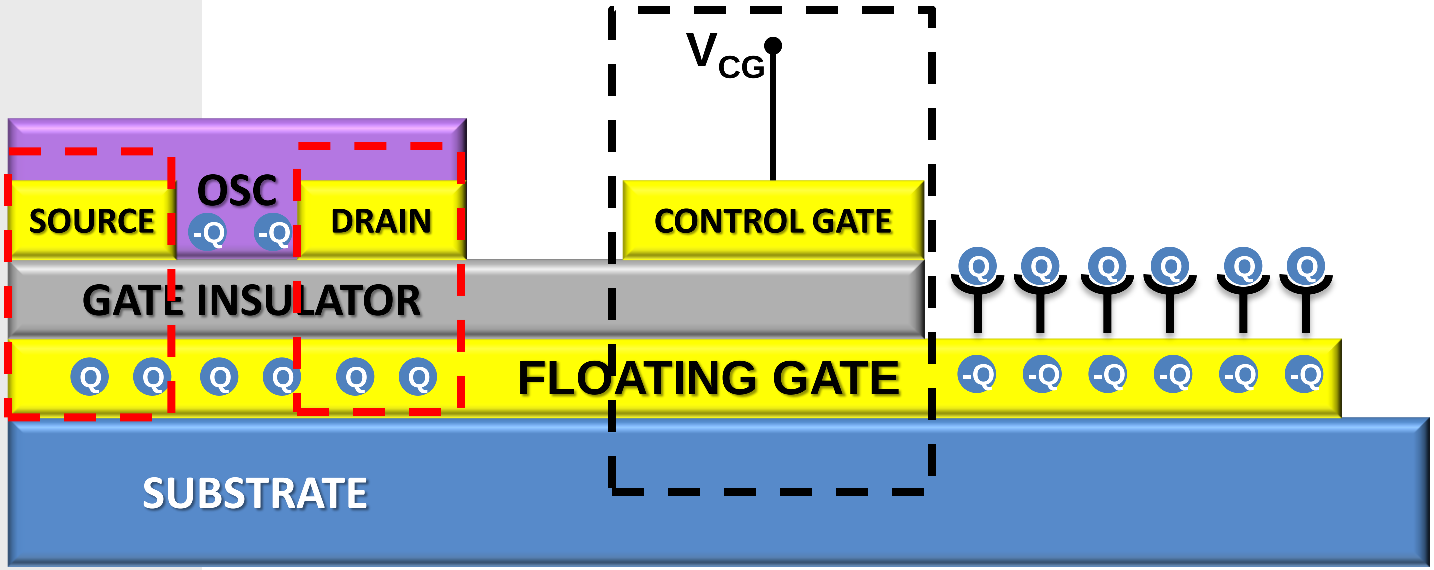
OCMFET

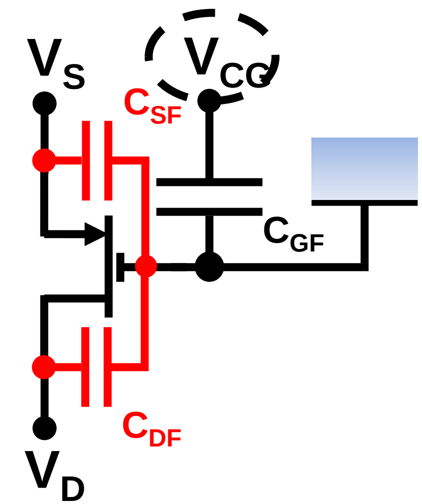


$$\Delta V_{th} = -\frac{\Delta Q}{C_{TOT}}$$

- The working principle is independent of the technology and can be employed for obtaining different kind of sensors
- No need of a reference electrode

Organic Charge-Modulated Field-Effect Transistor





$$Q_{FG} = C_{CF}(V_{FG} - V_{CG}) + C_{SF}(V_{FG} - V_S) + C_{DF}(V_{FG} - V_D) + Q_0 + Q_{ind}(Q_S)$$

$$V_{FG} = \frac{C_{CF}}{C_{CF} + C_{SF} + C_{DF}} V_{CG} + \frac{C_{SF}}{C_{CF} + C_{SF} + C_{DF}} V_S + \frac{C_{DF}}{C_{CF} + C_{SF} + C_{DF}} V_D + \frac{Q_0 + Q_{ind}(Q_S)}{C_{CF} + C_{SF} + C_{DF}}$$

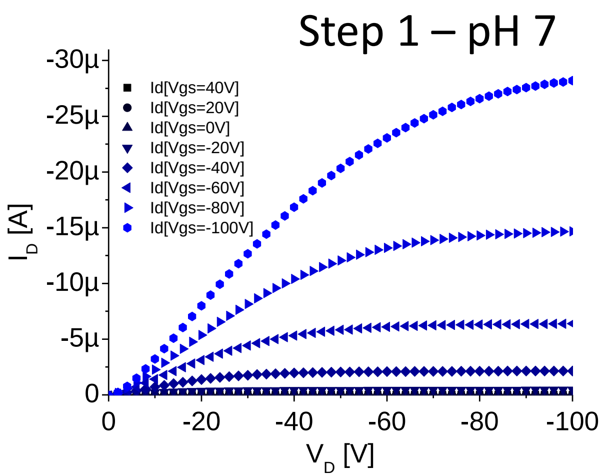
$$V_S = 0$$
$$C_{CF} >> C_{DF}, C_{SF}$$
$$Q_{ind} = -Q_S$$

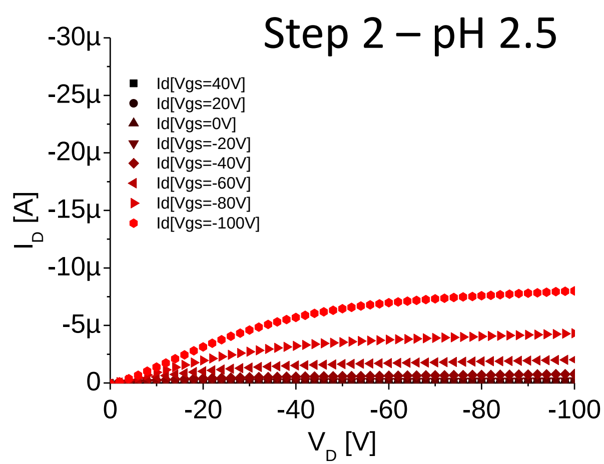
$$V_{FG} \approx V_{CG} + \frac{Q_0 - Q_S}{C_{CF} + C_{SF} + C_{DF}}$$

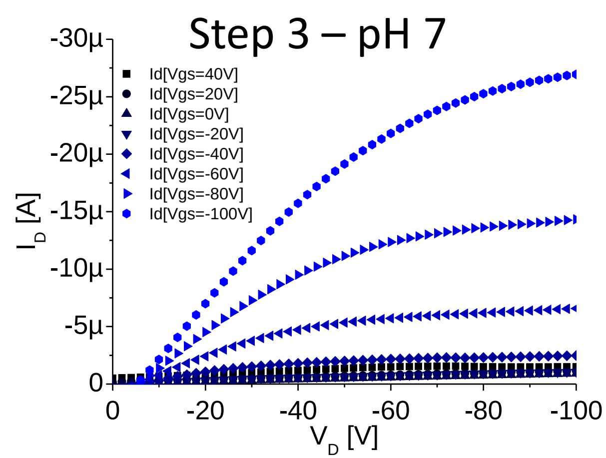
$$I_{DS} = k(V_{FG} - V_{TH})^2 \approx k\left[V_{CG} - \left(V_{TH} - \frac{Q_0 - Q_S}{C_{CF} + C_{SF} + C_{DF}}\right)\right]^2$$

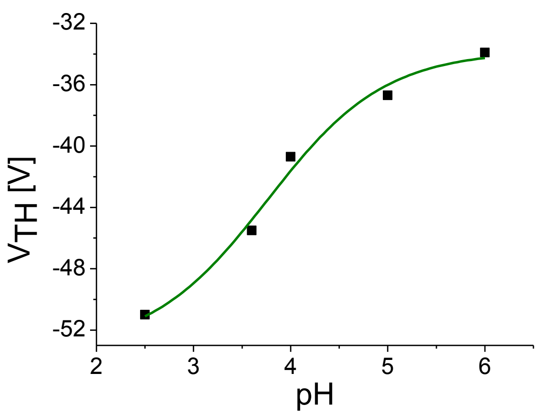
OCMFET: pH sensing

pH sensitivity is achieved functionalizing the floating gate by anchoring NH_2 groups (COOH) on its surface (2-Aminoethanethiol). Amino groups tend to protonate/deprotonate, according to the pH value of the solution





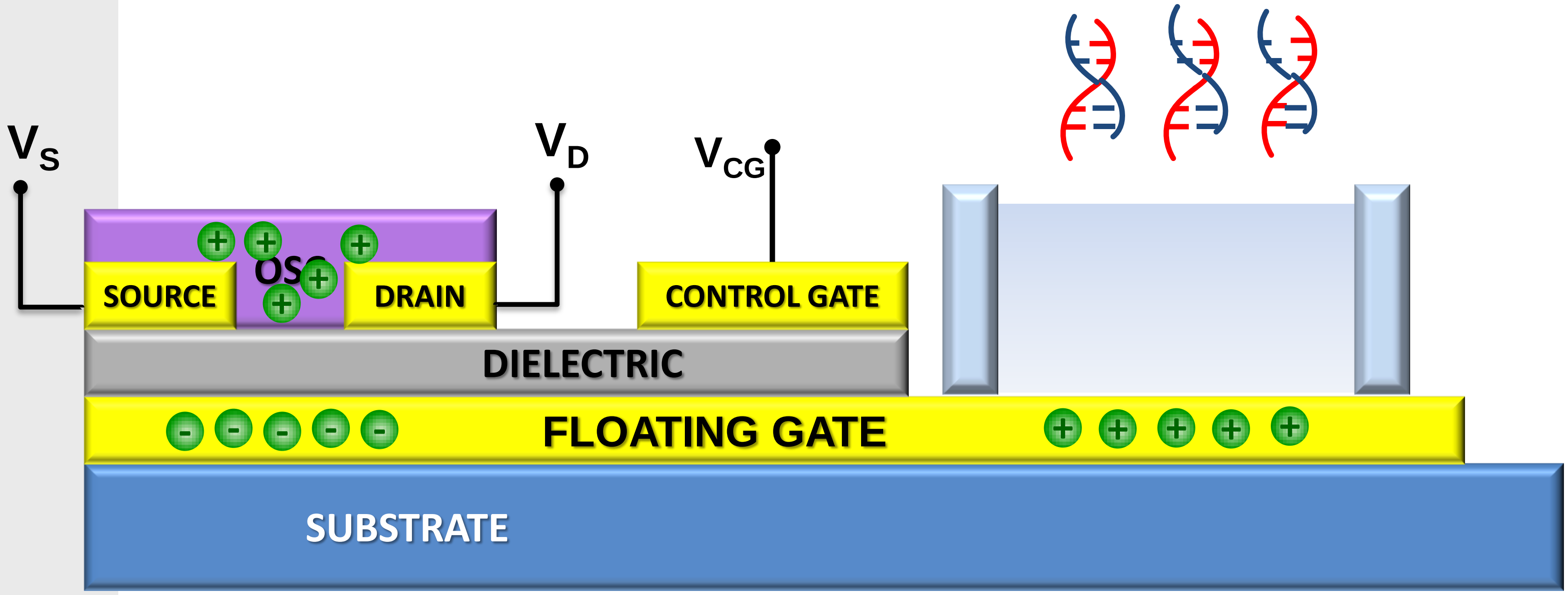


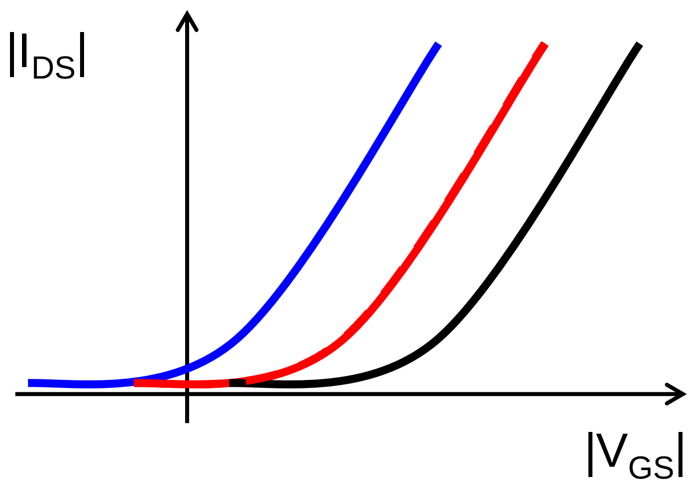


A. Caboni et al. Appl. Phys. Lett. 95, 123304 (2009)

A. Caboni et al. IEEE Sensors Journal 9, 1963 (2009)

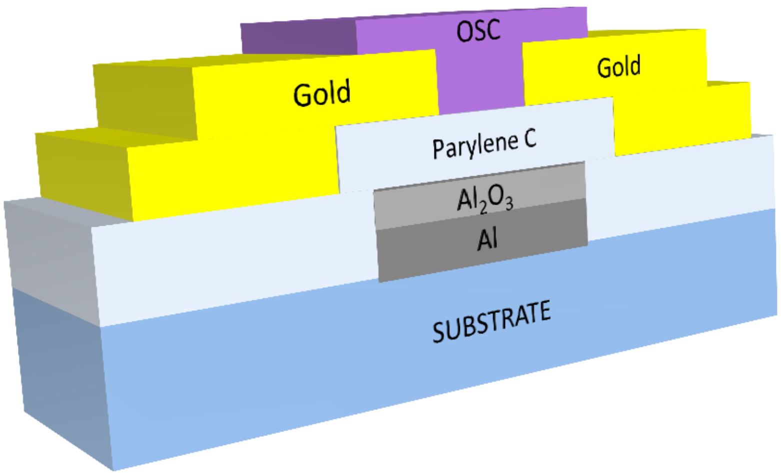
OCMFET: DNA sensing





Ultra-low voltage OTFTs structure

Bottom gate, bottom contact structure on flexible plastic substrates

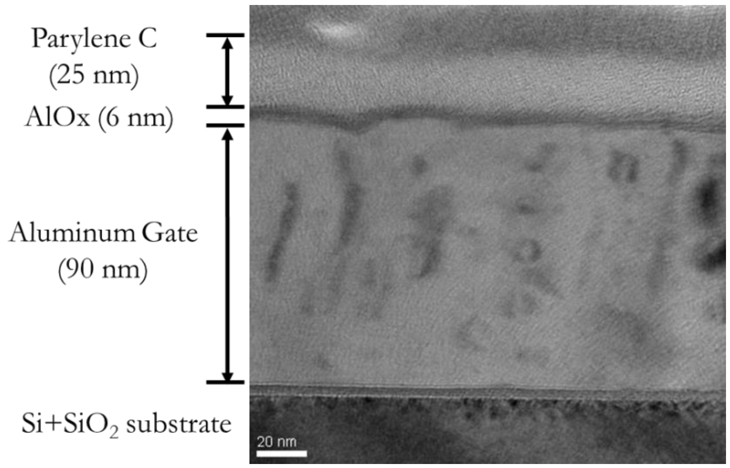


- **Gate: Aluminum**
- **Gate Dielectric:**

AlOx ***[UV-Ozone treatment at room temperature]***

Parylene C ***[deposited by CVD]***

[air-stable, robust, biocompatible and resistant to solvents; can be deposited in very thin films]

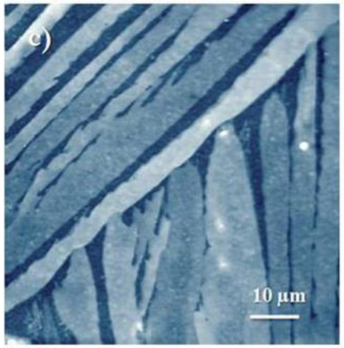


P. Cosseddu, et al. Appl. Phys. Lett. 100, 093305 (2012)

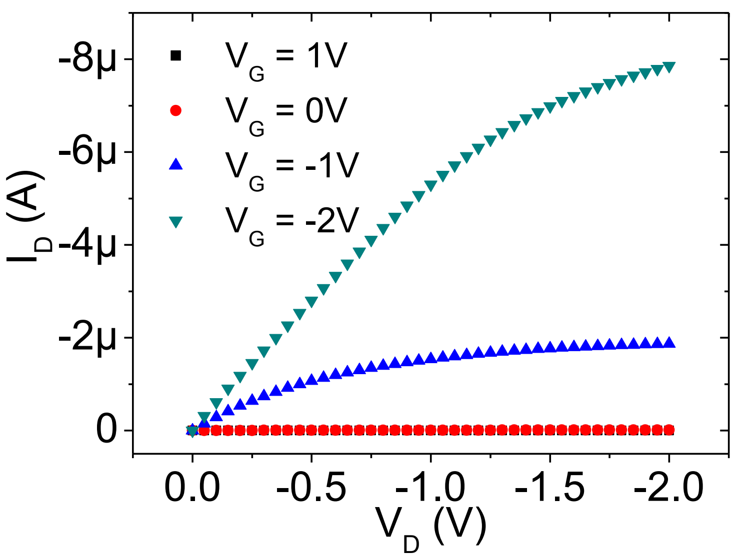
AlOx/Parylene C Double-Layer

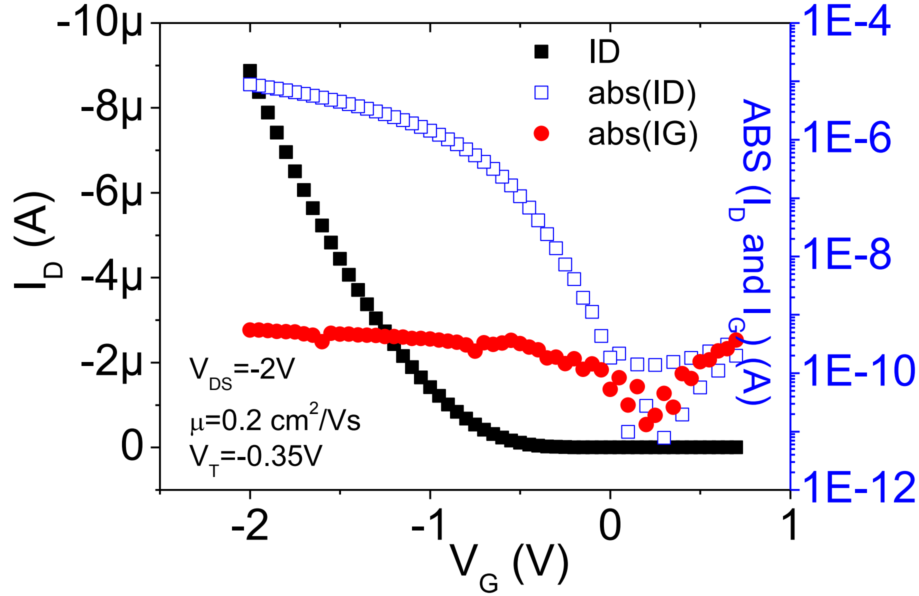
- ***High yield***
- ***Negligible hysteresis***
- ***Very small leakage current***

TIPS-Pentacene

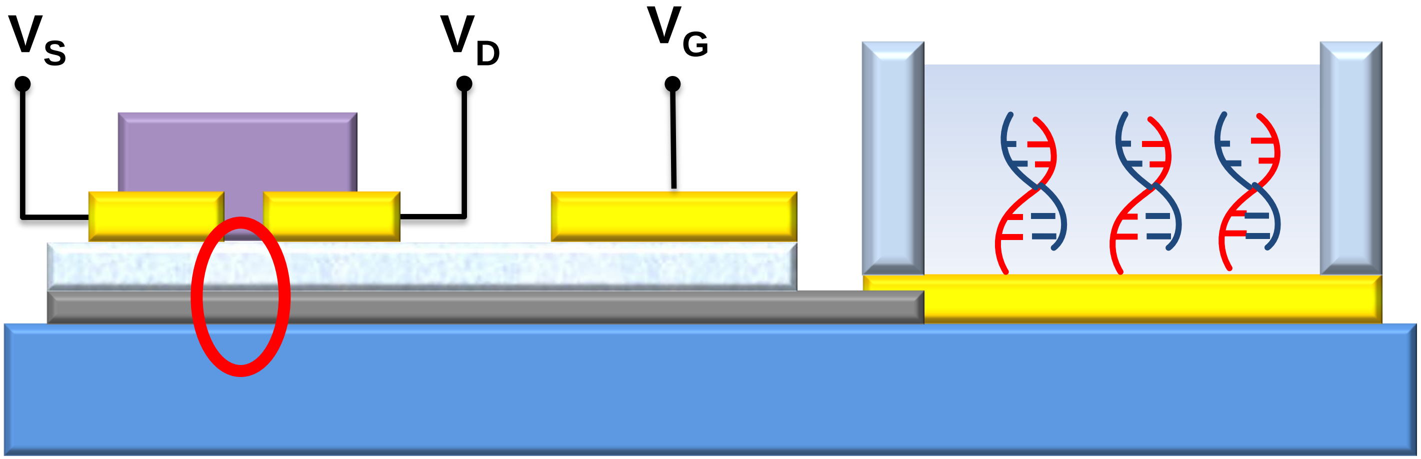


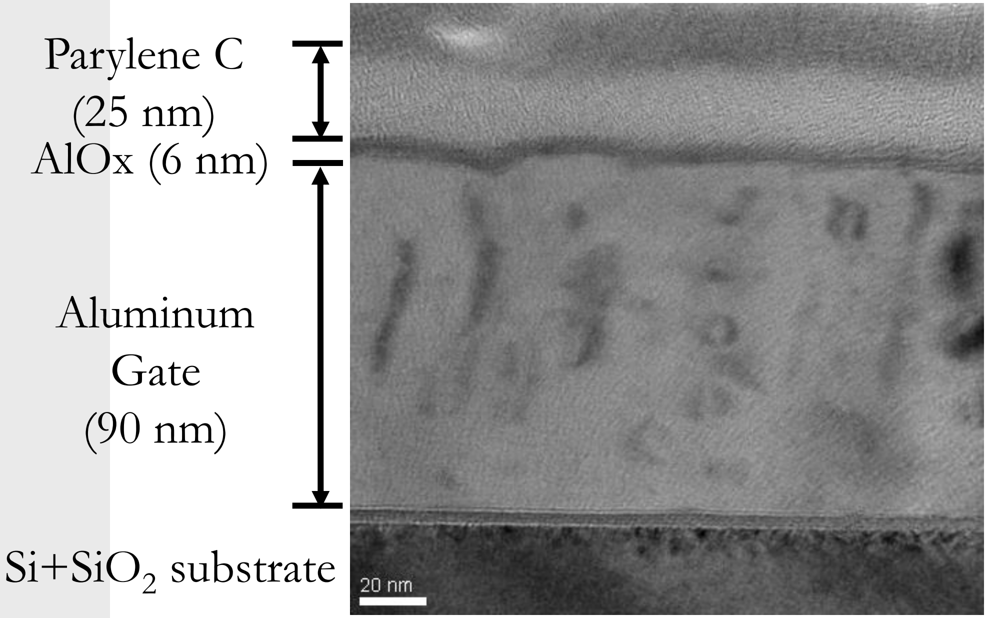
Insulating Structure	Capacitance [F/cm²]	I_G [A] J_G[A/cm²]	Vt [V]	μ [cm²/Vs]	S [mV/dec]	OTFTs Yield [%]
AlOx + Parylene	1.3 E-7	4 E-10 1.9 E-9	-0.2/-0.4	0.3	150	99%

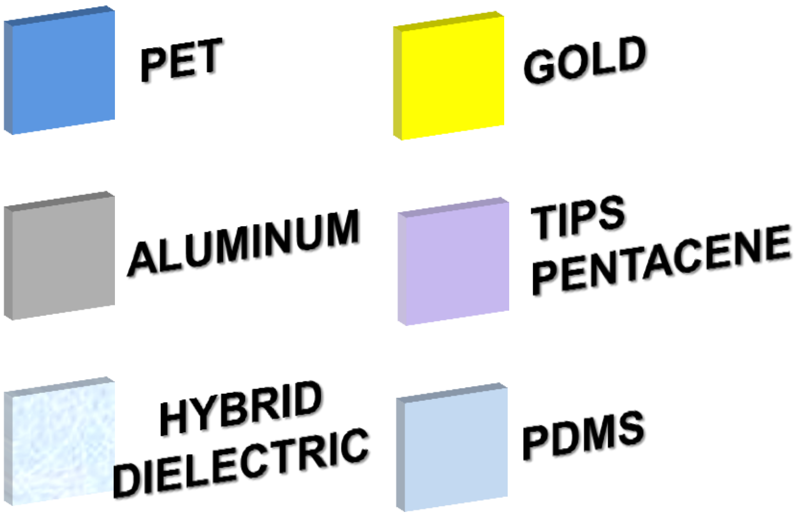




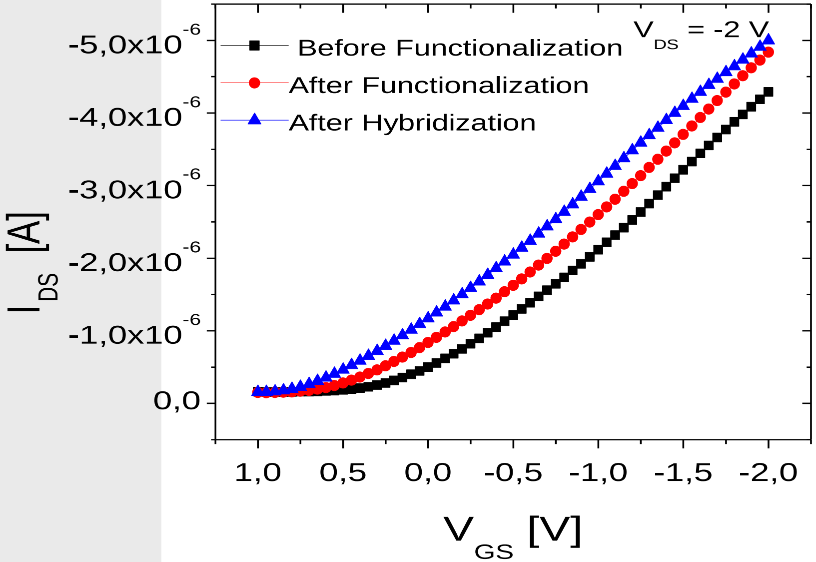
Low Voltage OCMFET for DNA sensing

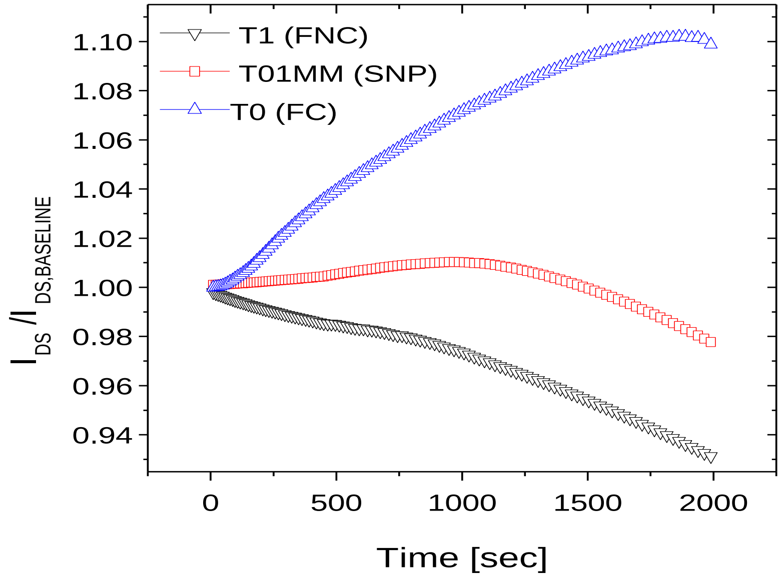


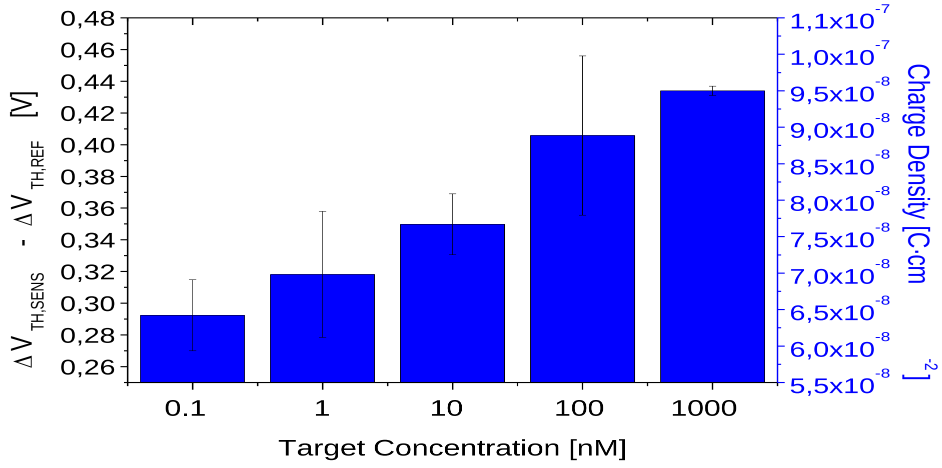




Low Voltage OCMFET-DNA sensing

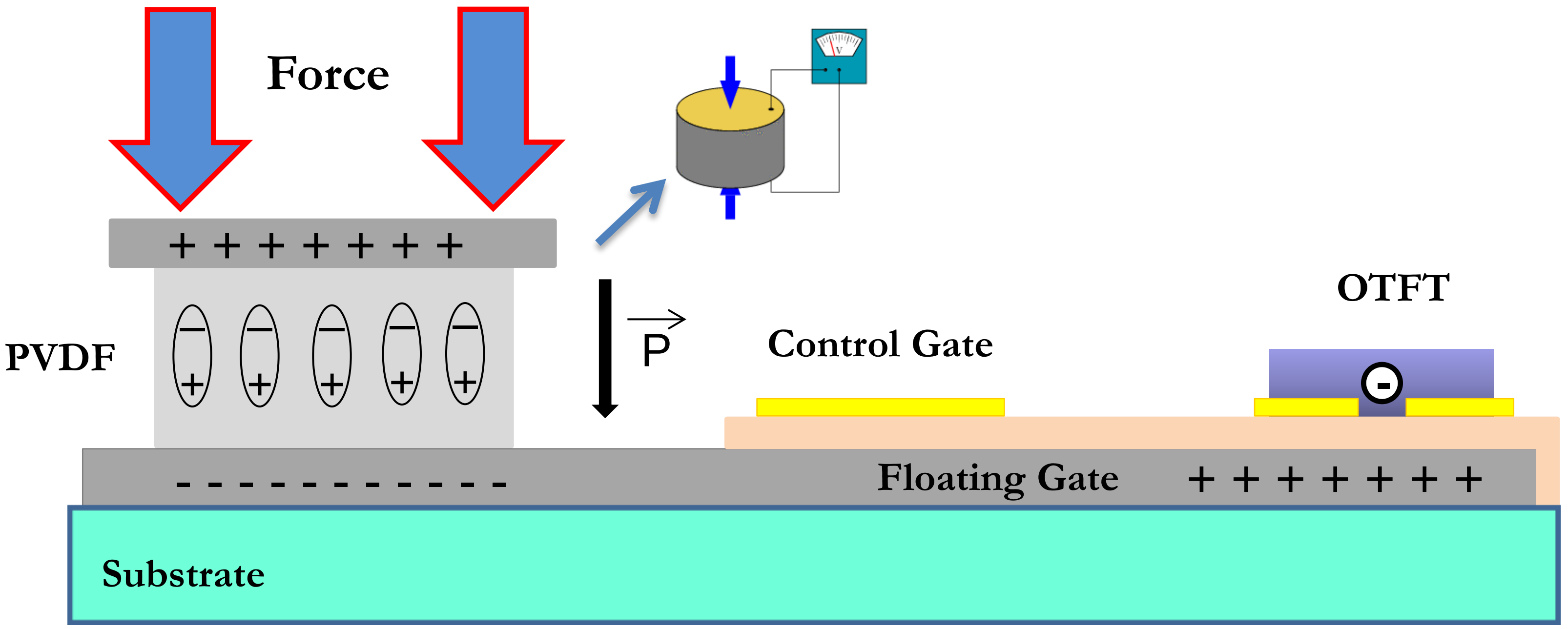






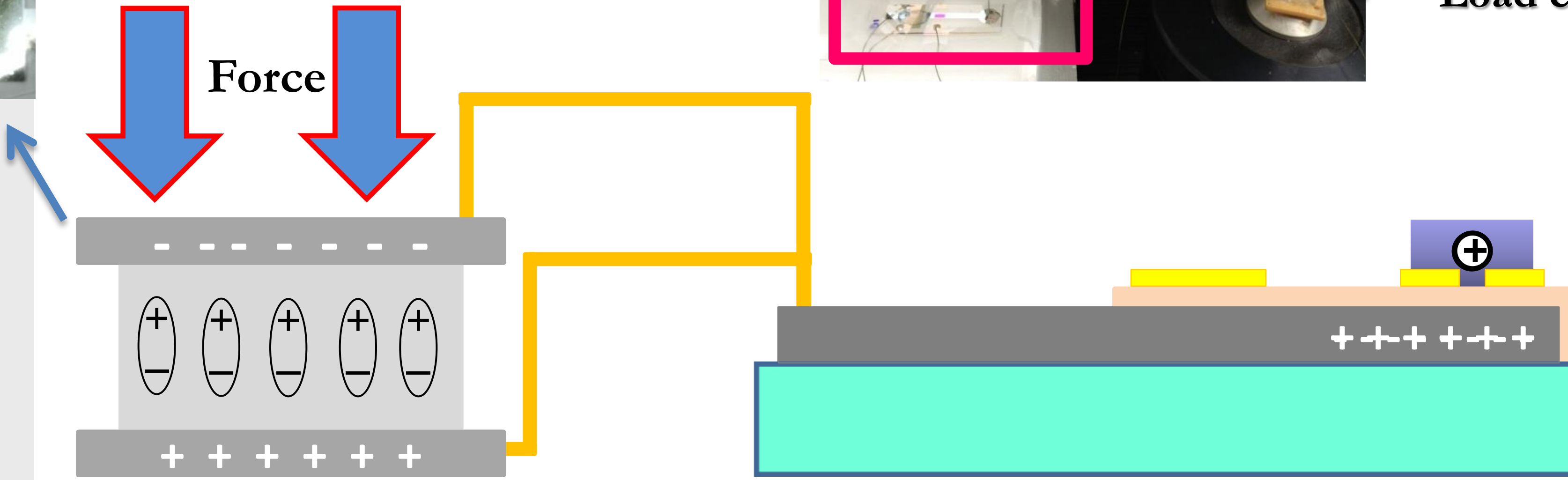
Lai et al., Adv. Mat. 25, 103-107, 2013

OCMFET-force sensing

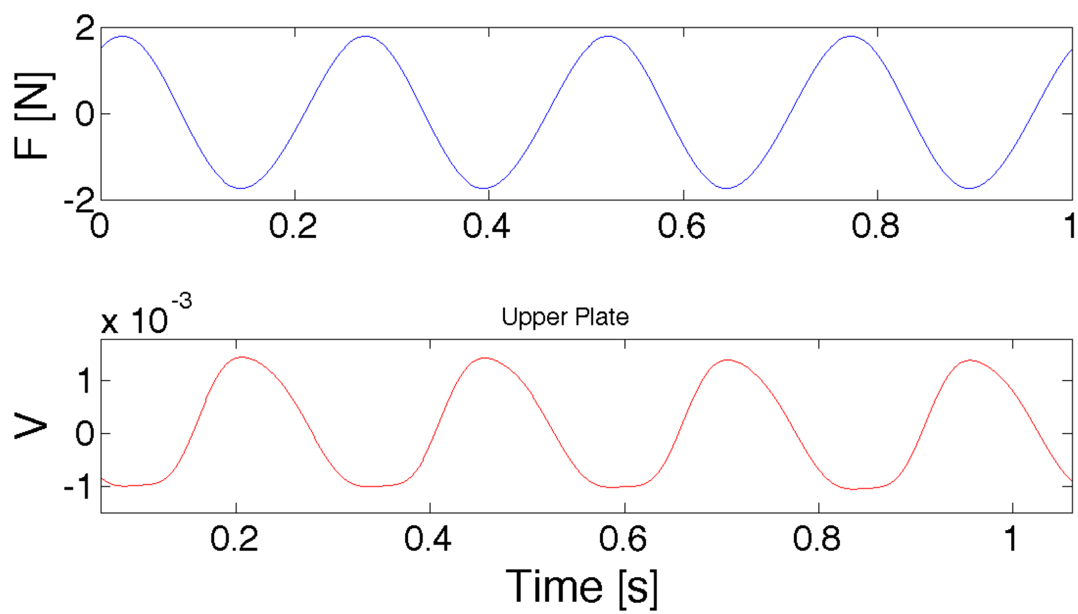


- A piezoelectric polymer, poly(vinylidenefluoride) (PVDF), is deposited on the sensing area.
- Applying a force on the PVDF film induces charges on the floating gate, thus shifting the OTFT threshold voltage → current variation

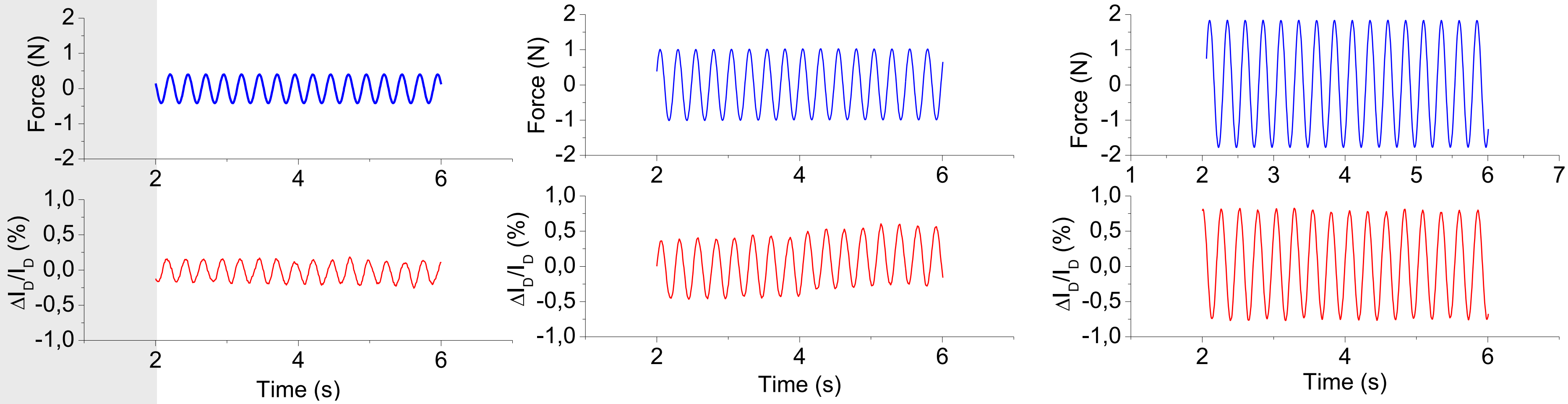
OCMFET-force sensing



Shaker +
Load cell



Electromechanical characterization @ 4 Hz

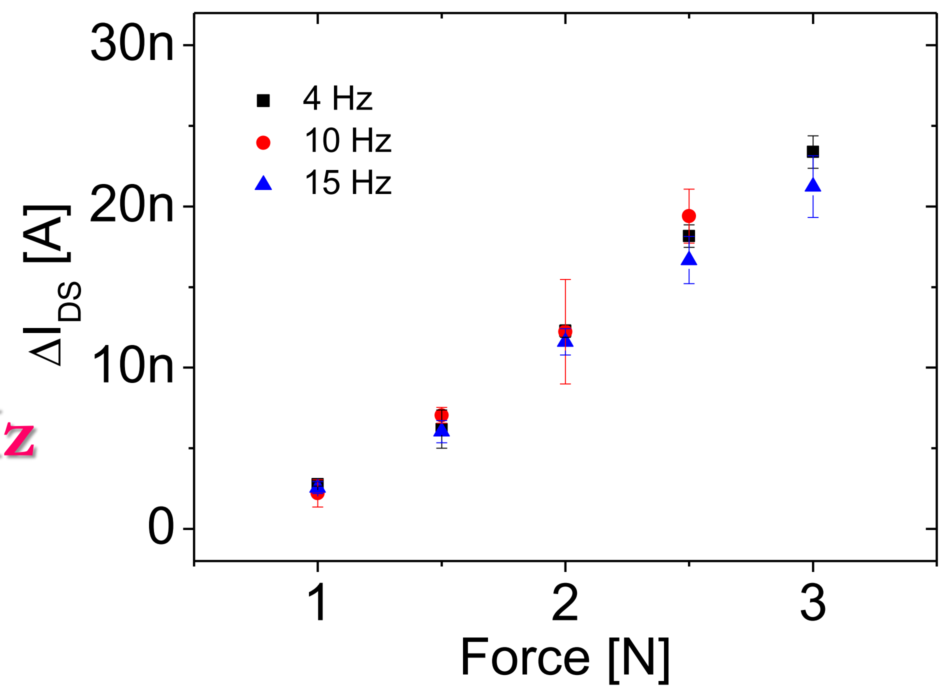


Linear behavior

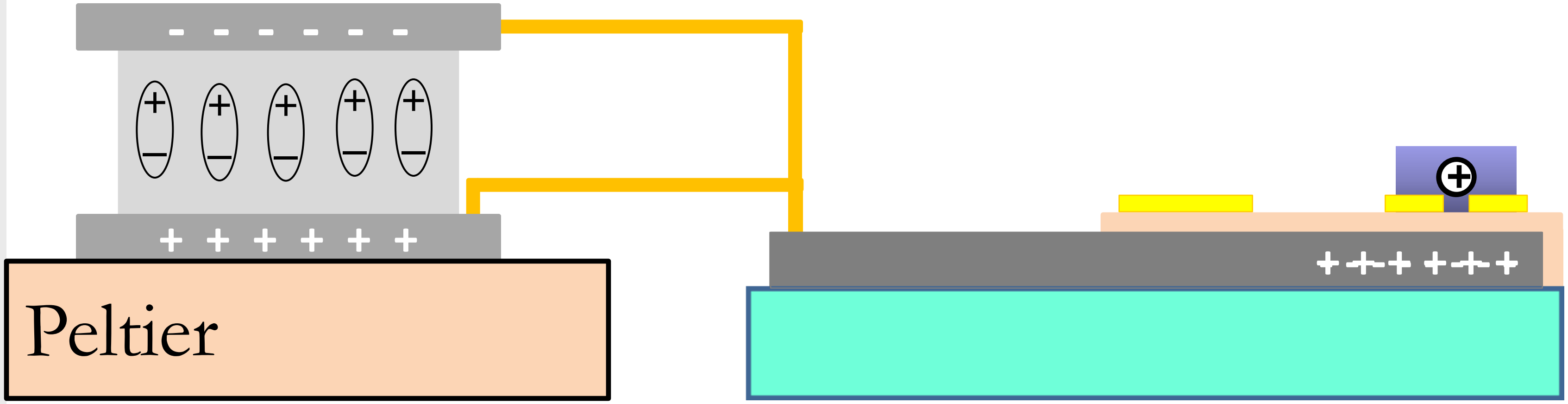
Working range: 0-3.5 N

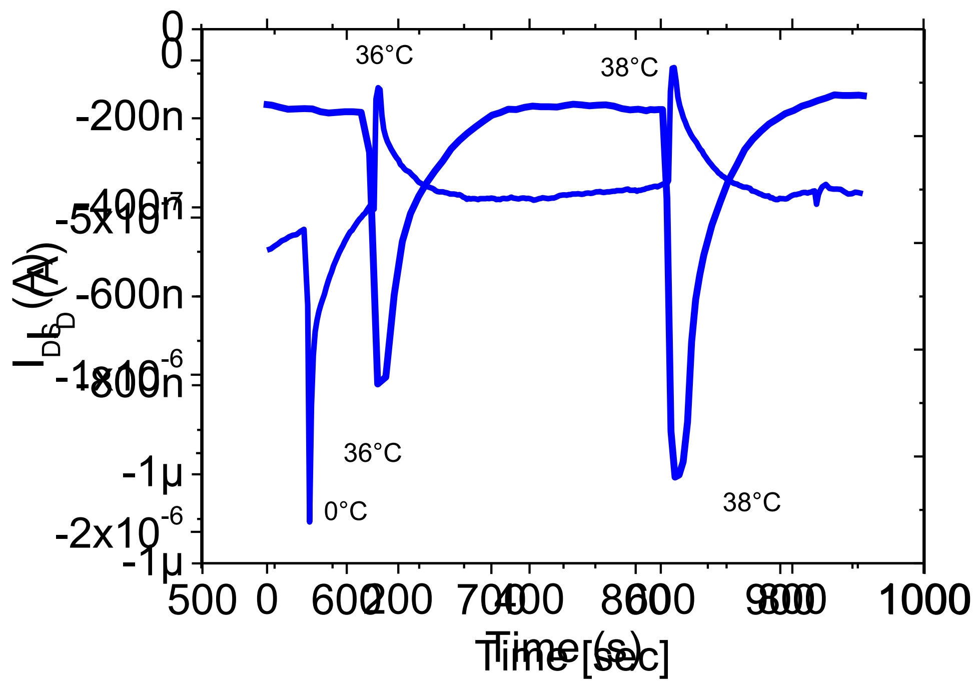
Resolution 0.1 N

Frequency range 0-15 Hz

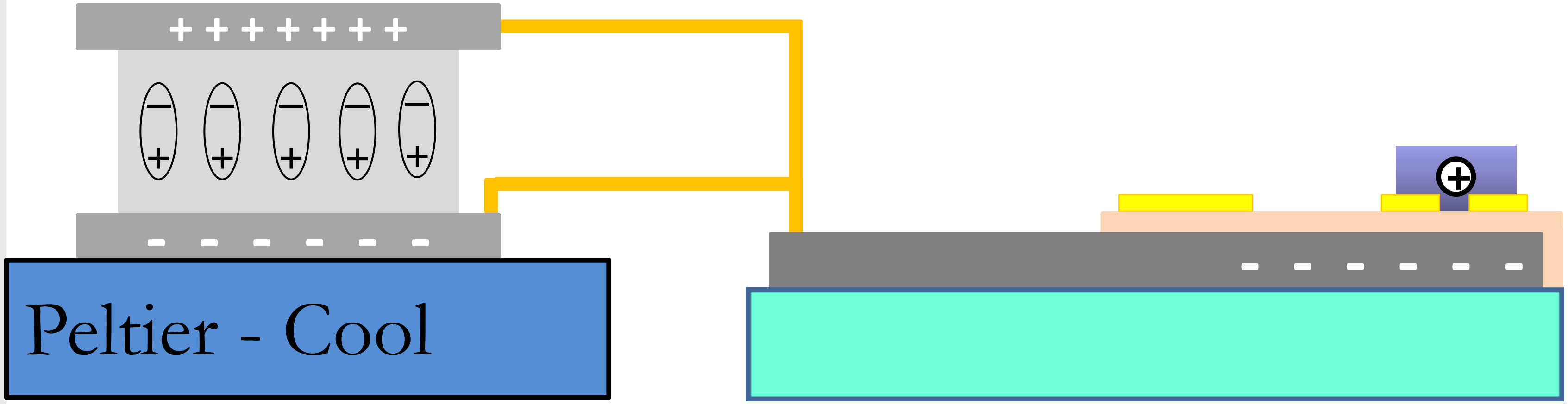


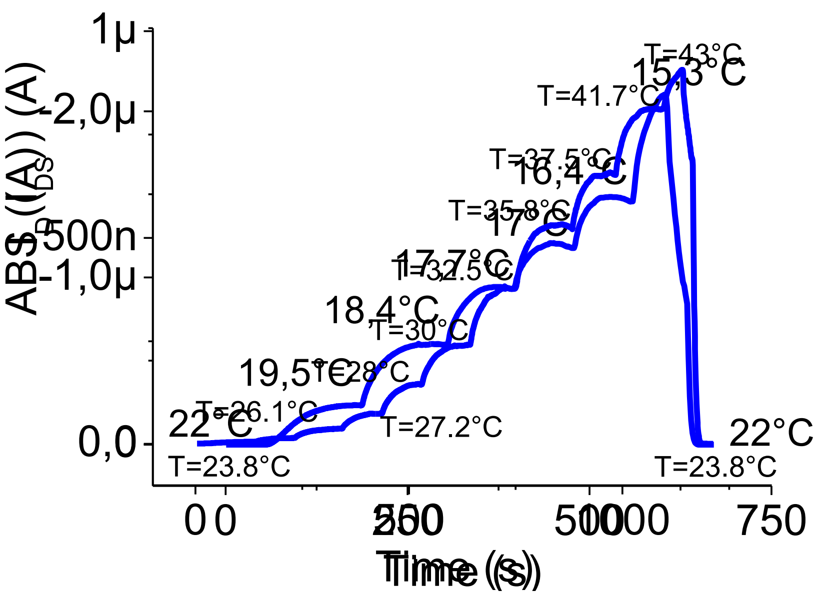
OCMFET- T sensing

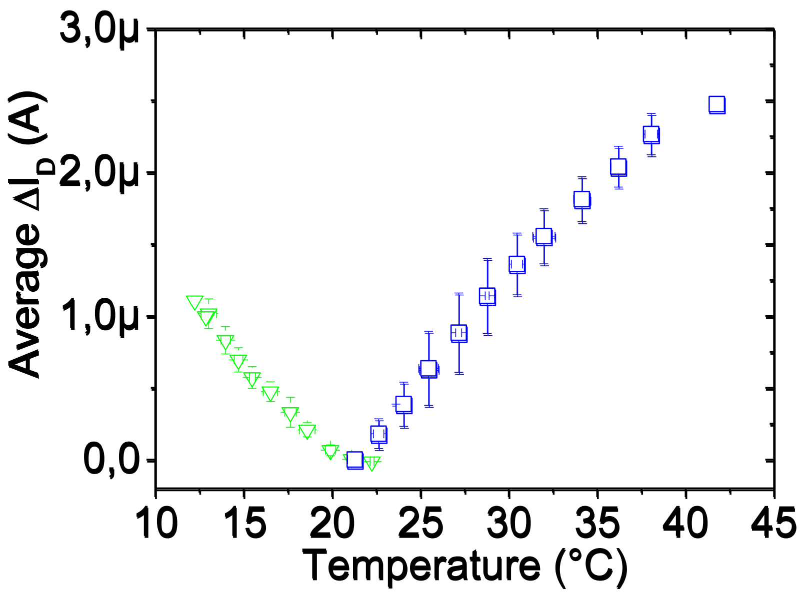




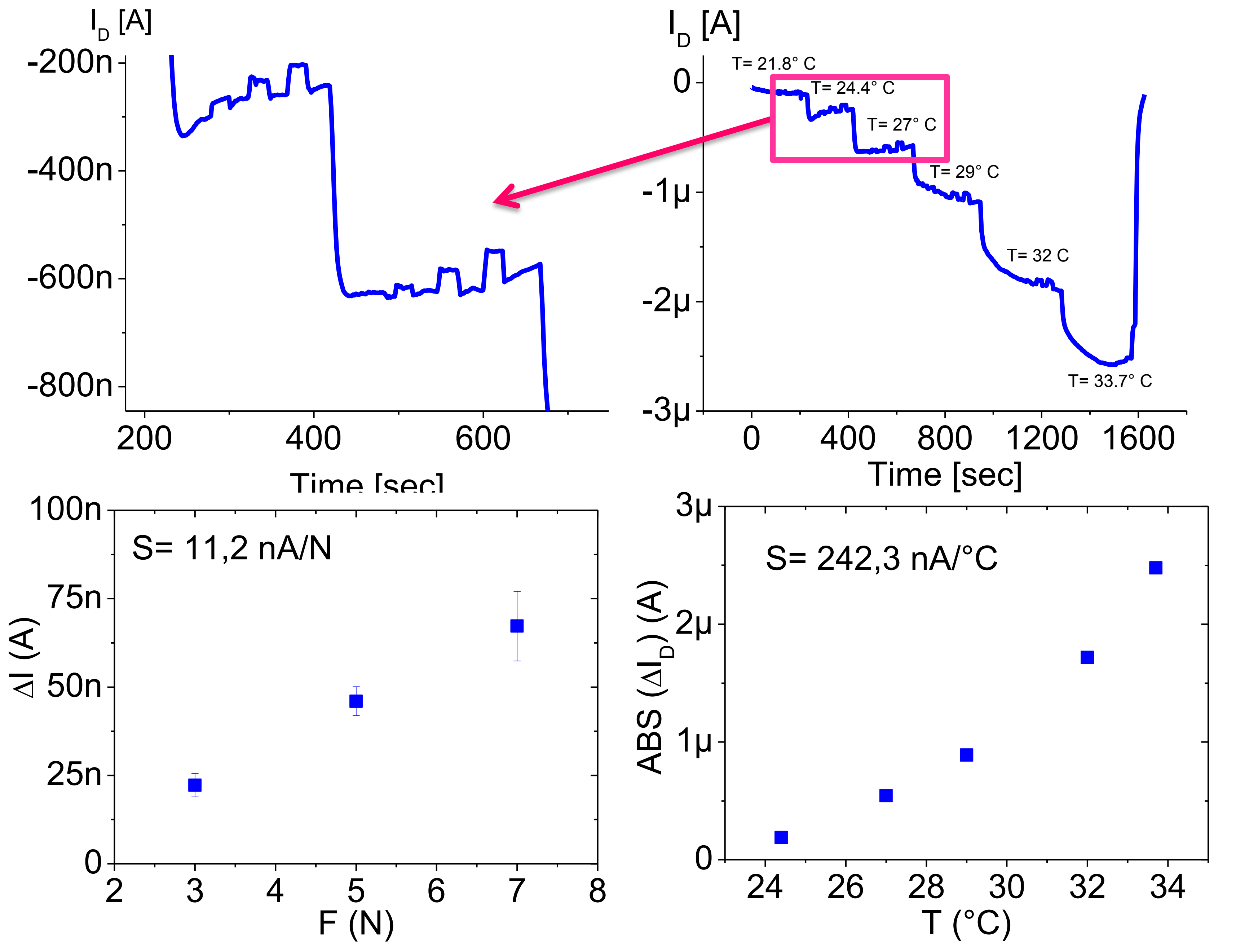
OCMFET- T sensing







OCMFET- bimodal sensing



What is the influence of mechanical deformation in OTFTs ?

- Capacitance changes in the gate dielectric

  S.C.B. Mannsfeld et al., Nature Materials 9 , 859–864 (2010)
- Interface between gate dielectric and organic semiconductor

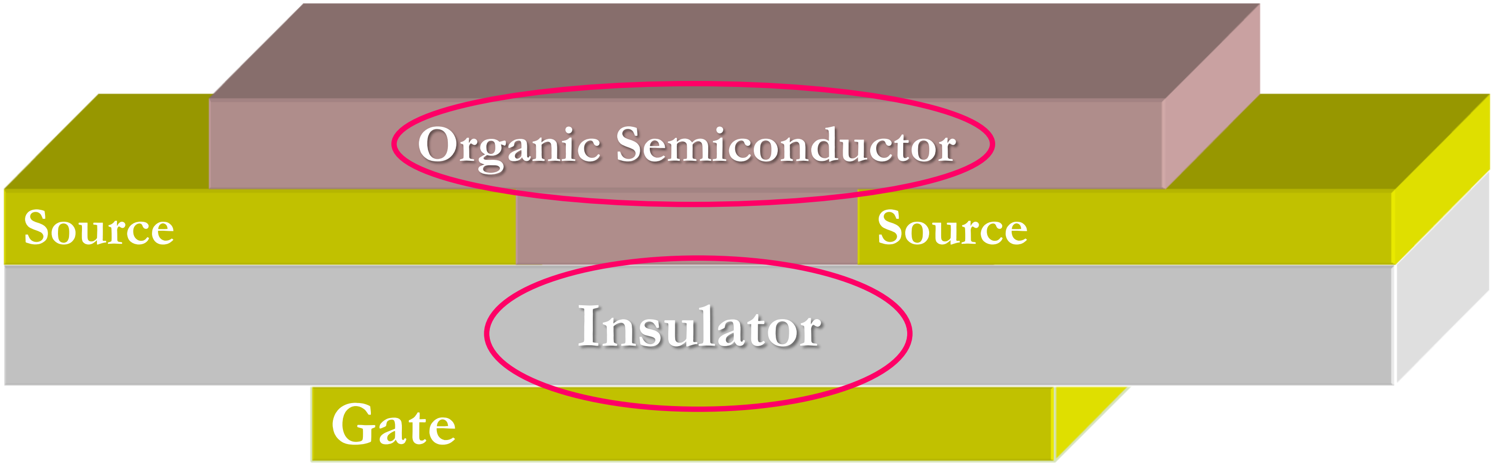
  A. N. Sokolov et al. Adv. Funct. Mater. 22, 175-183 (2012)
- **Morphological changes in the organic semiconductor active layer**

  P. Cosseddu et al. Org. Electr. 14, 206-211 (2013)/ EDL 33, 113 (2012), T. Sekitani et al APL 87, 173502 (2005)

Other issues:

Delamination → not reversible behavior

Cracks in the metal layers



Strain effects on OTFTs

Flexible substrate:

PET, PEN, Kapton

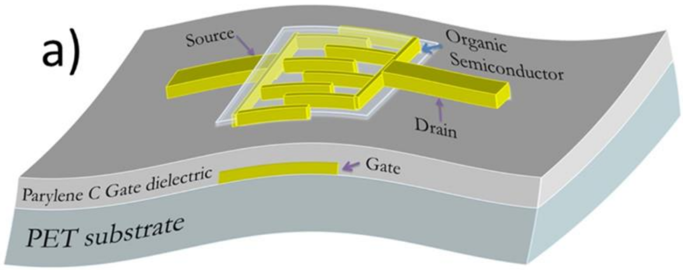
Gate dielectric:

Parylene C, PVA, PVP etc.

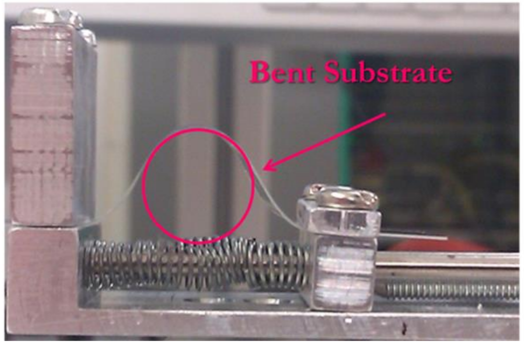
Organic Semiconductors:

- P3HT
- Pentacene *(different morphologies)*

a)



b)

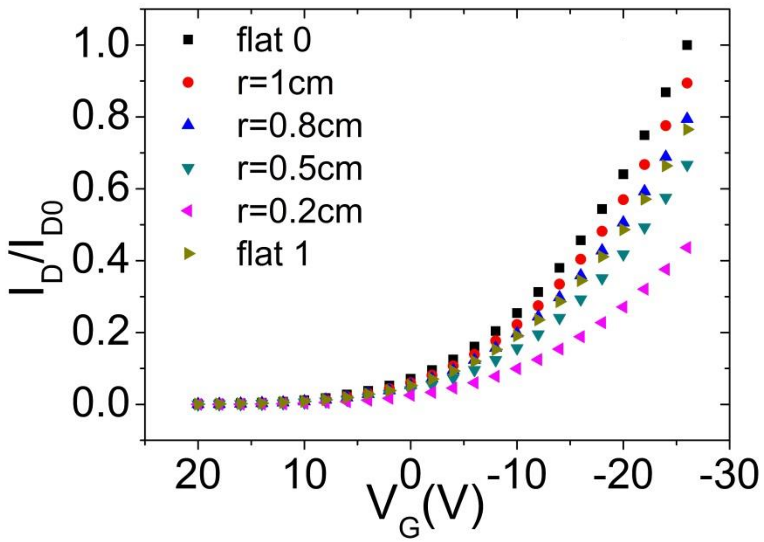


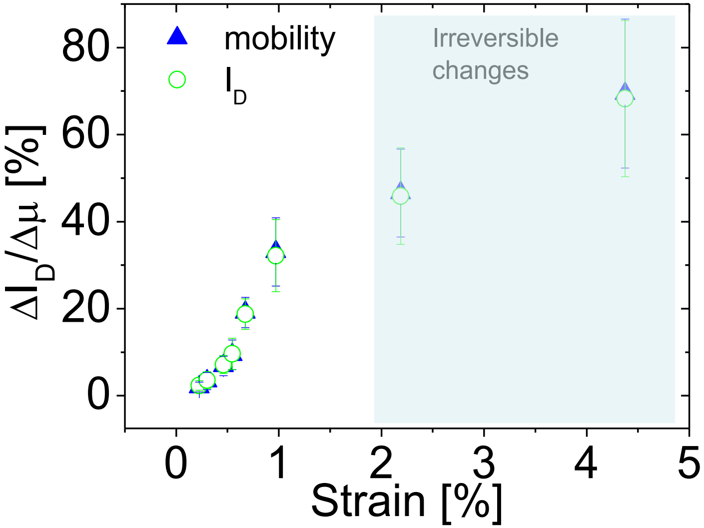
$$Strain = \left(\frac{d_f + d_s}{2*R}\right)\frac{\left(1+2\eta+\chi\eta^2\right)}{(1+\eta)(1+\chi\eta)} \Rightarrow Strain = \left(\frac{d_f}{2*R}\right)$$

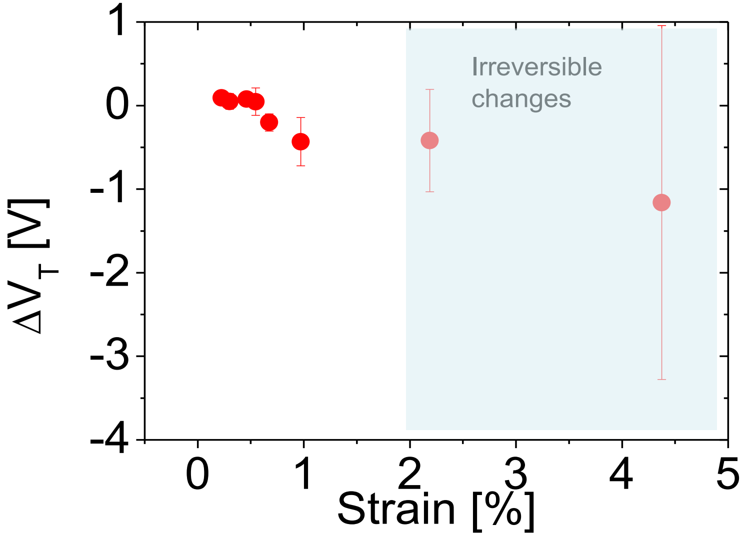
In which d_l and d_s are the thicknesses of the layer and of the substrate respectively, η is d_l/d_s, χ is the ratio between the Young moduli of the layer and of substrate ($\chi = Y_l/Y_s$) and R is the bending radius

Strain effects on the electrical characteristics

R [cm]	Strain [%]
3.9	0.2
2.9	0.3
1.9	0.5
1.3	0.7
0.9	1.0
0.4	2.2
0.2	4.4

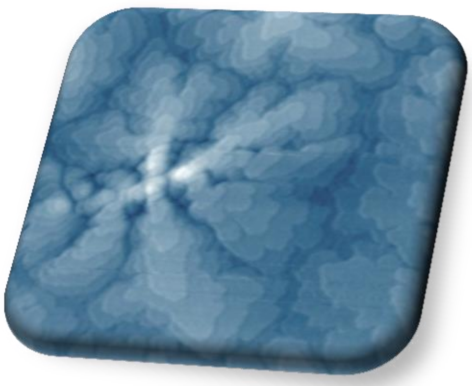


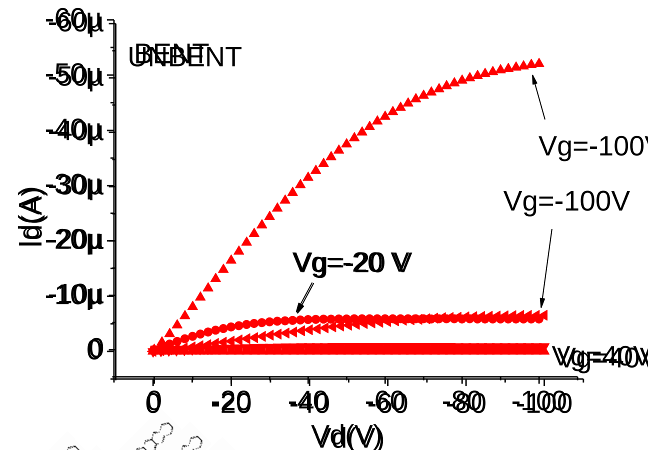


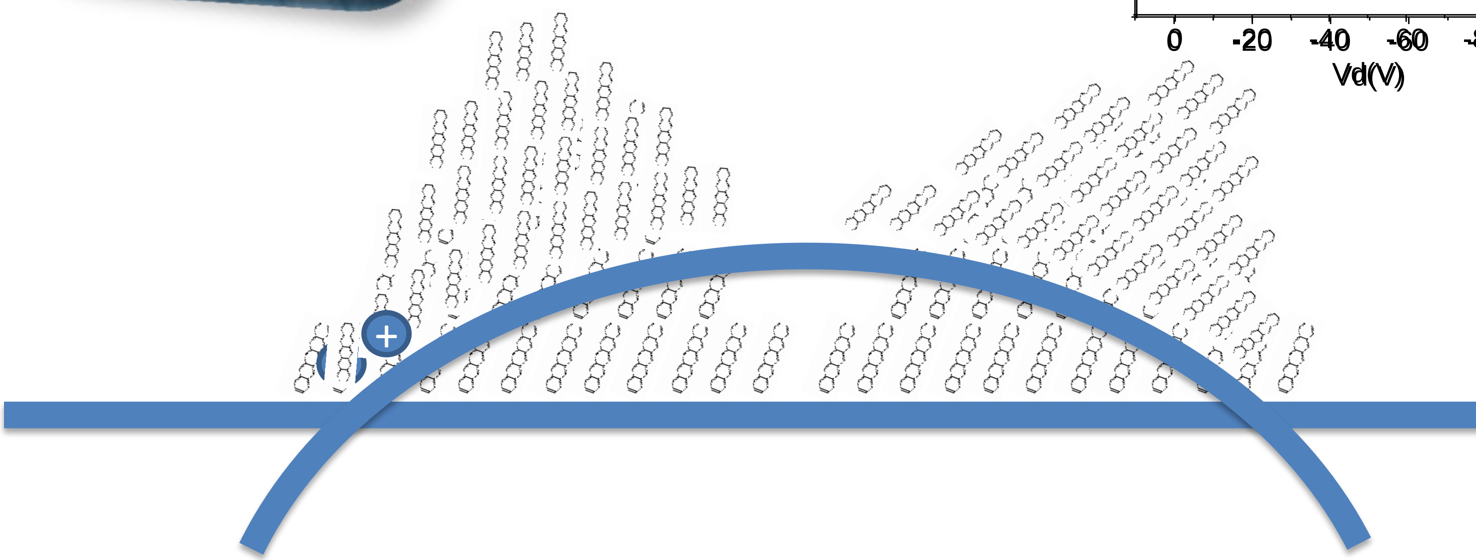


Effect of strain on OTFTs

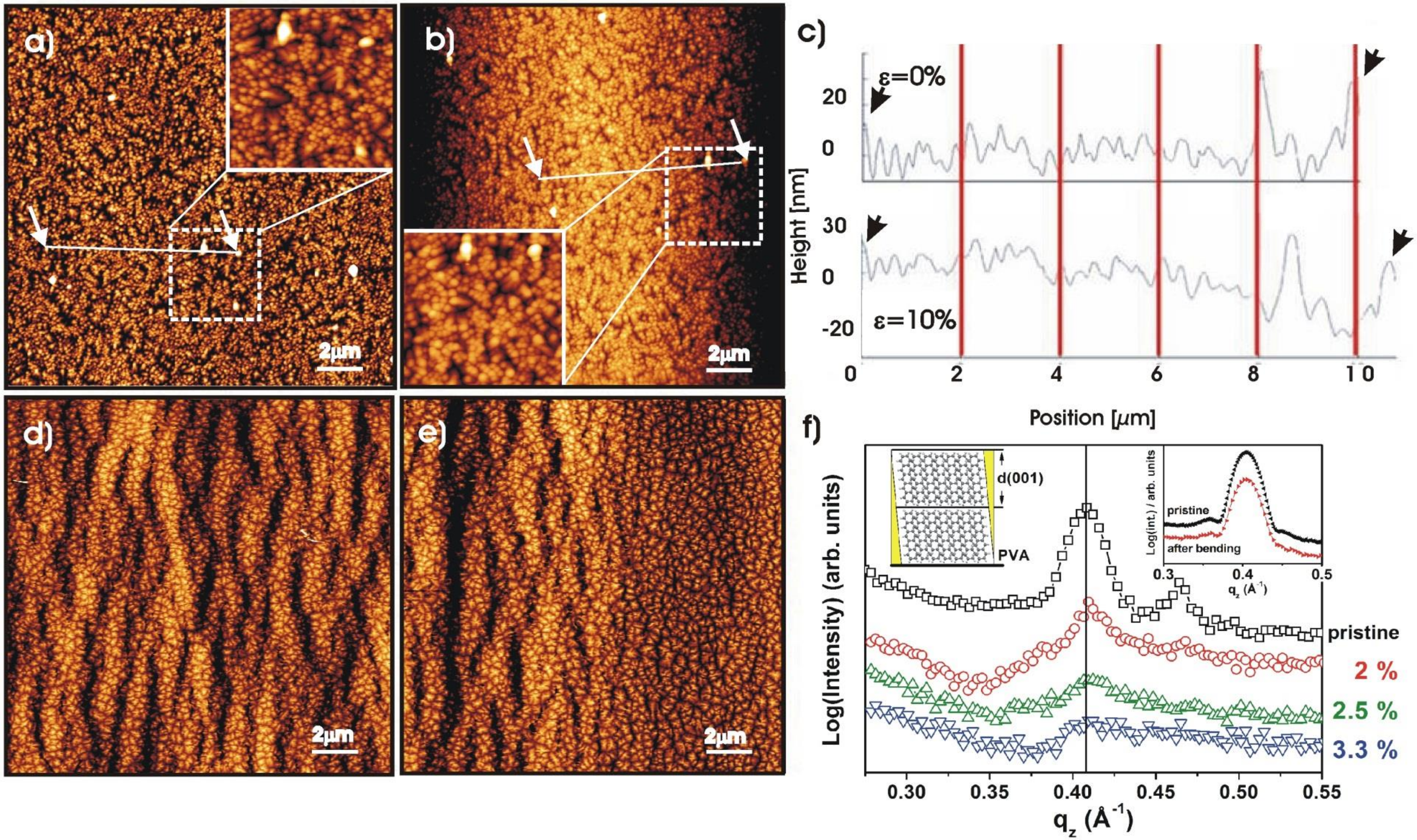
- Mechanical deformation induces morphological changes in the active layer
- Hopping barrier increases → current decreases!







Strain effects on structure and morphology

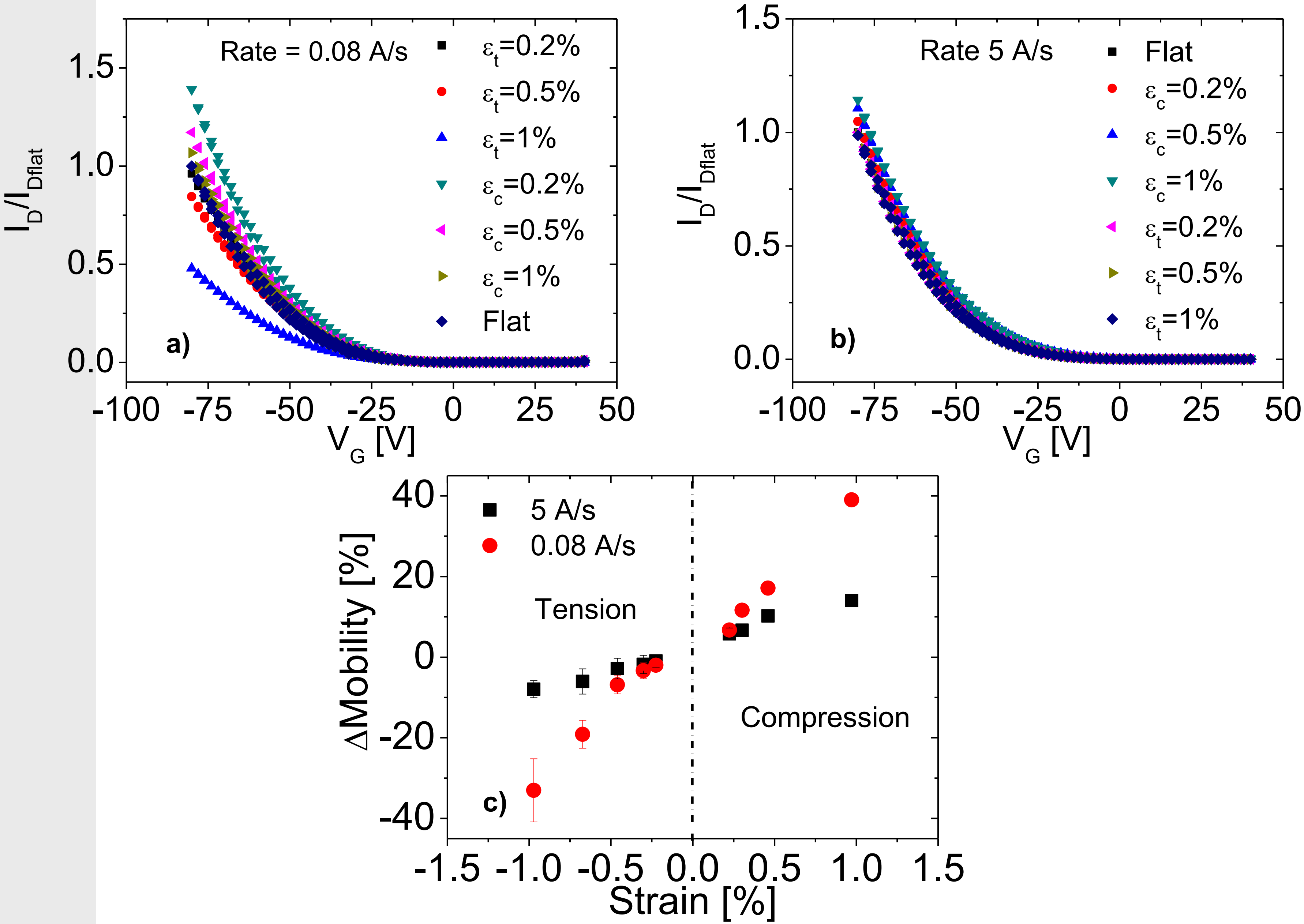


Response is more related to MORPHOLOGICAL CHANGES

Pentacene film properties are not permanently affected by mechanical deformation

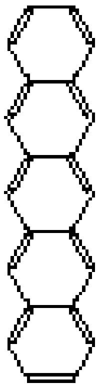
<u>V. Scenev</u>, P. Cosseddu, A. Bonfiglio, I. Salzmann, N. Severin, M. Oehzelt, N. Koch, J.P. Rabe, ***Org. Electr. 14, 1323-1329 (2013)***

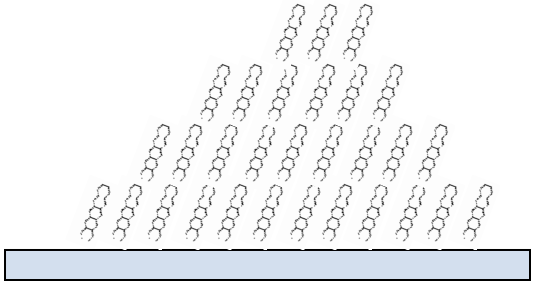
Tension – compression @ different rates



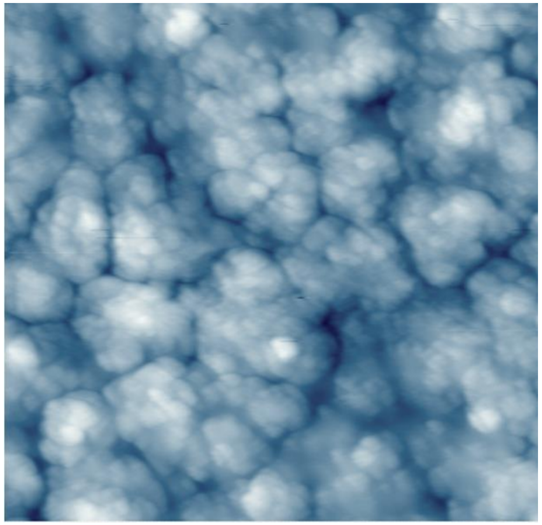
Effect of strain on OTFTs: Pentacene vs P3HT

Pentacene

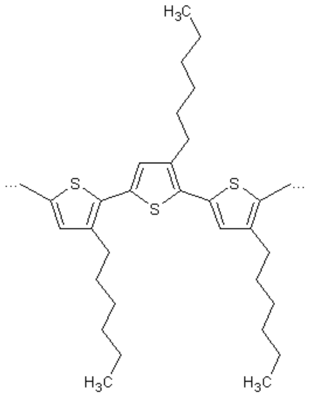


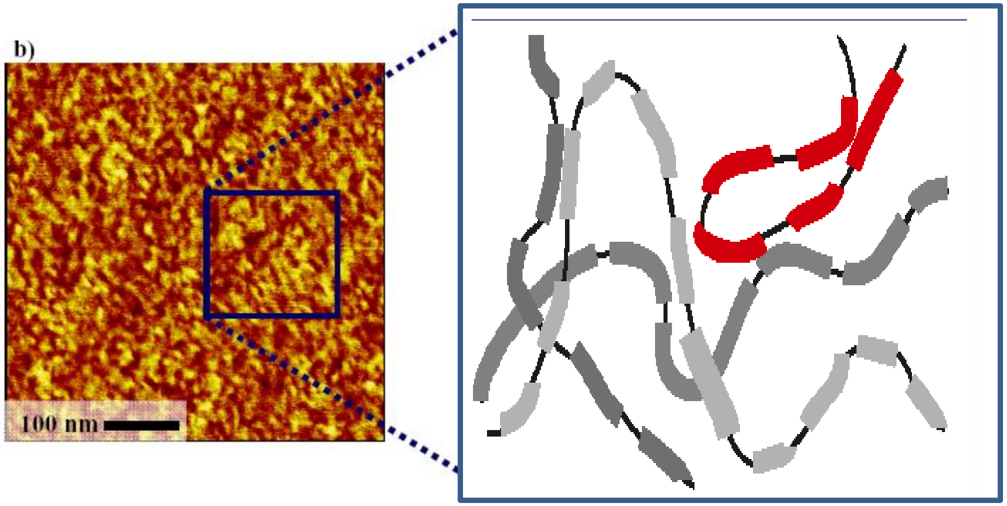


Well ordered even when deposited on "non ideal" plastic substrates



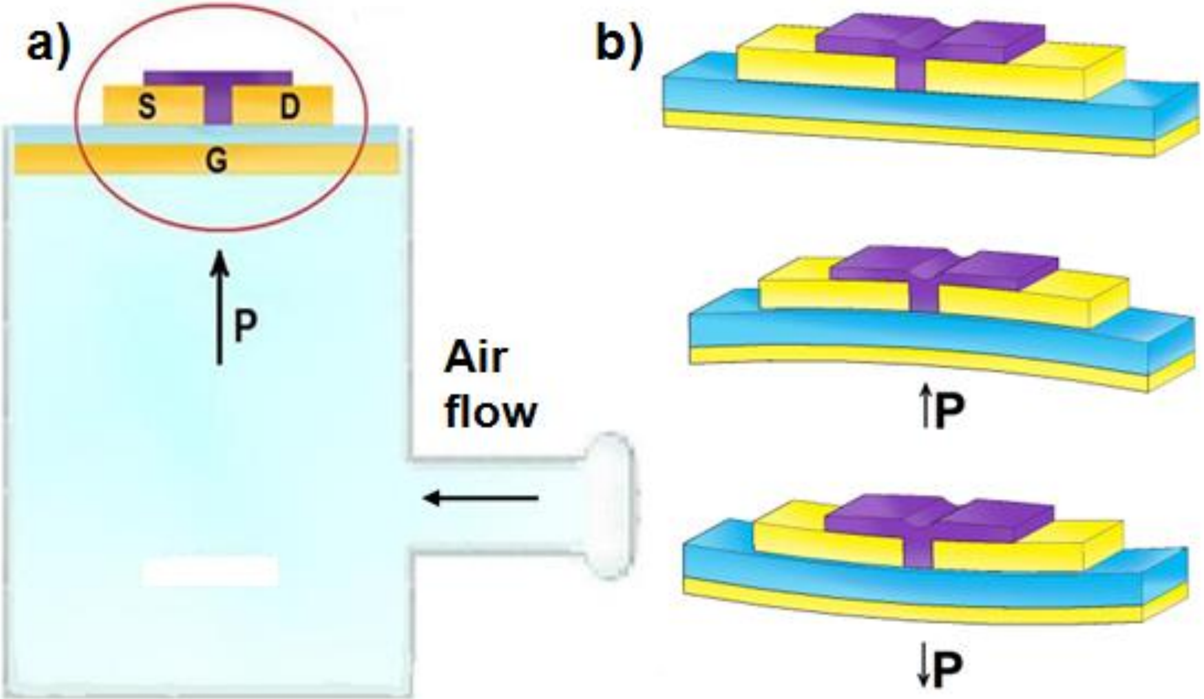
P3HT

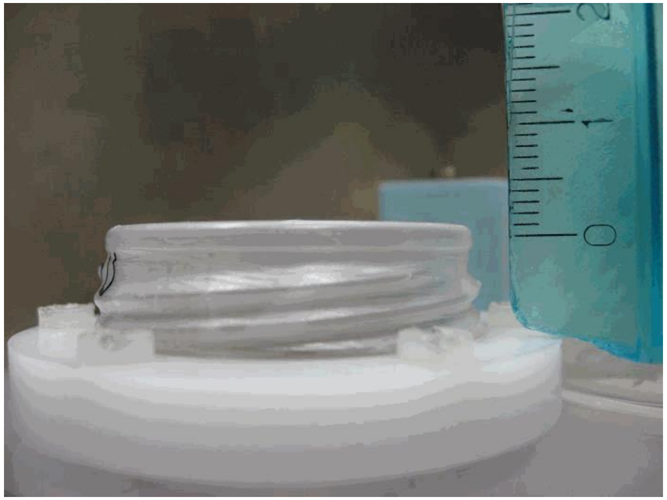




Highly disordered

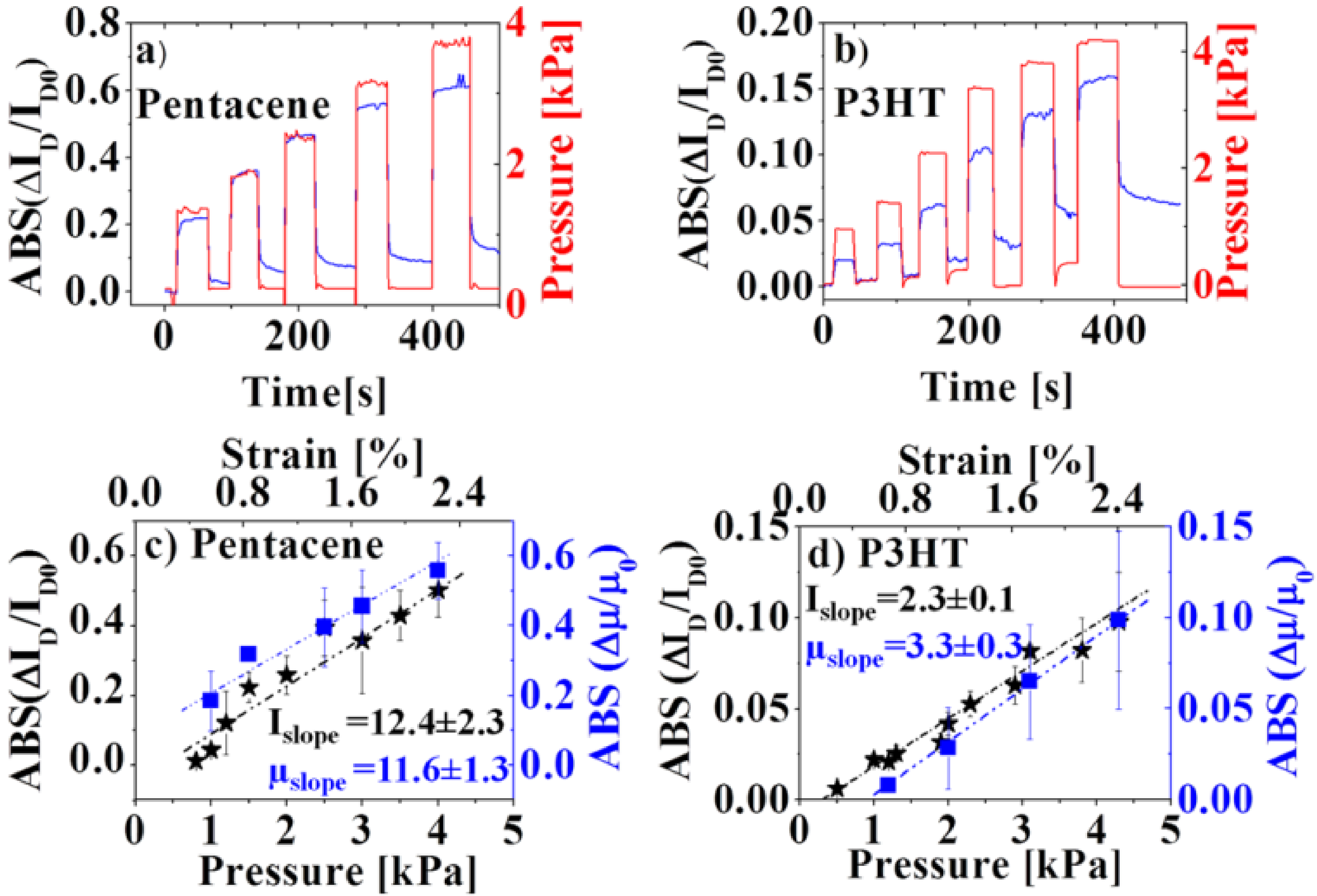
Effect of strain on OTFTs: Pentacene vs P3HT





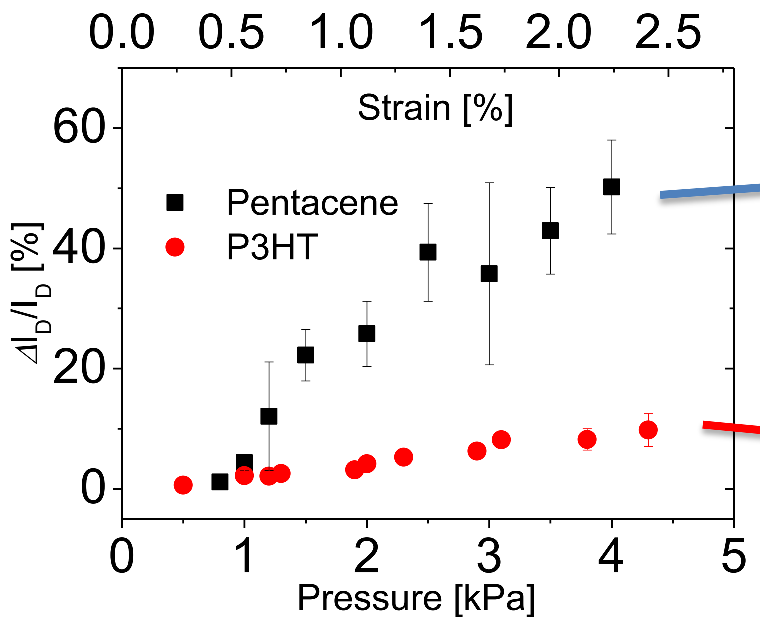
P. Cosseddu et al. IEEE Electron Device Letters 33 (2012) 113

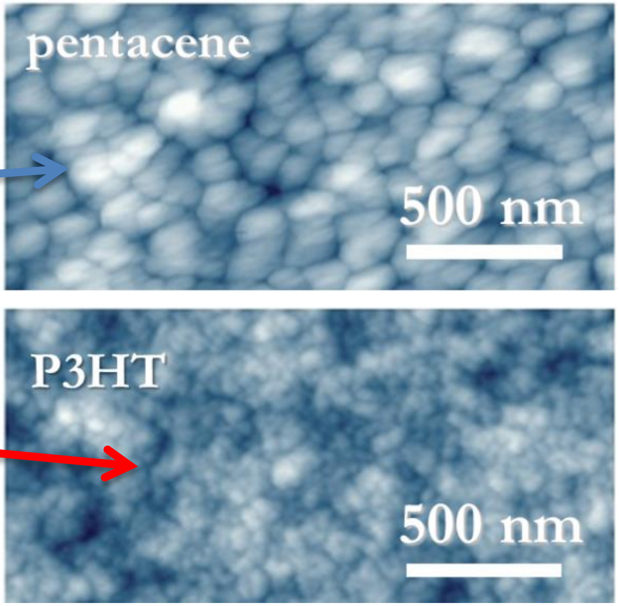
Effect of strain on OTFTs: Pentacene vs P3HT



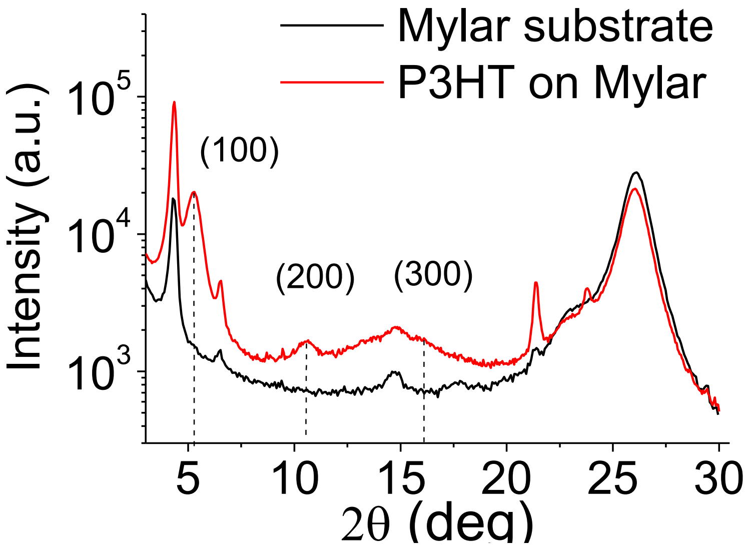
P. Cosseddu et al. IEEE Electron Device Letters 33 (2012) 113

Effect of strain on OTFTs: Pentacene vs P3HT





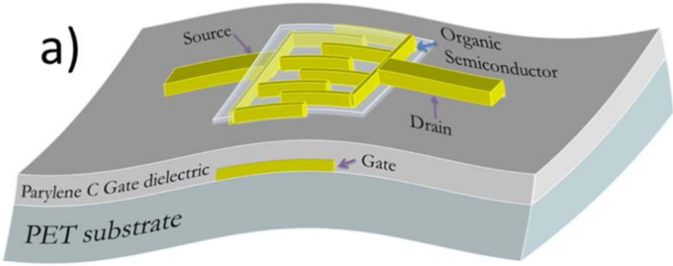
- **Pentacene devices are characterized by a much higher sensitivity**
- **P3HT disordered films, with very small grain dimensions showed a much lower sensitivity**



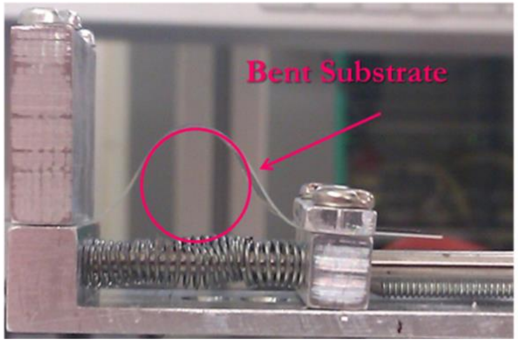
P. Cosseddu et al. IEEE Electron Device Letters 33 (2012) 113

Inducing morphological changes

a)

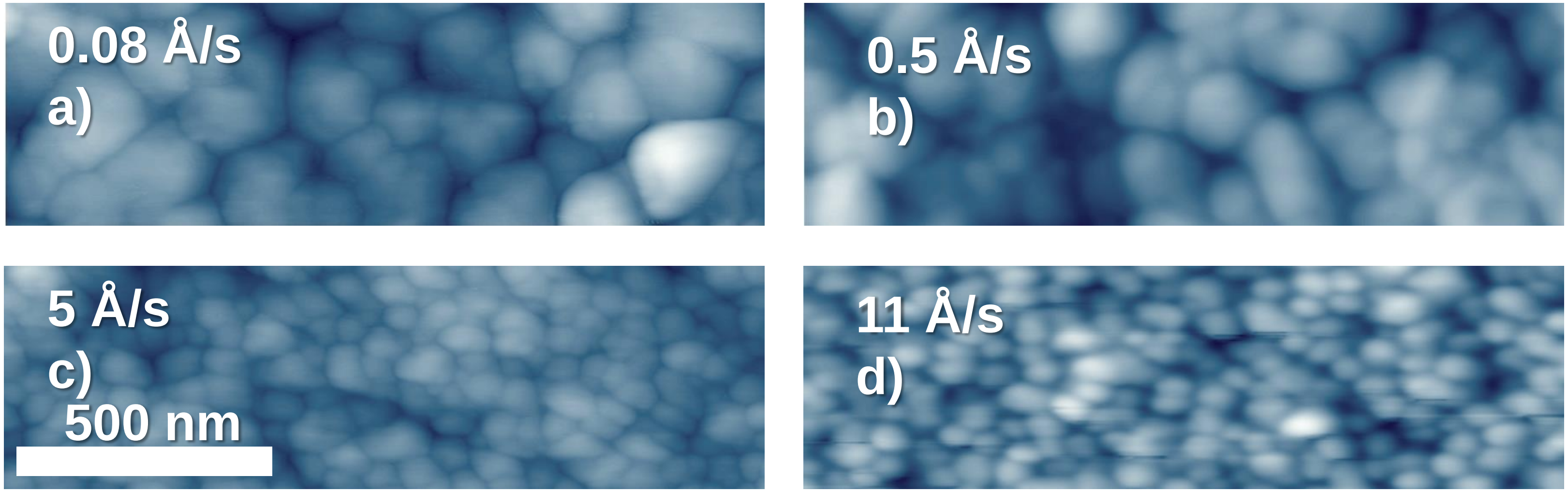


b)

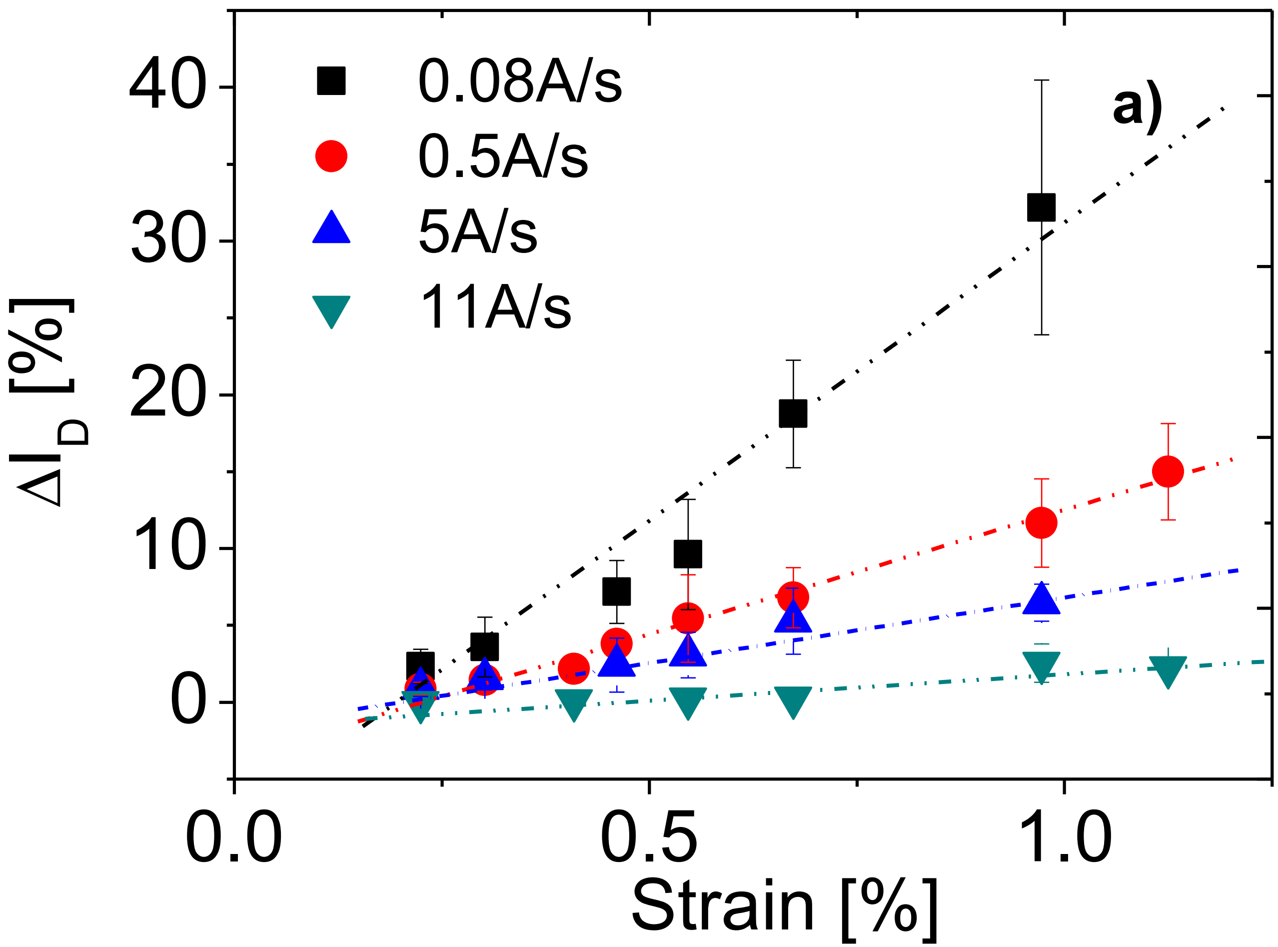


Pentacene based devices

As sensitivity to strain seems o be related to morphology, we have **intentionally modified the morphology** by changing the deposition rate



Influence of morphology on the sensitivity



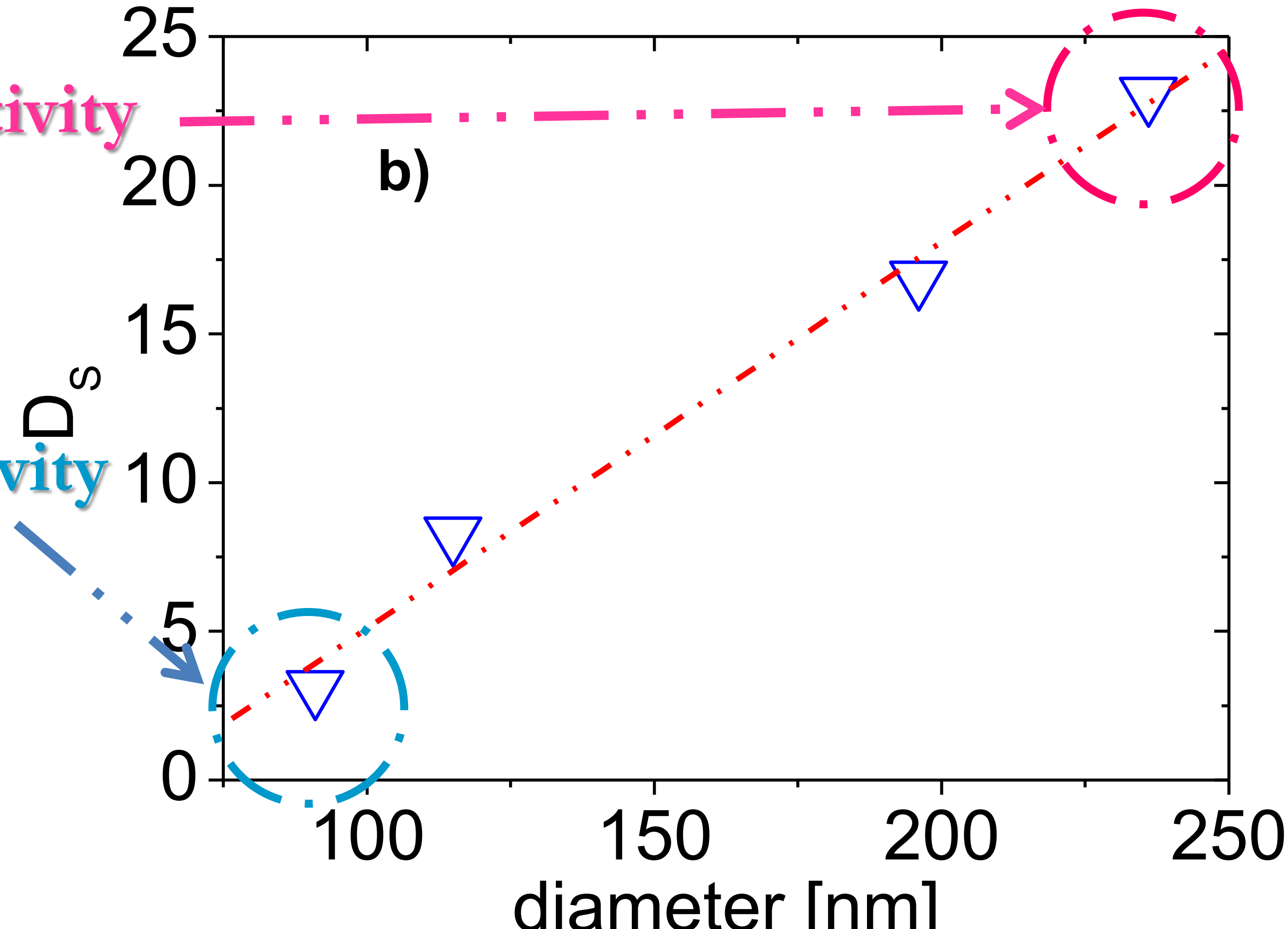
Morphological properties strongly influence the sensitivity to strain

Tuning the sensitivity

Sensitivity can be finely tuned by setting the deposition parameters

High sensitivity
Sensor applications

Low sensitivity
Flexible electronics



P. Cosseddu et al. Organic Electronics 14 (2013) 206–211

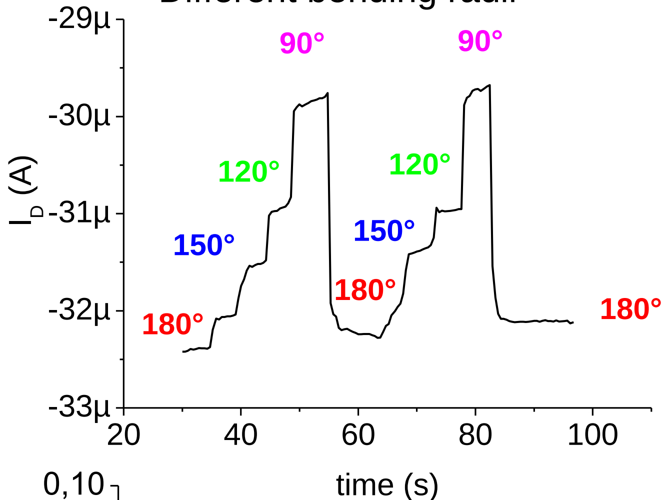
Mechanical sensing applications

The flexible devices can be transferred into a fabric and sewn

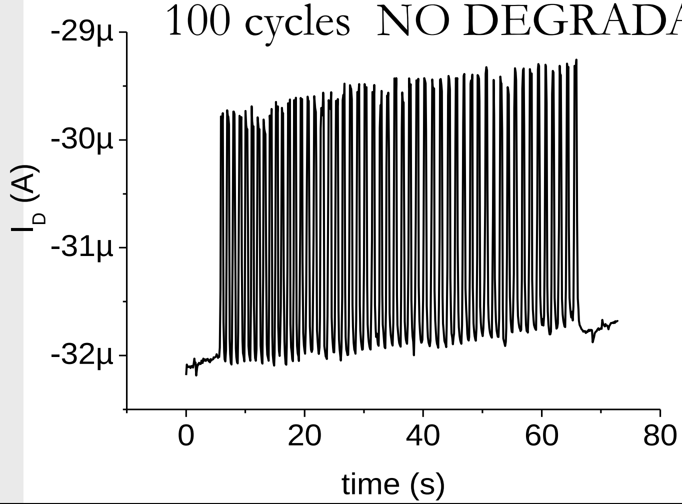
The sensorised fabric is still highly flexible and can be sewn on a glove for measurements

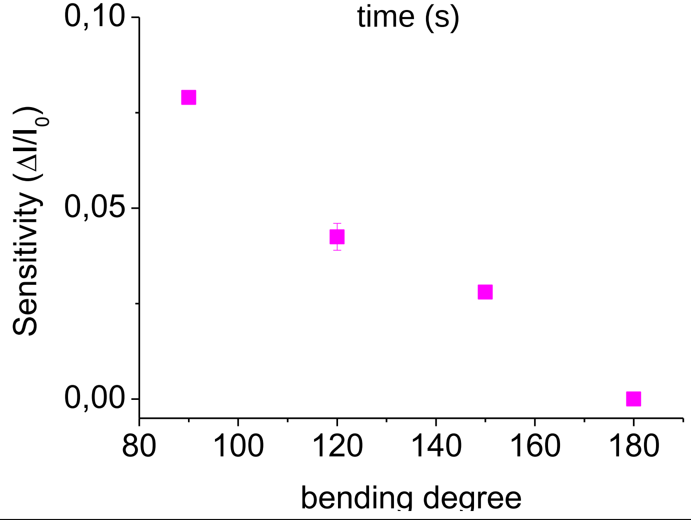
Applications: joints motion

Sensor applied onto a ribbon can be transferred onto clothes for **joints motion monitoring**

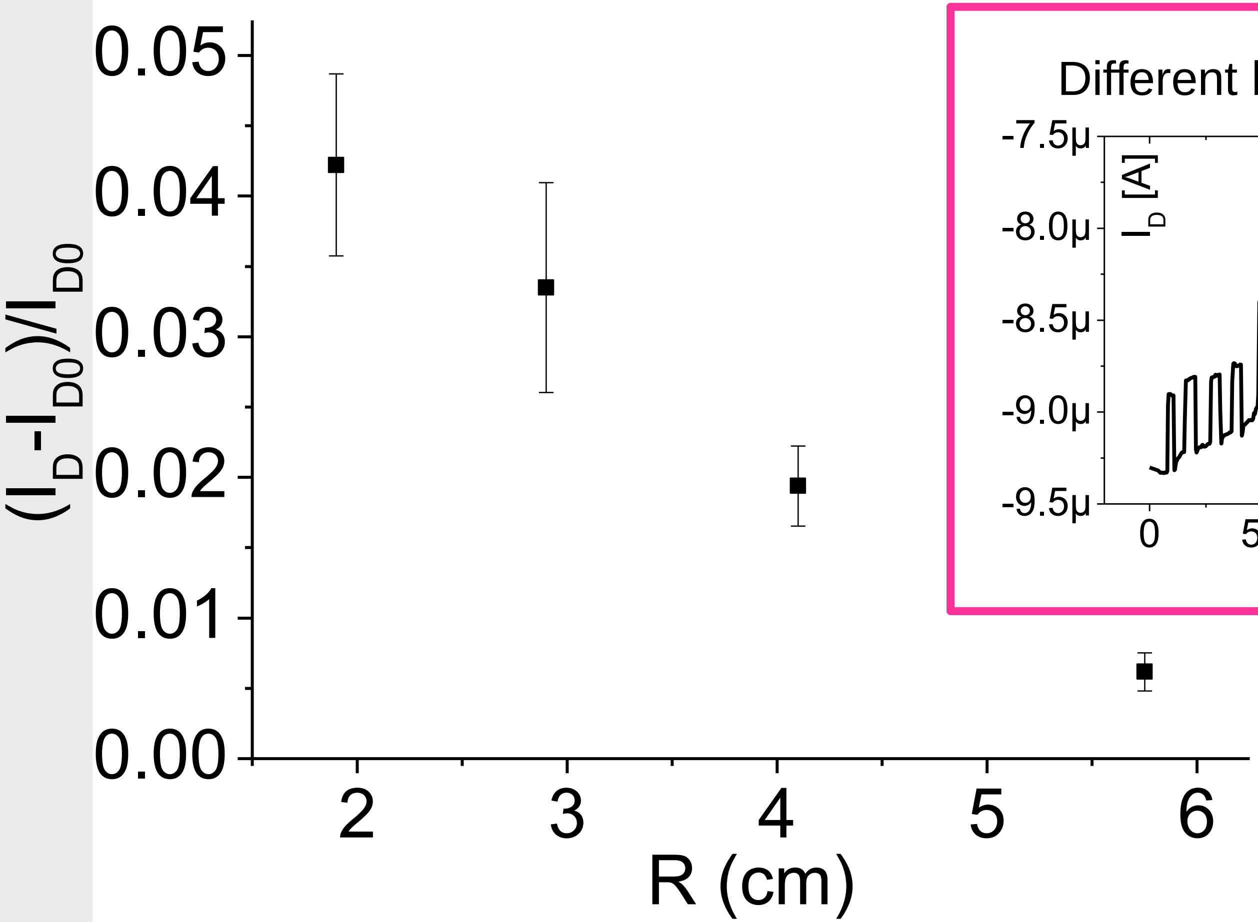


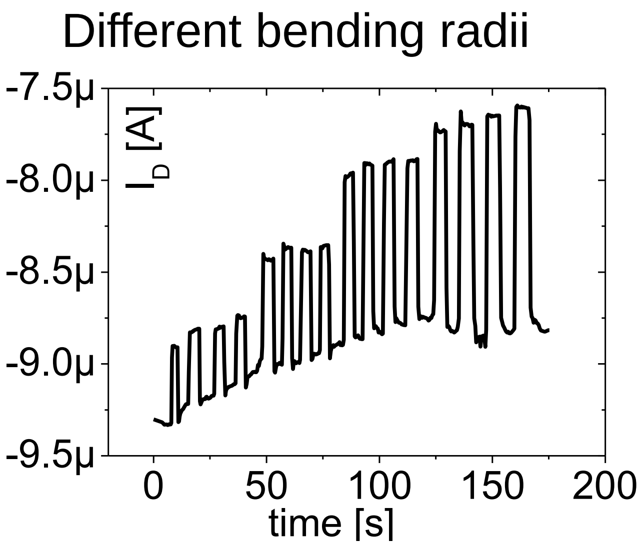
100 cycles NO DEGRADATION



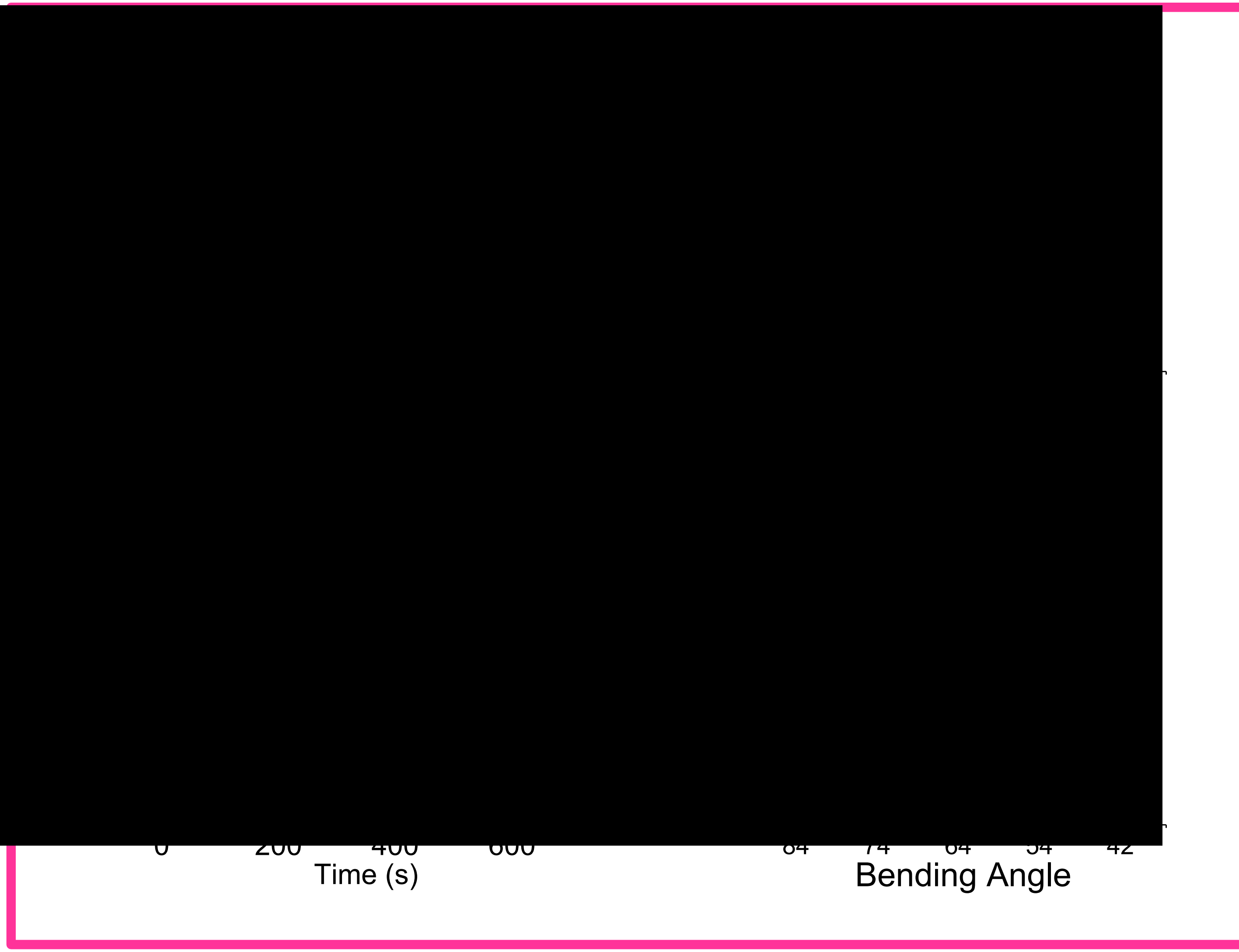


Applications: sensing glove

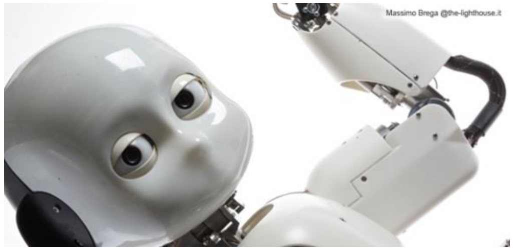




Applications: sensing glove



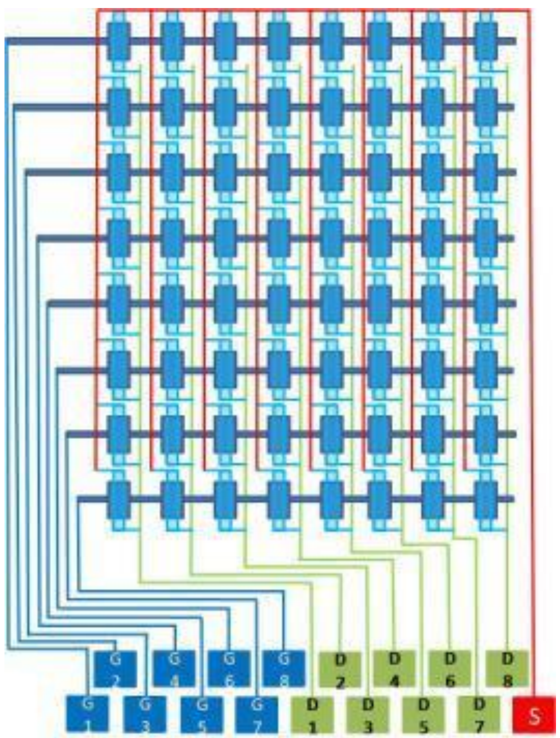
Applications: Artificial robot skin

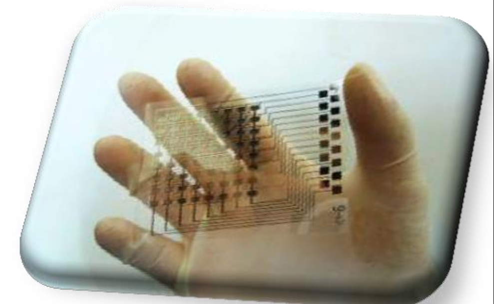


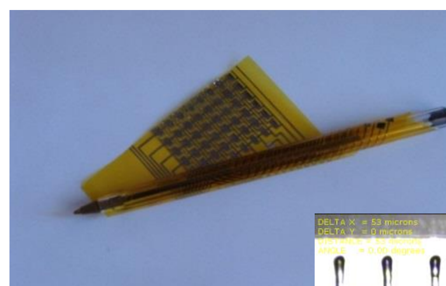
Develop a highly flexible, compliant system for tactile transduction

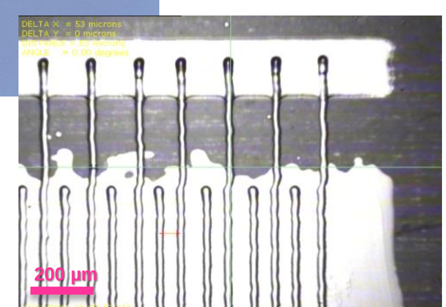
Inkjet printed matrices and arrays of OTFTs on plastic substrates

Skin-based Technologies and Capabilities for Safe, Autonomous and Interactive Robots



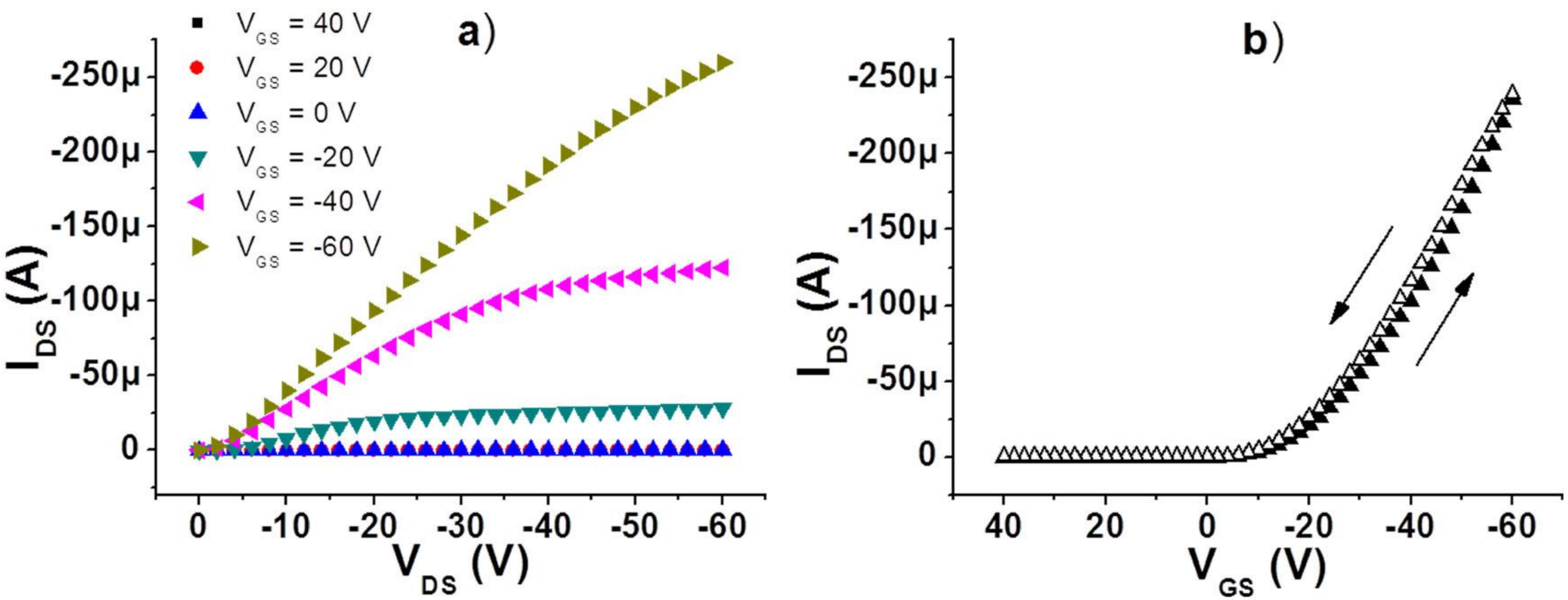






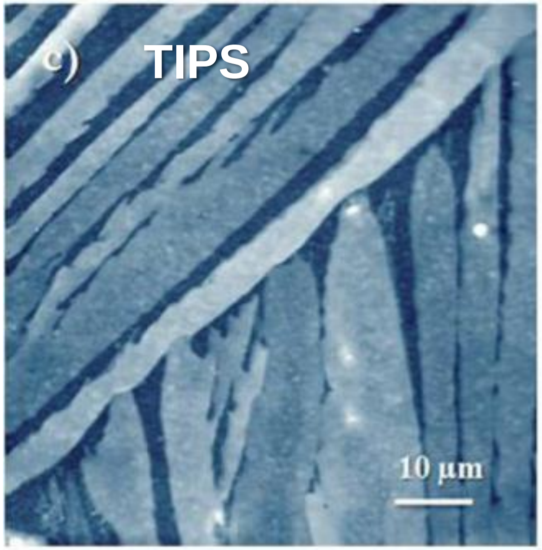
Applications: Artificial robot skin

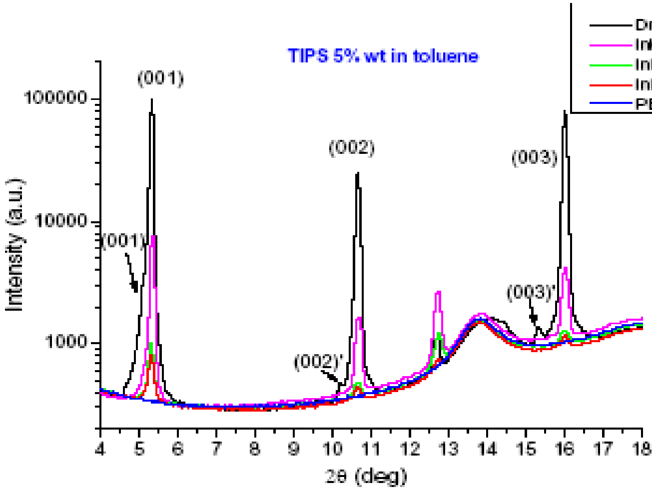
- t_{ins} = 1.54 µm, ε_r = 3.15 → C_{ins} = 1.8 nF/cm^2
- μ = 0.1 cm^2/Vs
- V_T = 4 ± 5 V
- $I_{ON}/I_{OFF} \approx 10^5$

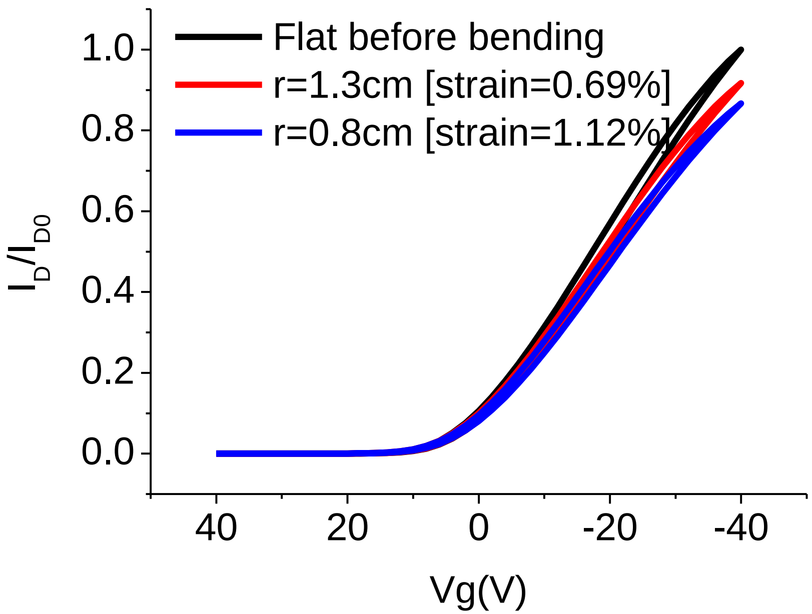


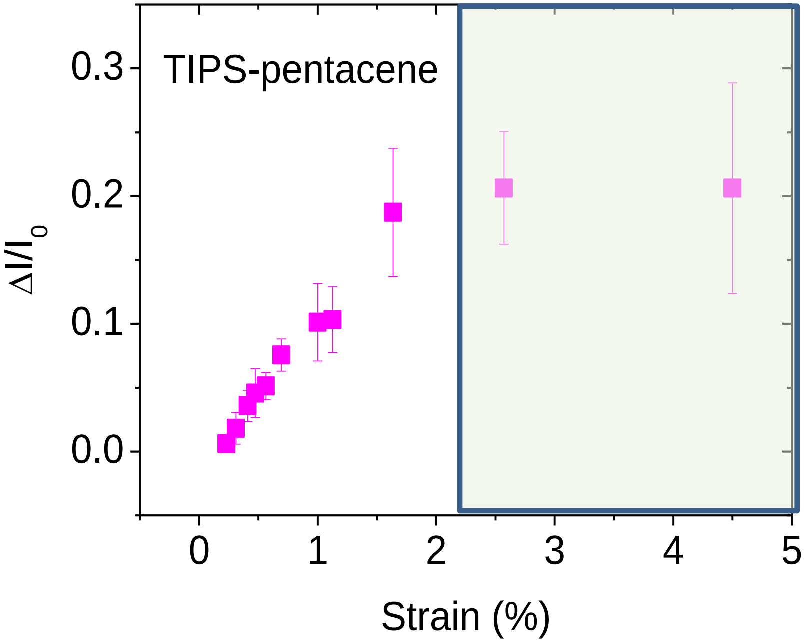
Strain sensitivity in TIPS based OTFTs

Highly crystalline TIPS-Pentacene films



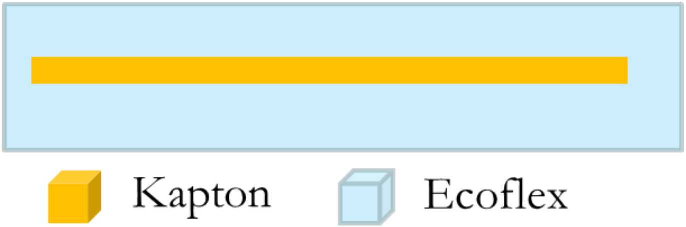






Artificial skin: Experimental set up

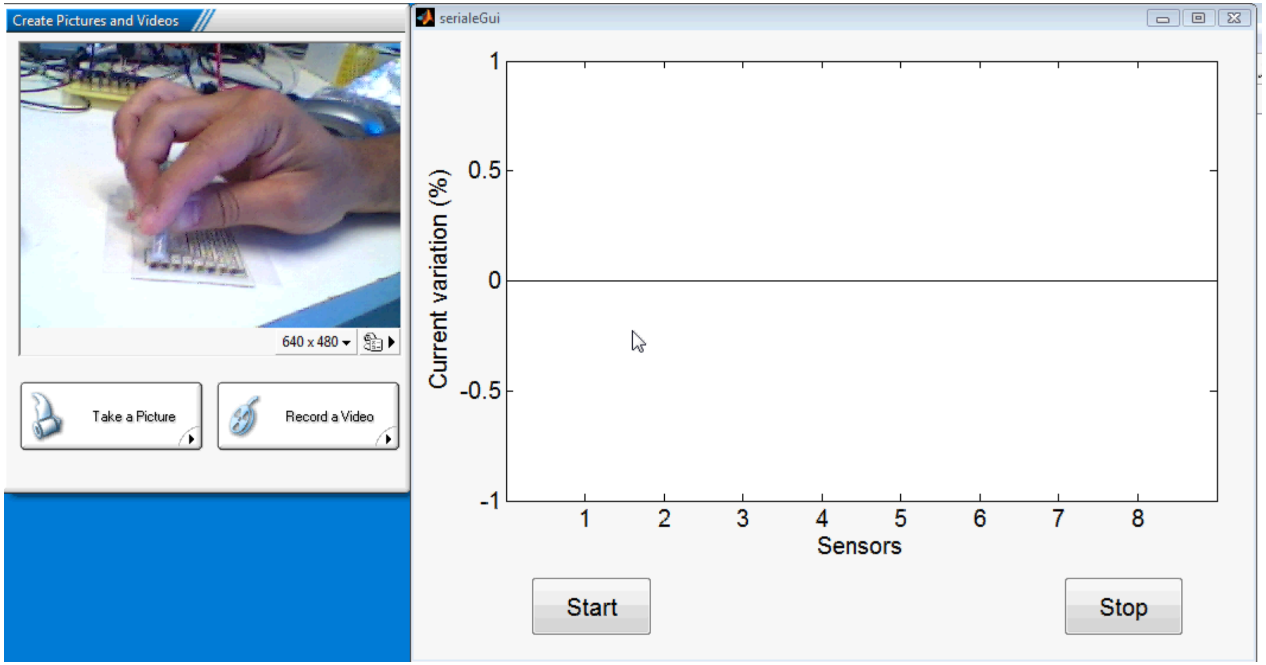
Embedding the organic substrates with elastomers



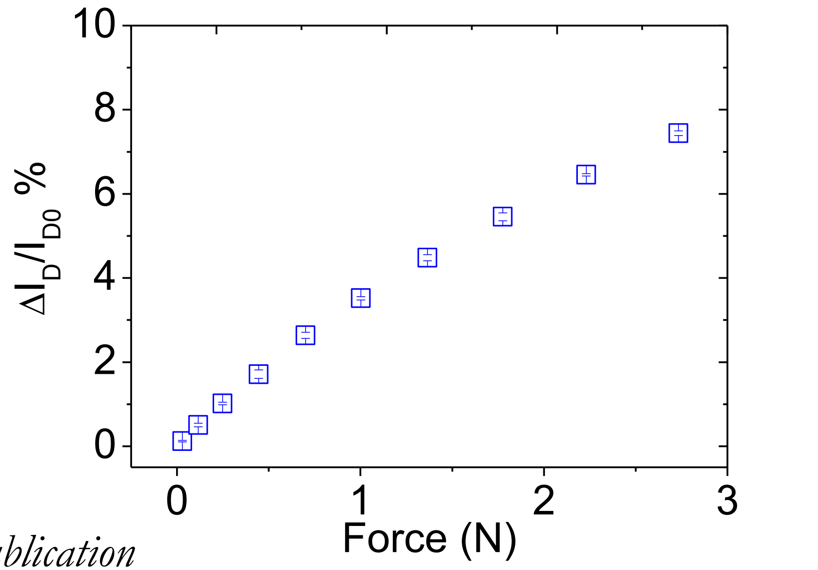
Mechanical properties and thickness of the elastomer influence the sensitivity *(Ecoflex → 1 + 1 mm)*

- Pressure exerted by a mechanical finger
- Hemispheric indenter (4 mm radius)
- Controlled input: Dz, F
- Output: ΔI/I
- Increasing pressures
- Different configurations

Artificial skin: electro-mechanical characterization



- Very good repeatability and sensitivity
- Working range 0 - 4 N
- Resolution = 0.1 N



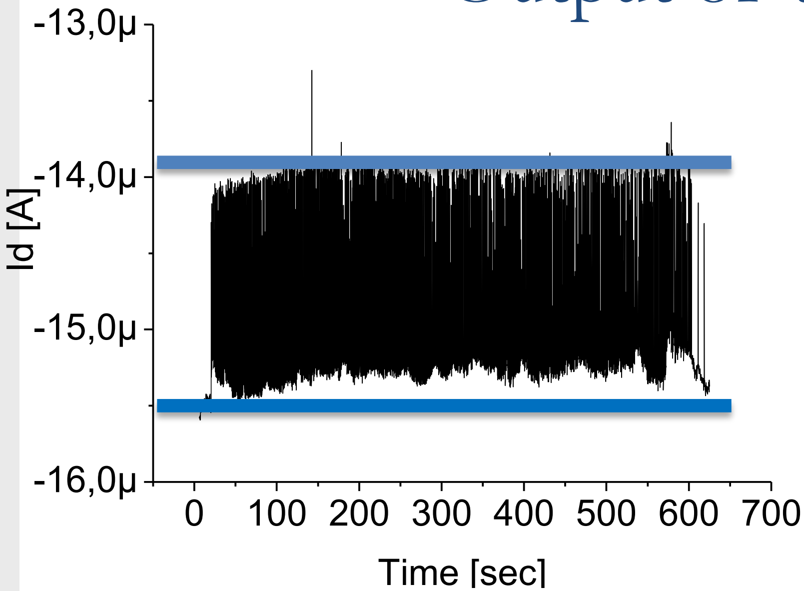
A. Loi et al. IEEE Sensors Journal, accepted for publication

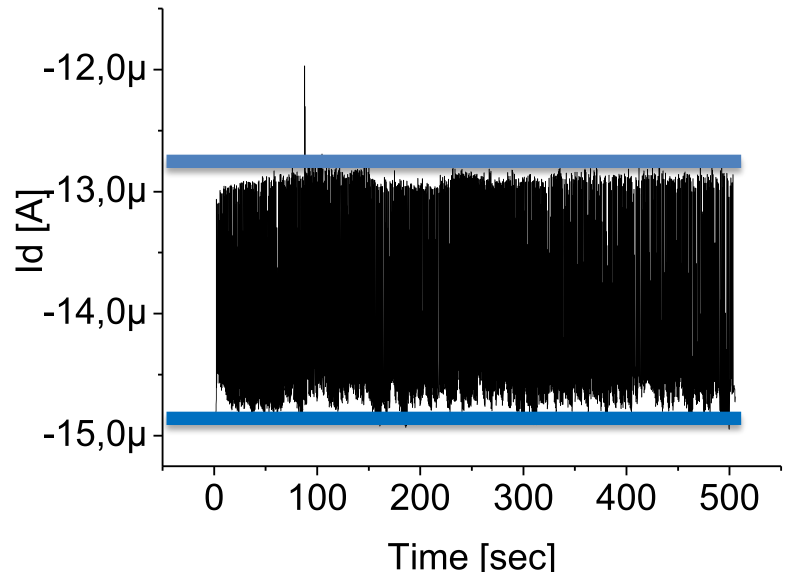
Artificial skin: electro-mechanical characterization

Mechanical Stress Tests

Applied force=2 N

Output of two different taxels





- ➢ Negligible current shift
- ➢ Reproducible response up to 1000 cycles

Is it possible to minimize the effect of mechanical deformation?

- Geometry an layout of the device
- Morphological and structural properties of the organic semiconductor layer

Geometry and layout of the device

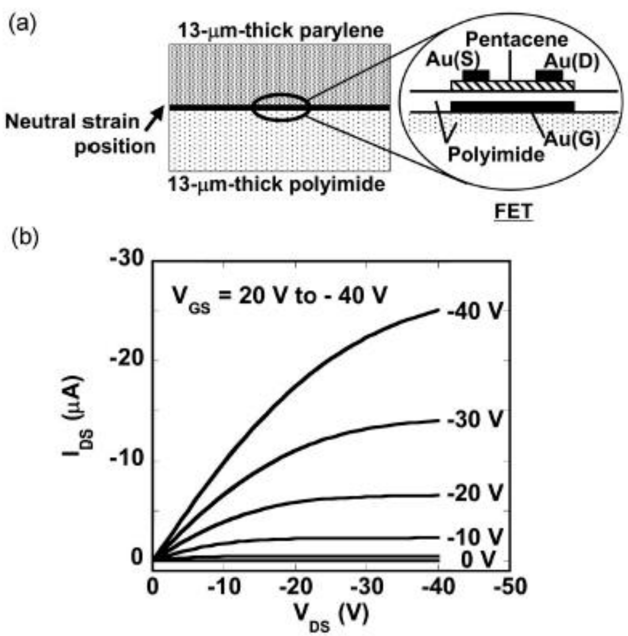
Surface strain depends on the bending radius, but also on the substrate thickness!!!

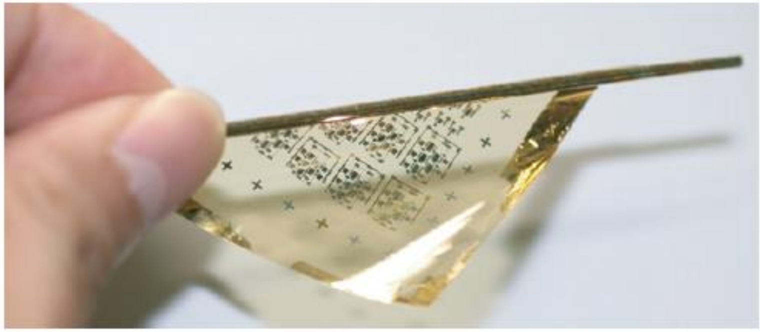
$$Strain = \left(\frac{d_f + d_s}{2 * R}\right)\frac{\left(1 + 2\eta + \chi\eta^2\right)}{\left(1 + \eta\right)\left(1 + \chi\eta\right)} \Rightarrow Strain = \left(\frac{d_f}{2 * R}\right)$$

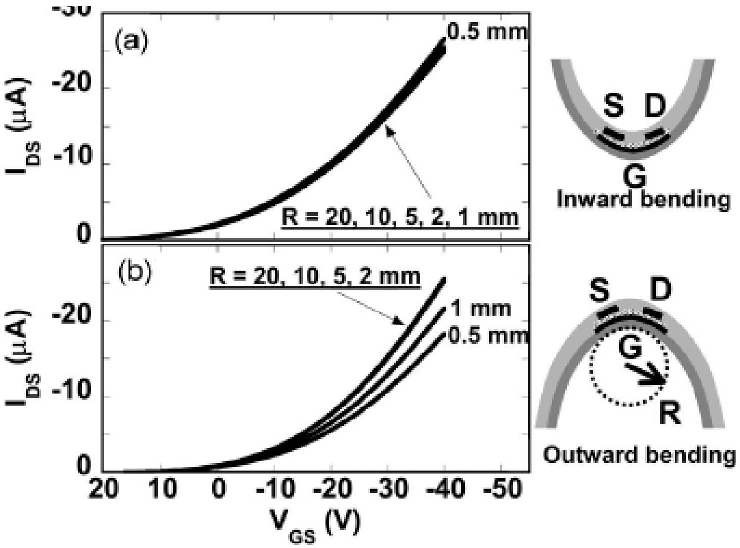
Two different approaches:

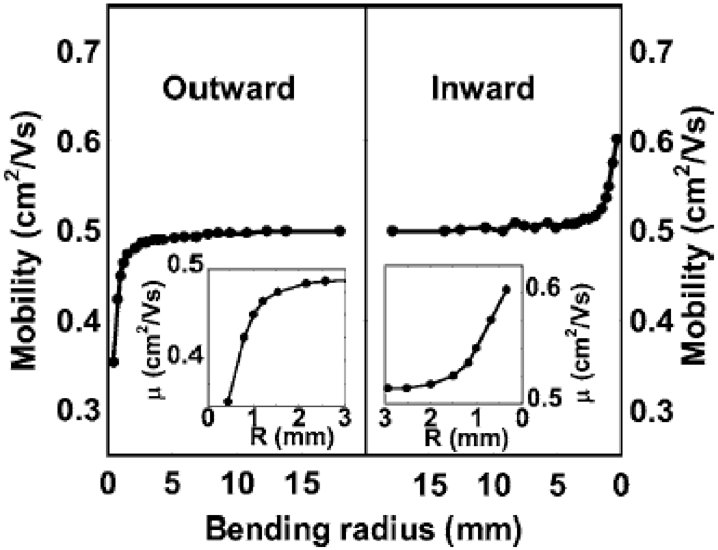
- Neutral strain position
- Thin substrates

OTFT in neutral strain position







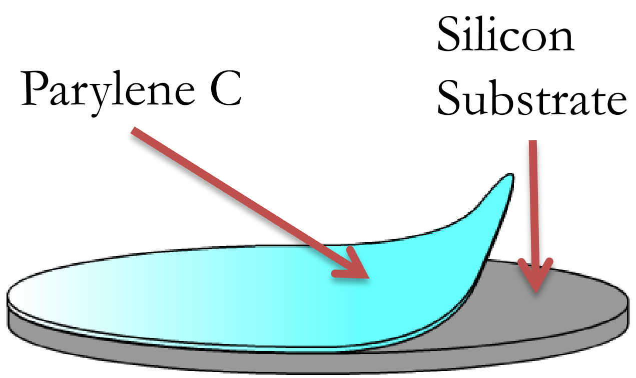


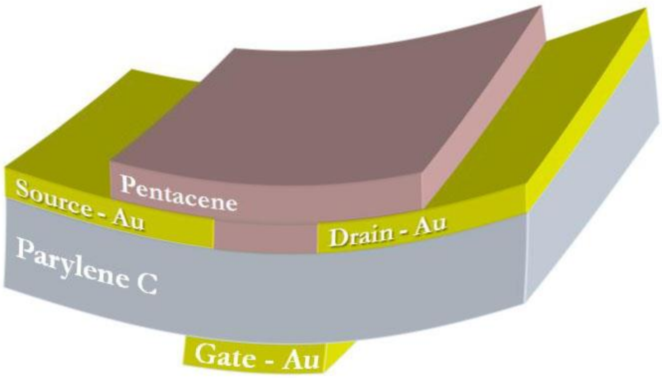
- *T. Sekitani et al. Appl. Phys. Lett. 87, 173502 (2005)*
- *T. Sekitani et al. Nature Mater. 9, 1015 (2010)*

Reducing strain by using thin substrates

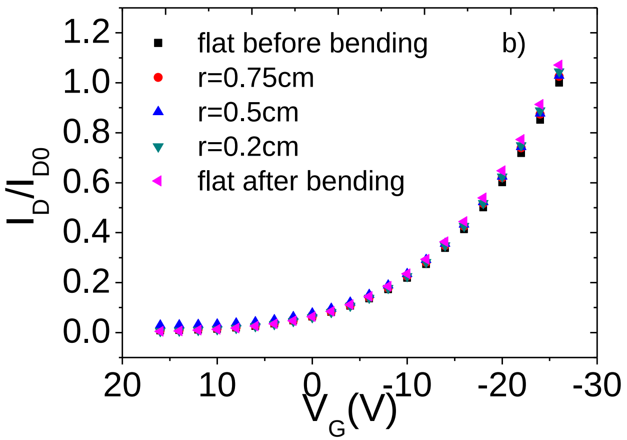
✓Parylene C films have been deposited on Silicon substrate (low surface corrugation)

✓After deposition the film can be peeled off



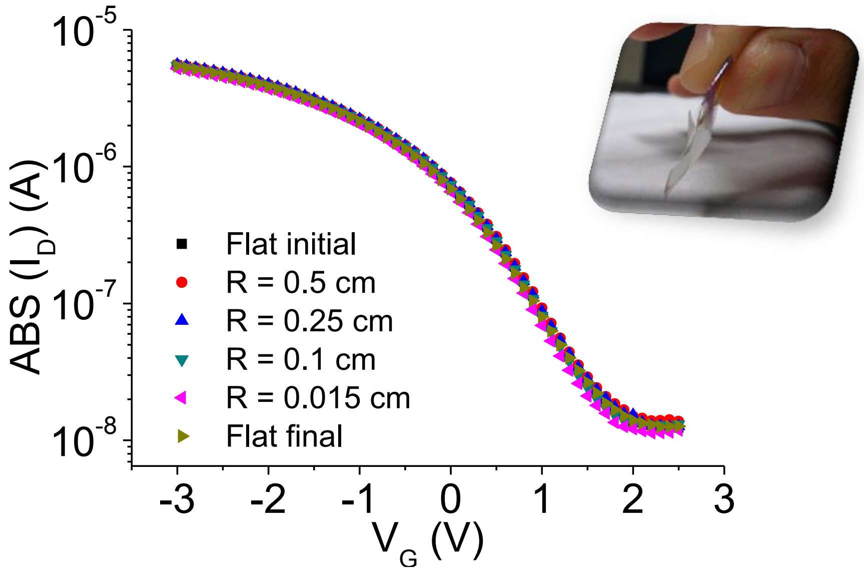


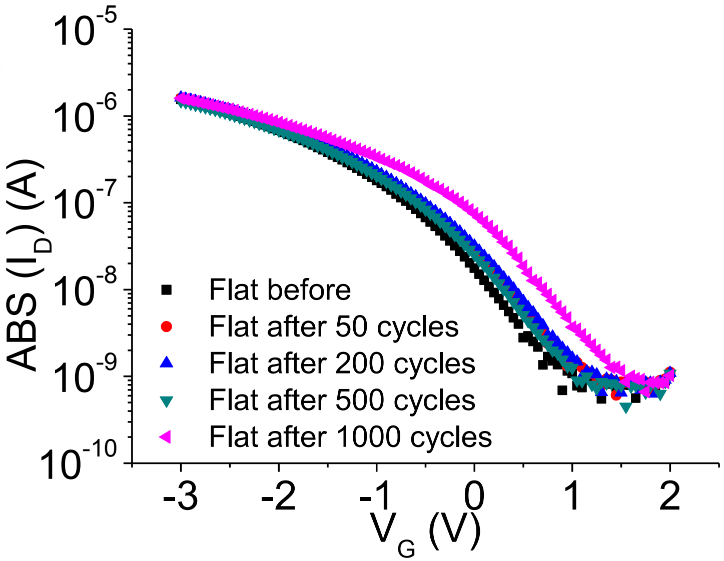
- **Devices are fabricated on freestanding thin films with thickness down to 400 nm**
- **Electrical performances are not affected by mechanical deformation**
- **Substrate thickness: 400nm vs 175µm → much lower surface strain for the same applied bending radius**



S. Selvarasah et al. , Sensors and Actuators A 145 (2008) 306

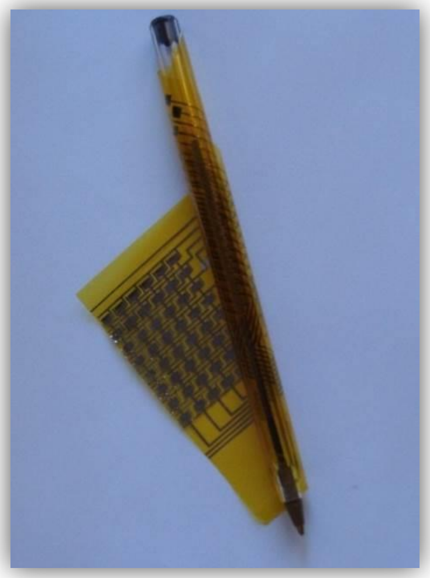
Highly flexible low voltage OTFTs





The devices were fabricated on highly flexible Kapton and PET substrates (nominal thickness from 1 to 10 um)

- Devices can be bent down to R=150 um
- Mechanical stress tests at the smallest R show a remarkable mechanical robustness



Tattoo-like electronics

- ✓Deposition of ultrathin, submicrometer, Parylene C films
- ✓Processing of the OTFTs
- ✓After deposition the film can be peeled off