OFETs as physical sensors

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Ph.D. Course – Bioengineering and robotics (XXX cycle)

Outline

What is a physical sensor?

Organic technology VS Inorganic technology

Temperature and force sensor

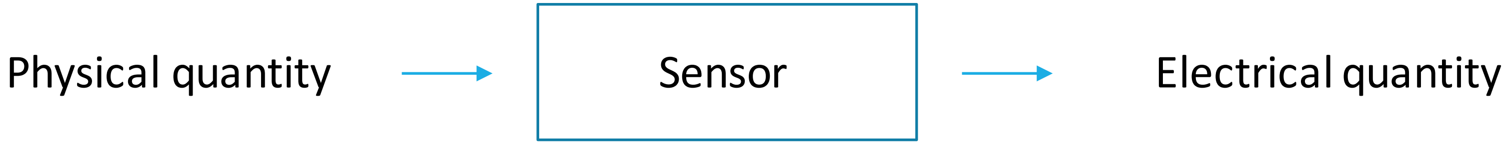
OFETs as physical sensors

Organic Charge Modulated FET (OCMFET)

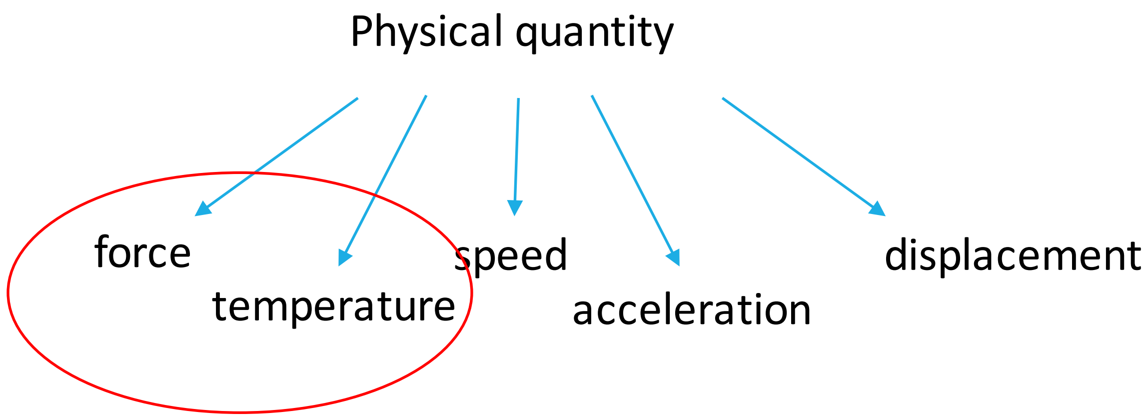
OCMFETs as physical sensors

What is a physical sensor?

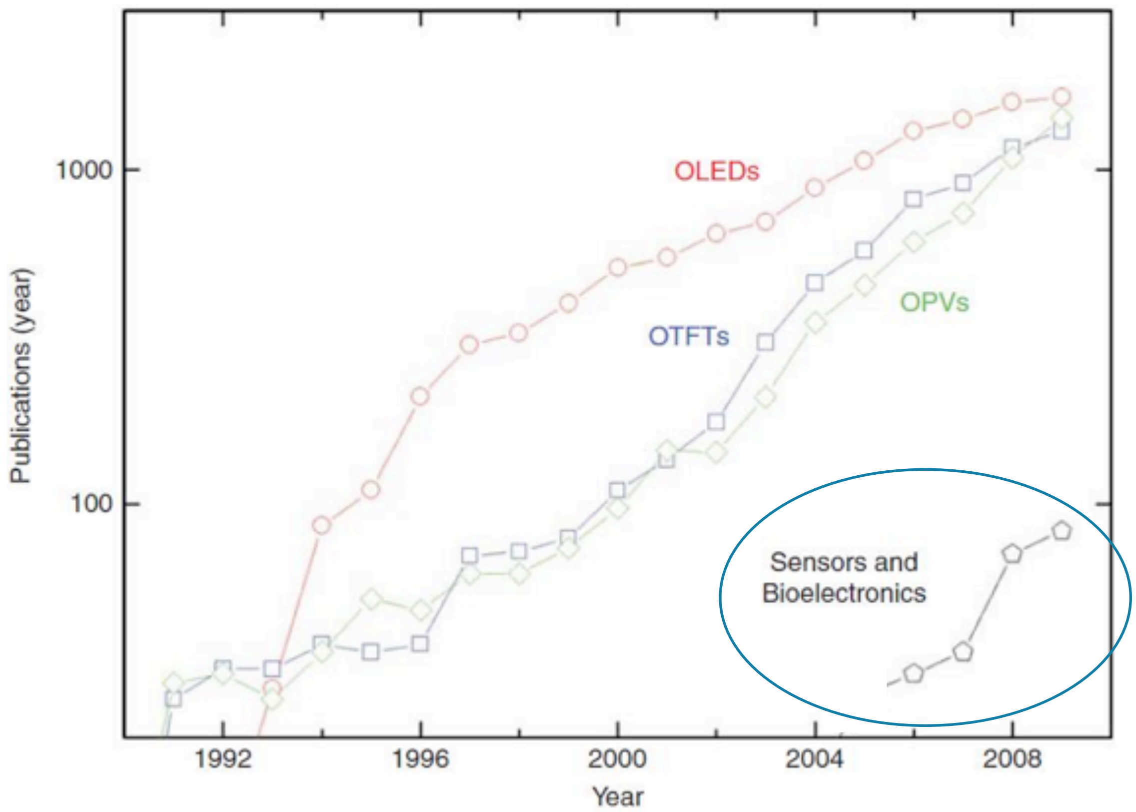
- A sensor is a part of a Measurement System whose purpose is to detect events and convert them into signals which can be read by an observer or an instrument



What is a physical sensor?



Temperature and force sensors



Organic technology VS Inorganic technology

ORGANIC:

- Fabrication process @ low temperature
- Low cost
- Thin and flexible films
- Tunable electrical properties

INORGANIC:

- High performances
- High reproducibility
- Stability in ambient condition
- High integration

Temperature and force sensors

- Depending on the transduction mechanism we can divide Physical Sensor into different categories:

Optoelectric sensors

Capacitive sensors

Piezo/Pyroelectric sensors

Resistance sensors

Inductive sensors

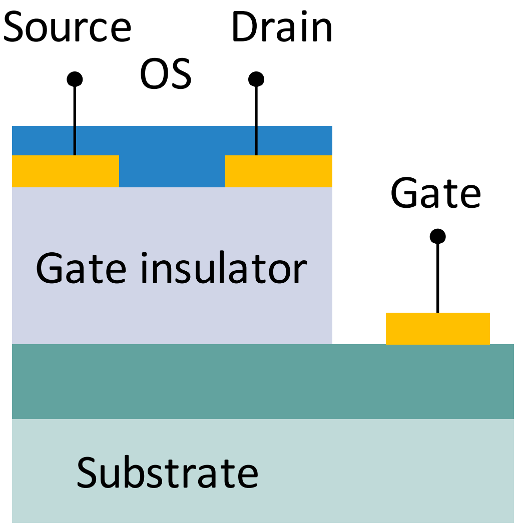
Temperature and force sensor

Transduction technique	Modulated parameter	Advantages	Disadvantages
Capacitive	Change in capacitance	Excellent sensitivity Good spatial resolution Large dynamic range	Stray capacitance Noise susceptible Complexity of measurement electronics
Piezoresistive	Changed in resistance	High spatial resolution High scanning rate in mesh Structured sensors	Lower repeatability Hysteresis Higher power consumption
Piezoelectric	Strain (stress) polarization	High frequency response High sensitivity High dynamic range	Poor spatial resolution Dynamic sensing only
Inductive LVDT	Change in magnetic coupling	Linear output Uni-directional measurement High dynamic range	Moving parts Low spatial resolution Bulky Poor reliability More suitable for force/torque measurement applications
Optoelectric	Light intensity/spectrum change	Good sensing range Good reliability High repeatability High spatial resolution Immunity from EMI	Bulky in size Non-conformable

[1] Tiwana et al. *Sensors and Actuators A 179, (2012) 17-31*

OFET as physical sensor

It's a three terminal structure, in which a voltage applied to the gate can affect the current flowing between source and drain electrodes (when a V_{DS} is applied)



$$I_{DS} = f(\mu, C_{ins}, W, L, V_{GS}, V_{DS}, V_{th}, R_C)$$

Advantages

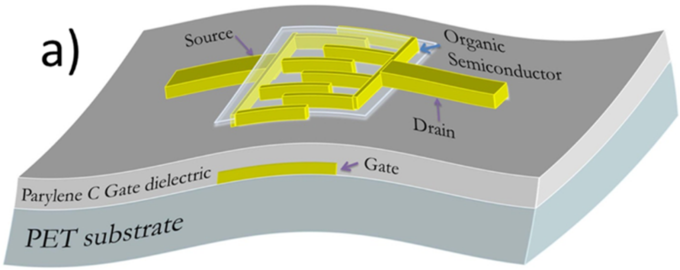
- Low power dissipation
- Local amplification
- Multiparameter device

OFET as physical sensor

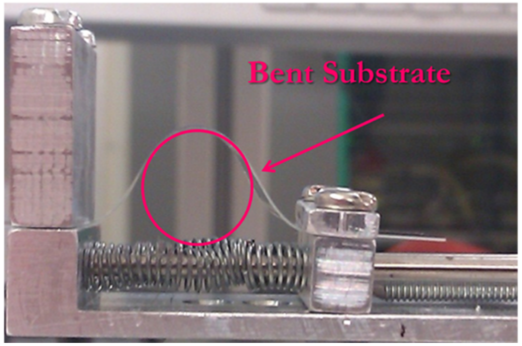
$$Strain = \left(\frac{d_l + d_s}{2 * R}\right)\frac{(1 + 2\eta + \chi\eta^2)}{(1 + \eta)(1 + \chi\eta)}$$

$$Strain \sim \left(\frac{d_s}{2 * R}\right)$$

a)

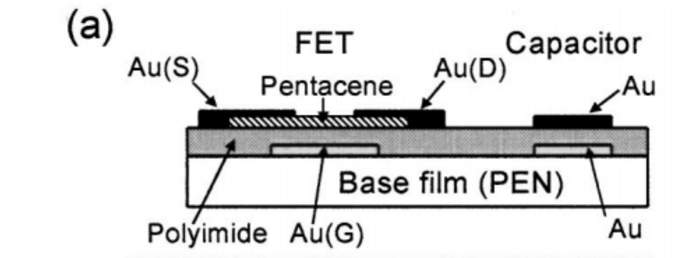


b)



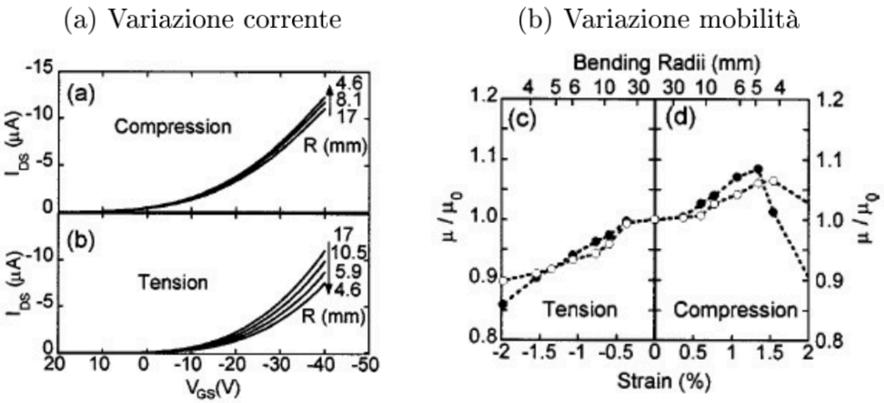
In which d_l and d_s are the thicknesses of the layer and of the substrate respectively, η is d_l/d_s, χ is the ratio between the Young moduli of the layer and of substrate ($\chi = Y_l/Y_s$) and R is the bending radius

OFET as physical sensor



Applying a tensile (compressive) stress a decrease (increase) in I_{DS} was observed

This phenomenon can be attributed to a variation of the active layer morphological and/or structural properties of the semiconductor film

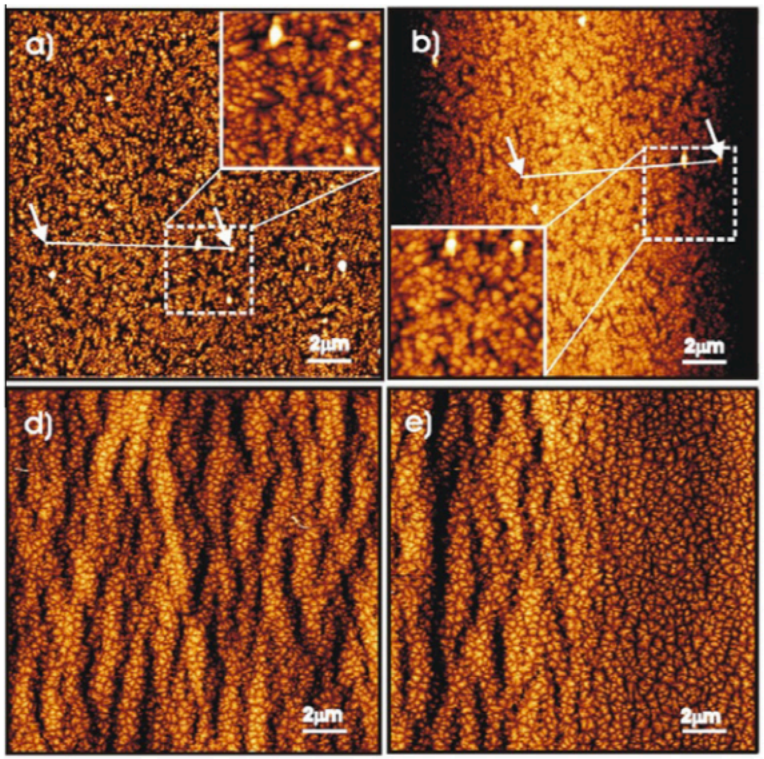


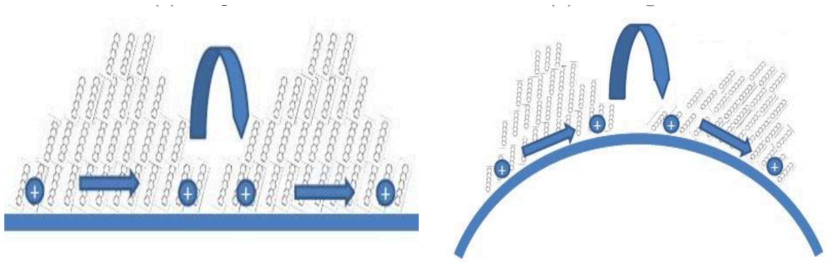
$$\mu \sim \mu_0 \exp\left(\frac{-\Delta E}{k_B T}\right)$$

$$\Delta E \propto -k_B T \, ln(1 + 0.05\epsilon)$$

[2] Sekitani et al. Appl. Phys. Lett. 86, 073511 (2005)

OFET as physical sensor



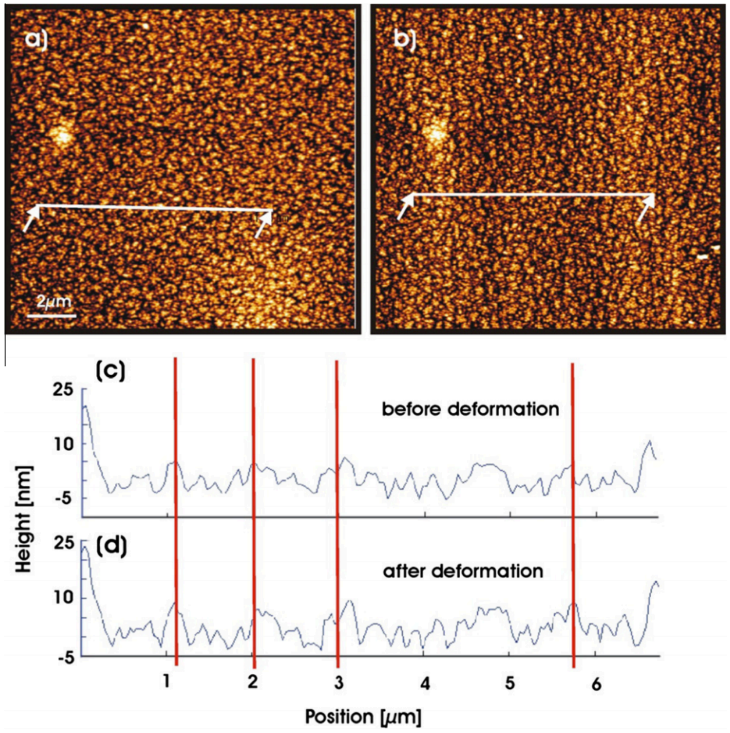


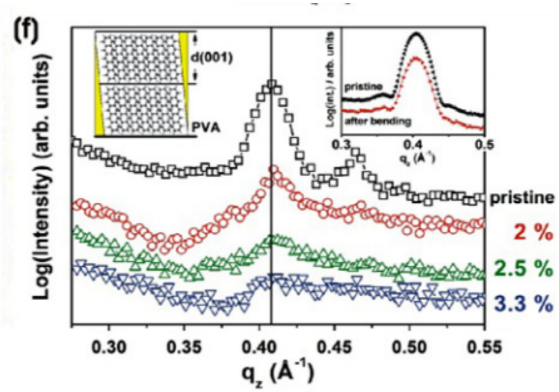
Response is more related to MORPHOLOGICAL CHANGES

Strains larger than 2% cause the formation of cracks within the gold electrodes on top of Pentacene film

[3] Scenev et al. Org. Electr. 14, (2013)

OFET as physical sensor



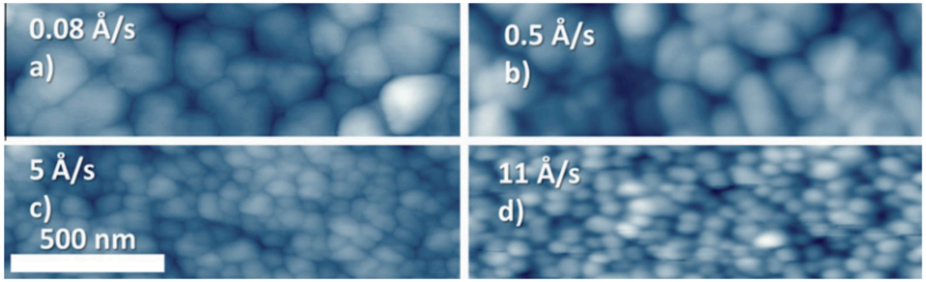


Reversible deformation up to 10% occurs for Pentacene on PVA substrates

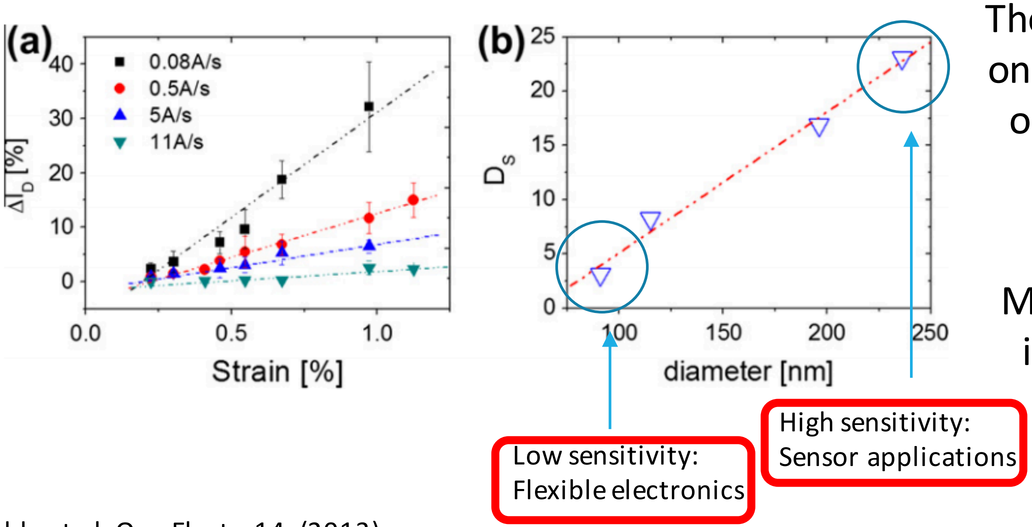
Tensile stress leaves the crystal structure unaffected: no phase transitions were observed

[4] Scenev et al. Org. Electr. 14, (2013)

OFET as physical sensor



Can morphological properties cause changes in sensitivity of organic semiconductors to mechanical deformations?



The influence of mechanical deformation on the electrical behavior of OTFTs based on Pentacene is strongly related to the morphological properties

Modulating the Pentacene morphology, it is possible to tune the sensitivity to surface strain in a predictable way

[4] Cosseddu et al. Org. Electr. 14, (2013)

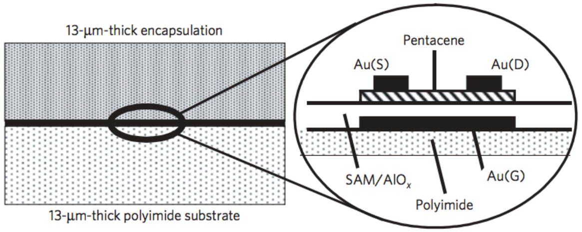
OFET as physical sensor

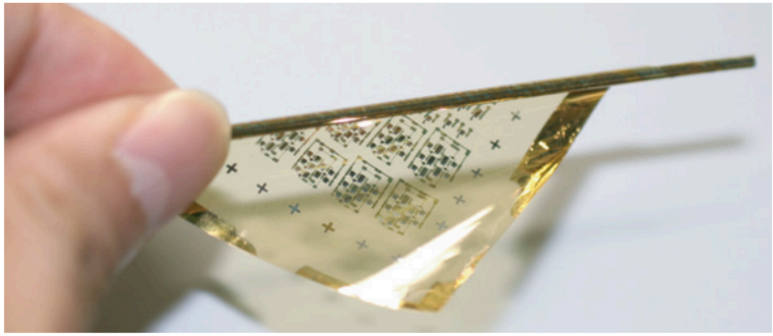
Strains larger than 2% cause the formation of cracks within the gold electrodes on top of Pentacene film

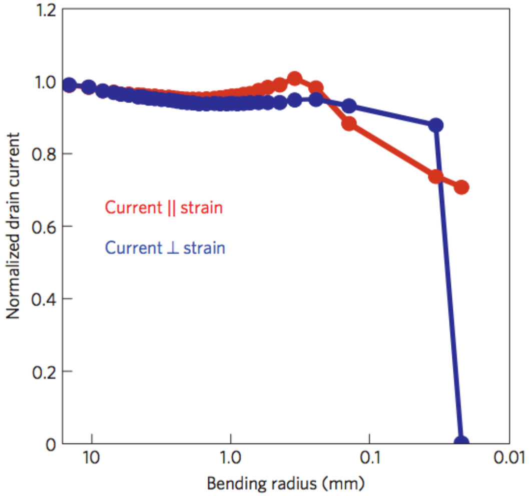
Solutions?

- Using conductive polymers es. PEDOT:PSS
- Neutral strain position
- Thin substrates

OFET as physical sensor







TFTs and circuits are located in the neutral strain position (where bending induced compressive and tensile strain cancel each other)

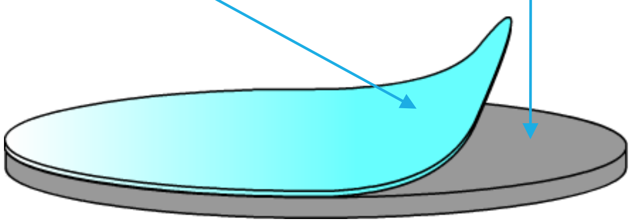
The devices into the neutral strain position operate reliably and with excellent performance characteristics while being folded into a bending radius as small as 100 μm

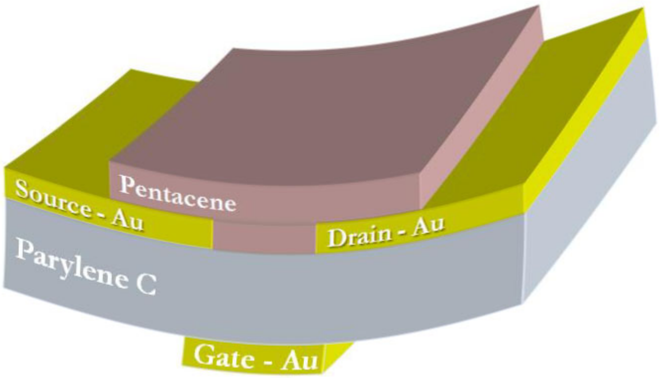
[5] Sekitani et al. Nat. Mater. 9, 1015 (2010)

OFET as physical sensor

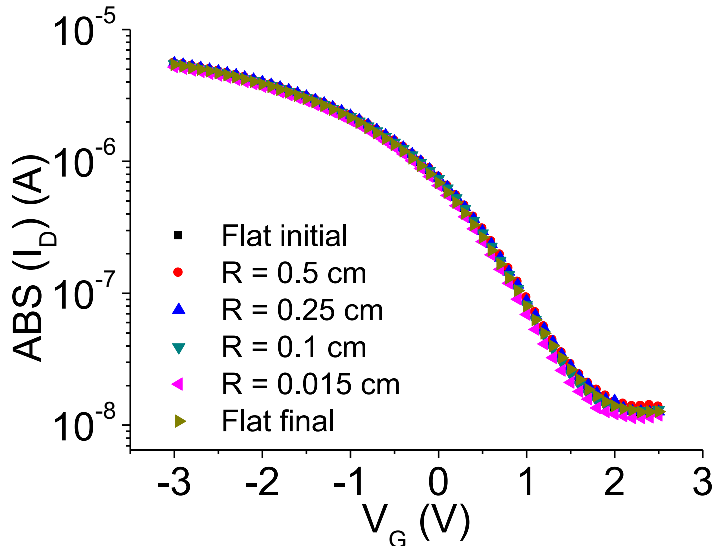
$$Strain \sim \left(\frac{d_s}{2 * R}\right)$$

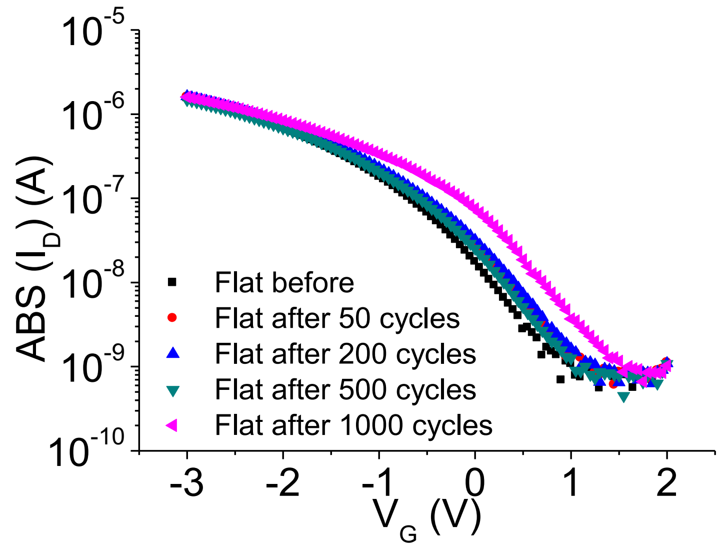
Surface strain depends on the bending radius, but also on the substrate thickness!!!





OFET as physical sensor

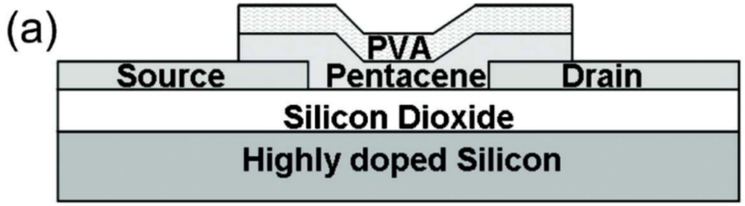


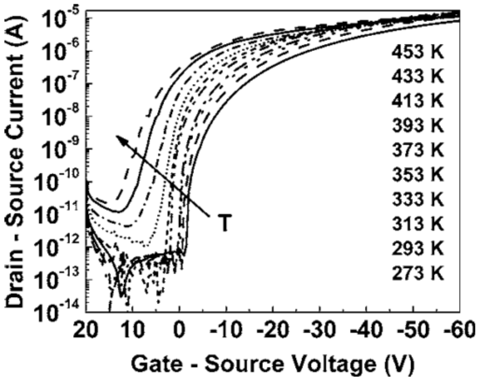


Substrate thickness: 400nm vs 175µm much lower surface strain for the same applied bending radius

Electrical performances are not affected by mechanical deformation

OFET as physical sensor





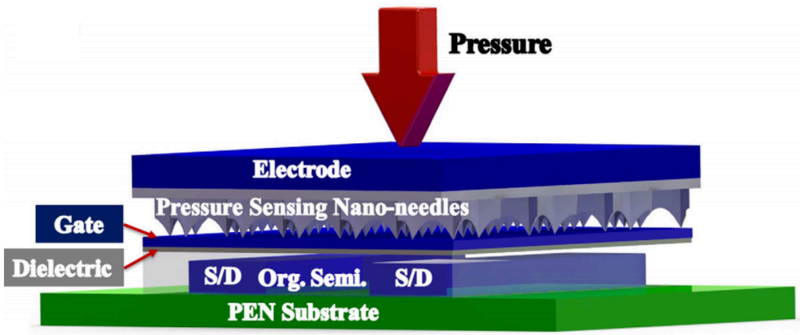
$$\mu \sim \mu_0 \exp\left(\frac{-\Delta E}{k_B T}\right)$$

The variation in the subthreshold drain current can be employed as a temperature sensing operation mode

The saturation current shows very little change compared to the subthreshold current

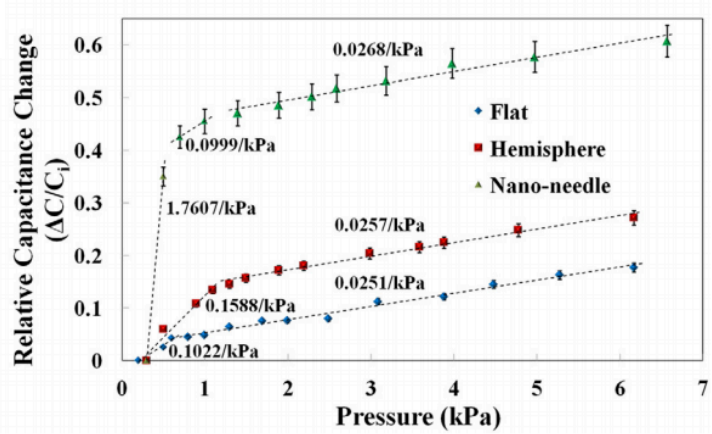
[6] Jung et al. Appl. Phys. Lett. 90, 062105 (2007)

OFET as physical sensor



The capacitive pressure sensor was integrated with printed organic thin film transistors to enable flexible, large-area tactile sensing applications

The pressure sensitivity of the sensor, in the low pressure range (<1kPa), is comparable to the sensitivity of human skin

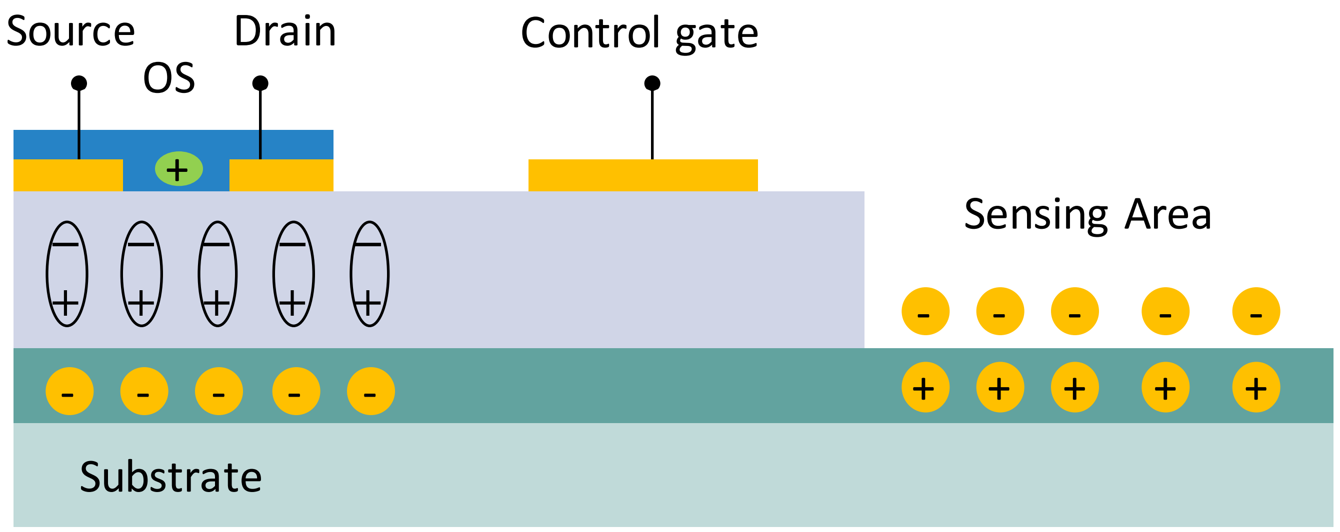


Depending on the type of dielectric it's possible to change the sensitivity

[7] Kim et al. Appl. Phys. Lett. 101, 103308 (2012)

From OFET to OCMFET

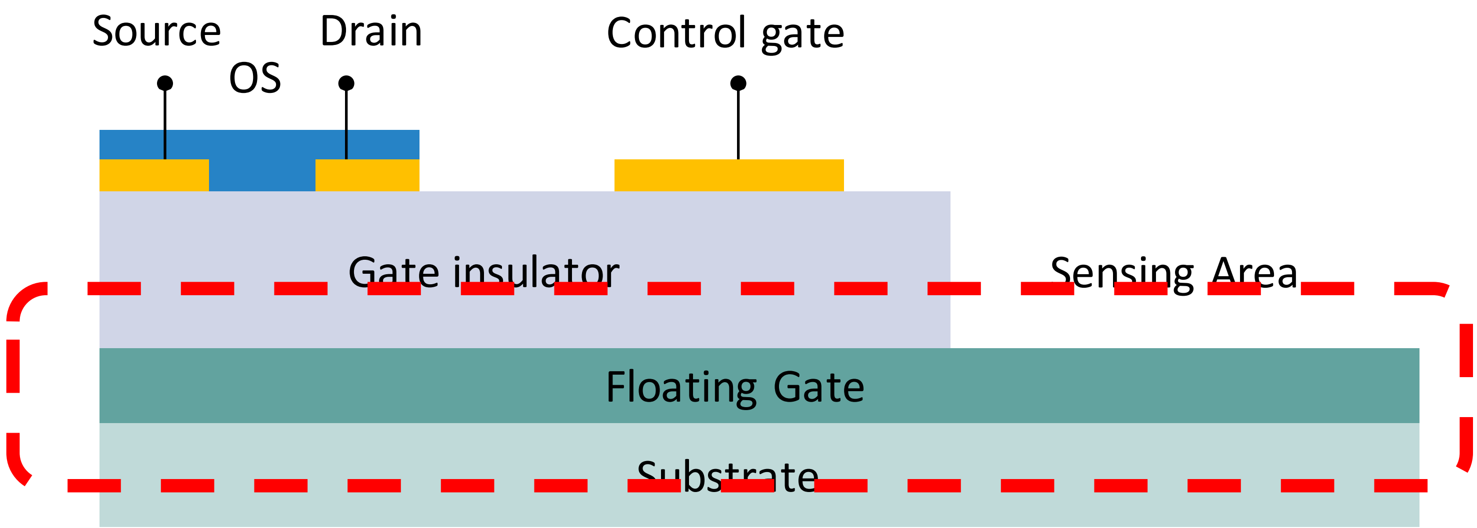
Is a floating-gate transistor, biased through a control capacitor, that is used as a charge sensor



Organic Charge Modulated FET (OCMFET) – Working principle

$$Q_F = C_{CF}(V_F - V_C) + C_{SF}V_F + C_{DF}(V_F - V_D) + Q_I$$

$$V_F(C_{CF} + C_{SF} + C_{DF}) = (Q_F - Q_I) + C_{CF}V_C + C_{DF}V_D$$



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$$V_F(C_{CF} + C_{SF} + C_{DF}) = (Q_F - Q_I) + C_{CF}V_C + C_{DF}V_D$$

$$V_F = +\frac{C_{CF}V_C}{C_{TOT}} + \frac{C_{DF}V_D}{C_{TOT}} + \frac{(Q_F - Q_I)}{C_{TOT}}$$

$$\boxed{V_F - V_{TH}} = V_C + \frac{C_{DF}V_D}{C_{TOT}} + \frac{(Q_F - Q_I)}{C_{TOT}} - V_{TH} = \boxed{V_C - V_{THF}}$$

$$V_C - V_{THF} \simeq V_C - \left(V_{TH} - \frac{C_{DF}V_D}{C_{TOT}} + \frac{(Q_F - Q_I)}{C_{TOT}}\right)$$

$$V_{THF} = V_{TH} - \frac{C_{DF}}{C_{TOT}}V_D - \frac{Q_F}{C_{TOT}} + \frac{Q_I}{C_{TOT}}$$

Organic Charge Modulated FET (OCMFET) – Working principle

The shift of the effective threshold voltage depends on the charge, accumulated on the FG, and the total capacitance of the structure

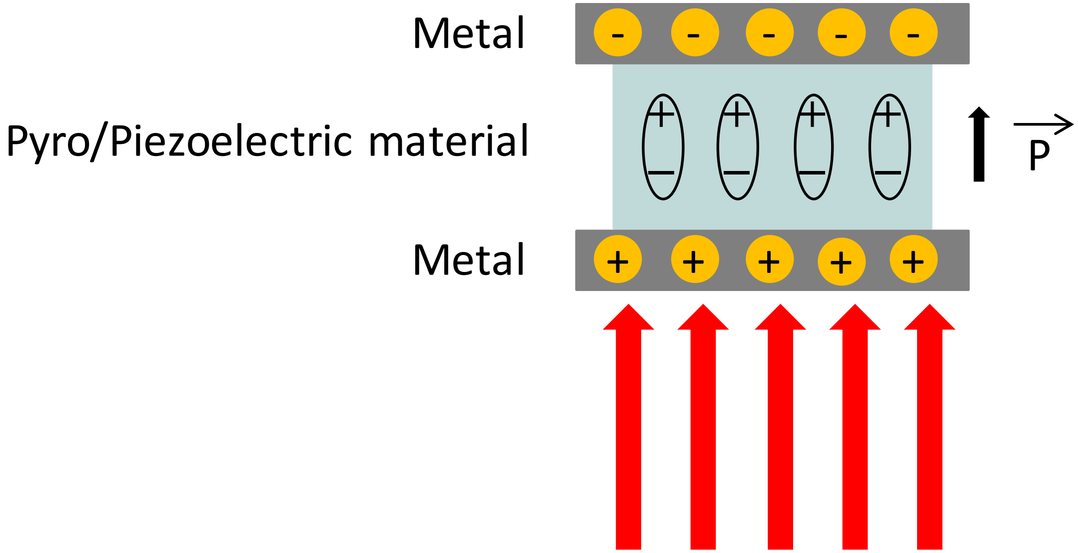
$$\Delta V_{TH} = -\frac{\Delta Q}{C_{TOT}}$$

→

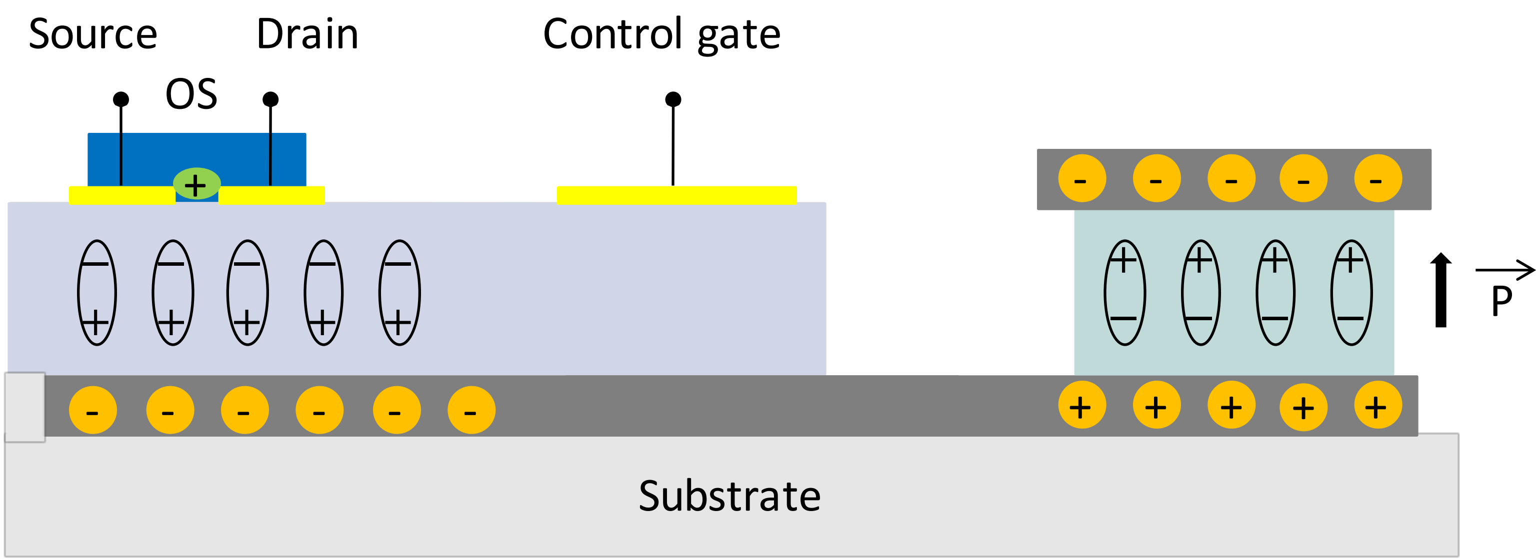
- Bio-chemical reactions
- Using sensible materials

OCMFET as physical sensor

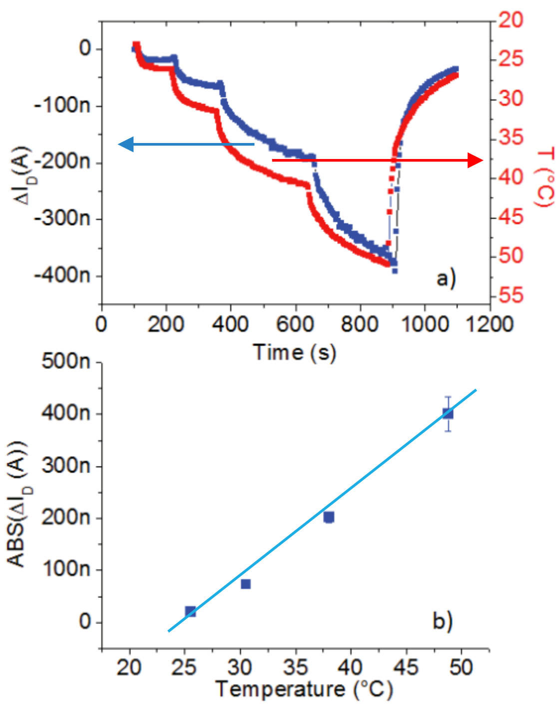
A temperature variation (or an applied force) induces a charge separation in the pyro/piezoelectric material

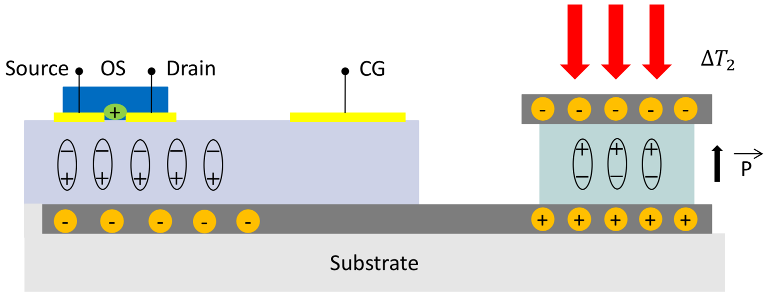


OCMFET as physical sensor



OCMFET as physical sensor

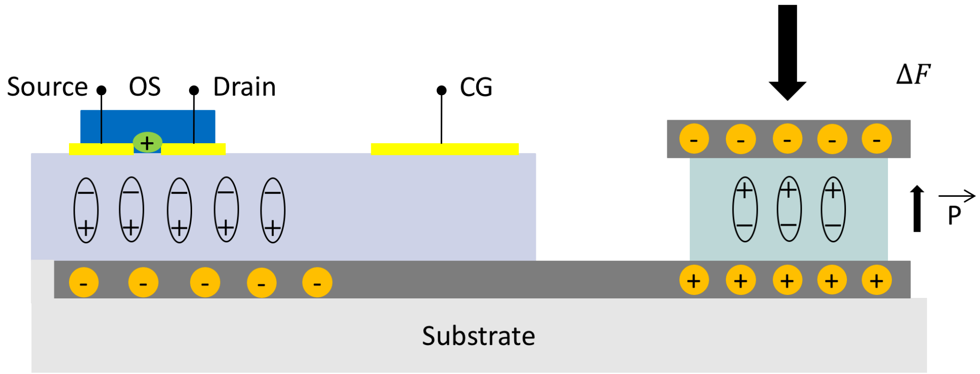


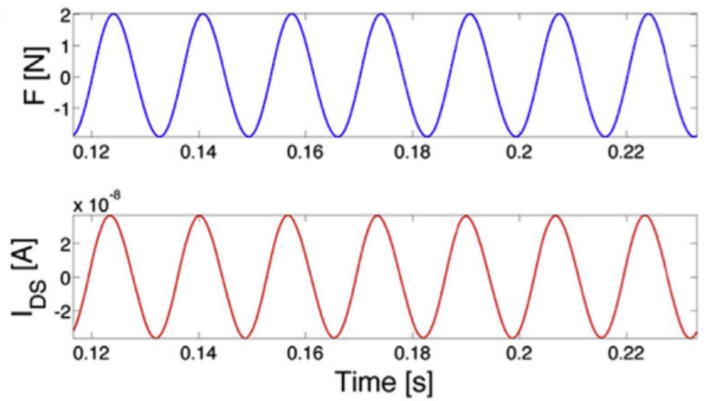


- Good reproducibility
- Quasi-linear response

[8] F. Viola et al. PRIME 2015, pp. 278-281

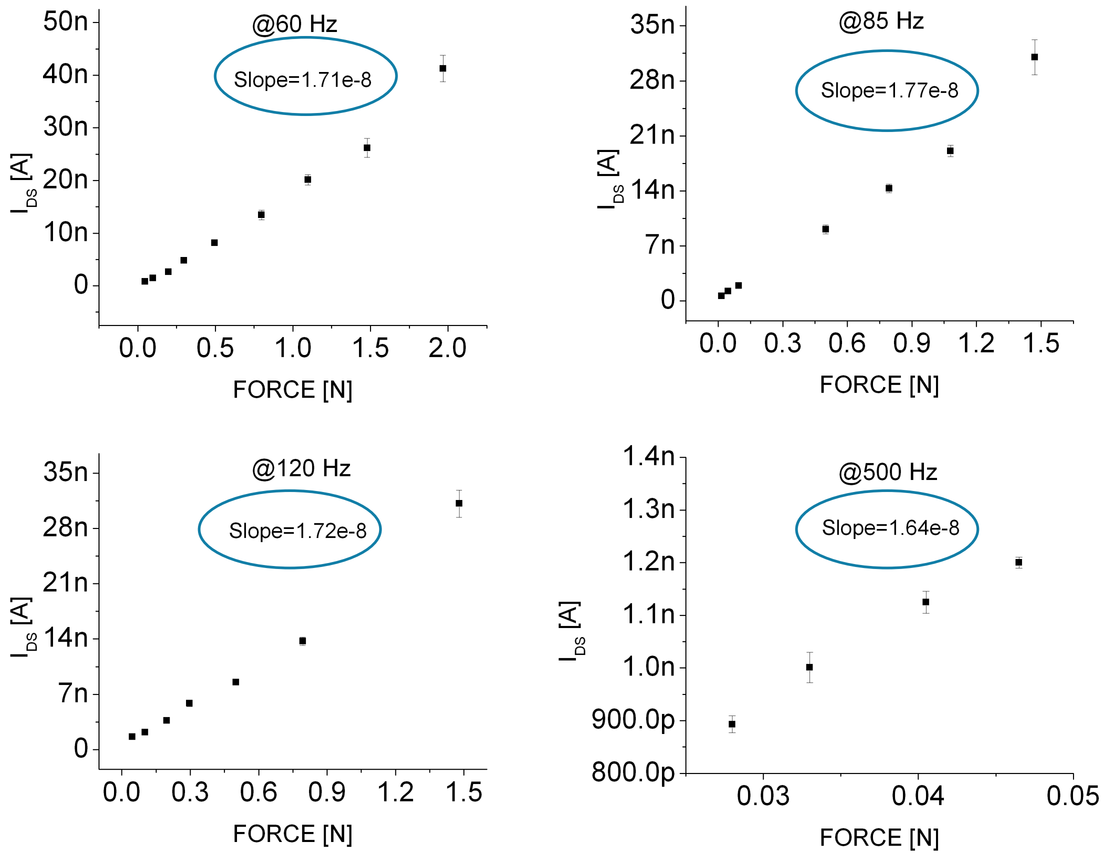
OCMFET as physical sensor





[9] A. Spanu, F. Viola et al. Organic Electronics 36 (2016)

OCMFET as physical sensor

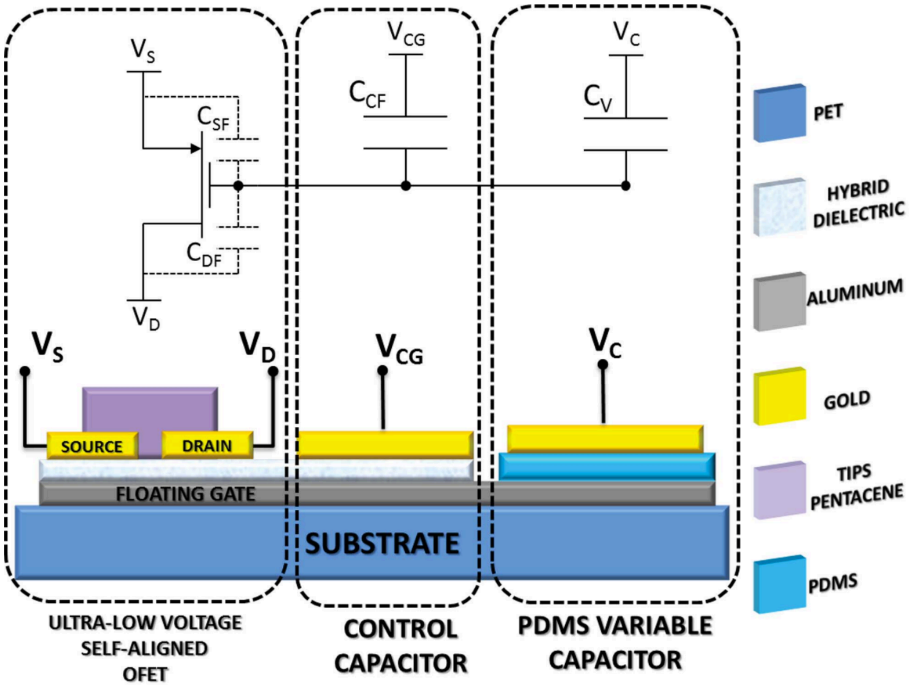


- Linear behaviour
- Reproducible response
- Constant sensitivity
- Hight resolution

(low than 20 mN)

[9] A. Spanu, F. Viola et al. Organic Electronics 36 (2016)

Pressure-Modulated FET PMOFET



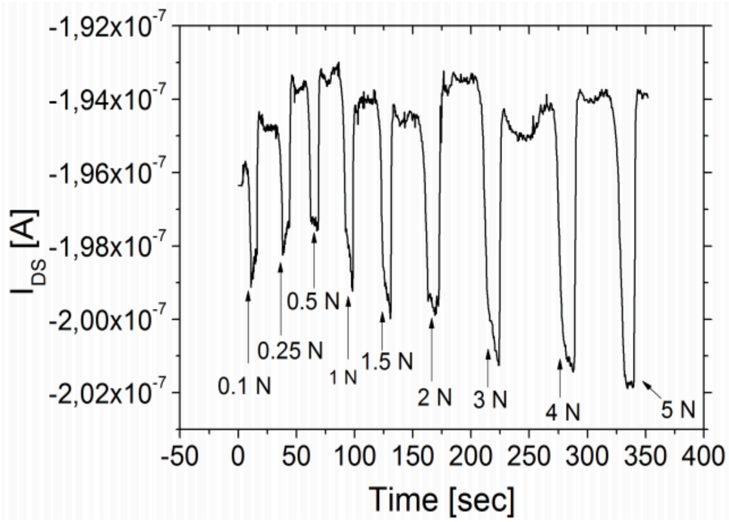
$$V_{FG} = \frac{C_{CF}}{C_{SUM}} V_{CG} + \frac{C_V}{C_{SUM}} V_C + \frac{Q_0}{C_{SUM}}$$

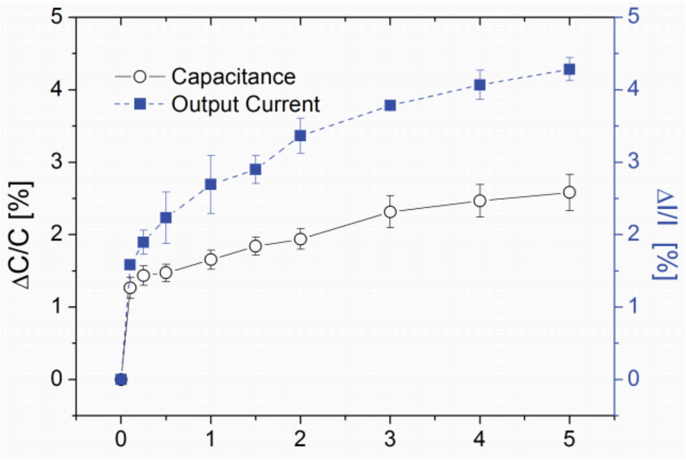
$$I_{DS} = k[(V_{FG} - V_{TH})V_{DS} - 0.5(V_{DS})^2]$$

[10] S. Lai et al. IEEE EDL vol.6 (2013)

Pressure-Modulated FET
PMOFET

Experimental results:





[10] S. Lai et al. IEEE EDL vol.6 (2013)

Thanks for your kind attention