OFET-based sensors

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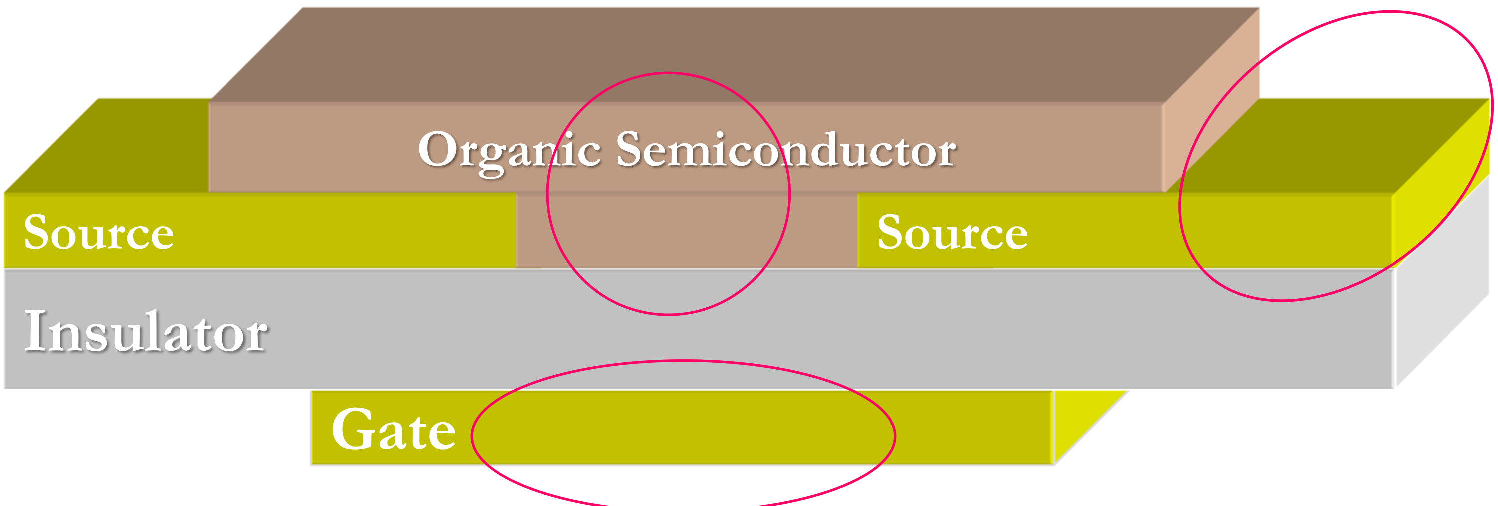
FET based sensors

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-based mechanical sensors

Strain effects on OTFTs

Flexible substrate:

PET, PEN, Kapton

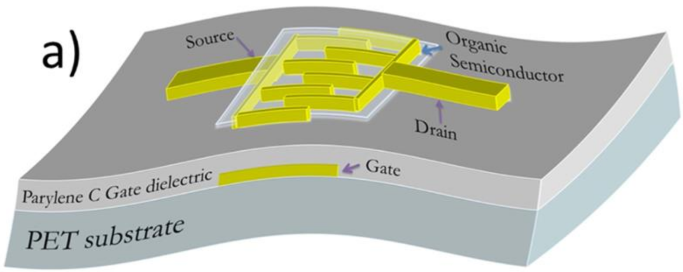
Gate dielectric:

Parylene C, PVA, PVP etc.

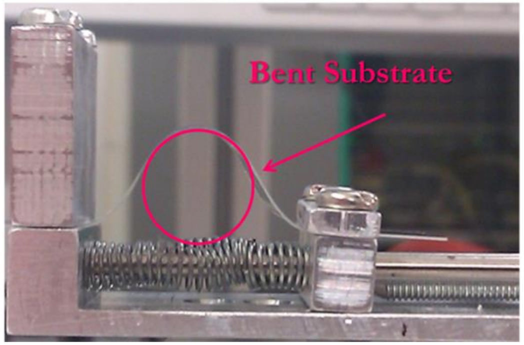
Organic Semiconductors:

- P3HT
- Pentacene *(different morphologies)*

a)



b)

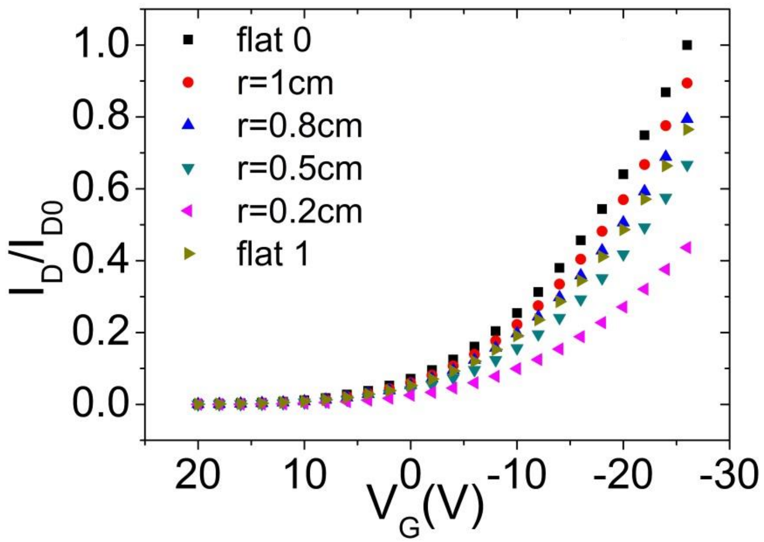


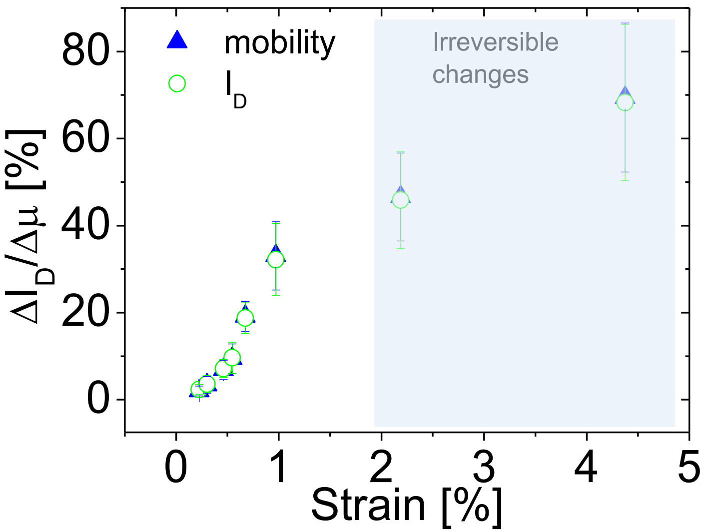
$$Strain = \left(\frac{d_f + d_s}{2*R}\right)\frac{\left(1+2\eta+\chi\eta^2\right)}{(1+\eta)(1+\chi\eta)} \Rightarrow Strain = \left(\frac{d_f}{2*R}\right)$$

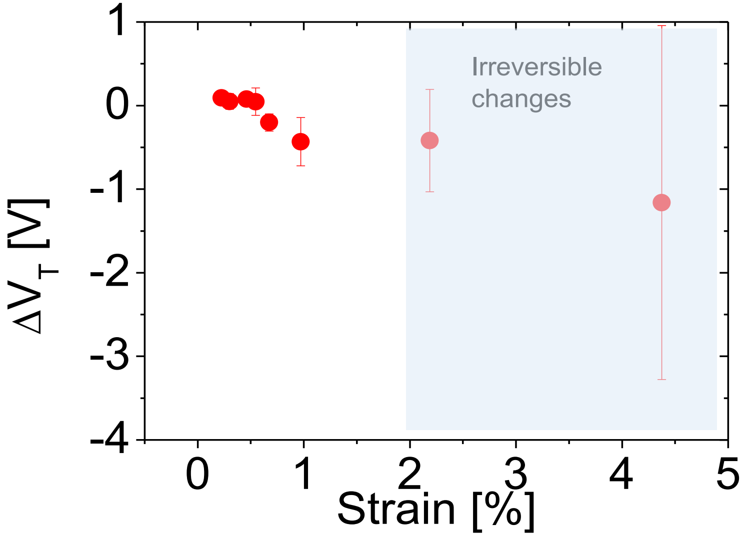
In which d_l and d_s are the thicknesses of the layer and of the substrate respectively, η is d_l/d_s, χ is the ratio between the Young moduli of the layer and of substrate ($\chi = Y_l/Y_s$) and R is the bending radius

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

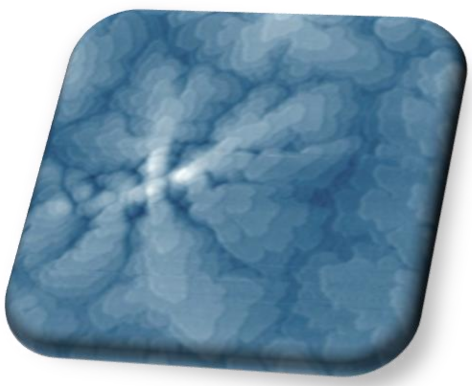


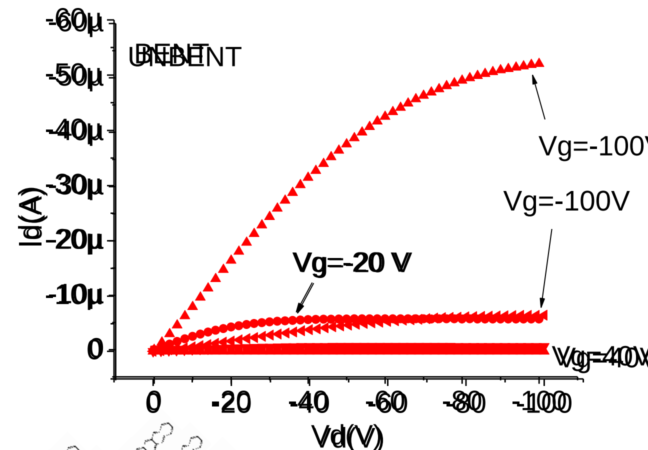


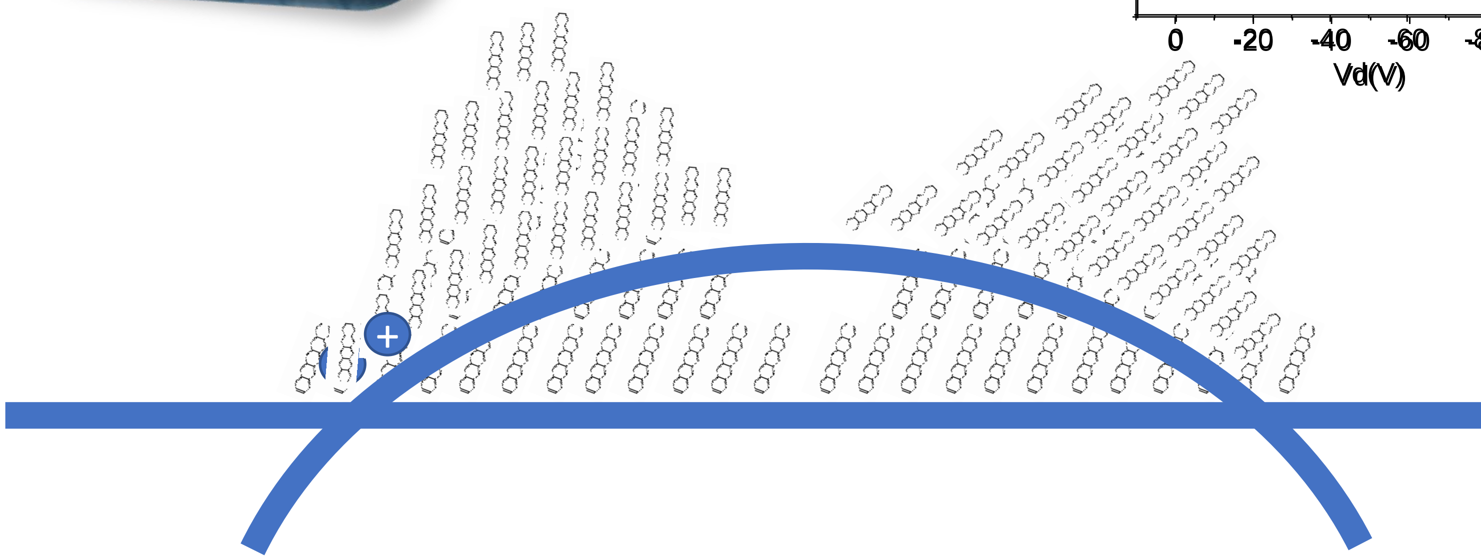


Effect of strain on OTFTs

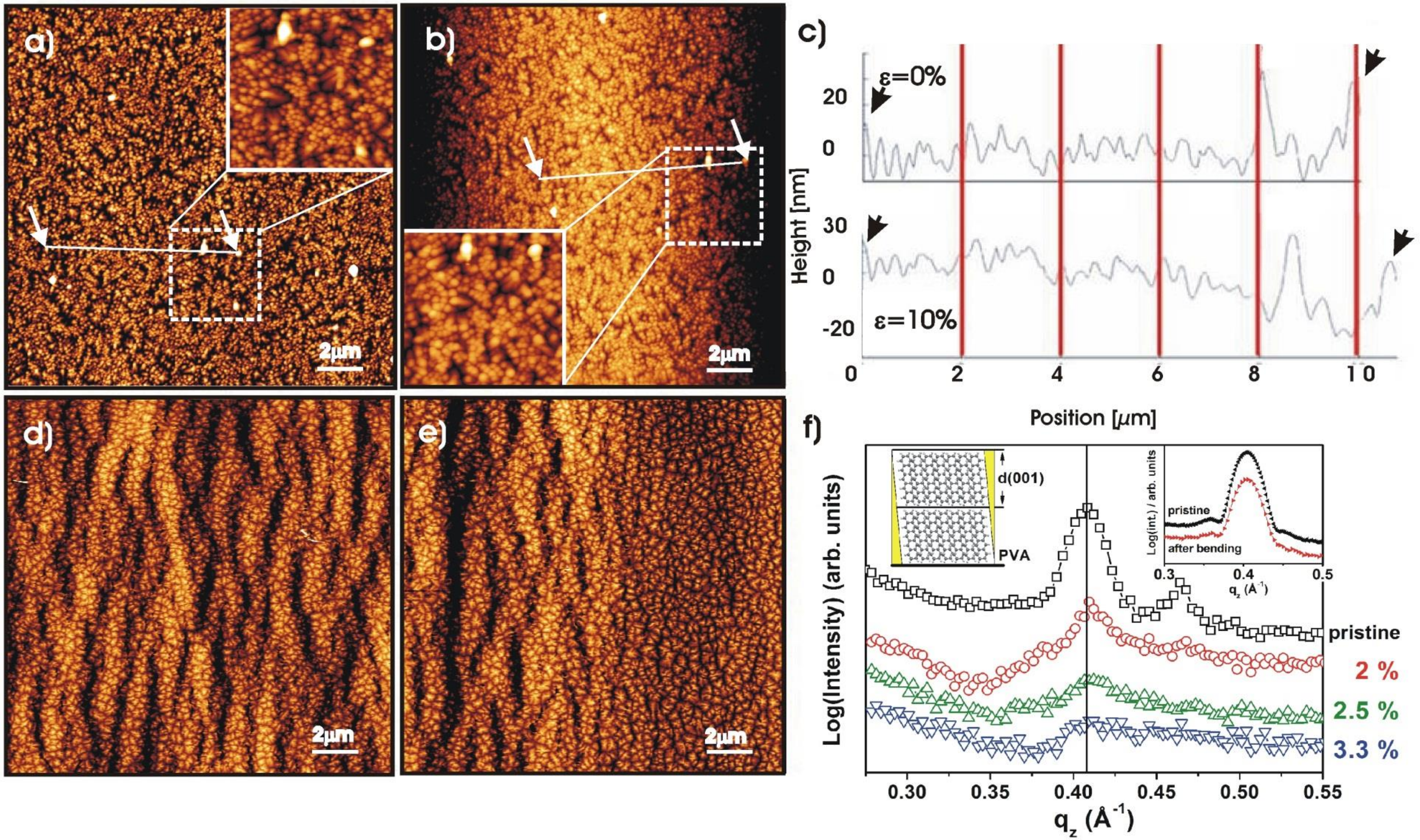
- Mechanical deformation induces morphological changes in the active layer
- Hopping barrier increases → current decreases!







Strain effects on structure and morphology

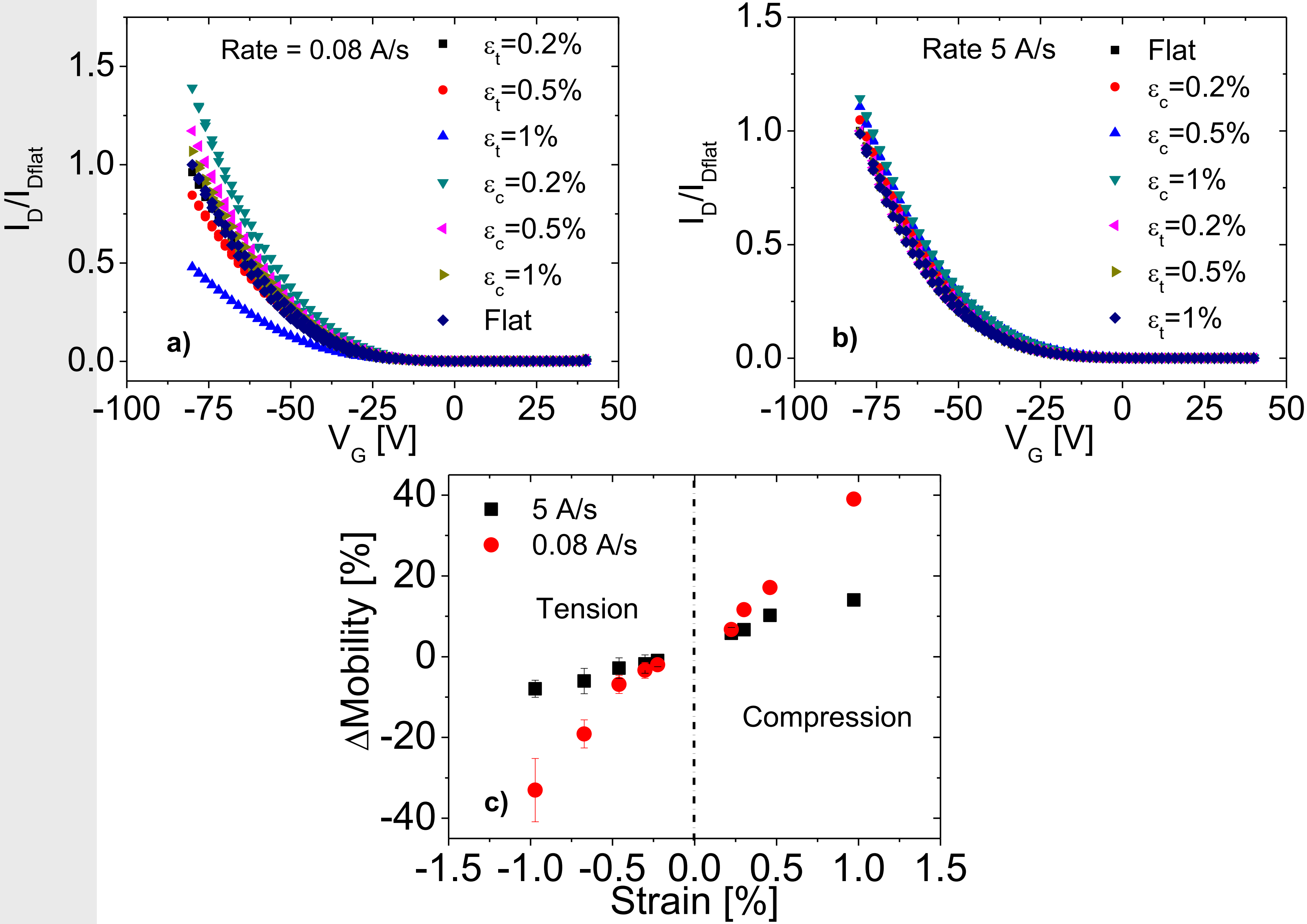


Response is more related to MORPHOLOGICAL CHANGES

Pentacene film properties are not permanently affected by mechanical deformation

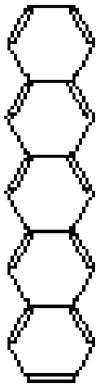
<u>**V. Scenev**</u>, P. Cosseddu, A. Bonfiglio, I. Salzmann, N. Severin, M. Oehzelt, N. Koch, J.P. Rabe, ***Org. Electr. 14, 1323-1329 (2013)***

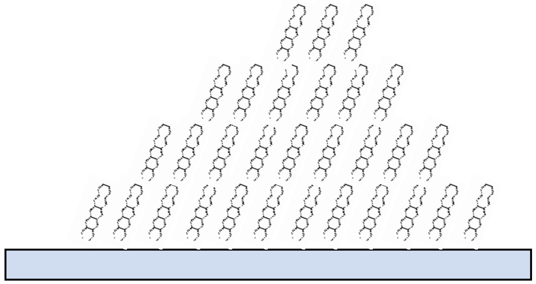
Tension – compression @ different rates



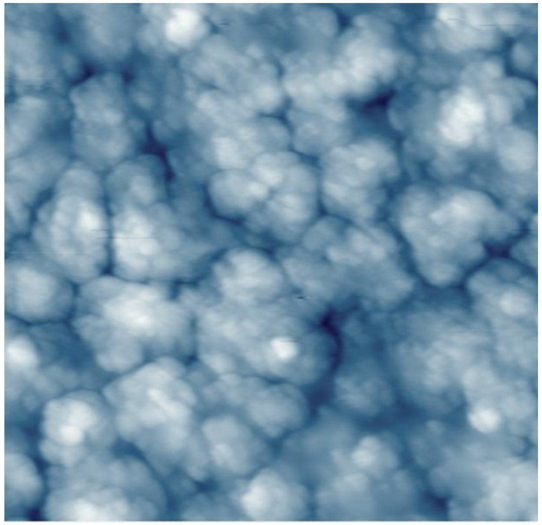
Effect of strain on OTFTs: Pentacene vs P3HT

Pentacene

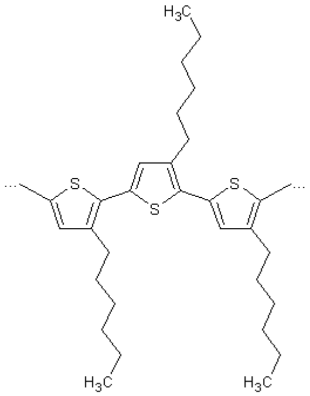


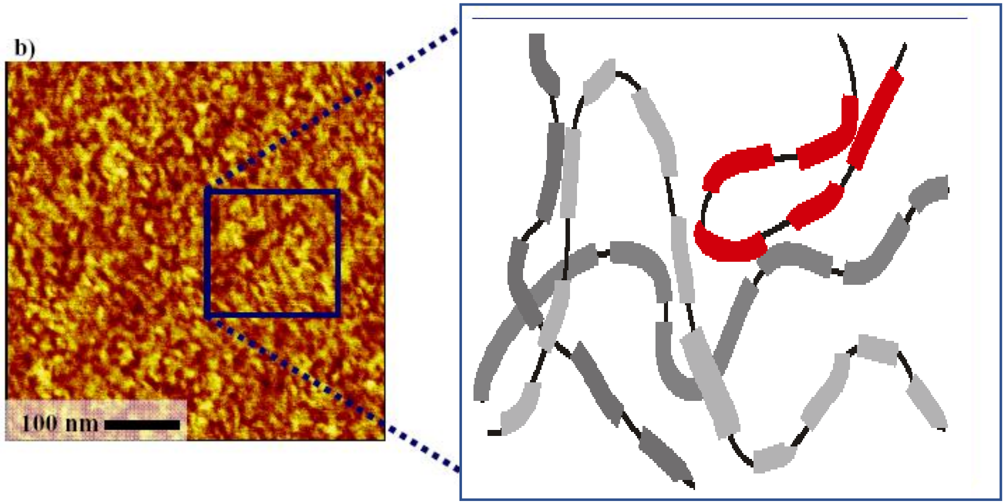


Well ordered even when deposited on "non ideal" plastic substrates



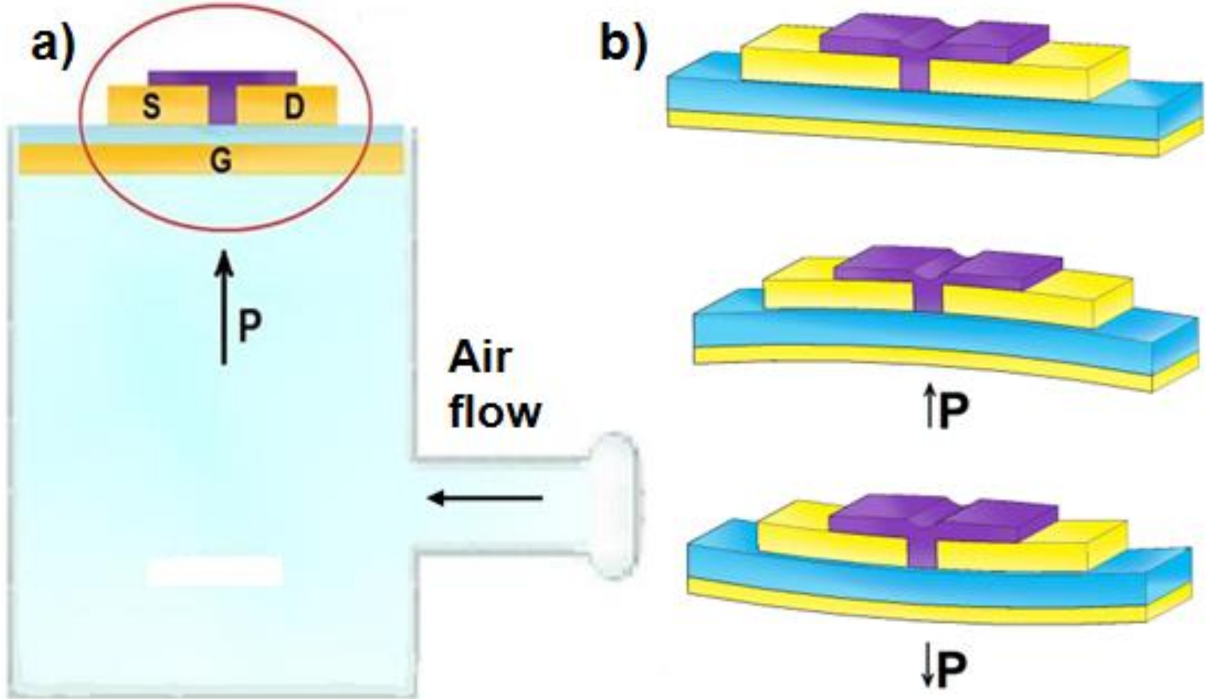
P3HT

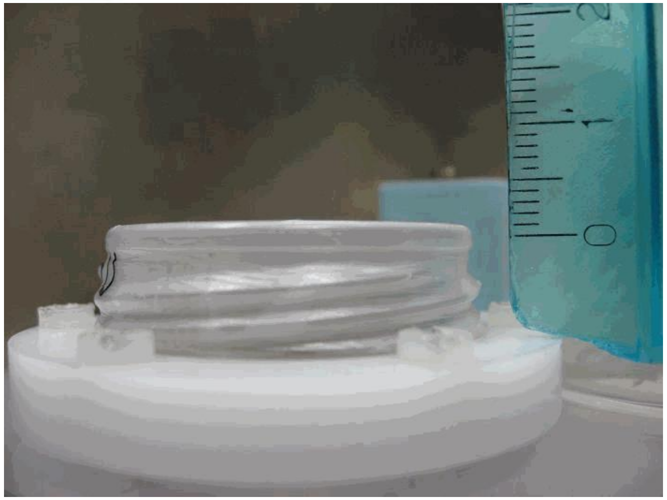




Highly disordered

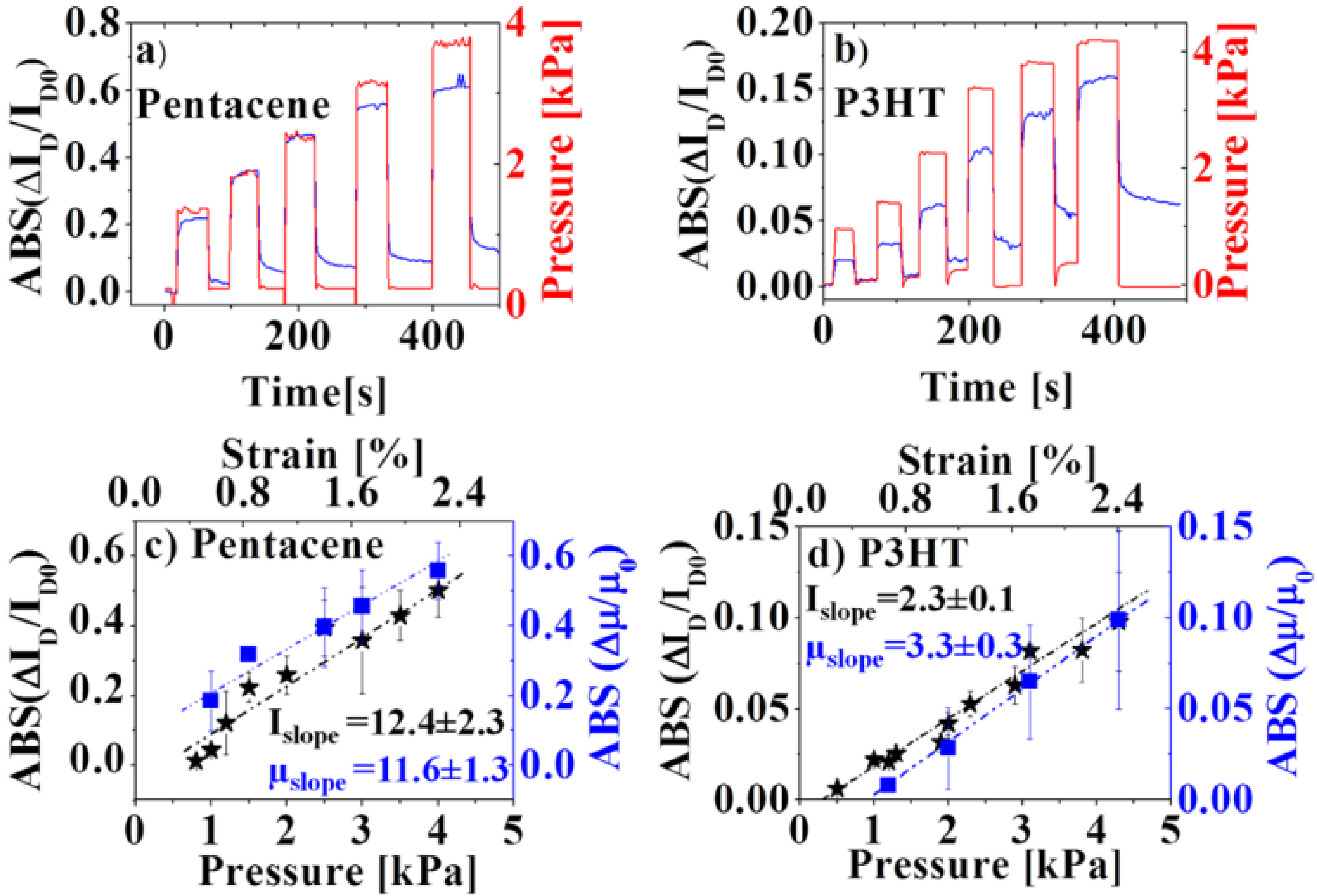
Effect of strain on OTFTs: Pentacene vs P3HT





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

Effect of strain on OTFTs: Pentacene vs P3HT



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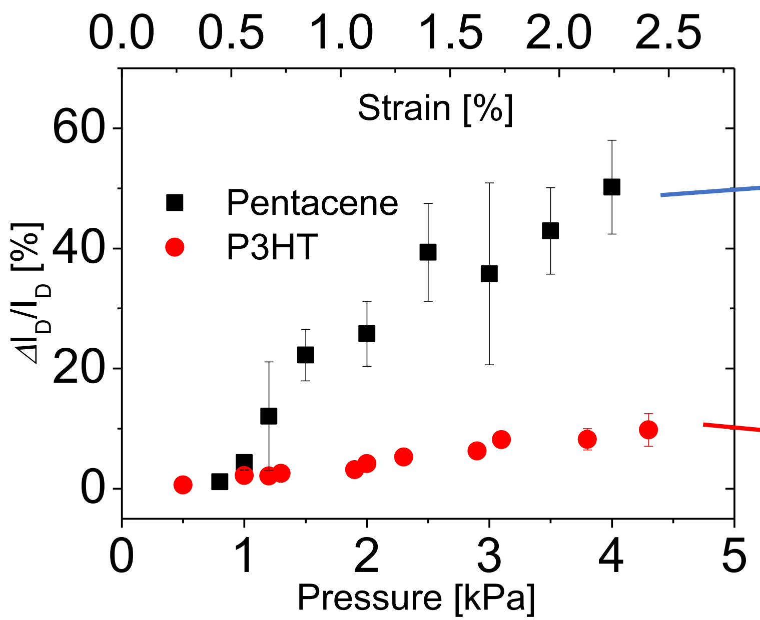
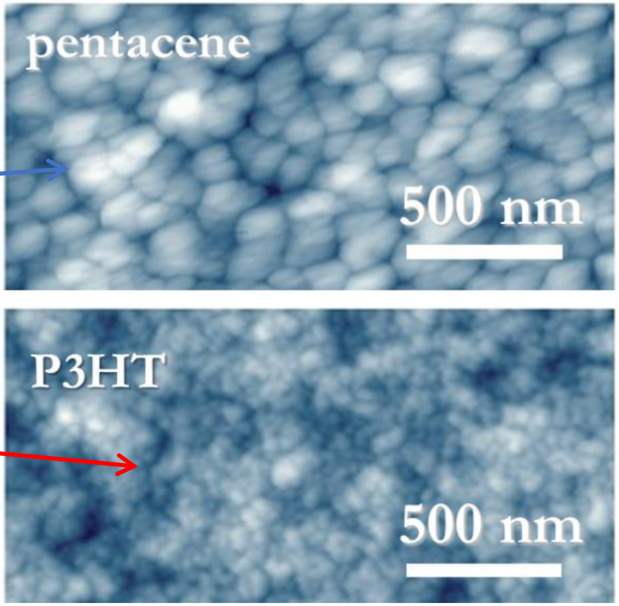
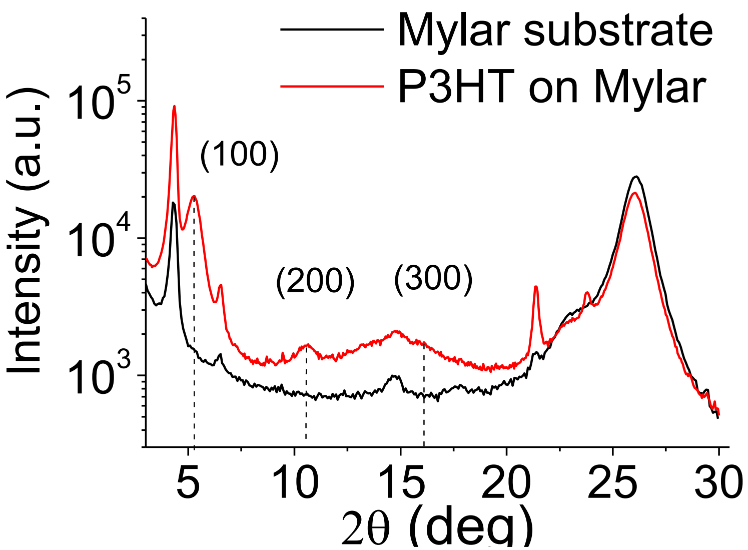
Influence of morphological properties on sensitivity to strain

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**



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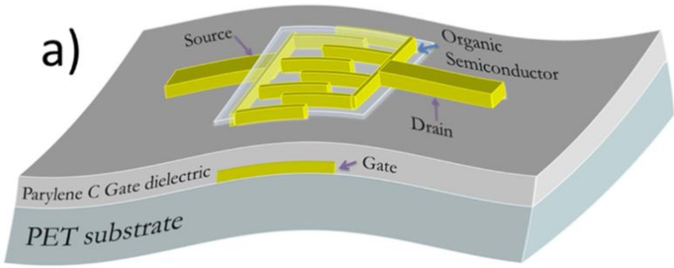
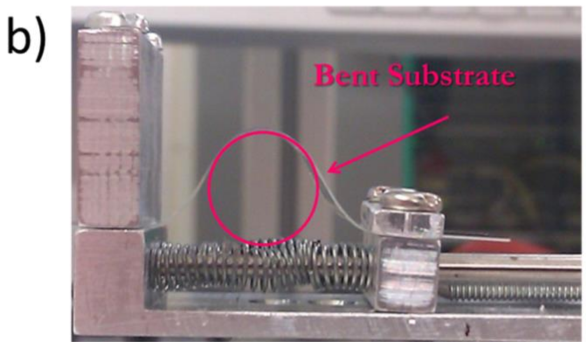
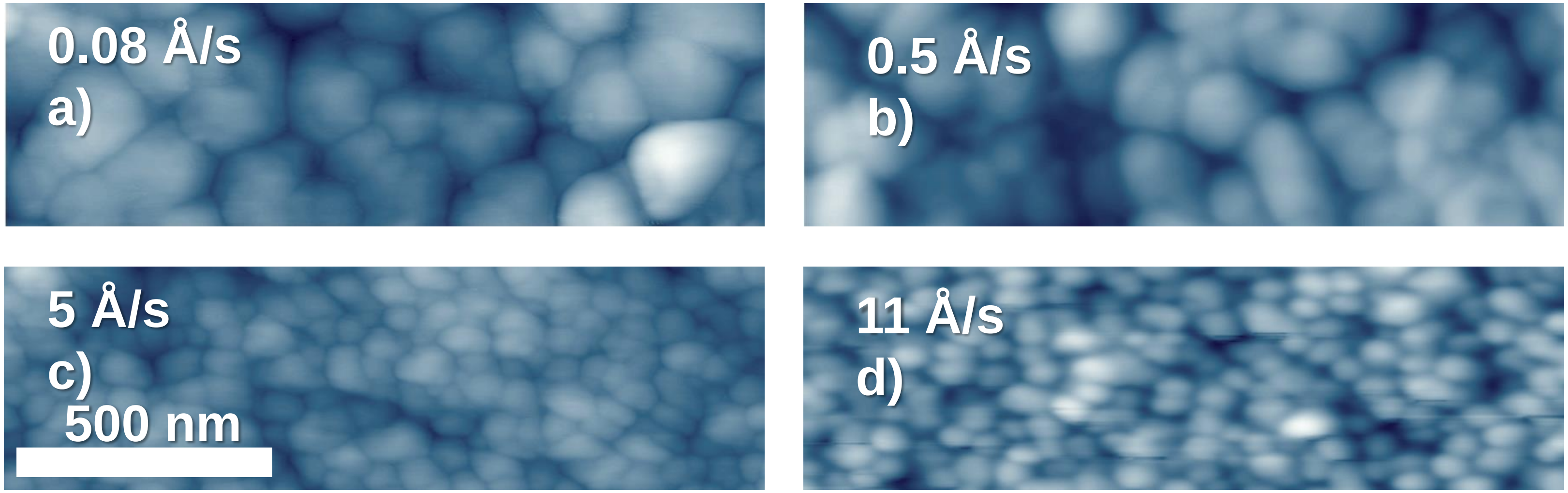
Inducing morphological changes



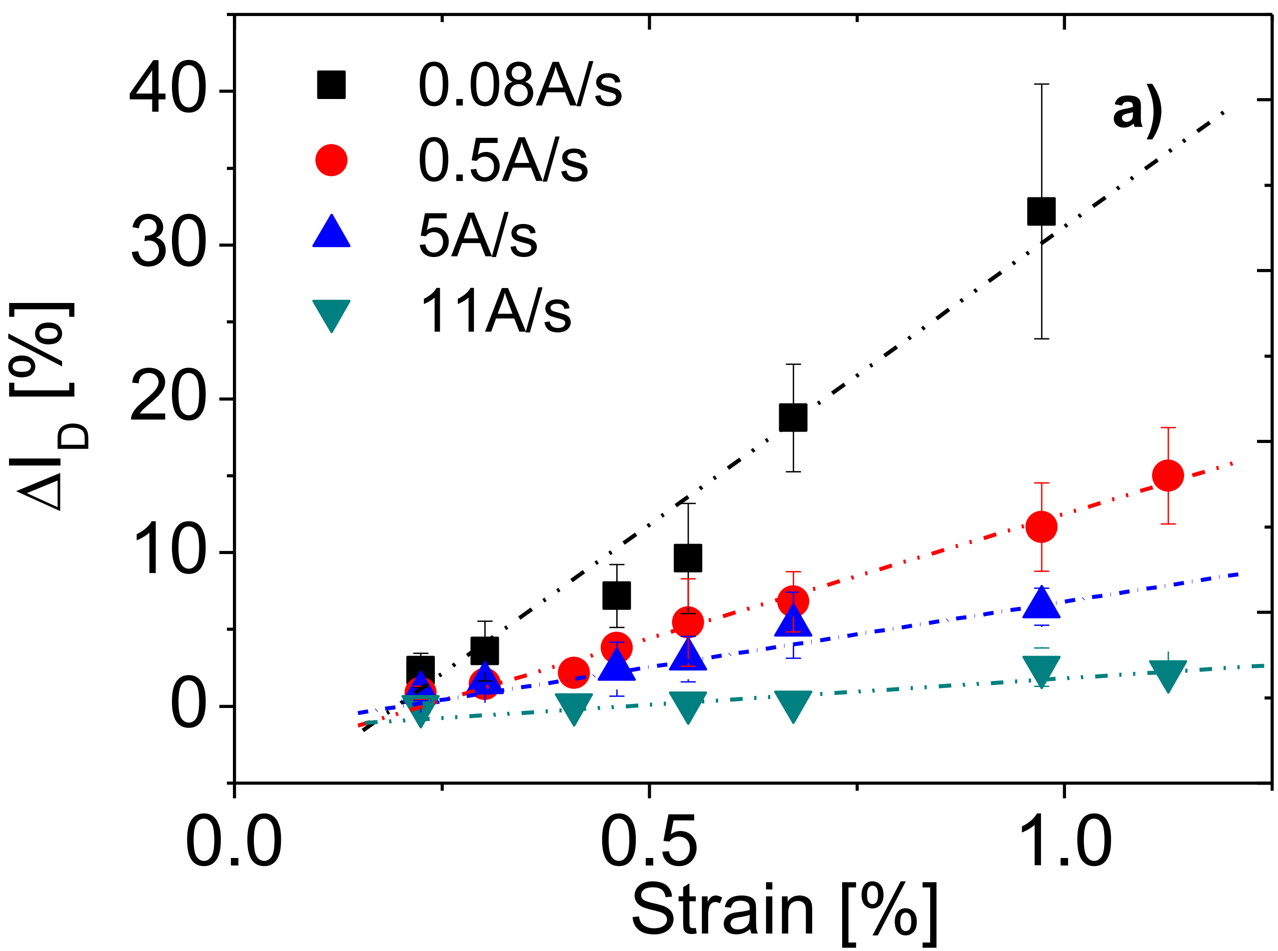


Pentacene based devices

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



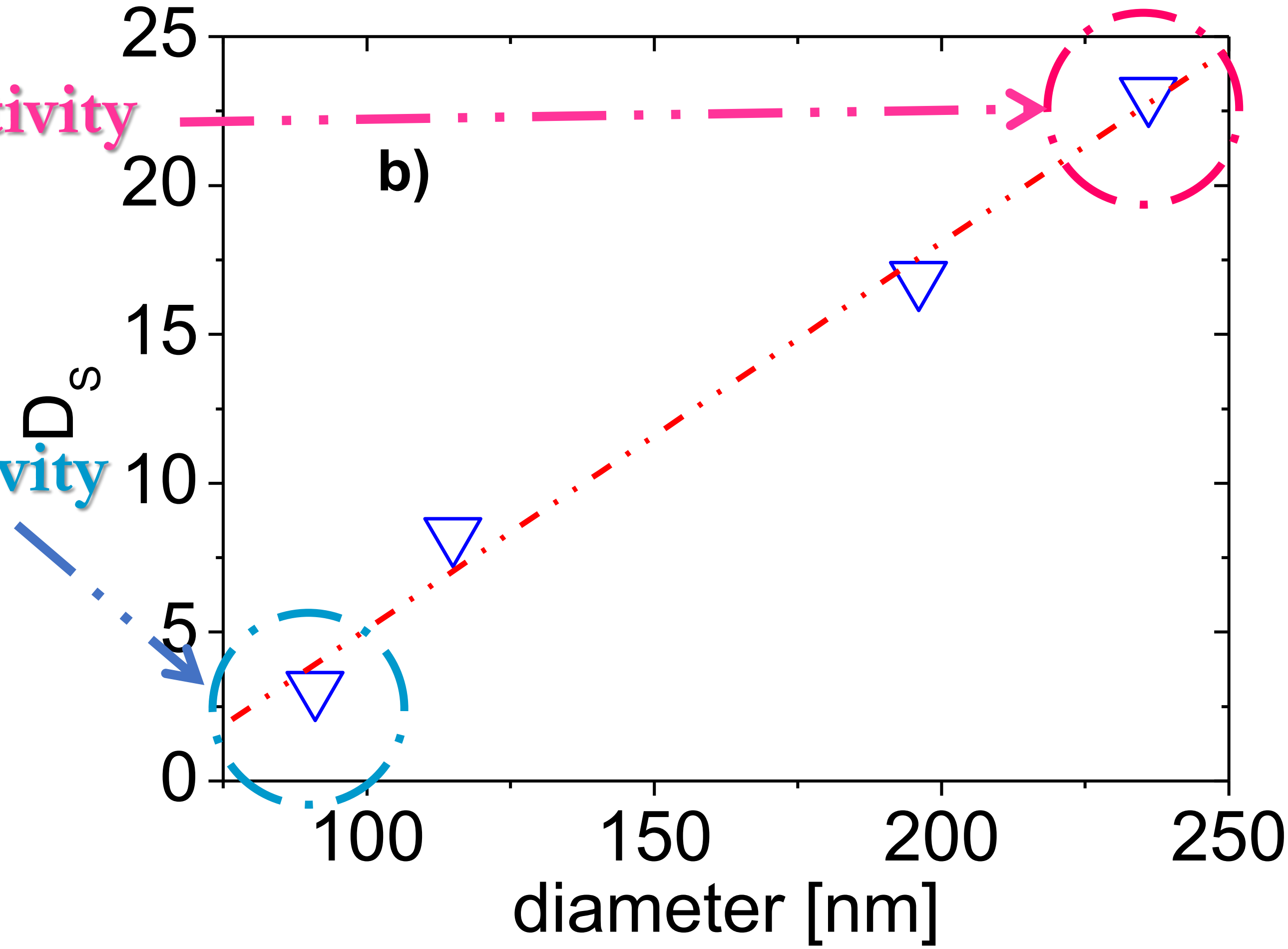
Morphological properties strongly influence the sensitivity to strain

Tuning the sensitivity

Sensitivity can be finely tuned by setting the deposition parameters

High sensitivity
Sensor applications

Low sensitivity
Flexible electronics



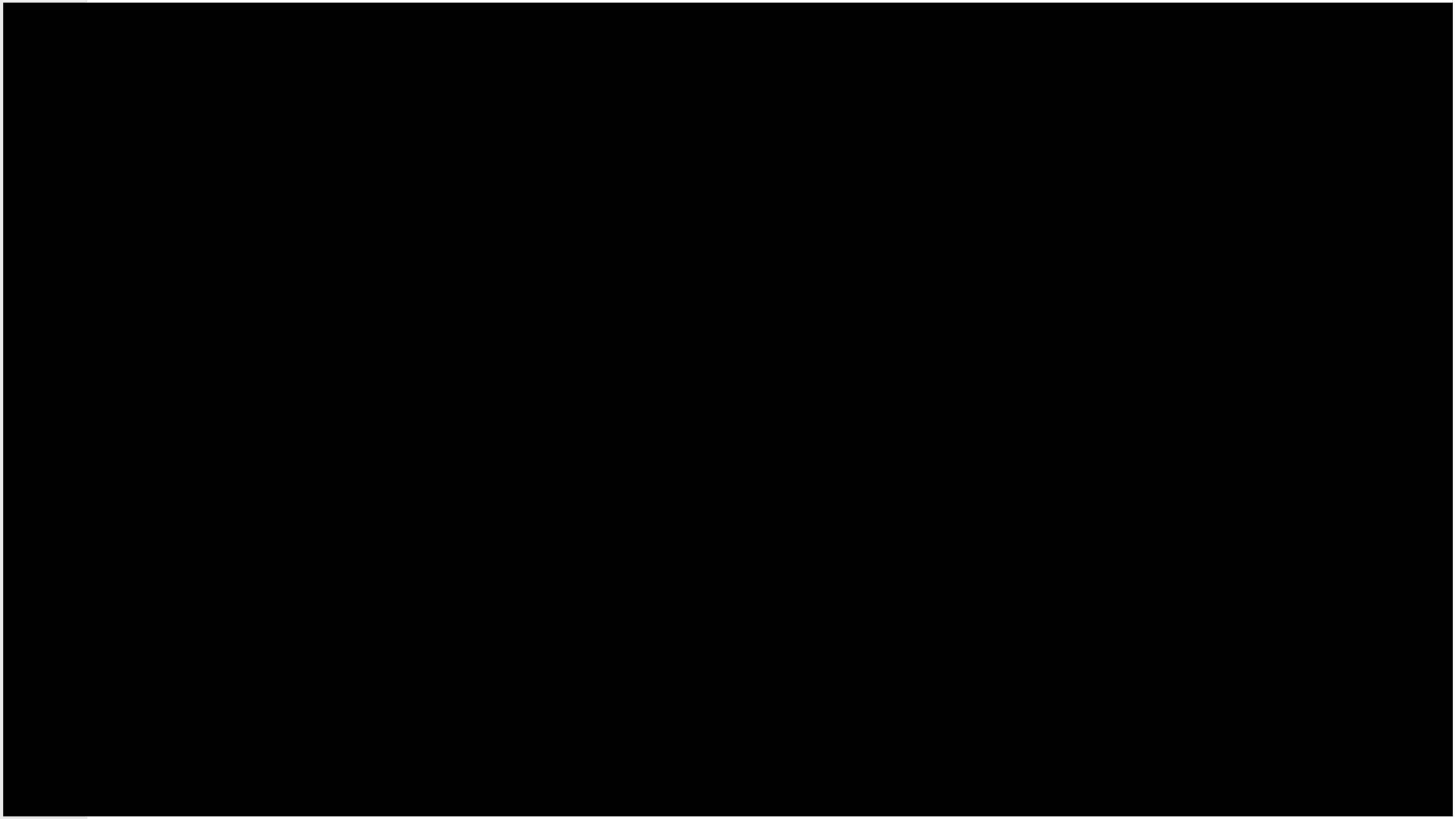
P. Cosseddu et al. Organic Electronics 14 (2013) 206–211

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

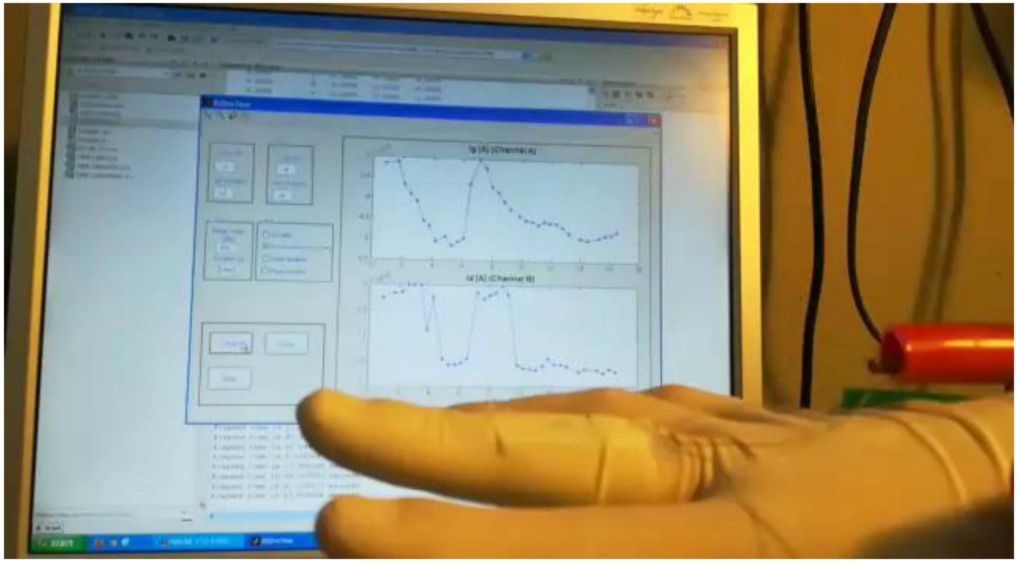
Applications: sensing glove



Applications: sensing glove

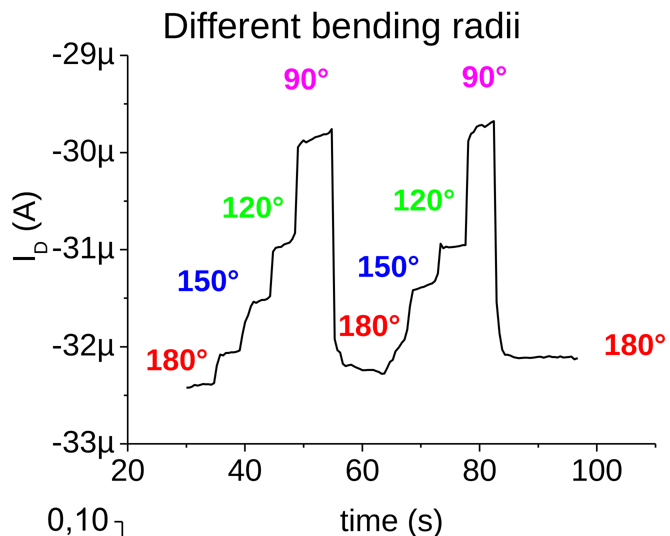
Low voltage OFET strain sensor

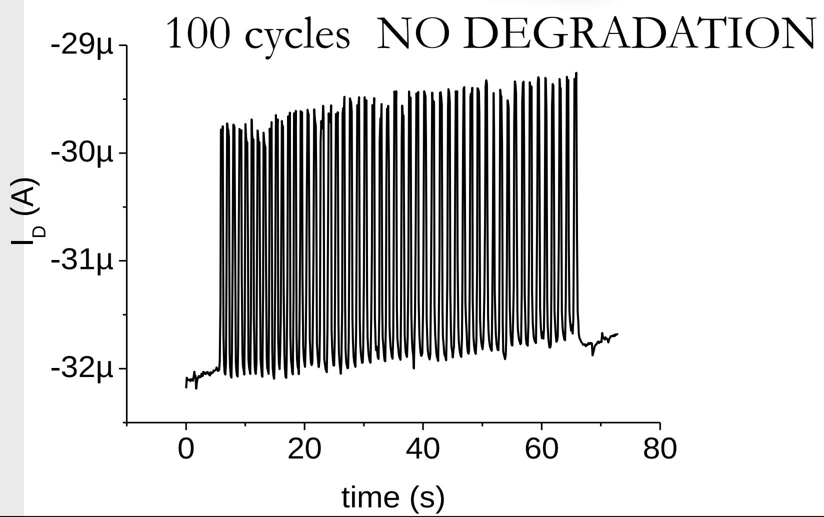
Inkjet Printed, low voltage OFET strain sensor

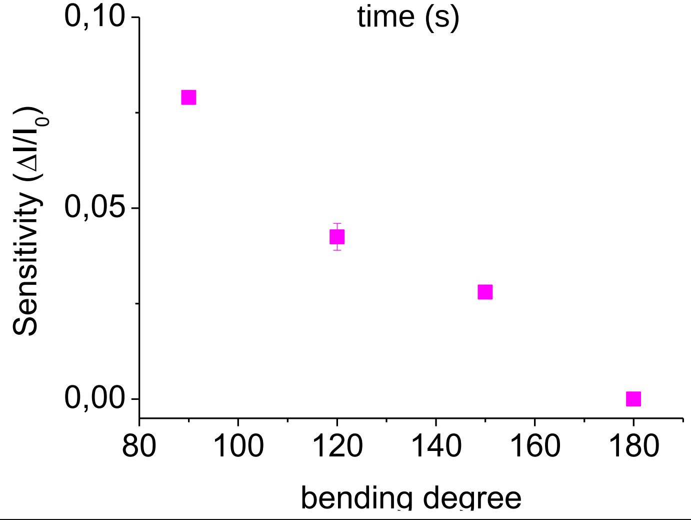


Applications: joints motion

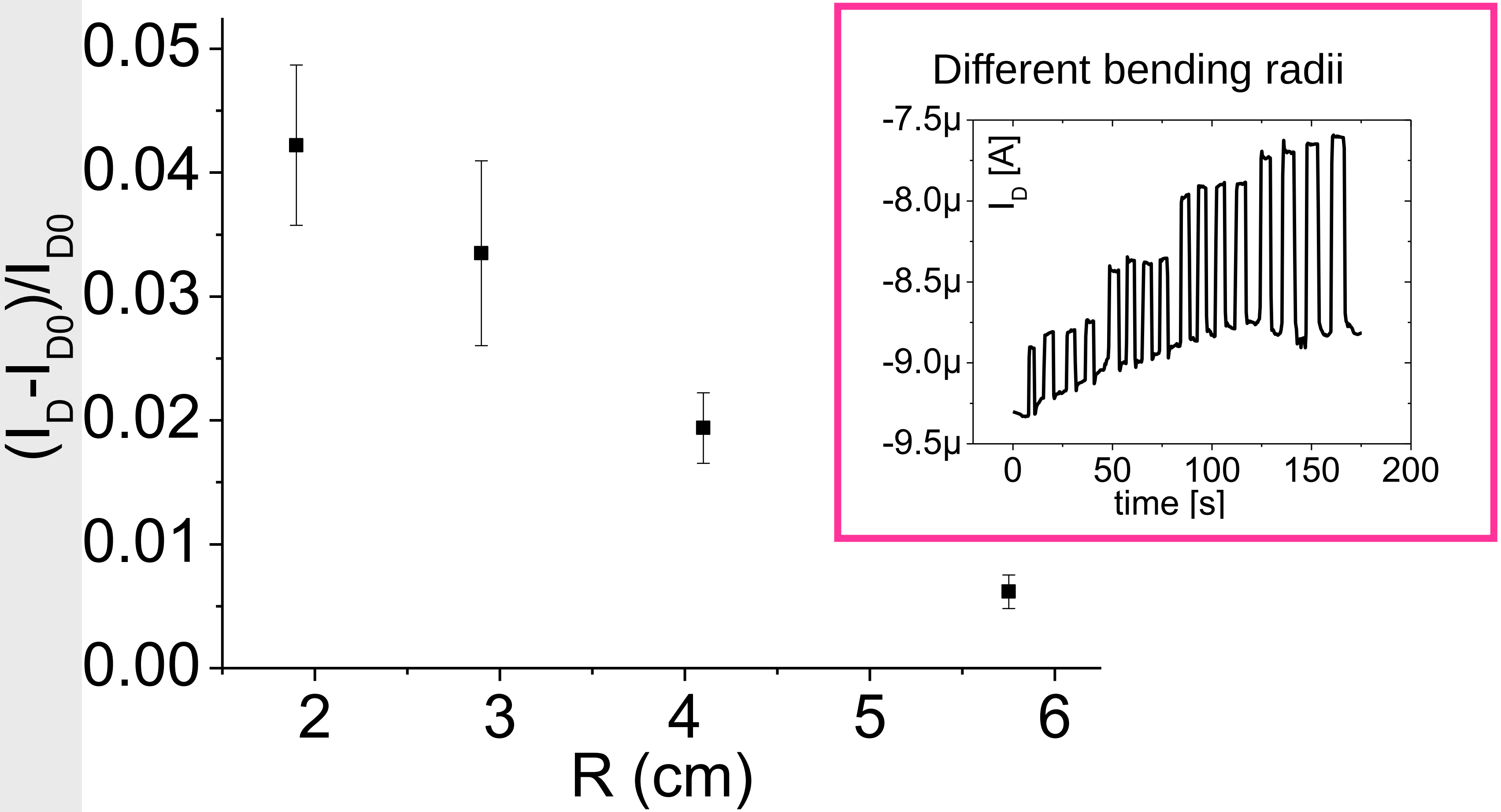
Sensor applied onto a ribbon can be transferred onto clothes for **joints motion monitoring**



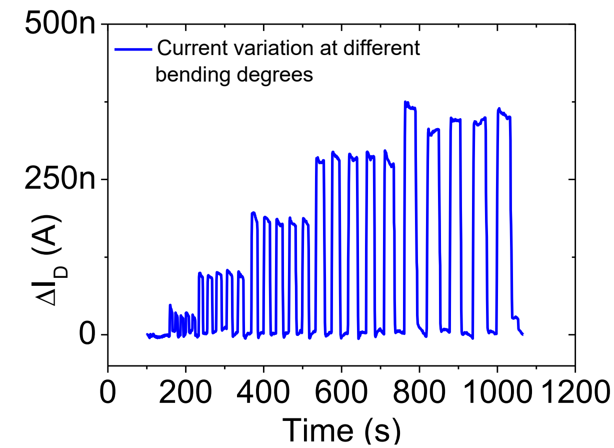


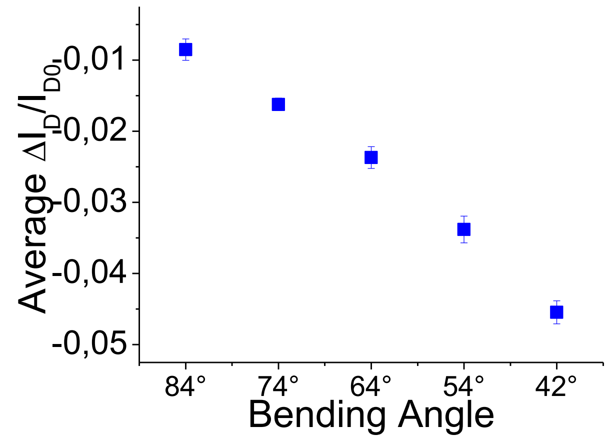


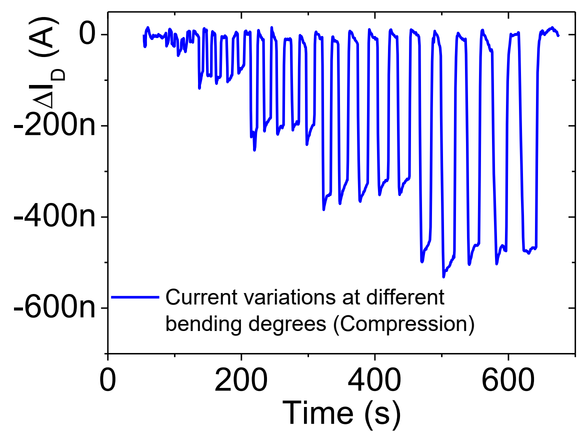
Applications: sensing glove

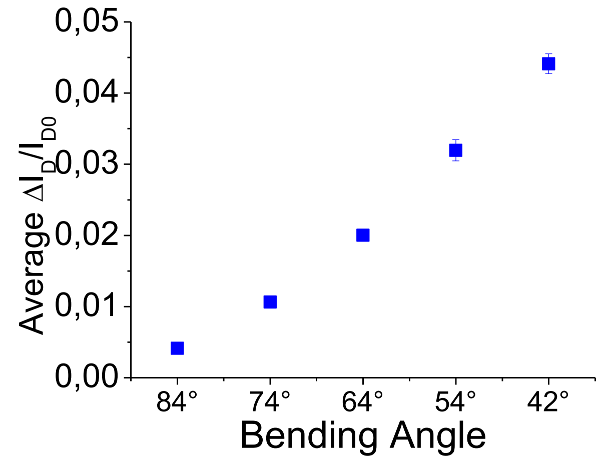


Applications: sensing glove

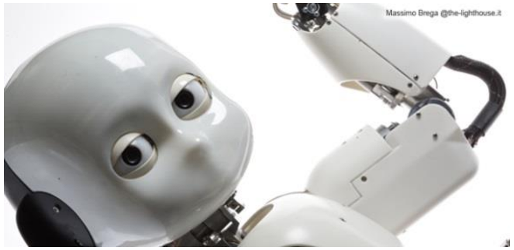








Applications: Artificial robot skin

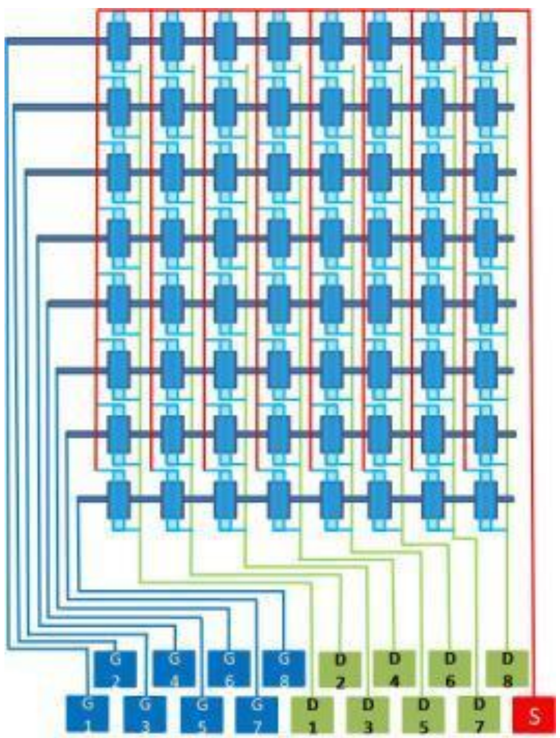


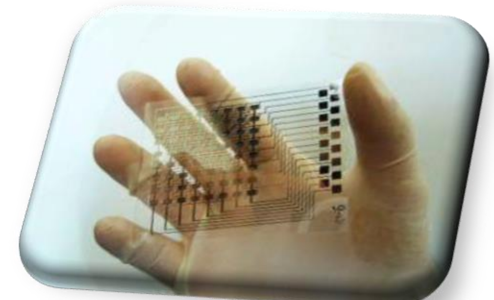
Develop a highly flexible, compliant system for tactile transduction

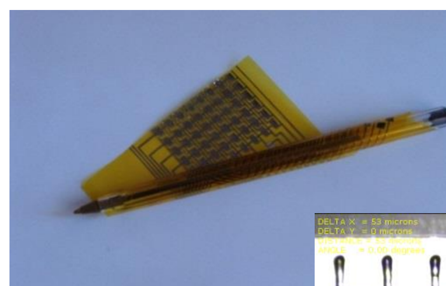
Inkjet printed matrices and arrays of OTFTs on plastic substrates

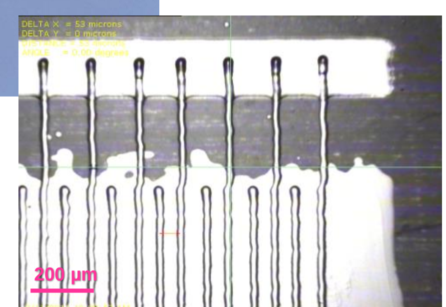
RoboSkin

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



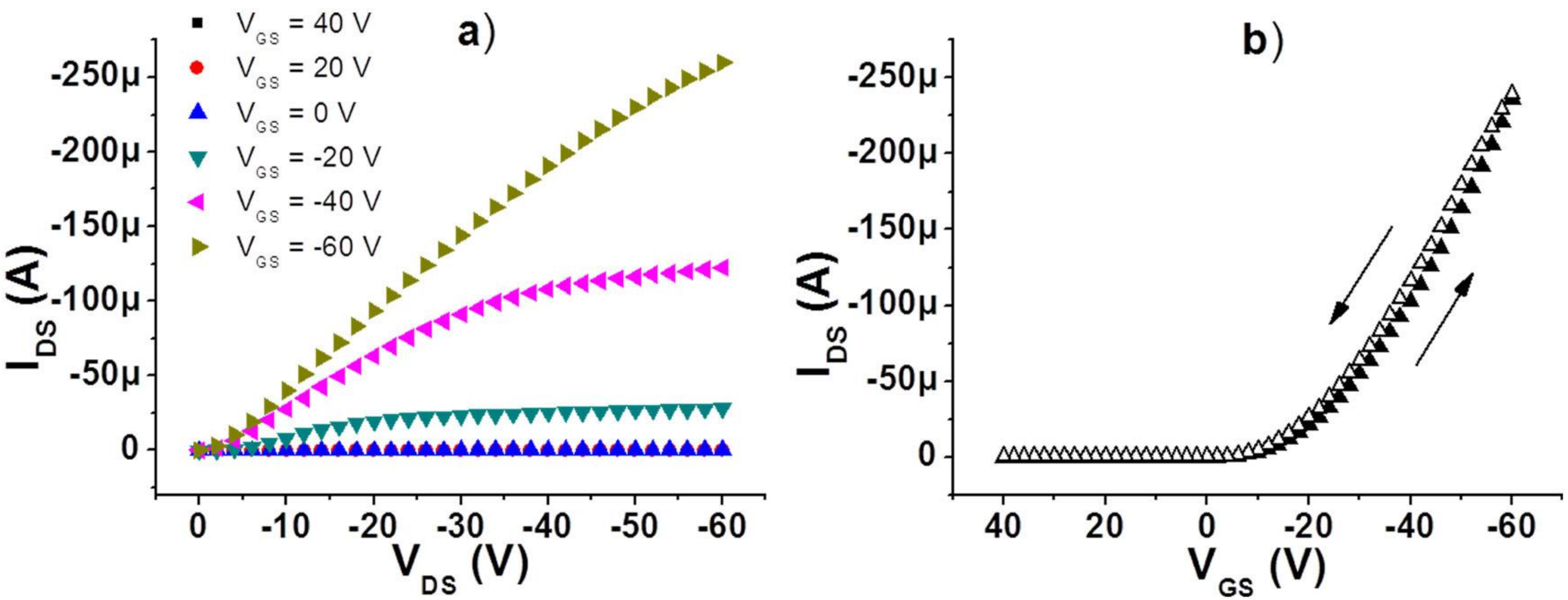






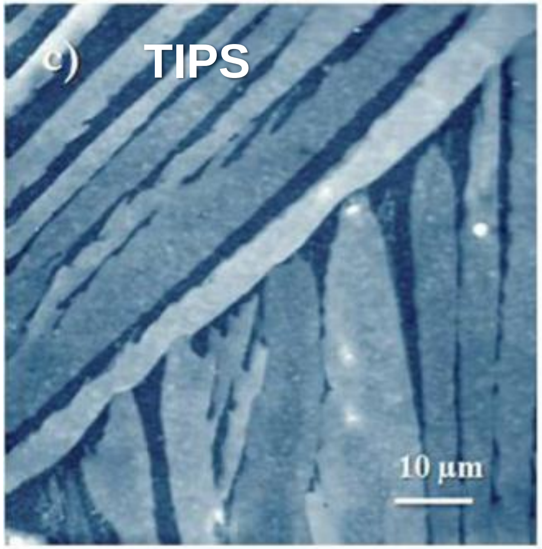
Applications: Artificial robot skin

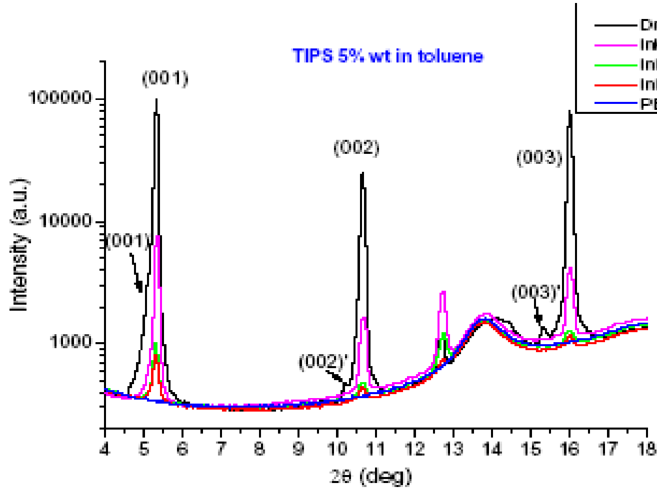
- t_{ins} = 1.54 µm, ε_r = 3.15 → C_{ins} = 1.8 nF/cm^2
- μ = 0.1 cm^2/Vs
- V_T = 4 ± 5 V
- $I_{ON}/I_{OFF} \approx 10^5$

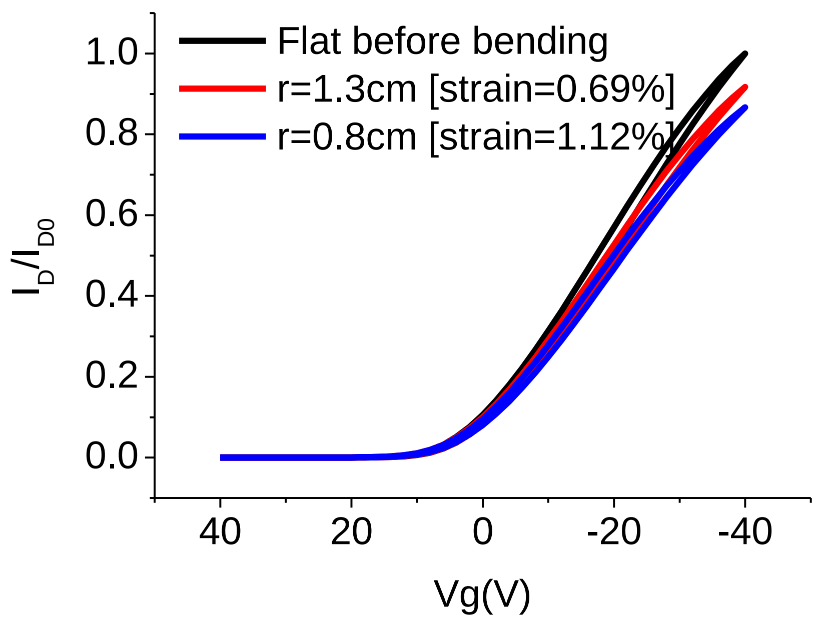


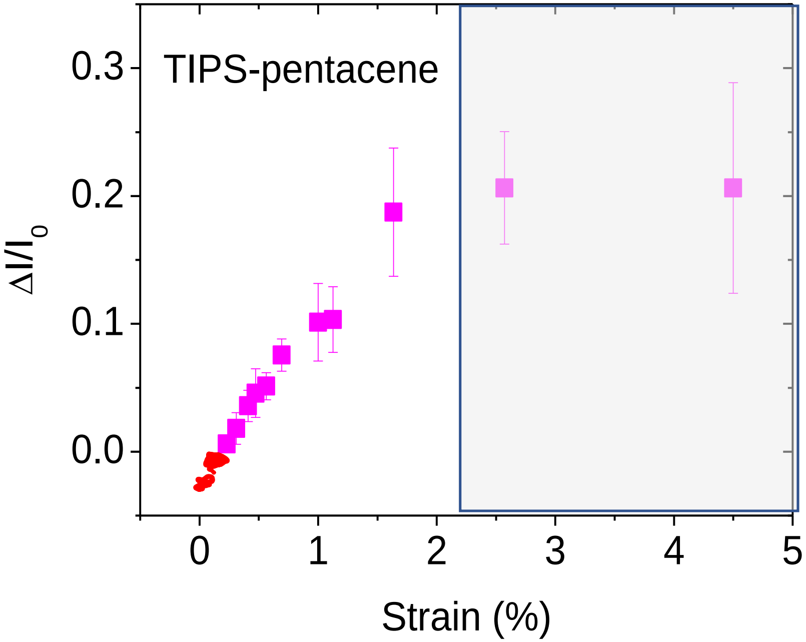
Strain sensitivity in TIPS based OTFTs

Highly crystalline TIPS-Pentacene films



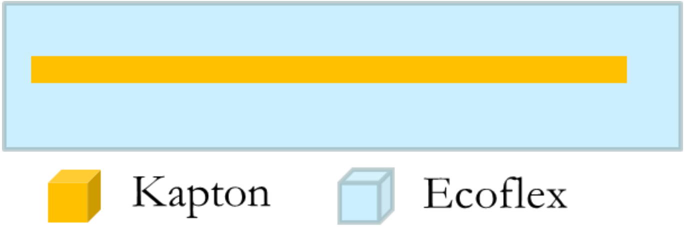






Artificial skin: Experimental set up

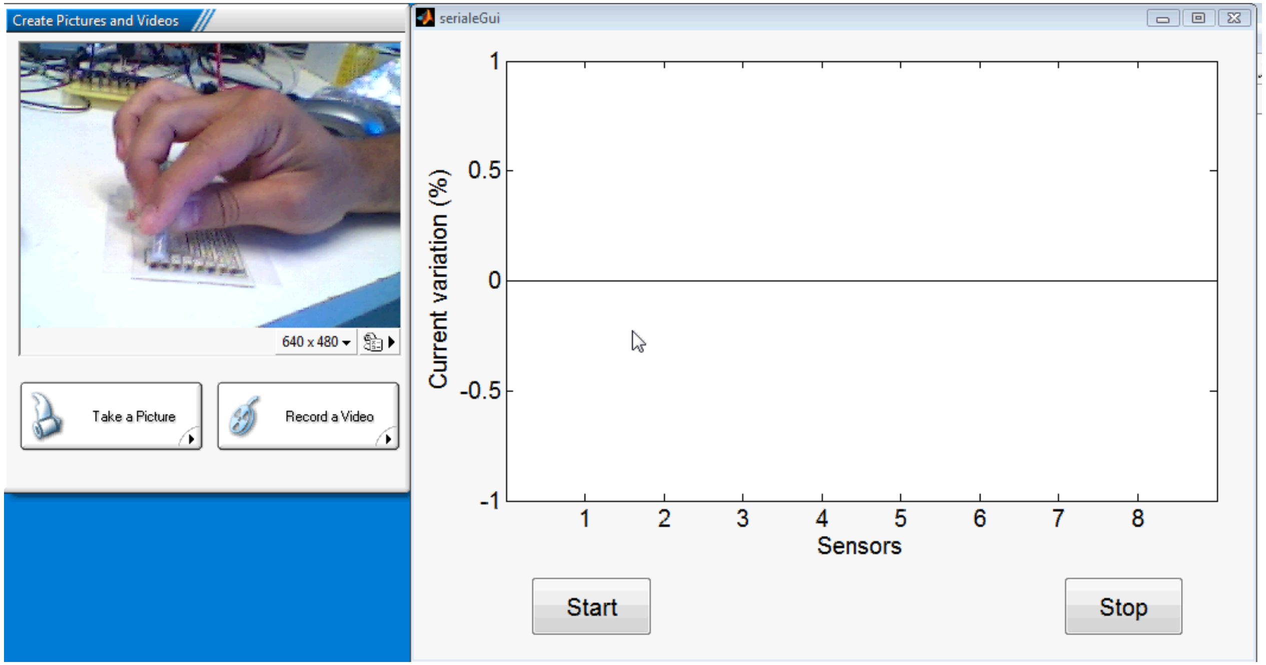
Embedding the organic substrates with elastomers



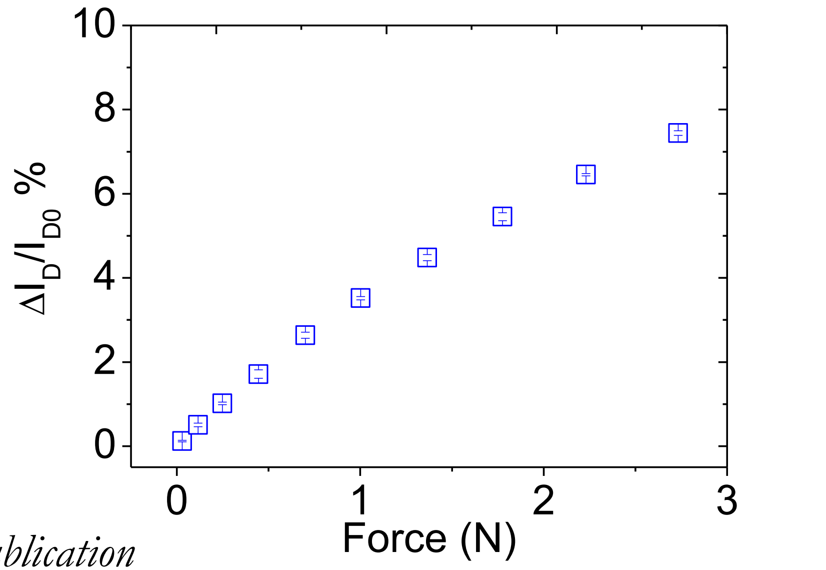
Mechanical properties and thickness of the elastomer influence the sensitivity *(Ecoflex → 1 + 1 mm)*

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

Artificial skin: electro-mechanical characterization



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



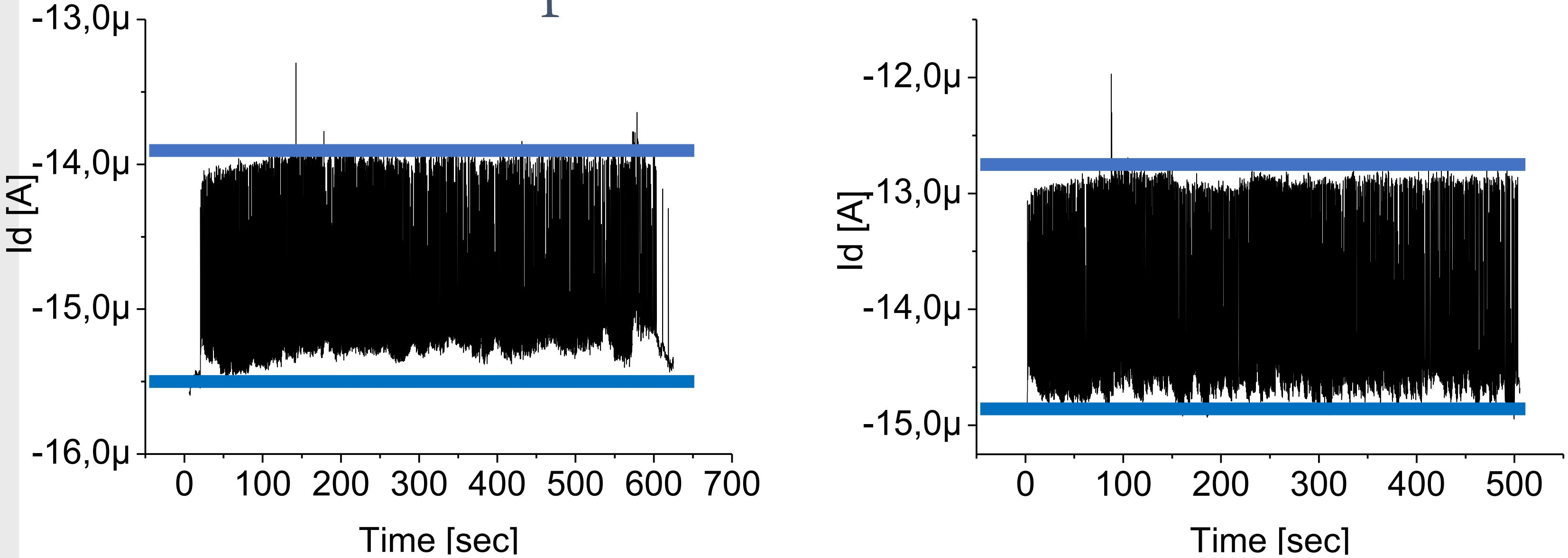
A. Loi et al. IEEE Sensors Journal, accepted for publication

Artificial skin: electro-mechanical characterization

Mechanical Stress Tests

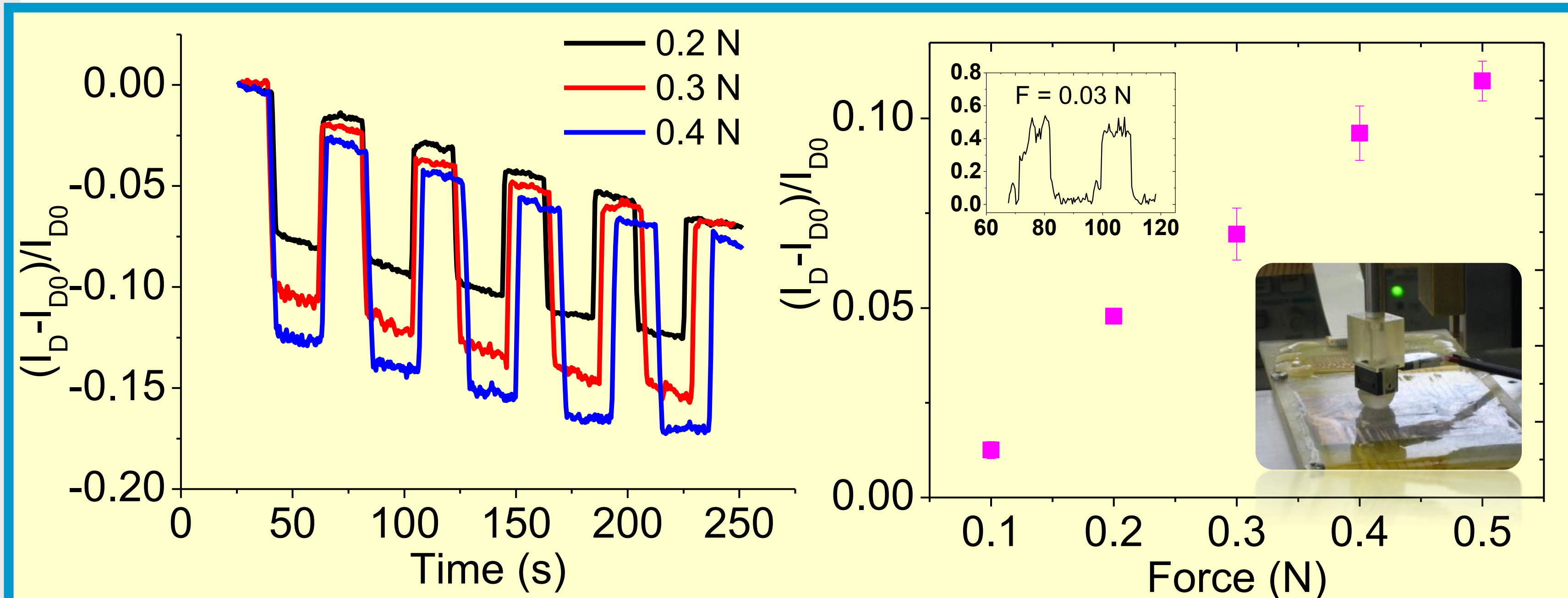
Applied force=2 N

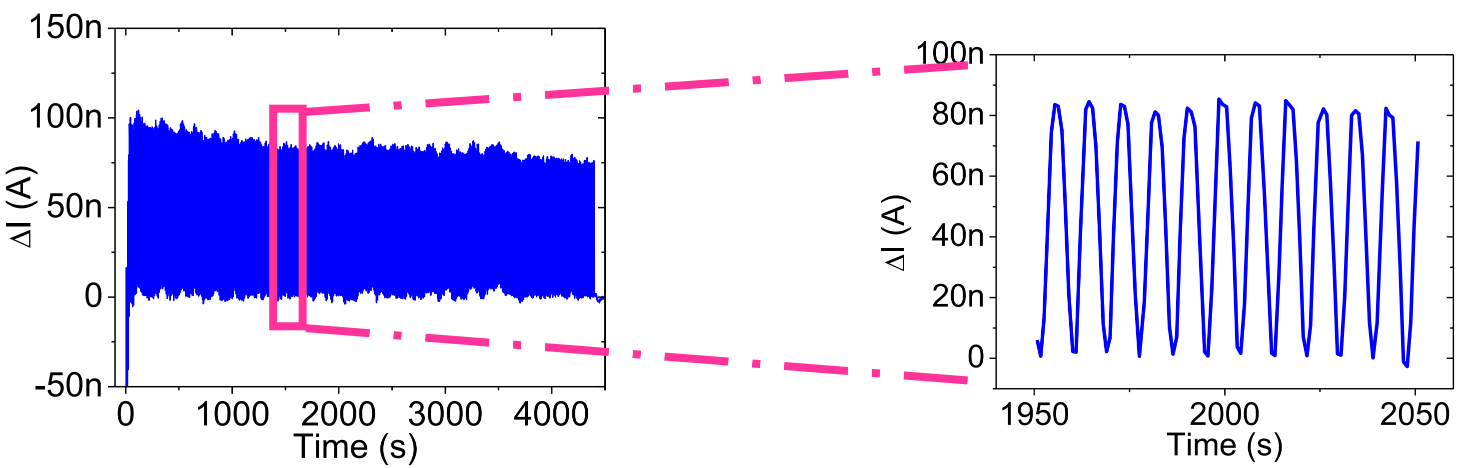
Output of two different taxels



- Negligible current shift
- Reproducible response up to 1000 cycles

Tactile sensing – low voltage OTFTs





The sensors can detect very small forces (0,03 N) and showed a very reproducible response, over more than 2000 cycles (F= 1 N)

Towards flexible devices

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

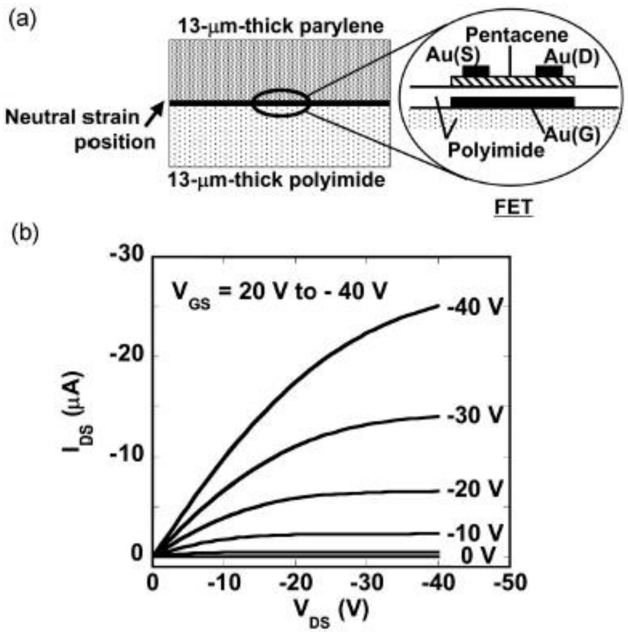
Surface strain depends on the bending radius, but also on the substrate thickness!!!

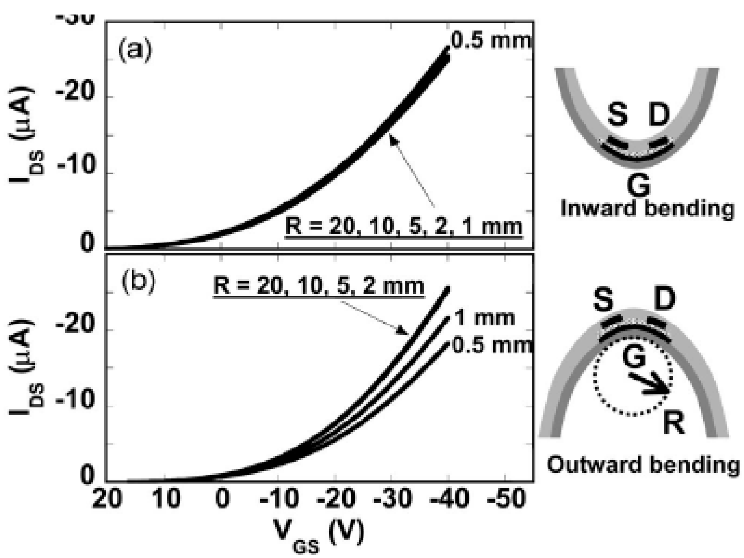
$$Strain = \left(\frac{d_f + d_s}{2 * R}\right)\frac{\left(1 + 2\eta + \chi\eta^2\right)}{\left(1 + \eta\right)\left(1 + \chi\eta\right)} \Rightarrow Strain = \left(\frac{d_s}{2 * R}\right)$$

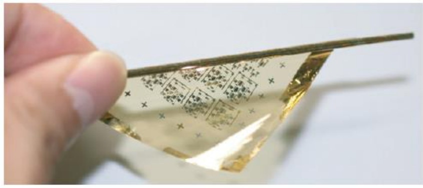
Two different approaches:

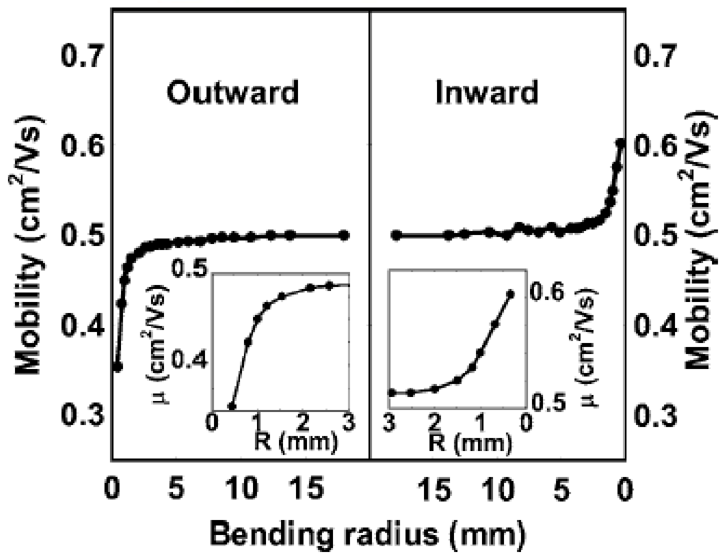
- Neutral strain position
- Thin substrates

OTFT in neutral strain position





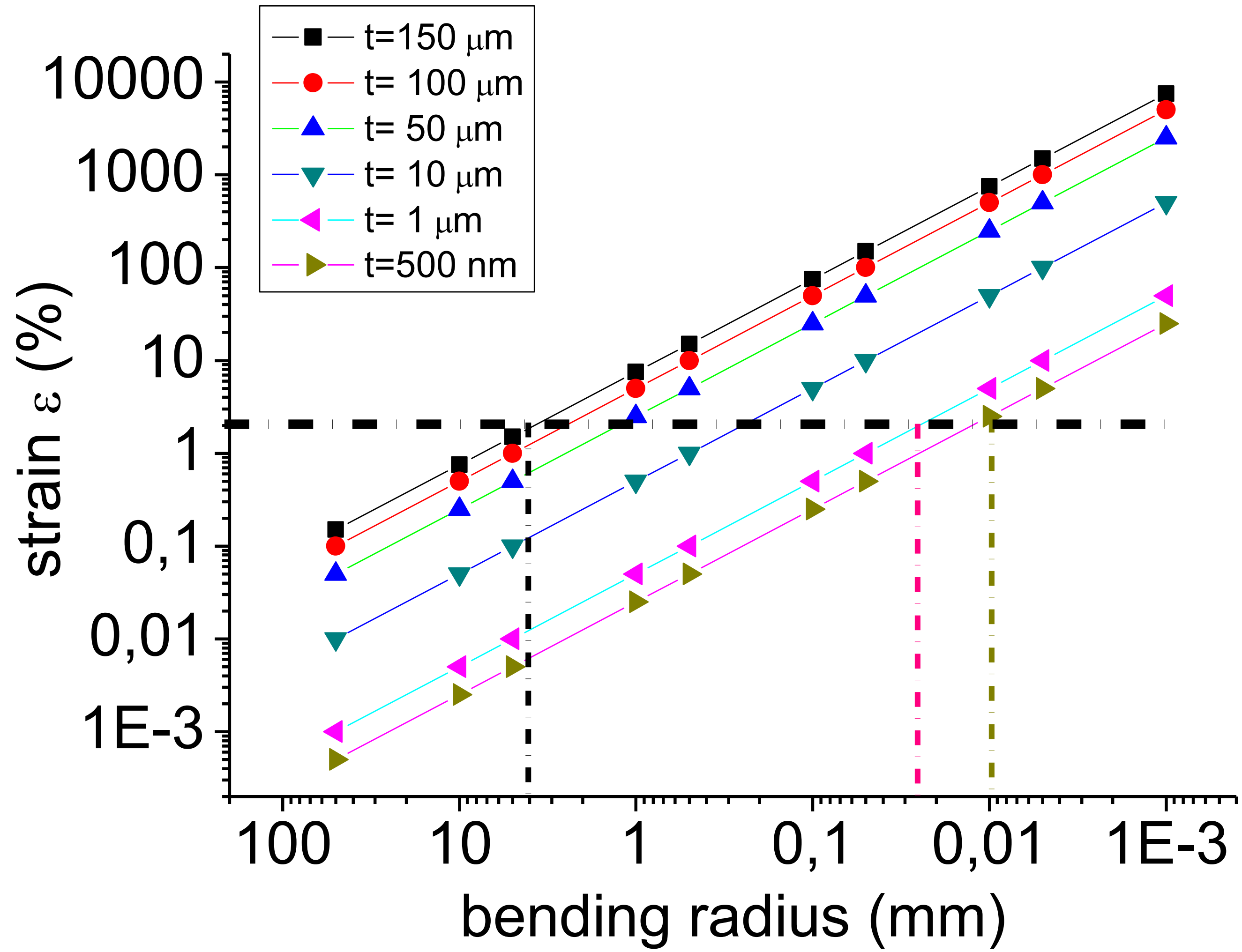




- *T. Sekitani et al. Appl. Phys. Lett. 87, 173502 (2005)*
- *T. Sekitani et al. Nature Mater. 9, 1015 (2010)*

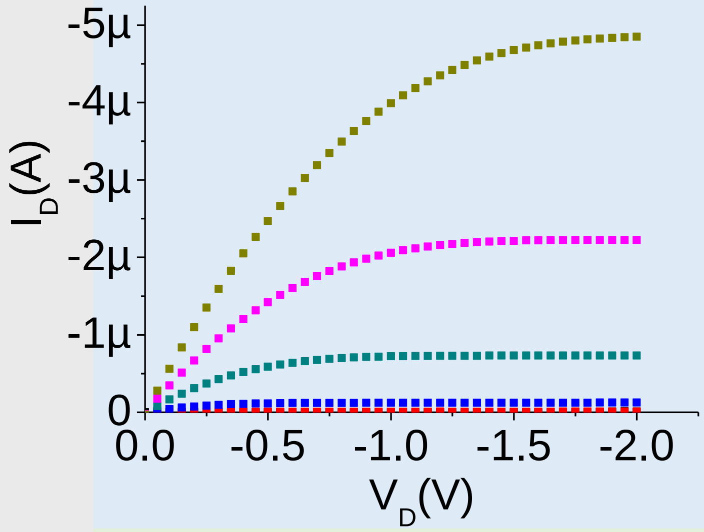
Reducing strain by using thin substrates

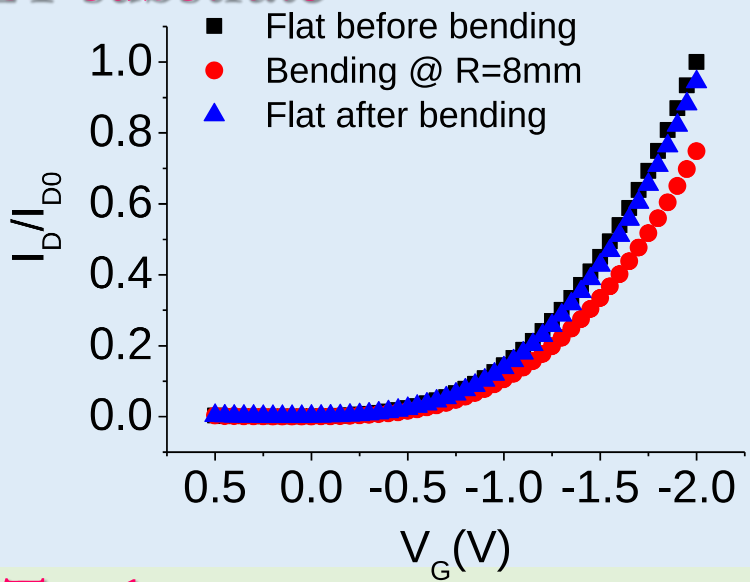
Reducing the substrate thickness leads to a smaller critical bending radius



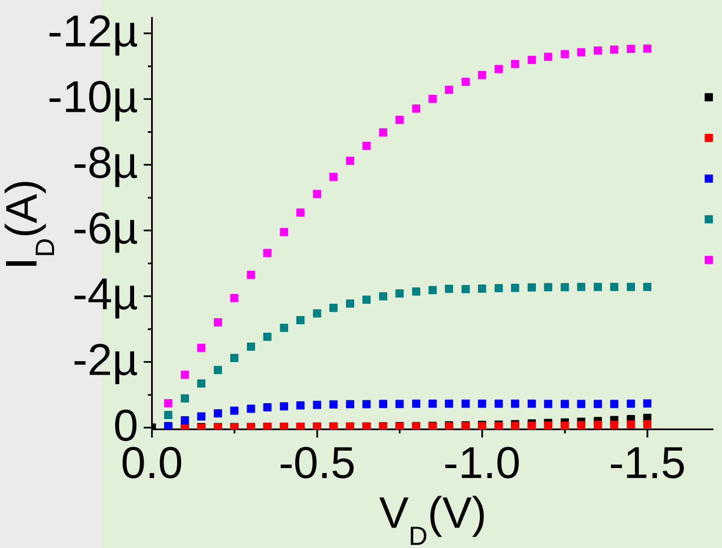
Towards mechanically stable OTFTs

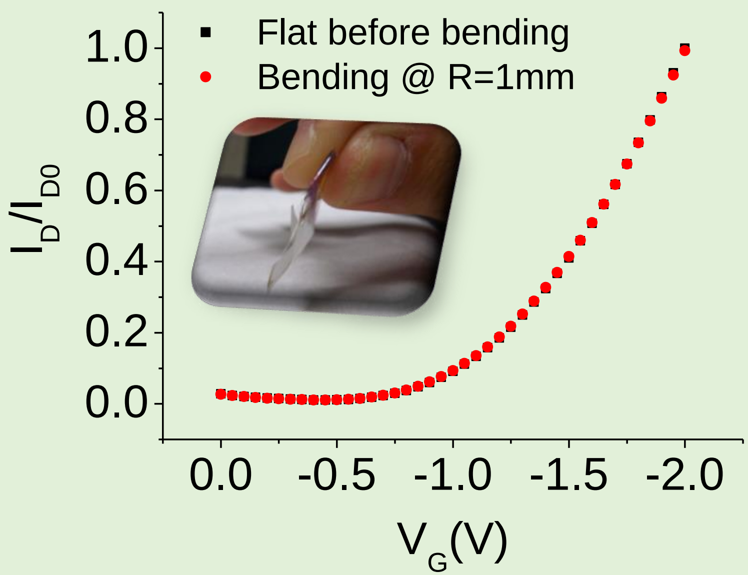
OTFTs fabricated on 175µm PET substrate





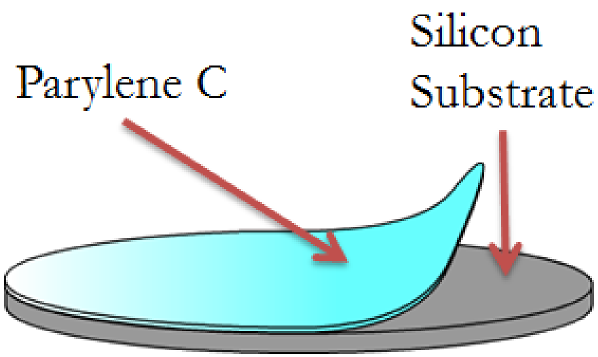
OTFTs fabricated on 1.5µm PET substrate





Highly flexible OFETs

- ✓Deposition of ultrathin, submicrometer, Parylene C films

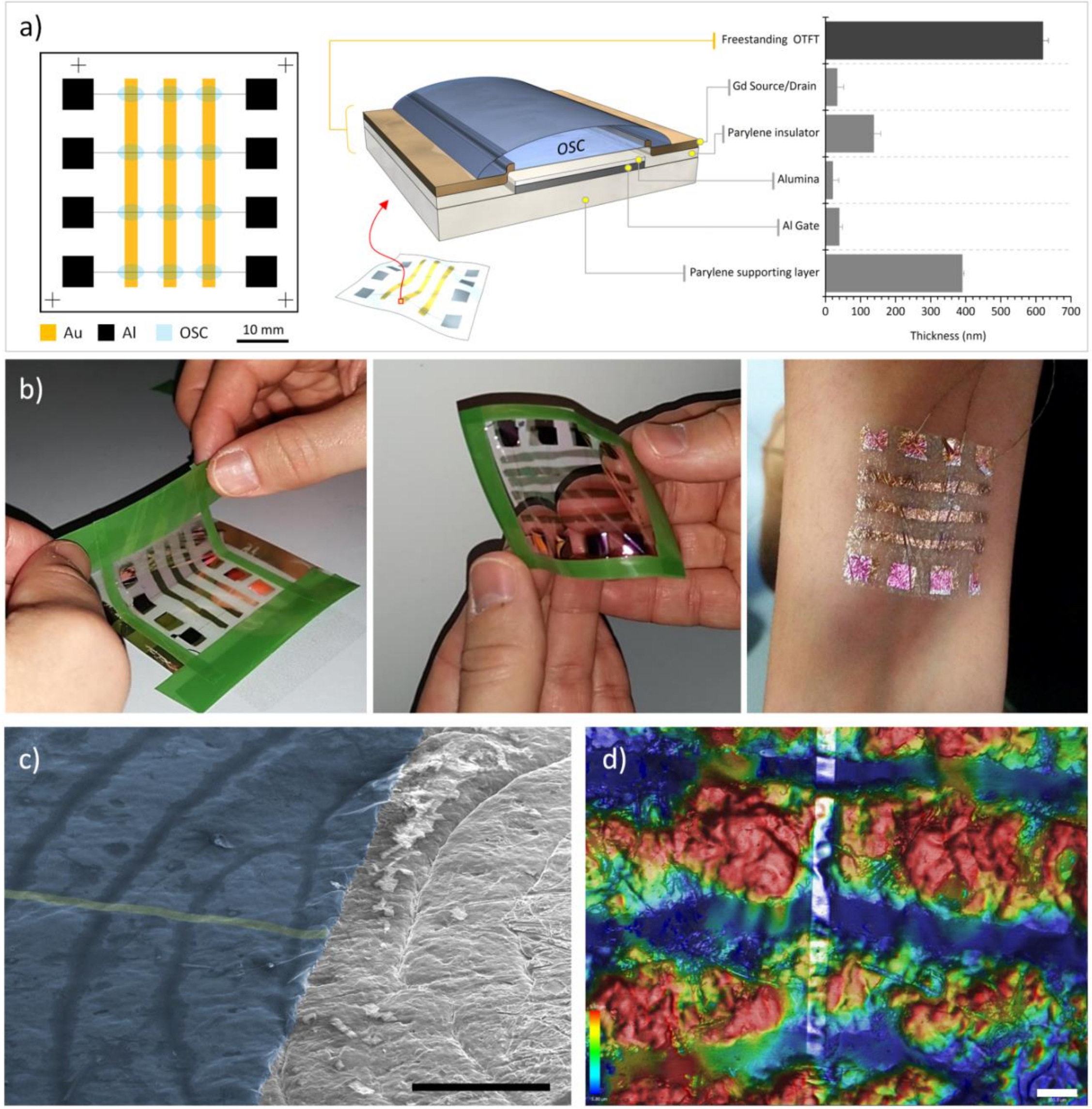


P. Cosseddu et al. *"Fully deformable organic thin film transistors with moderate operation voltage"* IEEE TED, 58, 3416-3421 (2011)

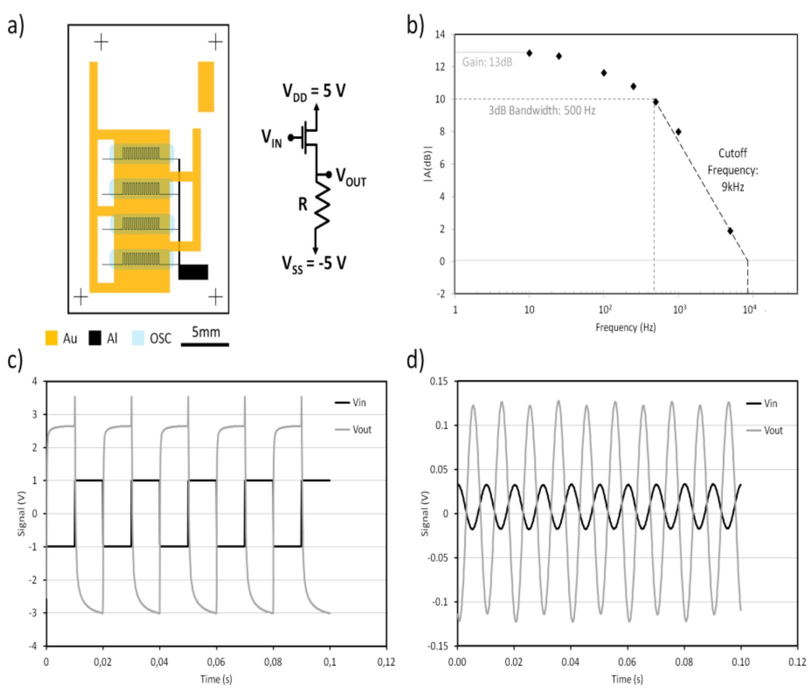
- ✓Patterning of the OFETs
- ✓After patterning the film can be peeled off

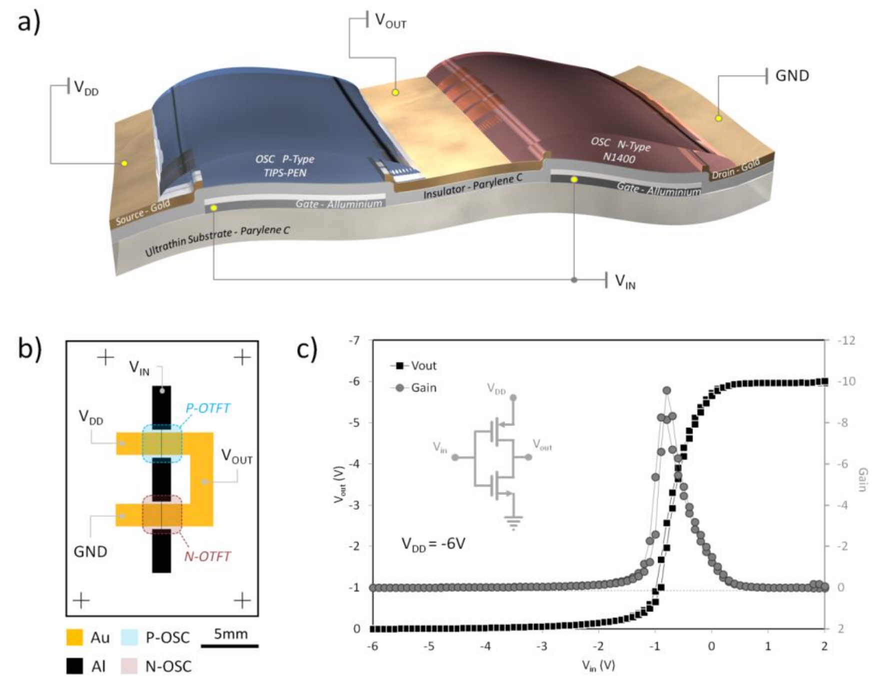
Total thickness smaller than 700 nm

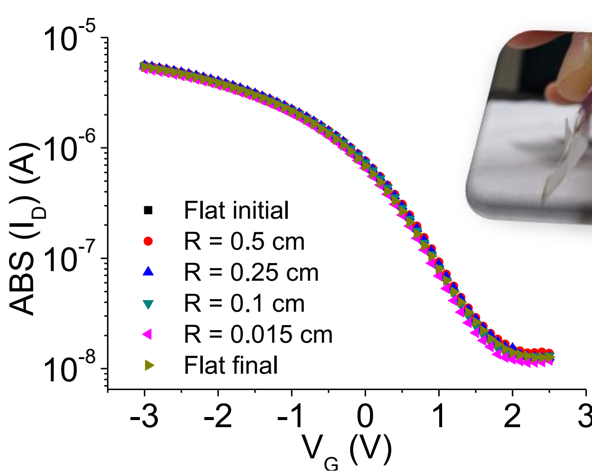
Reducing strain by using thin substrates

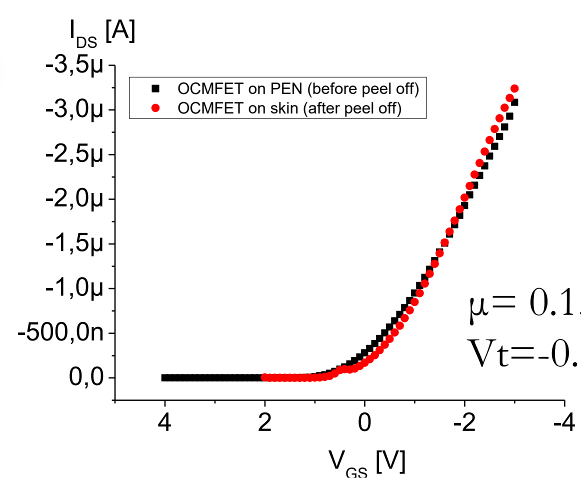


Highly flexible OFETs









μ= 0.15/0.2 cm^2/Vs

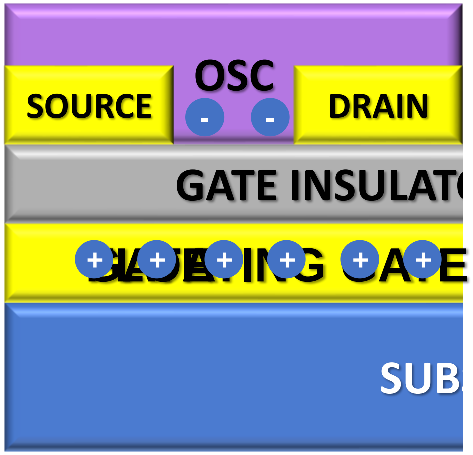
Vt=-0.1/0.5 V

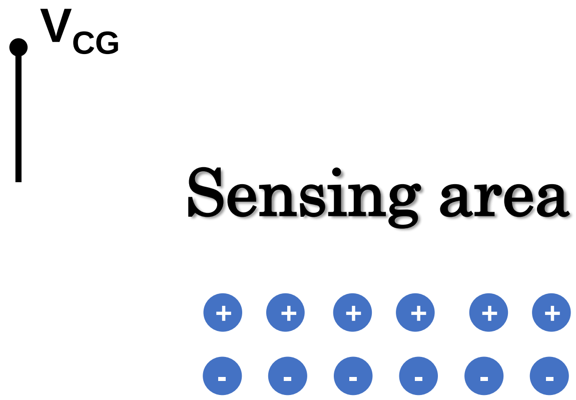
The Organic Charged Modulated Field Effect Transistor OCMFET-based sensors

Organic Charge-Modulated Field-Effect Transistor

OCMFET

OFET

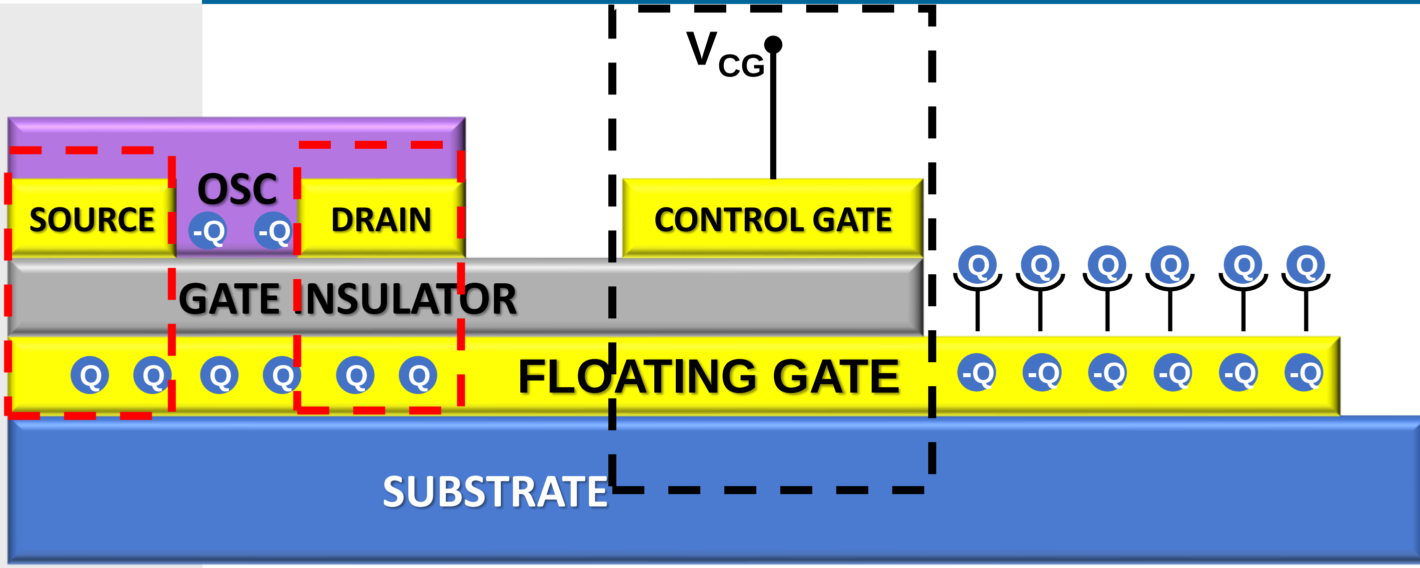


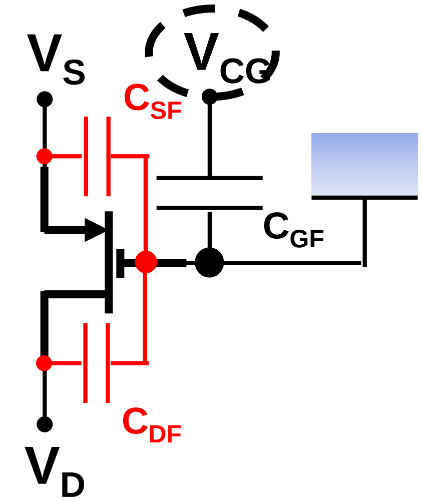


$$\Delta V_{th} = -\frac{\Delta Q}{C_{TOT}}$$

- 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





$$Q_{FG}=C_{CF}\left(V_{FG}-V_{CG}\right)+C_{SF}\left(V_{FG}-V_{S}\right)+C_{DF}\left(V_{FG}-V_{D}\right)+Q_0+Q_{ind}\left(Q_S\right)$$

$$V_{FG}=\frac{Q_{FG}}{C_{CF}+C_{SF}+C_{DF}}$$

$$V_{FG}=\frac{C_{CF}}{C_{CF}+C_{SF}+C_{DF}}V_{CG}+\frac{C_{SF}}{C_{CF}+C_{SF}+C_{DF}}V_{S}+\frac{C_{DF}}{C_{CF}+C_{SF}+C_{DF}}V_{D}+\frac{Q_0-Q_{ind}\left(Q_S\right)}{C_{CF}+C_{SF}+C_{DF}}$$

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

$$V_{FG}\approx V_{CG}+\frac{C_{DF}}{C_{TOT}}V_D+\frac{Q_0-Q_S}{C_{TOT}}$$

Organic Charge-Modulated Field-Effect Transistor

$$V_{FG} \approx V_{CG} + \frac{C_{DF}}{C_{TOT}} V_D + \frac{Q_0 - Q_S}{C_{TOT}}$$

$$V_{FG} - V_{Th} \approx V_{CG} + \frac{C_{DF}}{C_{TOT}} V_D + \frac{Q_0 - Q_S}{C_{TOT}} - V_{Th}$$

chiamo

$$V_{ThF} = V_{Th} - \frac{C_{DF}}{C_{TOT}} V_D - \frac{Q_0 - Q_S}{C_{TOT}}$$

$$C_{CF} >> C_{DF}, C_{SF}$$

$$\Delta V_{Th} = \frac{Q_0 - Q_S}{C_{TOT}} = -\frac{Q_S}{C_{TOT}}$$

$$Q_0 = 0$$

Example:

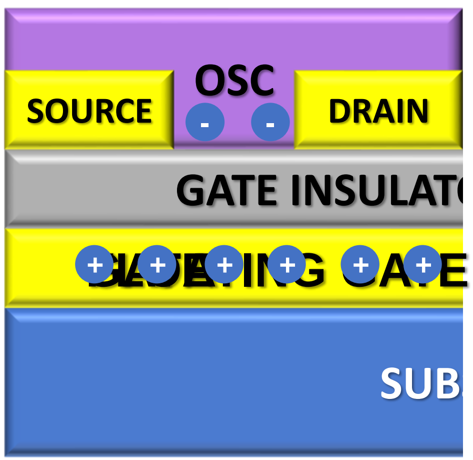
Positive charge on the sensing area is going to induce a negative variation of the threshold voltage

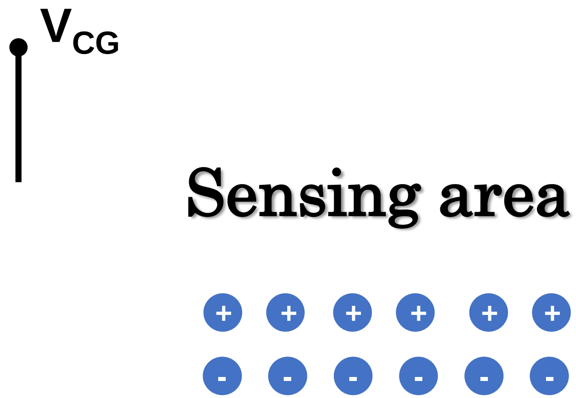
P-type OFET, more negative Vt, lower output current

Organic Charge-Modulated Field-Effect Transistor

OCMFET

OFET



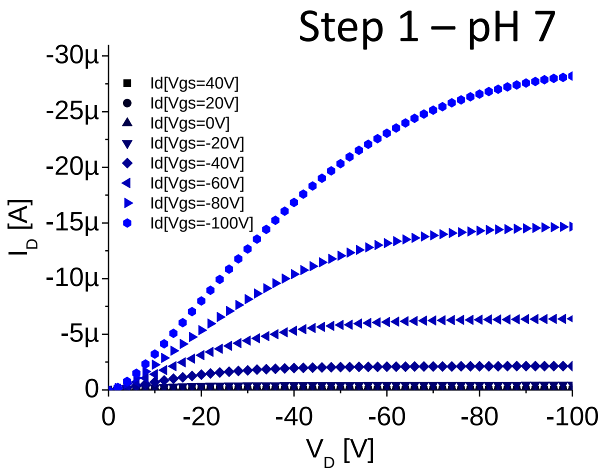


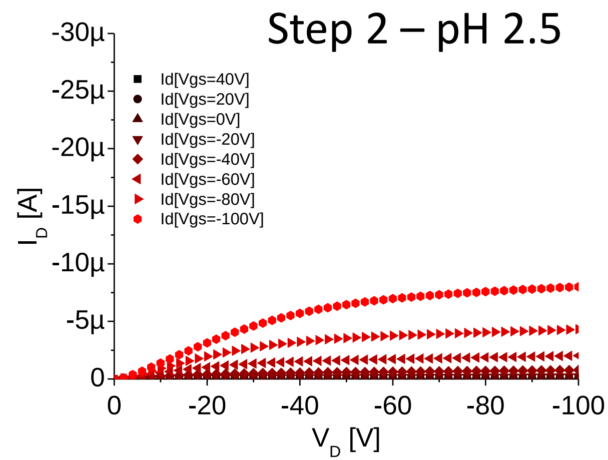
$$\Delta V_{th} = -\frac{\Delta Q}{C_{TOT}}$$

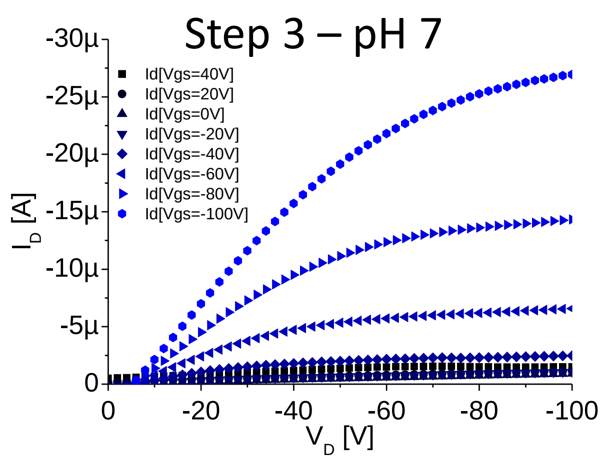
- The working principle is independent of the technology and can be employed for obtaining different kind of sensors
- No need of a reference electrode

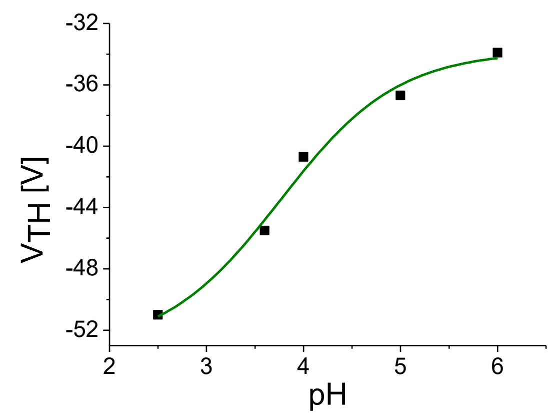
OCMFET: pH sensing

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



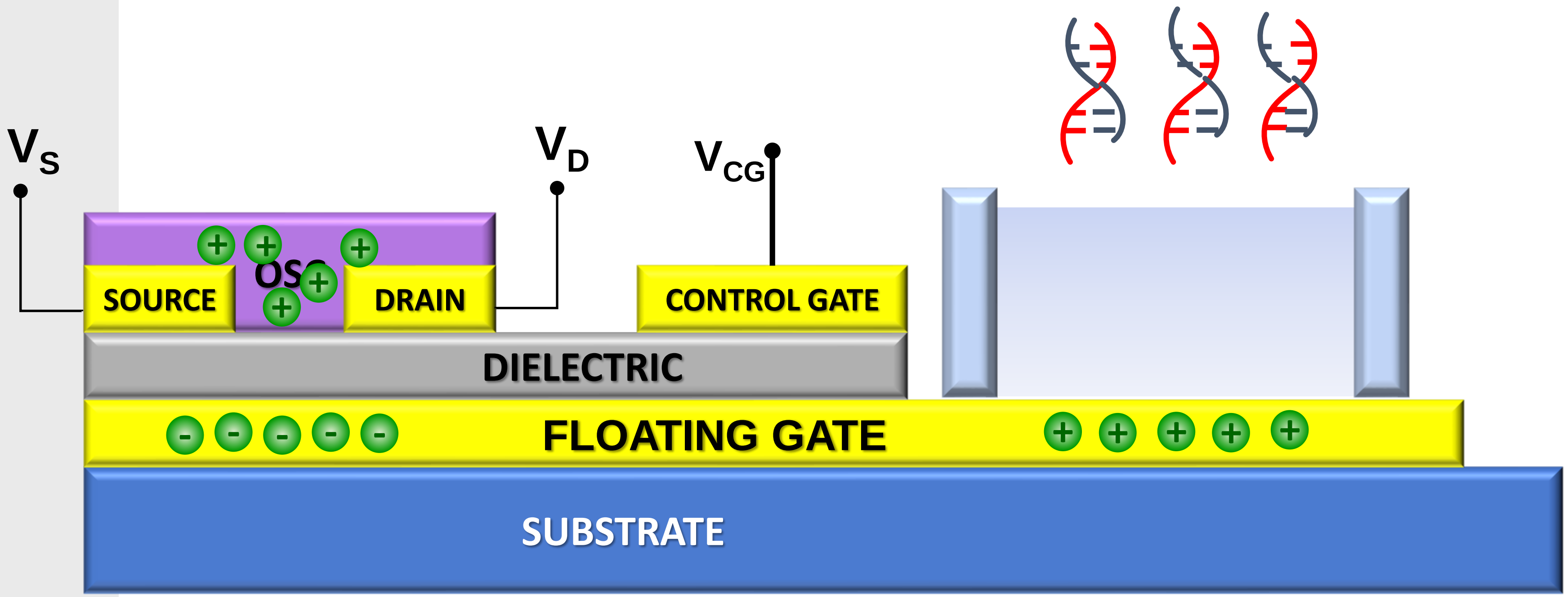


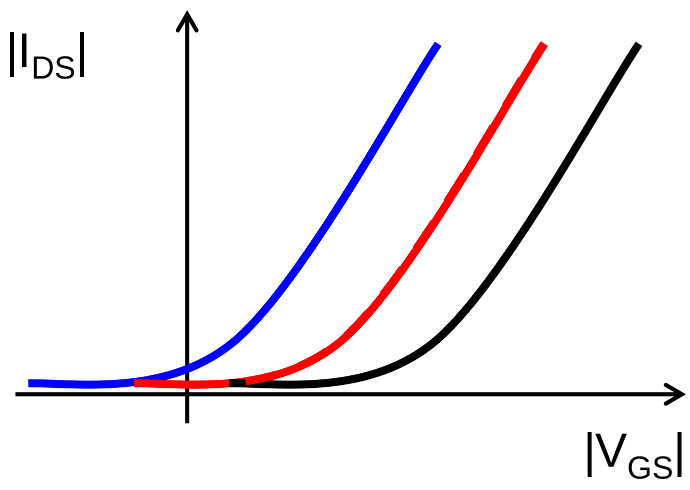




A. Caboni et al. Appl. Phys. Lett. 95, 123304 (2009)
A. Caboni et al. IEEE Sensors Journal 9, 1963 (2009)

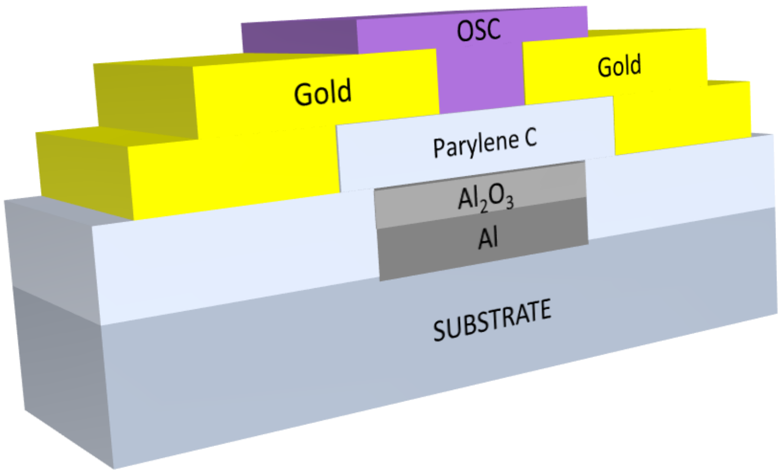
OCMFET: DNA sensing

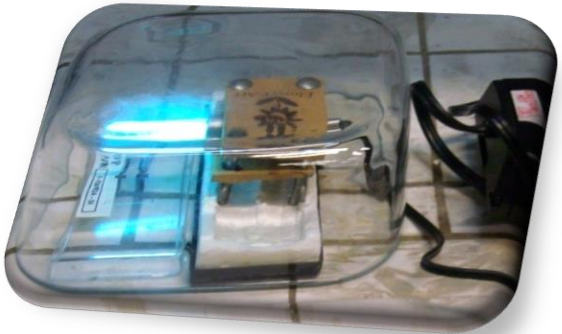




Ultra-low voltage OTFTs structure

Bottom gate, bottom contact structure on flexible plastic substrates



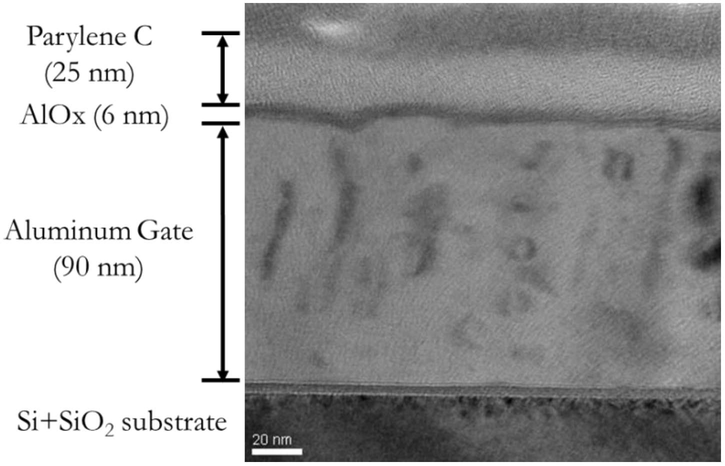


- **Gate: Aluminum**
- **Gate Dielectric:**

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]

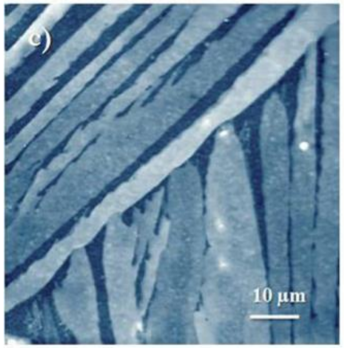


P. Cosseddu, et al. Appl. Phys. Lett. 100, 093305 (2012)

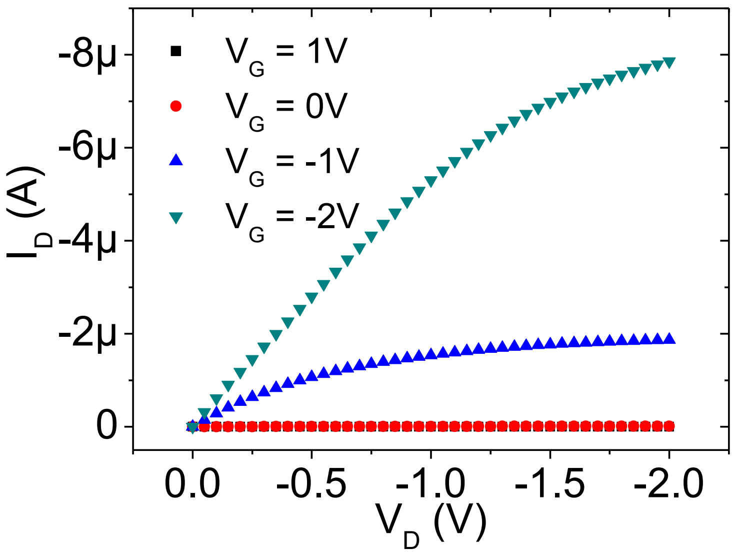
AlOx/Parylene C Double-Layer

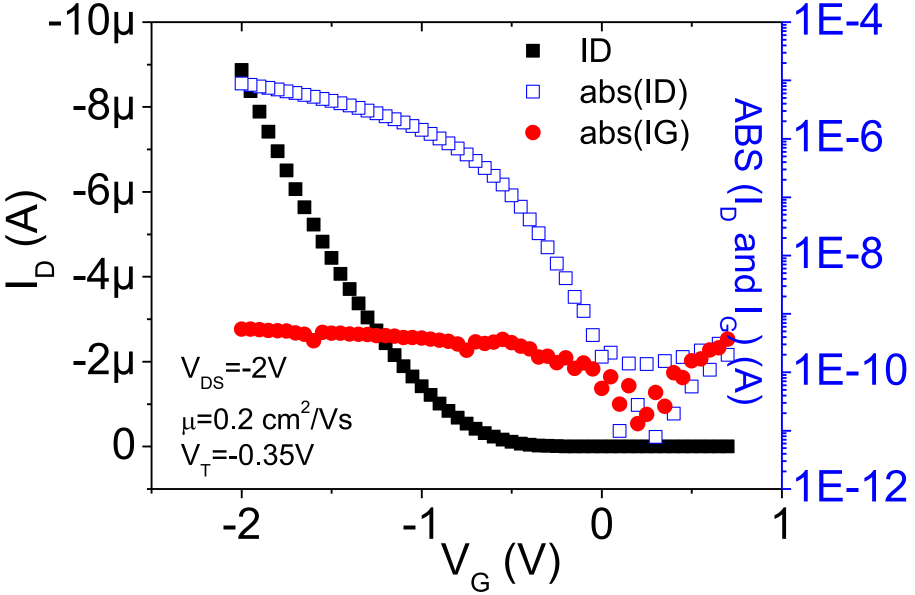
- *High yield*
- *Negligible hysteresis*
- *Very small leakage current*

TIPS-Pentacene

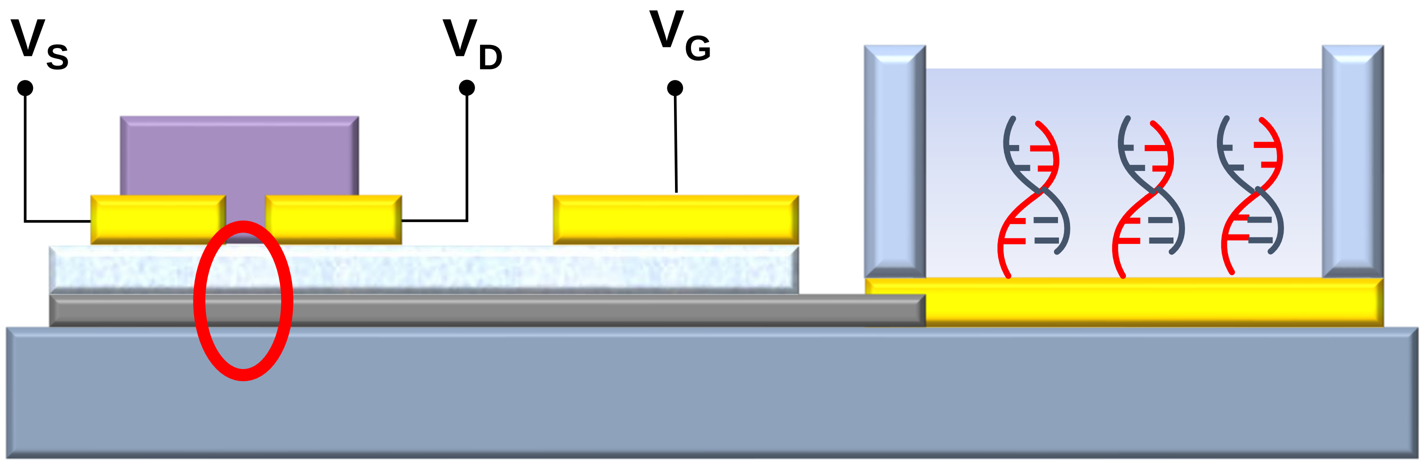


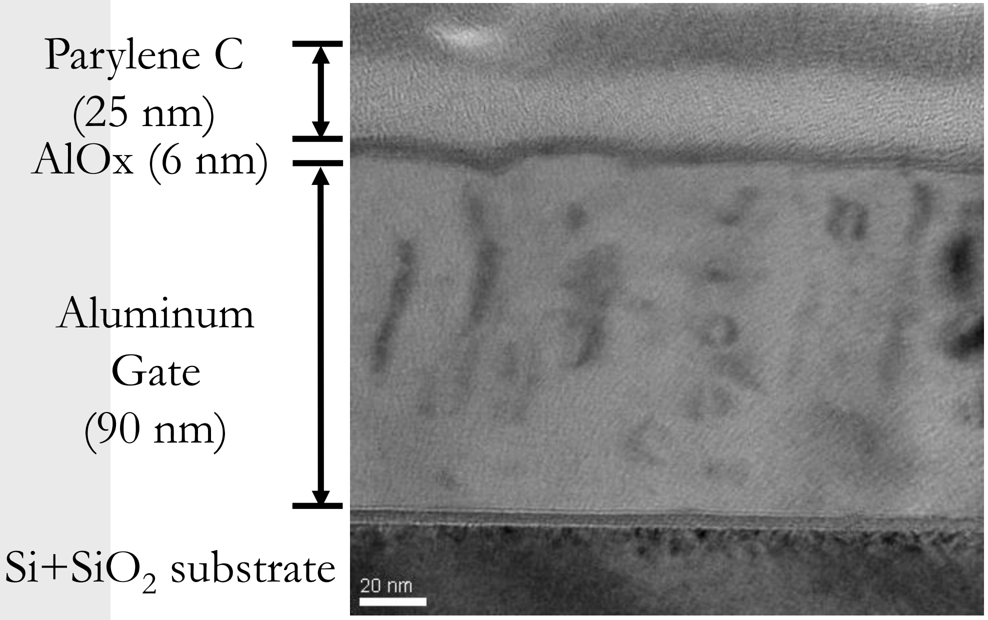
Insulating Structure	Capacitance [F/cm²]	I_G [A] J_G[A/cm²]	Vt [V]	μ [cm²/Vs]	S [mV/dec]	OTFTs Yield [%]
AlOx + Parylene	1.3 E-7	4 E-10 1.9 E-9	-0.2/-0.4	0.3	150	99%

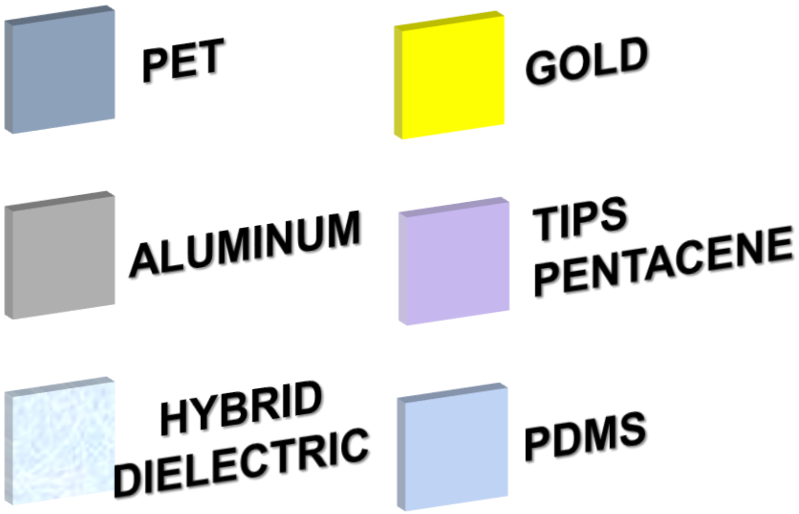




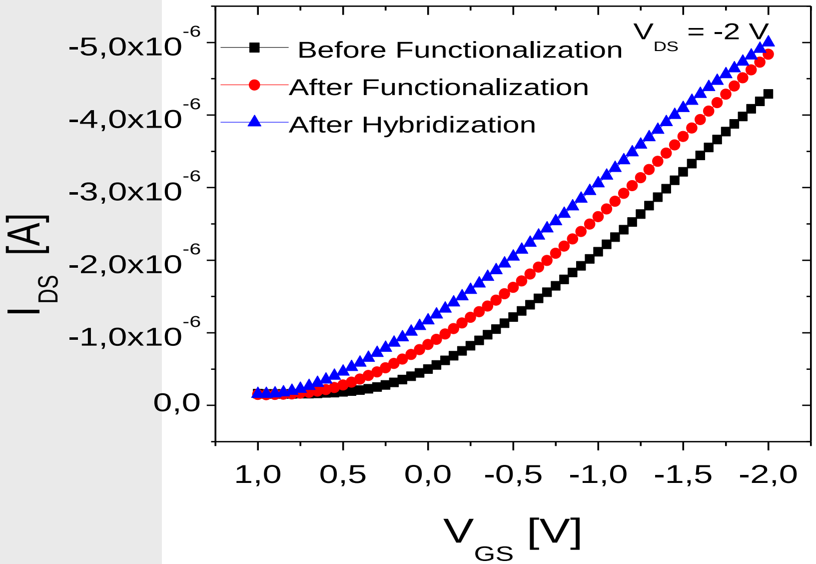
Low Voltage OCMFET for DNA sensing

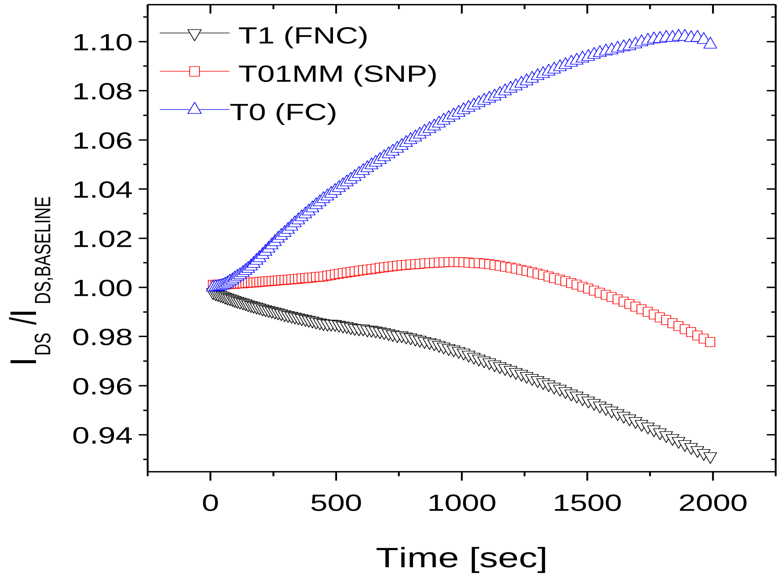


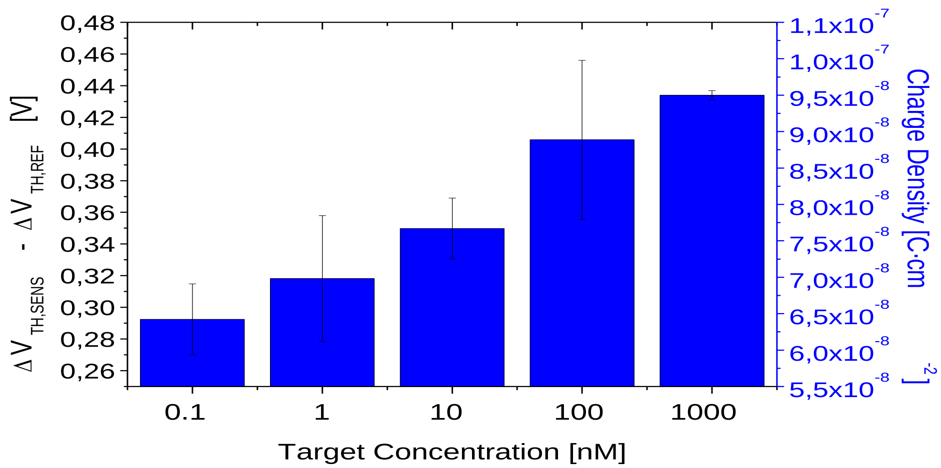




Low Voltage OCMFET-DNA sensing

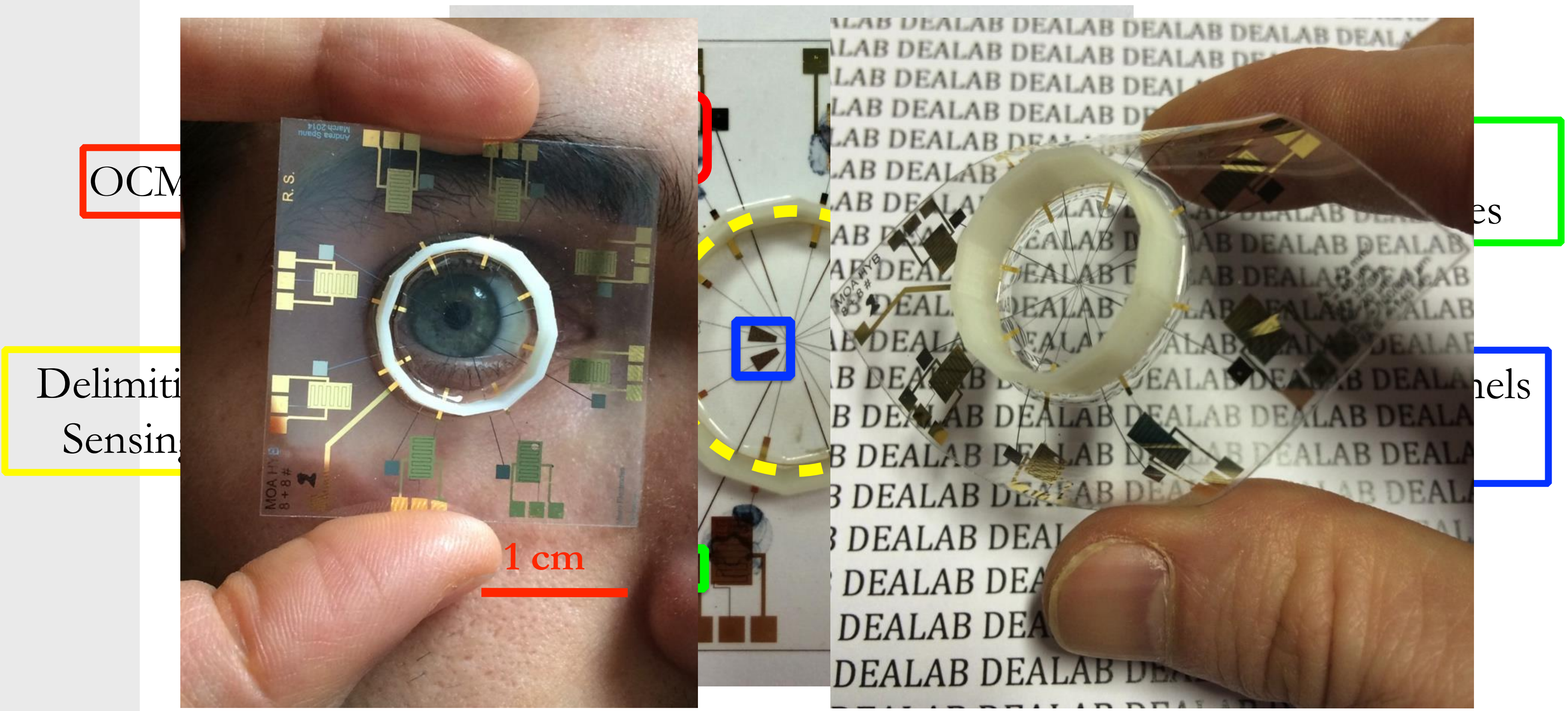






Lai et al., Adv. Mat. 25, 103-107, 2013

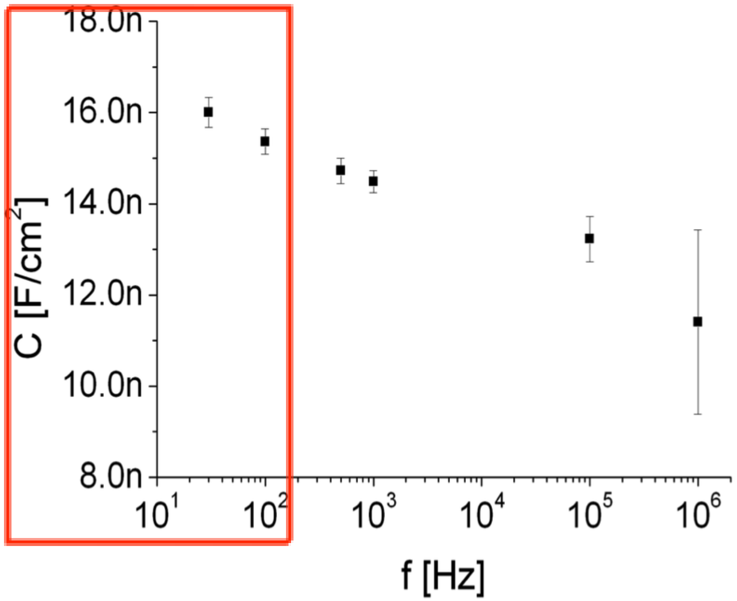
The Micro OCMFET Array - MOA

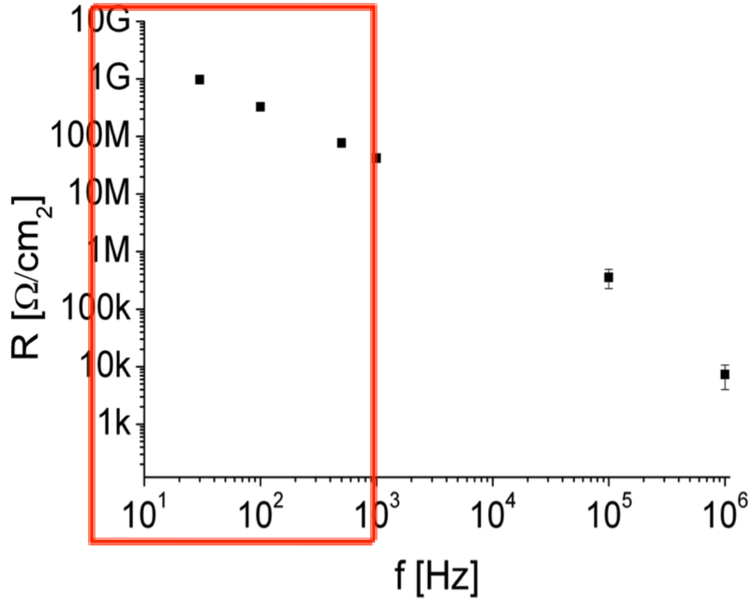


- Up to 16 OCMFET onto the same substrate
- Interdigitated source and drain contacts → larger output signals
- Sensing areas: 30x30 μm – 60x60 μm
- Passive microelectrodes integration → cross checking
- Predisposition to pH/temperature/strain (…) measurements

Titanium MOAs

The **aluminum** layer turned out to be **not suitable** for long-term applications (pinholes led the Al layer to dissolve after few days) Aluminum was replaced by **Titanium**

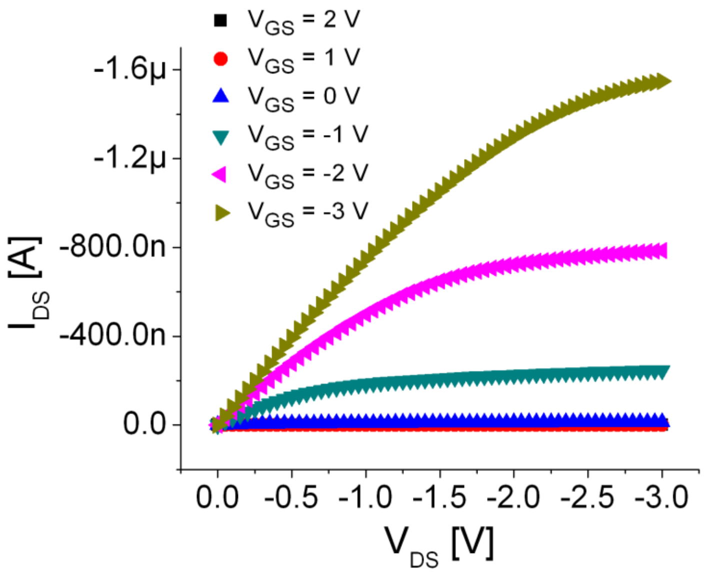


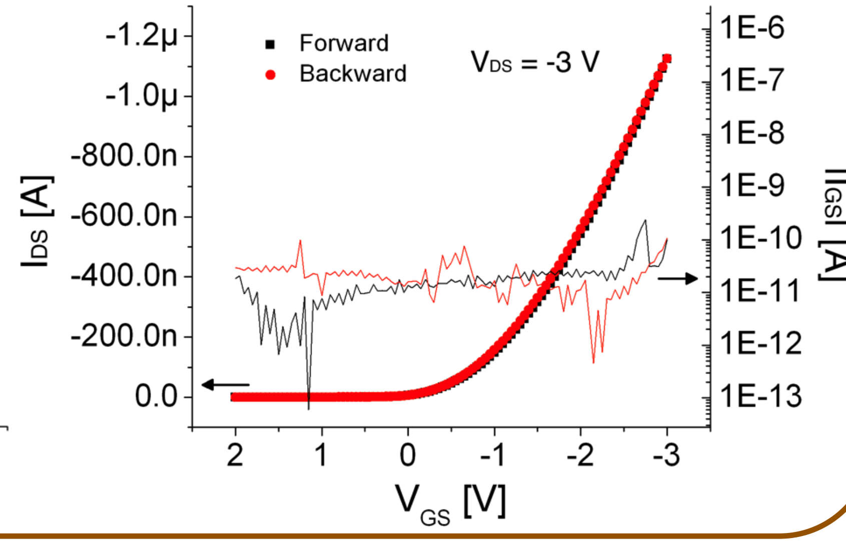


- Preliminary tests with native TiO_2/Par C (150 nm thick) capacitors
- Statistics on 18 capacitors
- Slightly lower parallel resistance with respect to Al/Par C structures

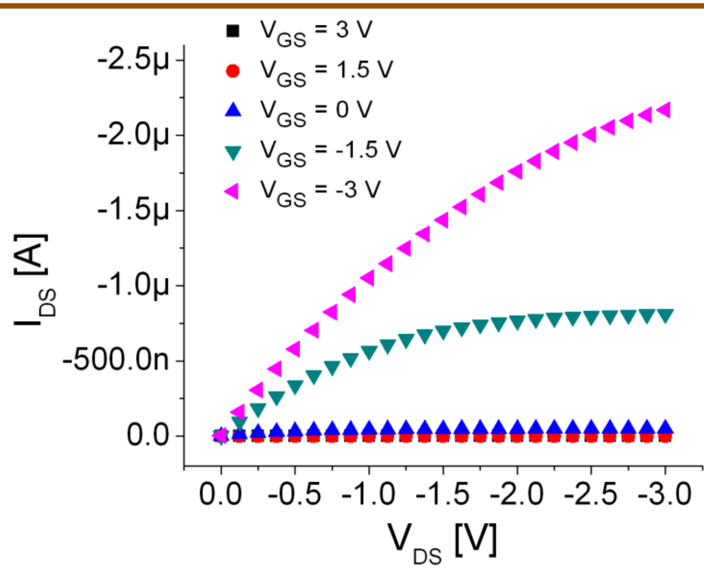
Titanium MOAs

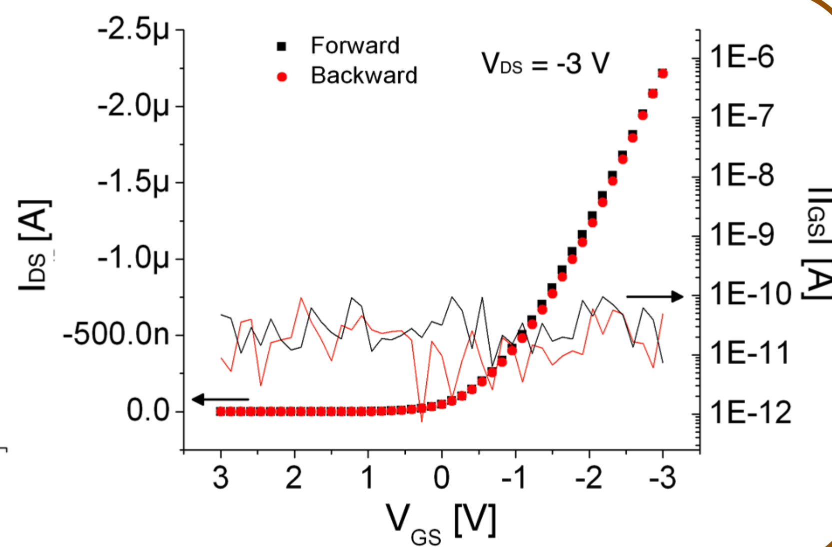
Al_2O_3/Par C OCMFET





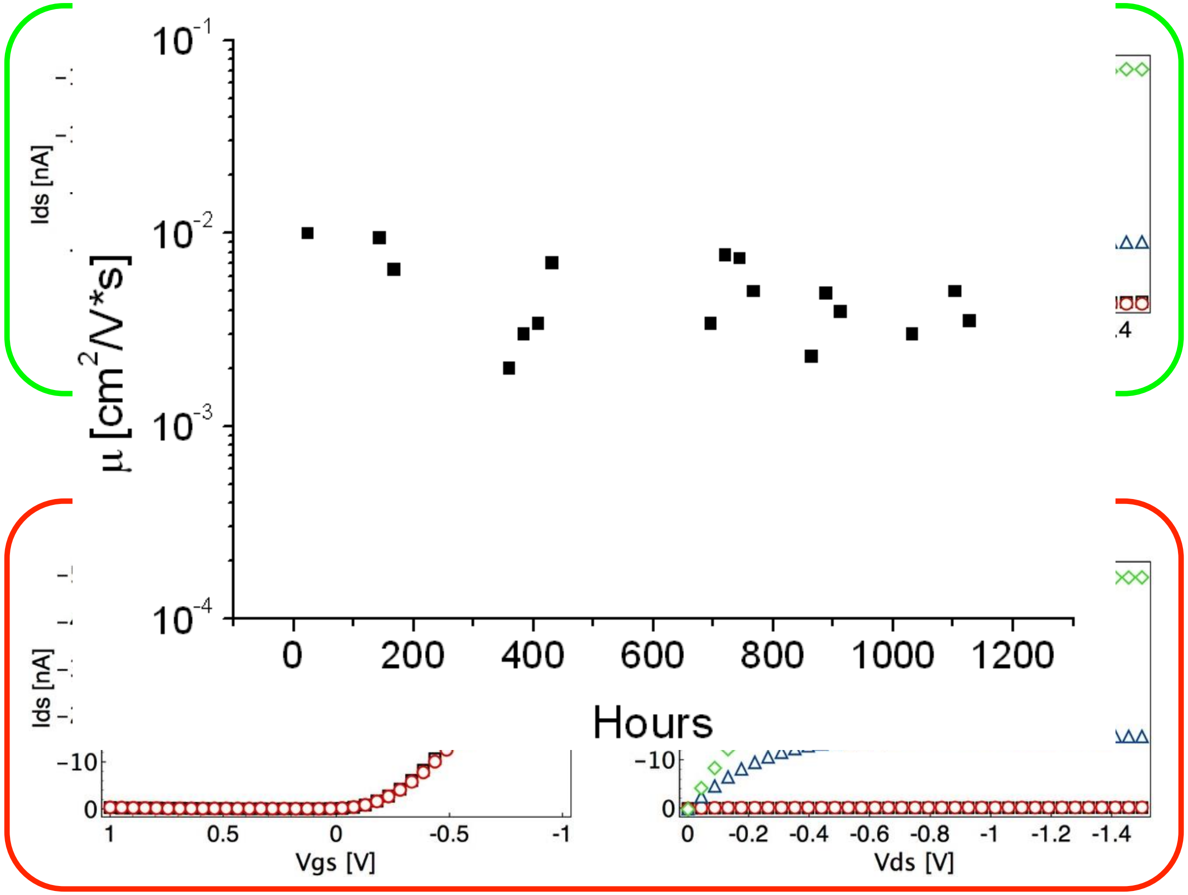
TiO_2/Par C OCMFET





Endurance assessment

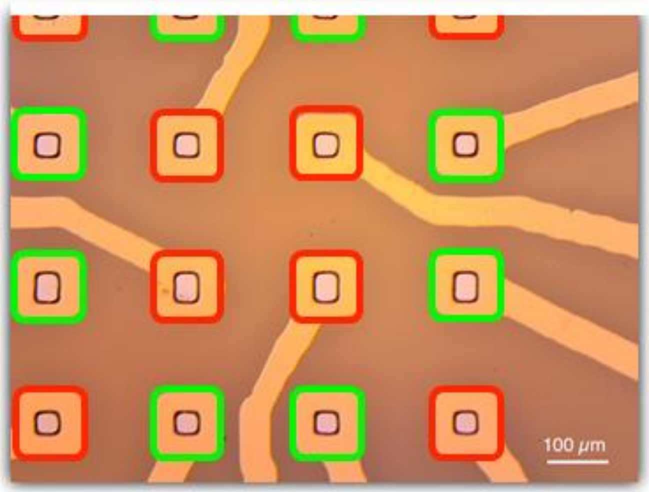
Incubation conditions: 37° C, 95% humidity, and 5% CO_2



MOAs passivation

A good tracks passivation is important **to reduce the noise** and to precisely delimit the sensing areas (fine spatial localization of the detected signals)

Photoresist passivation

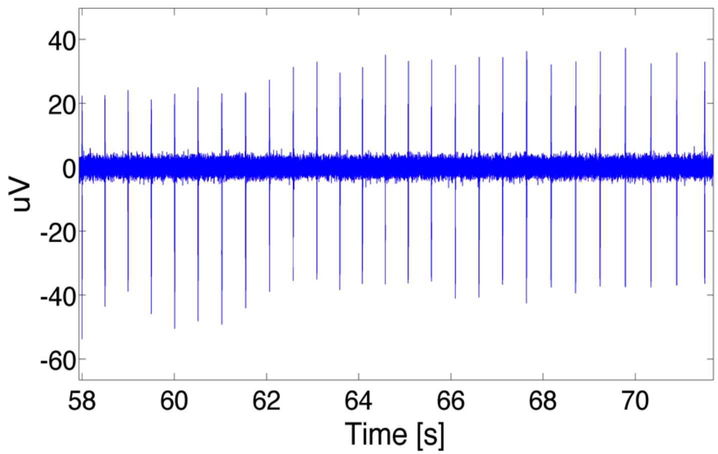


- Low cost commercially available photoresist (AZ1518 from Microposit)
- No additional plasma treatment
- High reproducibility
- **In order to host cells, the probe area is coated by a thin film of collagen and fibronectin**

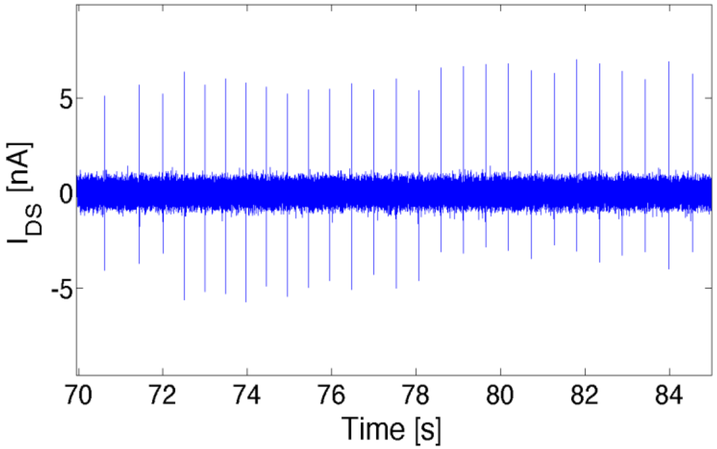
Monitoring cardiomyocytes activity

- Rat cardiomyocytes primary cultures
- Measurements performed @ 37 °C
- $V_{GS}=V_{DS}= -1$ V
- All the experiments have been carried out inside a Faraday cage
- Activity of the same culture measured with different methods (Multi Channel Systems MEA1060 Amplifier)
- <u>No need of a reference electrode</u>

Microelectrode Recording

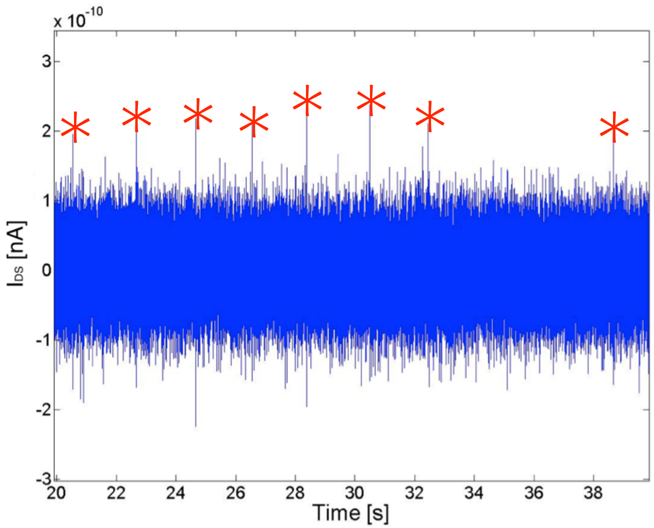


OCMFET Recording



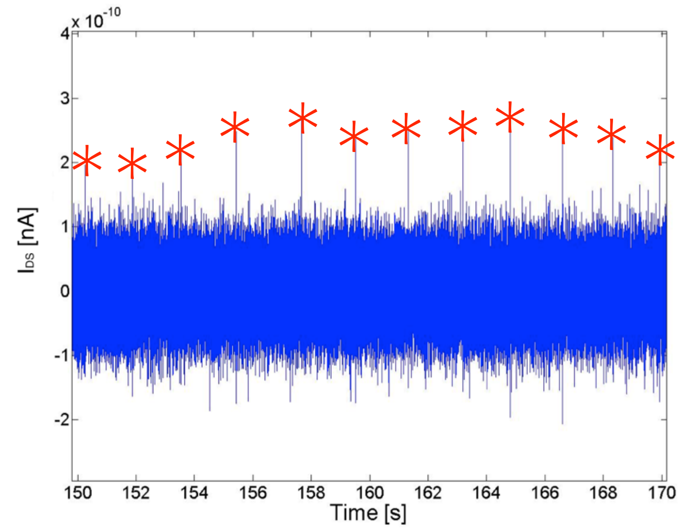
A. Spanu et al. An organic transistor-based system for reference-less electrophysiological monitoring of excitable cells. *Sci. Rep.* **5**, 8807 (2015) doi:10.1038/srep08807.

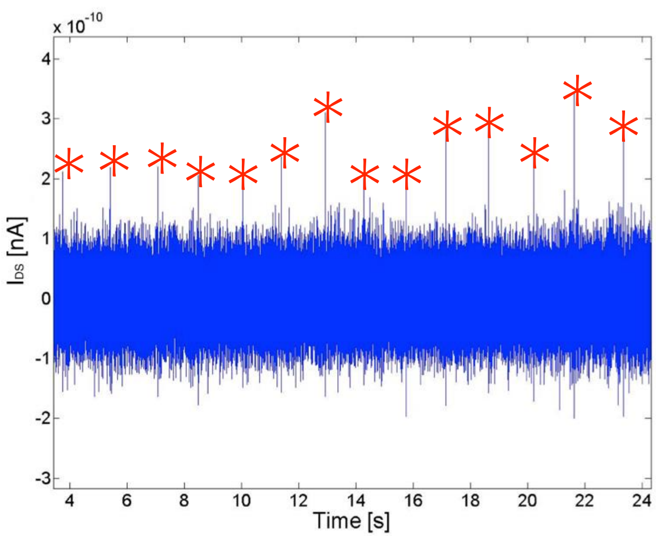
Thermal modulation of cardiomyocytes activity



From 35 °C to 40 °C

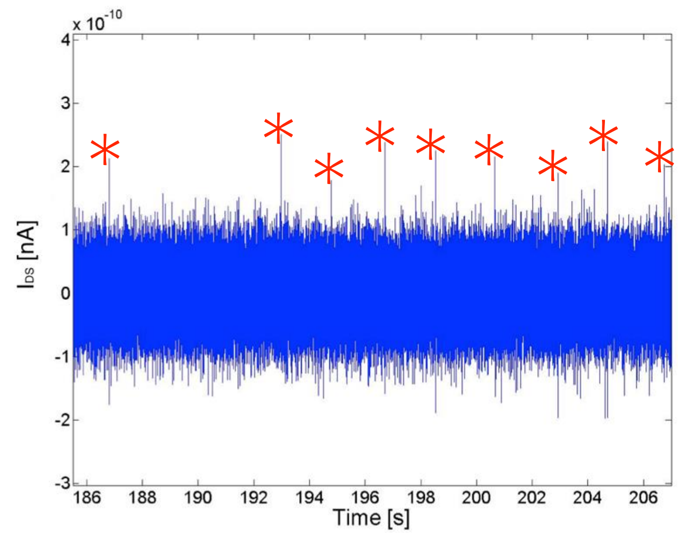
Beat Rate:
From 0.4 to 0.7 Hz



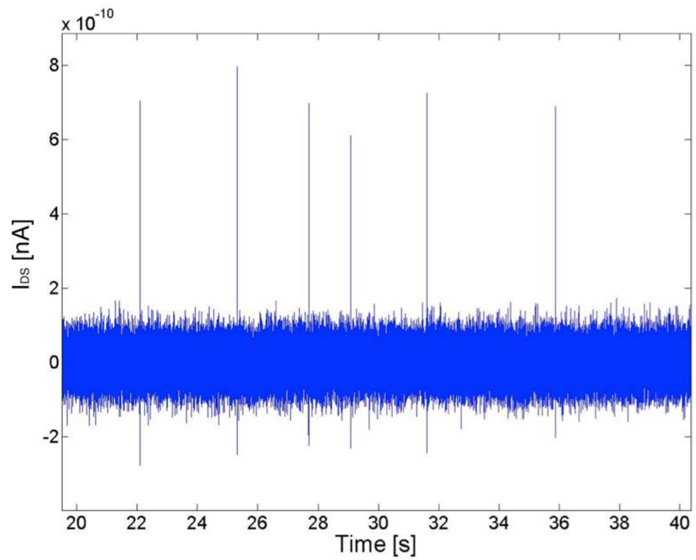


From 40 °C to 35 °C

Beat Rate:
From 0.7 to 0.4 Hz

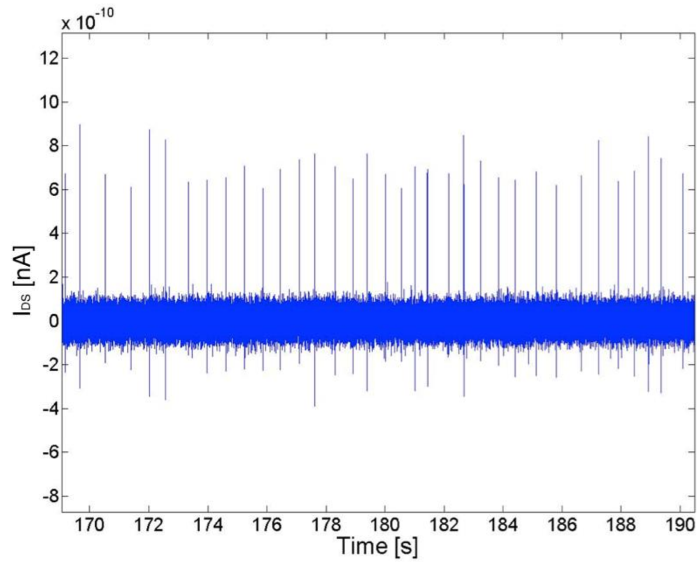


Chemical modulation of cardiomyocytes activity



Basal activity @ 37° C

Spike frequency: 0.3 Hz

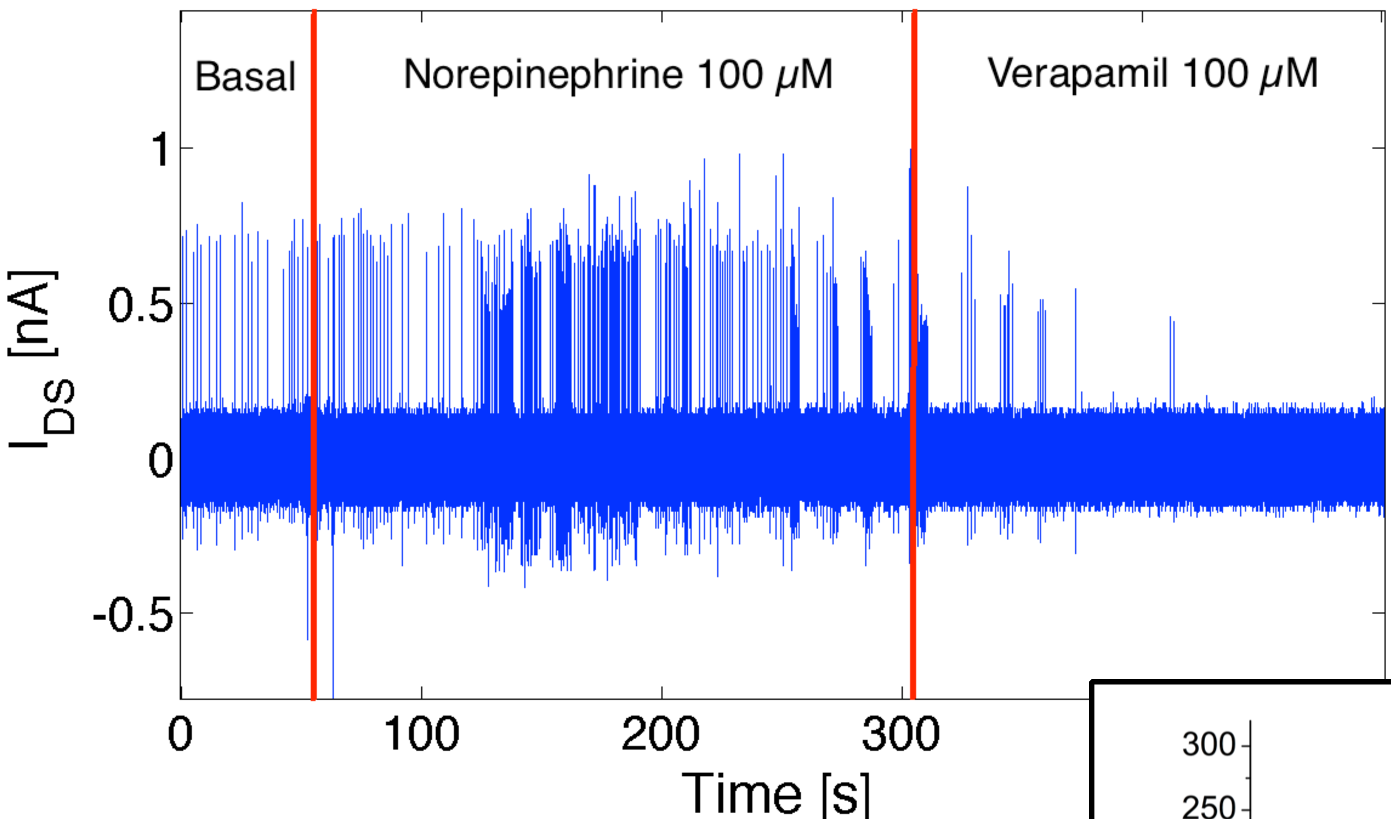


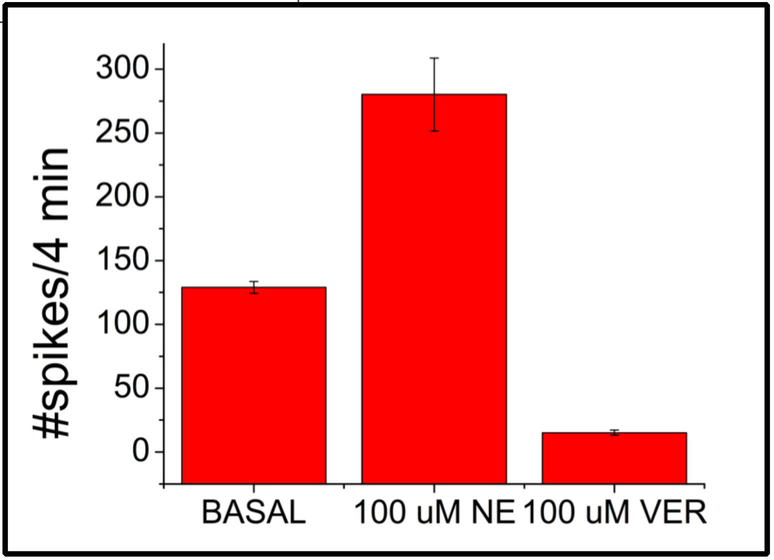
Norepinephrine (100 µM)

A neurotransmitter that acts as a cardio-stimulant

Spike frequency: 1.6 Hz

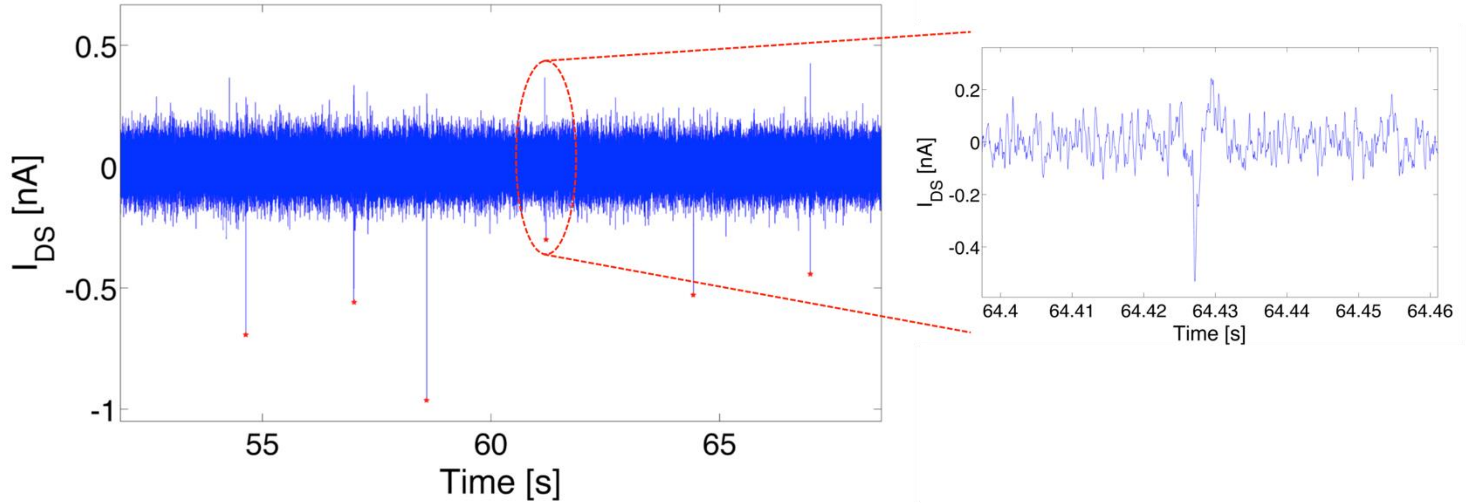
Chemical modulation of cardiomyocytes activity



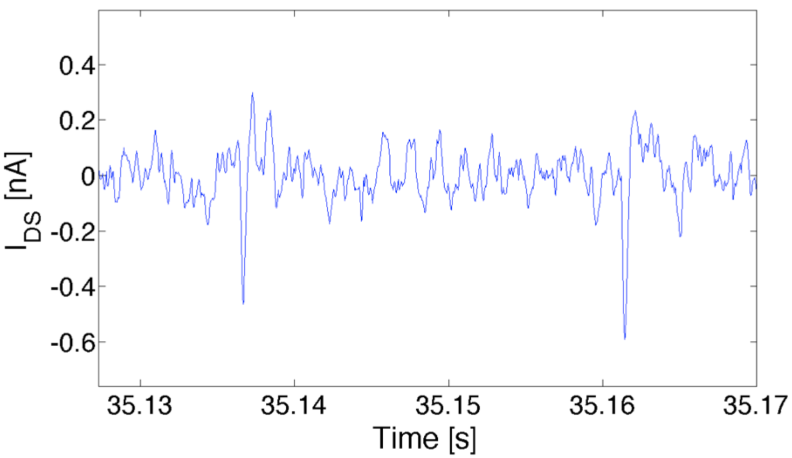


Statistics on 5 working OCMFETs on the same substrate

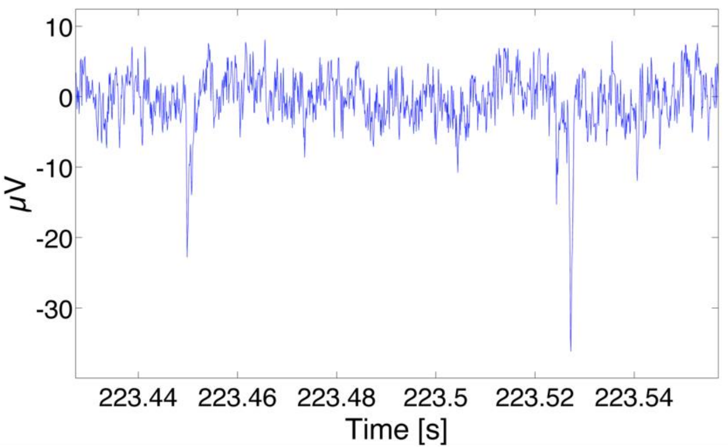
Striatal neurons: technology validation



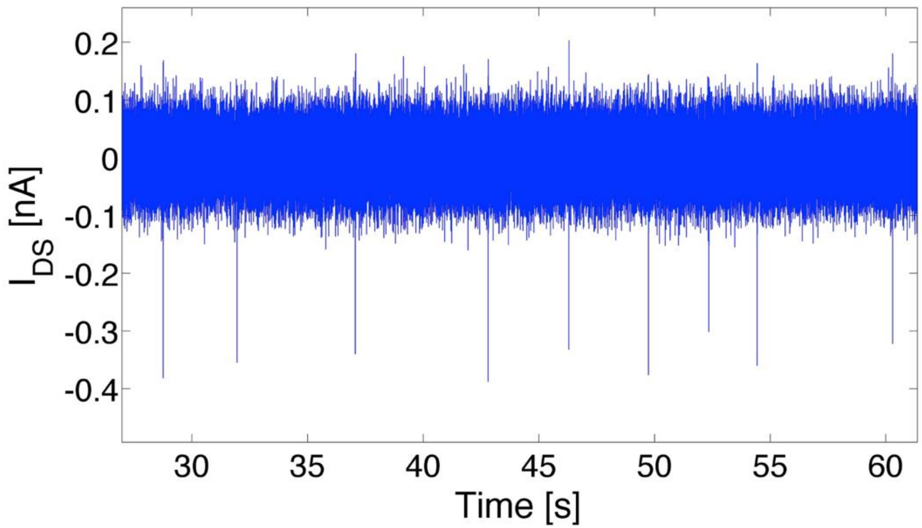
OCMFET Recording



Microelectrode Recording

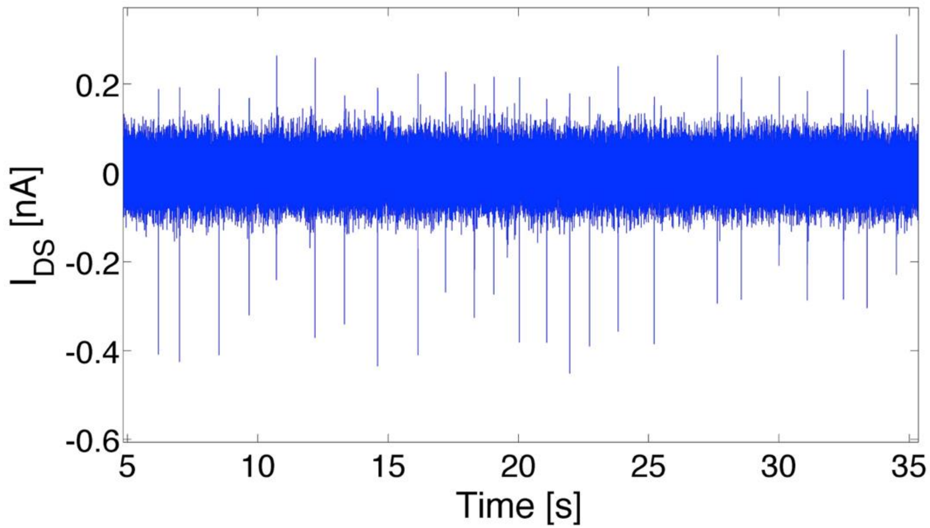


Hippocampal neurons - chemical modulation



Basal activity @ 37° C

Spike frequency: 0.3 Hz

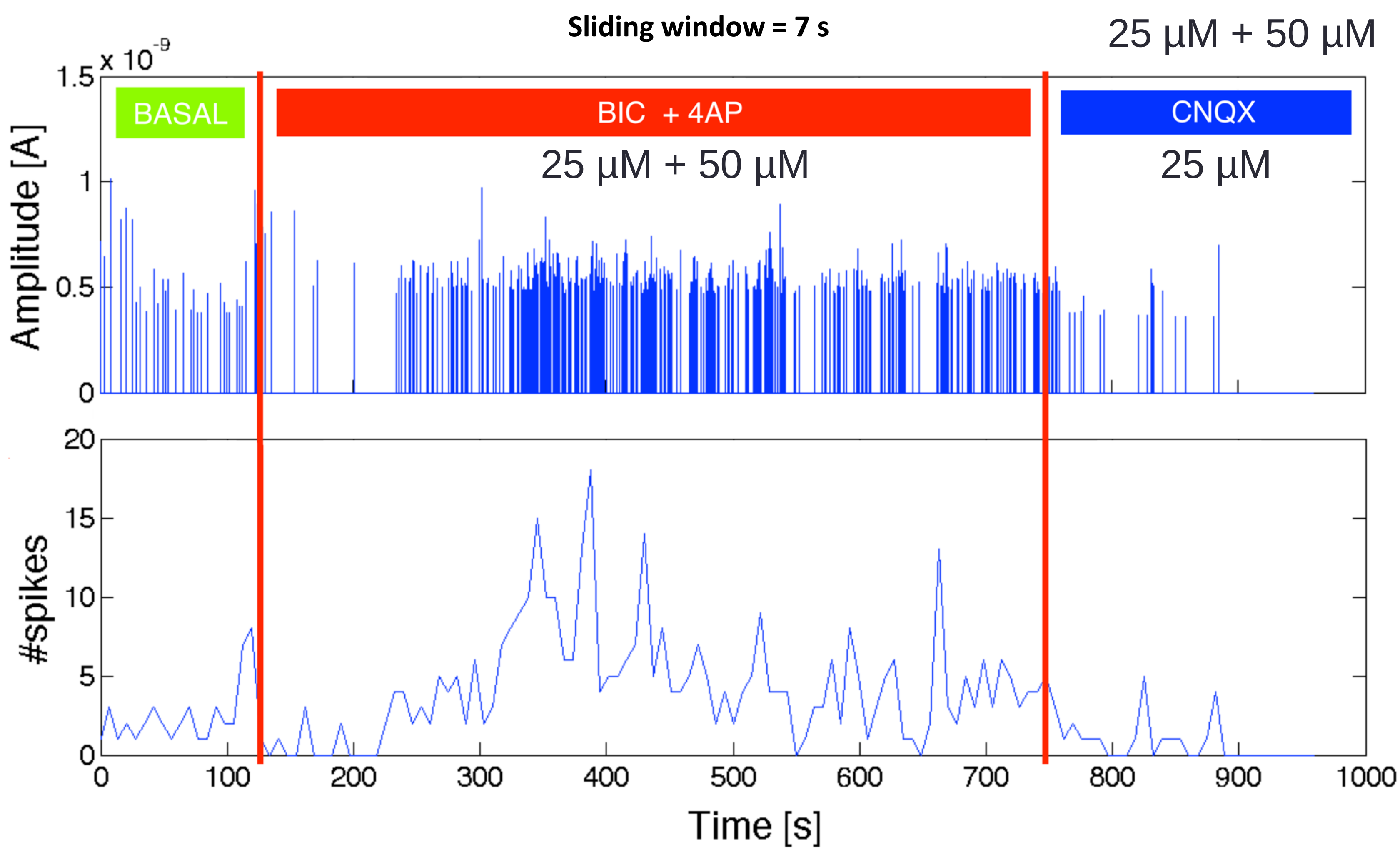


50 µM 4Amino Pyridine (4AP):
Reduction of the threshold of excitability

Spike frequency: 0.9 Hz

25 µM Bucuculline (BIC):
Blockade of the inhibitory action of $GABA_A$ receptors

Hippocampal neurons - chemical modulation

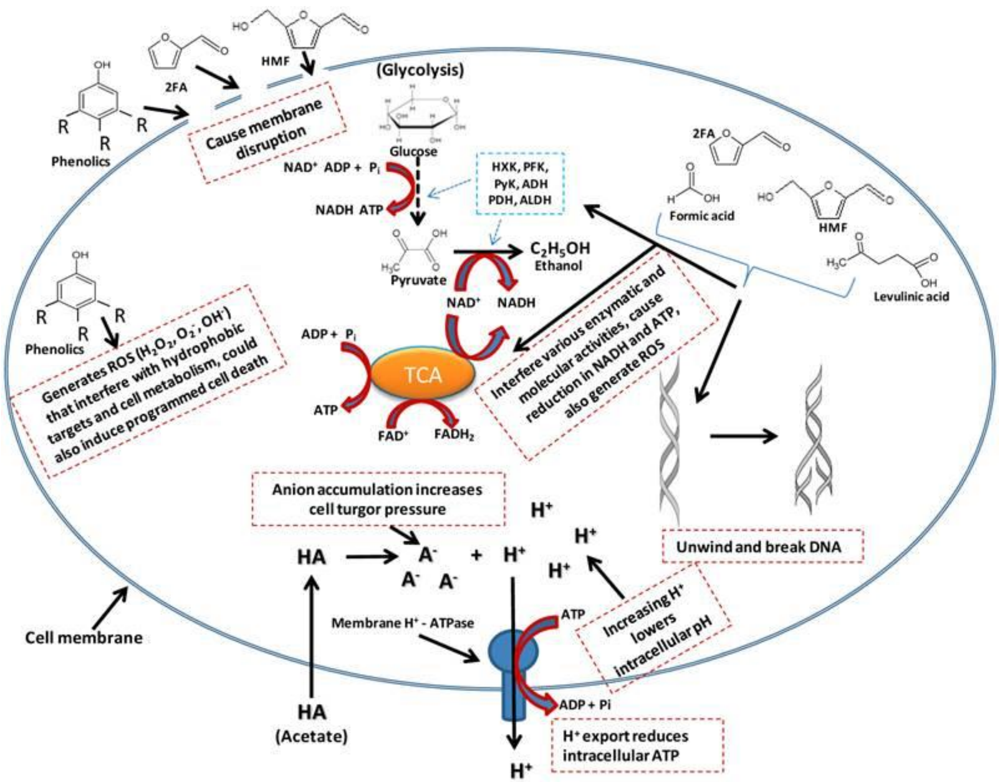


Toward a multisensing MOA device

pH sensors using OCMFETs

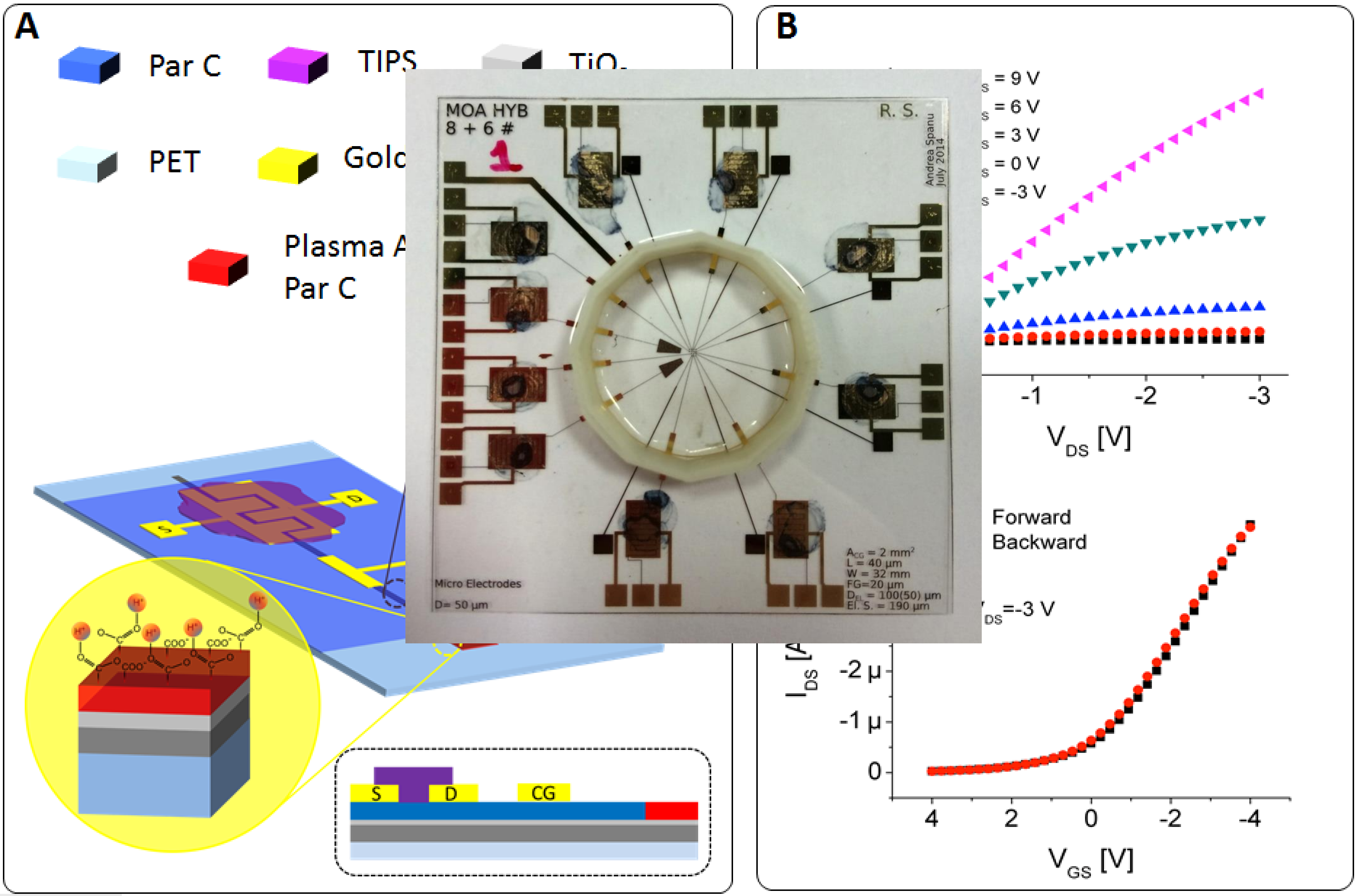
Monitoring pH during in vitro and in vivo electrophysiological applications is very important since **living cells are sensitive to pH changes of the surrounding medium**.

Furthermore, local pH variation are associated to **cells metabolic activity.**



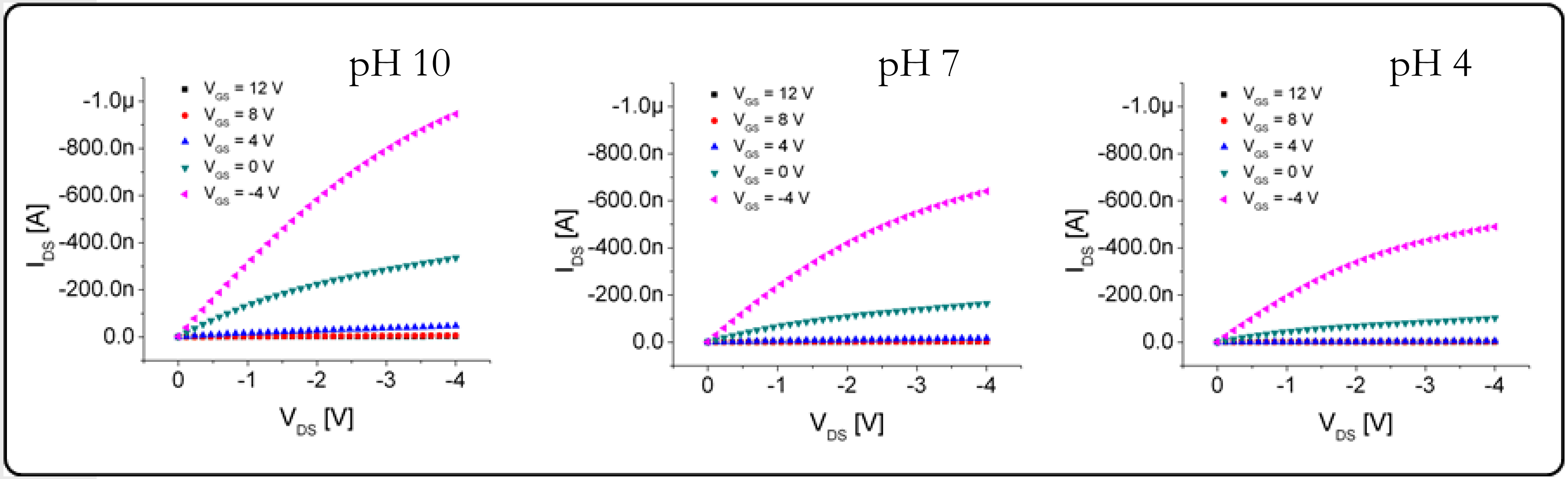
Martinoia, S. et al. Development of ISFET array-based microsystems for bioelectrochemical measurements of cell populations. *Biosens. Bioelectron.* **16**, 1043–1050 (2001).

pH sensors using OCMFETs



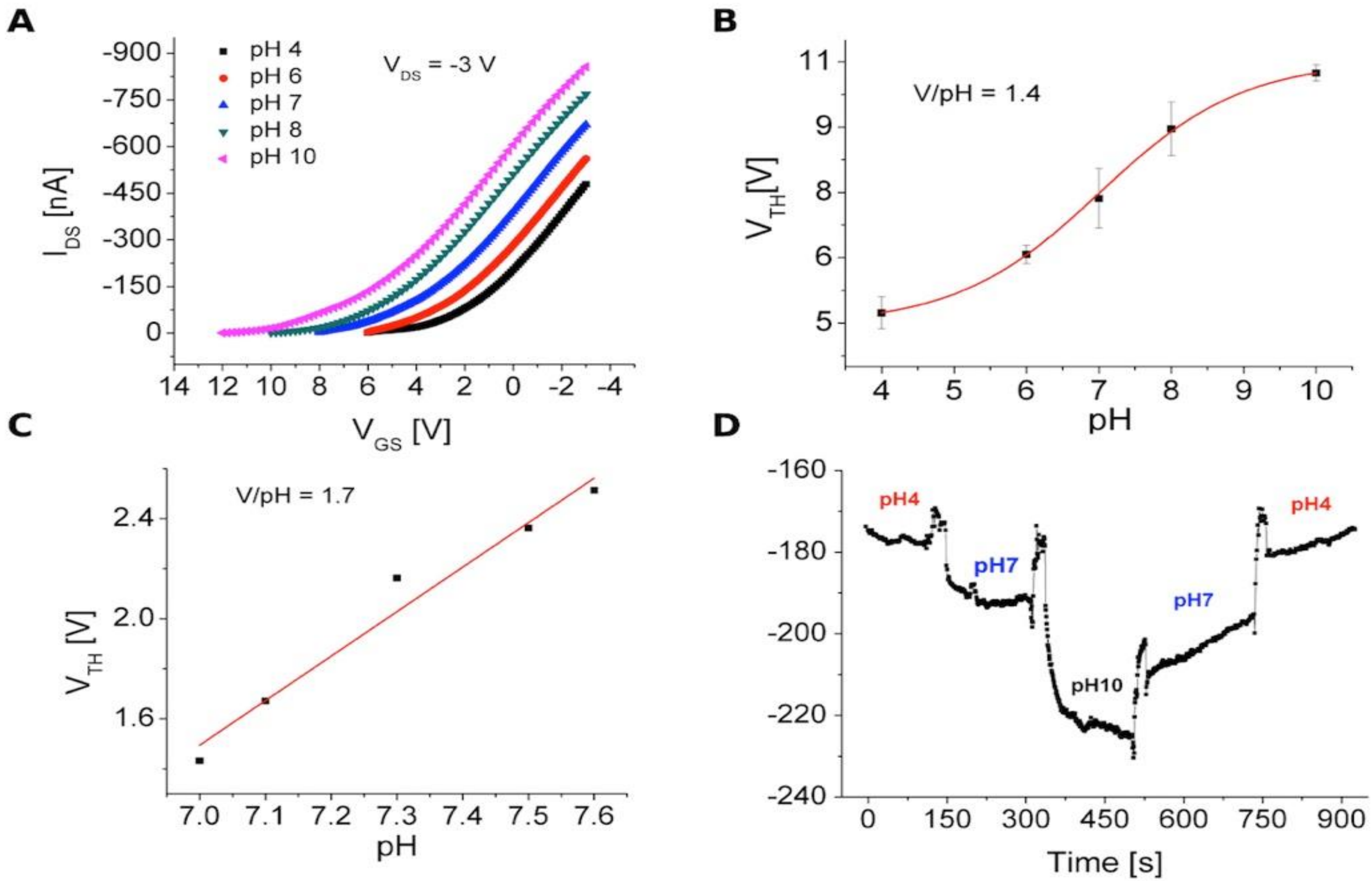
pH sensors: Static characterization

When Parylene C is activated by plasma-oxygen, -COOH functional group are dissociated to negatively charged -COO-

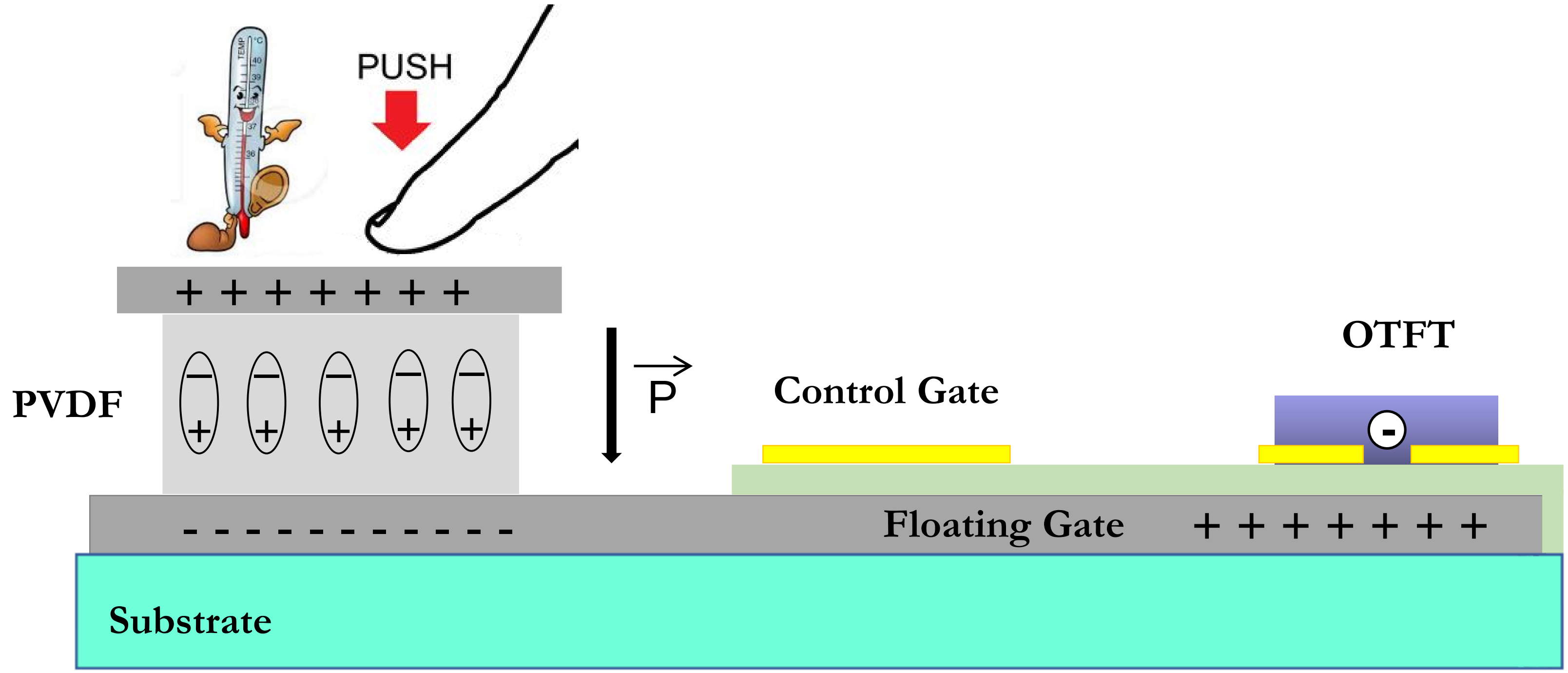


The -COOH -> / <- -COO- + H+ are reversible with pH.

pH sensors characterization

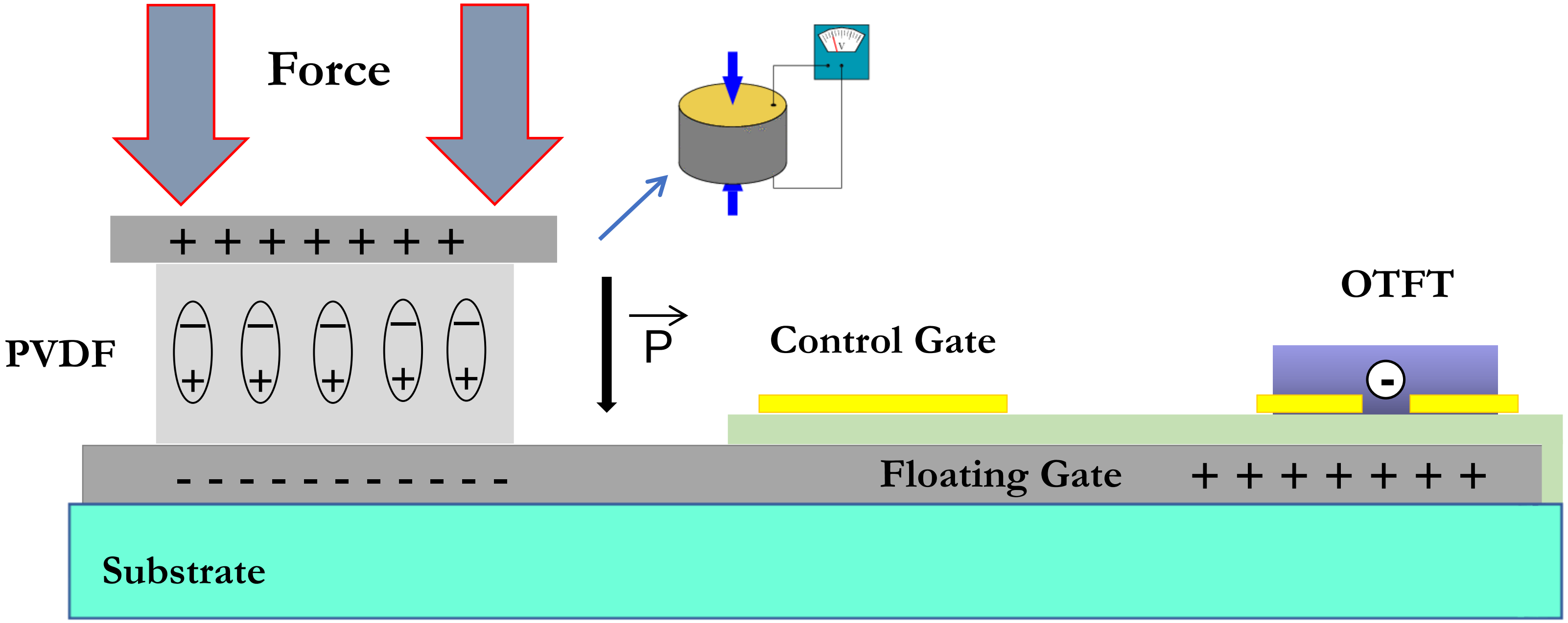


OCMFET – tactile sensor



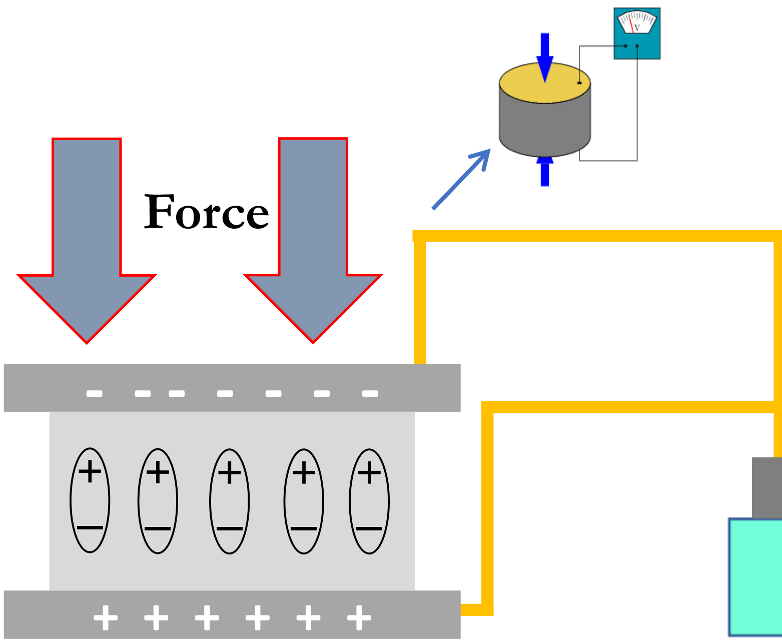
- Integration of a piezo/pyro electric polymer on the OCMFET sensing area
- The charges induced by mechanical/thermal stimuli lead to a variation of the OTFT threshold voltage

OCMFET-force sensing

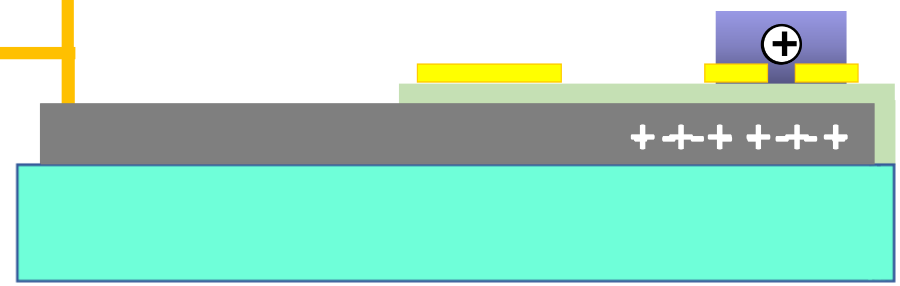


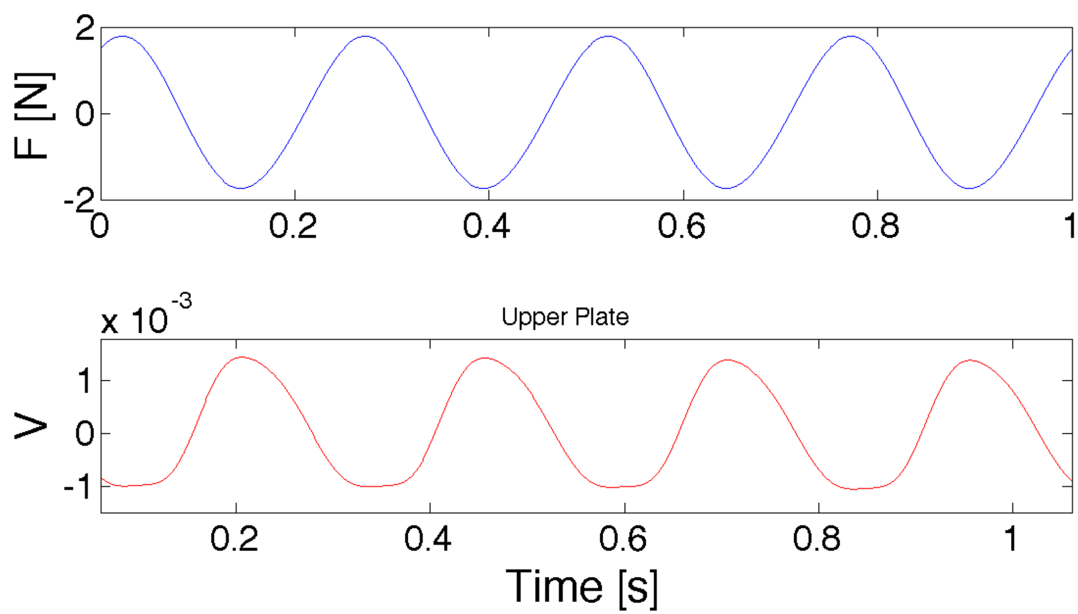
- A piezoelectric polymer, poly(vinylidenefluoride) (PVDF), is deposited on the sensing area.
- Applying a force on the PVDF film induces charges on the floating gate, thus shifting the OTFT threshold voltage → current variation

OCMFET-force sensing

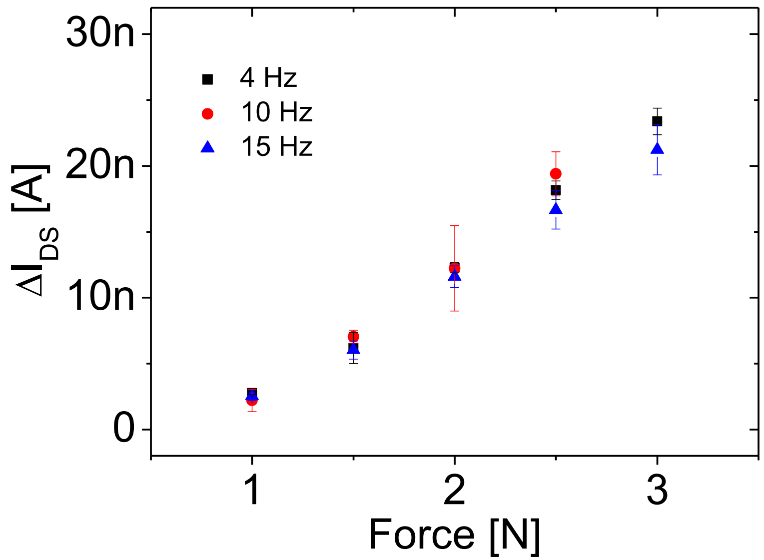


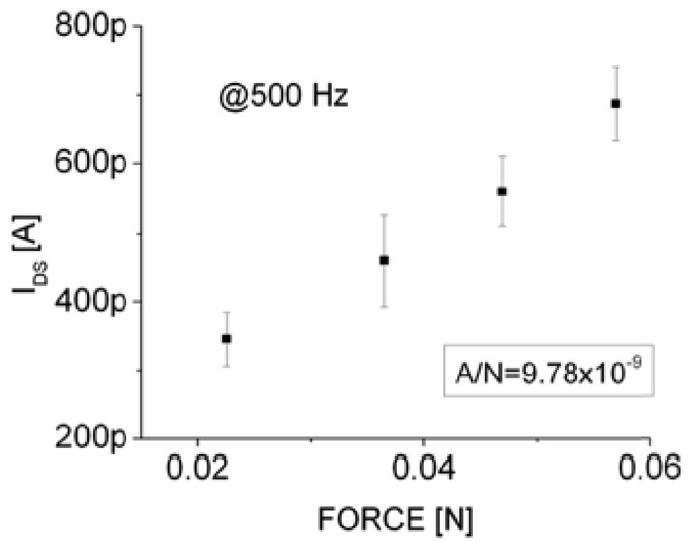
Shaker +
Load cell

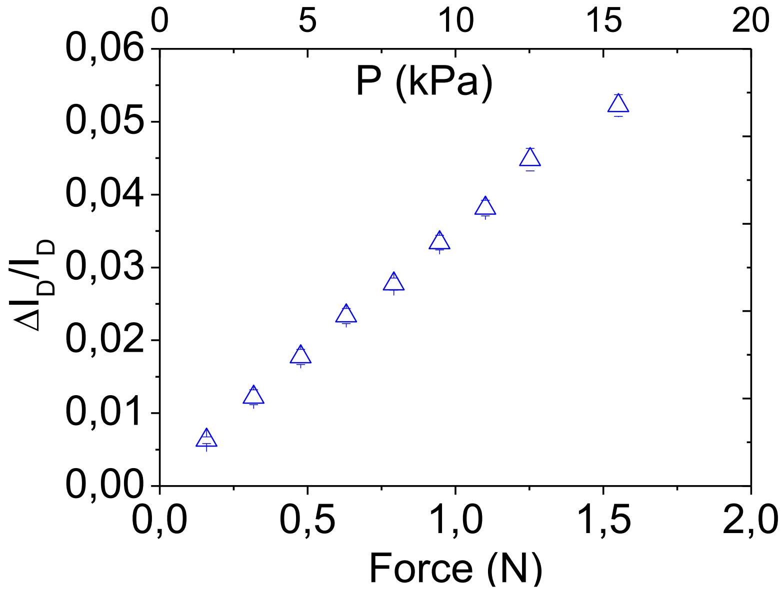




Pressure Sensors



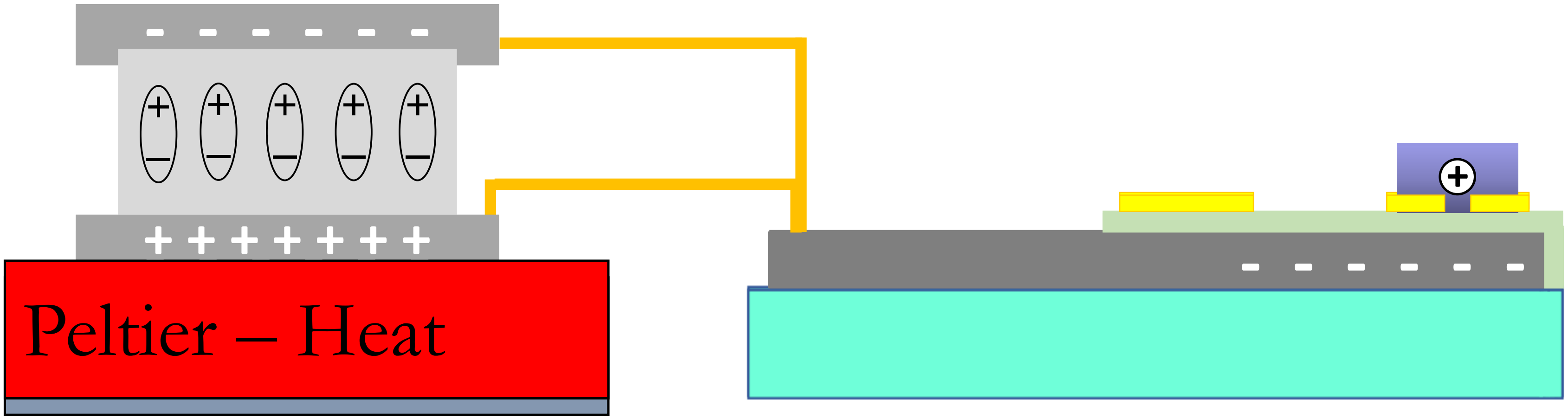


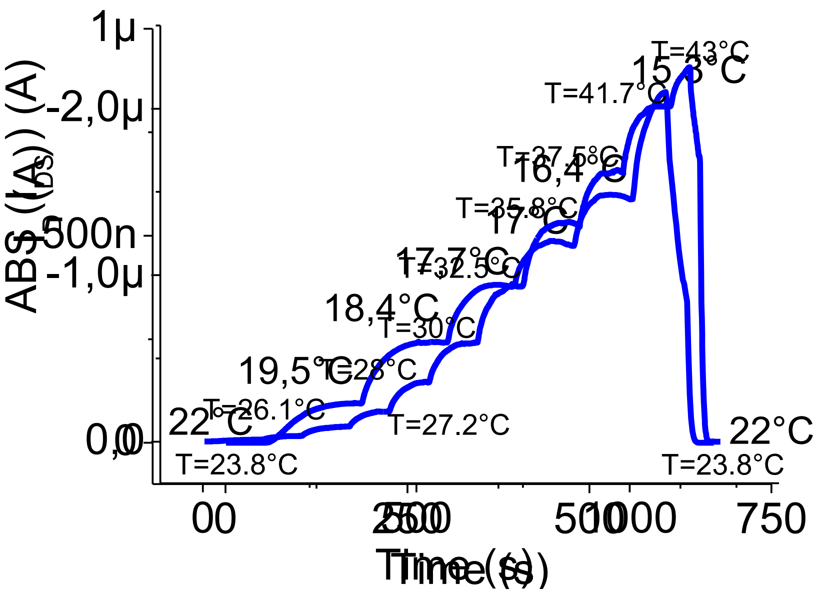


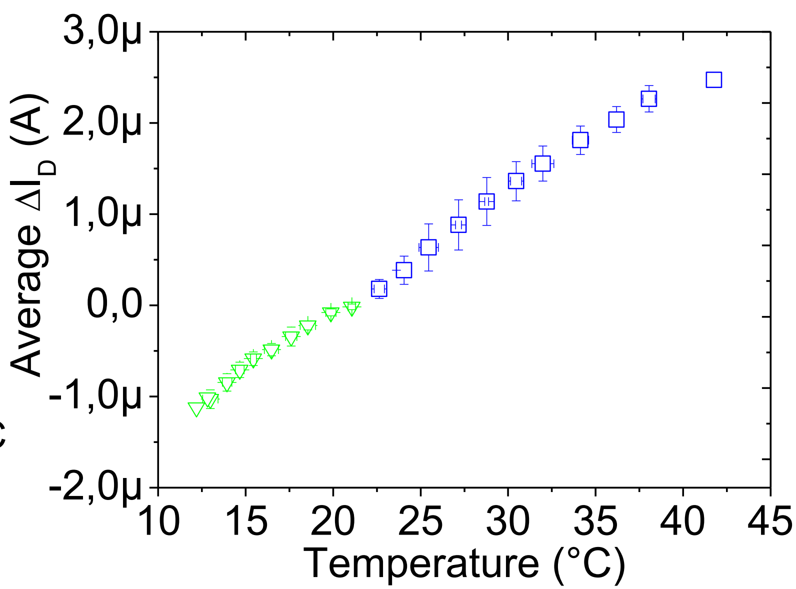
Linear behavior
Working range: 0 – 3.5 N
Resolution 0.02 N
Pressure as low as 200 Pa
Frequency range 0-500 Hz

A. Spanu, L. Pinna, F. Viola, L. Seminara, M. Valle, A. Bonfiglio, P. Cosseddu, *A high-sensitivity tactile sensor based on piezoelectric polymer PVDF coupled to an ultra-low voltage organic transistor*, Organic Electronics 36, 57-60, 2016

OCMFET- T sensing

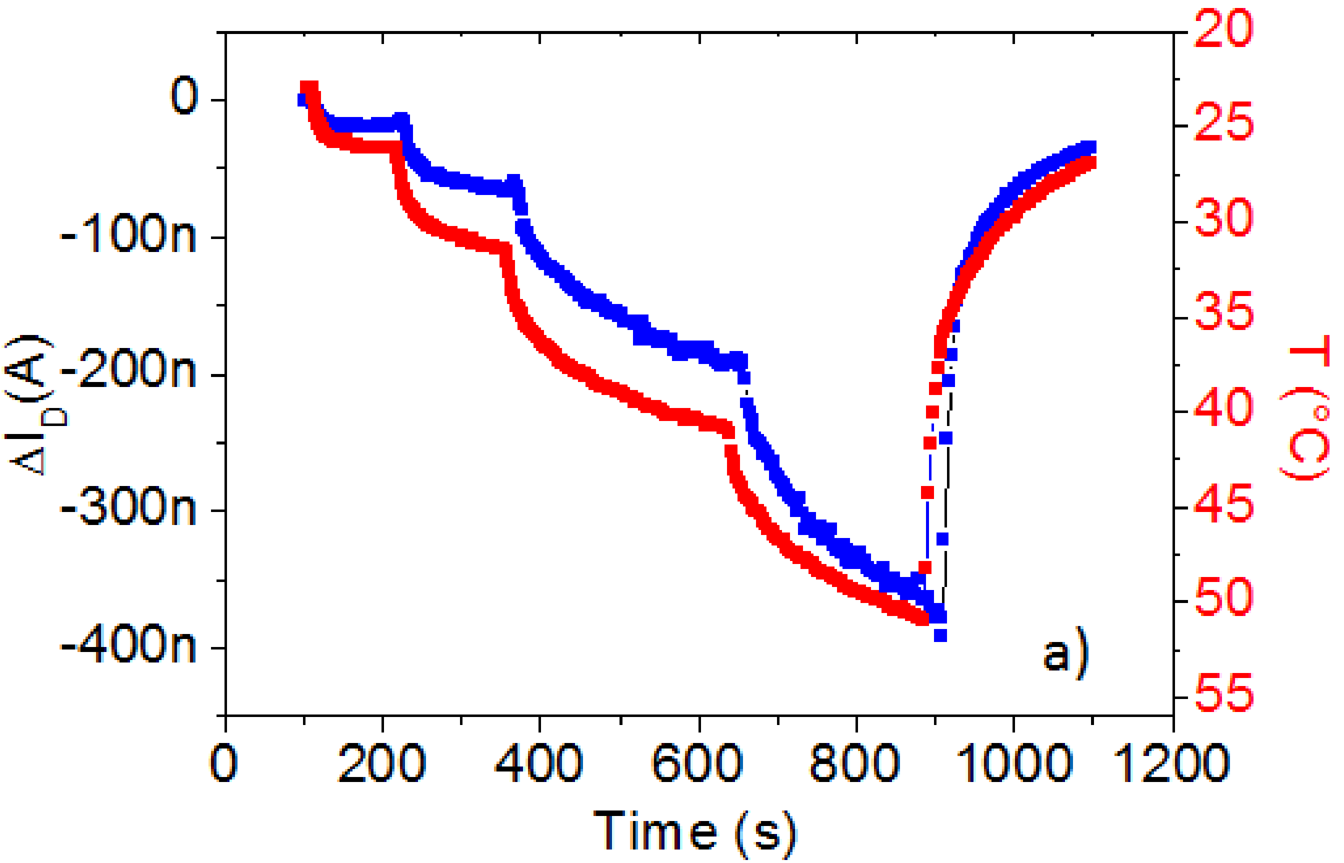






P. Cosseddu, F. Viola, S. Lai, L. Raffo, A. Bonfiglio, *A temperature transducer based on a low-voltage organic thin-film transistor detecting pyroelectric effect*, IEEE Electron Device Letters 35 (12), 1296-1298, 2014

OCMFET- T sensing

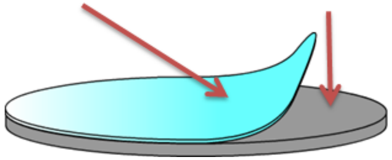


The temperature of the sensing area has been increased by using the Peltier cell and constantly monitored by means of an infrared thermometer (**PyroCouple PC21MT-1 - CALEX Electronics Limited**).

The dynamic of the device response very nicely reproduces the real temperature variation on the sensing area, meaning that **the performance of the pyro-OCMFET is comparable to the one of the commercial infrared thermometer used for these experiments.**

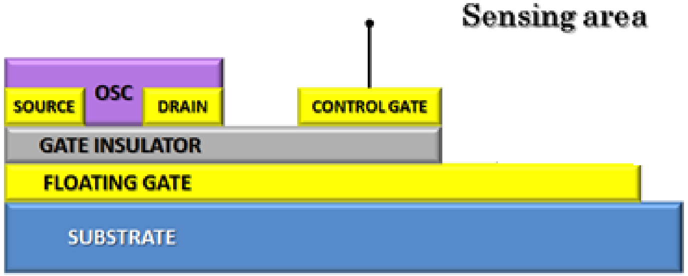
Ultraconformable electronics

✓Deposition of ultrathin, submicrometer, Parylene C films



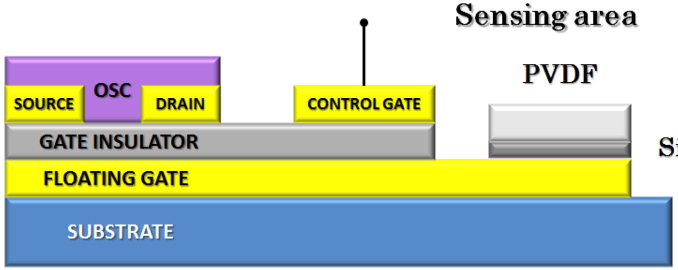
P. Cosseddu et al. *"Fully deformable organic thin film transistors with moderate operation voltage"* IEEE TED, 58, 3416-3421 (2011)

✓Patterning of the OCMFETs

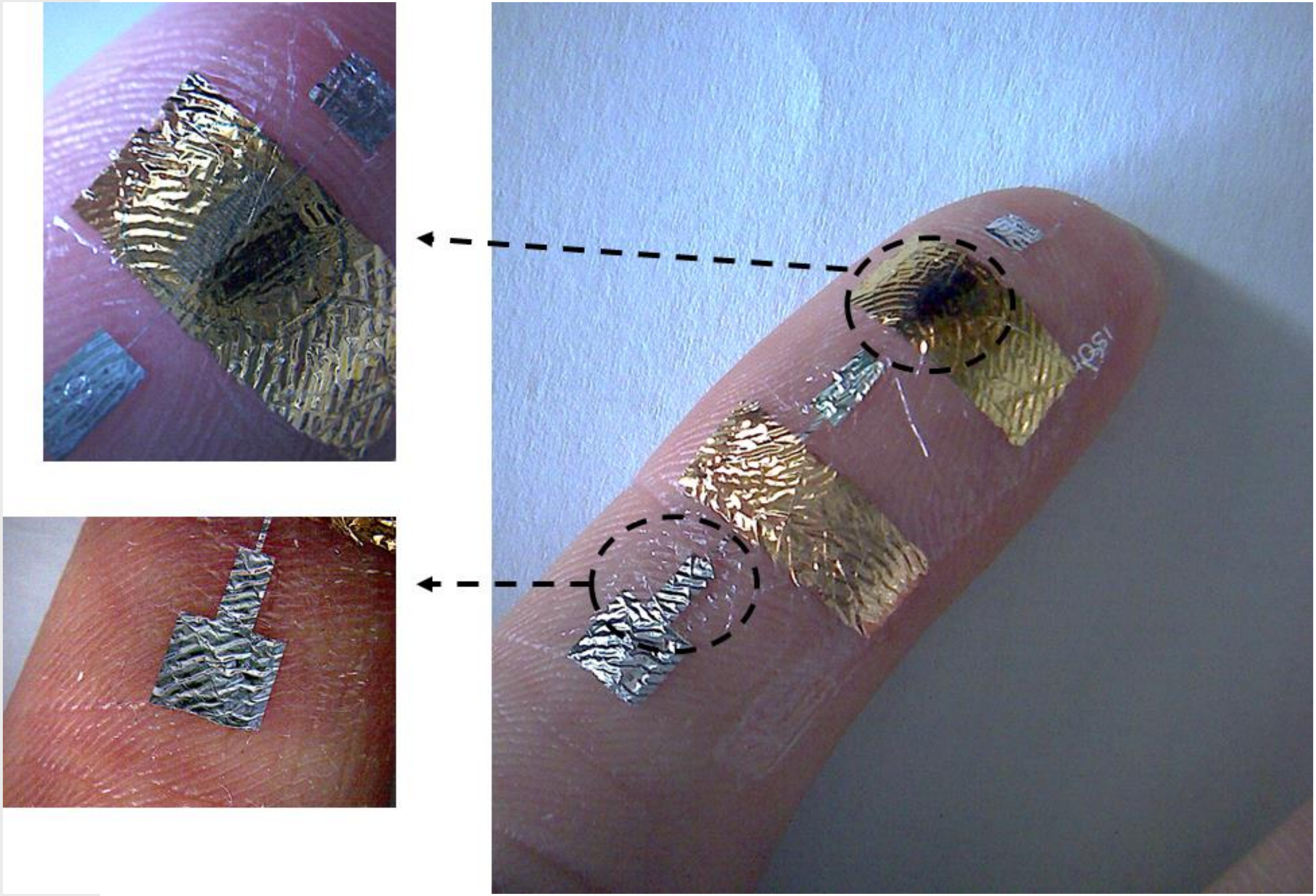


Total thickness smaller than 700 nm

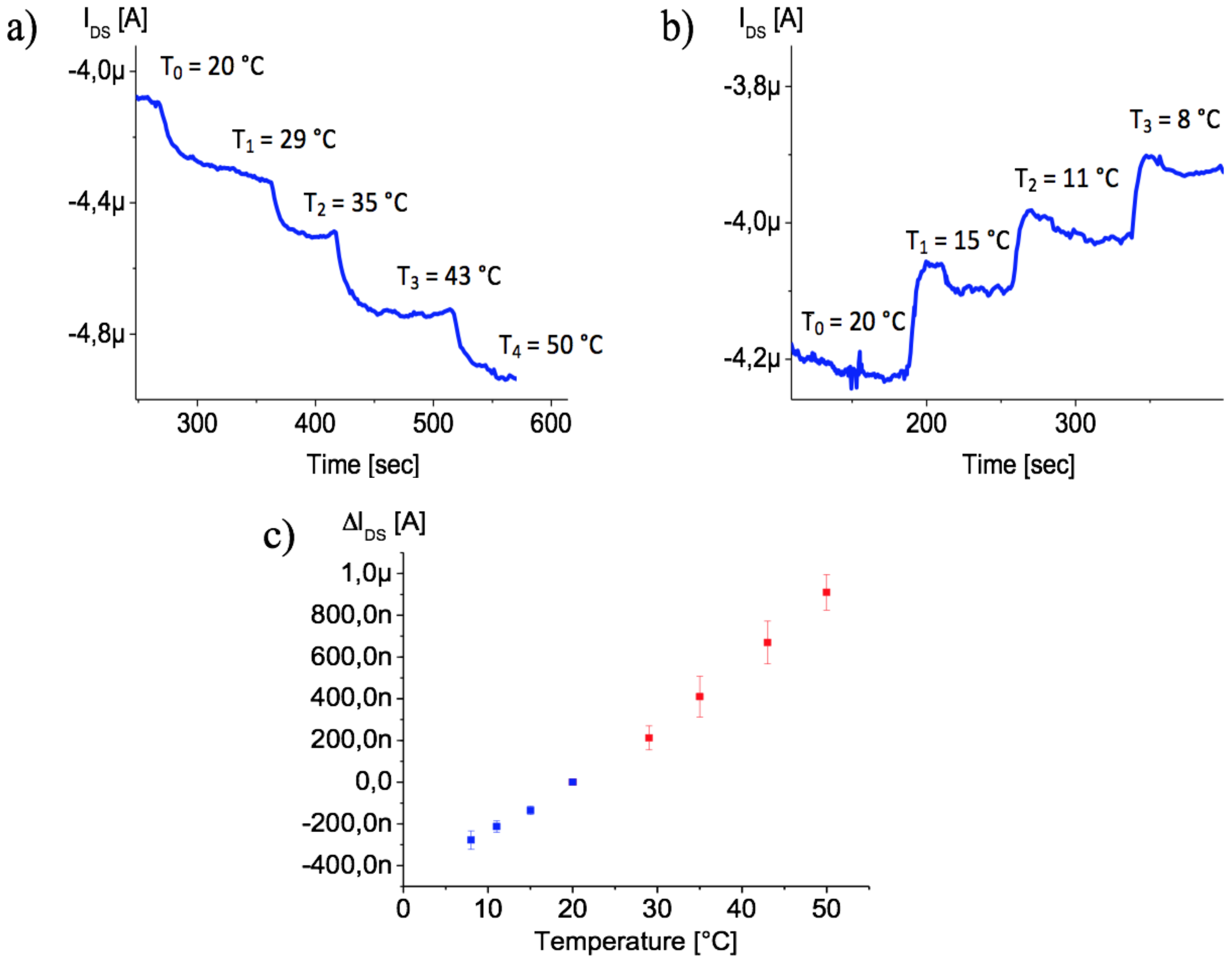
✓Spin coating and poling of a thin PVDF-TrFE film onto the sensing area



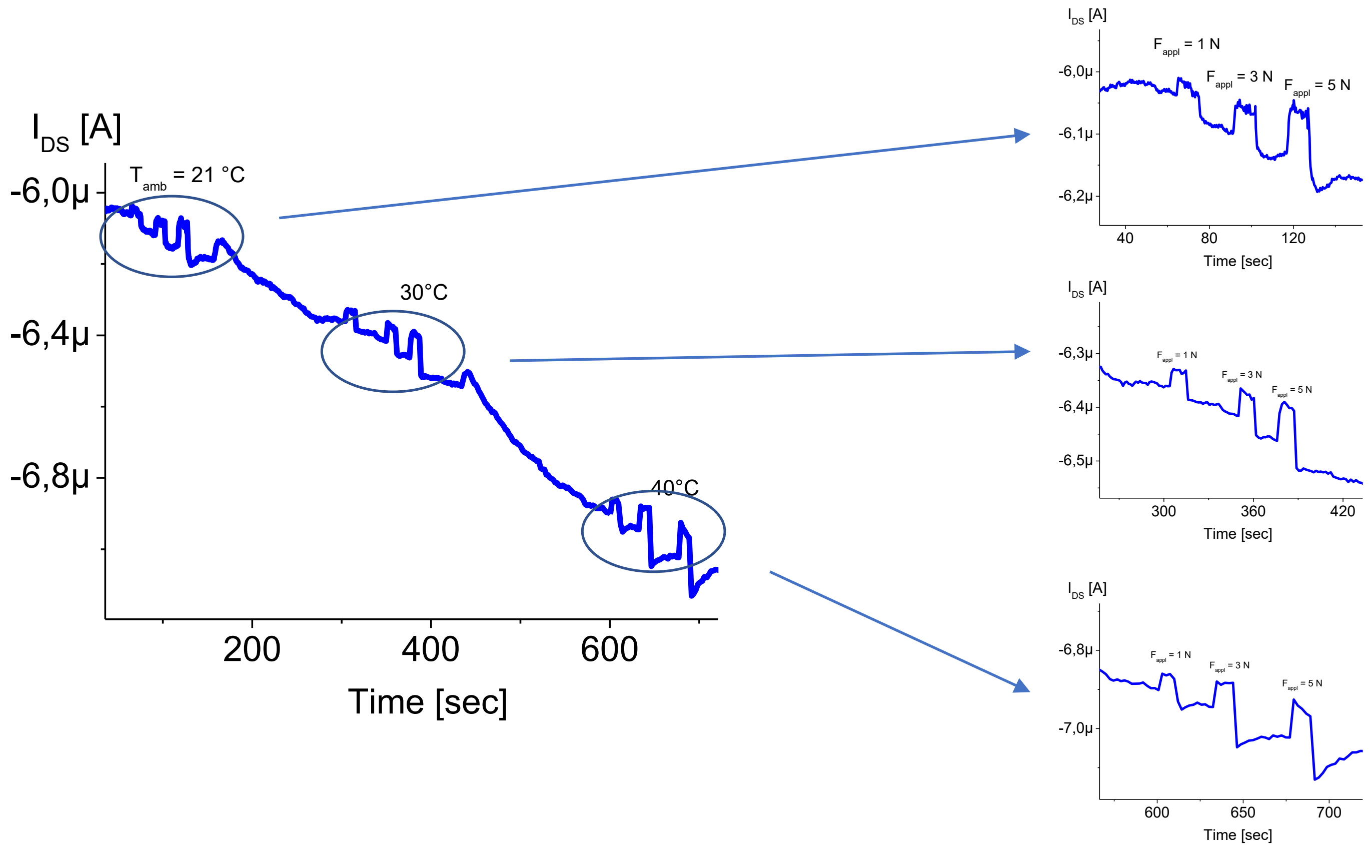
Ultraconformable electronics



Submicrometer OCMFET - T sensors

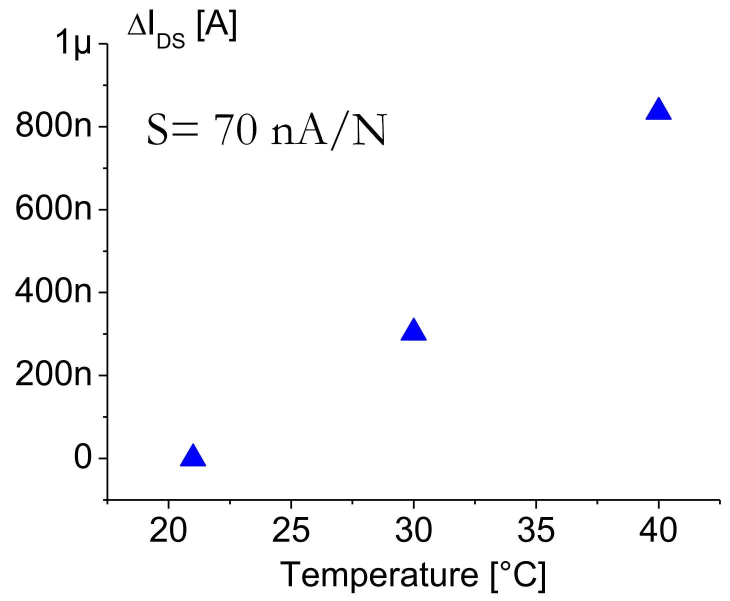


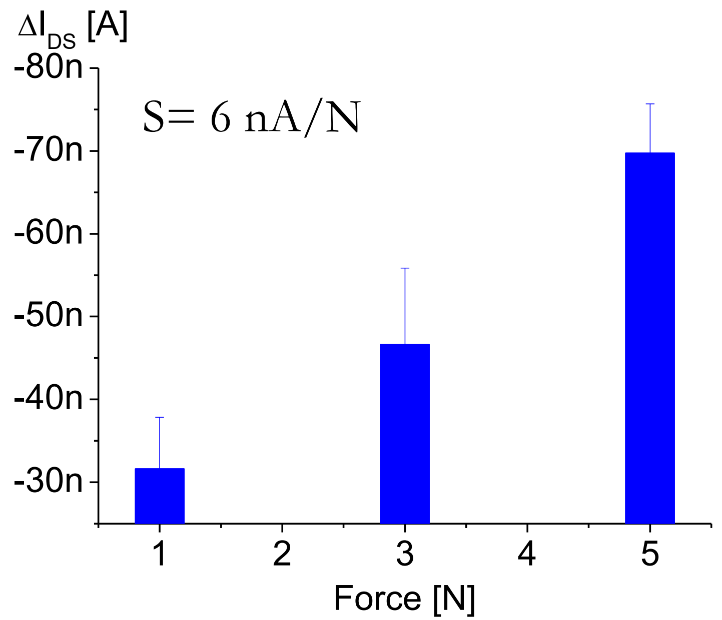
OCMFET- bimodal sensing



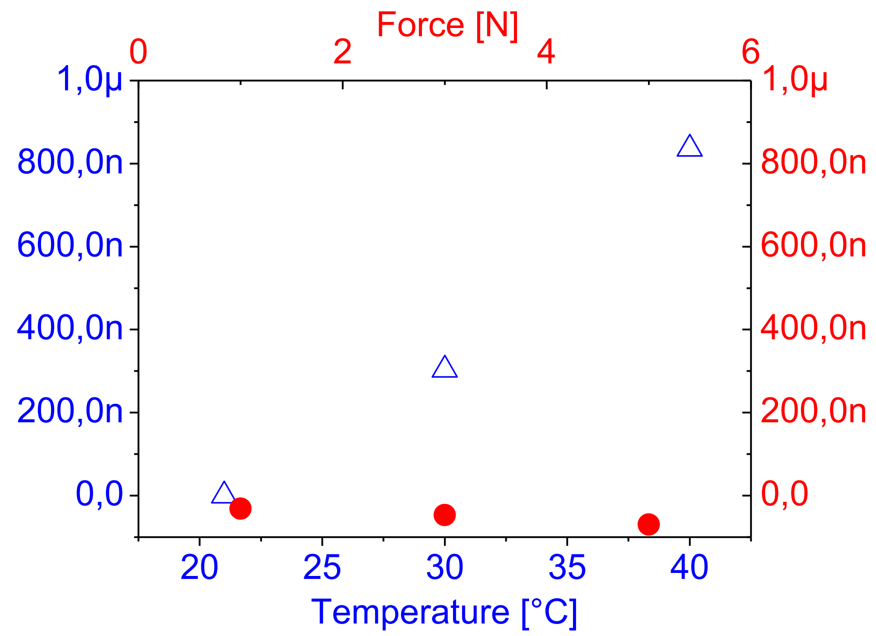
- Temperature is increased linearly
- Output current increases linearly with T
- At the same time a mechanical stimulus is applied leading to a clear reduction of the current

OCMFET- bimodal sensing





The sensitivity (slope of the calibration curve) of force (ΔI/N) transduction is 10 times smaller than the one obtained for temperature (ΔI/°C)

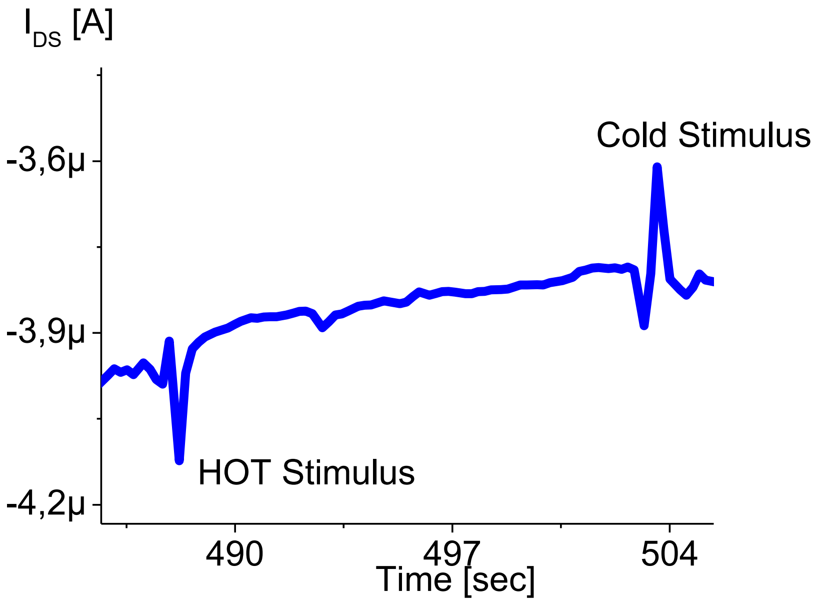


T measurements on skin: preliminary results

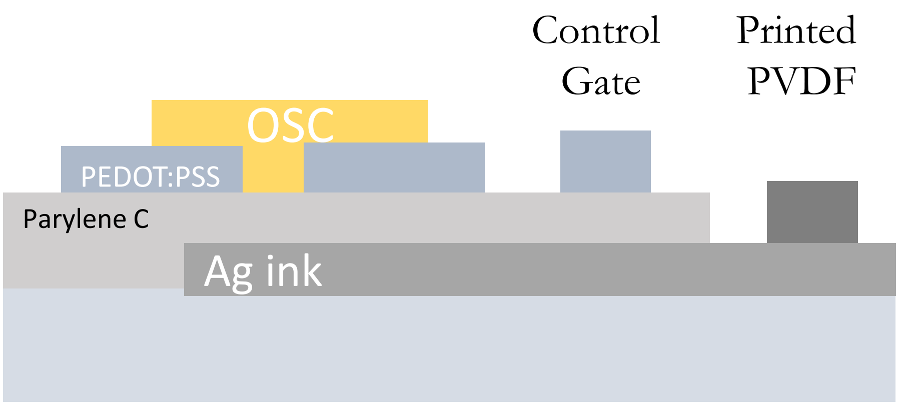
After transferring the sensor on the skin

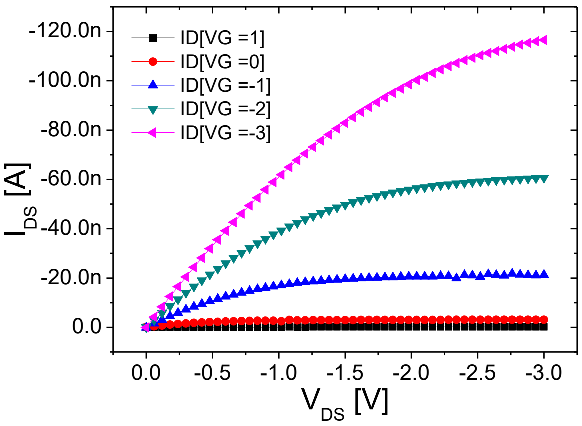
The sensor is still able to detect thermal stimuli

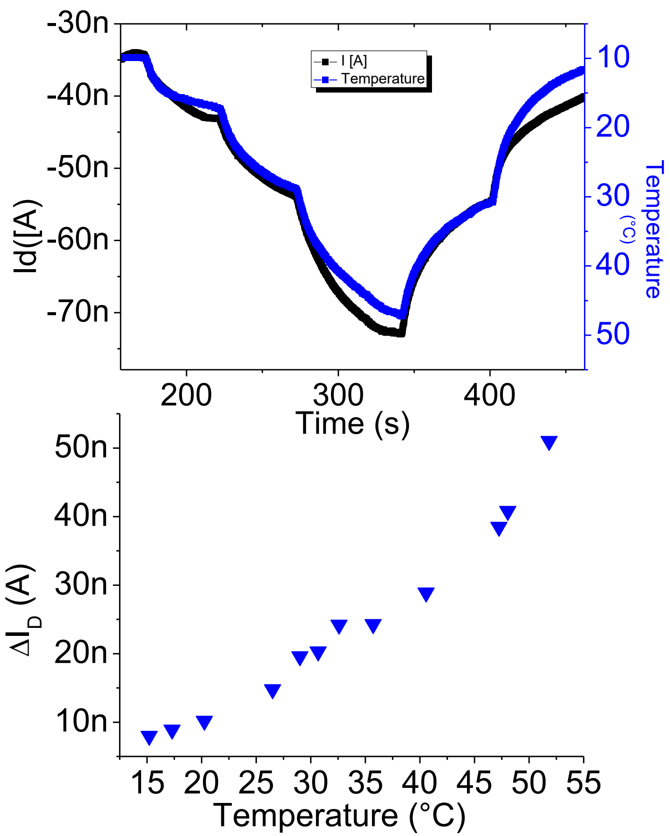
I_{DS} increases for hot and decreases for cold stimuli

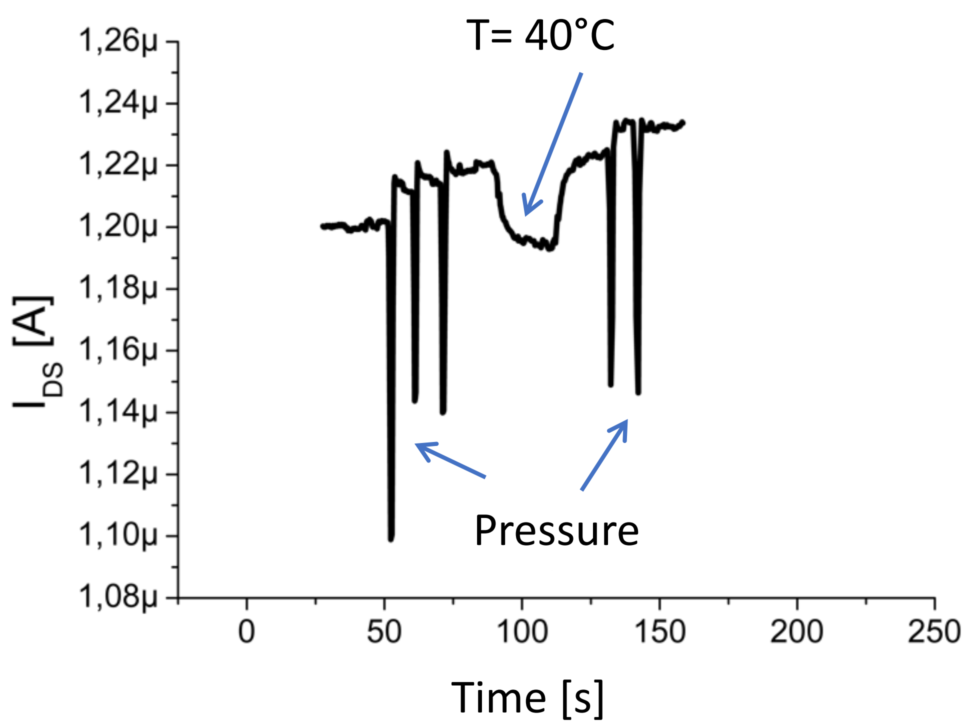


Inkjet printed OCMFET: preliminary results

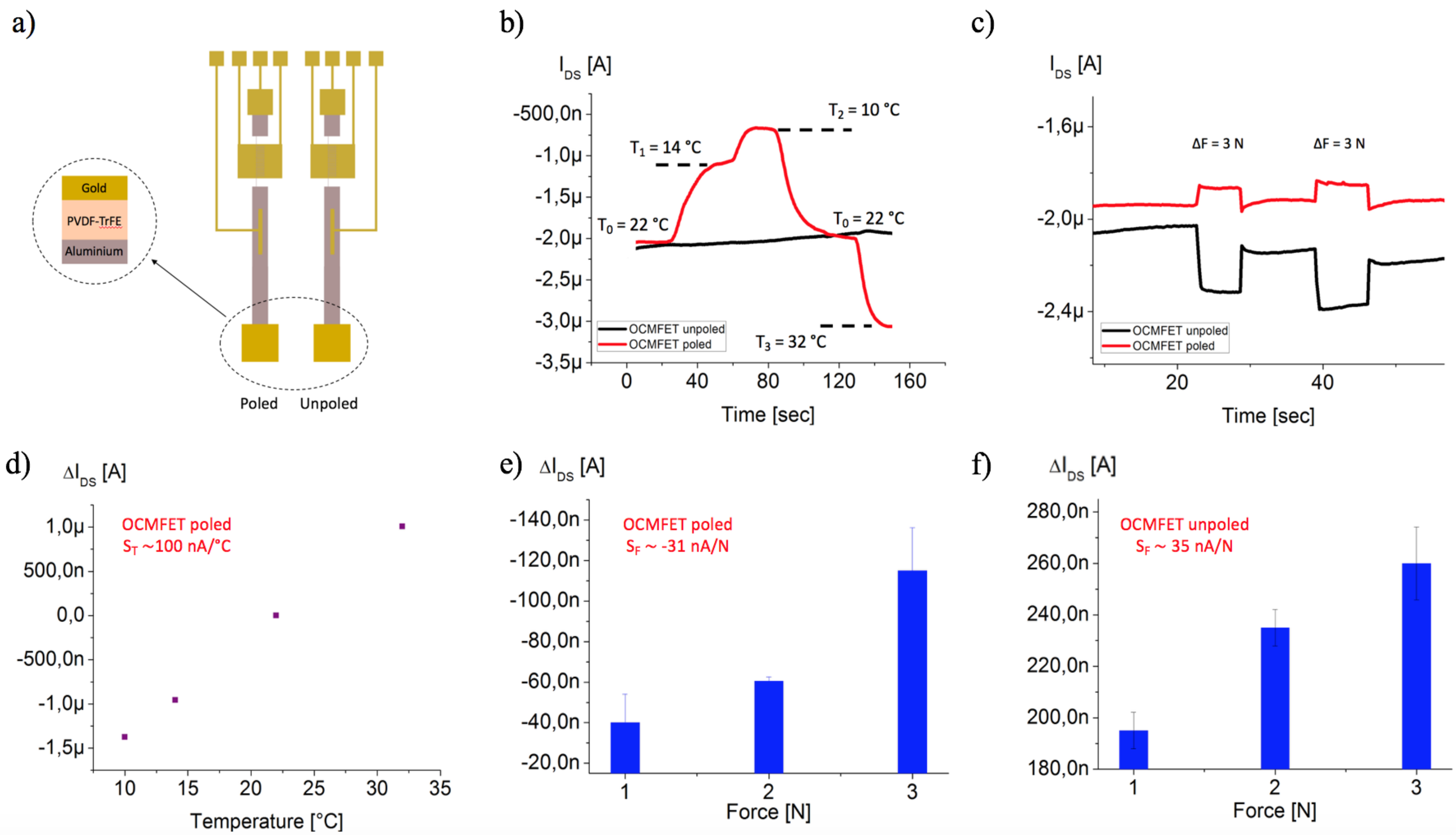




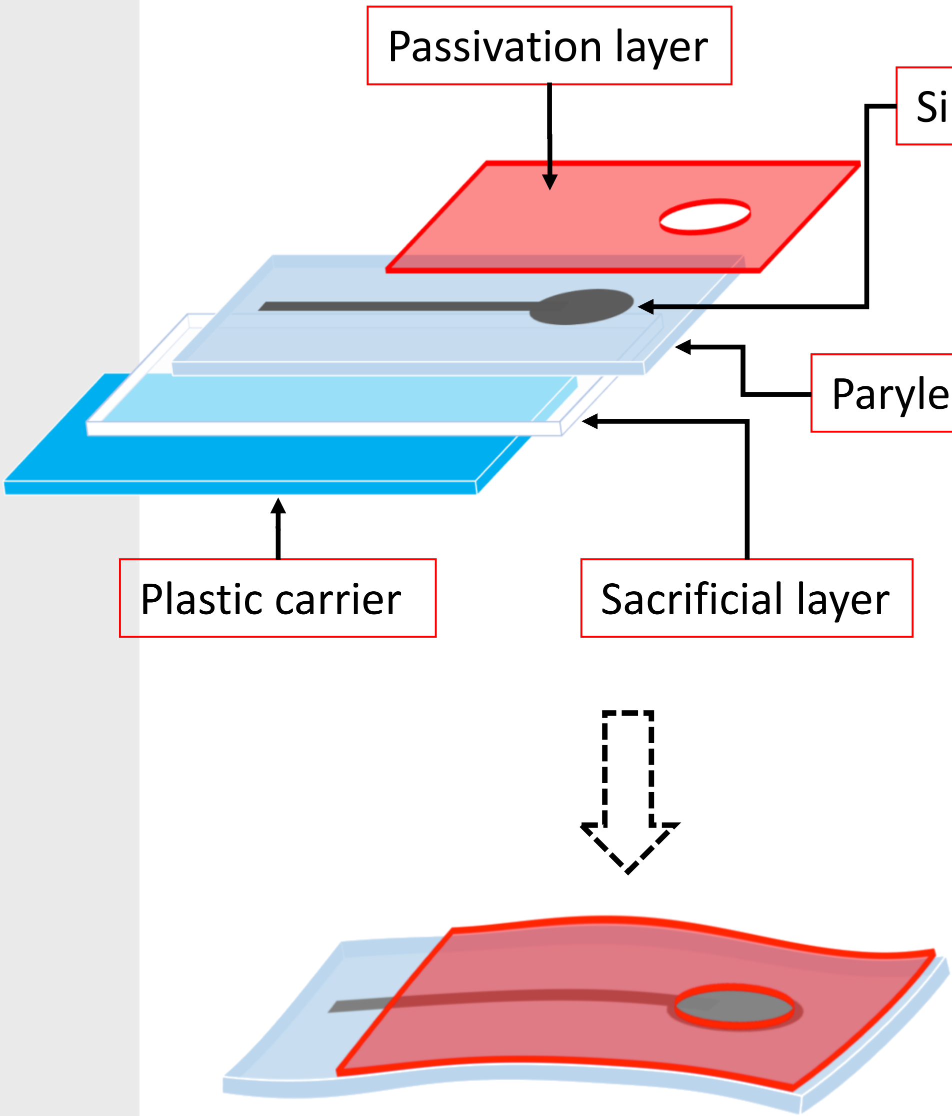




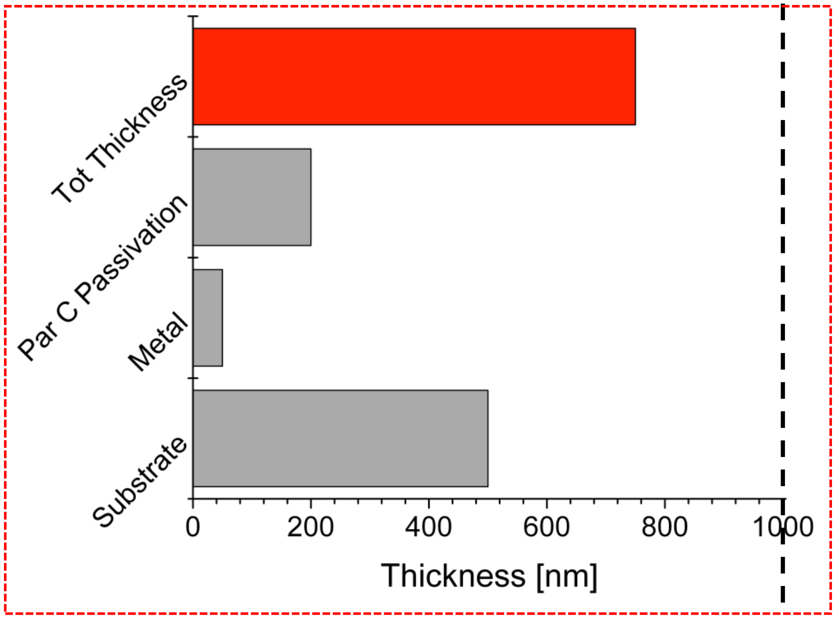
Multi-modal tactile sensor



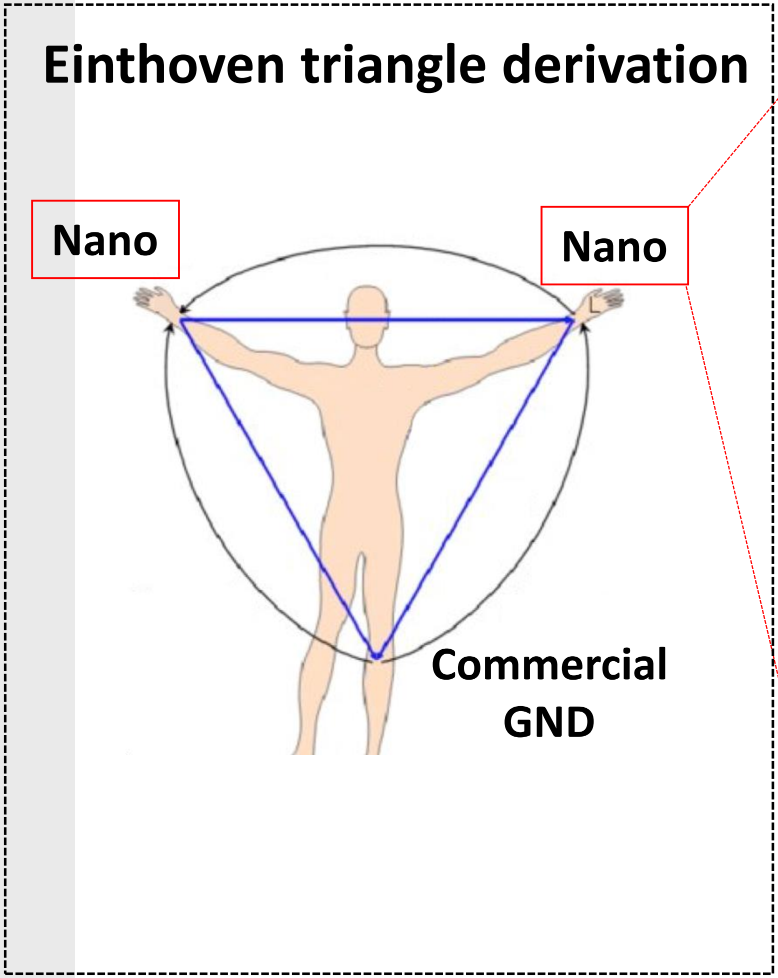
Ultraconformable electronics

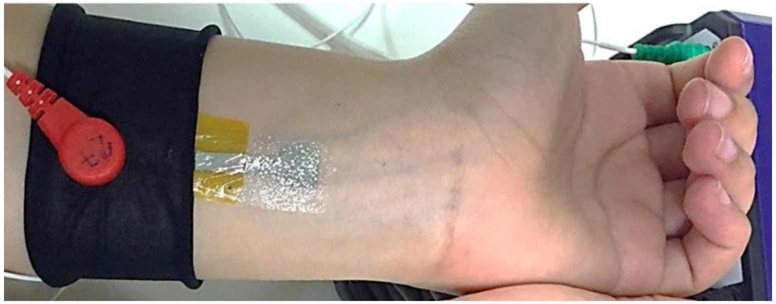


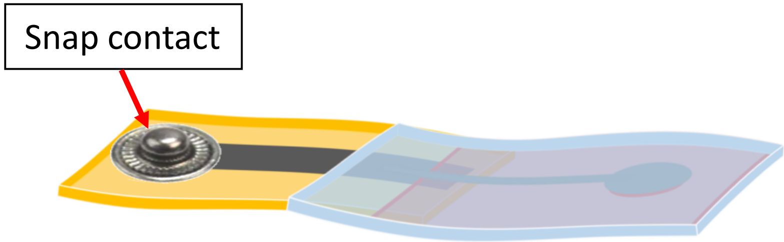
Total thickness in the range 500-800 nm



Ultraconformable electronics



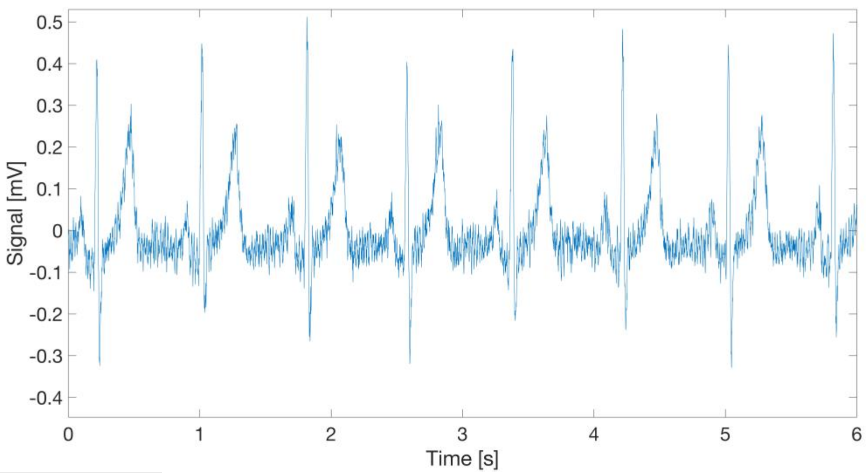


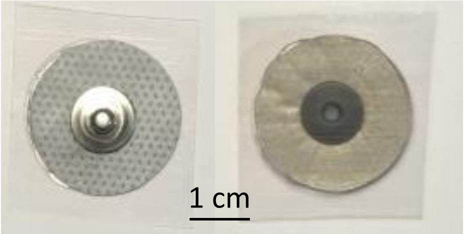


Silver on 13 μm-thick Kapton with snap contact.

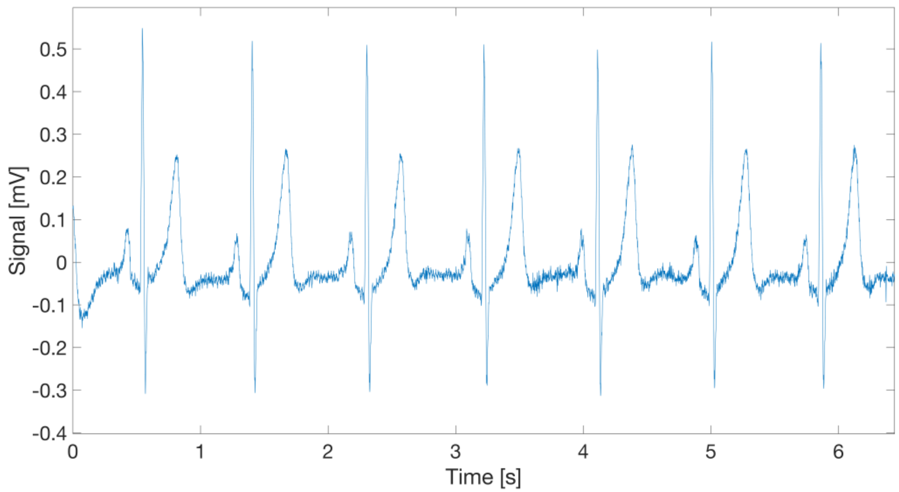
Ultraconformable electronics

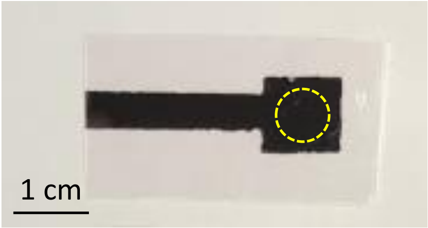
Commercial adhesive surface electrodes
(Neurotab – Spes Medica)



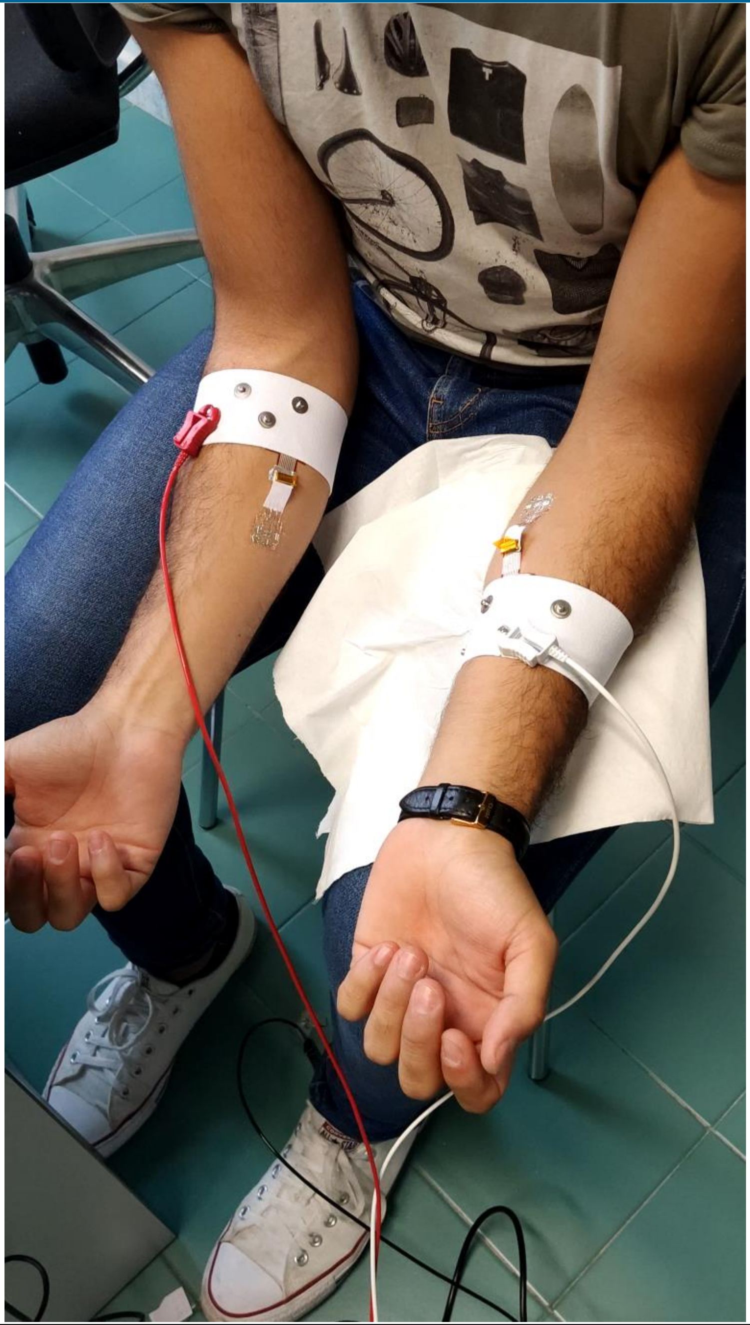


Nanoelectrodes with Parylene C passivation





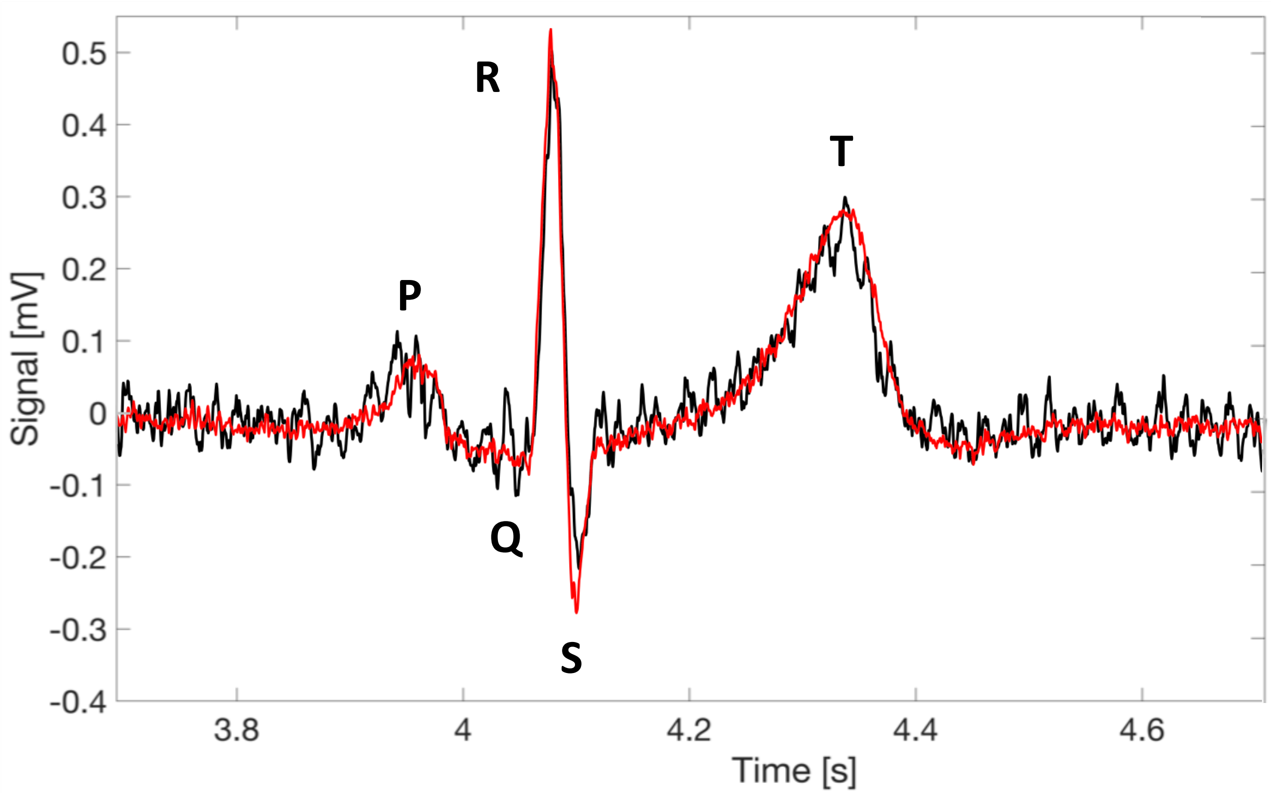
Ultraconformable electronics



Ultraconformable electronics

Black: commercial disposable adhesive surface electrode (Neurotab – Spes Medica)

Red: nanoelectrode with Parylene C passivation



Nanoelectrodes

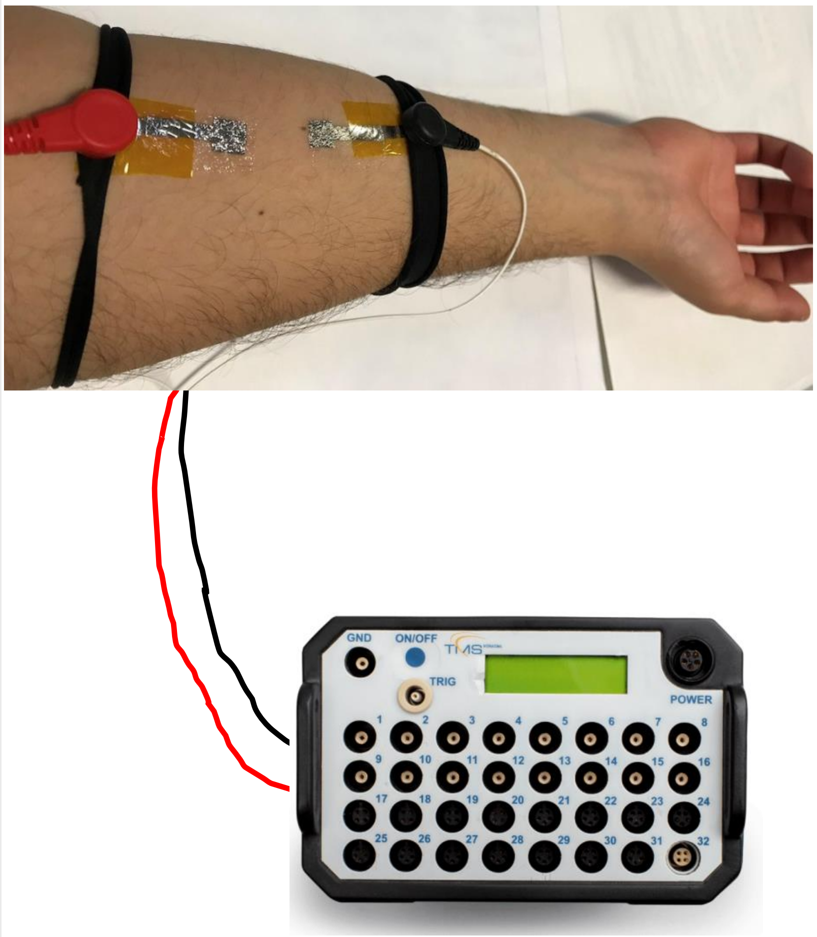
SNR=23.1

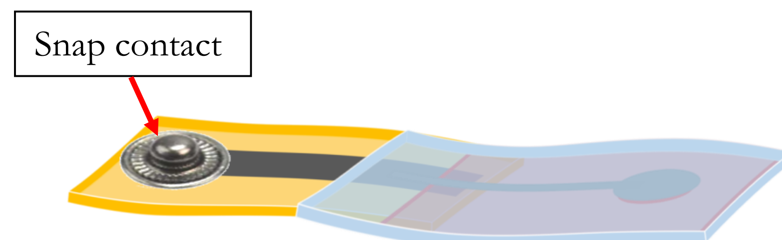
Commercial electrodes

SNR=18.9

Ultraconformable electronics

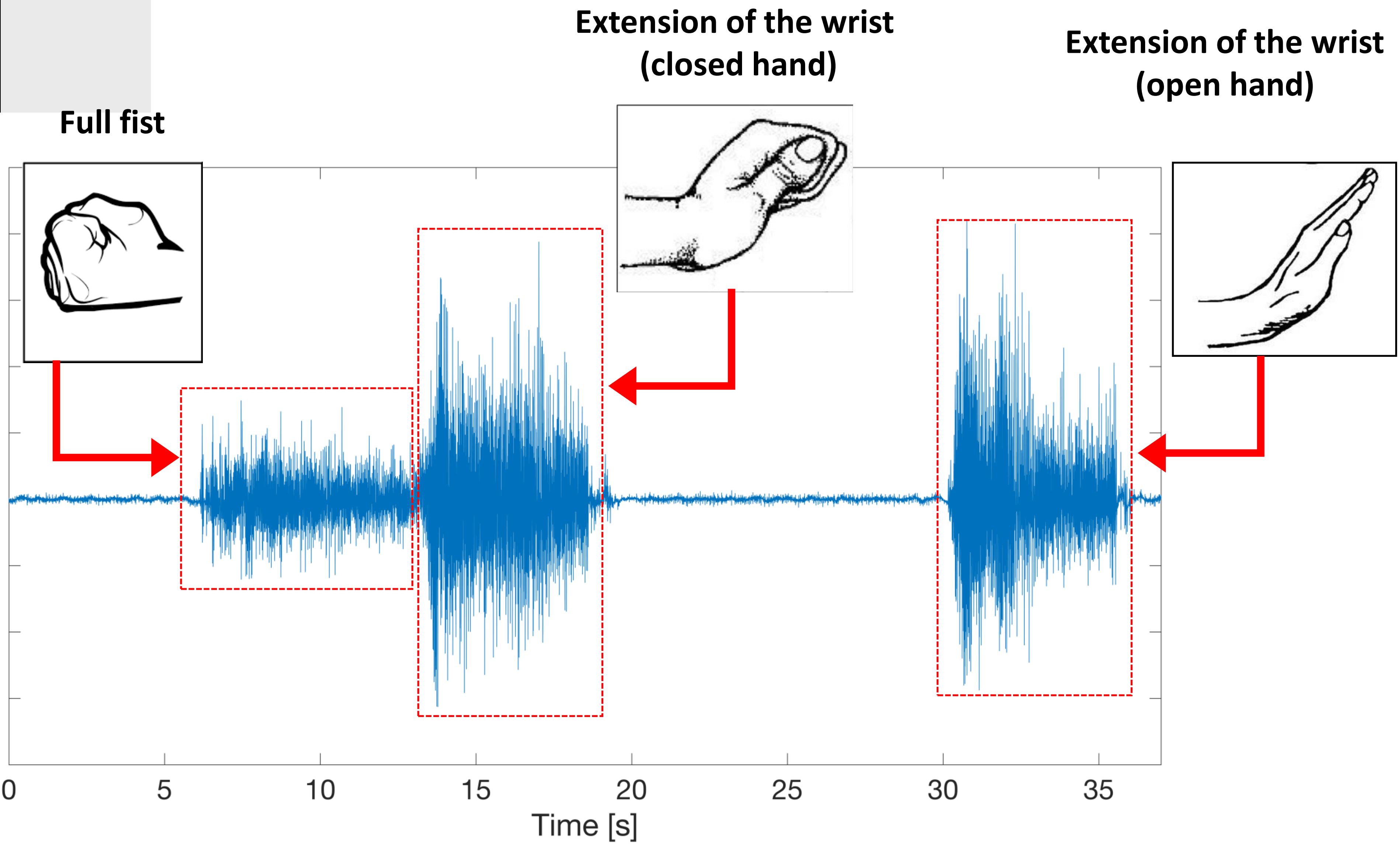
Target muscle: Flexor carpi ulnaris





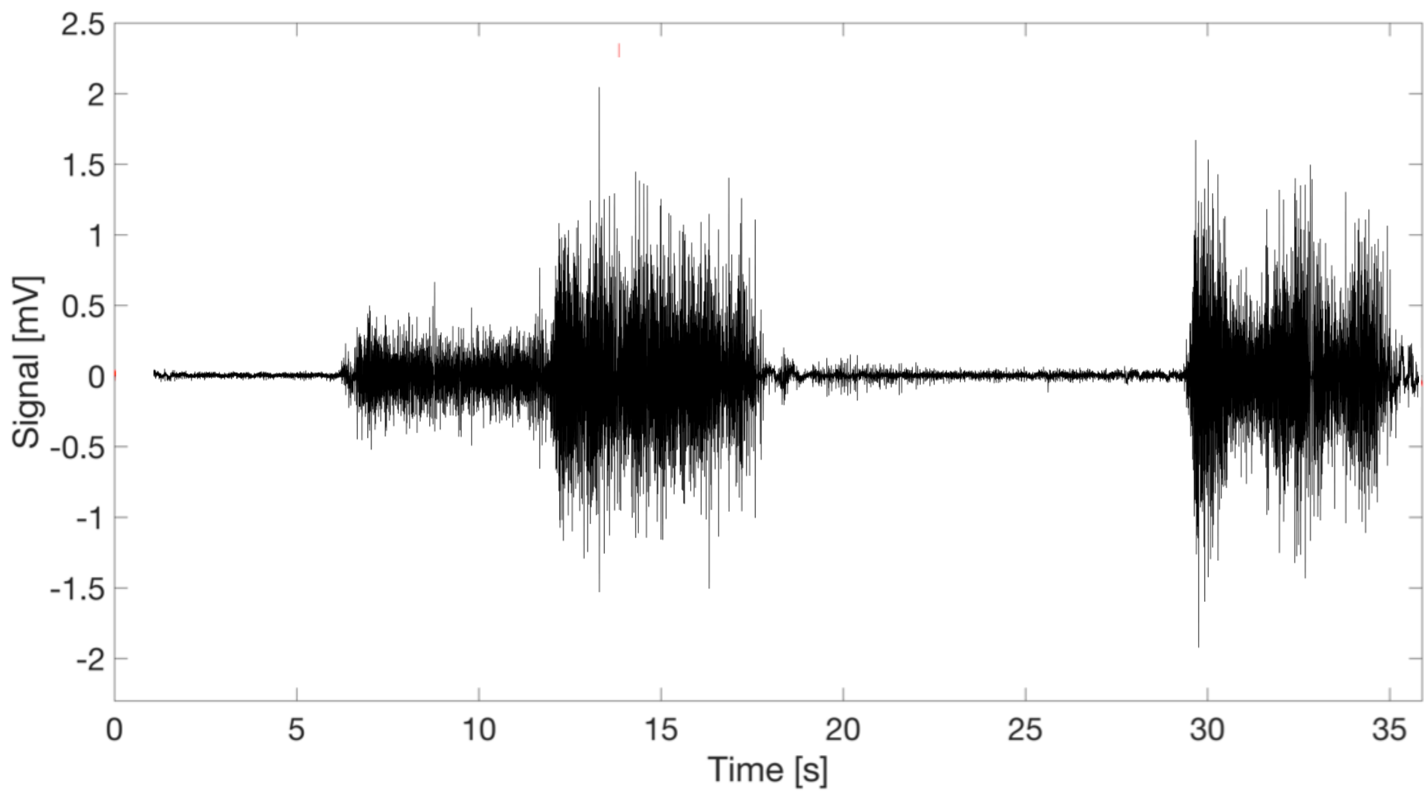
Aluminum on 13 μm-thick Kapton with snap contact.

Ultraconformable electronics



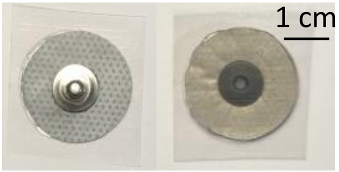
Ultraconformable electronics

Black: commercial disposable adhesive surface electrode (Neurotab – Spes Medica)



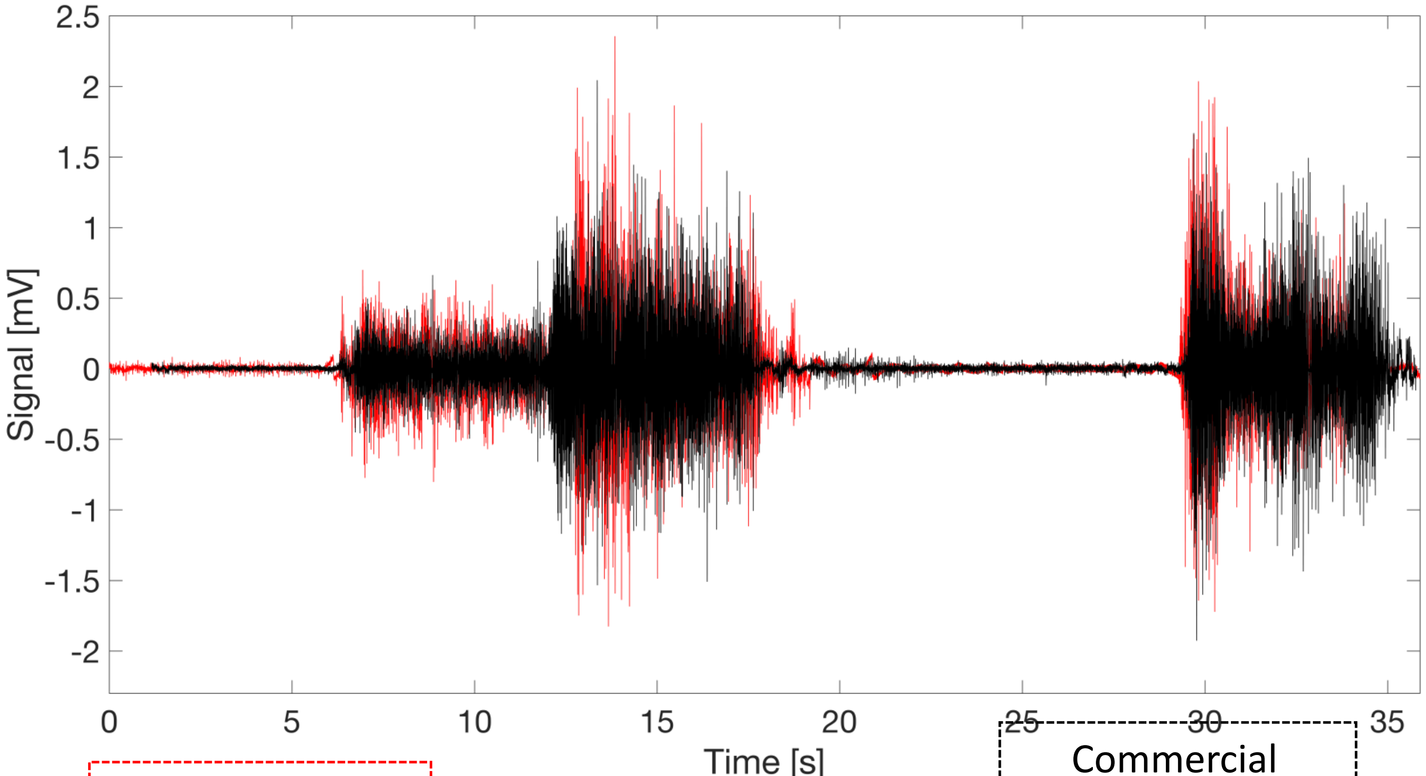
Commercial electrodes

SNR=15.3



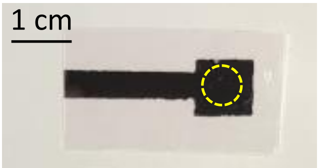
Ultraconformable electronics

Black: commercial disposable adhesive surface electrode (Neurotab – Spes Medica)
Red: nanoelectrode with Parylene C passivation



Nanoelectrodes

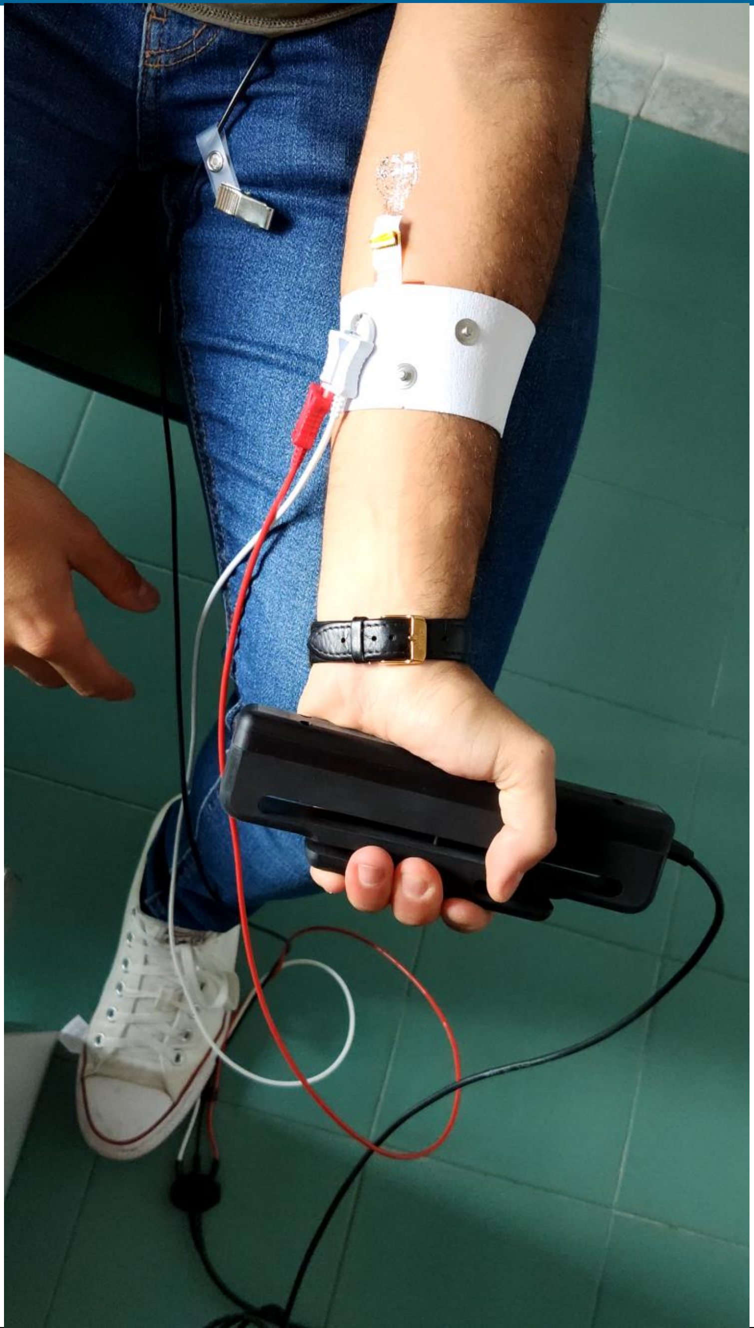
SNR=15.8



Commercial electrodes

SNR=15.3

Ultraconformable electronics

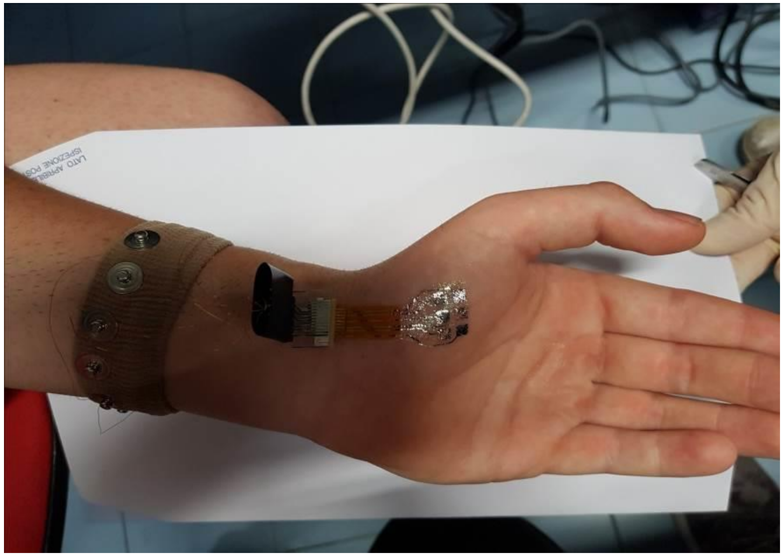


Targeting Thenar Eminecence

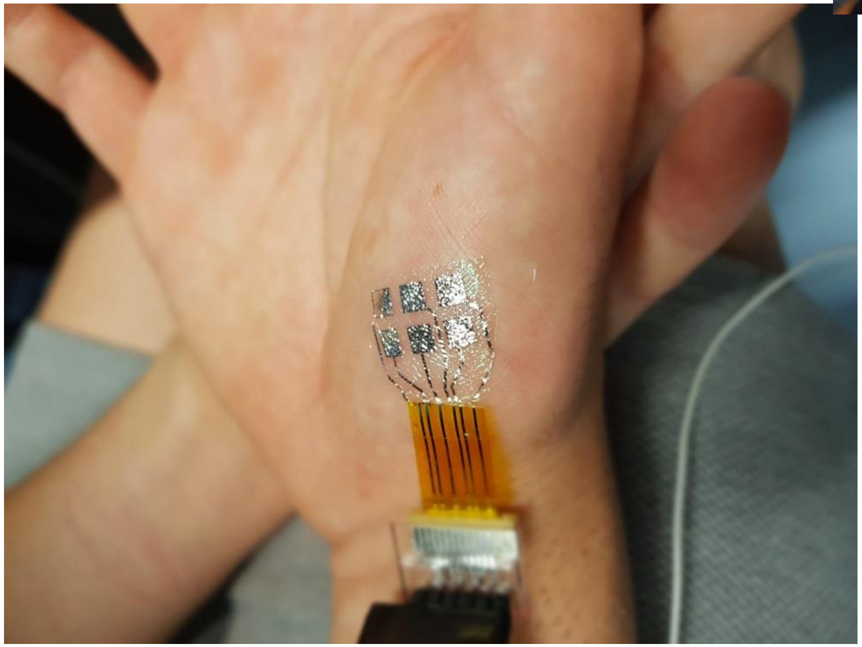
Carpal tunne syndrome usually brings to an atrophy of thenae eminecence muscles

Ultraconformable electronics

- Tattoable connection
- Thicknes increaeses from measuring area to snap connection
- From 500 nm to 2-3 um



Commercial vs Tattoo



Commercial vs Tattoo