Organic electronics for wearable applications

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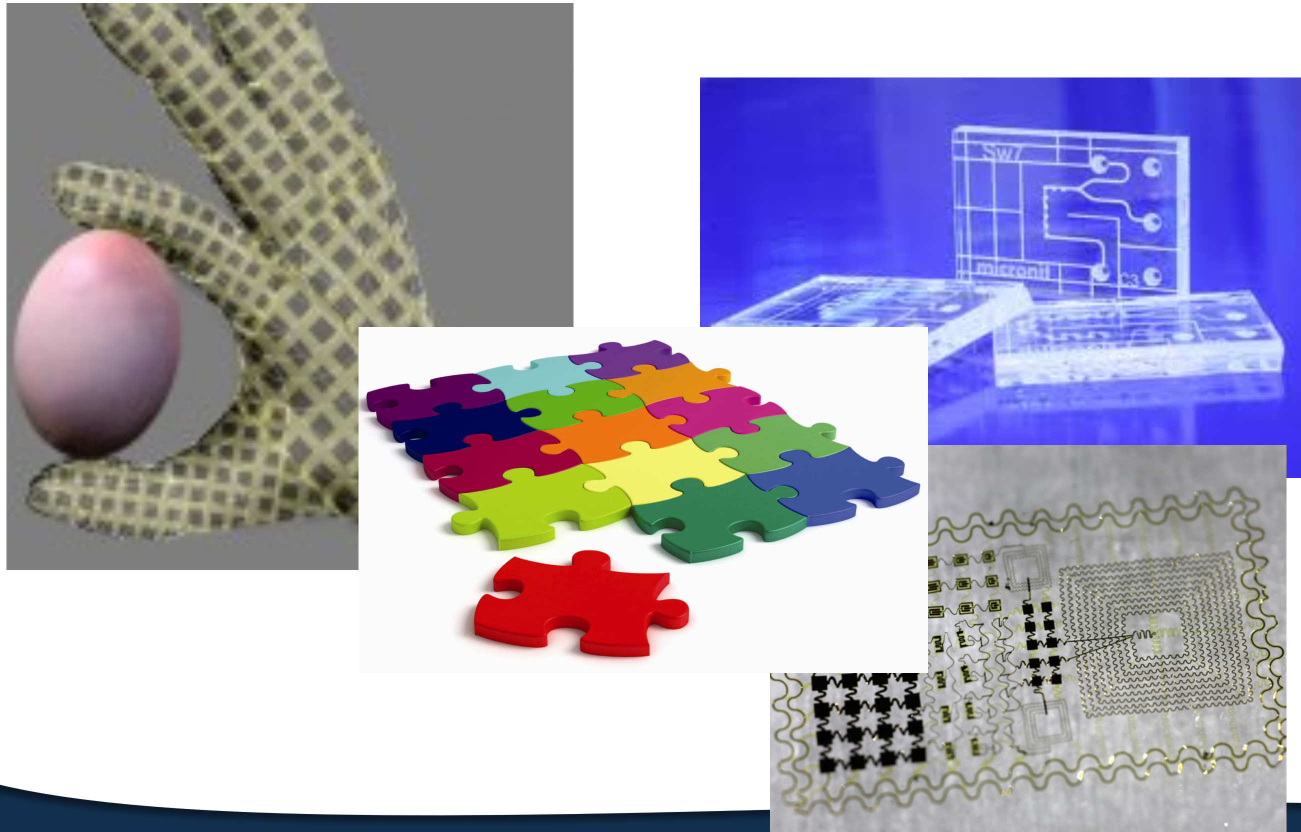
Advanced Course on
"ORGANIC ELECTRONICS : principles, devices and applications"
Milan, November 27th, 2015

Outline

- ✓ Introduction to Bioelectronics & Wearable Electronics
- ✓ Main constraints of the application
- ✓ Introducing a novel sensing device: the OCMFET
    - ✓ Pressure sensors: piezoelectric vs. capacitive effect
    - ✓ Temperature sensors
- ✓ From plastic to fabric: a novel substrates for conformable sensors

Bioelectronics & Wearable Electronics

Bioelectronics: employing electronic devices for monitoring biological systems



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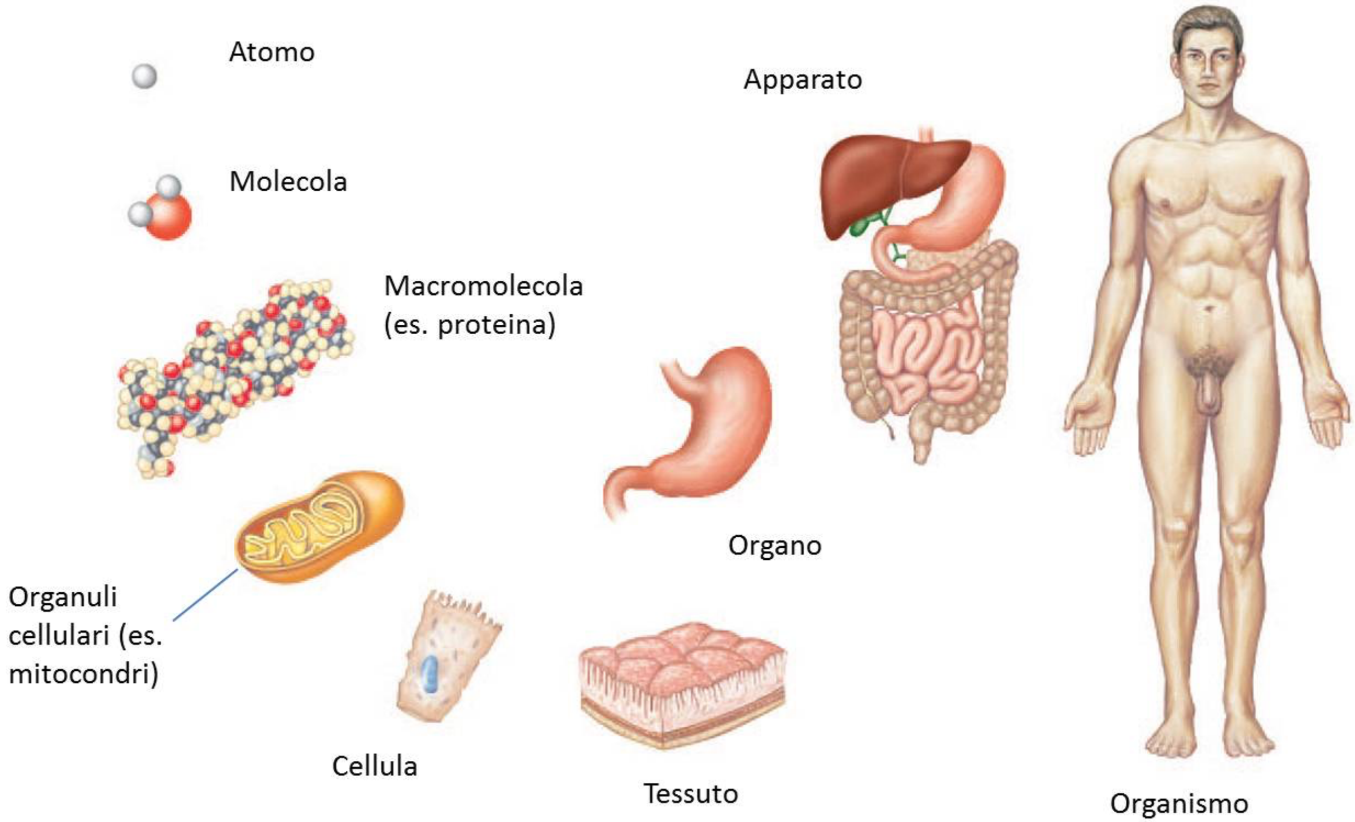
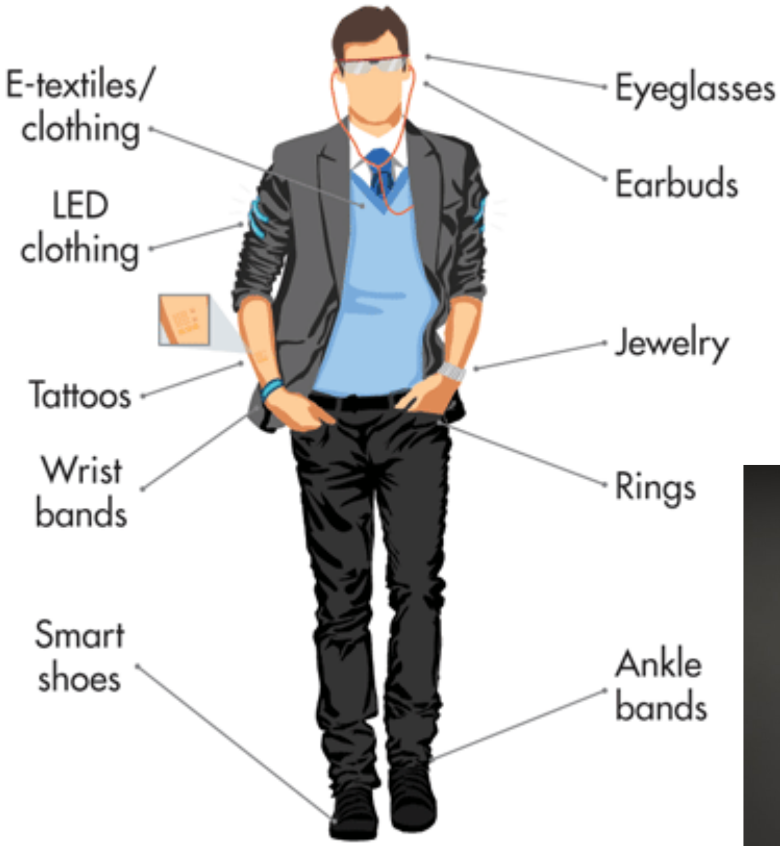
About Bioelectronics' target:

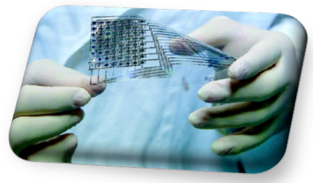


Soft Materials but … Complex systems!

What about Wearable Electronics?

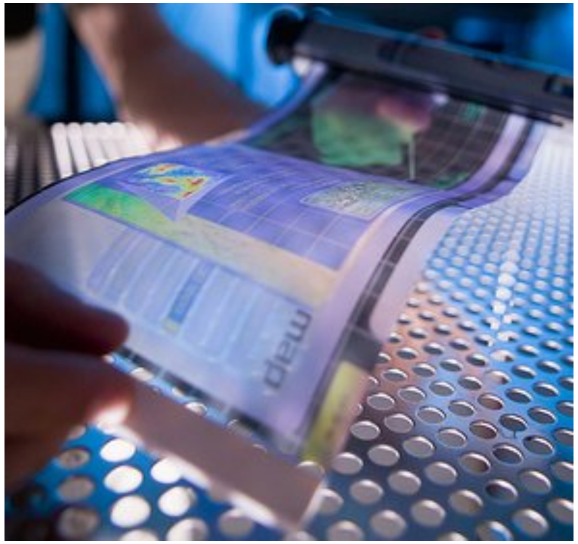


Which materials for Wearable Electronics?



- Very low cost materials and technologies suitable for Large Areas Applications
- Semiconductors, Insulators, Conductors
- Possibility to realize circuits and sensors
- Flexibility → possibility of application to any kind of flexible surfaces (paper, fabric and 3D structures) or directly onto the skin
- Flexibiility → unaffected by mechanical stimuli!
- Wearability → moderate operational voltages (if in contact with the skin)
- Wearability → interface with readout (Wearable systems must include data processing and/or transmission via Bluetooth™ or Wi-Fi™)

What about Organic Materials?

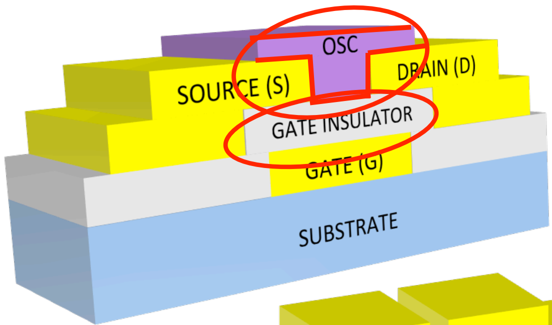


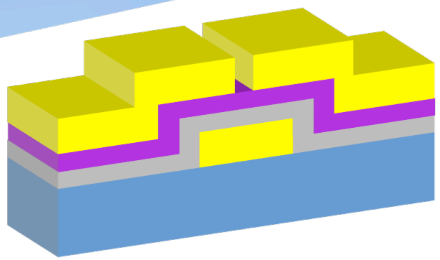
- ✓ Flexibility;
- ✓ Transparency;
- ✓ Large area production at low costs;
- ✓ Wide range of employable materials.
- ✓ Biocompatibility ;

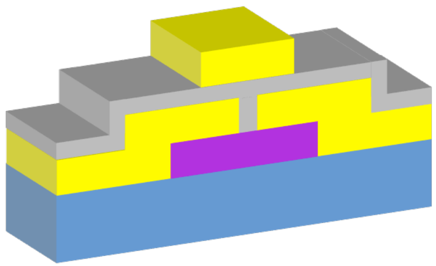
Organic transistors as good device candidates for Wearable Electronics

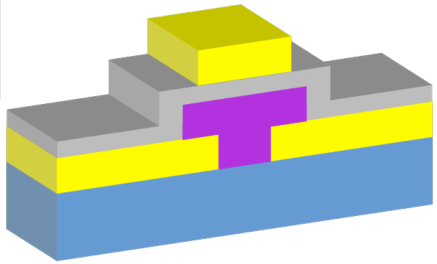
- ✓ Different geometries are possible
- ✓ Different, low cost, fabrication methods
- ✓ They may be employed as sensors

$$I_{DS} = f\left(\mu, C_{INS}, W, L, V_{GS}, V_{DS}, V_{TH}, R_C\right)$$









Main constraints of the application

Strain effects on OTFTs

Flexible substrate:

PET, PEN, Kapton

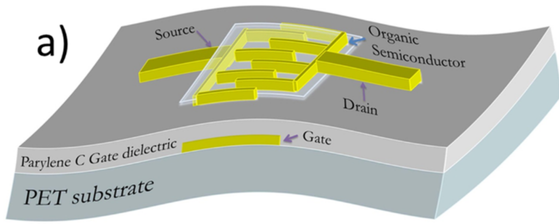
Gate dielectric:

Parylene C, PVA, PVP etc.

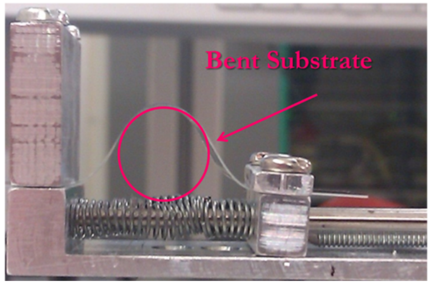
Organic Semiconductors:

- P3HT
- Pentacene *(different morphologies)*

a)



b)

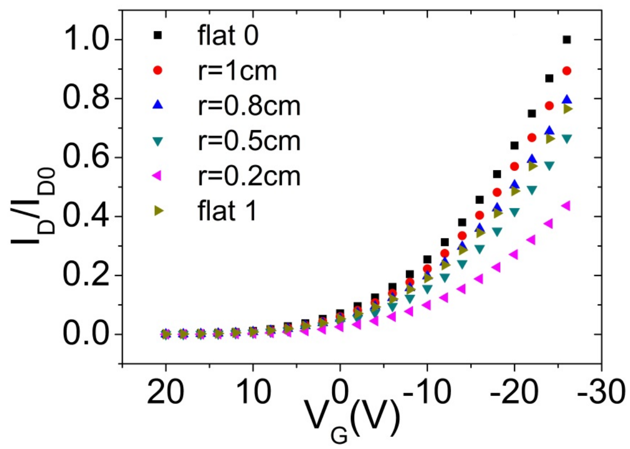


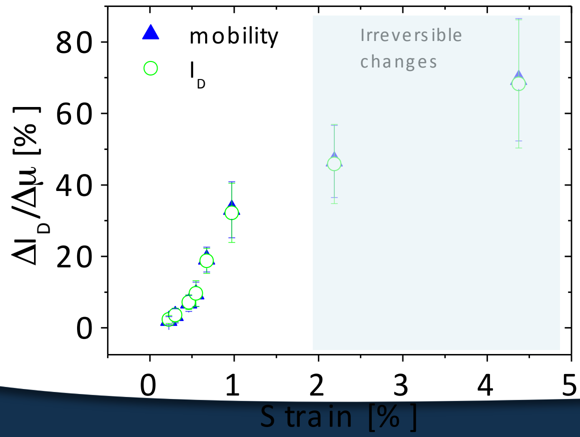
$$Strain = \left(\frac{d_l + d_s}{2 * R}\right)\frac{\left(1 + 2\eta + \chi\eta^2\right)}{(1+\eta)(1+\chi\eta)} \quad \Rightarrow \quad Strain = \left(\frac{d_S}{2 * R}\right)$$

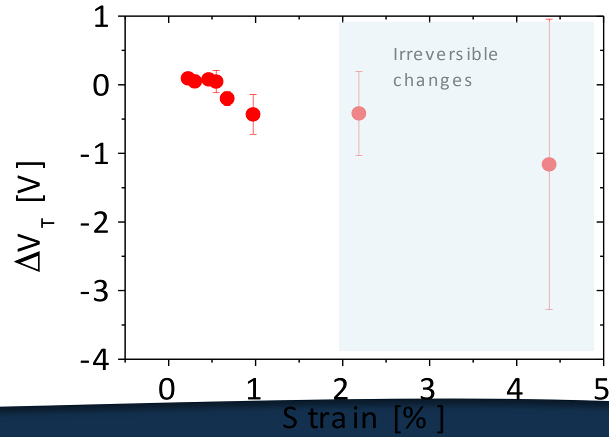
In which d_l and d_s are the thicknesses of the layer and of the substrate respectively, η is d_l/d_s, χ is the ratio between the Young moduli of the layer and of substrate ($\chi = Y_l/Y_s$) and R is the bending radius

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

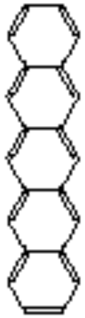


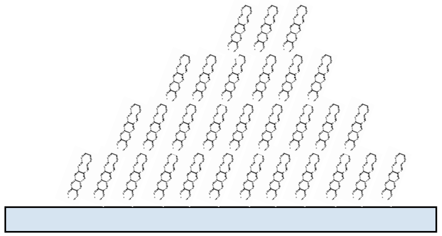


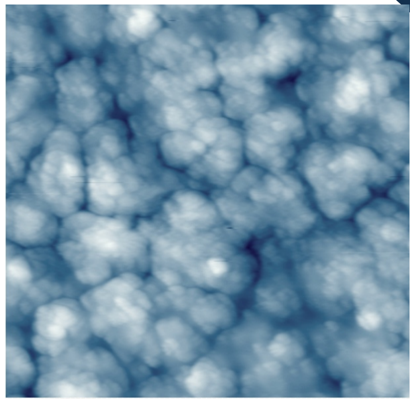


Effect of strain on OTFTs: Pentacene vs P3HT

Pentacene

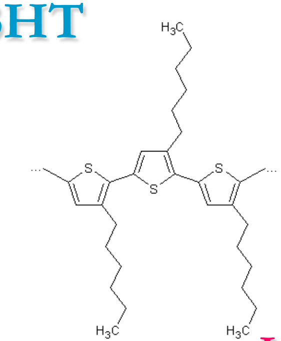


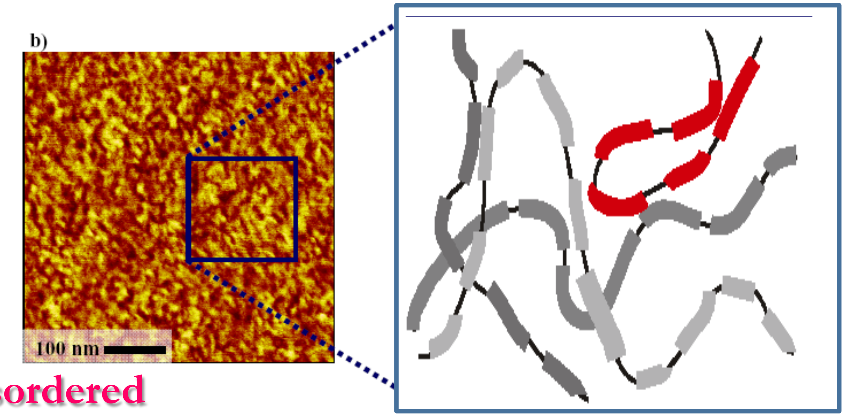




Well ordered even when deposited on "non ideal" plastic substrates

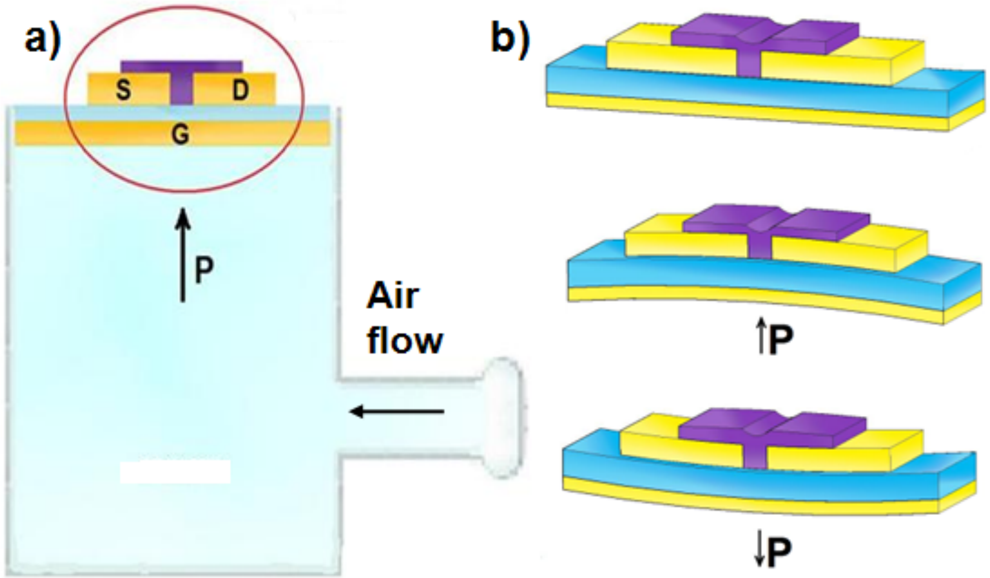
P3HT

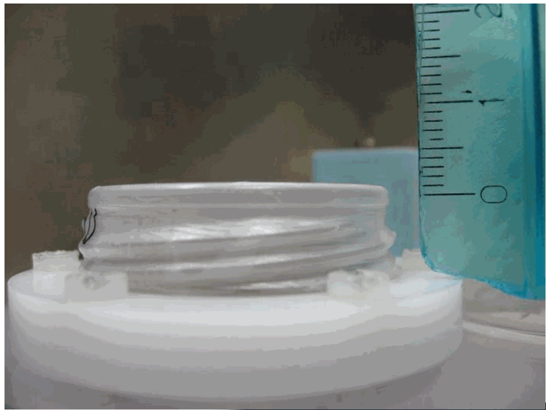




Highly disordered

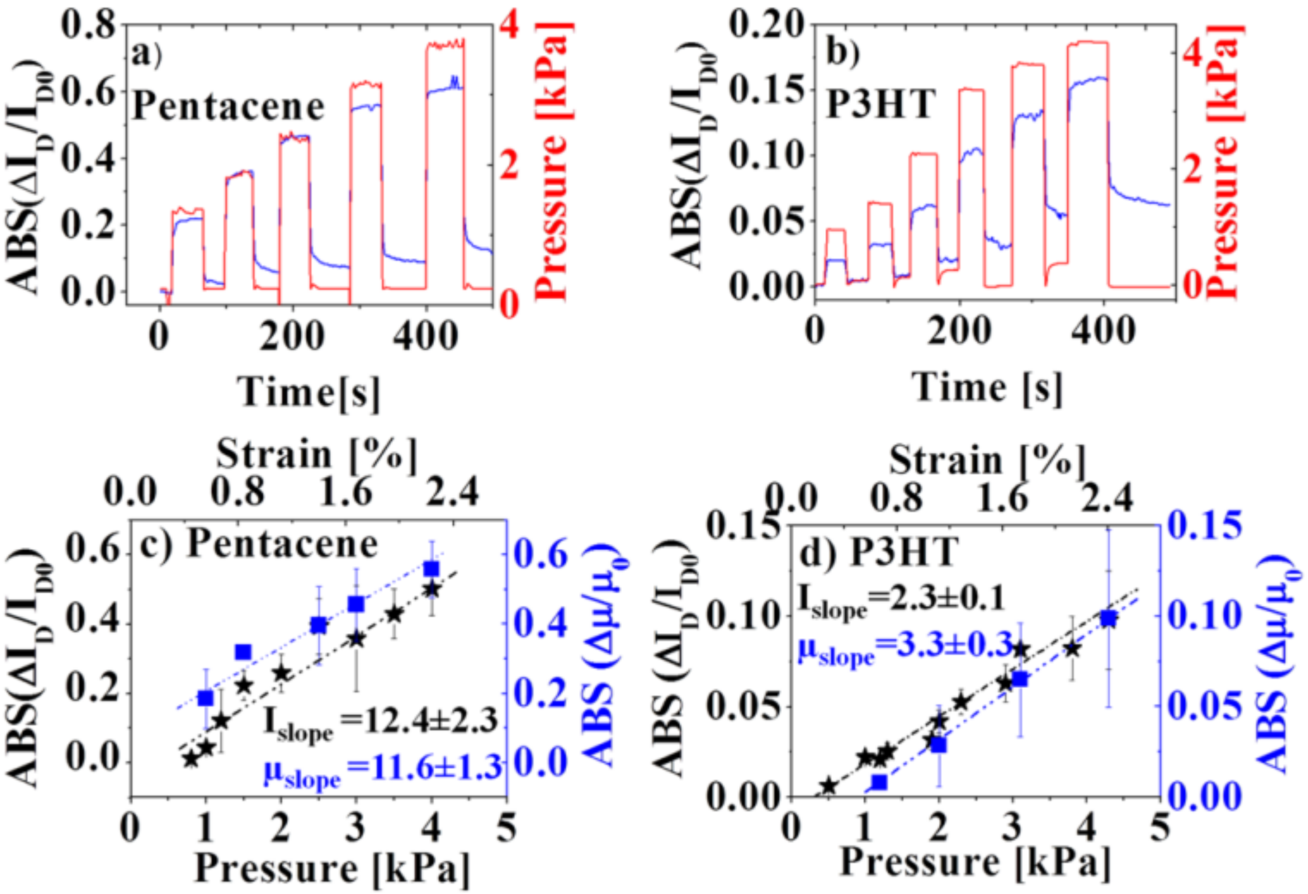
Effect of strain on OTFTs: Pentacene vs P3HT



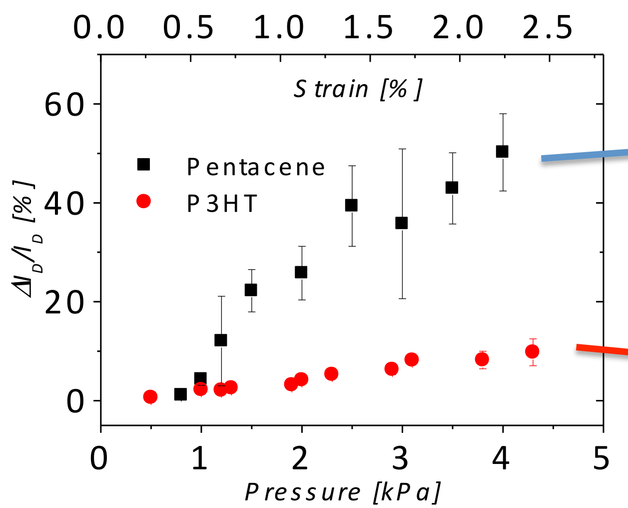


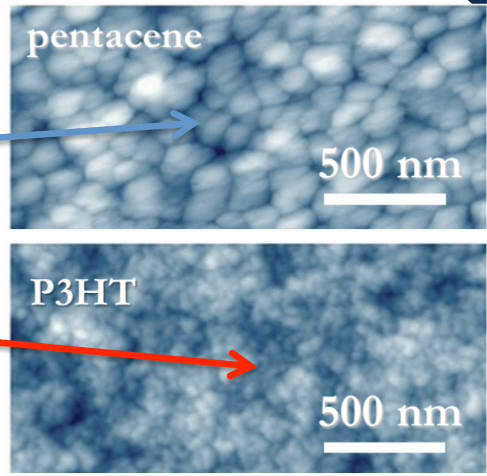
P. Cosseddu et al. IEEE Electron Device Letters 33 (2012) 113

Effect of strain on OTFTs: Pentacene vs P3HT

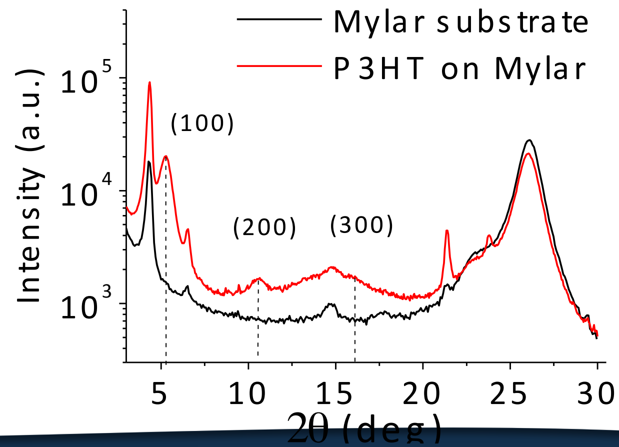


Effect of strain on OTFTs: Pentacene vs P3HT





- 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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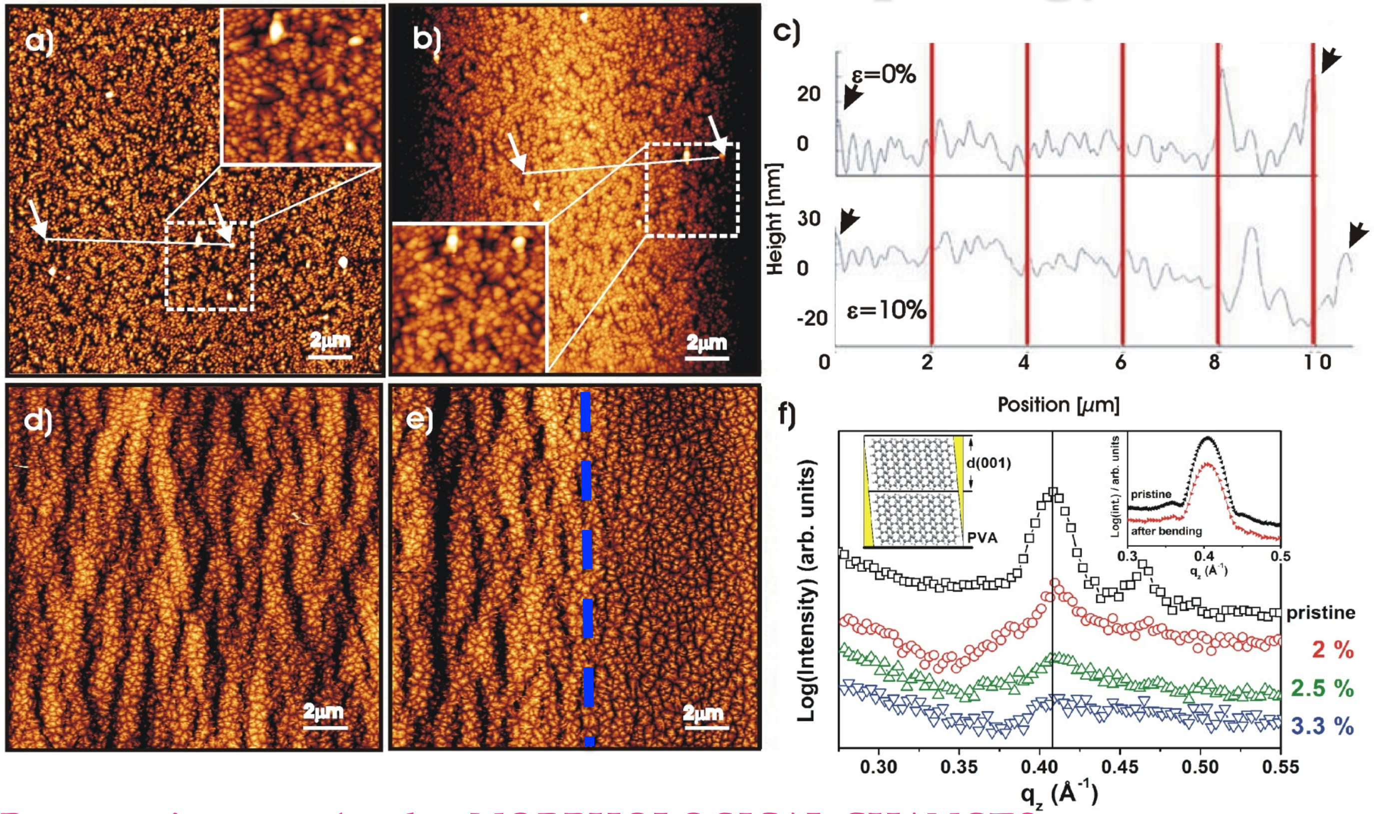
Strain effects on structure and morphology



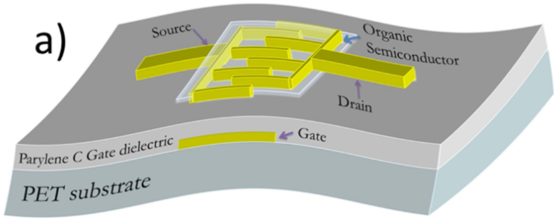
Response is more related to MORPHOLOGICAL CHANGES

Pentacene film properties are not permanently affected by mechanical deformation

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

Inducing morphological changes

a)



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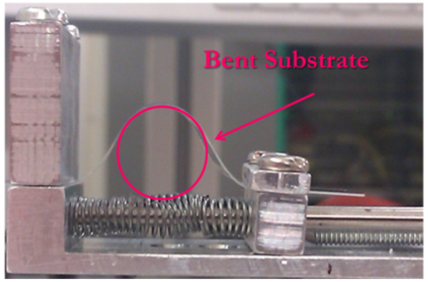
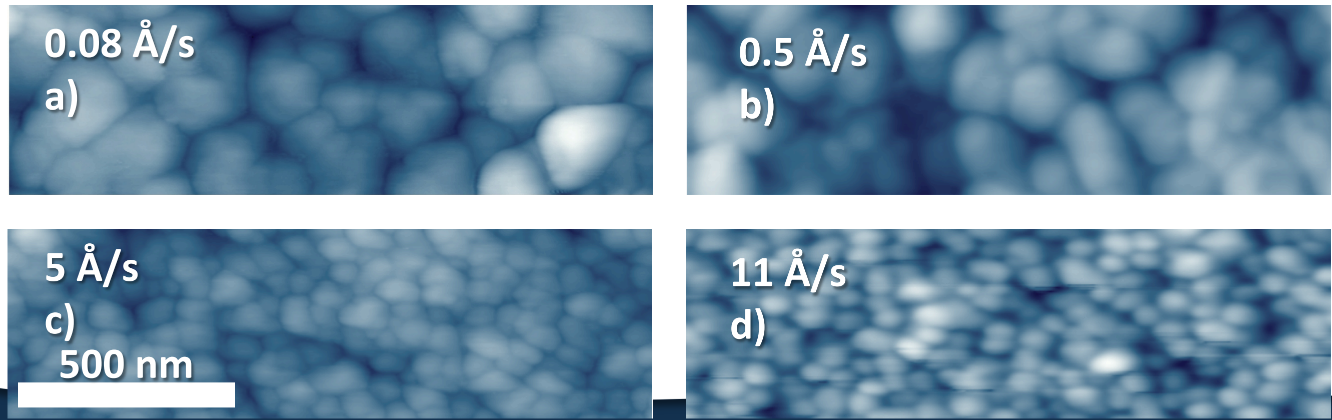
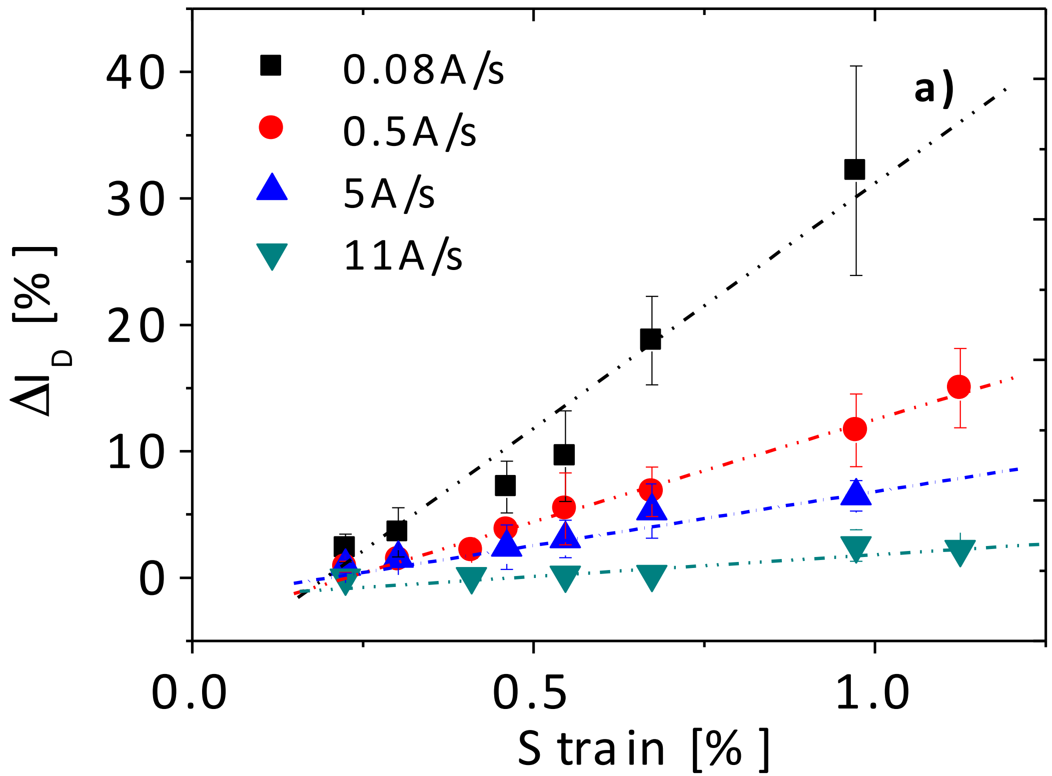


Pentacene based devices

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

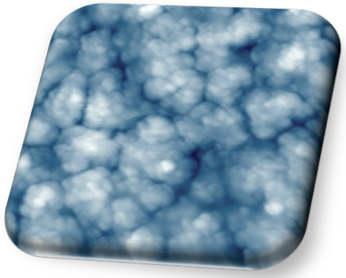


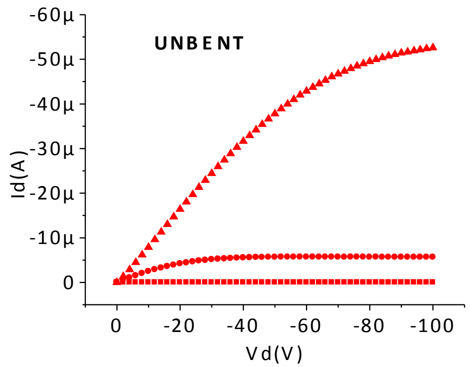
Influence of morphology on the sensitivity

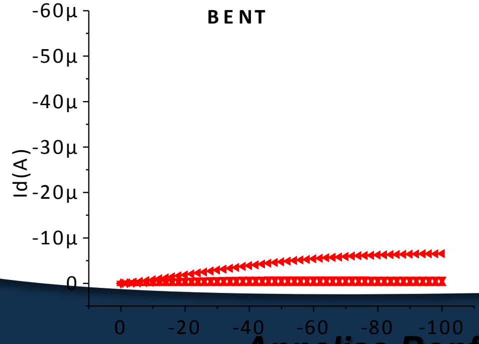


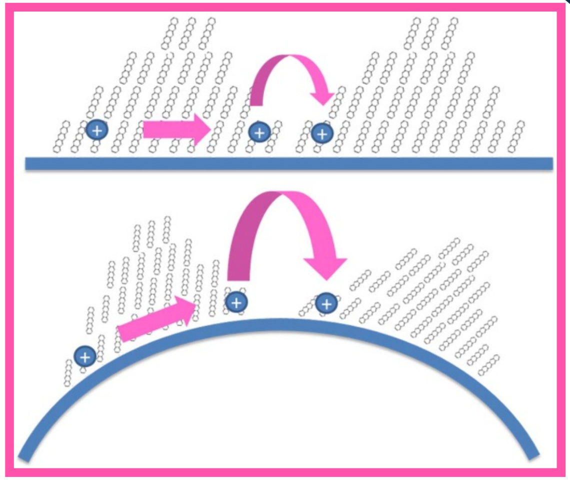
Morphological properties strongly influence the sensitivity to strain

Effect of strain on OTFTs









- Mechanical deformation induces morphological and/or structural changes in the active layer

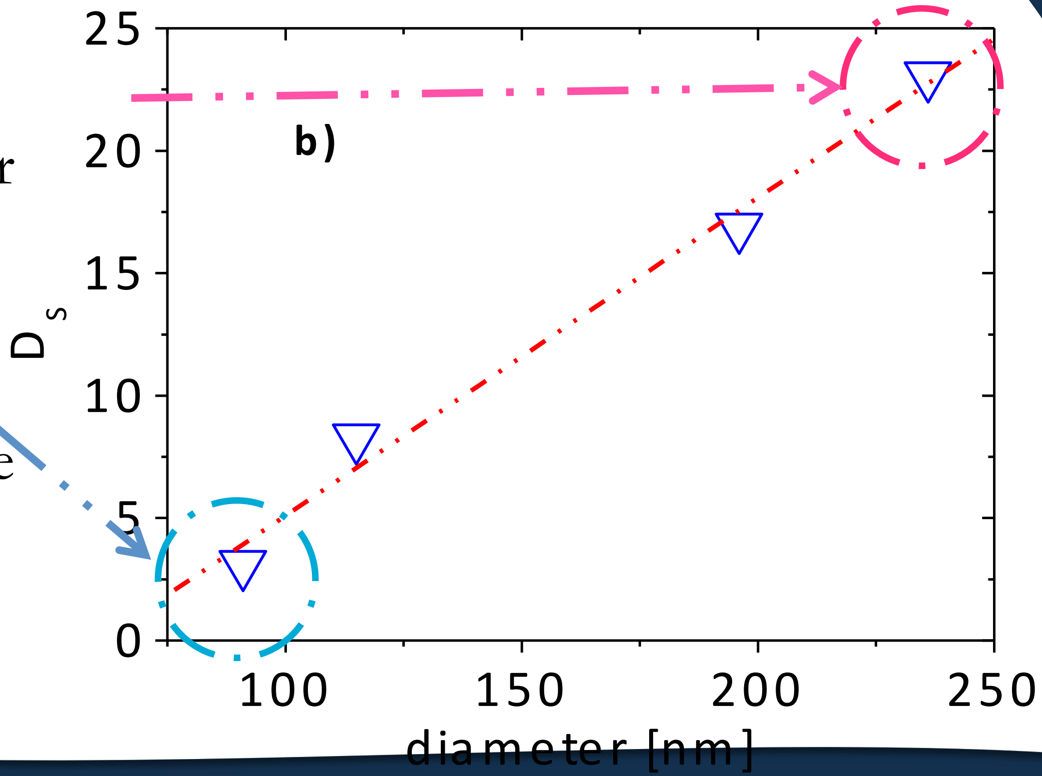
- Hopping barrier increases → current decreases!

Tuning the sensitivity

Sensitivity can be finely tuned by setting the deposition parameters

High sensitivity
Sensor applications

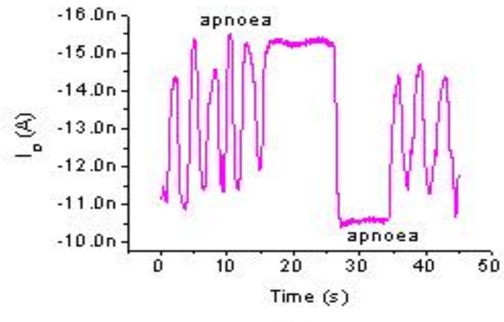
Low sensitivity
Flexible electronics



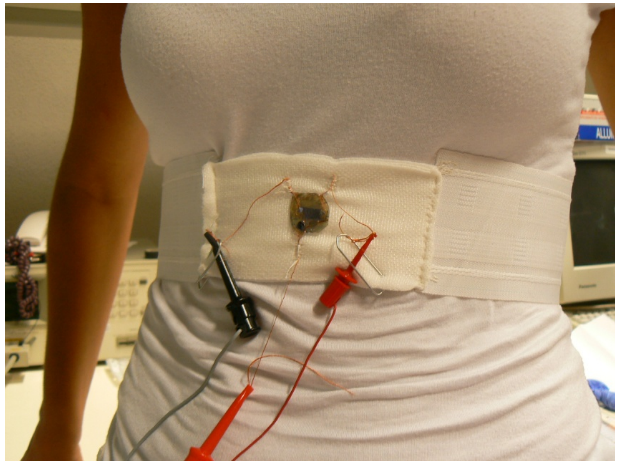
P. Cosseddu et al. Organic Electronics 14 (2013) 206–211

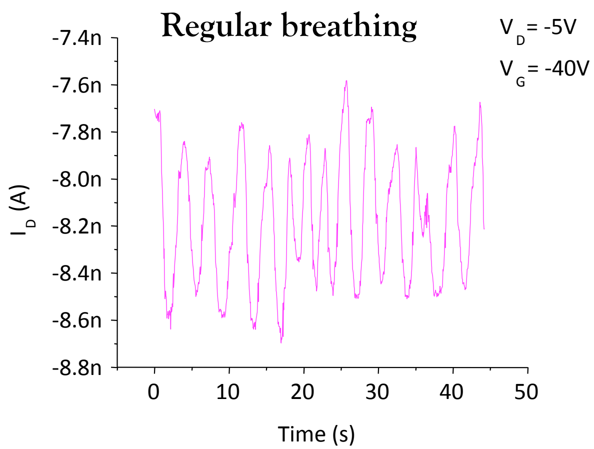
Applications: breath rate

Sensor applied to a chest bandage for **breathing monitoring**



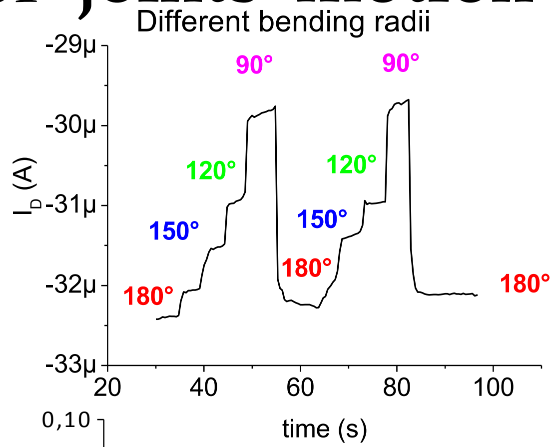
(b)

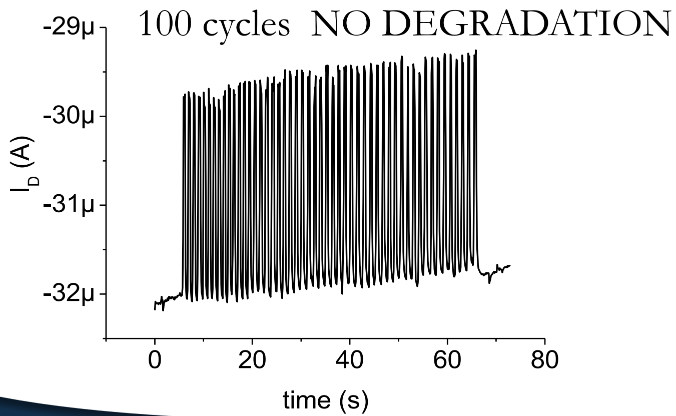


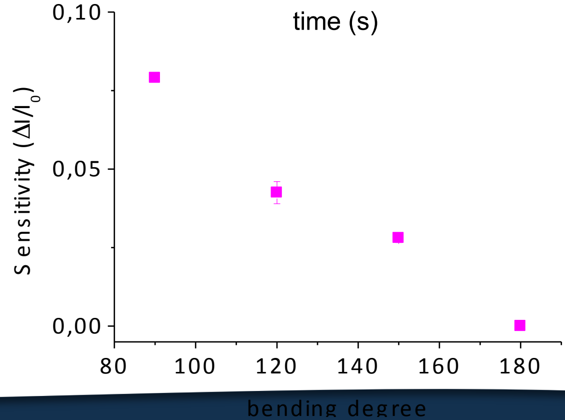


Applications: joints motion

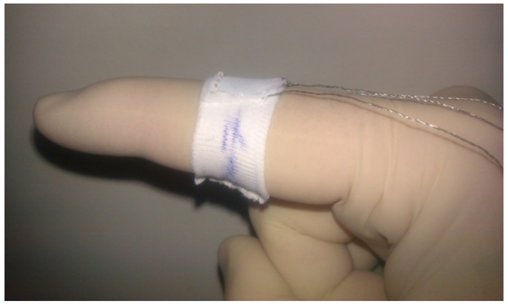
Sensor applied onto a ribbon can be transferred onto clothes for **joints motion monitoring**

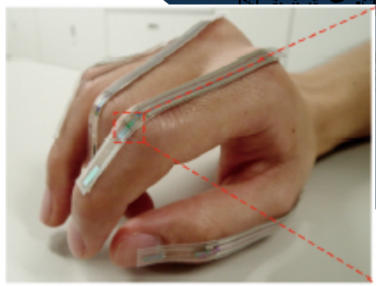


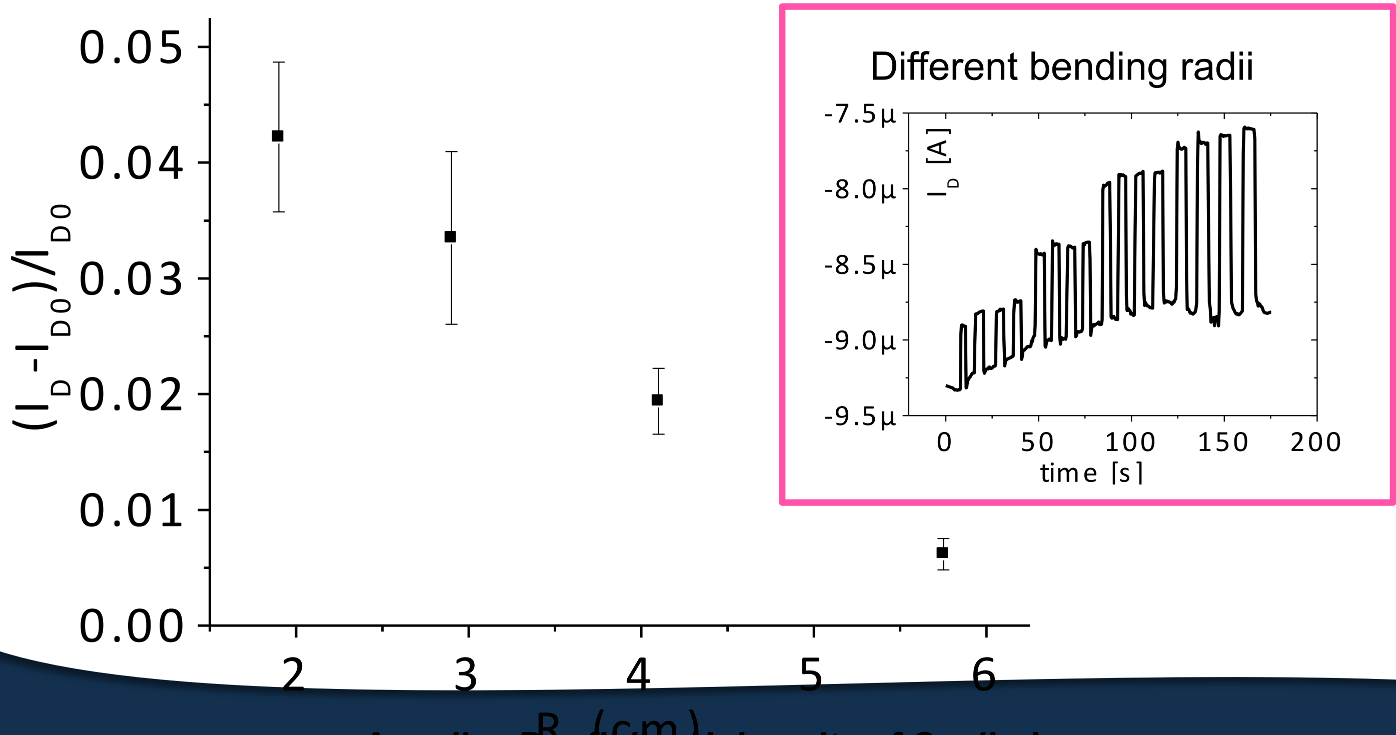




Applications: sensing glove







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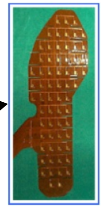
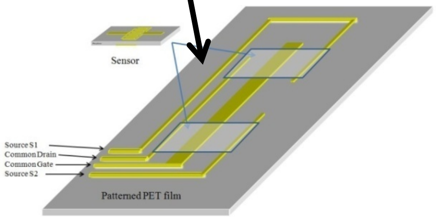
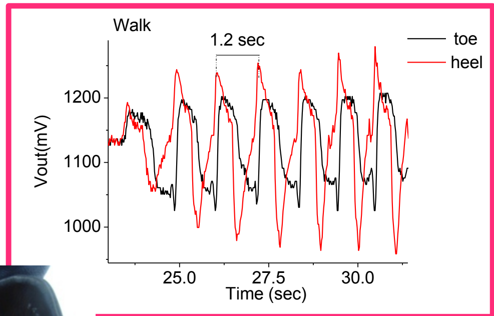
Applications: sensing shoesole

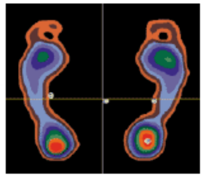
- Weight distribution
  → matrix of pressure sensors

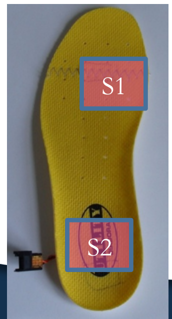


- Gait phases analysis and fall detection
  → sensorized shoe sole with 2 sensors

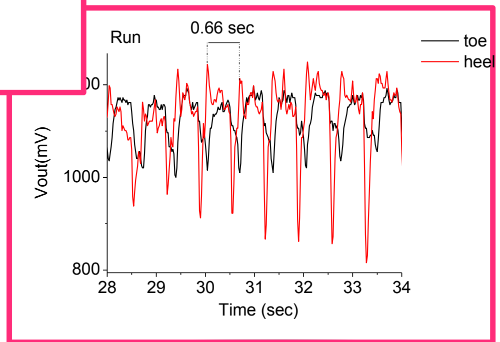




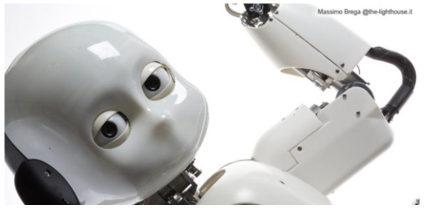




PROETEX



Applications: Artificial robot skin

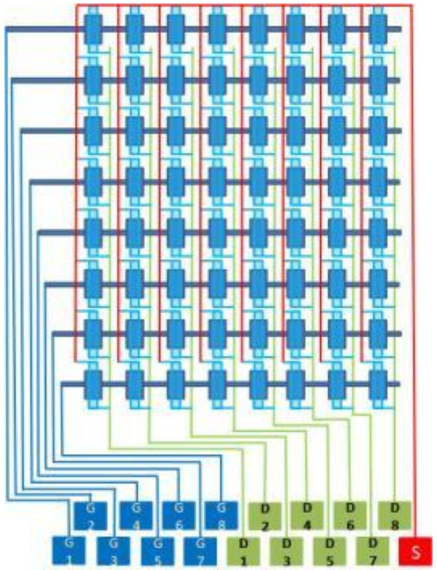


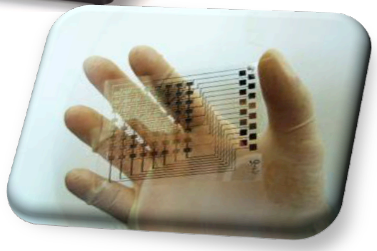
Develop a highly flexible, compliant system for tactile transduction

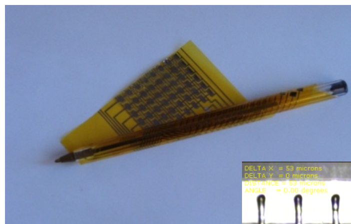
Inkjet printed matrices and arrays of OTFTs on plastic substrates

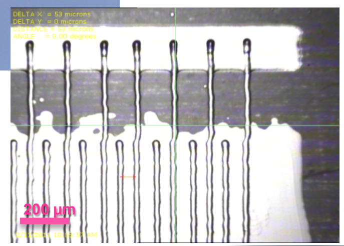
RoboSkin

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



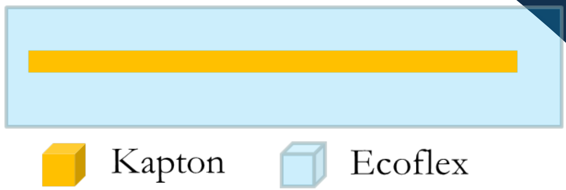






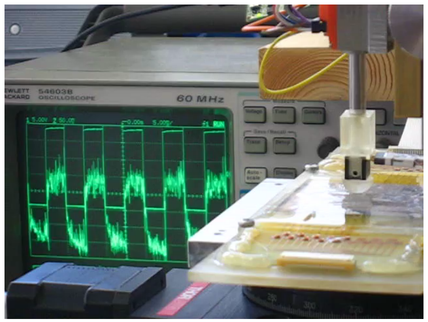
Artificial skin: Experimental set up

Embedding the organic substrates with elastomers

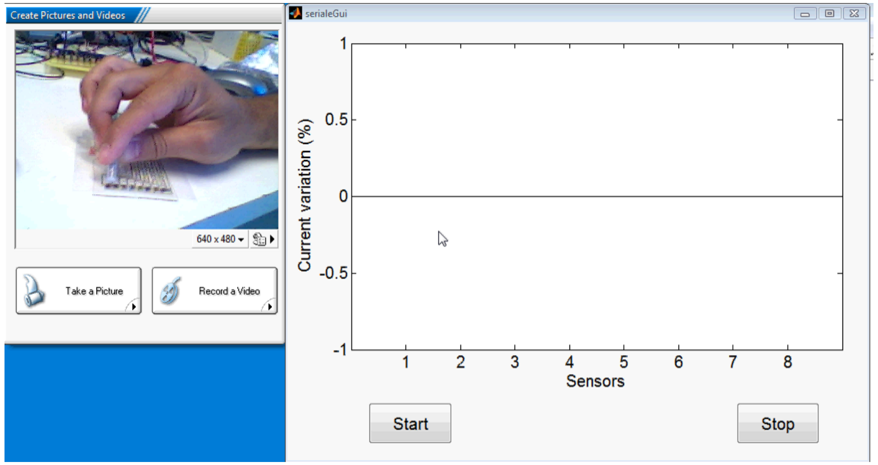


Mechanical properties and thickness of the elastomer influence the sensitivity *(Ecoflex → 1 + 1 mm)*

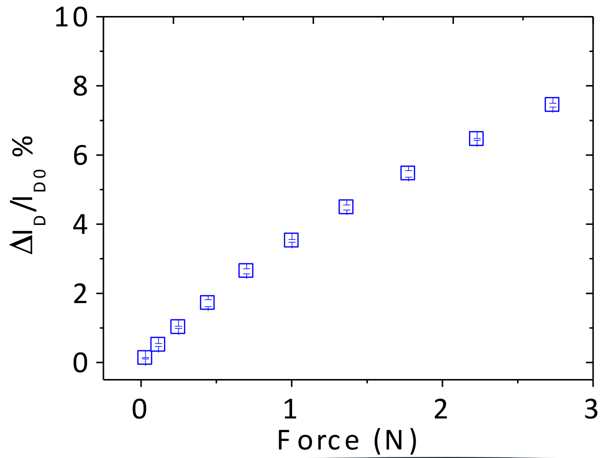
- Pressure exerted by a mechanical finger
- Hemispheric indenter (4 mm radius)
- Controlled input: Dz, F
- Output: $\Delta I/I$
- Increasing pressures
- Different configurations



Artificial skin: electro-mechanical characterization



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



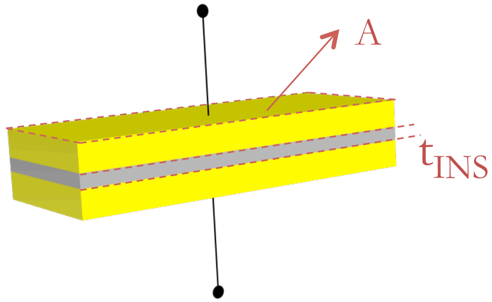
A. Loi et al. IEEE Sensors Journal accepted for publication

Towards realistic applications: other challenges of OTFT-based sensors

- ✓ **Operating voltages** of organic transistors are **typically high** (tens of volts):
  - ✓ Reduced portability;
  - ✓ Reduced integration;
  - ✓ A problem for biological applications!
- ✓ **Operating frequencies** of organic transistor are **typically low** (hundred of hertz):
  - ✓ Slow response at mechanical stimuli;
  - ✓ Insensitivity to fast biochemical events (e.g., cell activity);
- ✓ The **semiconductor stability** is **heavily affected by the environment**:
  - ✓ Damages from mechanical stimuli;
  - ✓ Damages from liquids → strong limitation for biological applications

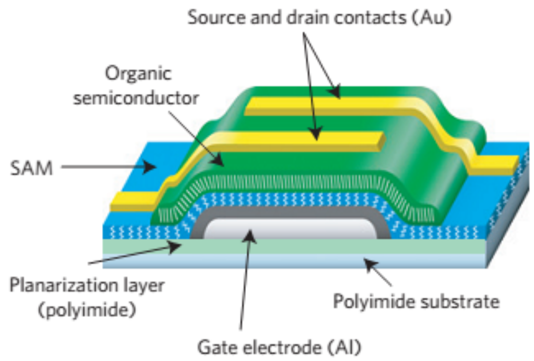
Towards high-performances OTFTs: decreasing the bias voltage

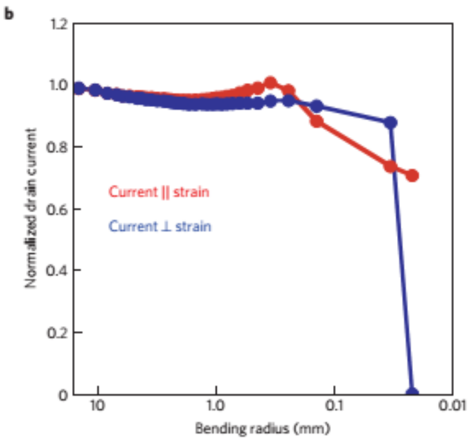
$$I_{DS} = \mu C_{INS} \frac{W}{L} f\left(V_{GS}, V_{DS}\right)$$

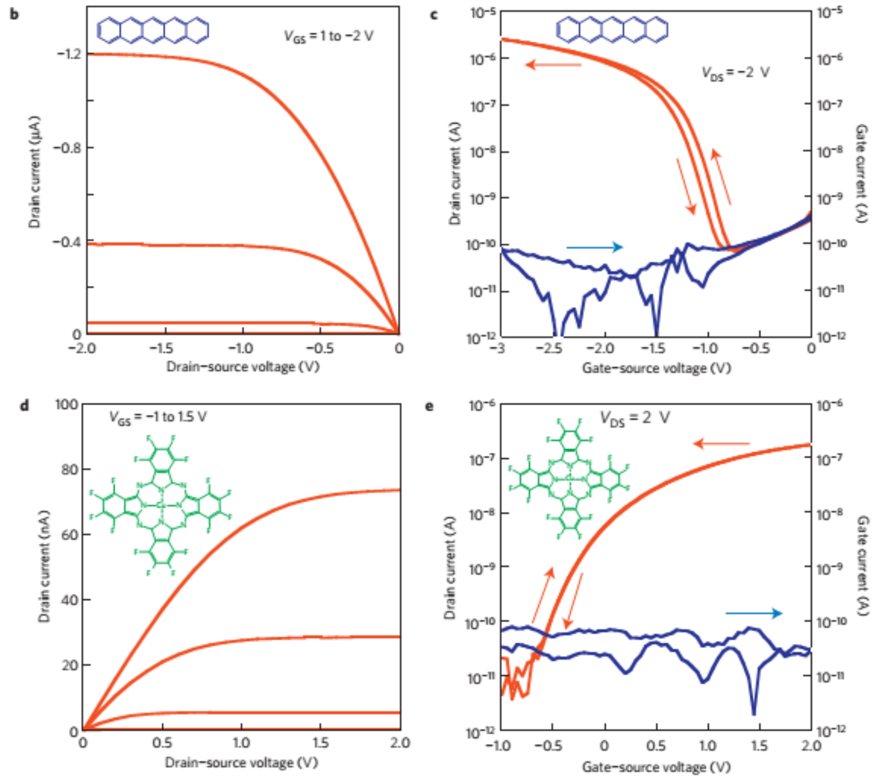


$$C_{INS} = \frac{\varepsilon_r \varepsilon_0}{t_{INS}}$$

Towards high-performances OTFTs

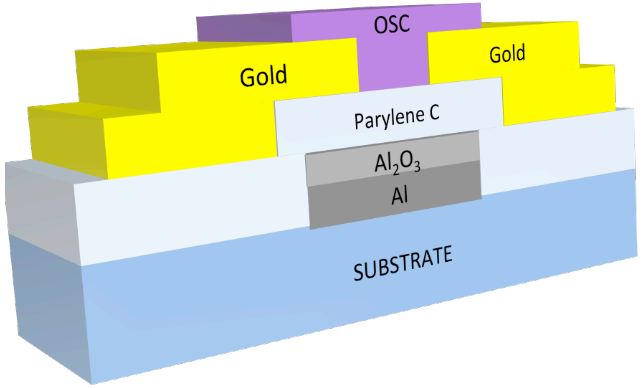




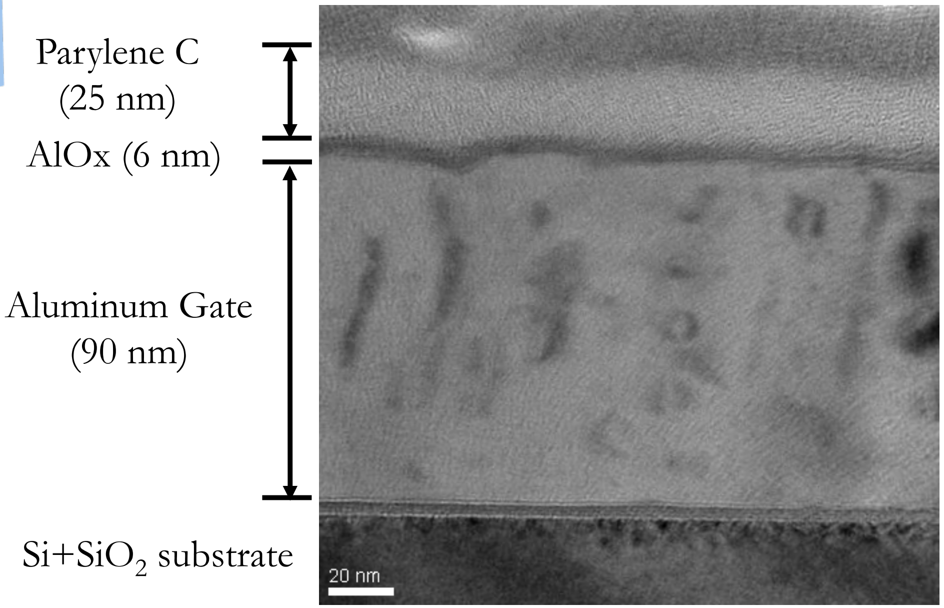


Sekitani et al., *Nat. Mater.*, 9, 1015-1022, 2010

Ultra-low voltage OFETs

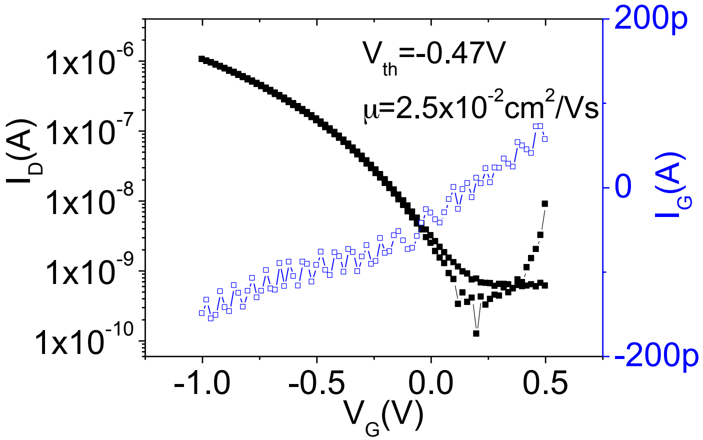


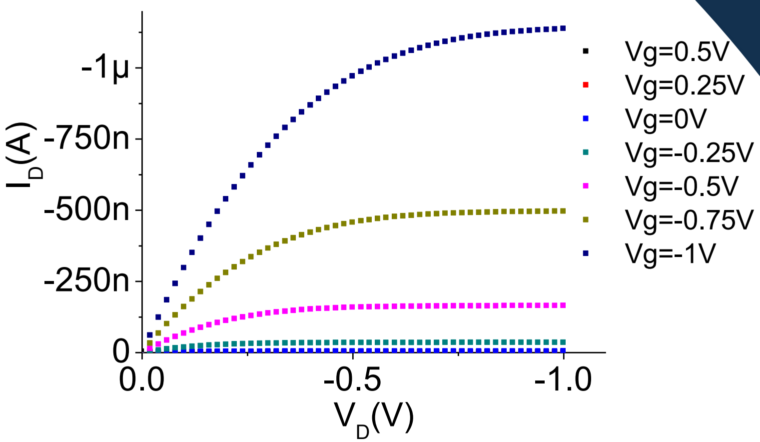
Cosseddu et al. , Applied Physics Letters, 100(9):093305, 2012



- ✓ Aluminum oxide can be deposited or directly grown on the aluminum gate by several techniques (anodization, plasma/UV oxidation, etc.)
- ✓ Parylene C can be deposited at room temperature on large areas by Chemical Vapor Deposition

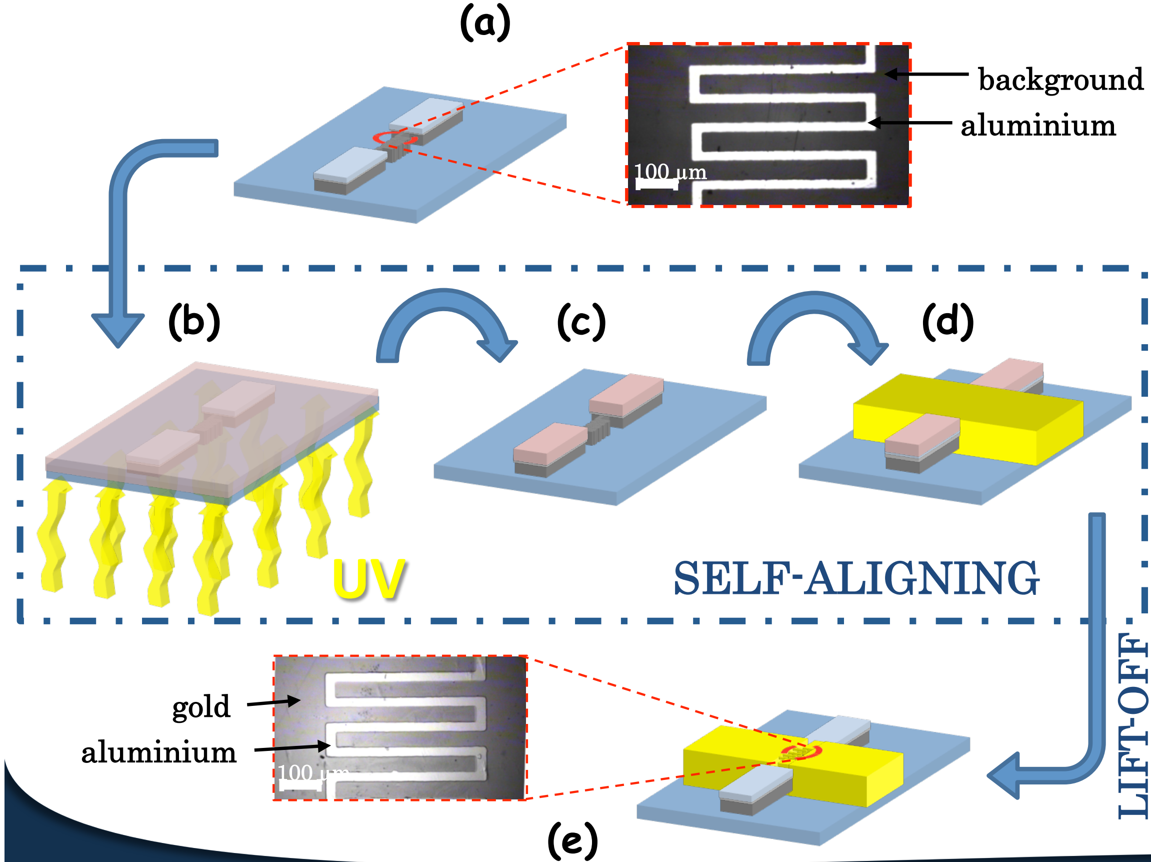
Ultra-low voltage OFETs





Insulating Structure	Capacitance [F/cm^2]	I_G [A] J_G[A/cm^2]	Vt [V]	μ [cm^2/Vs]	S [mV/dec]	Nt [cm^{-2}eV^{-1}]	OTFTs Yield [%]
Al_2O_3 + 25nm Parylene	$1.3\cdot10^{-7}$	$4\cdot10^{-10}$ $1.9\cdot10^{-9}$	-0.5	$6\cdot10^{-2}$	350	$4\cdot10^{12}$	90%

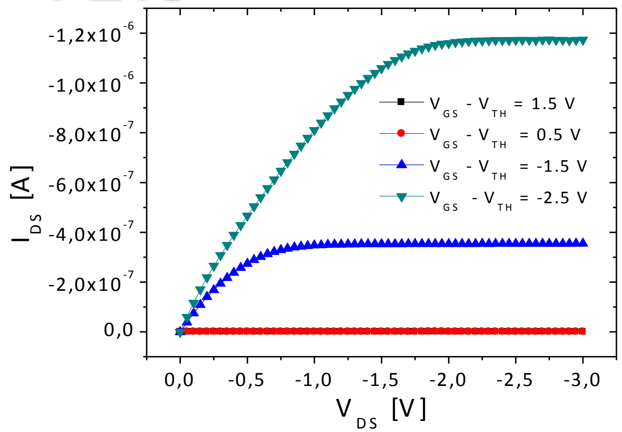
Improving the operating frequency: self-alignment

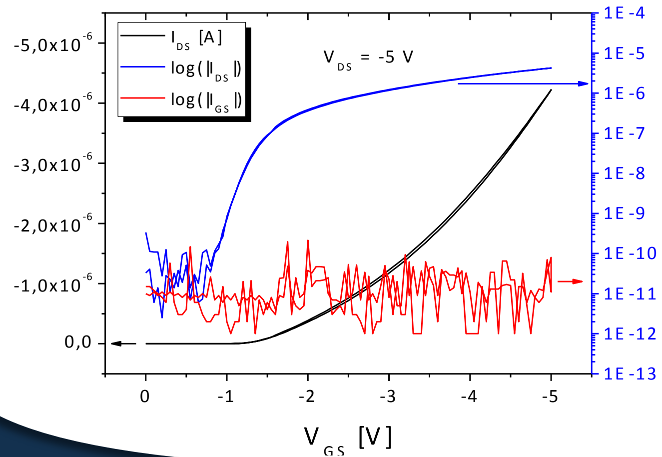


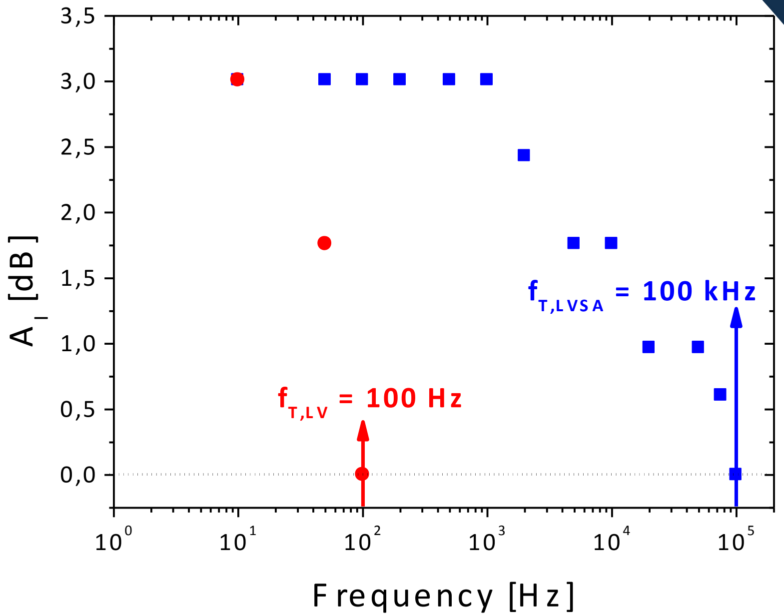
$$f_C = \frac{g_m}{2\pi\left(C_G + C_P\right)} =$$

$$= \frac{f\left(\mu C_{INS}\frac{W}{L}, V\right)}{2\pi\left(C_G + C_P\right)}$$

Self-aligned, ultra-low voltage organic FETs



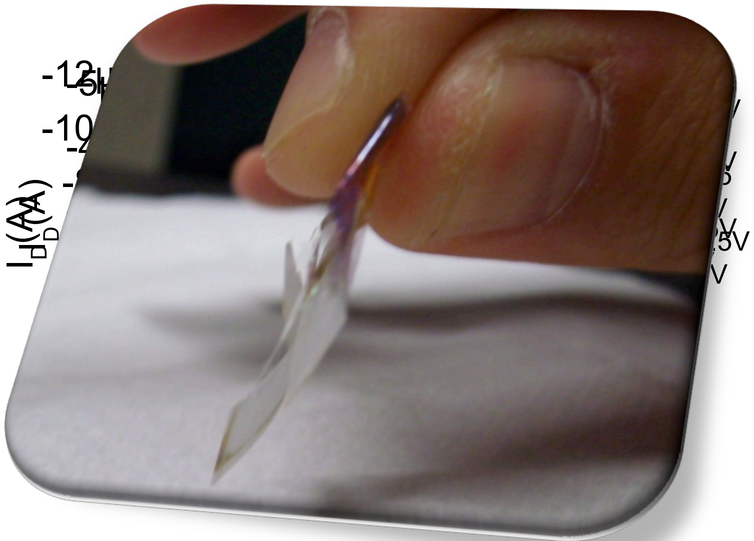


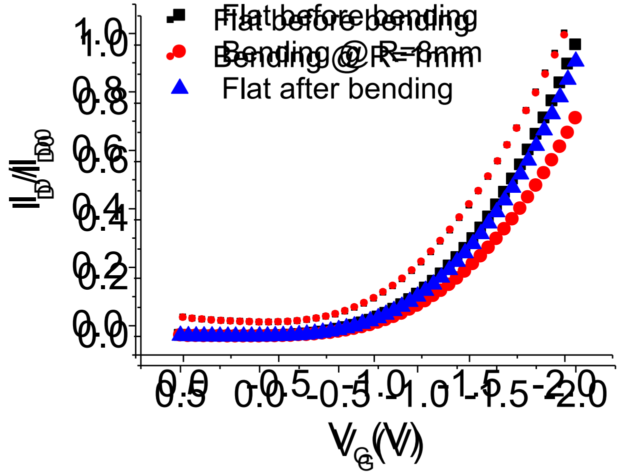


Lai et al. , Organic Electronics, 14, 754-761, 2013

Sensitivity to strain of low voltage OTFT

OTFTs fabricated on 175μm PET substrate



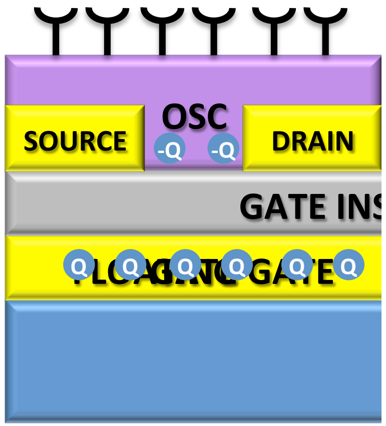


Strain (ε)=d/2R
d~substrate thickness
R=bending radius

Sensors for physical parameters

Introducing a novel TFT-based sensing approach

OCMFET = Organic Charge-Modulated FET

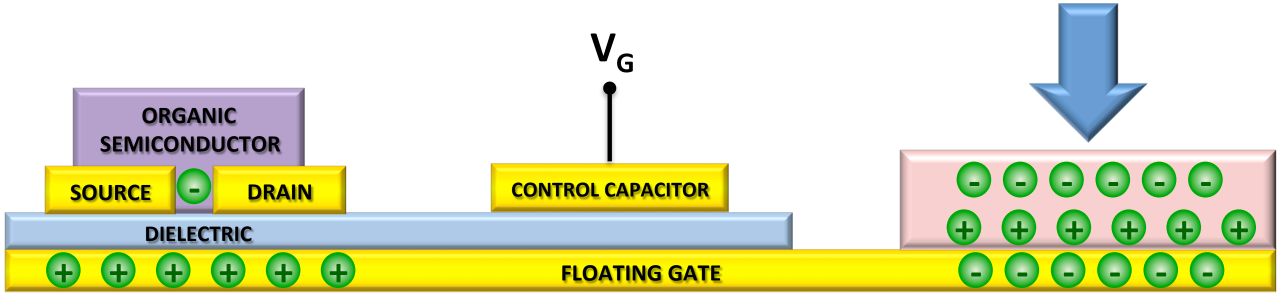


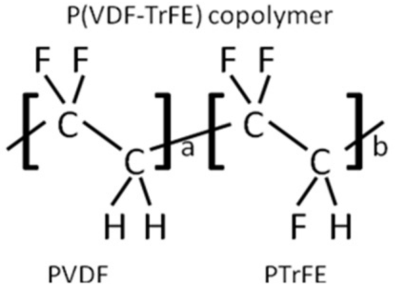
$$V_{FG} = \frac{C_{CF}}{C_{CF} + C_{DF} + C_{SF}} V_{CG} + \frac{C_{DF}}{C_{CF} + C_{DF} + C_{SF}} V_{DS} + \frac{Q_0 + Q_{ind}(Q_S)}{C_{CF} + C_{DF} + C_{SF}}$$

$$I_{DS} = k\left[\left(V_{FG} - V_{TH}\right) - \frac{V_{DS}}{2}\right] V_{DS}$$

The working principle is independent from the tecnology and can be employed for obtaining different kind of sensors.

OCMFET as pressure sensor

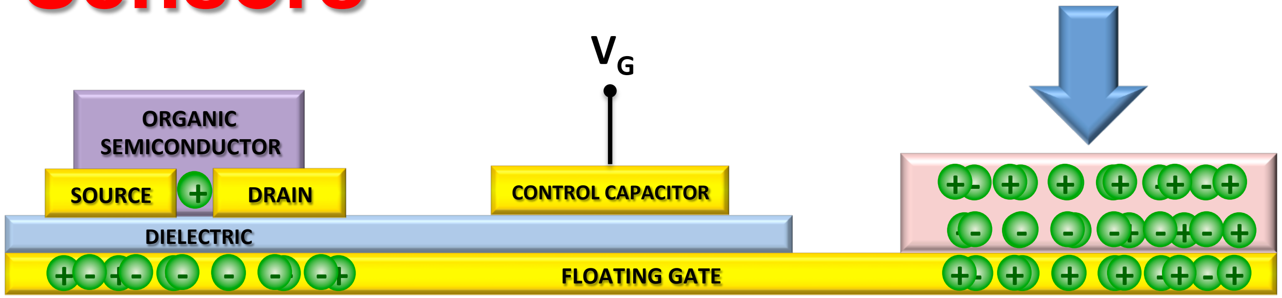


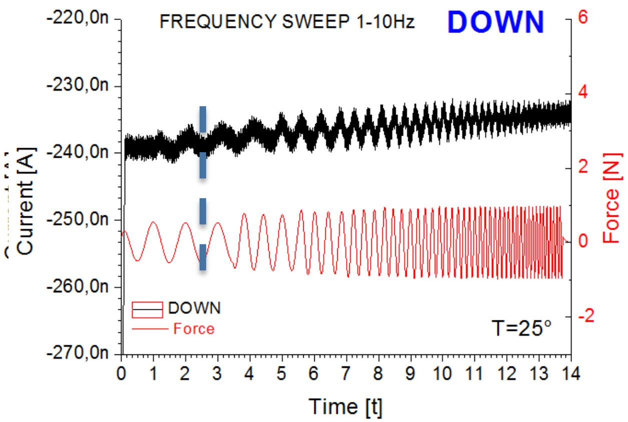


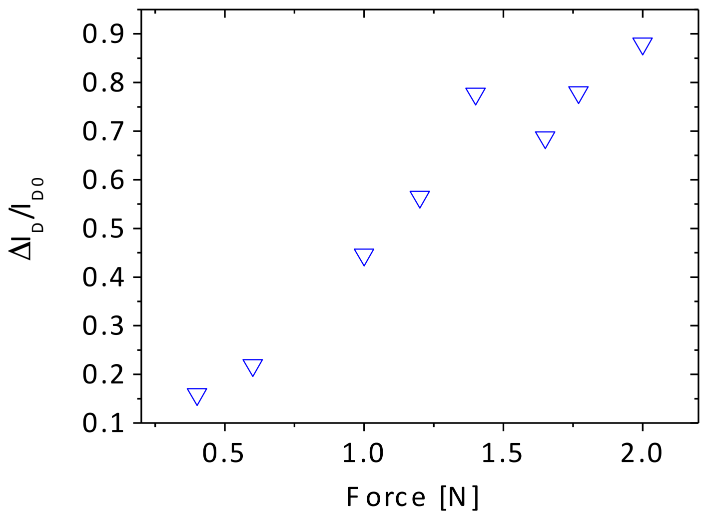
$$V_{FG} = \frac{C_{CF}}{C_{CF} + C_{SF} + C_{DF}} V_{GS} + \frac{C_{DF}}{C_{CF} + C_{SF} + C_{DF}} V_{DS} + \frac{Q_0 + Q_{ind}}{C_{CF} + C_{SF} + C_{DF}}$$

$$I_{DS} = \mu C_{INS} \frac{W}{L} \left[(V_{FG} - V_{TH}) V_{DS} - \frac{V_{DS}^2}{2} \right]$$

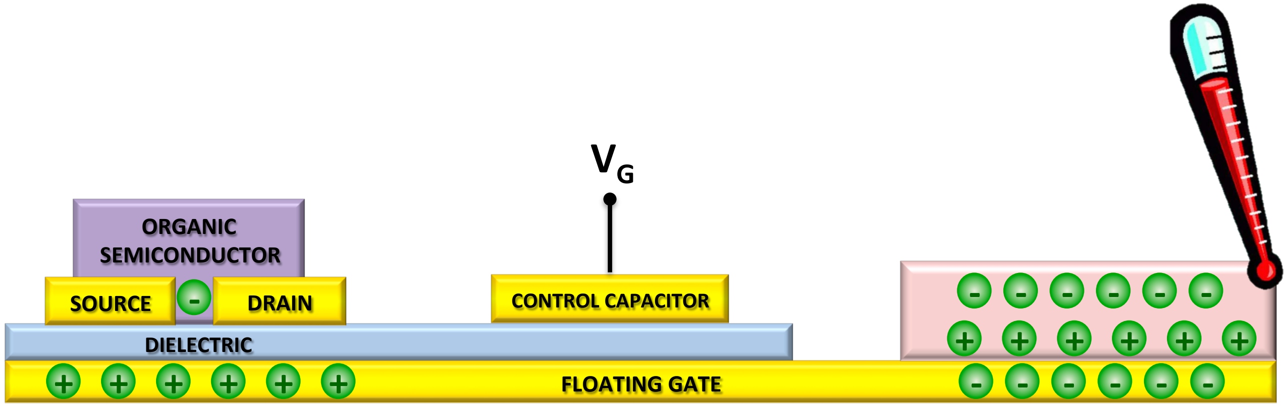
OCMFET as Pressure Sensors

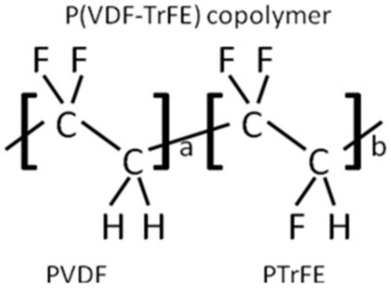






OCMFET as temperature sensor

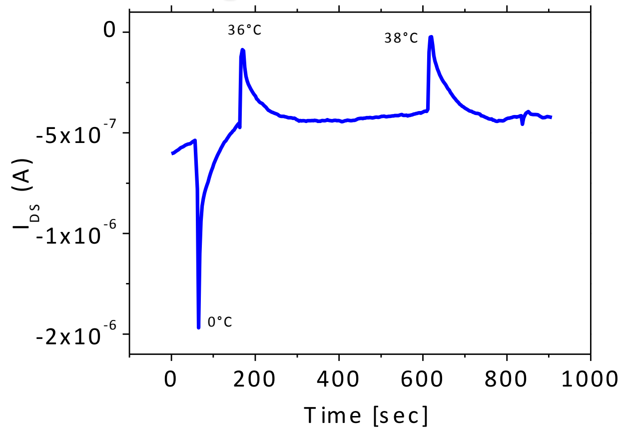


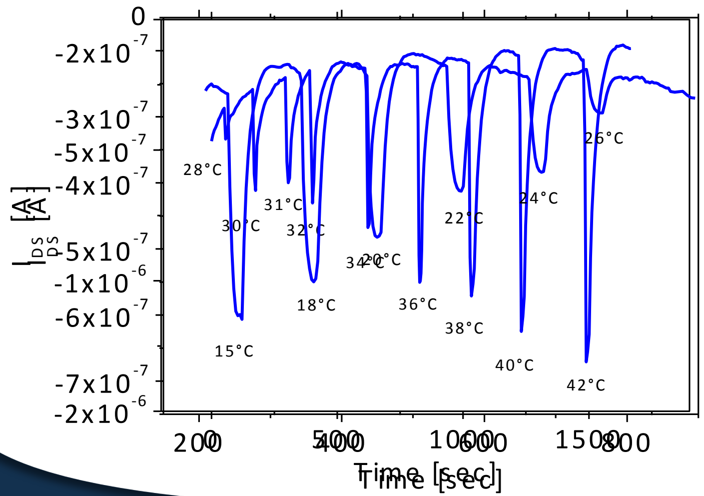


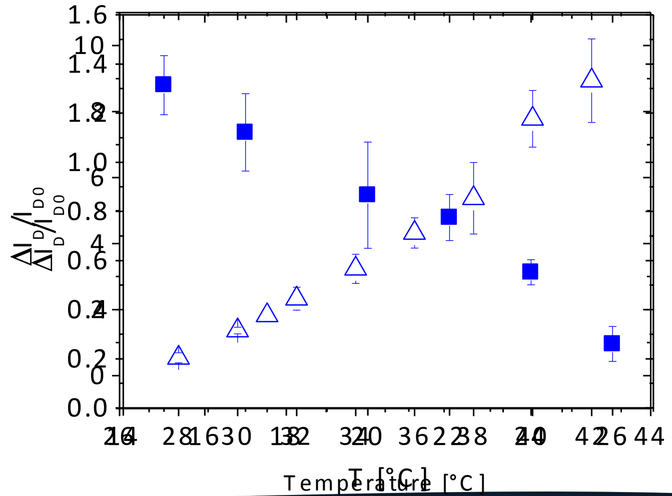
$$V_{FG} = \frac{C_{CF}}{C_{CF} + C_{SF} + C_{DF}} V_{GS} + \frac{C_{DF}}{C_{CF} + C_{SF} + C_{DF}} V_{DS} + \frac{Q_0 + Q_{ind}}{C_{CF} + C_{SF} + C_{DF}}$$

$$I_{DS} = \mu C_{INS} \frac{W}{L} \left[(V_{FG} - V_{TH}) V_{DS} - \frac{V_{DS}^2}{2} \right]$$

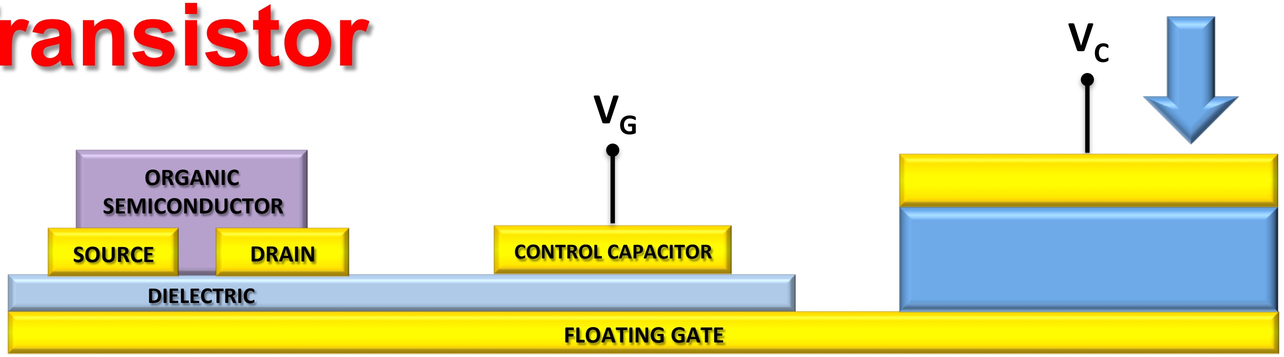
OCMFET as temperature sensor

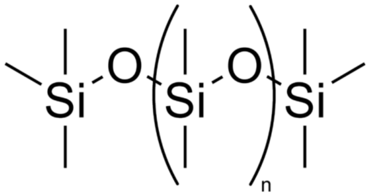






Pressure-Modulated Organic Field-Effect Transistor



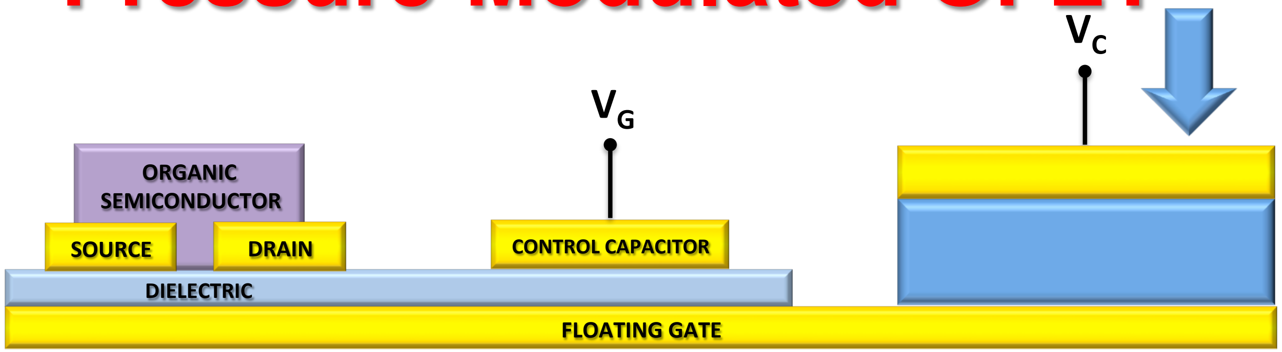


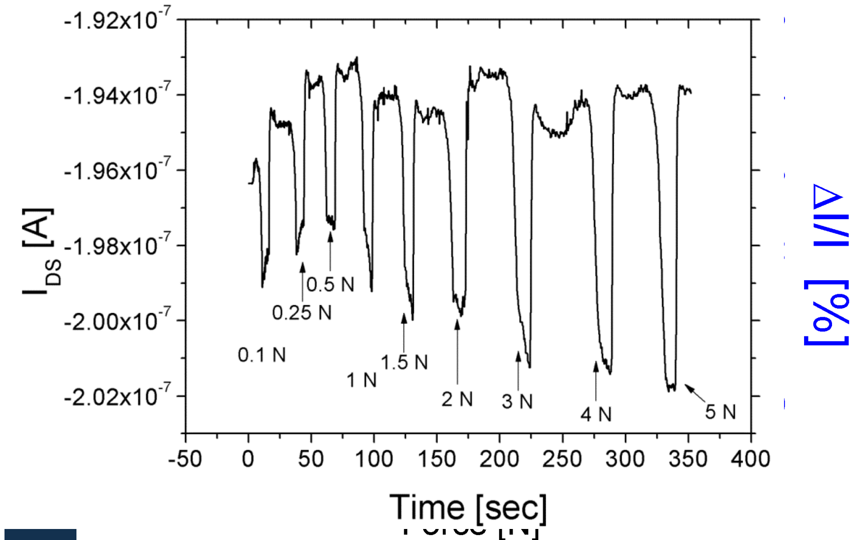
Polydimethylsiloxane (PDMS)

$$V_{FG} = \frac{C_{CF}}{C_{CF}+C_{SF}+C_{DF}+C_V}V_{GS} + \frac{C_{DF}}{C_{CF}+C_{SF}+C_{DF}+C_V}V_{DS} + \frac{C_V}{C_{CF}+C_{SF}+C_{DF}+C_V}V_C$$

$$I_{DS} = \mu C_{INS}\frac{W}{L}\left[(V_{FG}-V_{TH})V_{DS} - \frac{V_{DS}^2}{2}\right]$$

Pressure-Modulated OFET





With respect to PVDF:

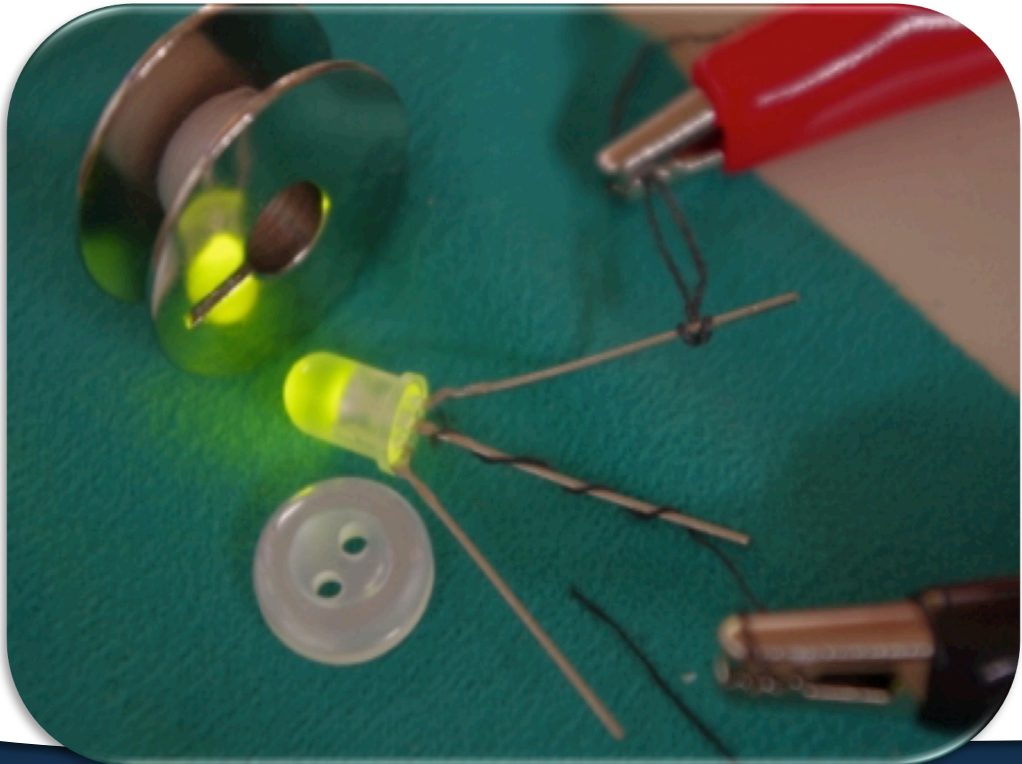
- − Slower response
- + Temperature independent
- + Low noise

Lai et al. , IEEE Electron Device Letters, 34(6), 801-803, 2013

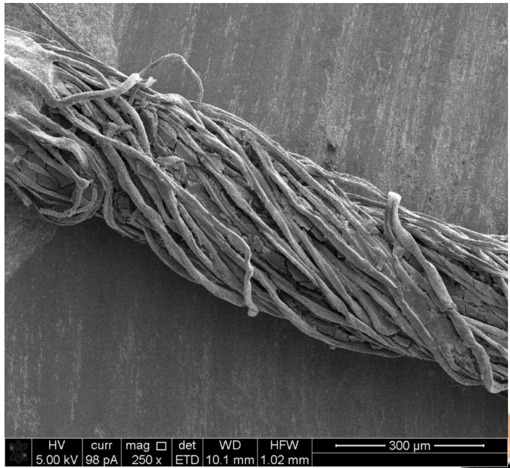
Playing with textiles

FROM WEARABLE ELECTRONICS TO SMART TEXTILES

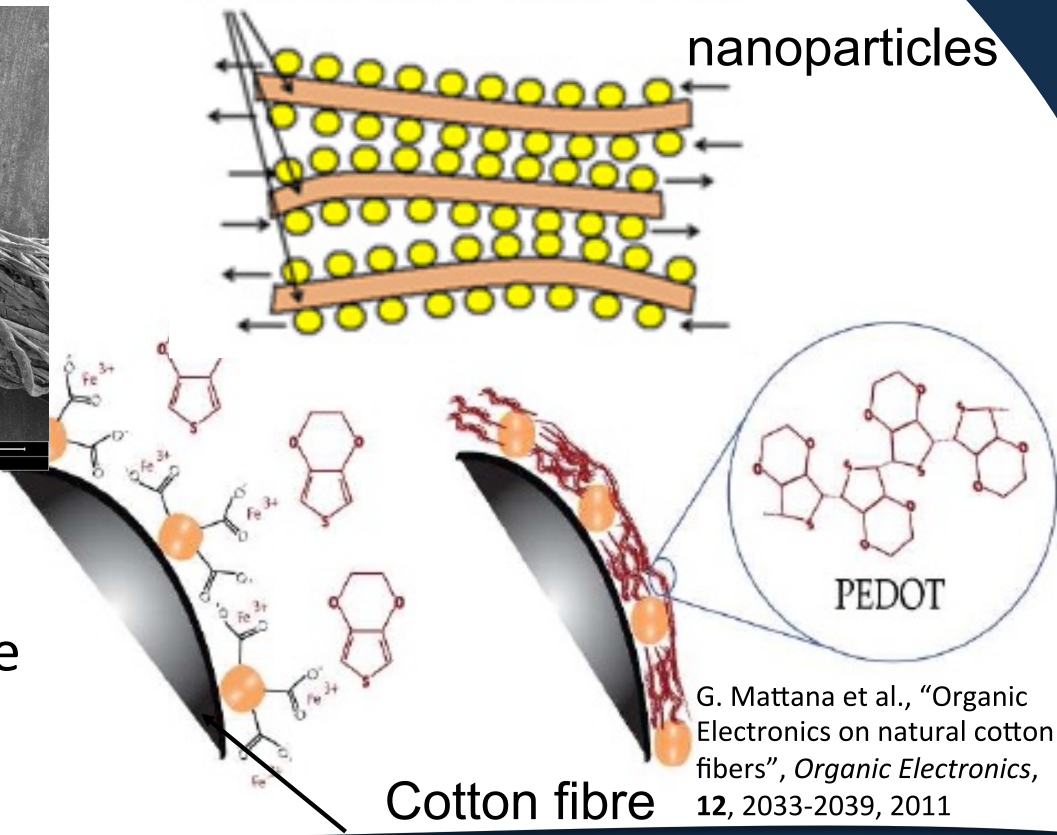
CONDUCTIVE FIBRES



Conductive Cotton fibres

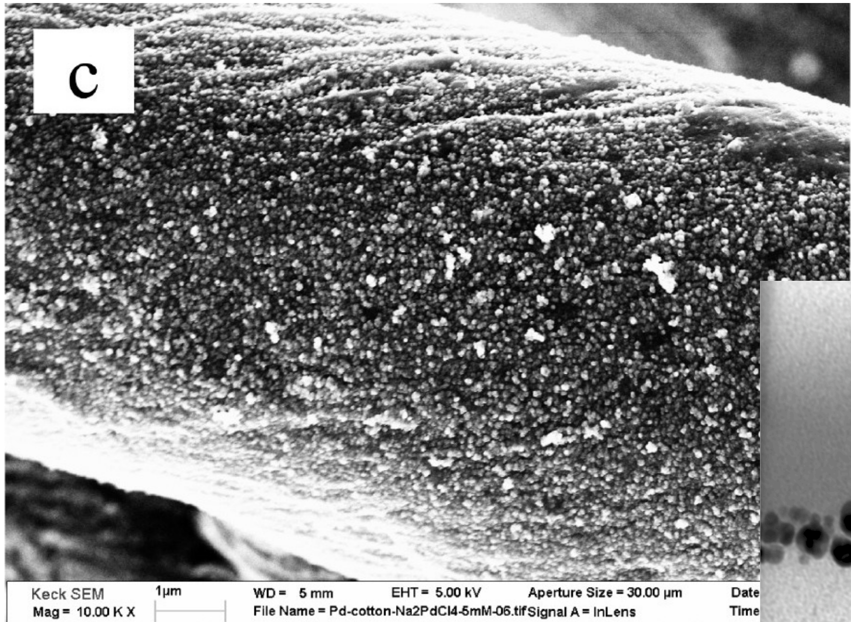


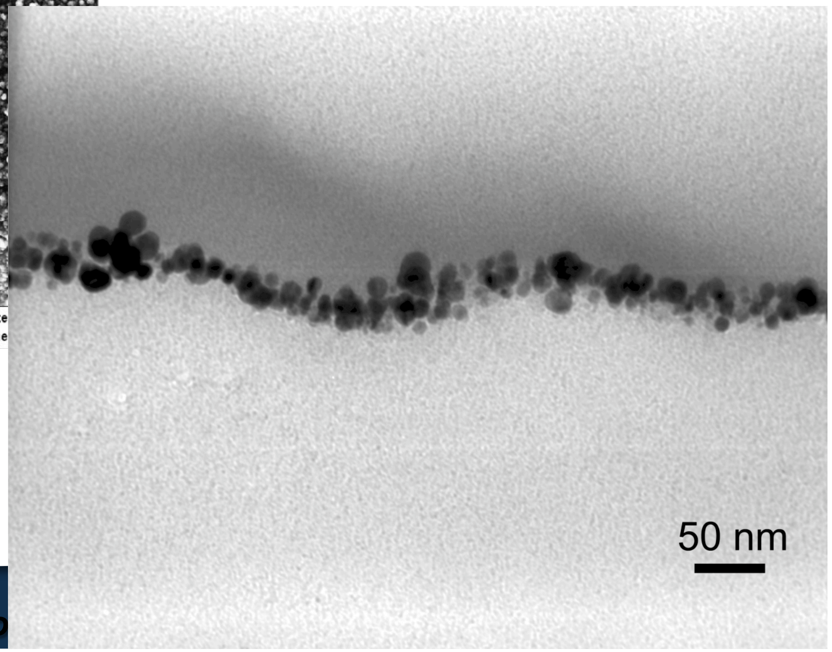
at the nanoscale



G. Mattana et al., "Organic Electronics on natural cotton fibers", *Organic Electronics*, **12**, 2033-2039, 2011

Conductive Cotton fibres





G. Mattana et al., "Organic Electronics on natural cotton fibers", *Organic Electronics*, **12**, 2033-2039, 2011

Conductive Cotton fibres

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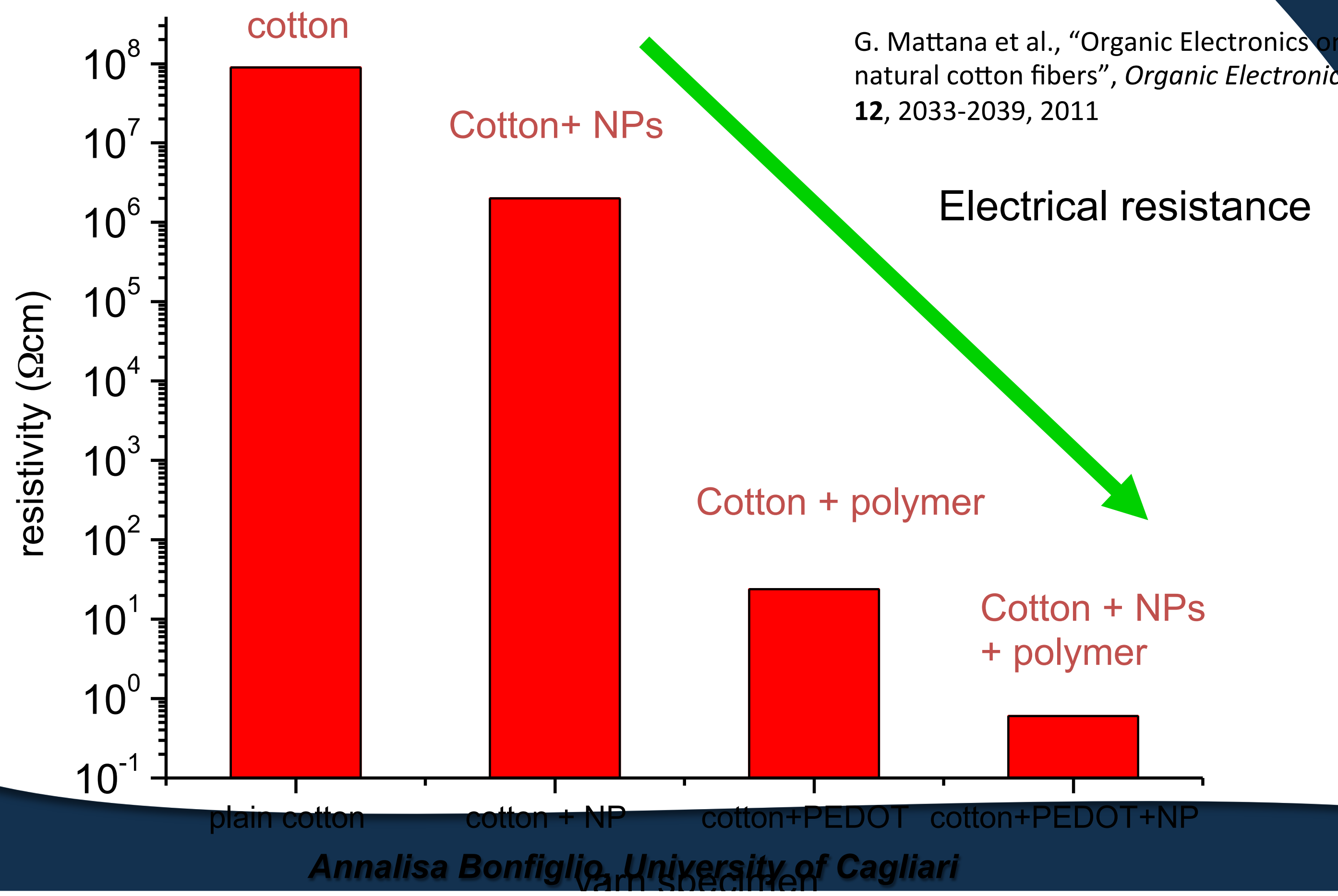
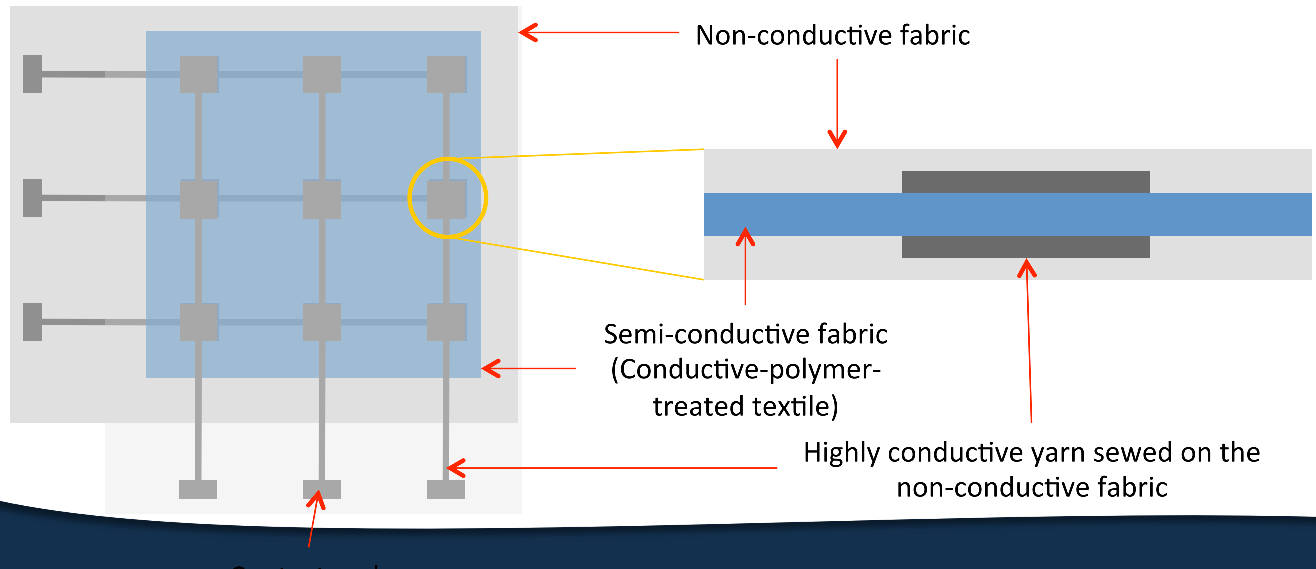


Textile Tactile Sensor: an array of all-textile pressure sensors

- An all-textile sensor for measuring the pressure distribution between two contacting surfaces.
- The force sensing elements consist in a conductive-polymer treated fabric sandwiched between to two pads of highly conductive yarn sewed on a non conductive fabric.

Example of the new textile tactile sensor

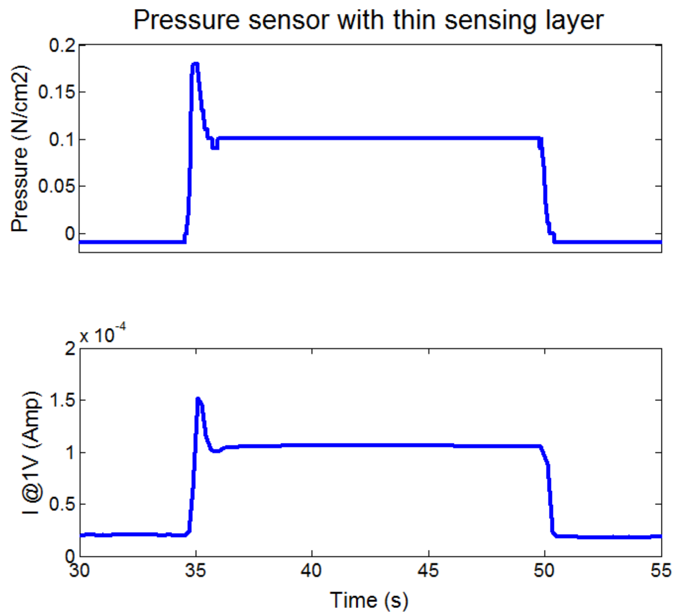
Detail of the sensing elements



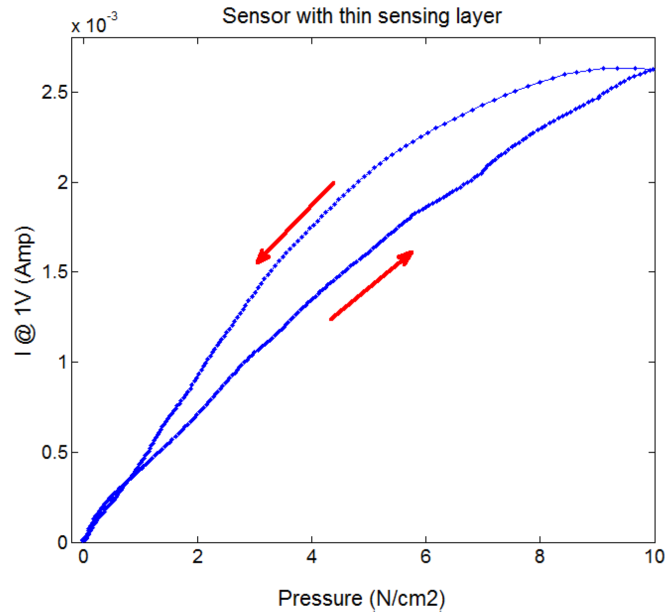
Sensor response to a pressure

- Tactile sensors with square sensing elements of 1cm spaced 3cm were used for the experiments
- Data is shown for sensors with thin sensing layer (cotton fabric).

Response to a pressure step

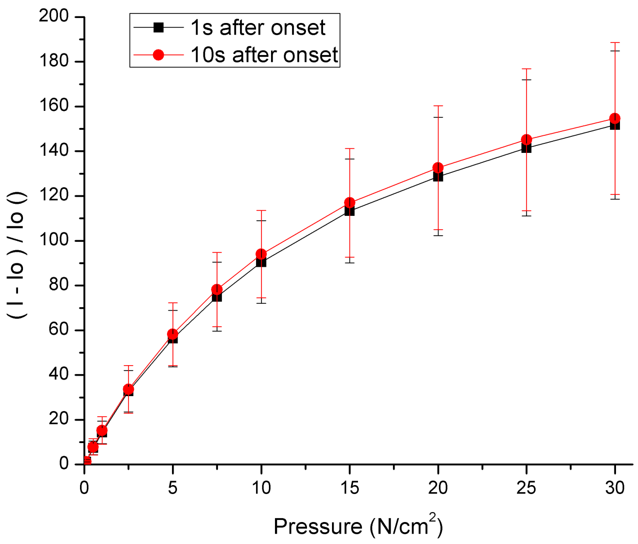


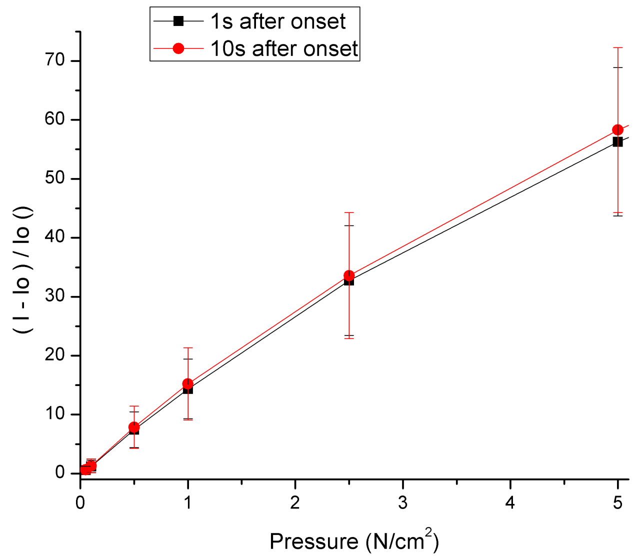
Response to a pressure ramp



Tactile sensor calibration curve

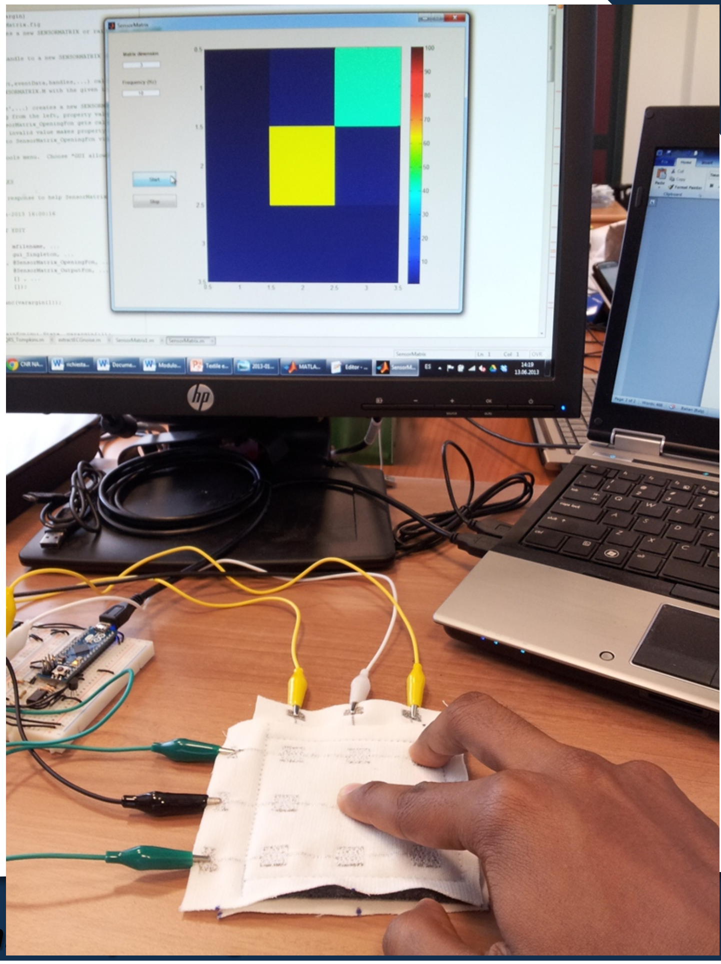
- Measurements were done after 1 and 10 seconds after the onset of the applied pressure.
- The behavior is almost linear up to 10N/cm^2 of pressure.
- Current increase more than 10 times every 1 N/cm^2 of pressure along the first 10N/cm^2
- Curves are constructed with the mean value and the standard deviation measured for 4 different sensing elements





Textile tactile sensor prototype

- The resistance of the sensing elements behave almost inversely proportional to the pressure applied.
- The sensor can be interconnected to multiplexing electronics for reading the output of each sensing element and communicate the readings to a computer.
- A software can then be used to visualize the magnitude and spatial distribution of the forces applied on the tactile sensor.
- Link for video



GRIP GLOVE

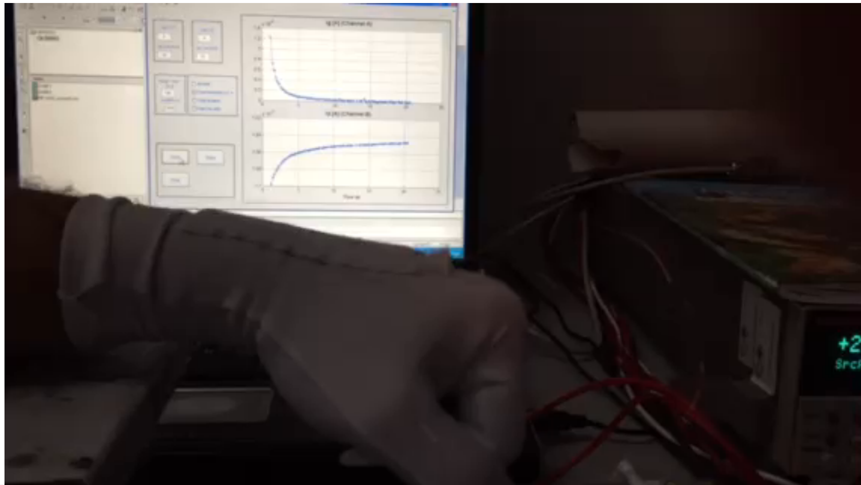
WRIST GLOVE

Grip Glove

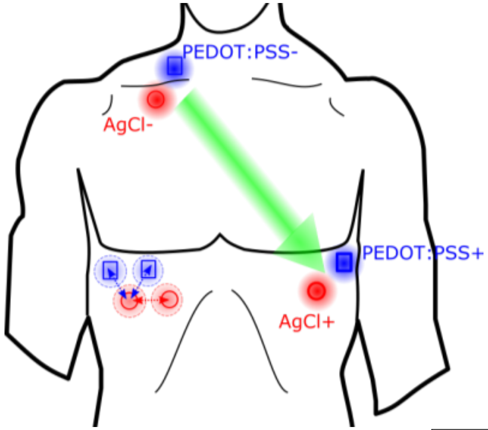
Sensors on the palm

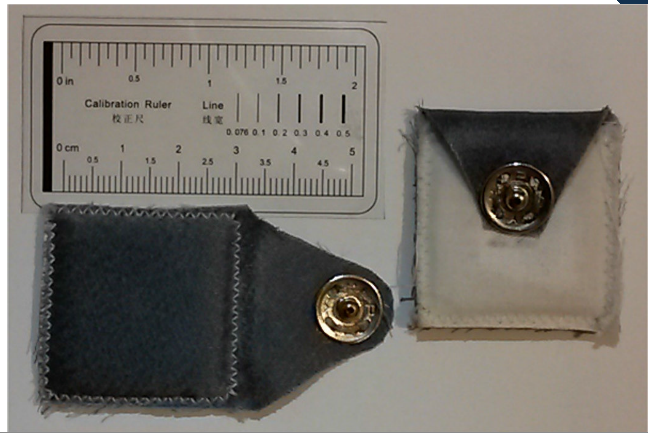
and on the fingers

WRIST motion detector



Biopotential recording by textile electrodes



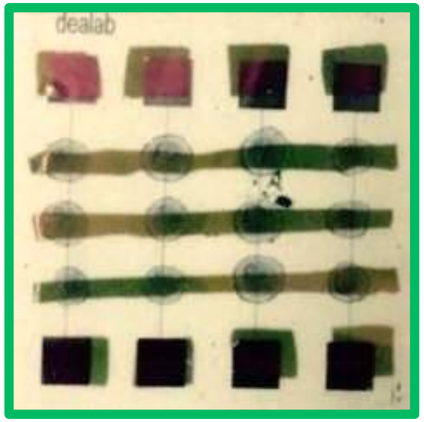


golden standard electrode

textile electrode

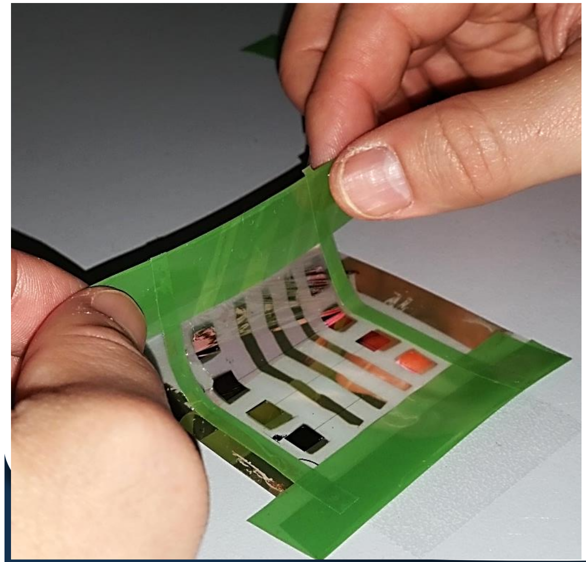
The future: more than wearable

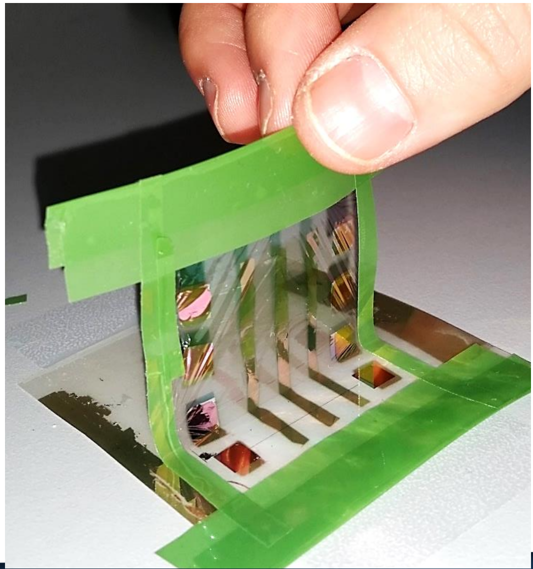
FREE-STANDING OTFTs : FABBRICATION PROCESS

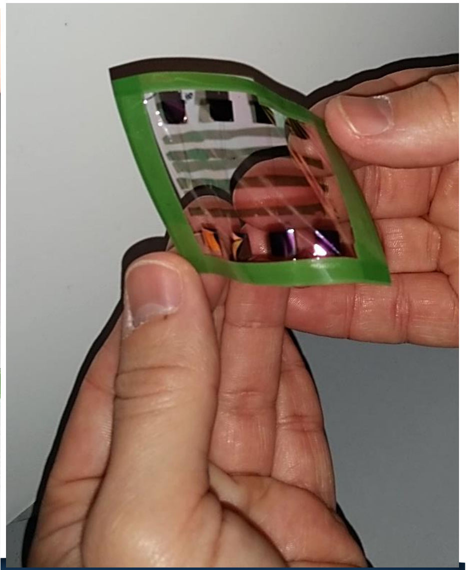


SUPPORTED ULTRA THIN OTFT

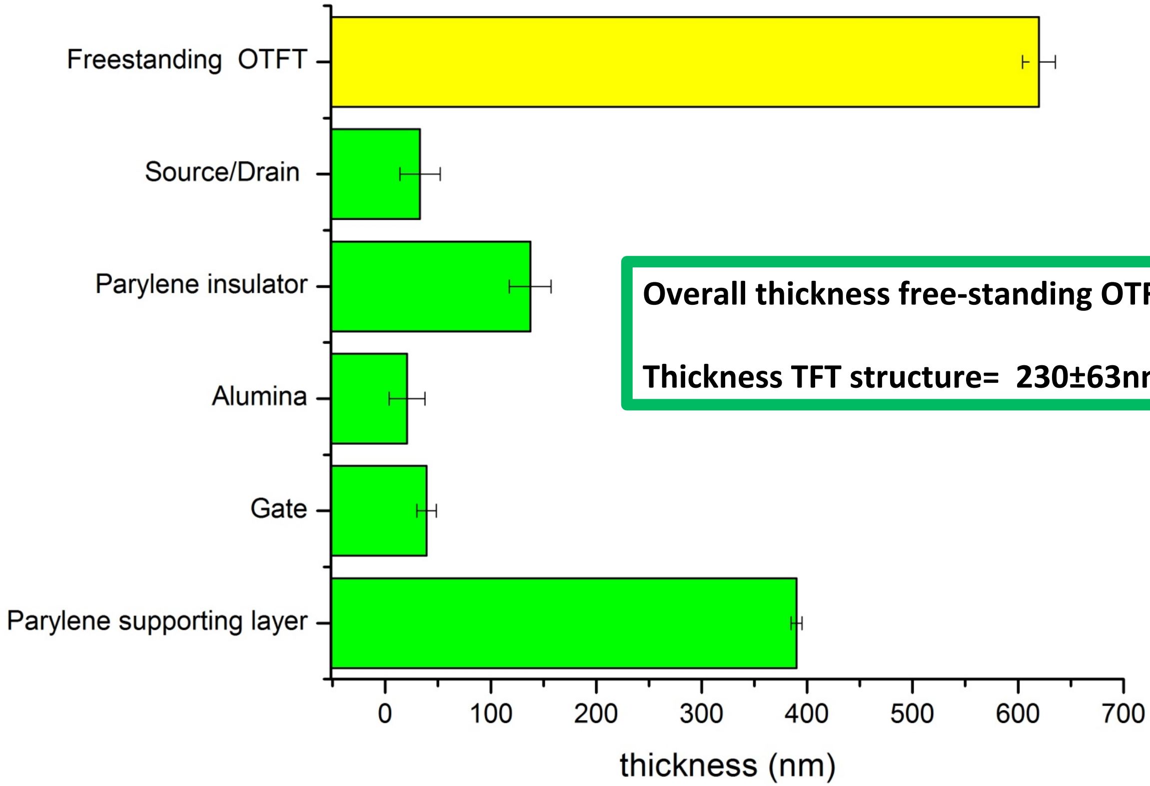
FREE-STANDING ULTRA THIN OTFT







THICKNESS OF FREE-STANDING OTFTs

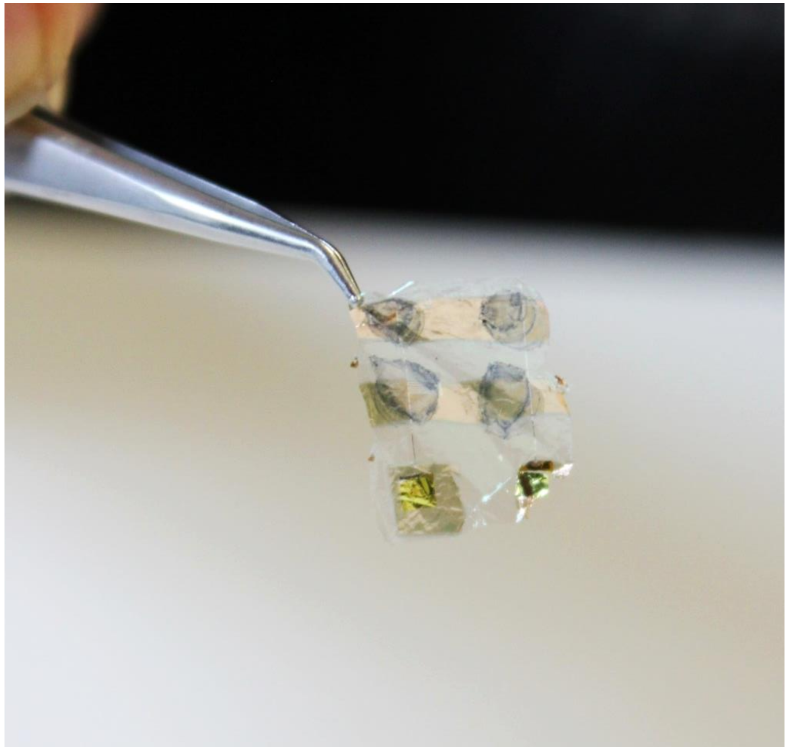


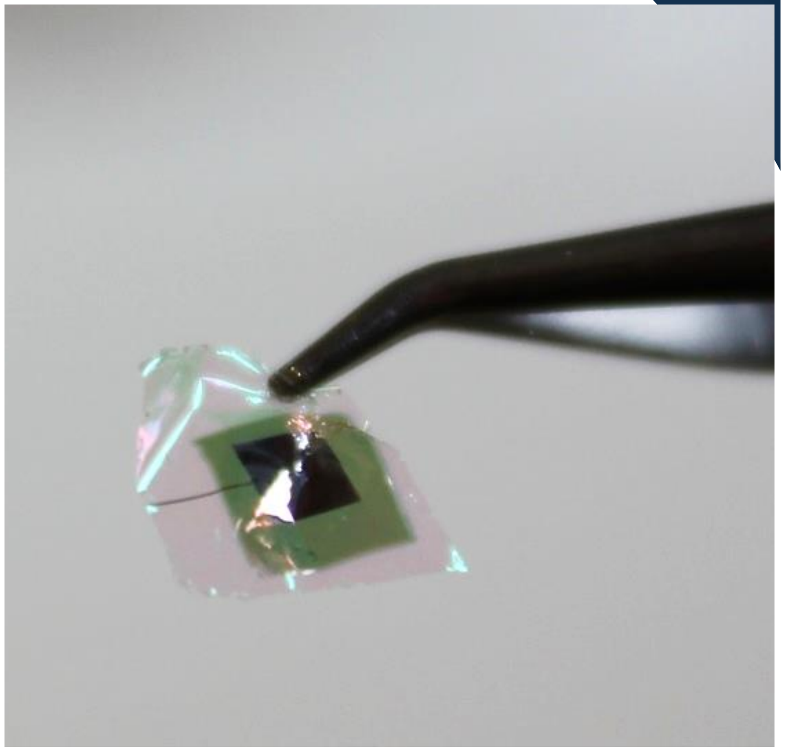
Overall thickness free-standing OTFT = 620±15 nm

Thickness TFT structure= 230±63nm

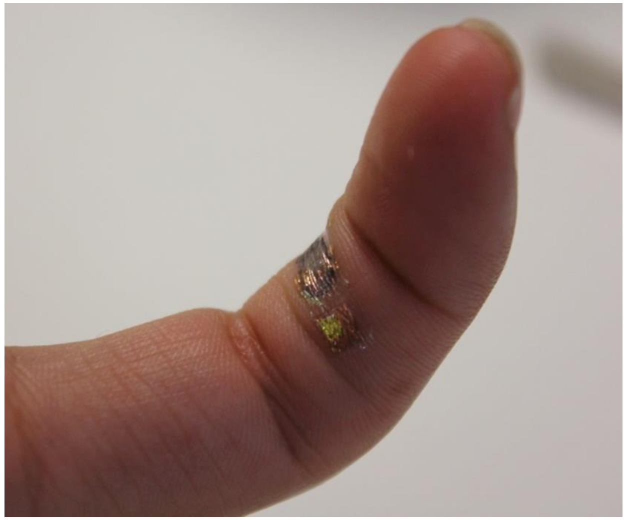
SUBMICROMETER FREE-STANDING OTFTs

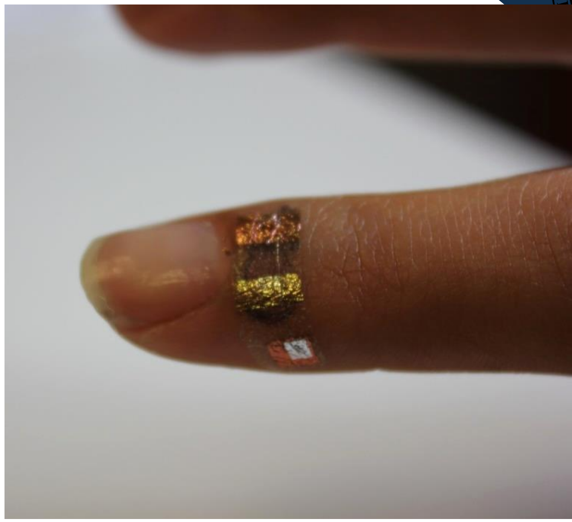
ULTRA- CONFORMABLE OTFTs

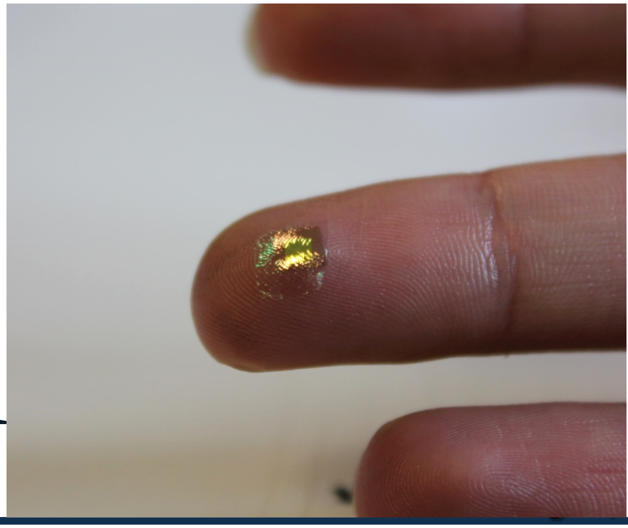




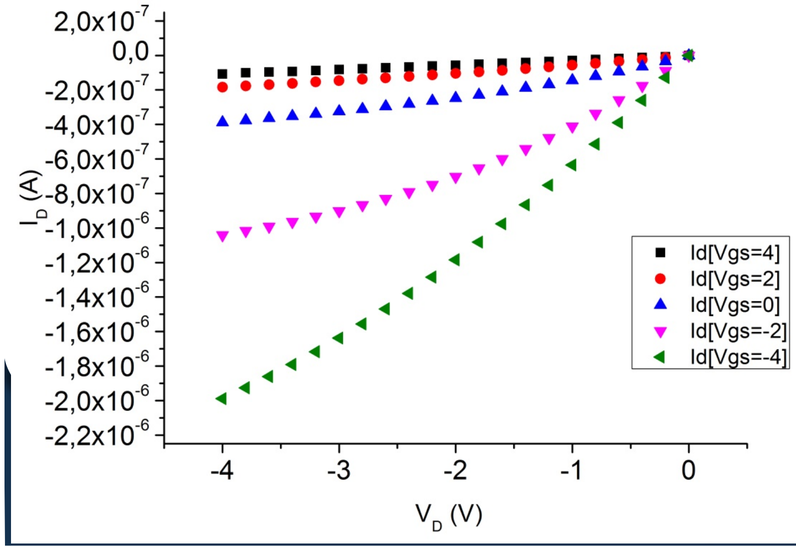
SUBMICROMETER FREE-STANDING OTFTs ONTO THE SKIN

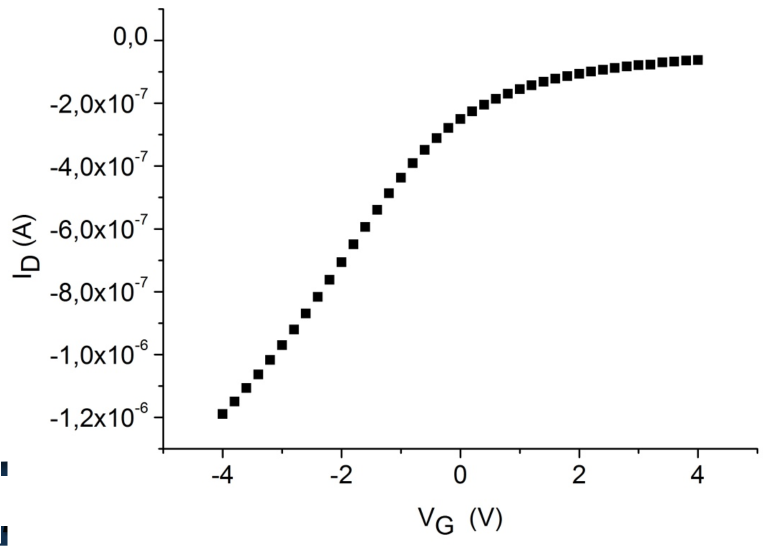






FREE-STANDING OTFTs ONTO THE SKIN





Conclusions

- ✓ Organic semiconductors are attracting materials for wearable applications
- ✓ Organic devices may be easily embedded in a garment
- ✓ Organic conductors and semiconductors may also be used for treating textiles at the fibre level → textile sensors and electrodes
- ✓ The future: from wearable to skin electronics

DEALAB

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DIEE - University of Cagliari

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Andrea Spanu, Ph. D. Student

Alberto Loi, Ph. D. Student

Giulia Casula, Ph.D. Student

RoboSkin

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REGIONE AUTONOMA DELLA SARDEGNA

THANK YOU!