Organic Field-Effect Devices for clinical applications

Corso di Tecnologie e Dispositivi
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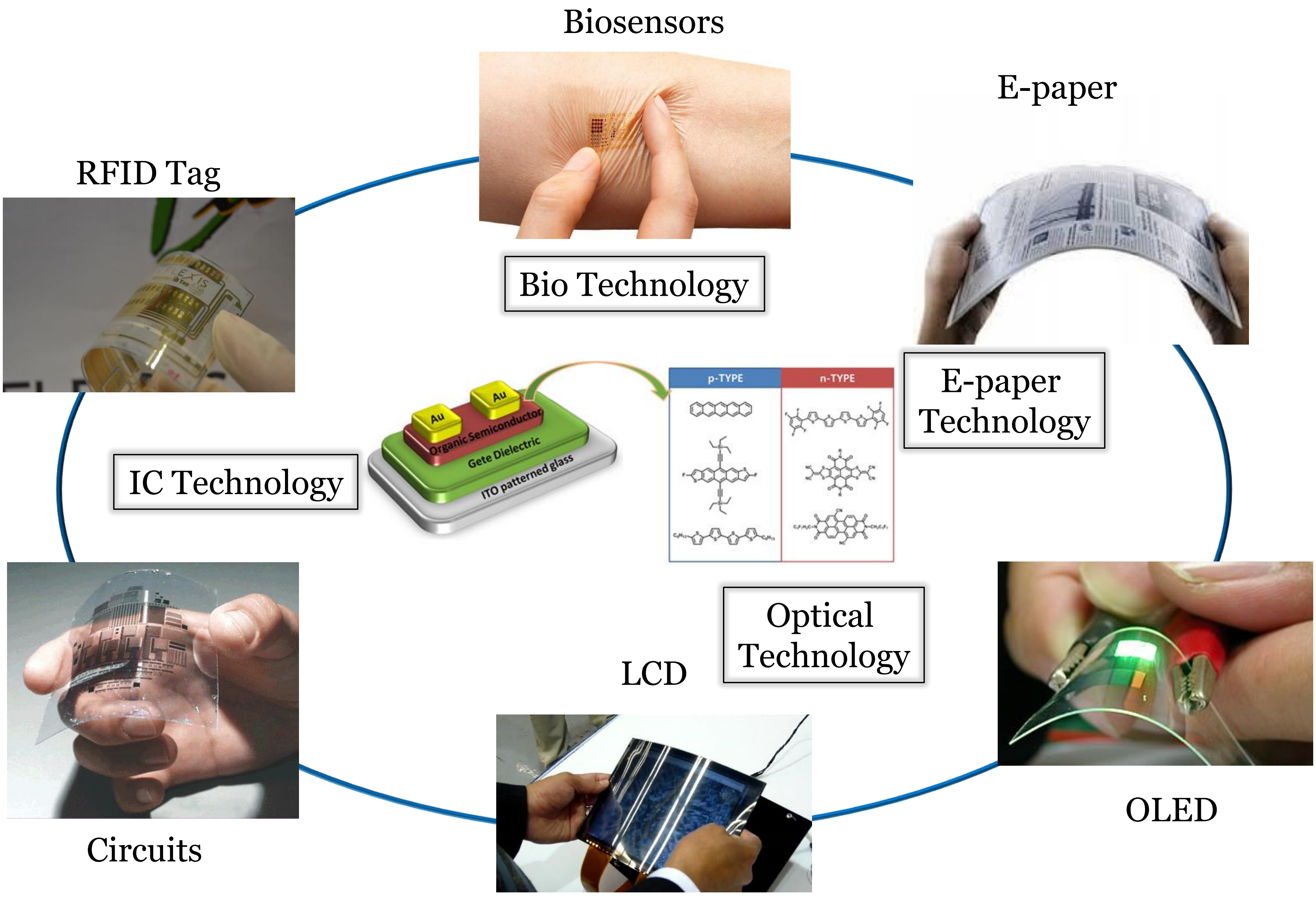
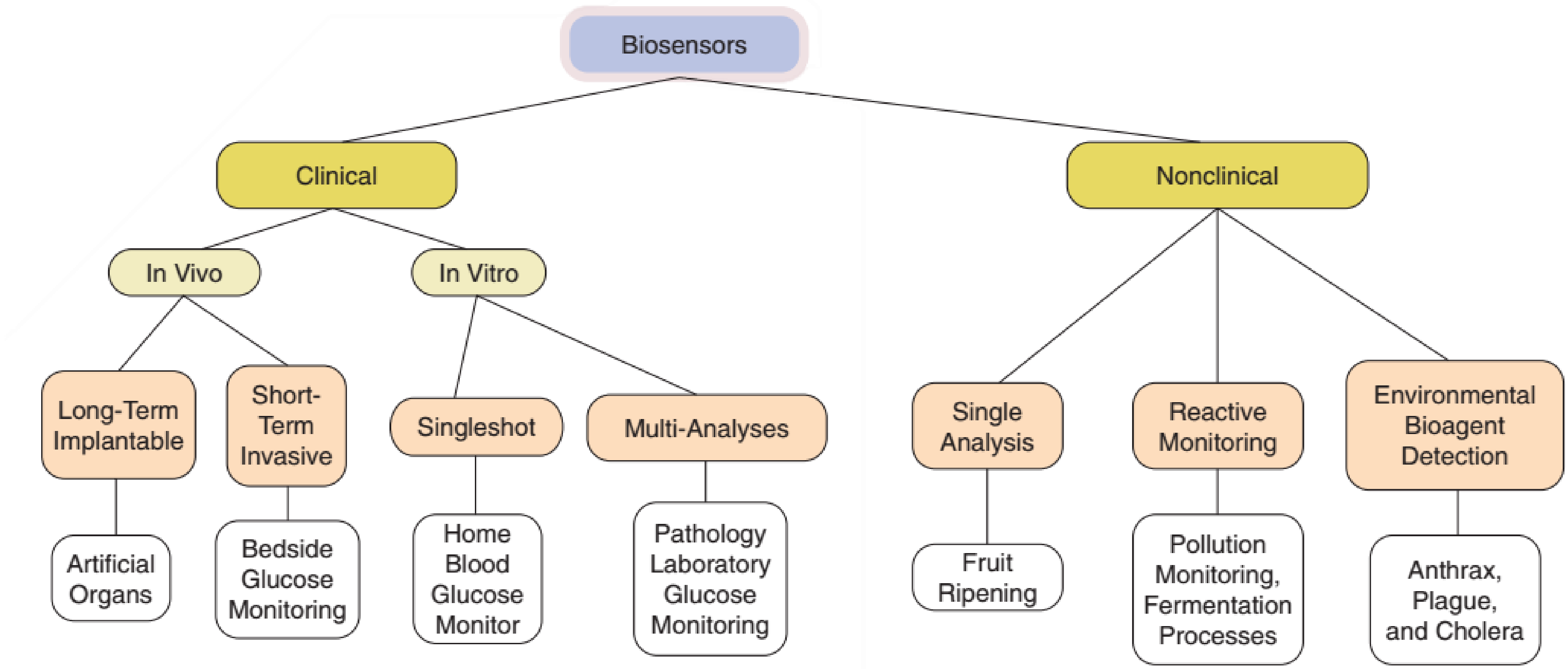
Outline

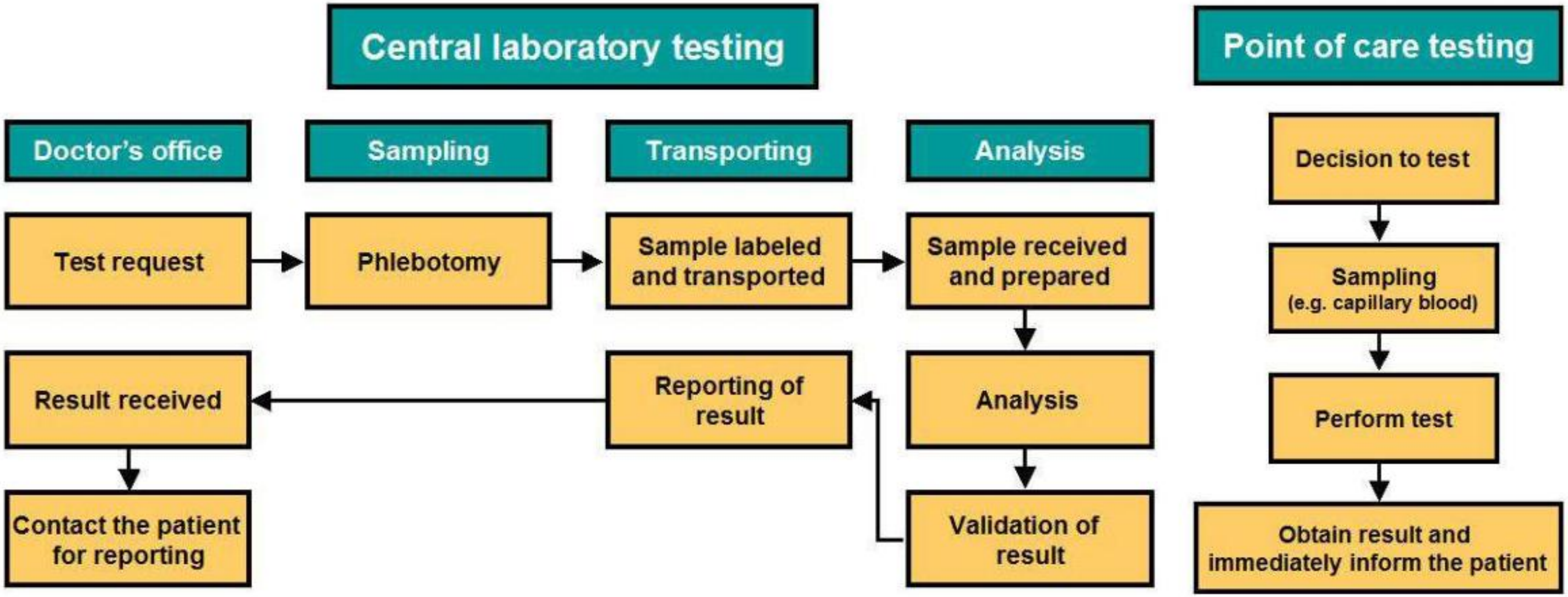
- Introduction: motivation, definition, classification
- Surface functionalization
- OTFT-based biosensors
- Transduction mechanisms
- Suitable structures for bio-related sensing applications

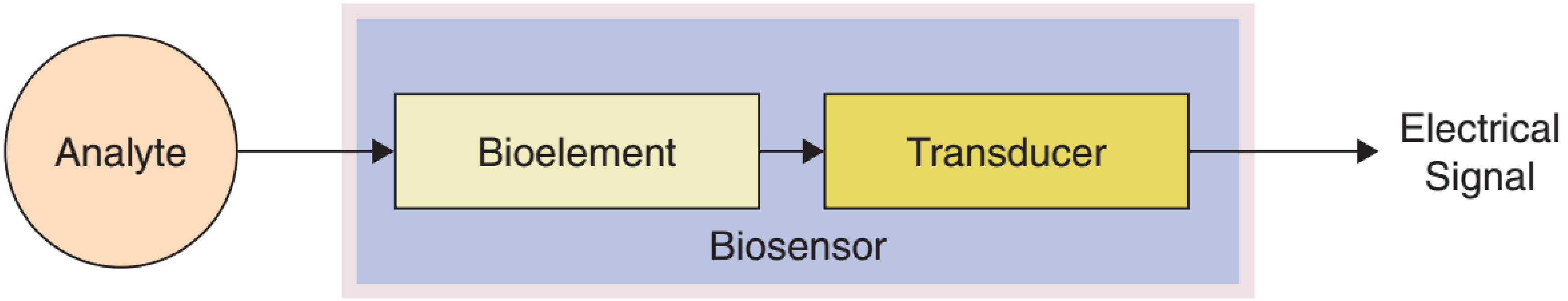

Biosensors
E-paper
RFID Tag
Bio Technology
E-paper Technology
IC Technology
Au
Au
Organic Semiconductor
Gete Dielectric
ITO patterned glass
p-TYPE
n-TYPE
Optical Technology
LCD
OLED
Circuits

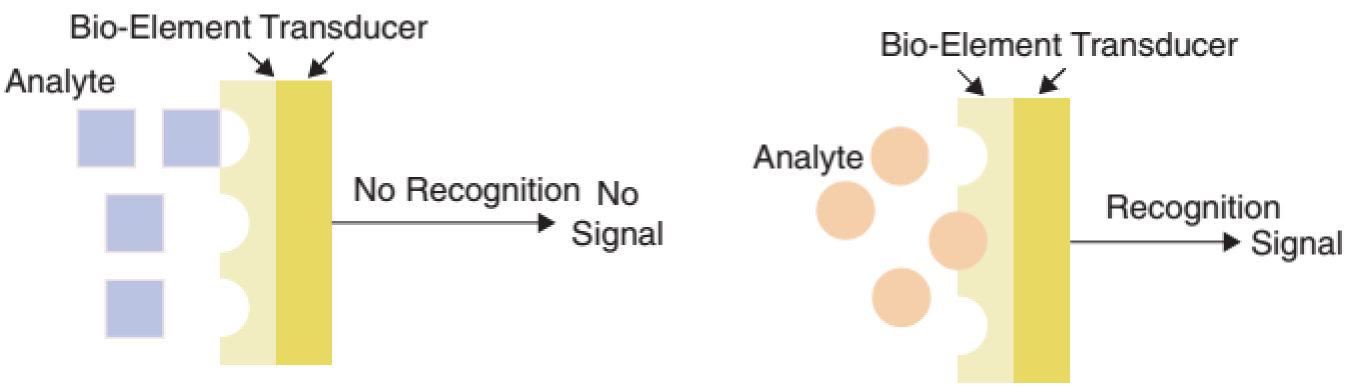
Introduction

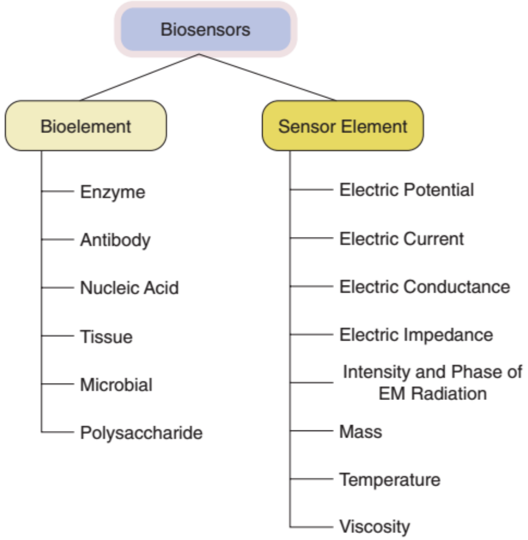


Motivation


Central laboratory testing
Point of care testing
Doctor's office
Sampling
Transporting
Analysis
Test request
Phlebotomy
Sample labeled and transported
Sample received and prepared
Analysis
Validation of result
Reporting of result
Result received
Contact the patient for reporting
Decision to test
Sampling (e.g. capillary blood)
Perform test
Obtain result and immediately inform the patient





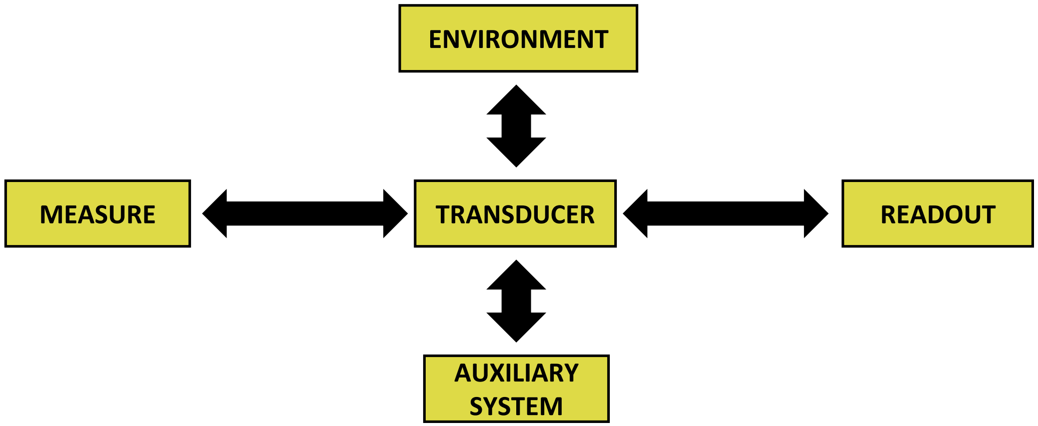


<u>Def:</u> A device that uses specific biochemical reactions mediated by <u>isolated enzymes, immunosystems, tissues, organelles or whole cells</u> to detect chemical compounds usually by electrical, thermal or optical signals. (IUPAC)

Analytical figures of merit

- Selectivity
- Sensitivity
- Reversibility, hysteresis
- Long-term reliability and stability
- Fast response
- Dynamic and calibration range
- Linearity, precision and accuracy
- Recovery time
- SNR
- Limit of Detection (LOD)
- Limit of Quantitation (LOQ)

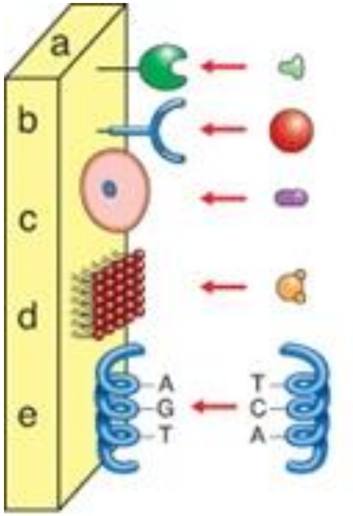
- Materials
- Physical/Chemical properties
- Measurement system
- Measurement environment



Selectivity

Def: Selectivity of a method refers to the extent to which it can determine particular analytes under given conditions in mixtures or matrices, simple or complex, without interferences from other components. (IUPAC)

Def: Specificity is the ultimate of Selectivity (IUPAC)



Binding selectivity

Chemoselectivity

LBF, Langmuir-Blodgett Film

SAM, Self-Assembled Monolayer

Electrochemical

Surface functionalization

Deposition methods:

- Spin coating
- Vapour deposition

} Multilayer

- Atomic layer deposition
- Self-assembly

} Monolayer

Film's relevant properties:

- Wettability
- Uniformity and pinholes
- Chemical reactivity
- Electronic interactions
- Thermal stability

Surface functionalization

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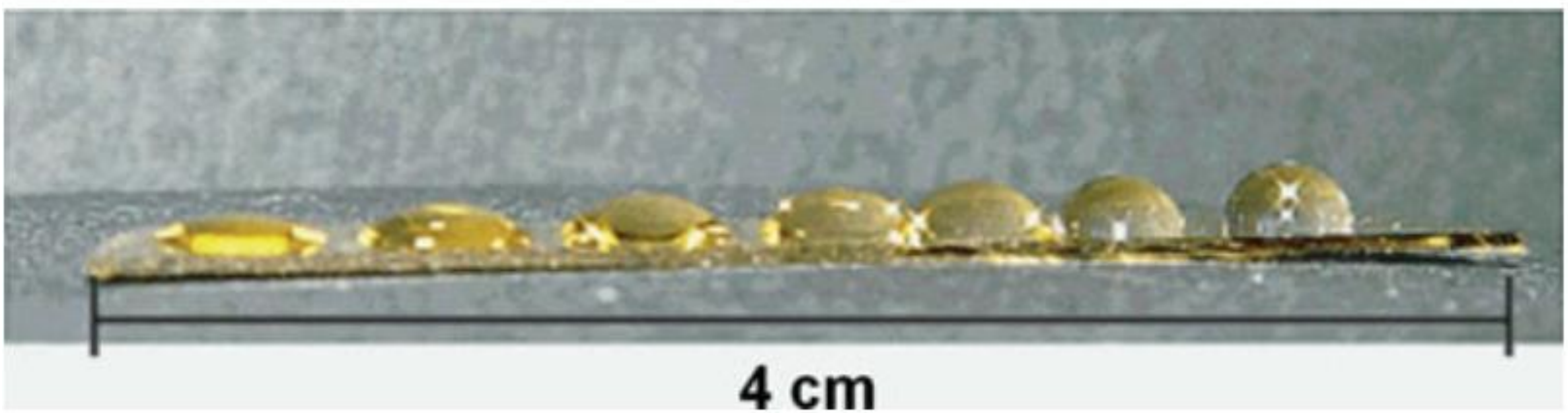
Film's relevant properties:

- **Wettability**
- Uniformity and pinholes
- Chemical reactivity
- Electronic interactions
- Bond strength



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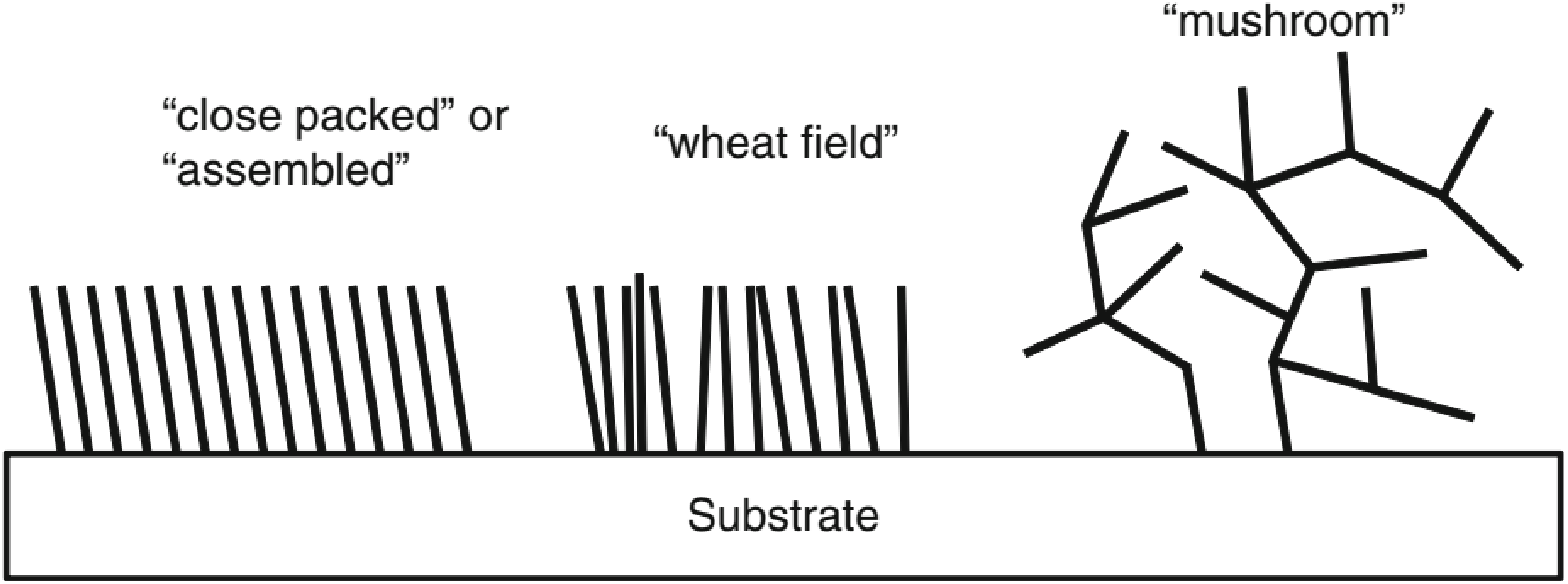

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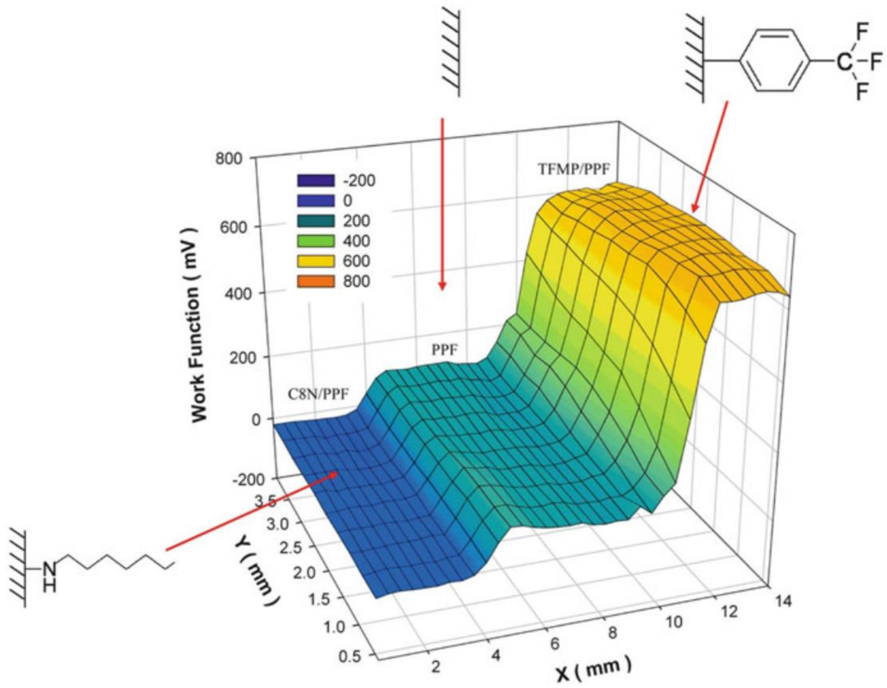

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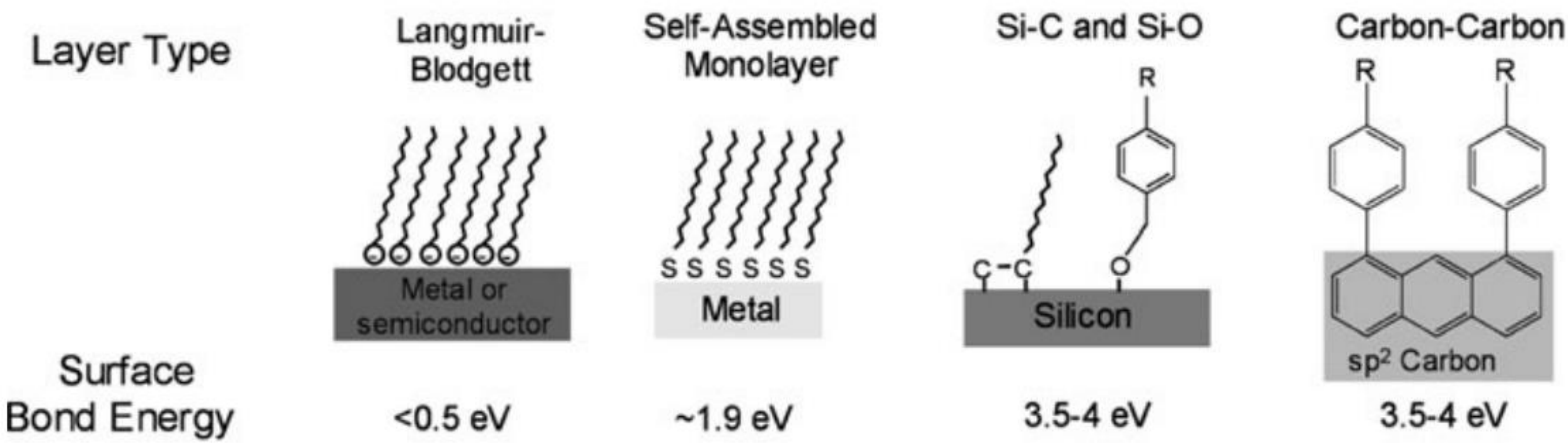
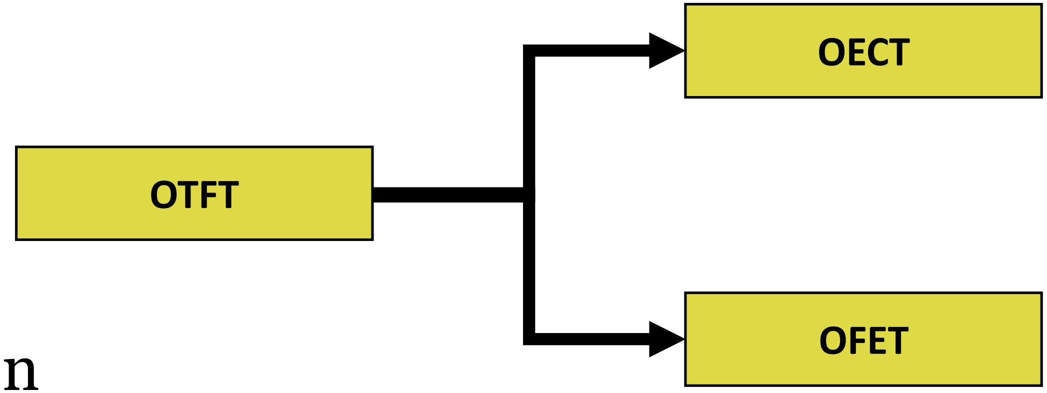


Organic, transistor-based, biosensors

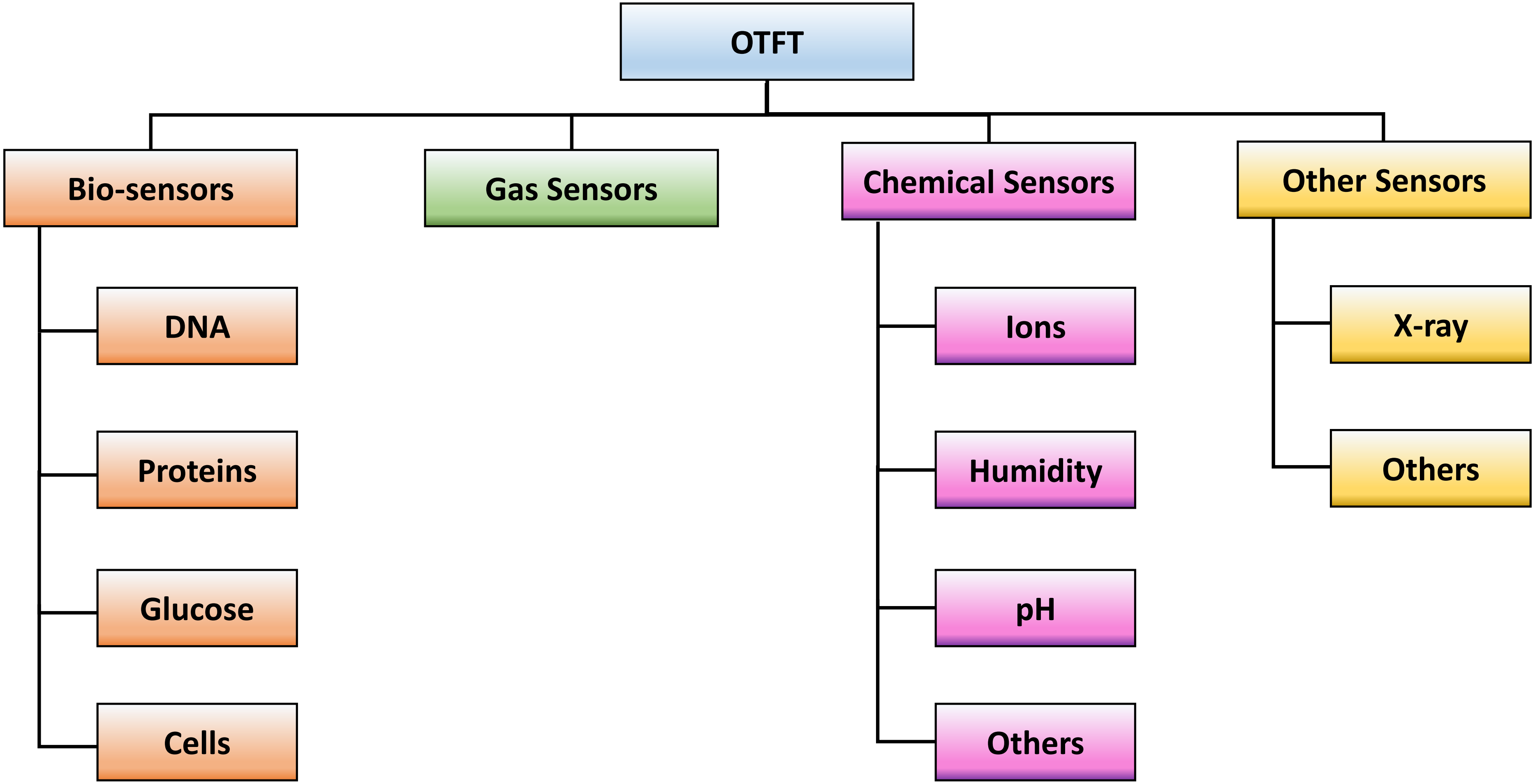
Why OTFT?

- Transistors:
  - ➢ Amplification
  - ➢ Label free

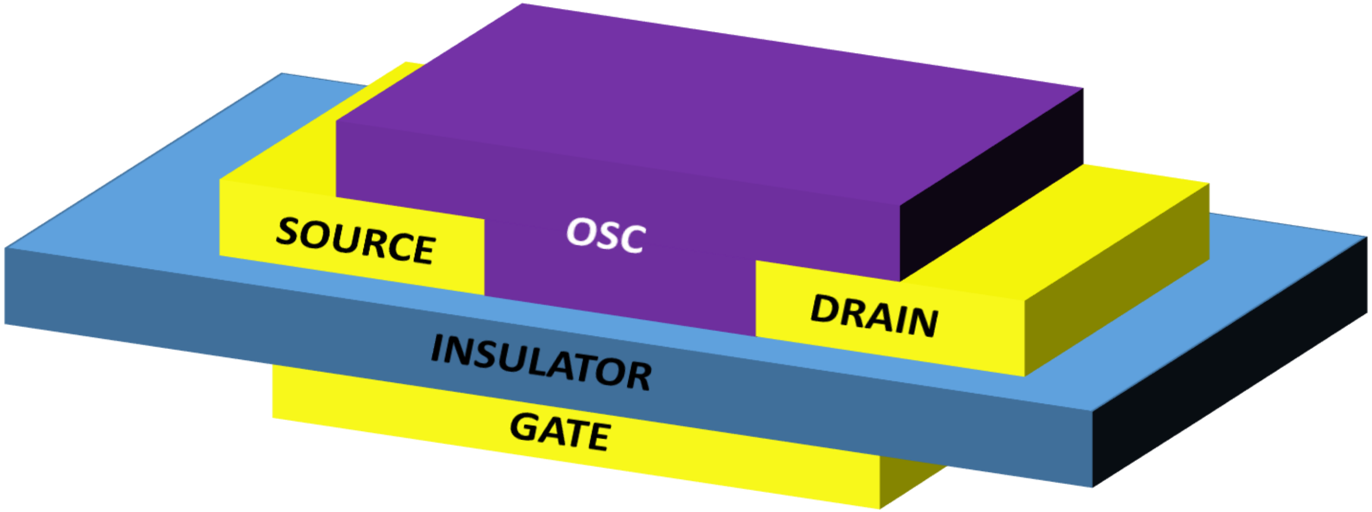
- Materials:
  - ❖ Biodegradable
  - ❖ Biocompatible
  - ❖ Flexible
  - ❖ Cost effective
  - ❖ Large area production



OFET sensors



Sensing mechanisms



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

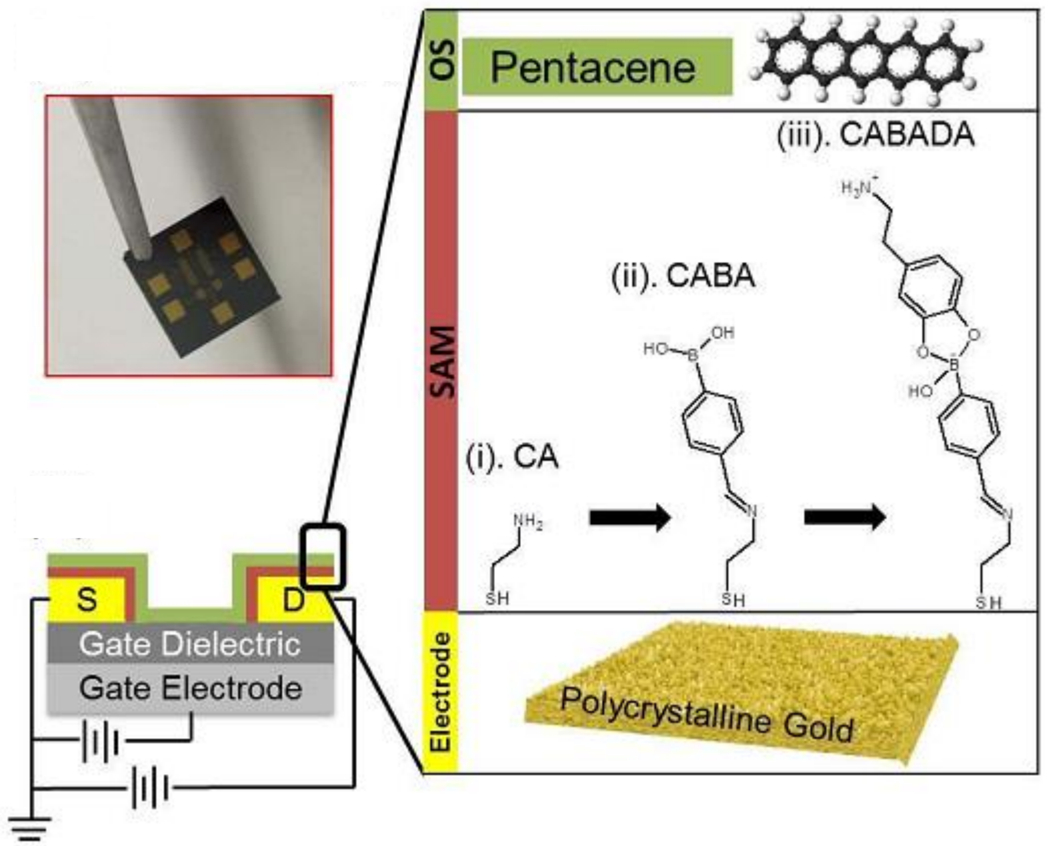
Sensing area:

- Active semiconductor/electrolyte
- Gate/electrolyte
- Semiconductor
- Electrodes

Sensing mechanisms:

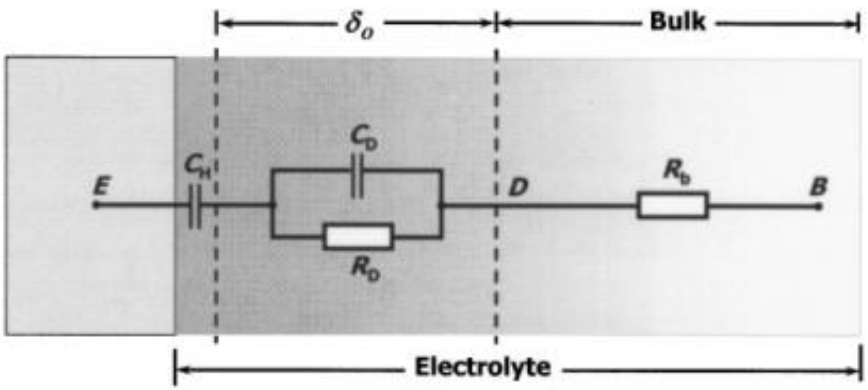
- Morphology variation
- Charge injection
- Field effect modulation

Charge injection modulation

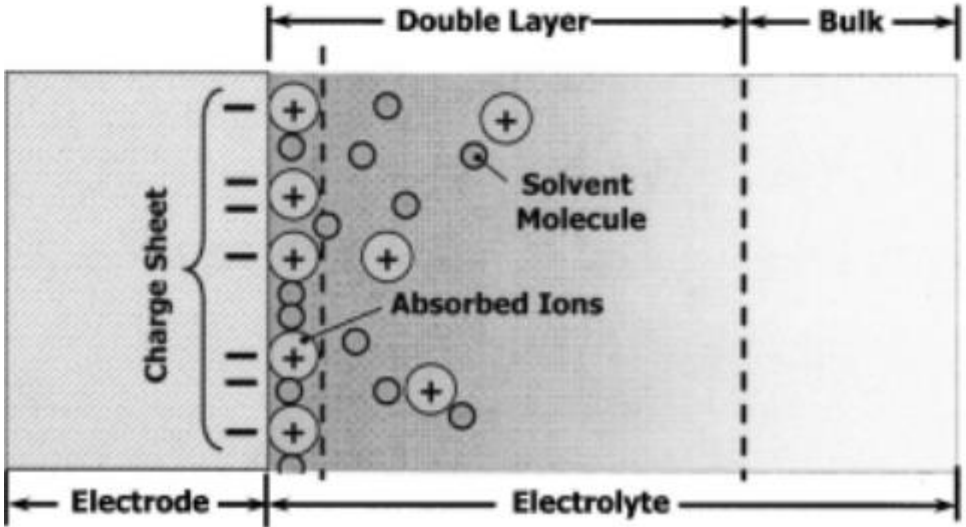


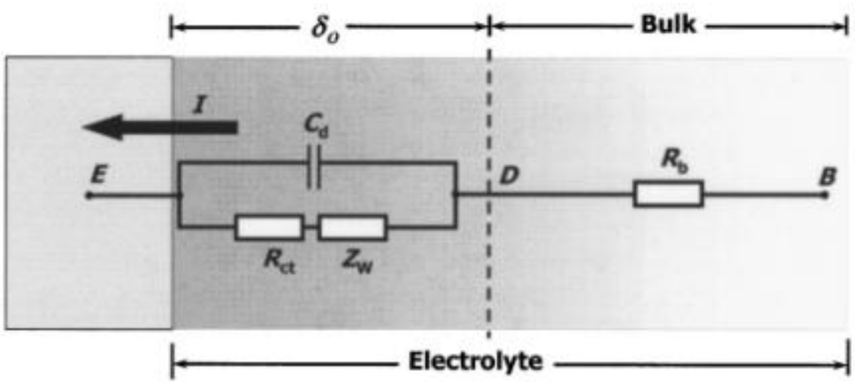
Charge-Injection Organic Gauges to Detect Dopamine Down to the Nanomolar Scale
Francesca Leonardi, Stefano Casalini, Cristiano Albonetti, Alessandro Kovtun, Andrea Liscio, and Fabio Biscarini (2015)

Electrode/Electrolyte interface

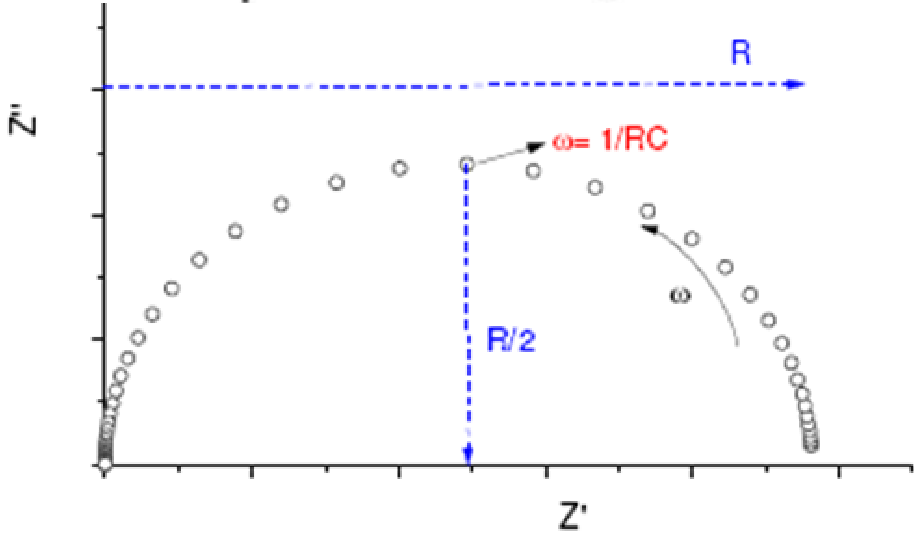


Perfectly Polarizable Electrode

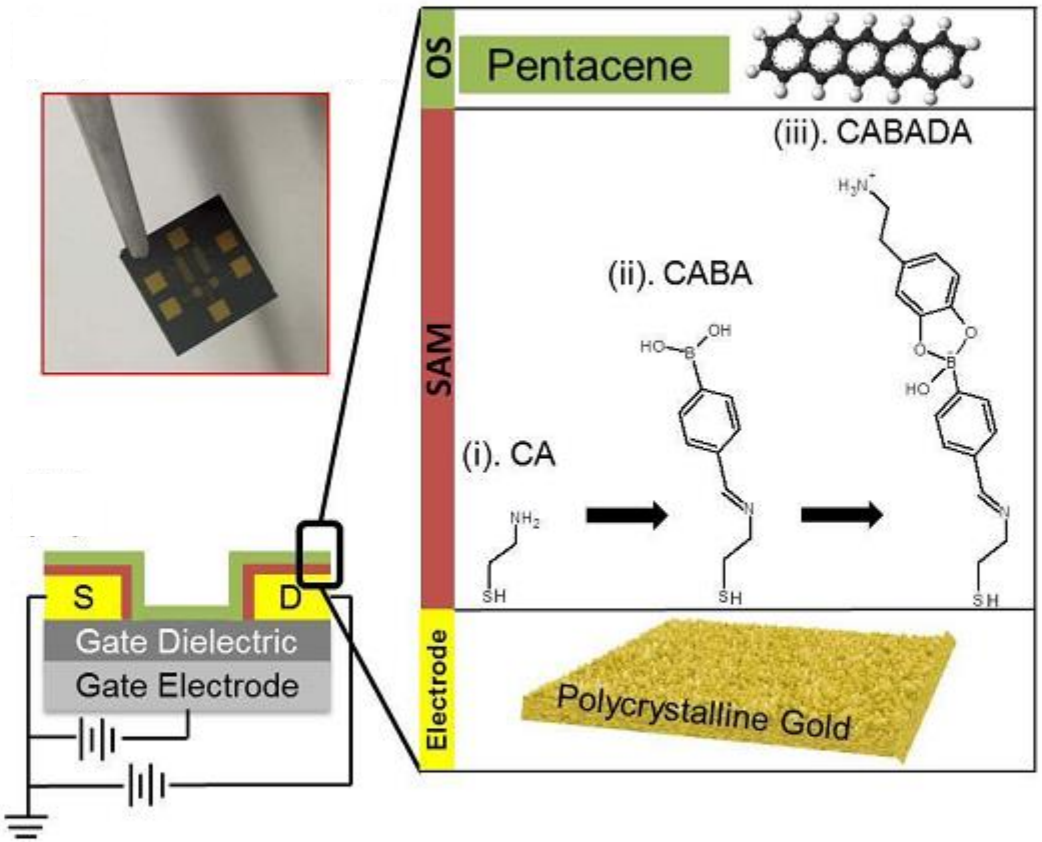


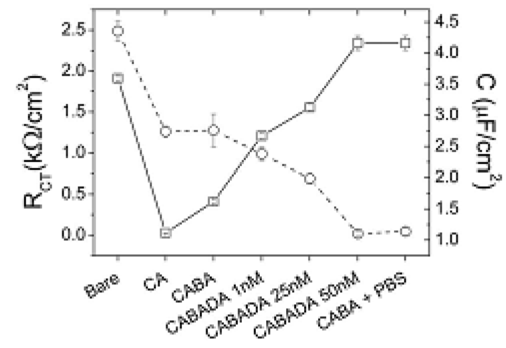


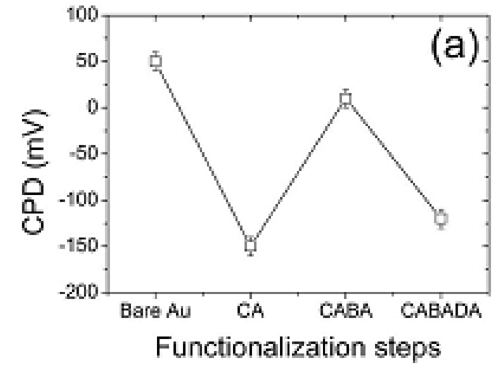
Perfectly non Polarizable Electrode

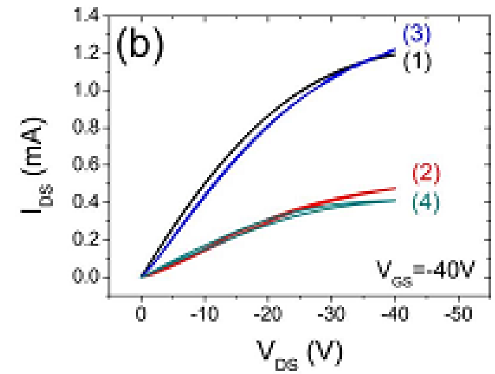


Charge injection modulation



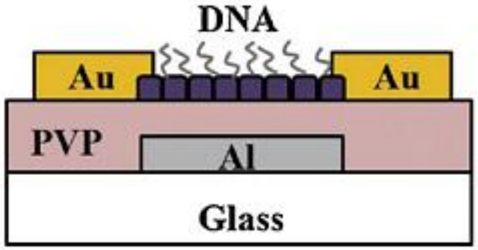


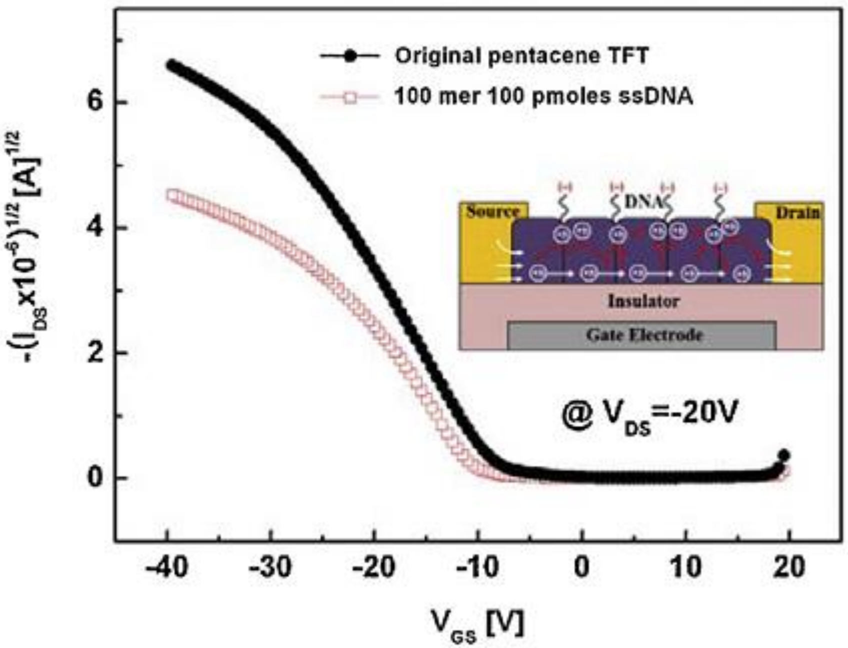


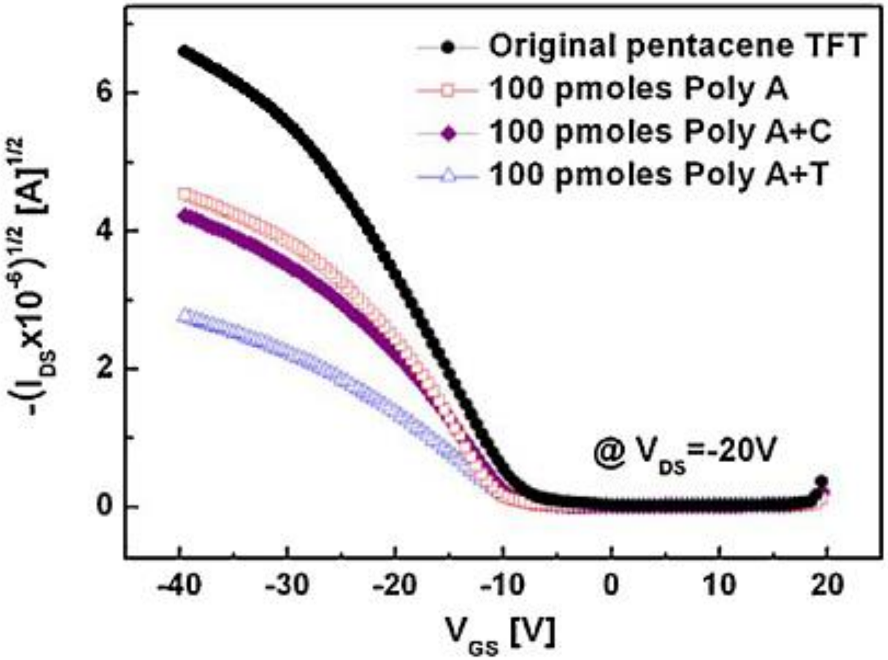


Charge-Injection Organic Gauges to Detect Dopamine Down to the Nanomolar Scale
Francesca Leonardi, Stefano Casalini, Cristiano Albonetti, Alessandro Kovtun, Andrea Liscio, and Fabio Biscarini (2015)

DNA hybridization based on pentacene TFTs

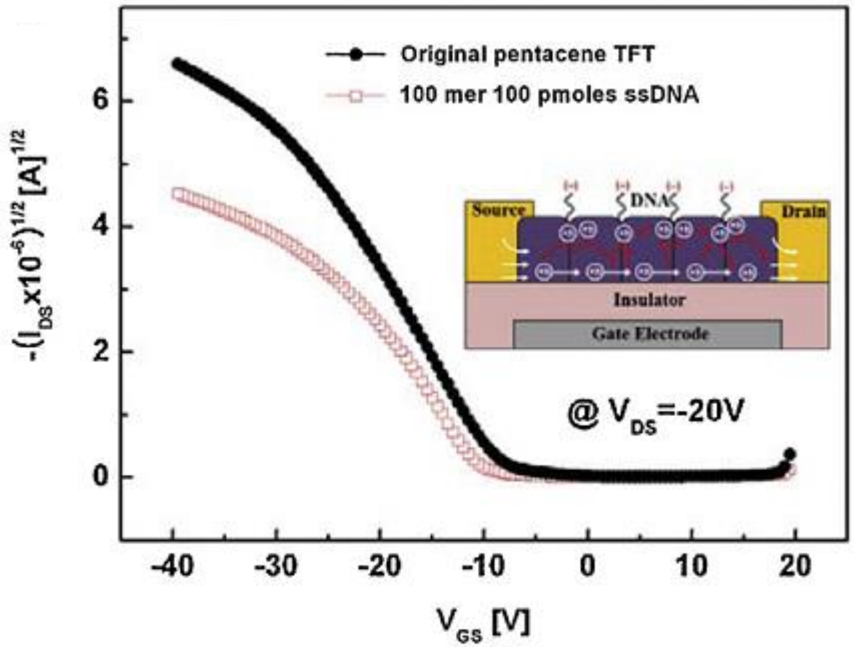


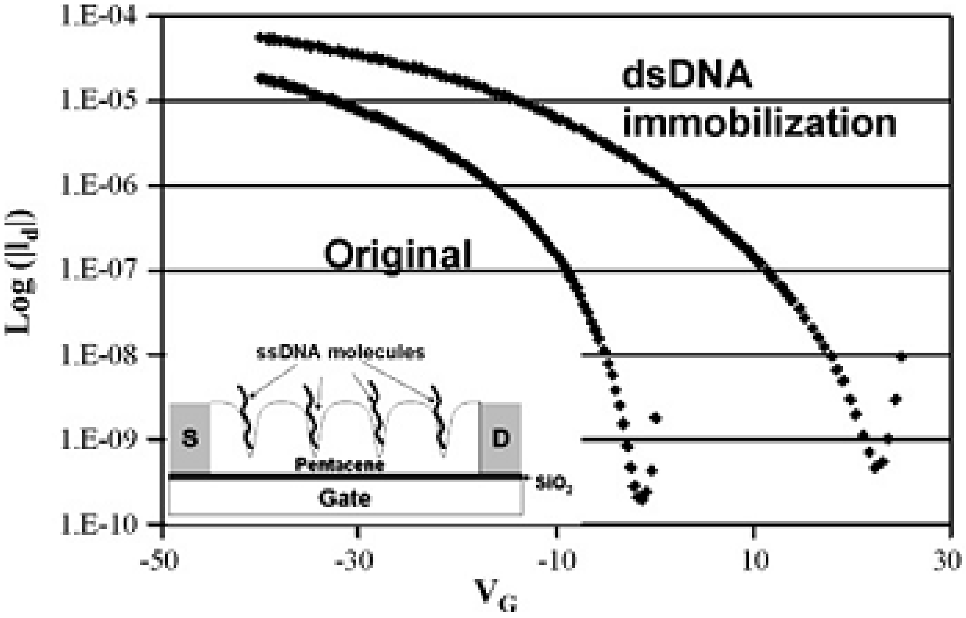




DNA hybridization sensor based on pentacene thin film transistor
Jung-Min Kim, Sandeep Kumar Jha, Rohit Chand, Dong-Hoon Lee, Yong-Sang Kim (2011)

DNA hybridization based on pentacene TFTs





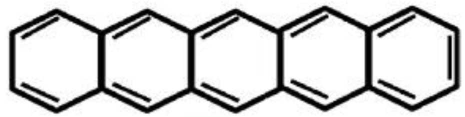
DNA hybridization detection with organic thin film transistors:
Toward fast and disposable DNA microarray chips
Qintao Zhang, Vivek Subramanian (2007)

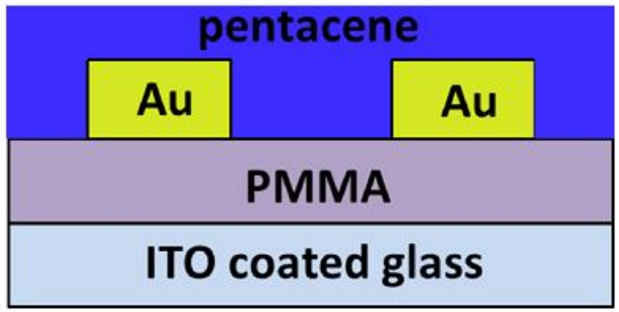
DNA hybridization sensor based on pentacene thin film transistor
Jung-Min Kim, Sandeep Kumar Jha, Rohit Chand, Dong-Hoon Lee, Yong-Sang Kim (2011)

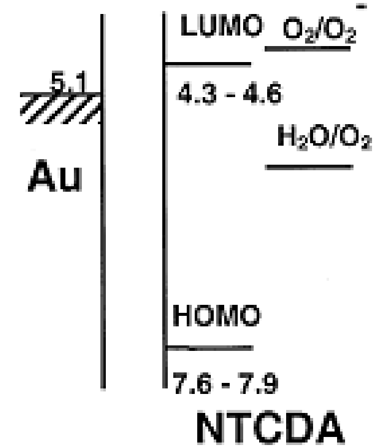
Gas sensors: an overview

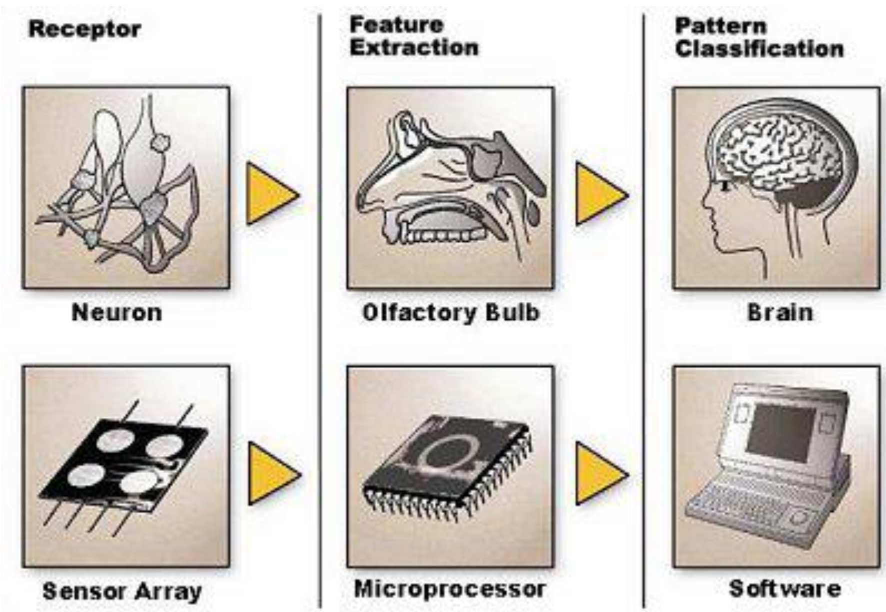
Applications

- Nose
- Tongue
- …









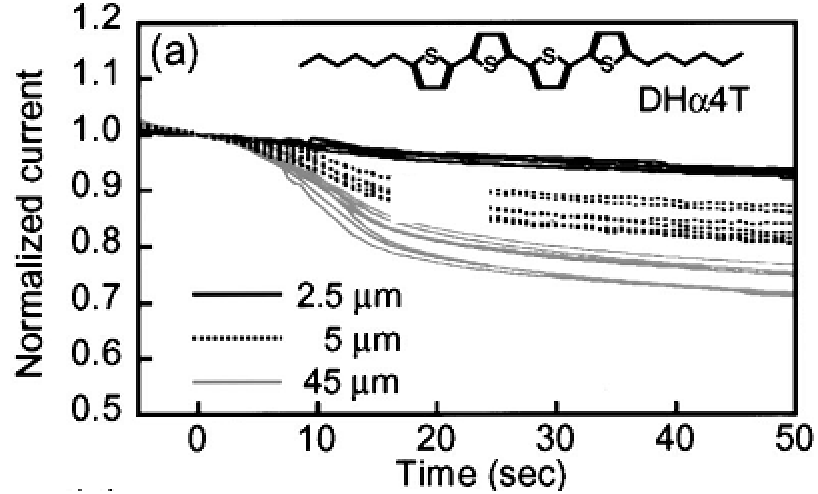
- OSC molecular structure
- Degree of crystallization
- Grain boundaries
- Surface roughness

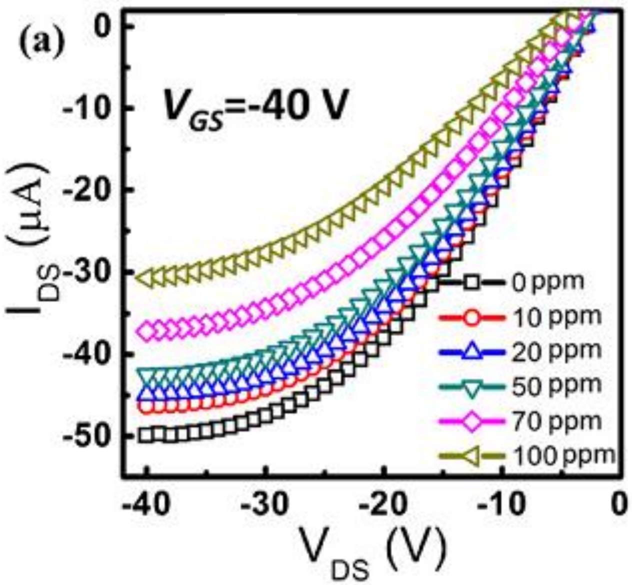
Changing parameters

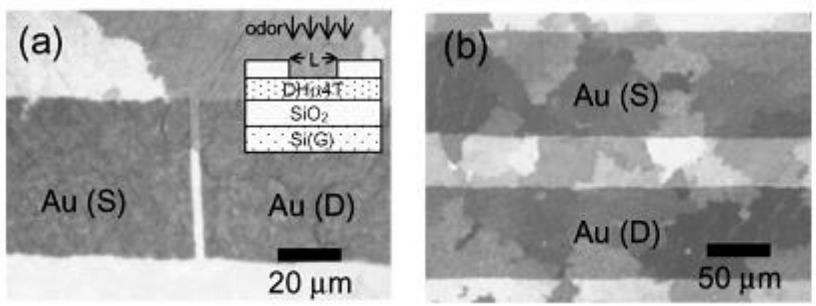
- Off state current
- V_{TH}
- μ

Multi-parameter gas sensors based on organic thin-film-transistors
L. Torsi, A. Dodabalapur, L. Sabbatini, P.G. Zambonin (2000)

Gas sensors



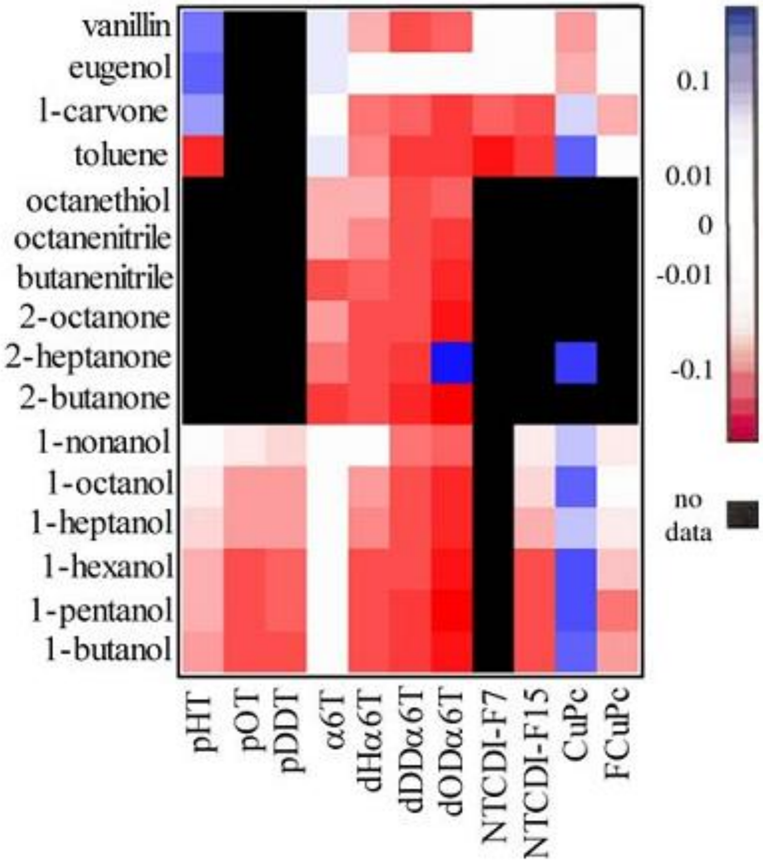




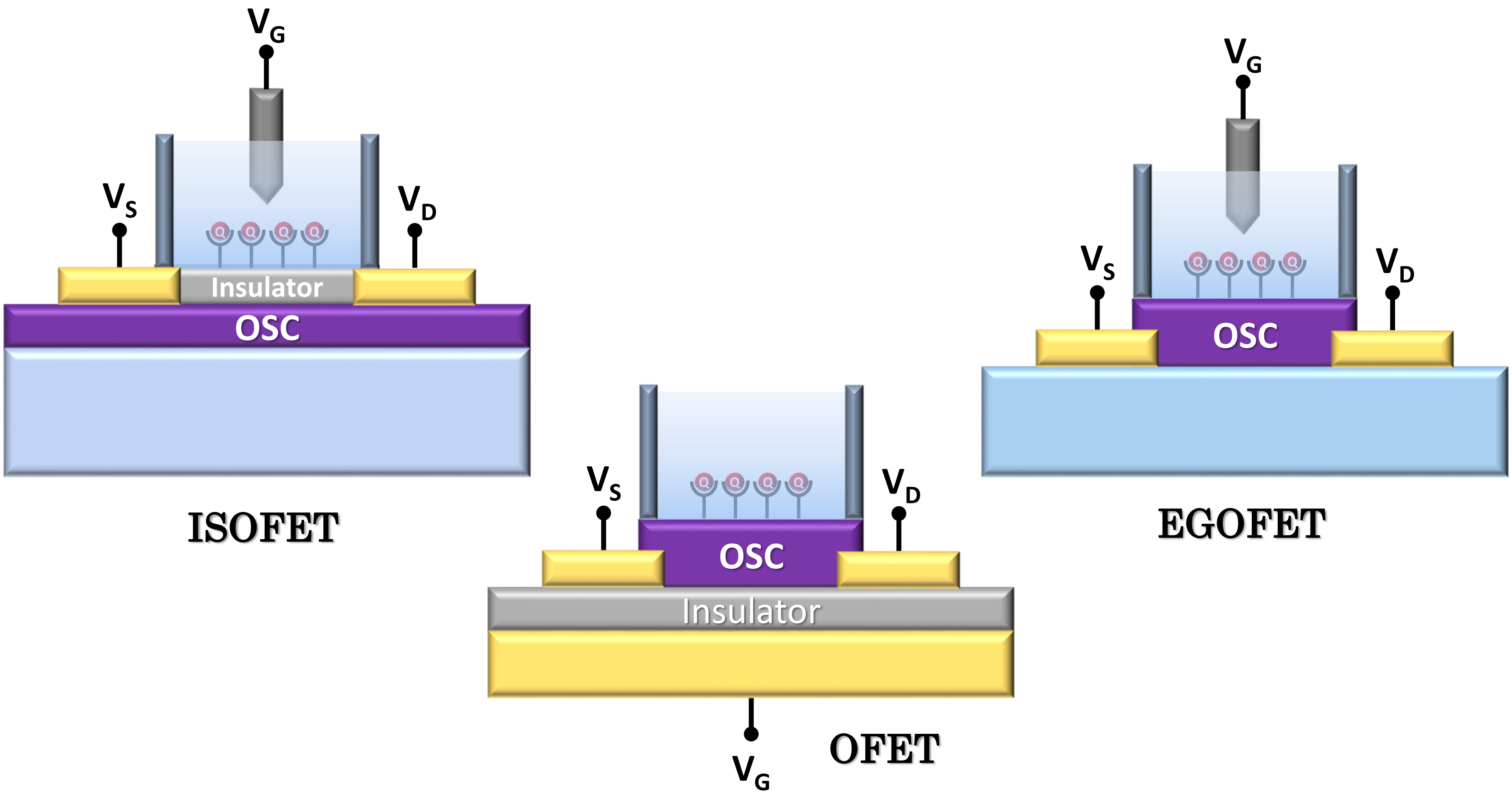
Vapor sensing with a,v-dihexylquarterthiophene field-effect transistors: The role of grain boundaries
Takao Someya, Howard E. Katz,Alan Gelperin, Andrew J. Lovinger, and Ananth Dodabalapur (2002)

Ammonia gas sensor based on pentacene organic field-effect transistor
Junsheng Yu, Xinge Yu, Lin Zhang, Hongjuan Zeng (2015)

Active layer	Analyte
Phthalocyanine	Oxygen, Iodine, Bromine, NO2, Ozone, Alchools, Ketones, Thiols, Nitriles, Esters
Naphthalene tetracarboxylic dianhydride	Nitrogen, Oxygen, Alcohols, Ketones, Thiols, Nitriles, Esters
Pentacene	1-Pentanol, Aqueous analytics
Oligothiophenes	Alcoholes, Ketones, Thiols, Lactic acid, Glucose
Polythiophenes	Ammonia, Chloroform, Alcohols, Esters, Nitriles

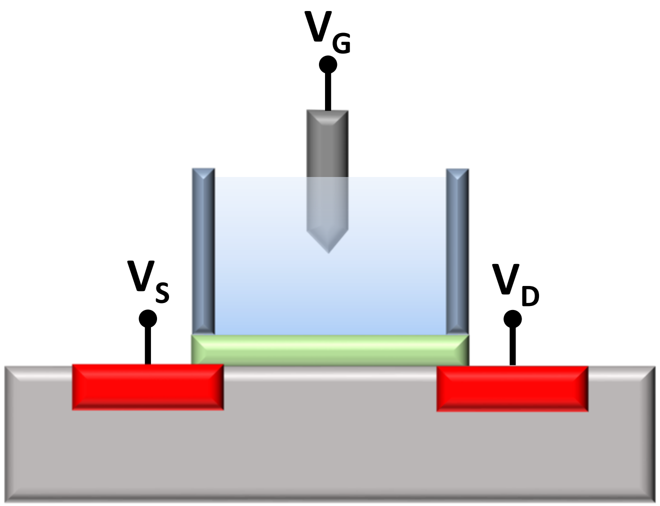


Structures



V_G
V_S
V_D
Insulator
OSC
ISOFET
V_G
V_S
V_D
OSC
EGOFET
V_S
V_D
OSC
Insulator
V_G
OFET

ISFET



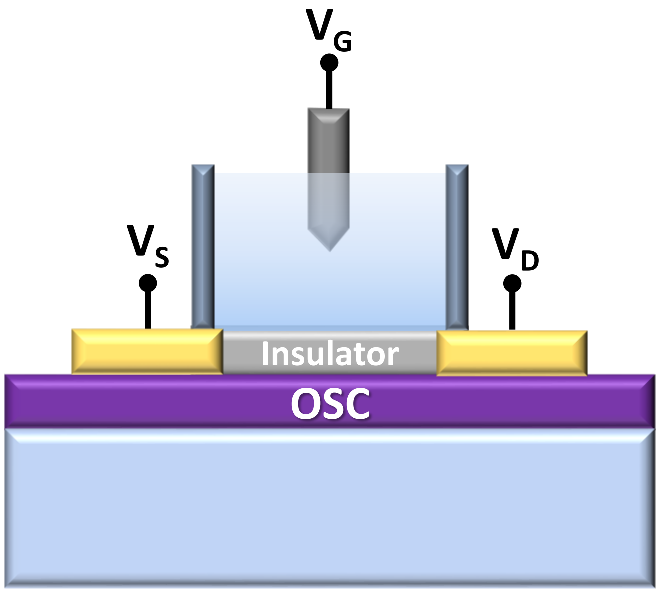
$$V_{FB} = \left(E_{ref} + \phi_{ij}\right) - (\phi_{eo} - \chi_e) - \chi_{Si} - Q_0/C_{ox}$$

$$V_T^* = V_T + E_{ref} + \phi_{ij} + \chi_e - \phi_{eo}(pH) - \Phi_m/q$$

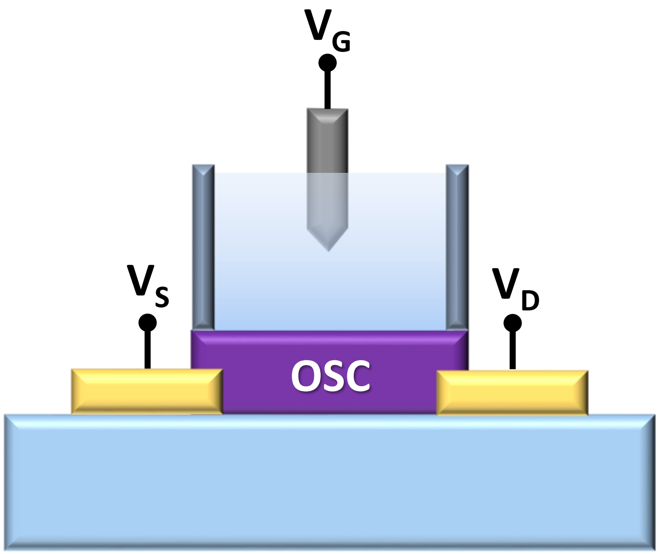
$\boldsymbol{\phi_{ref}}$:reference electrode potential referred to the vacuum level;
$\boldsymbol{\phi_{ij}}$: potential difference (liquid-junction) between the reference solution and the electrolyte;
$\boldsymbol{\phi_{eo}}$: potential drop in the electrolyte at the interface with the insulating oxide;

$\boldsymbol{\chi_e}$: dipole surface potential in the solution;
$\boldsymbol{\chi_{Si}}$: semiconductor work function;
$\boldsymbol{Q_0}$: charge (per unit area);
$\boldsymbol{C_{ox}}$: oxide capacitance (per unit area);

From ISFET to EGOFET

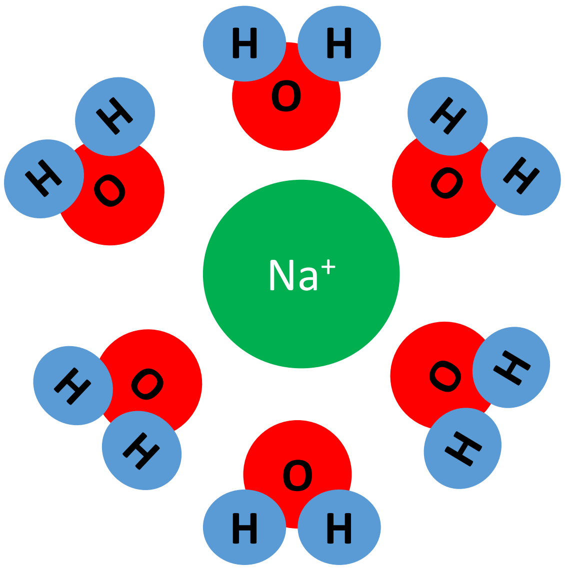


ISOFET

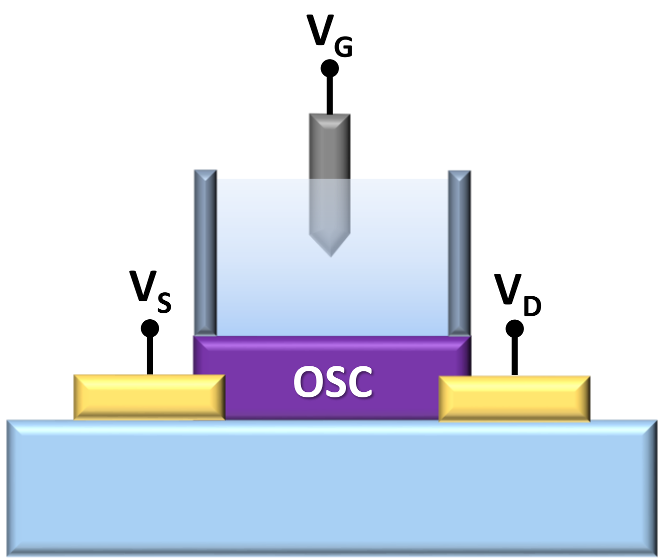


EGOFET

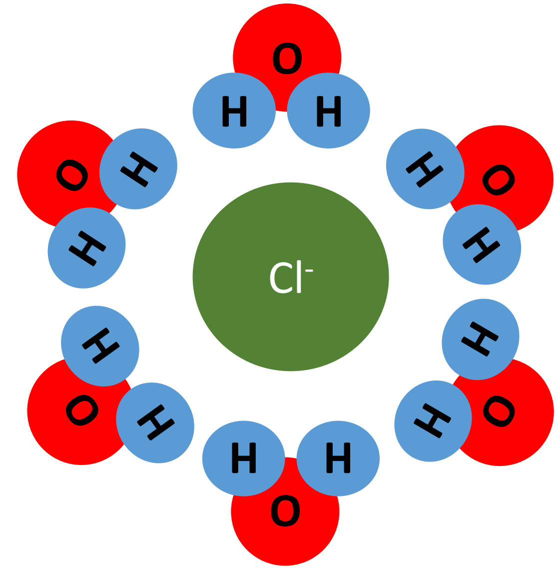
Electrolyte: solvation



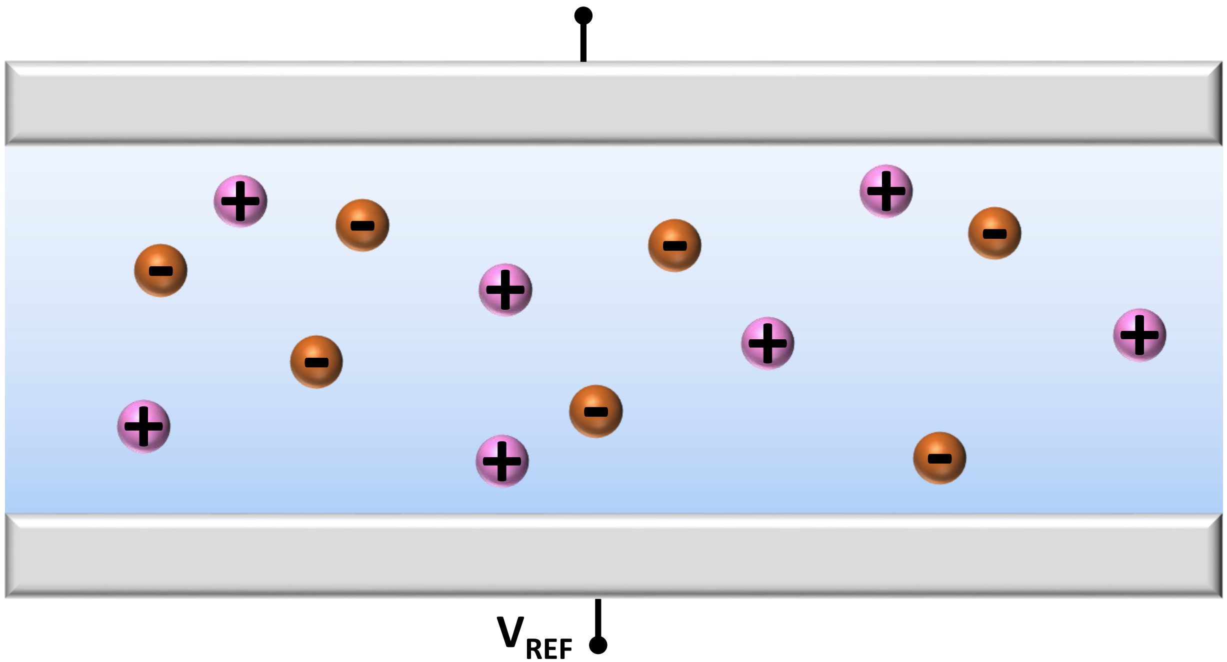
$$\mathrm{NaCl} \xrightarrow{H_2O} \mathrm{Na}^+ + \mathrm{Cl}^-$$

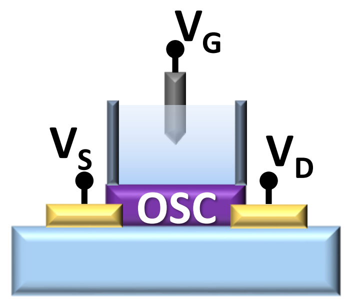


EGOFET



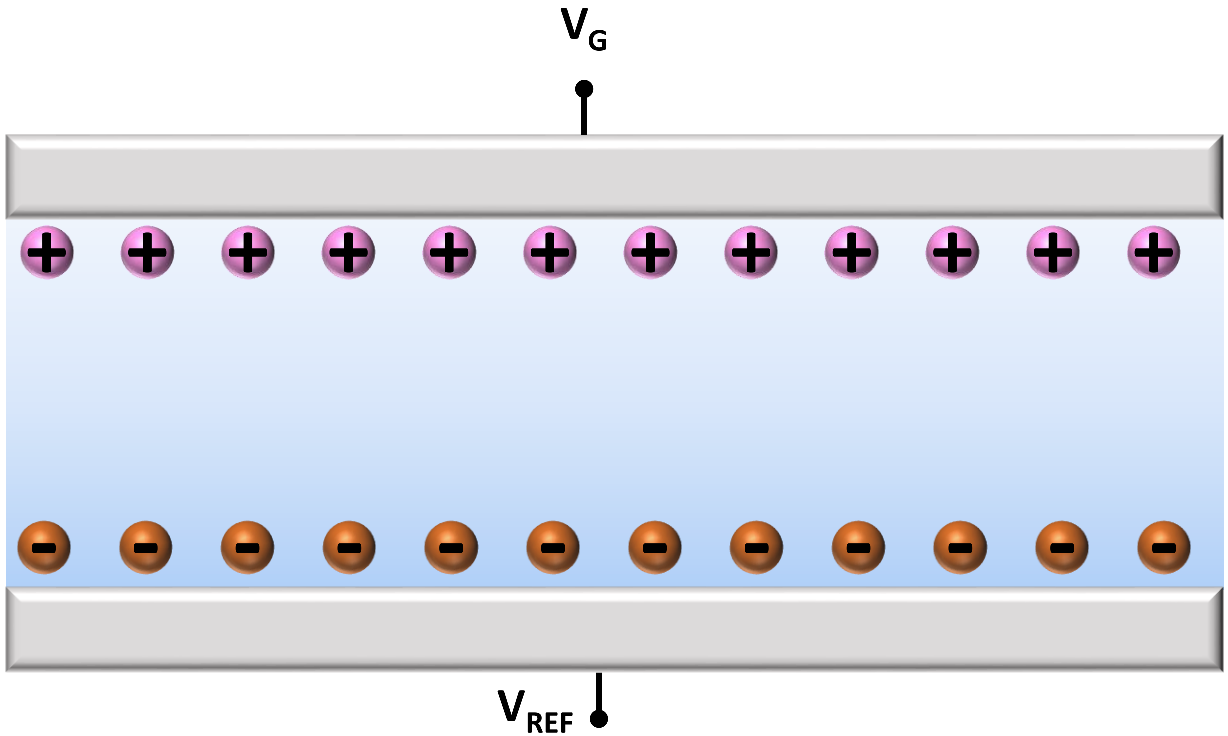
Electrolyte: polarization

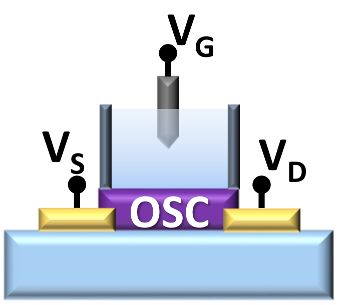




EGOFET

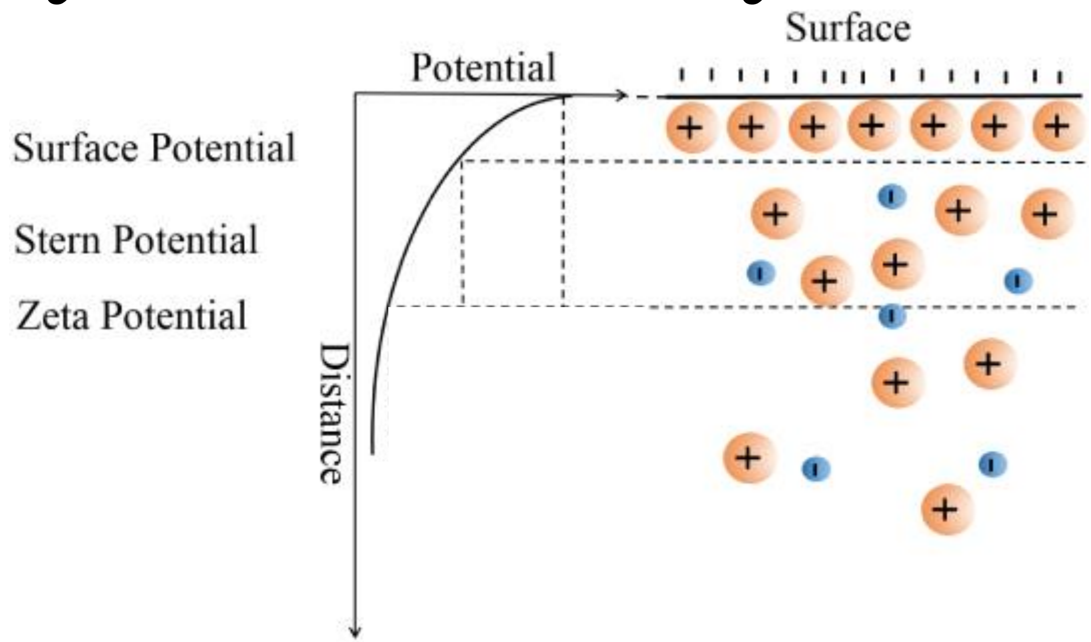
Electrolyte: polarization





EGOFET

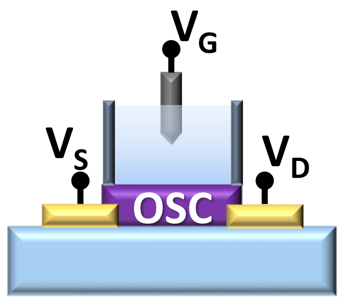
Electrolyte: double layer



$$\frac{d^2\varphi(x)}{dx^2} = -\frac{\rho(x)}{\varepsilon}$$

$$q_{dl} = \int_0^{+\infty} \rho(x)dx$$

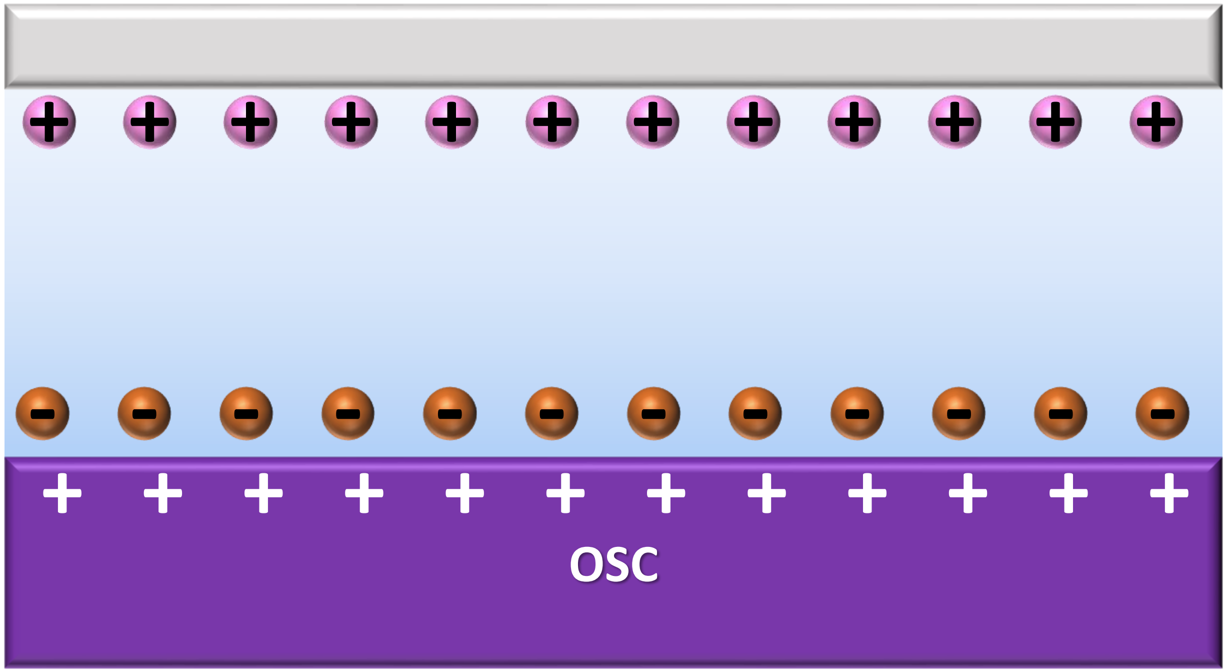
$$C_{dl} \cong \frac{\varepsilon}{\lambda_D} A$$



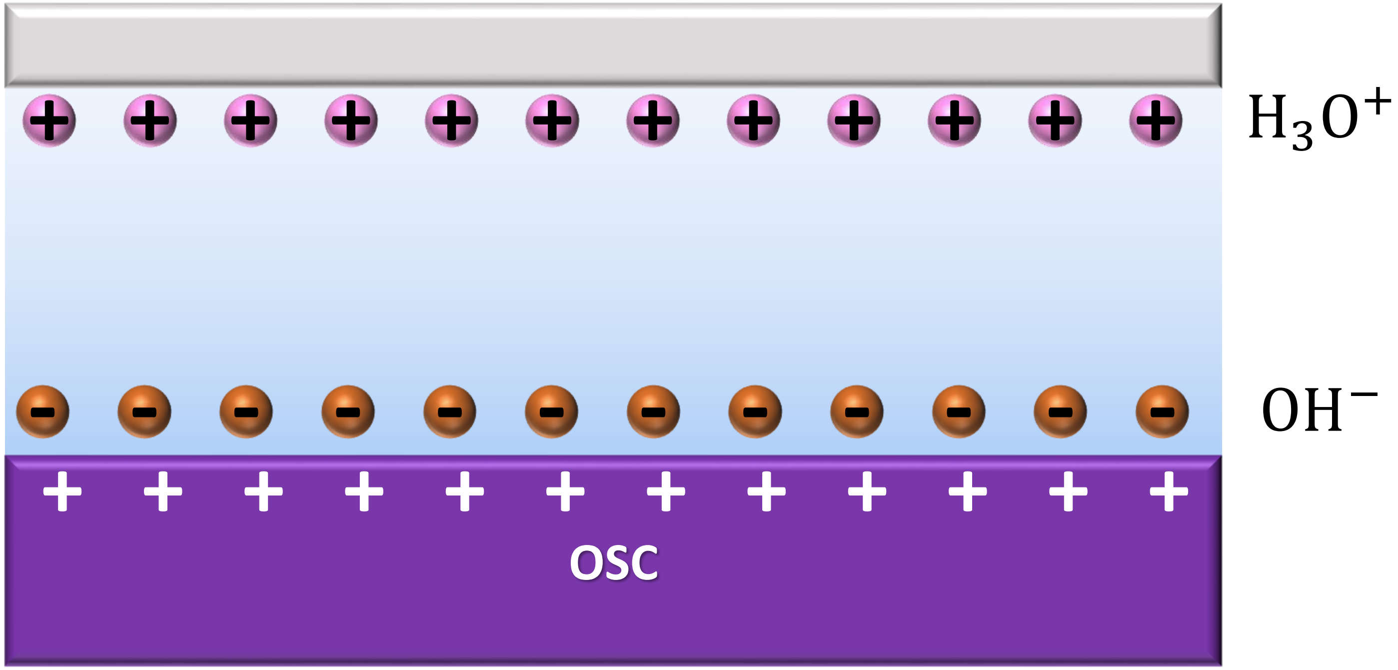
EGOFET

C_{dl} : 10 – 100 μF · cm^{-2}
C_{ins} : 10 nF · cm^{-2}

EGOFET: working principle



WGOFET



Water self ionization:

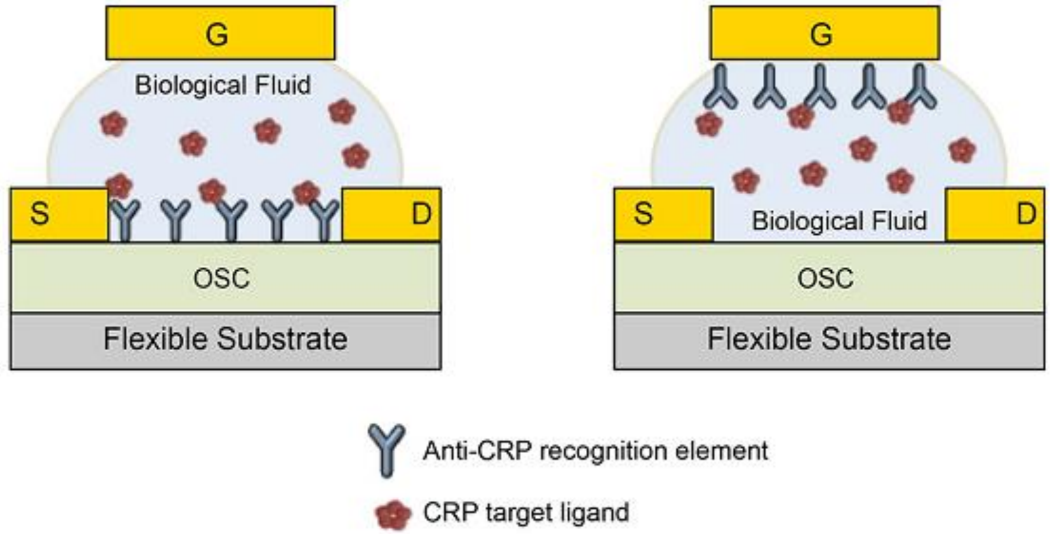
$$2H_2O \rightleftharpoons H_3O^+ + OH^-$$

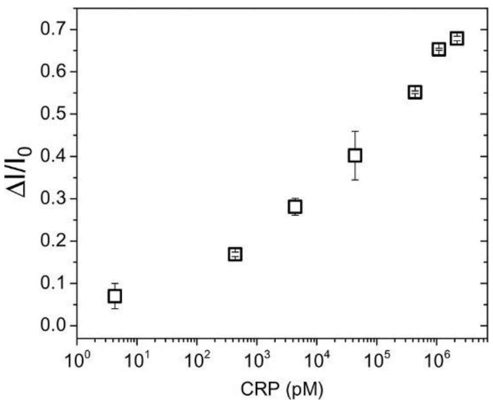
A T = 300 K

$$[H_3O^+] = [OH^-] = 10^{-7}\ M$$

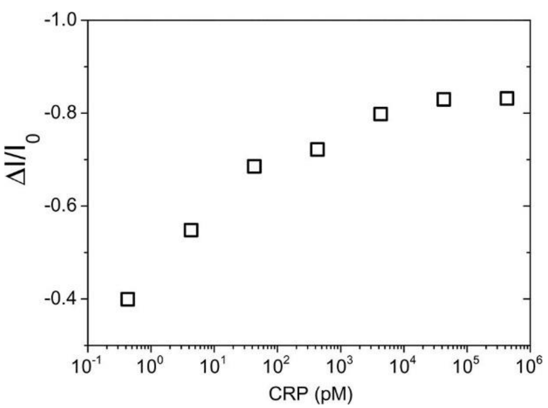
POC biosensors: EGOFET

Point-of-care (POC) biosensors are integrated diagnostic devices that allow the detection of clinically relevant biomarkers in biological fluids (blood, urine, saliva, sweat, and tears) outside conventional laboratories.





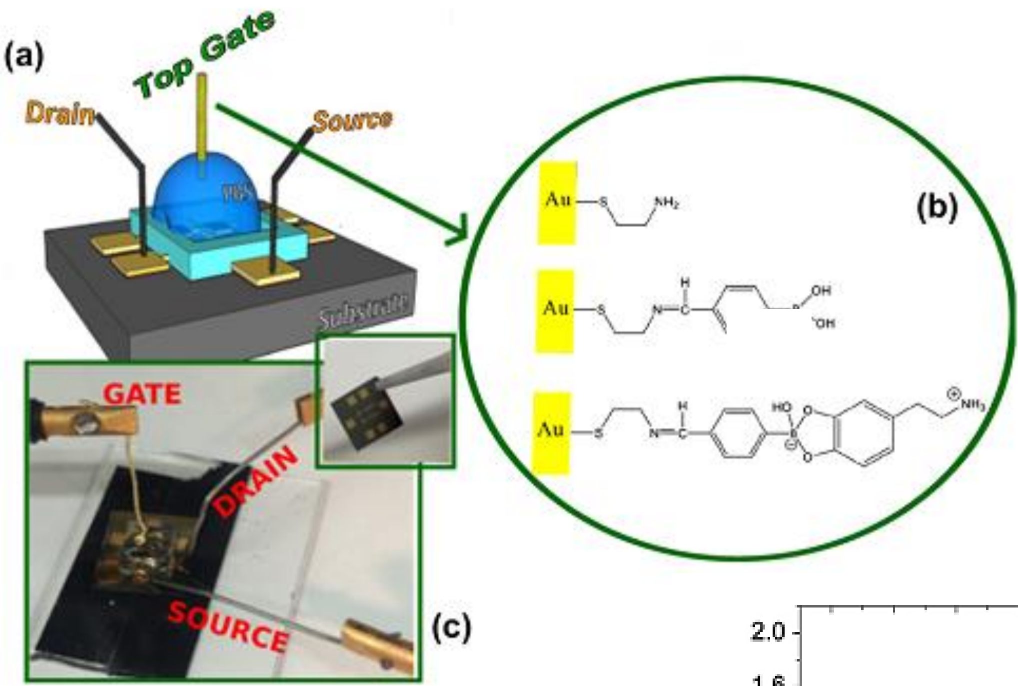
OSC

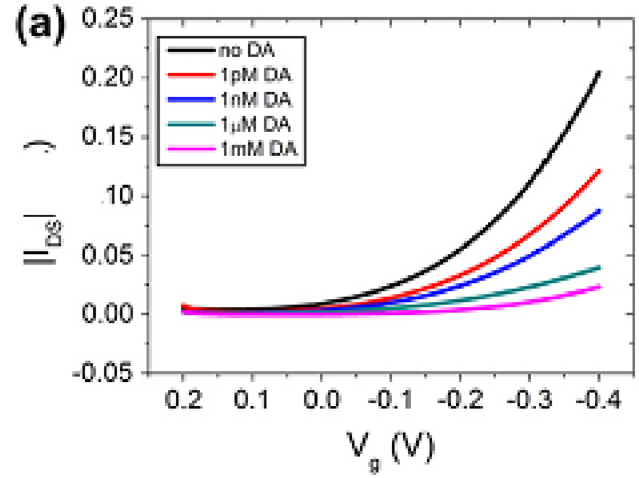


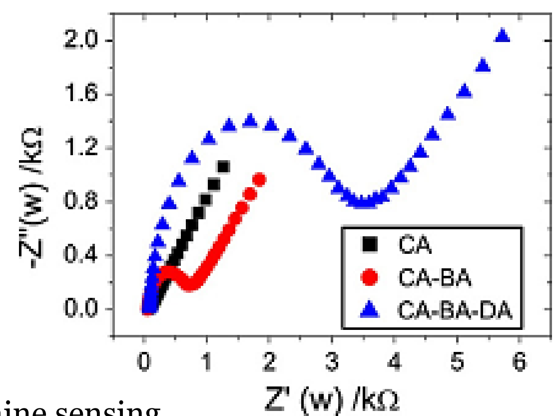
GATE

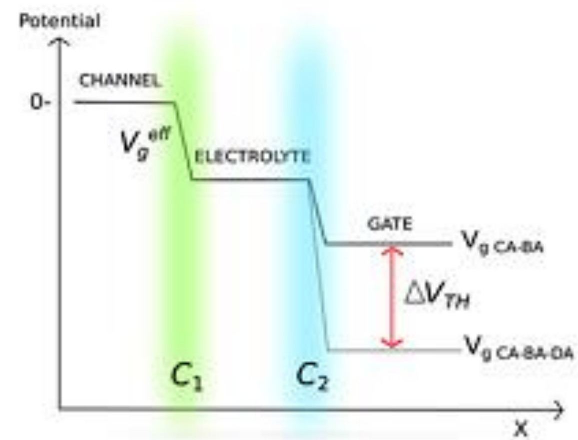
Ultrasensitive printable biosensors for point-of-care applications
Maria Magliulo, Mohammad Yusuf Mulla, Kyriaki Manoli, Donato De Tullio, Preethi Seshadri, Gaetano Scamarcio, Gerardo Palazzo and Luisa Torsi (2012)

POC biosensors: dopamine



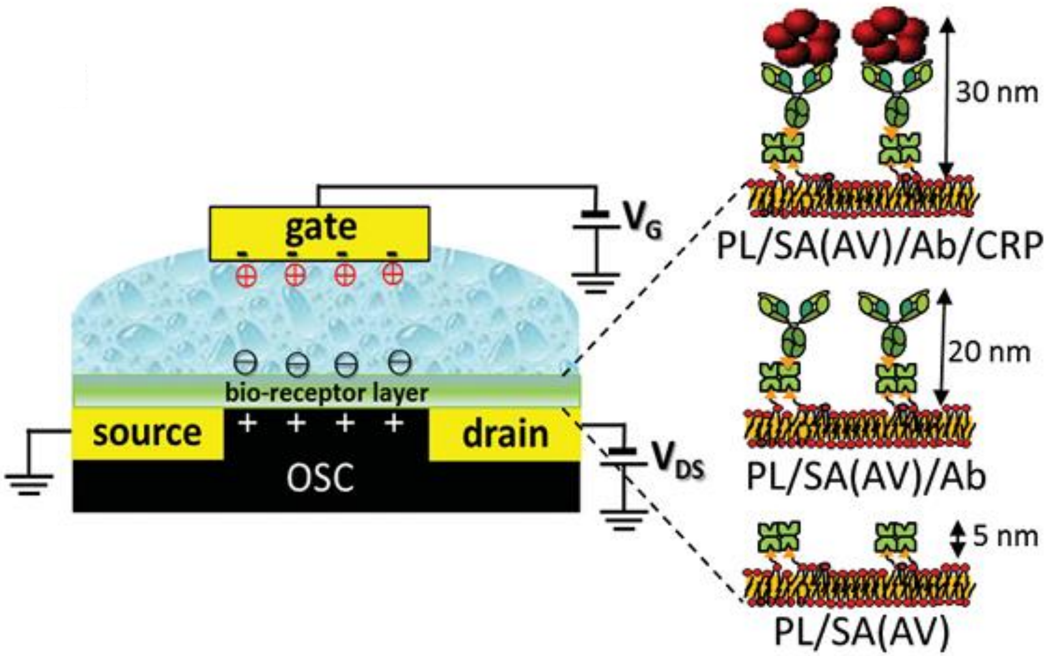


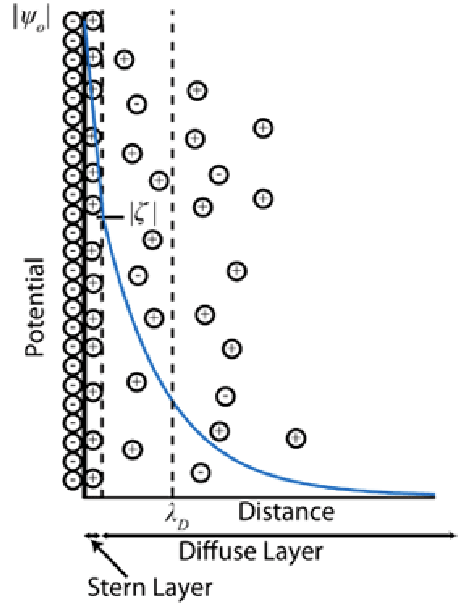


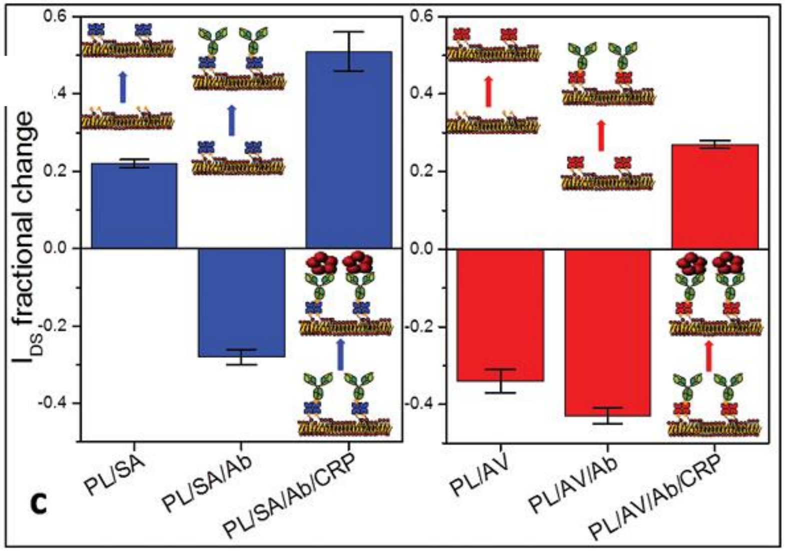


Organic field-effect transistor for label-free dopamine sensing
S. Casalini, F. Leonardi, T. Cramer, F. Biscarini (2013)

Debye Length

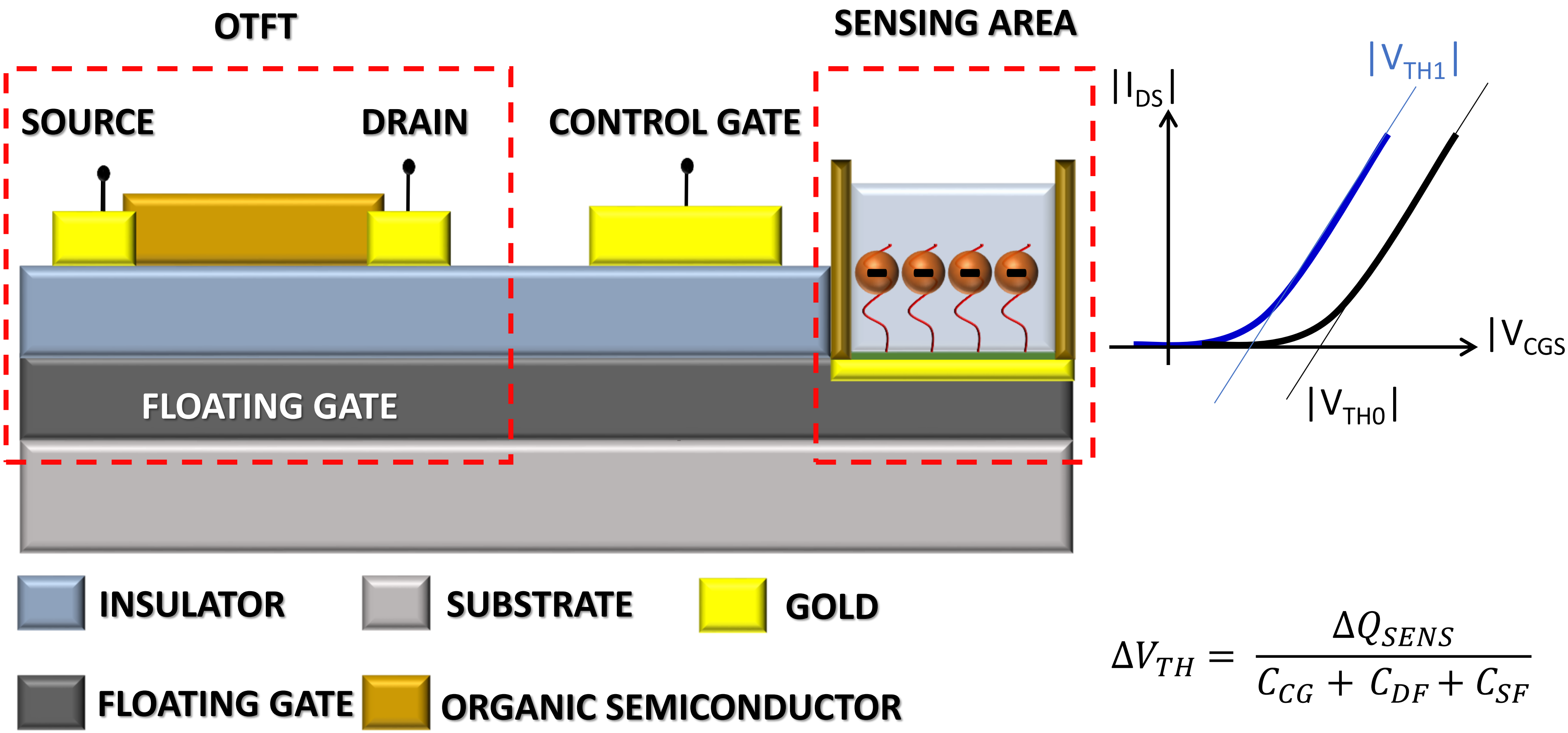






Detection Beyond Debye's Length with an Electrolyte-Gated Organic Field-Effect Transistor
Gerardo Palazzo , * Donato De Tullio , Maria Magliulo , Antonia Mallardi , Francesca Intranuovo, Mohammad Yusuf Mulla , Pietro Favia , Inger Vikholm-Lundin , and Luisa Torsi (2015)

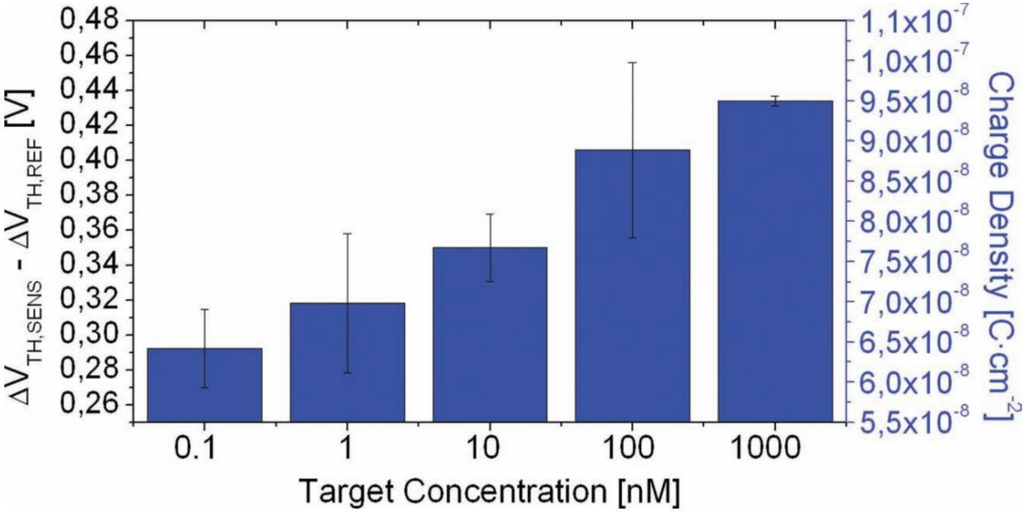
OCMFET: DNA hybridization

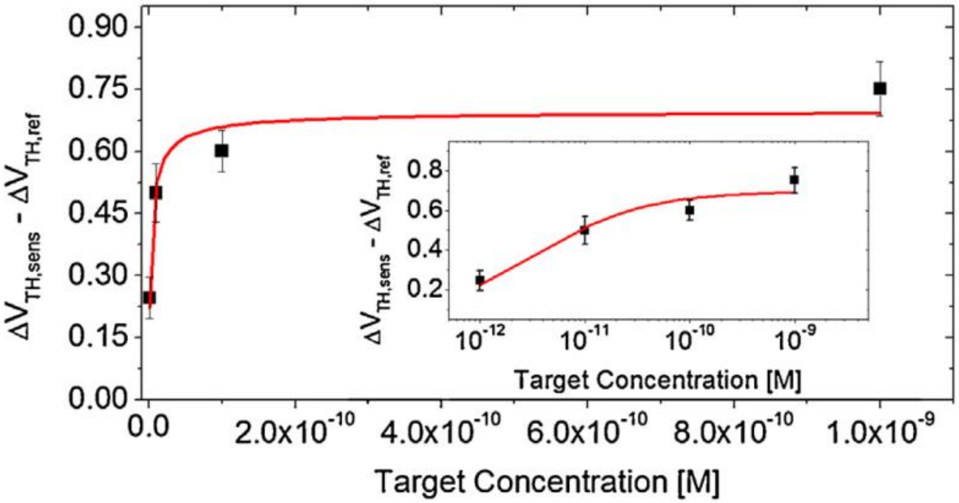


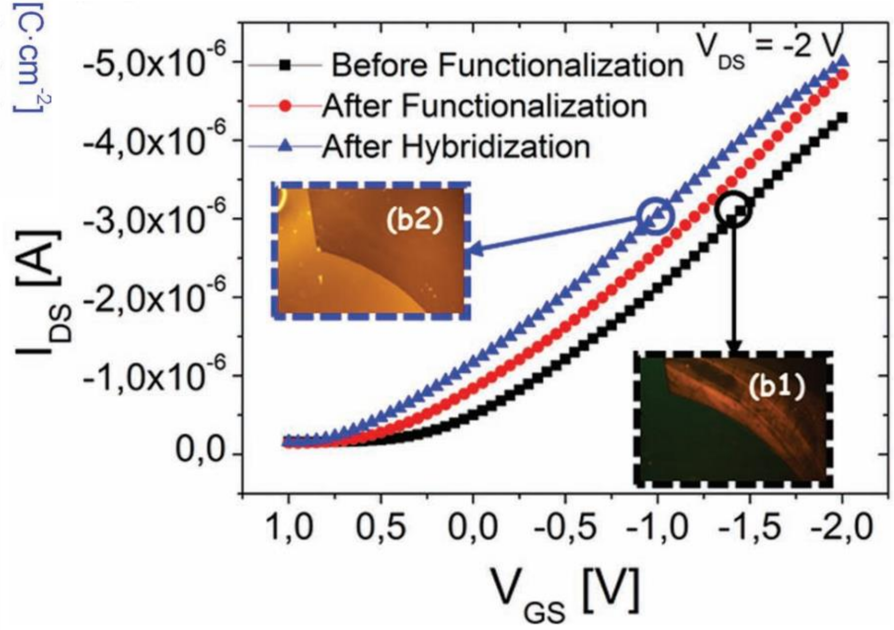
$$\Delta V_{TH} = \frac{\Delta Q_{SENS}}{C_{CG} + C_{DF} + C_{SF}}$$

$$V_{FG} \approx \frac{C_{CG}}{C_{CG} + C_{DF} + C_{SF}} V_{CGS} + \frac{Q_{SENS}}{C_{CG} + C_{DF} + C_{SF}} + \frac{Q_0}{C_{CG} + C_{DF} + C_{SF}}$$

OCMFET: DNA hybridization

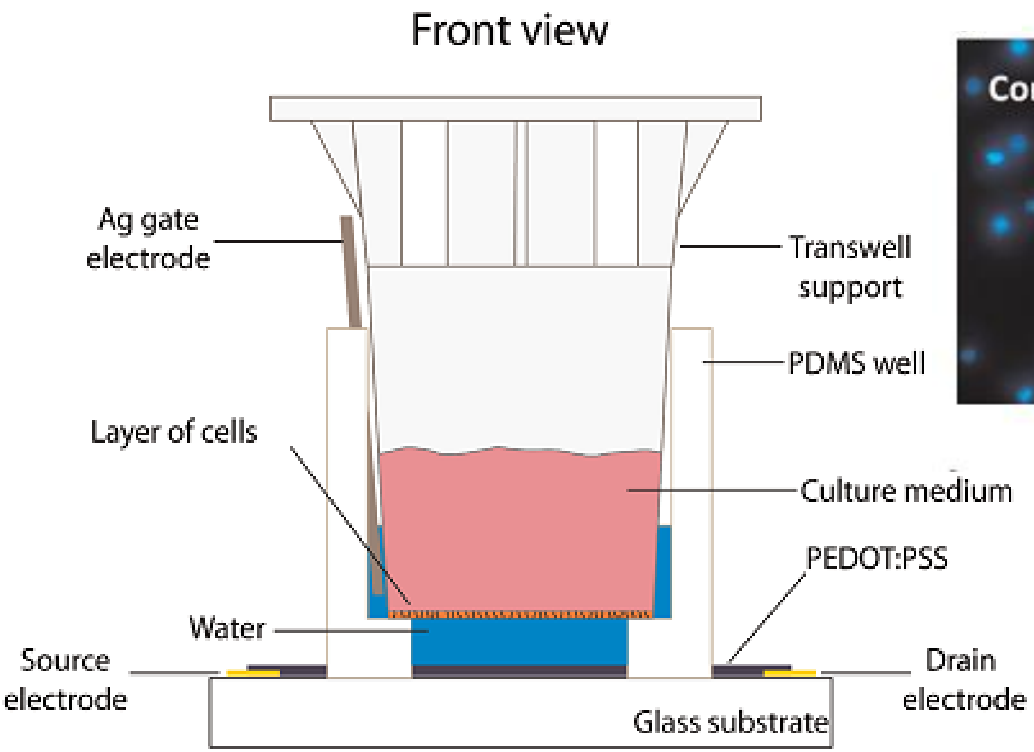


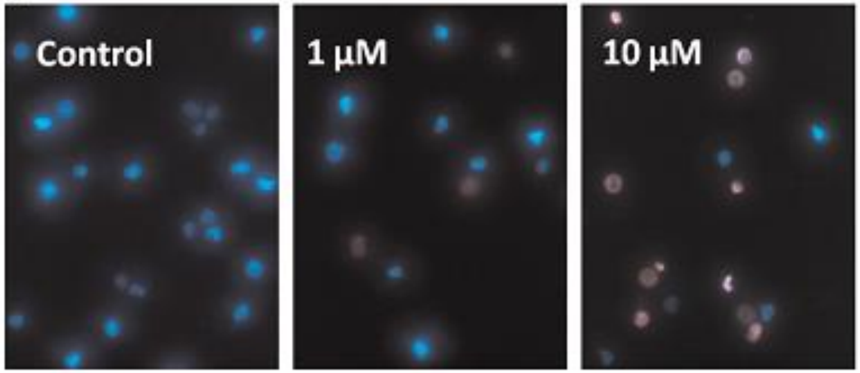


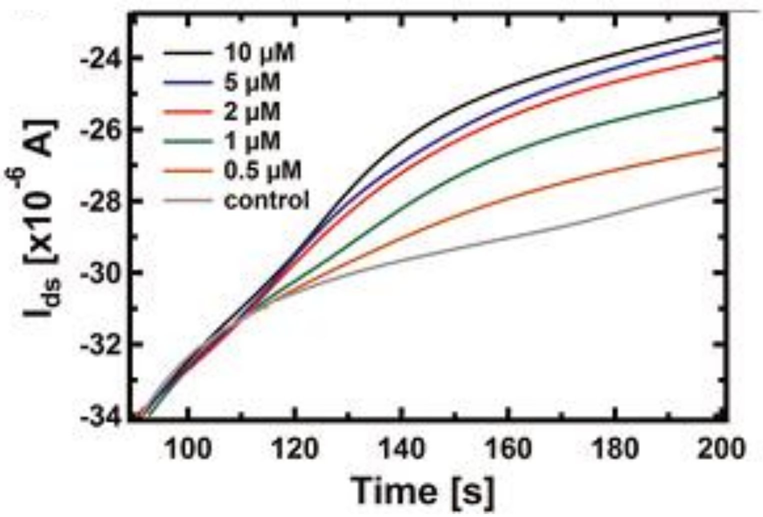


S. Lai, M. Demelas, G. Casula, P. Cosseddu, M. Barbaro, and A. Bonfiglio, **Adv. Mater.** 25, 103 (2013)

Membrane: cell death monitoring







Drug-induced cellular death dynamics monitored by a highly sensitive organic electrochemical system
Agostino Romeo, Giuseppe Tarabella, Pasquale D'Angelo, Cristina Caffarra, Daniele Cretella, Roberta Alfieri, Pier Giorgio Petronini, Salvatore Iannotta (2015)

Summary

1. (Bio)sensor figures of merit: features, properties, issues

- Materials
- Chemical properties
- Surface functionalization

2. Transistor-based structures sensing

- Structures: working principle
- Transduction mechanisms
- Applications
- Advantages/Disadvantages