MINES Saint-Étienne
Une école de l'IMT

Institut Mines-Télécom

Smartees webinar

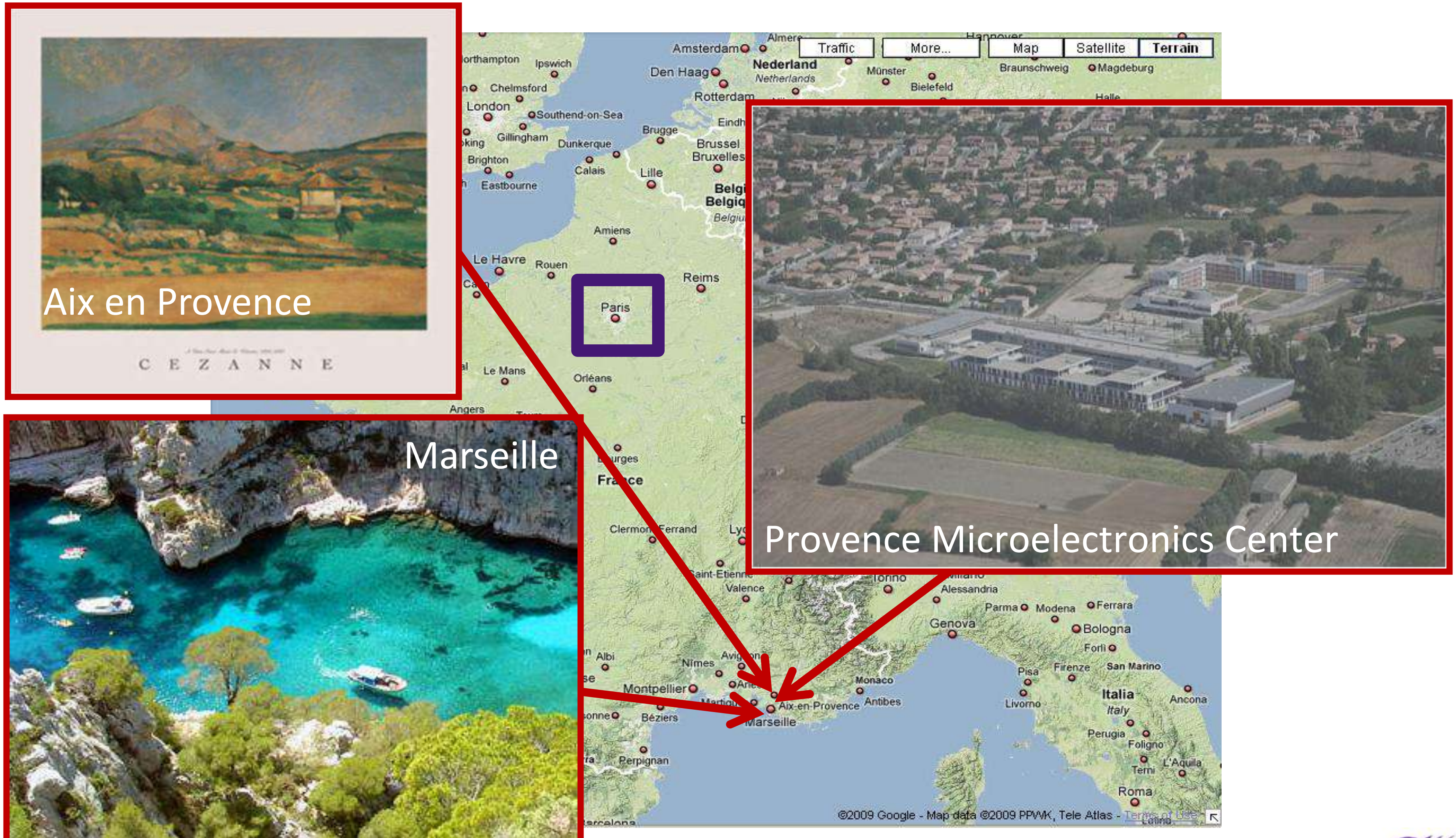
Organic printed & flexible electronic devices for health applications

Sébastien Sanaur

Online, June 2nd, 2021

INSPIRING INNOVATION INNOVANTE PAR TRADITION

Location: Gardanne City (South France)



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Centre de Microélectronique de Provence (CMP)

- One of the 5 Centers of ‘**Ecole Nationale Supérieure des Mines de Saint-Etienne**’ (*Graduate School of Engineering*)
  - Delivers *Master’s Degree (M1&2) + PhD (via Lyon Doctoral School)*

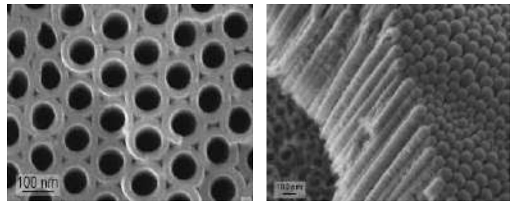
- 4 Research laboratories:
  - Secured Architectures & Systems,
  - Manufacturing Sciences and Logistics,
  - Bioelectronics,
  - Flexible Electronics.
- Start-ups incubator,
- 600 m^2 clean-room facilities.


CMP

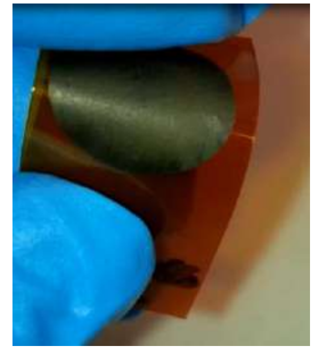
“Exploring New Microelectronics Technology and Devices for Innovative Applications”

Department of Flexible Electronics

Materials

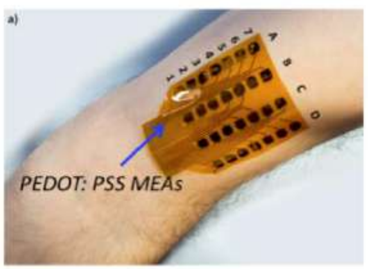


Fabrication of nanomaterials
(TiO_2 nanotubes)



Thermoelectric and
et piezoelectric inks

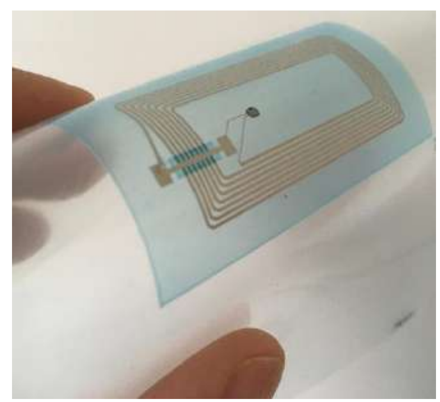
Devices



Sensors
Antennas
Production/storage of energy

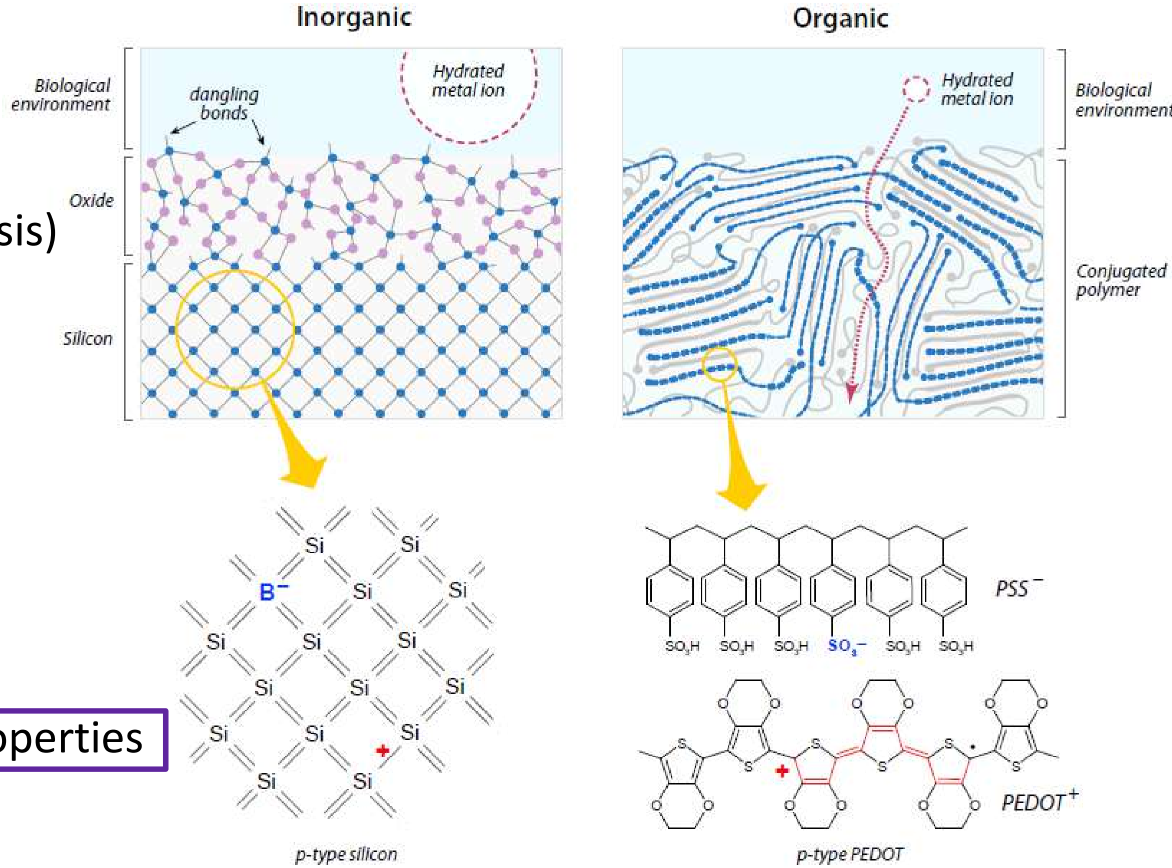
Organic Flexible & Printed electronics

Integration



Organic printed & flexible electronic devices for health applications

Why π-conjugated polymers in health applications?



- Tunability of properties (synthesis)
- Low-temperature processing
- Ideal surfaces/interfaces
- High ion mobilities
- Electronic excitations affect properties

J. Rivnay, R.M. Owens, and G.G. Malliaras, Chem. Mater. 26, 679 (2014).

Organic Mixed Ion-to-Electron Conductors (OMIECs):
« Ideal » candidates for interfacing with biological media

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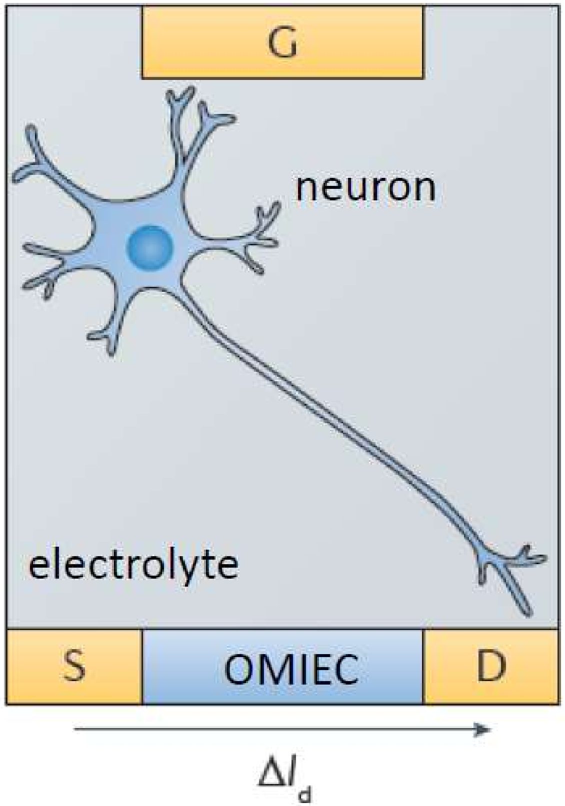
OECTs in Bioelectronics[%]



- High SNR (local signal amplification) into the brain (stimulate and record), the heart, the muscles
- Record electrophysiological activities (EEG, ECG, EOG, EMG) on the skin

OECT as neural activity sensor

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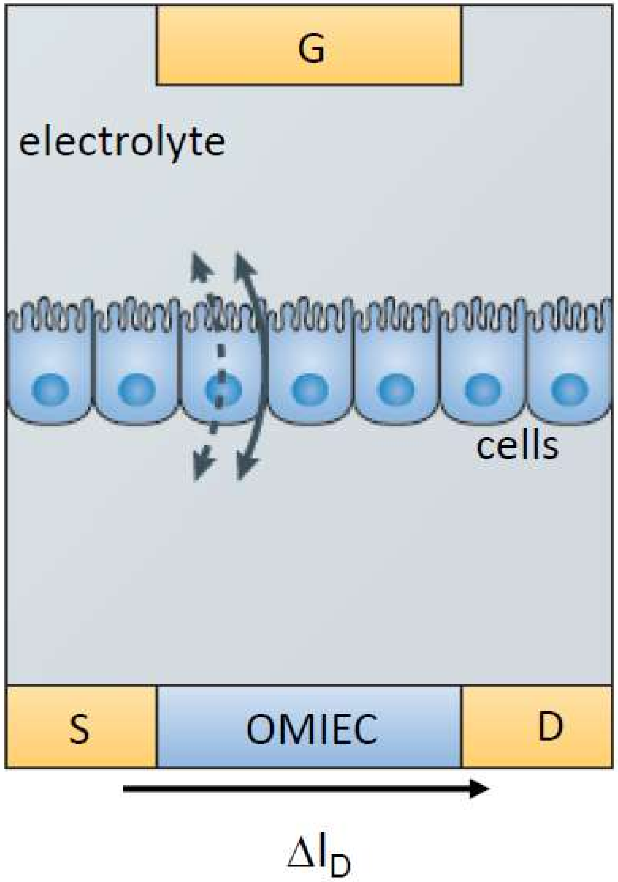
% Malliaras, G., Rivnay, J., Inal, S., Salleo, A., Owens, R., & Berggren, M.. Nature Reviews Materials, 3, 17086 (2018)

OECTs in Bioelectronics[%]



- monitor cell coverage, barrier tissue formation and cellular health for nonelectrogenic cells, such as epithelial cells
- study ion channels in supported lipid bilayers assembled on OMIEC channels
- Monitor 3D cells culture to control their integrity and effect of toxic compounds
- Control arrangement of epithelial cells; control 3D cells culture

OECT as impedance sensors

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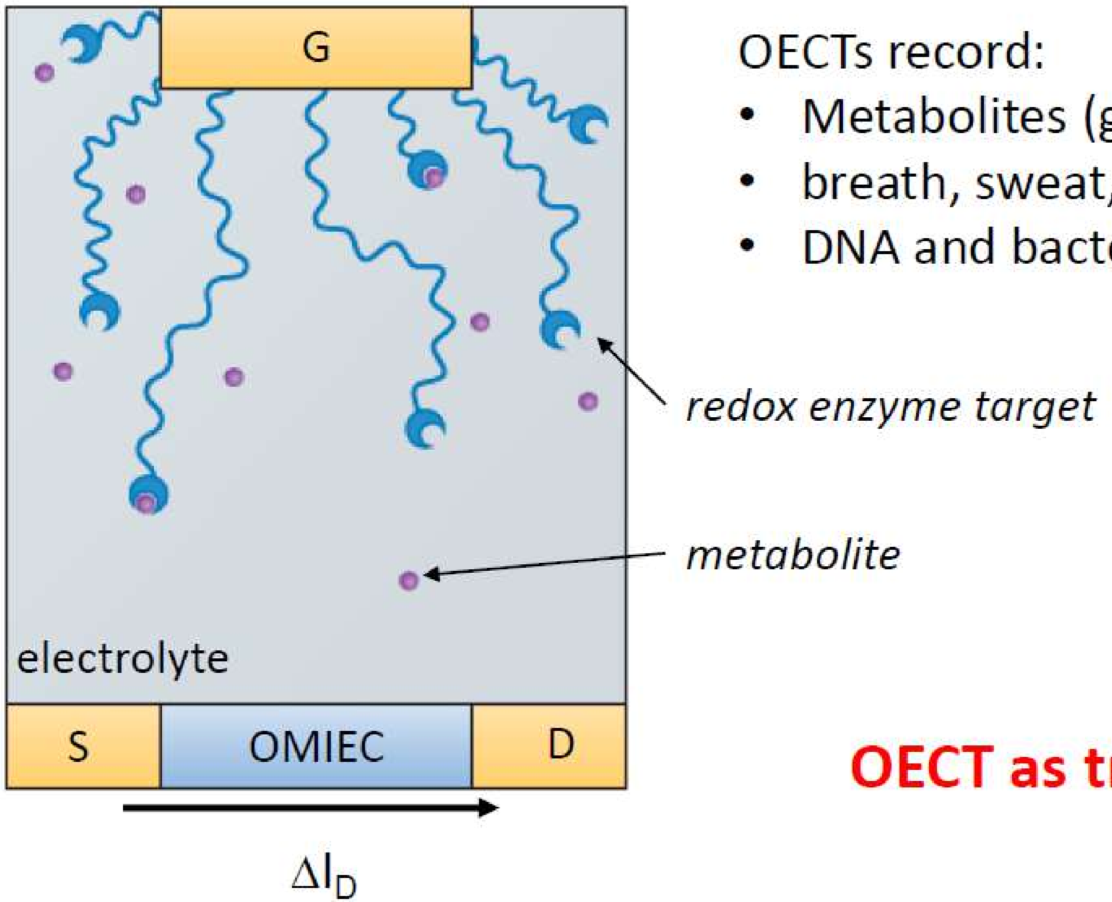
% Malliaras, G., Rivnay, J., Inal, S., Salleo, A., Owens, R., & Berggren, M.. Nature Reviews Materials, 3, 17086 (2018)

OECTs in Bioelectronics[%]



OECTs record:

- Metabolites (glucose, lactate)
- breath, sweat, saliva or cell culture media
- DNA and bacteria

OECT as transducer in biosensors

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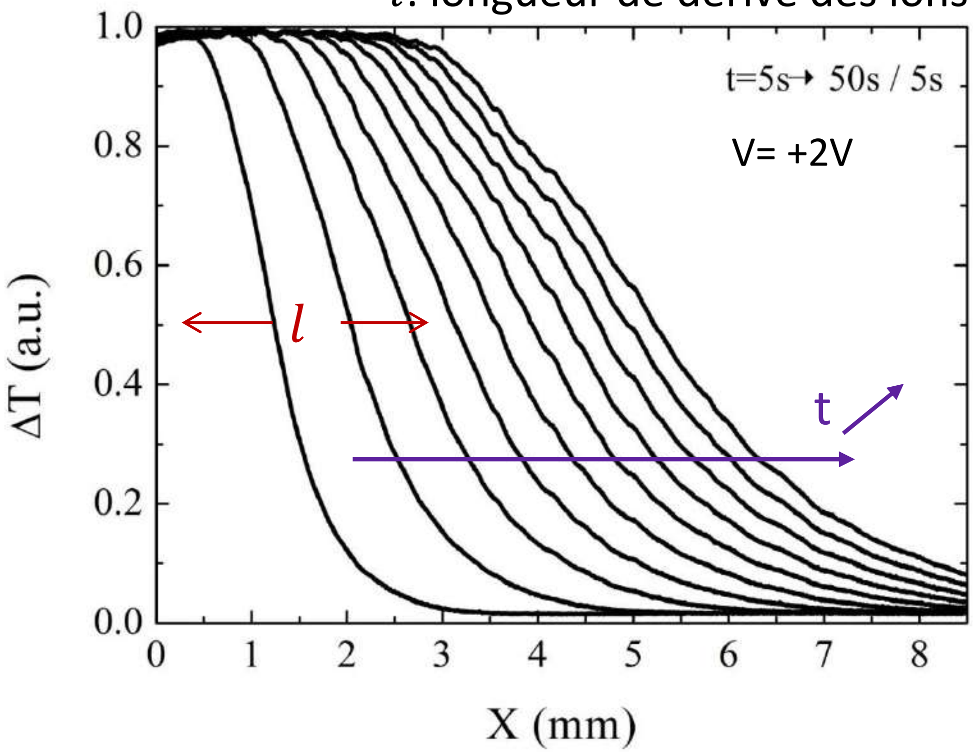
% Malliaras, G., Rivnay, J., Inal, S., Salleo, A., Owens, R., & Berggren, M.. Nature Reviews Materials, 3, 17086 (2018)

Ion transport in PEDOT:PSS

l: longueur de dérive des ions



Transmittance profile vs length of dedoping in PEDOT: PSS

Analytic model: $l = \sqrt{2\mu V t}$

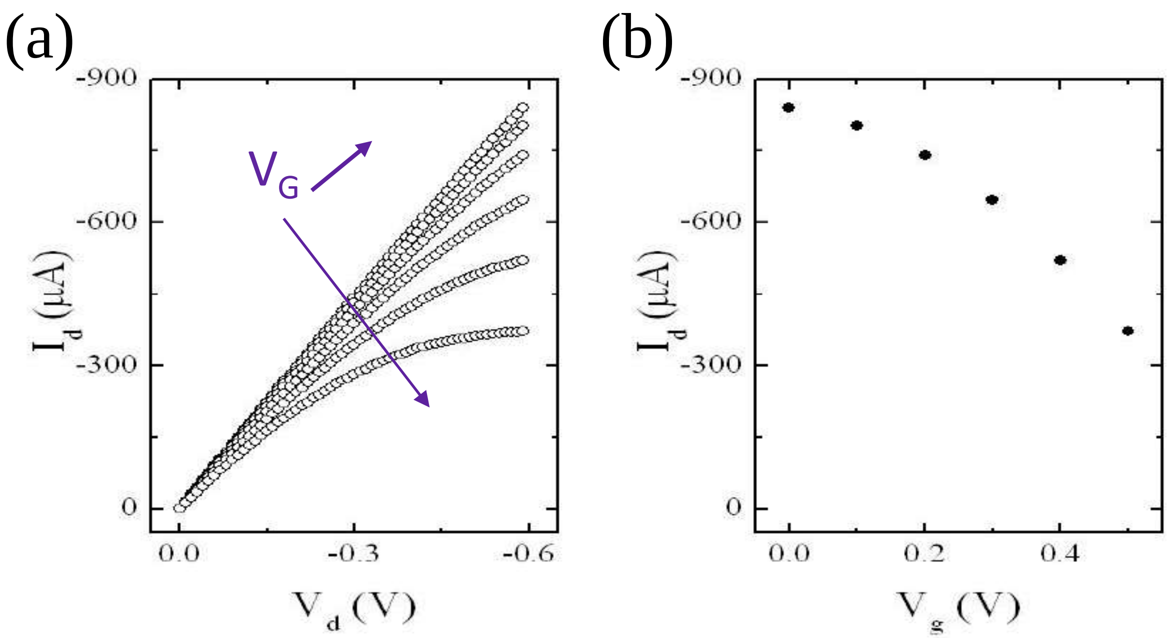
Ion	Mobility (μ) in PEDOT:PSS ($cm^2.V^{-1}.s^{-1}$)
H^+	$(39 \pm 0.2) . 10^{-4}$
K^+	$(14 \pm 0.2) \cdot 10^{-4}$
Na^+	$(9.3 \pm 0.4) \cdot 10^{-4}$
$C_5H_{14}NO^+$	$(4.5 \pm 0.4) \cdot 10^{-4}$

Mobilities of different ions in PEDOT:PSS

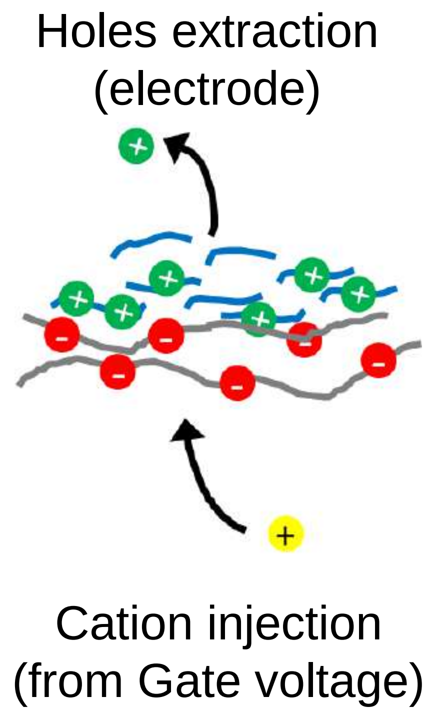
Direct measurement of ion mobilities in the device architecture (1D)

E. Stavrinidou, P. Leleux, H. Rajaona, D. Khodagholy, J. Rivnay, M. Lindau, S. Sanaur and G. G. Malliaras, Adv. Mater. 25 (32), 4488 (2013)

Organic ElectroChemical Transistors (OECTs)



*Transfer curve (a) and output curve (b) of PEDOT:PSS OECTs**



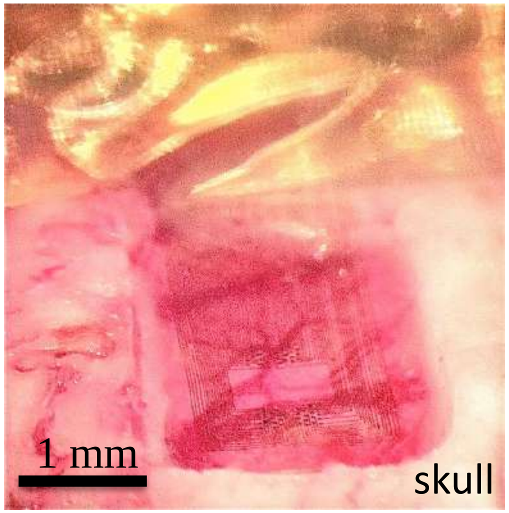
OECT operation mechanism

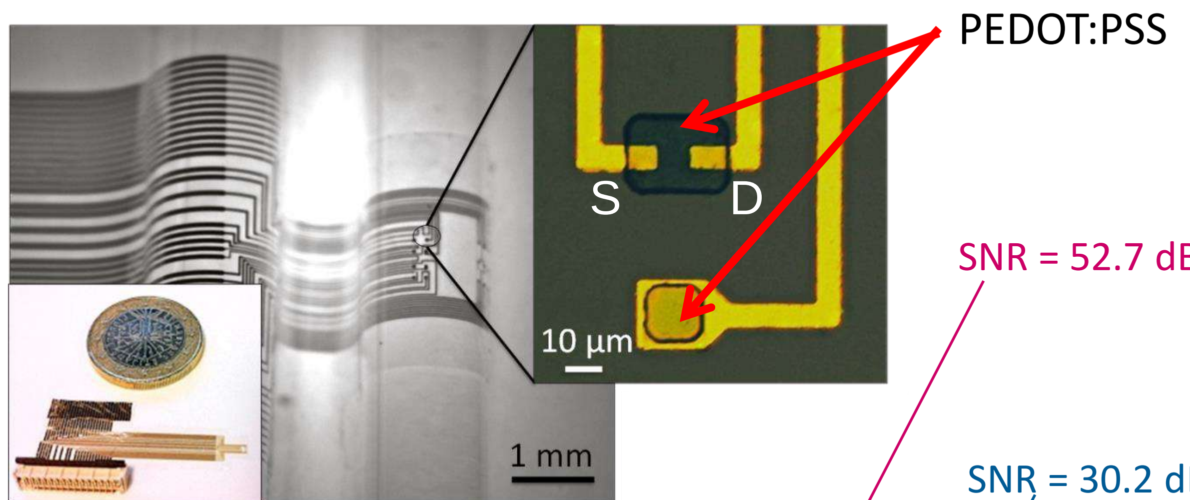
**D. Khodagholy, M. Gurfinkel, E. Stavrinidou, P. Leleux, T. Hervé, S. Sanaur, and G. G. Malliaras, Applied Physics Letters, 99(16), 163304 (2011)*

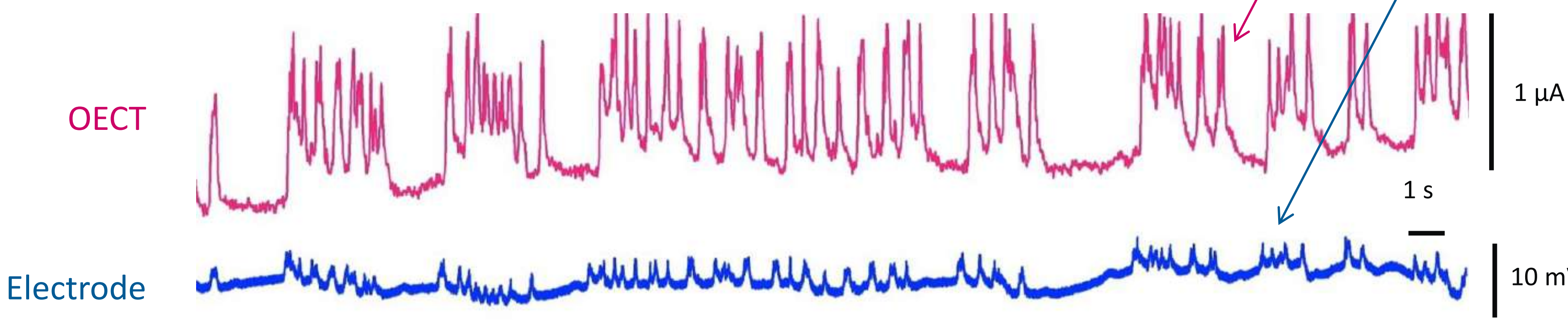
Outline

- Organic Bioelectronics
  - Ion mobility, OECTs
  - Interfacing with biological environment
- Inkjet Printed Devices/ Sensors
  - Electronics: Interconnections, capacitors, OTFTs,
  - BioMedical: in-vitro MEAs, OECTs, EMG, ECG
  - Organic Oxymeter: OLEDs, OPDs
- Conclusion & Perspectives

PEDOT:PSS OECTs interfacing with the brain



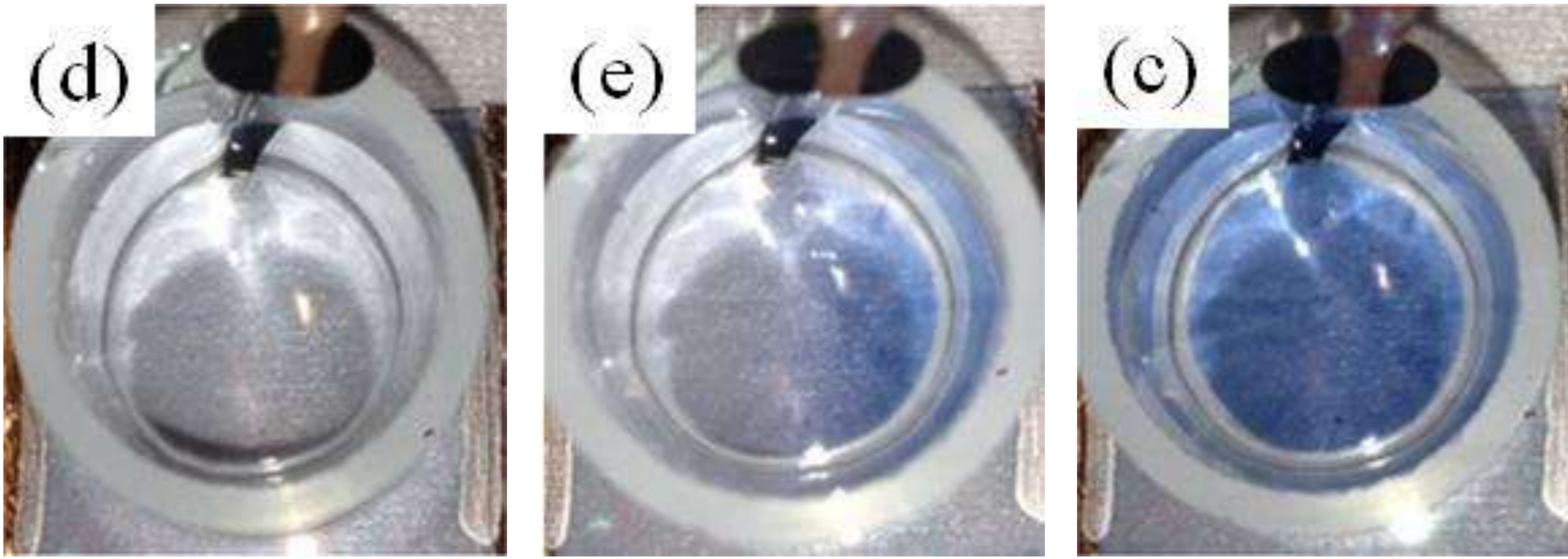




Improved *In-Vivo* Electrophysiological recording (ECoG)*

*D. Khodagholy, T. Doublet, P. Quilichini, M. Gurfinkel, P. Leleux, A. Ghestem, E. Ismailova, T. Herve, S. Sanaur, C. Bernard, and G.G. Malliaras , *Nature Comm.* 4, 1575 (2013)

Tuning the directionality and speed in cell migration

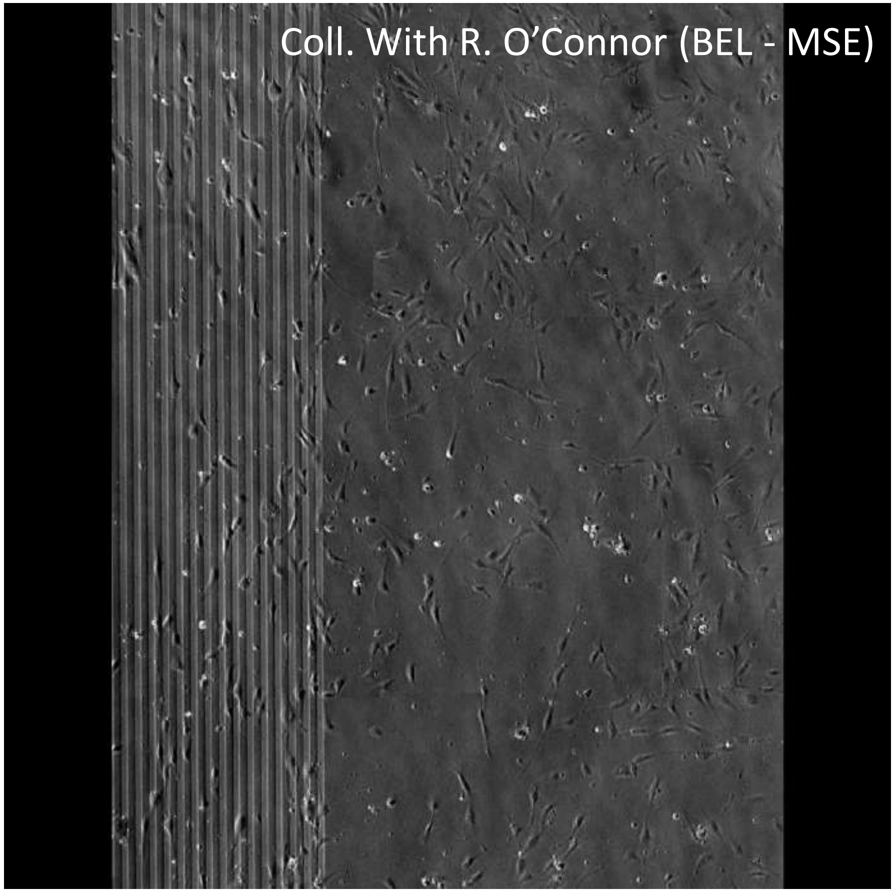


oxidized | gradient | reduced

Electrochemical gradient in PEDOT:PSS for tuning cell migration

M. ElMahmoudy et al., J. Appl. Polym. Sci., 136(5), 47029 (2018)

Tuning the directionality and speed in cell migration



Directionality by surface structuration (pitch= 50µm)

***In vitro* platform for cellular guidance**

M. ElMahmoudy et al., J. Appl. Polym. Sci., 136(5), 47029 (2018)

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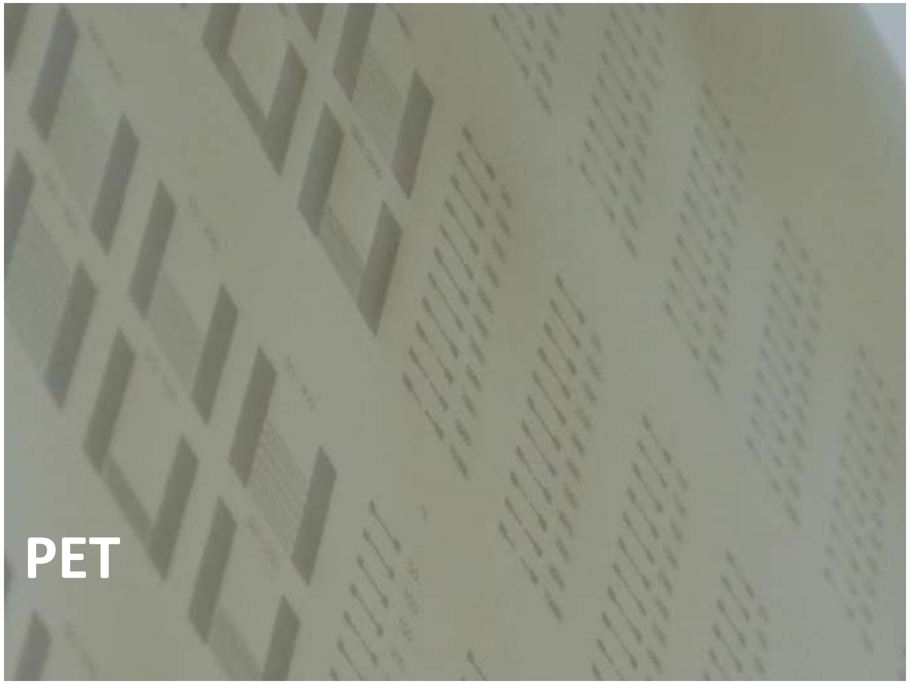
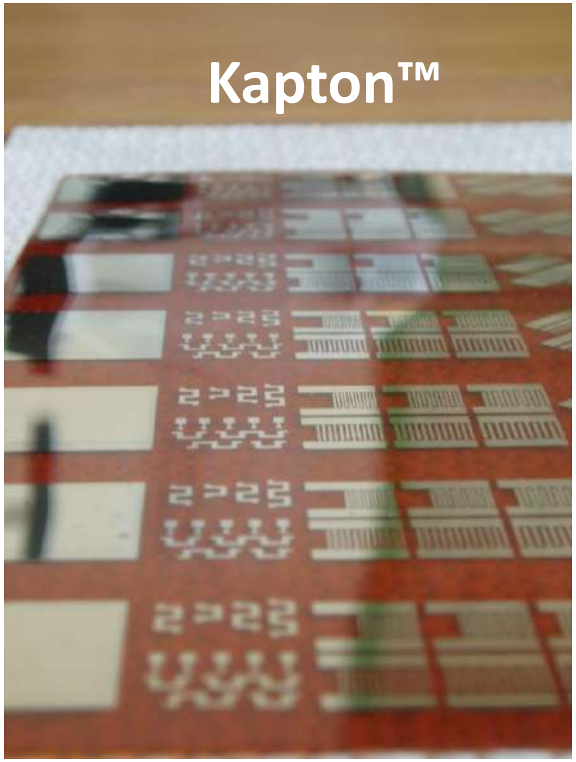
Inkjet printing: Devices





Multi nozzle (256 nozzles) inkjet printing platform

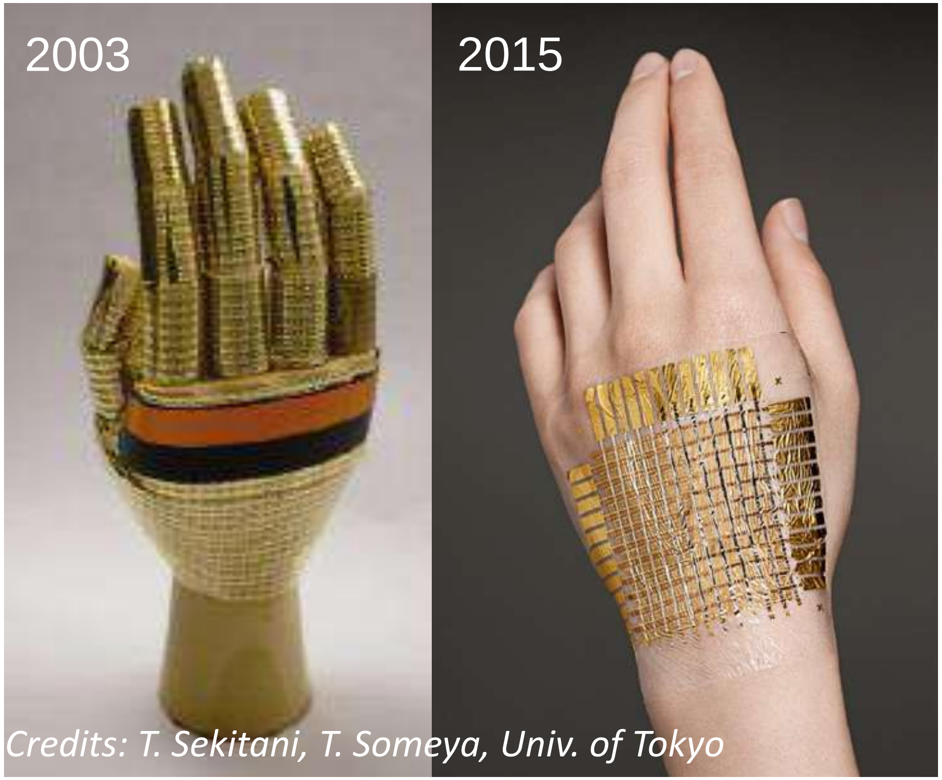
Large area printing – semi industrial prototype

*A. Yakoub et al., JETPAC: a novel semi-industrial prototyping tool for printed electronics, LOPE-C (**2009**)*

Motivation: Organic Electronics → Flexible → Ultra-Flexible

Integration of ultra-flexible substrates → skin-electronics

Flexible displays (OLEDs + OTFTs)



Smart artificial skin (OTFTs + T°/ pressure sensors)

Low fabrication temperature

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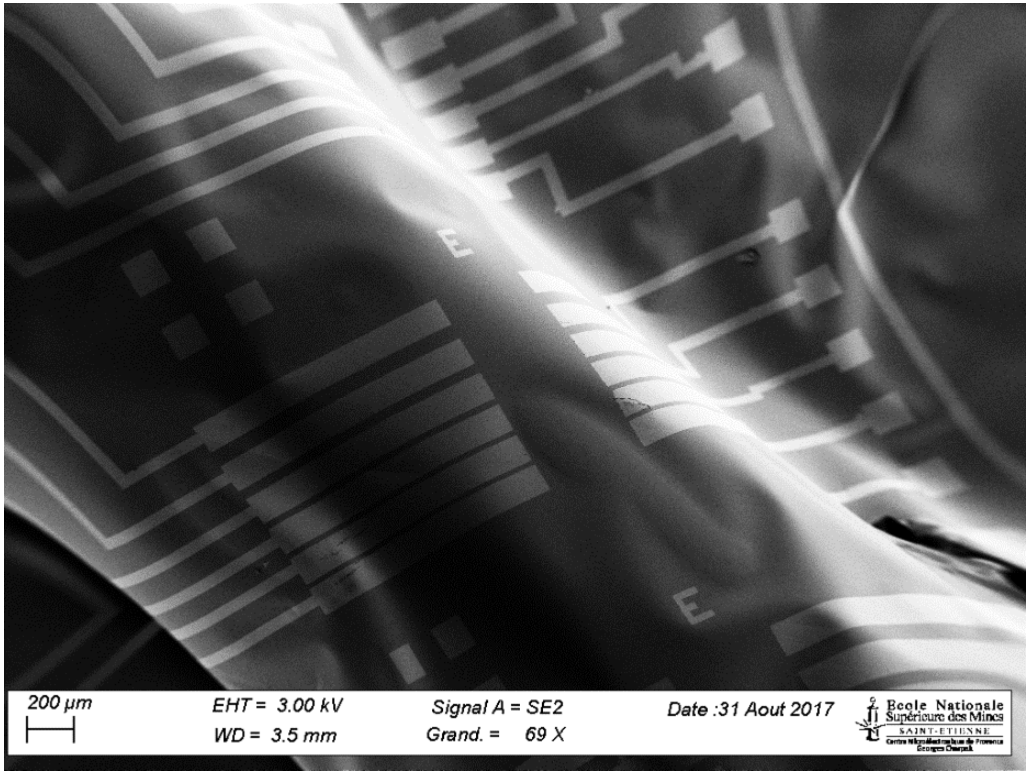
Ultra-flexible OTFTs



SEM picture: Source/ Drain electrodes (Parylene C 2µm-thick)

OTFTs enrolling

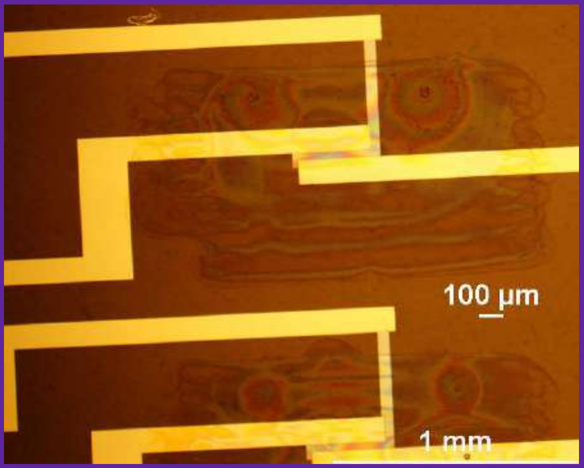
L. Fliegans, M. Morvan, S. Bensalem, C. Calmes, J. Anthony, S. Sanaur, Phys. Stat. Solid. A, 216 (22), 1900617 (2019)

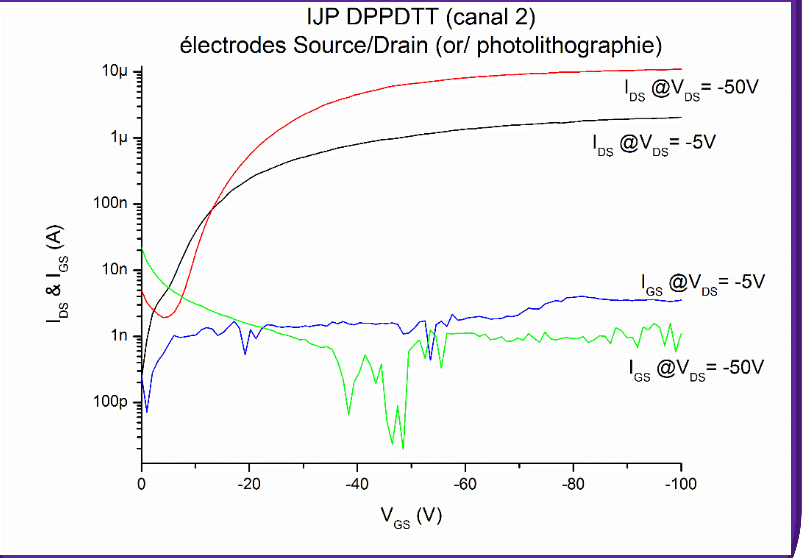
OTFTs by IJP

S. Sanaur, A. Whalley, B. Alameddine, M. Carnes, C. Nuckolls, Org. Electronics, 7(5), 423-427 (2006)

M. Barret, S. Sanaur, P. Collot, Mat. Res. Soc. Symp. Proc., 1003-O09-09 (2007)

Ultraflexible OTFTs





Inkjet Printed OTFTs

Inkjet Printed & ultraflexible OTFTs

Master 2 Internships (non published results, 2017)

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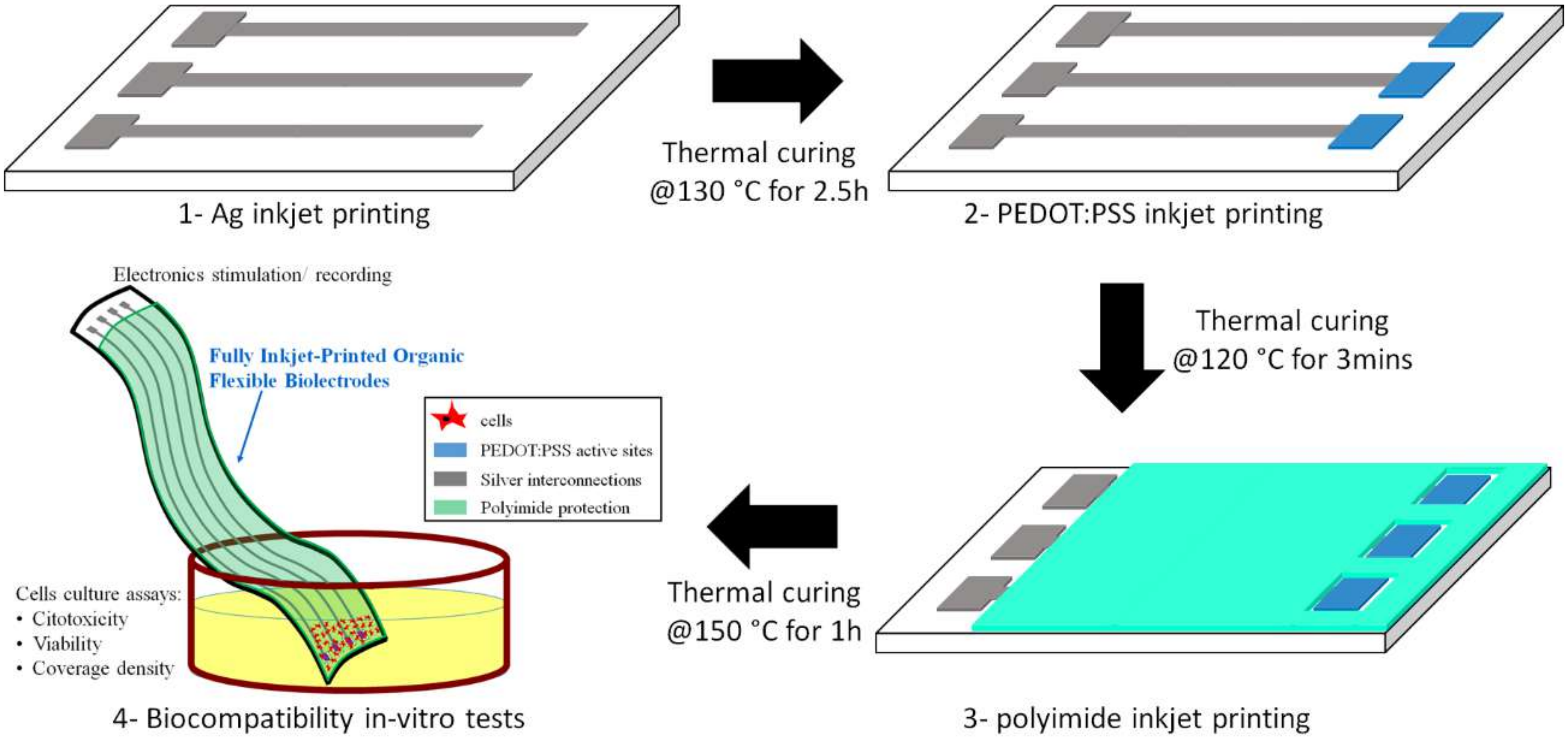
In vitro MEAs



Schematics of fully inkjet printed MEAs

J. S. Mandelli, J. Koepp, A. Hama, S. Sanaur, G. A. Rae, C. R. Rambo (https://doi.org/10.1007/s10544-020-00542-z)

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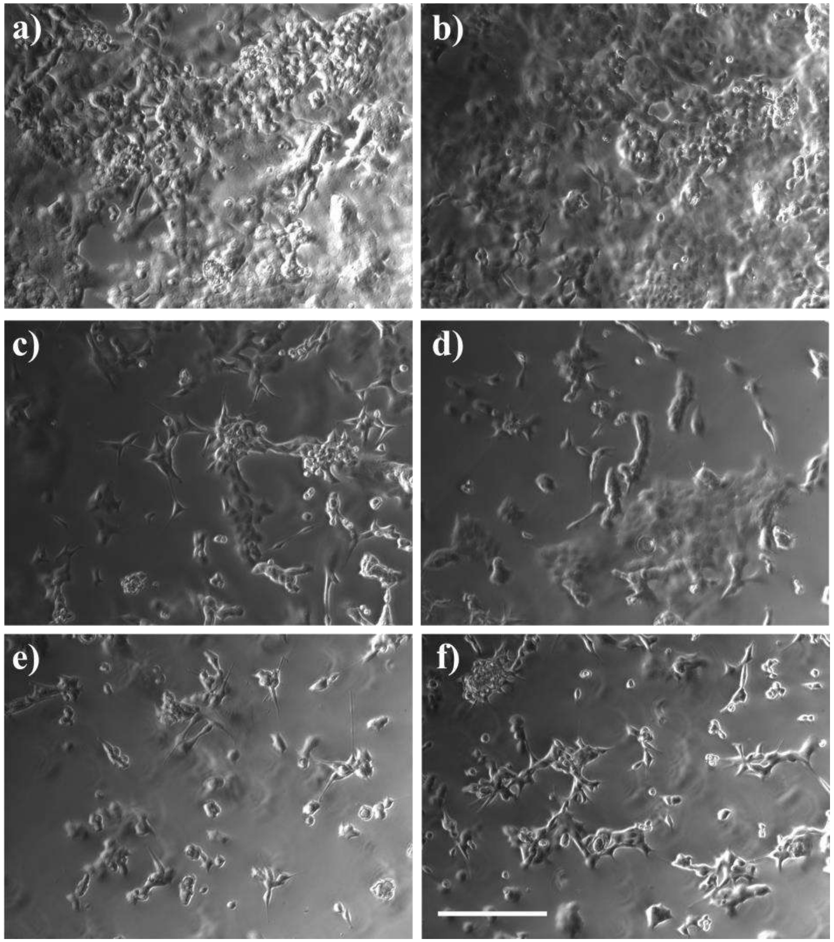
In vitro MEAs - biocompatibility



Typical images of PC-12 cells growth:

- on petri dish (a) (Control)
- on inkjet printed polyimide rectangles after 96 h of cells culture.

  Square areas are:
  - 3 mm^2 (b),
  - 6 mm^2 (c),
  - 12 mm^2 (d),
  - 24 mm^2 (e)
  - 48 mm^2 (f) surface areas.

No cells death after 96 hours

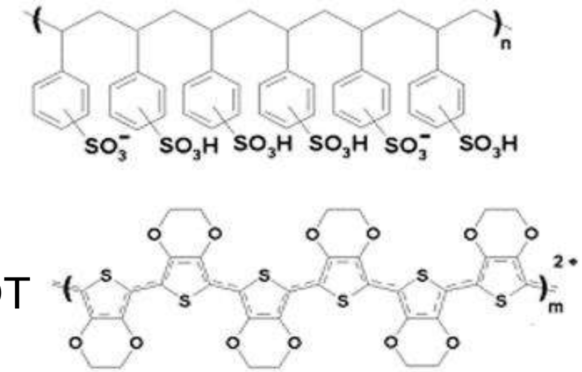
Biocompatible Fully-IJP organic MEAs

J. S. Mandelli, J. Koepp, A. Hama, S. Sanaur, G. A. Rae, C. R. Rambo (https://doi.org/10.1007/s10544-020-00542-z)

Inkjet Printed OECTs (1/2)

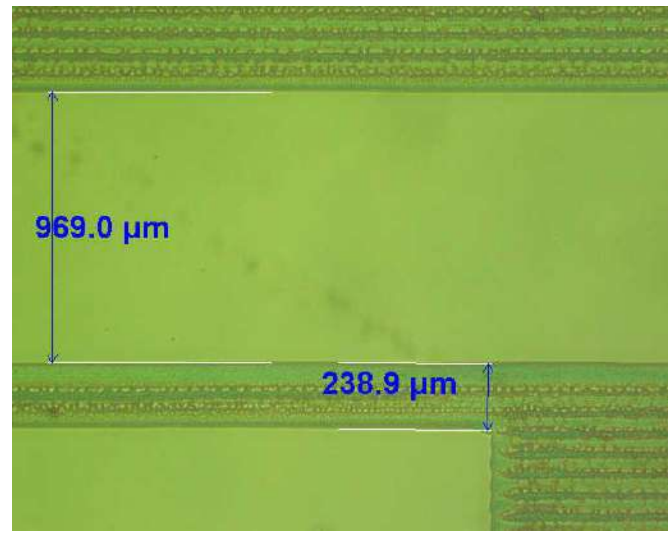
PSS

PEDOT



PEDOT:PSS molecular architecture

Inkjet printing/ Dimatix
16 nozzles printhead

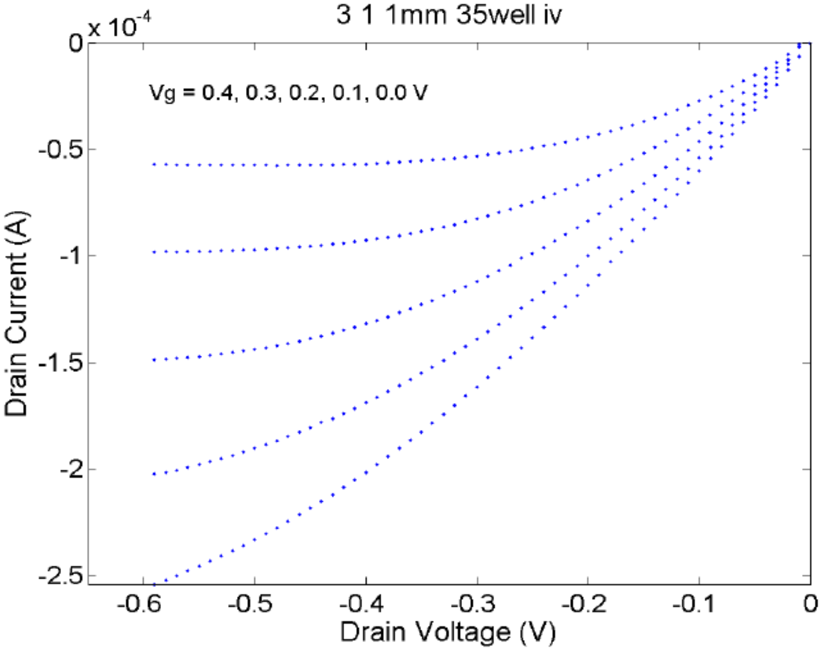


Zoom on OECTs pad and channel

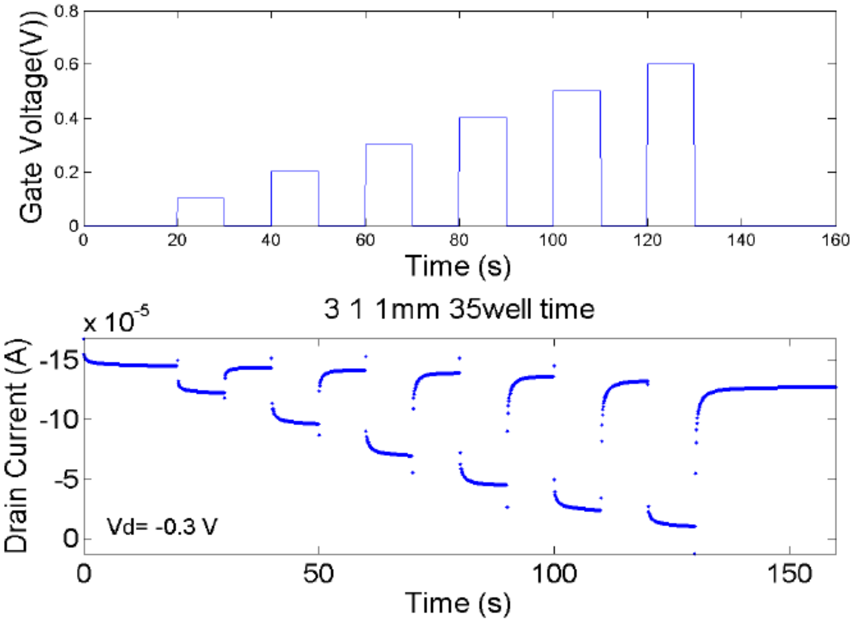
Several OECTs geometry

J. Mandelli, M. Pillers et al., Spring E-MRS (2012)

Inkjet Printed OECTs (2/2)



OECTs: output curve

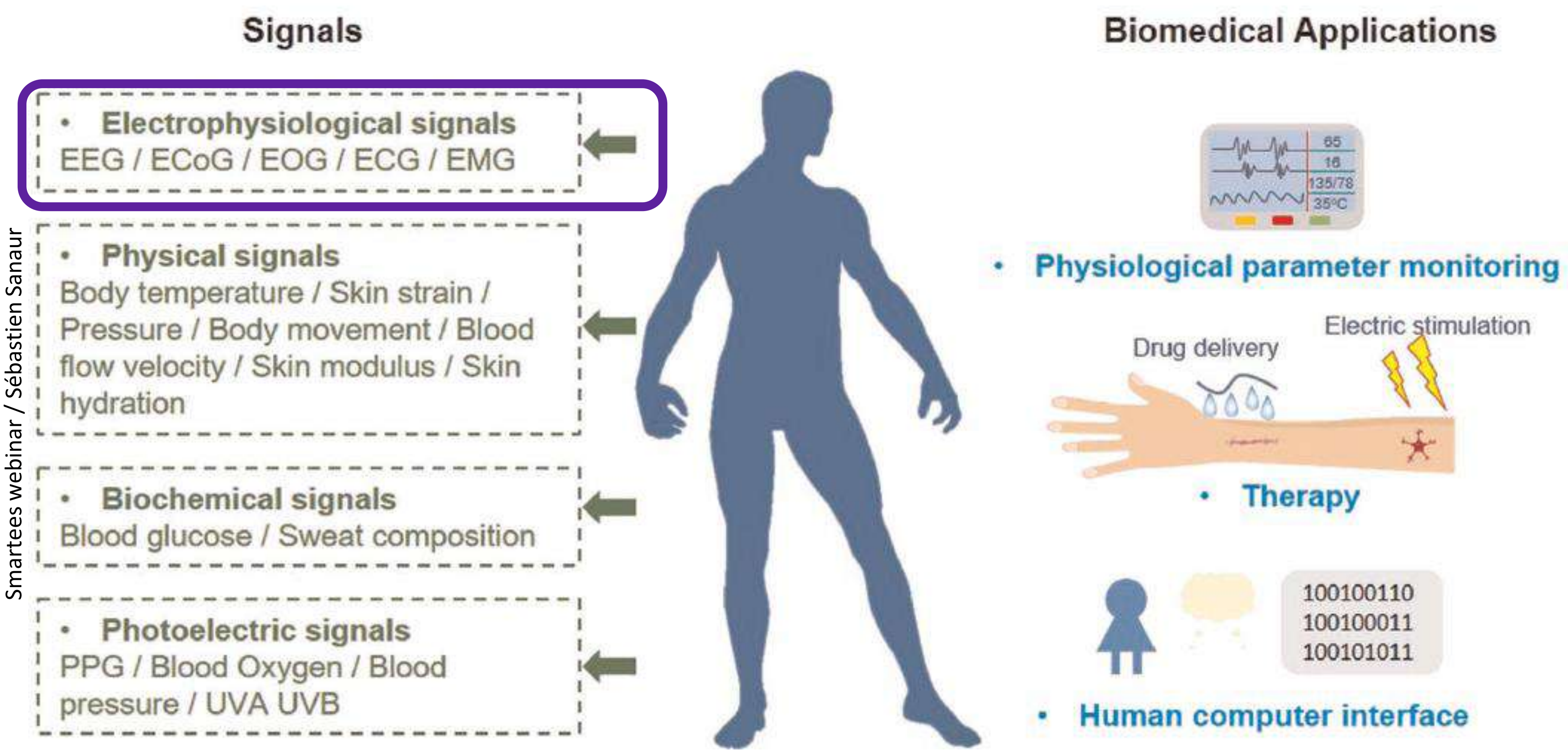


OECTs (Drain current): response time for gate pulsing

« Active » devices in direct operation with biological media

J. Mandelli, M. Pillers et al., Spring E-MRS (2012)

Organic Electronics in « Bio » applications



Wearable applications integrating biomedical devices

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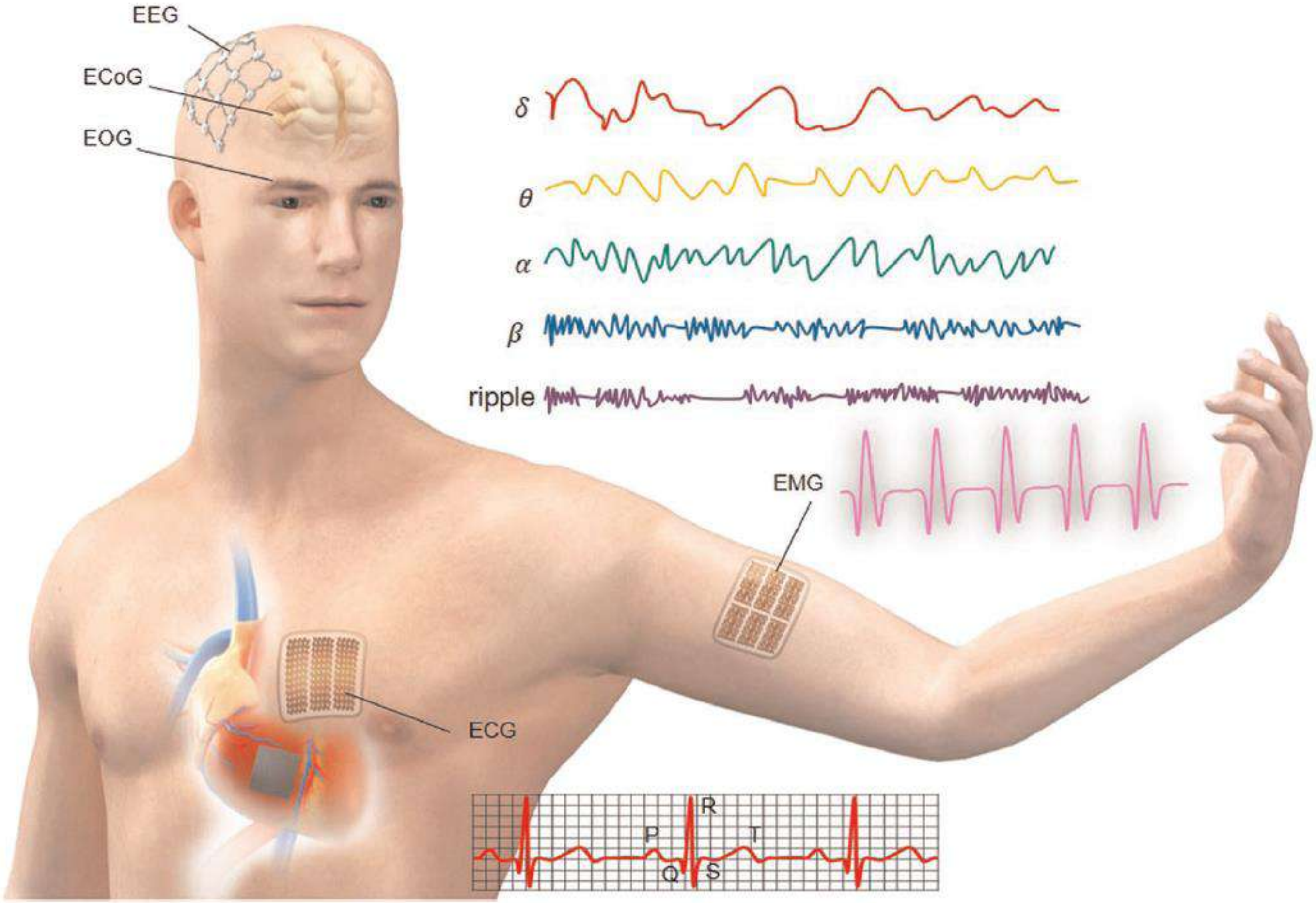
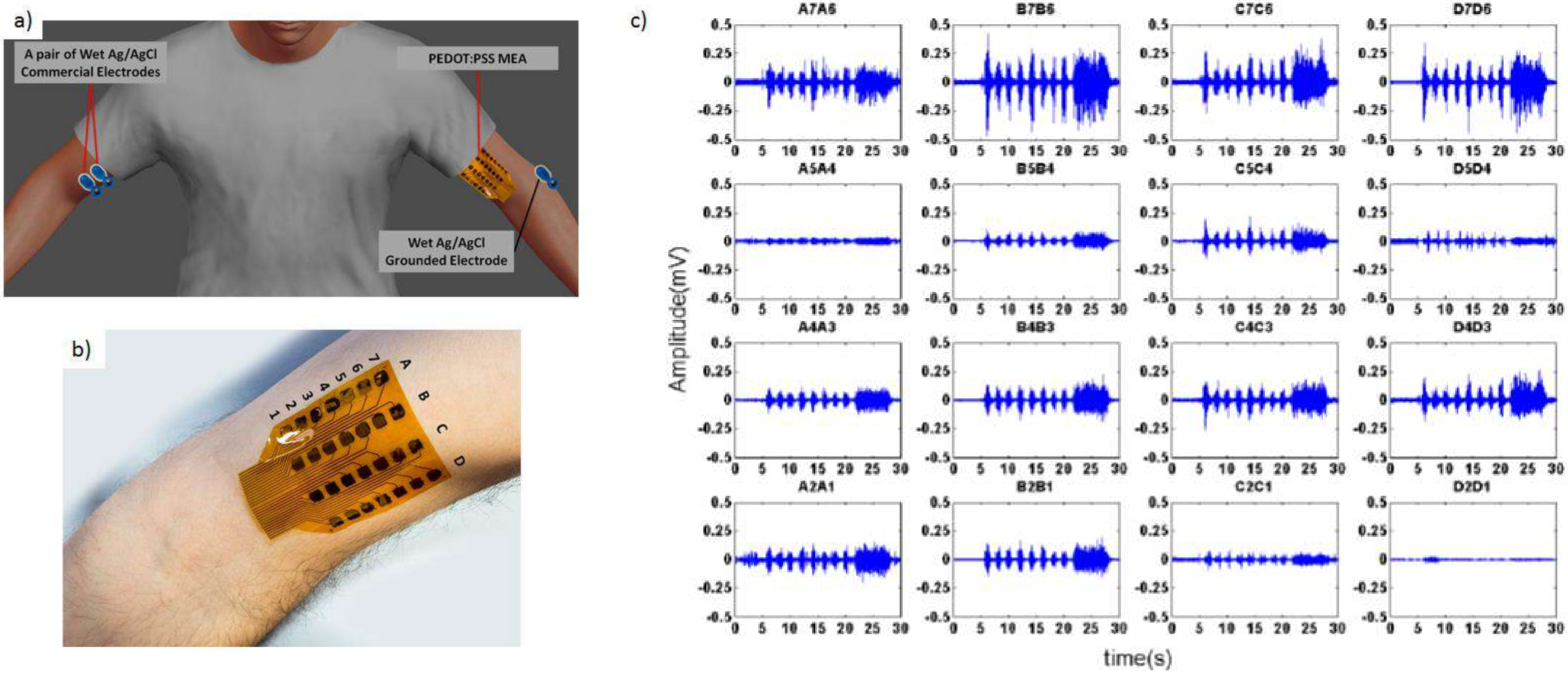
Organic Electronics in « Bio » applications



Electrophysiological signals

Neuromuscular recording (sEMG MEAs by IJP)



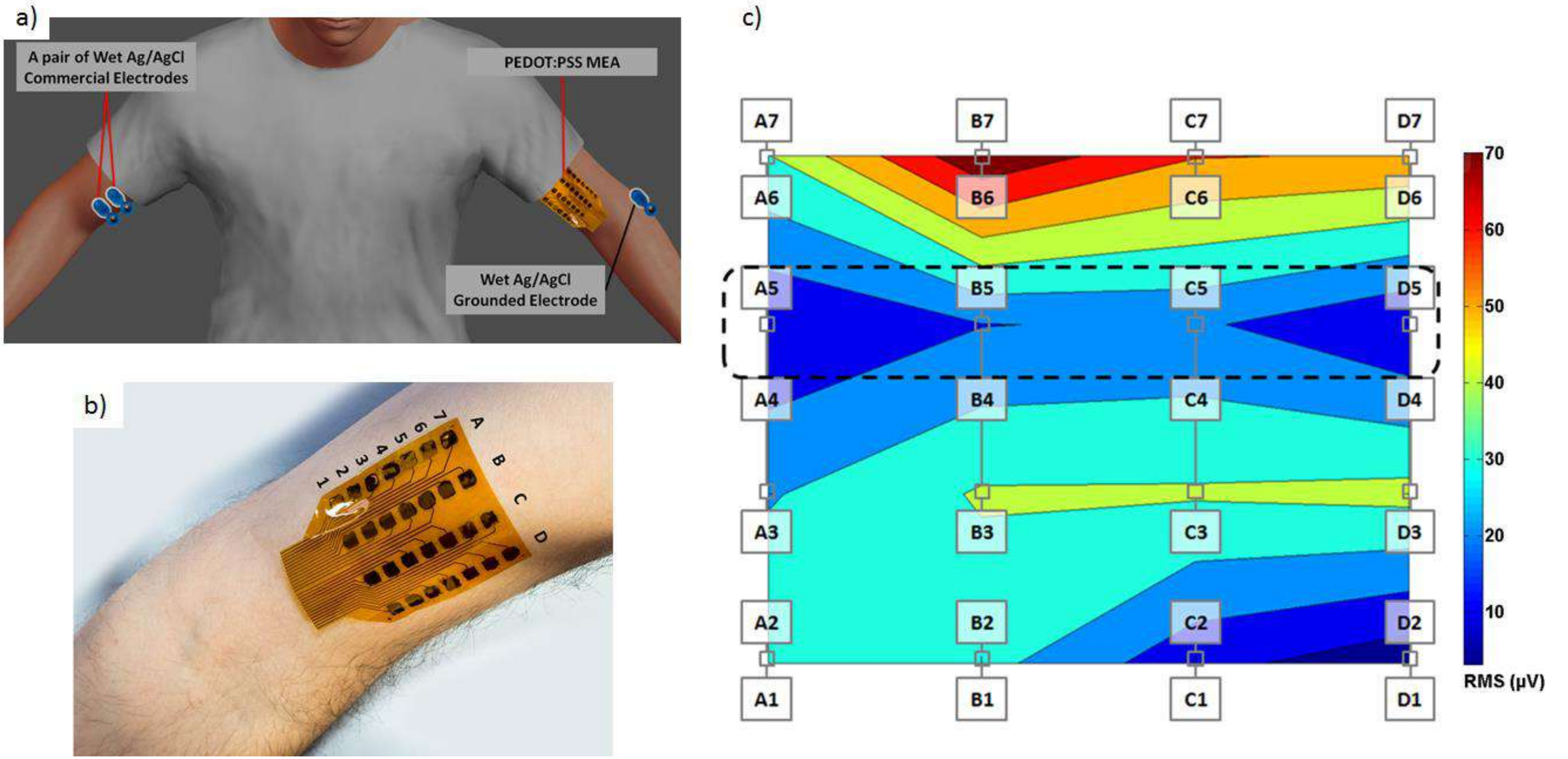
a) Electromyography setup (sEMG), b) picture of PEDOT:PSS sEMG MEAs on the surface of the skin, c) 16 sEMG signals

Cutaneous electrophysiology. Wellness & Health applications.

T. Roberts, J. De-Graaf, C. Nicol, T. Hervé, M. Fiocchi, S. Sanaur, Adv. Health. Mat., 5(12), 1462–1470 (2016)

Inkjet Printed physiological electrodes

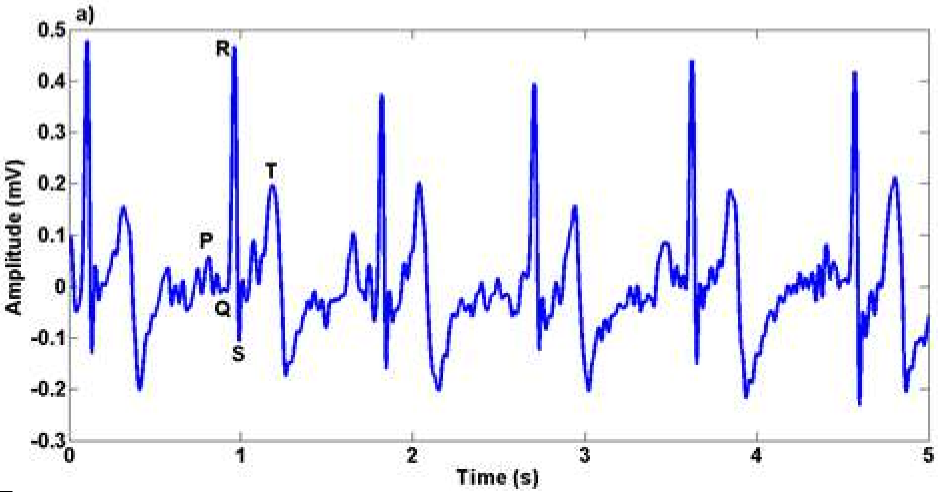
- ElectroMyoGraphic (EMG) sensors



a) EMG, b) IJP PEDOT:PSS MEAs sensors, c) EMG signals cartography.

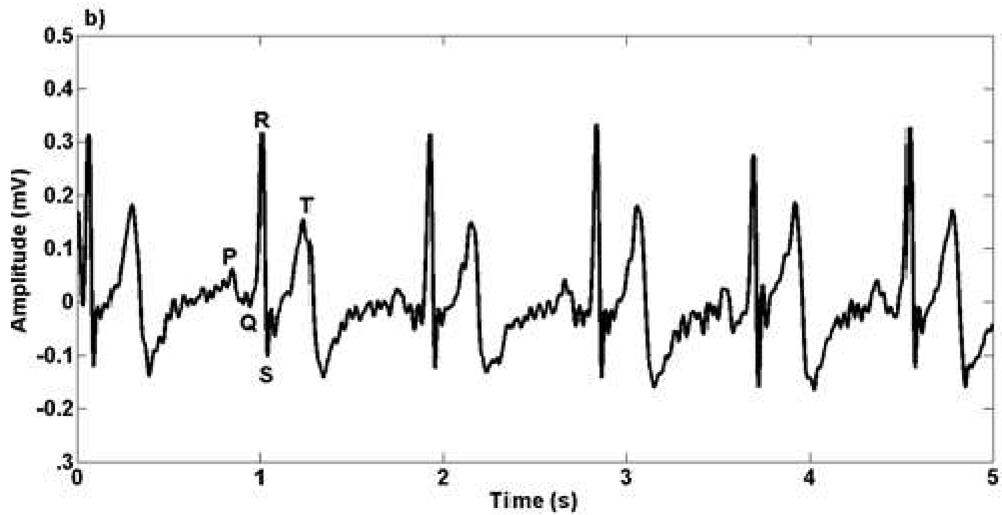
T. Roberts, J. De-Graaf, C. Nicol, M. Fiocchi, S. Sanaur, Adv. Health. Mat., 5(12), 1462–1470 (2016)

Skin-electrophysiology: electrocardiography (ECG)



PEDOT:PSS

Ag/ AgCl



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Health & Wellness Wearables

*Adv. Health. Mat., 5(12), 1462–1470 (**2016**)*

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Organic Electronics in « Bio » applications

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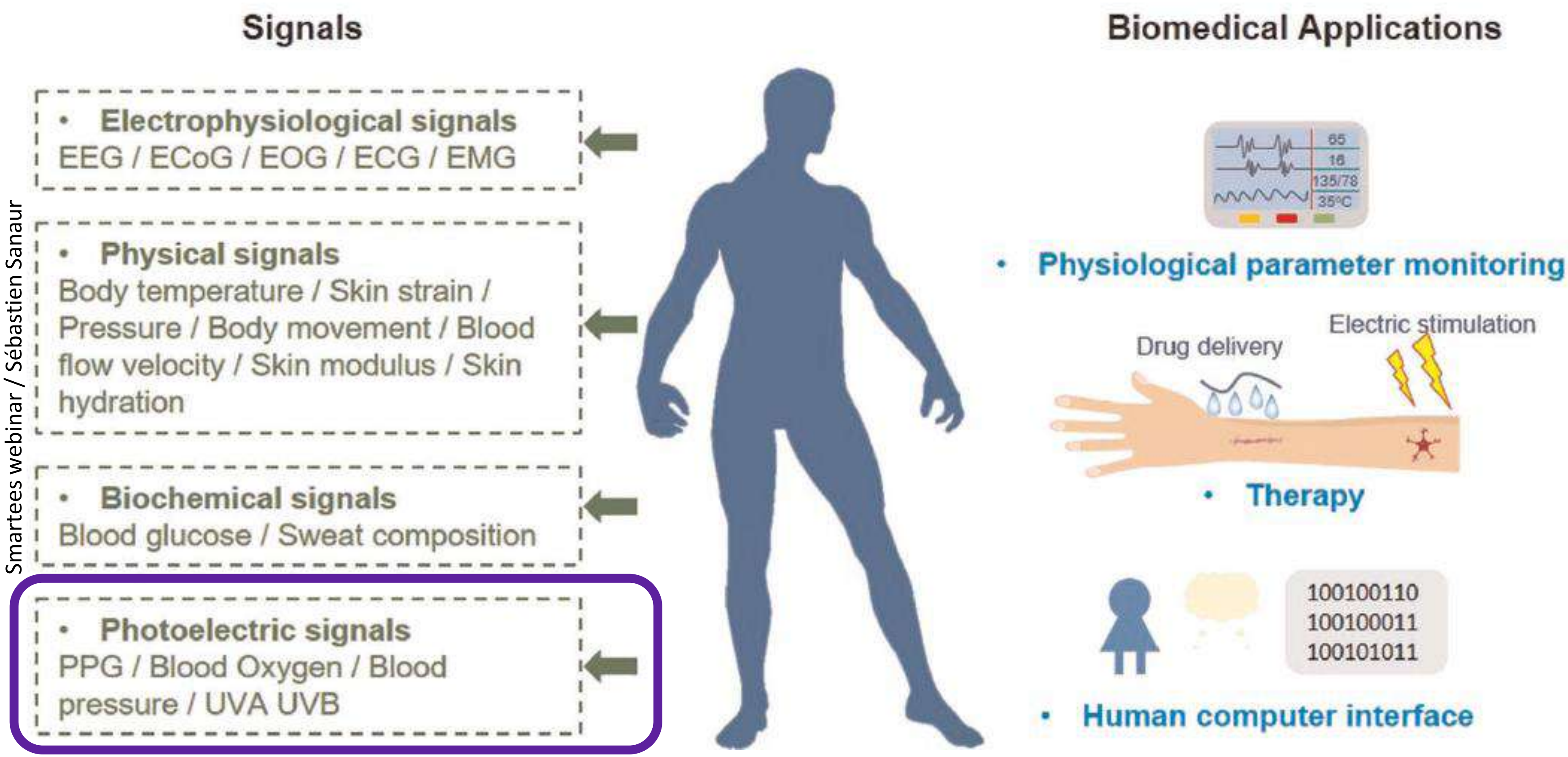

Wearable applications integrating biomedical devices

Oximeter: measurement principle

Hb: desoxygenated Hemoglobin
HbO_2: oxygenated hemoglobin

Light emission:
1 $\lambda_{em.}$ > 805 nm
1 $\lambda_{em.}$ < 805 nm

To record oxygen content in th blood (Hb/ HbO_2 ratio)

Red (R) → Hb
InfraRed (IR) → HbO_2

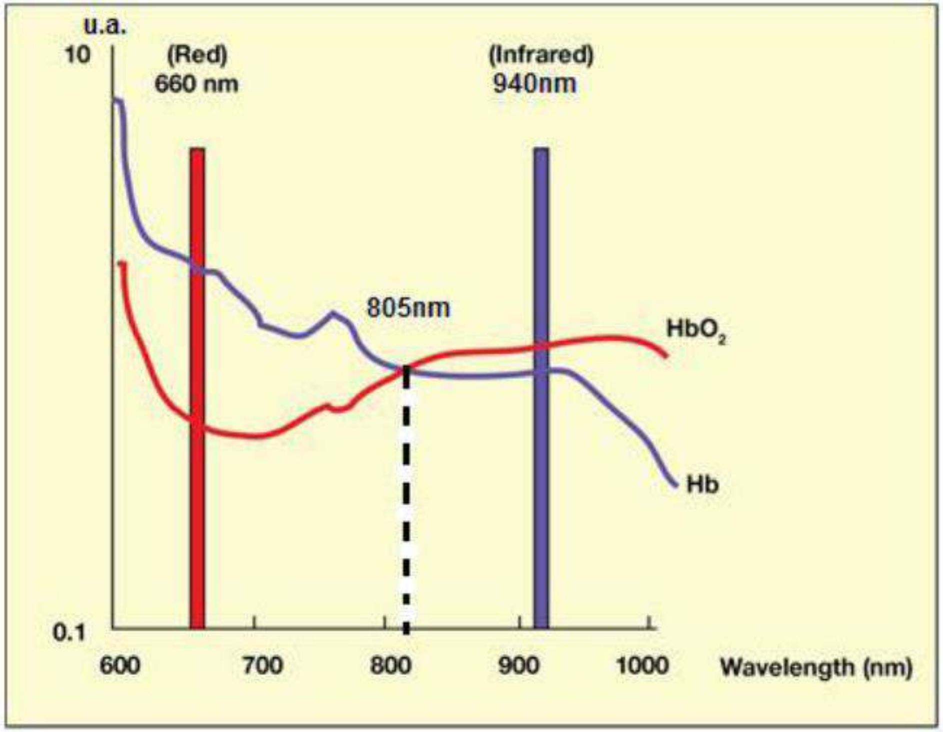

Figure 1 Oxygenated versus de-oxygenated blood light absorption of IR and RED

Oximeter (medical device)
Light emission @660nm et @940 nm

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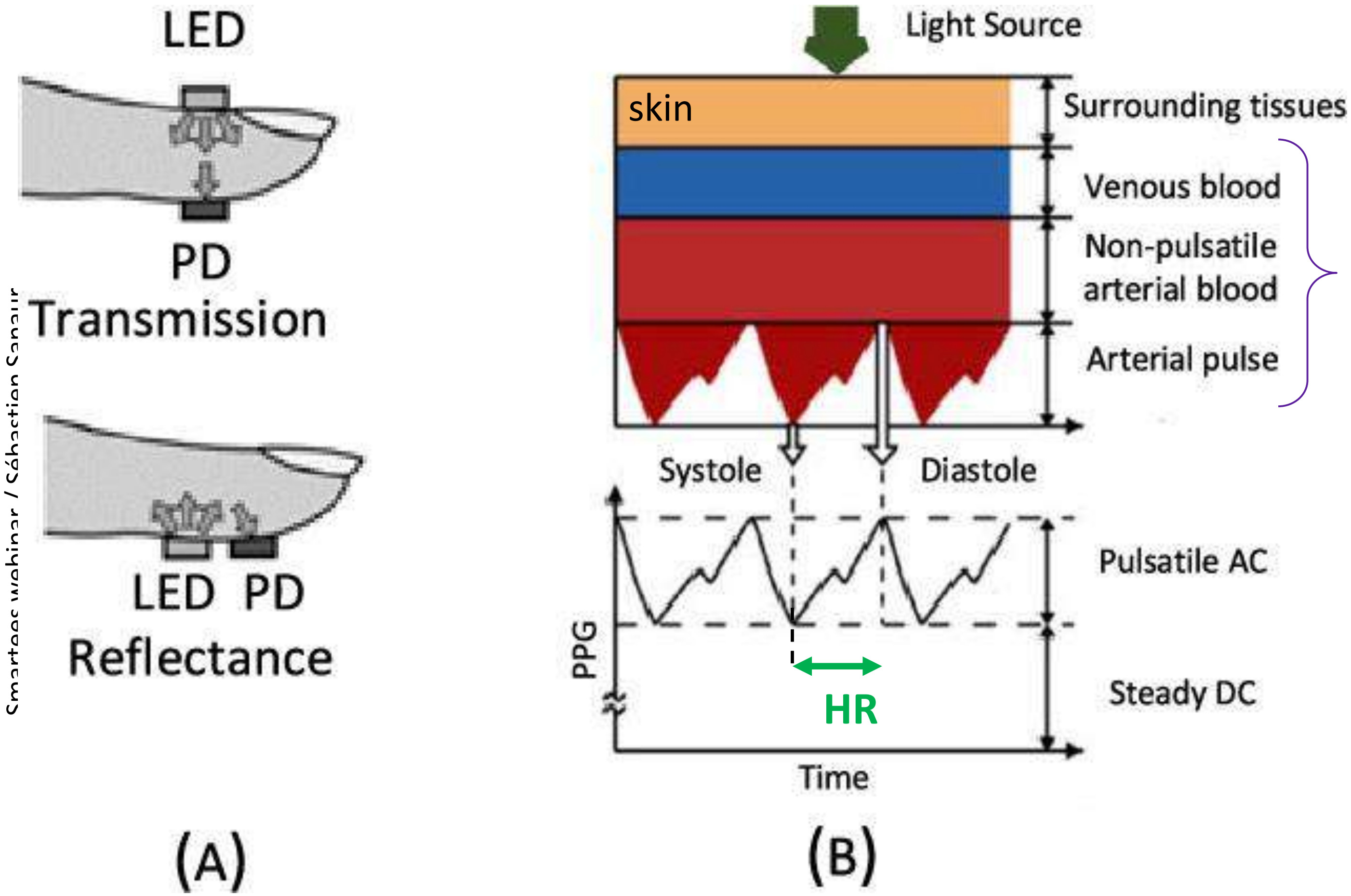
Oxymeter/ PhotoPlethysmoGraphy (PPG)



HR: Heart Rate

$$\frac{R}{IR} = \left(\frac{AC_R}{DC_R} \Big/ \frac{AC_{IR}}{DC_{IR}} \right)$$

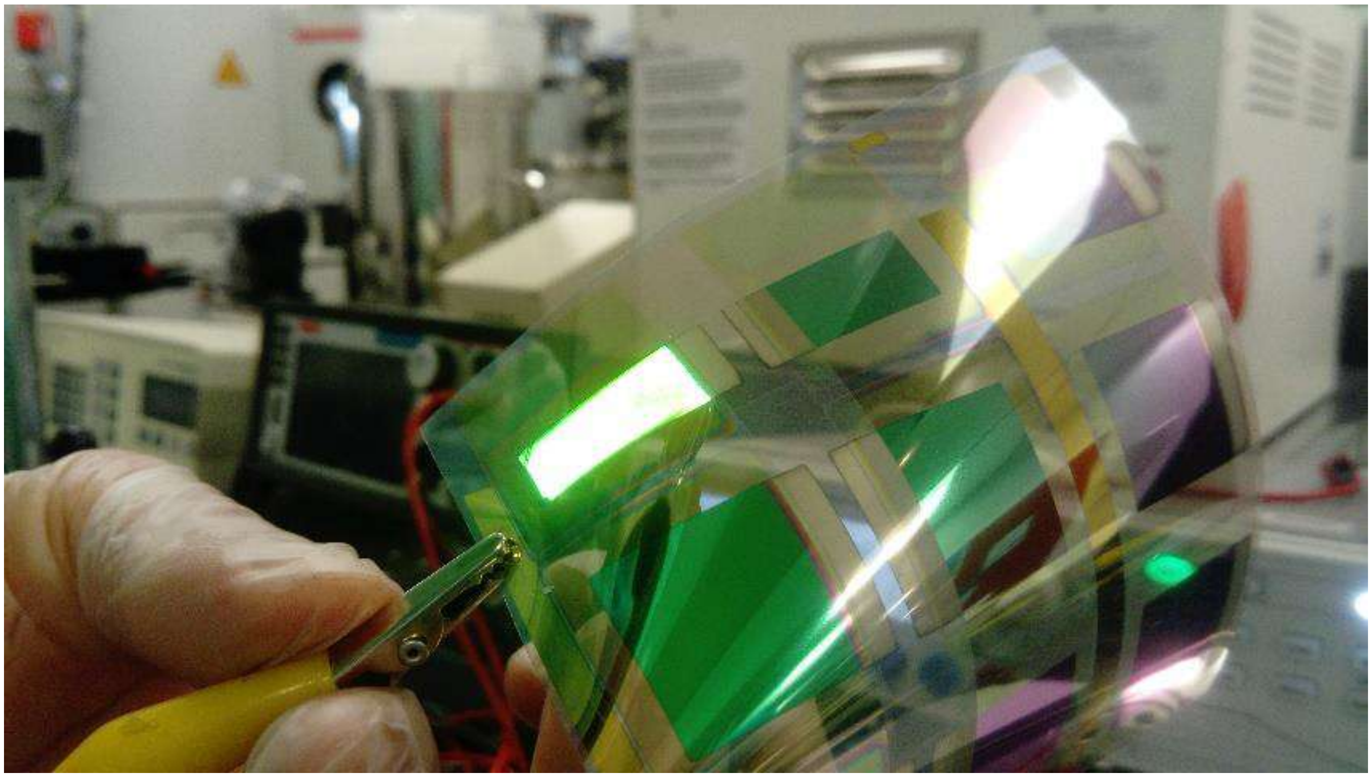
SpO_2, SaO_2,
Blood pressure,…

(A) Light-emitting diode (LED) and photodetector (PD) placement for transmission and reflectance-mode photoplethysmography (PPG). (B) Variation in light attenuation by tissue

Green OLEDs

With Coll. TECMOLED

PET or Glass substrate



adhesive
LiF / Al
ETL
HBL
EML
EBL
HTL (P doped)
ITO
glass or PET

Phosphorescence OLED based-structure

Flexible OLEDs

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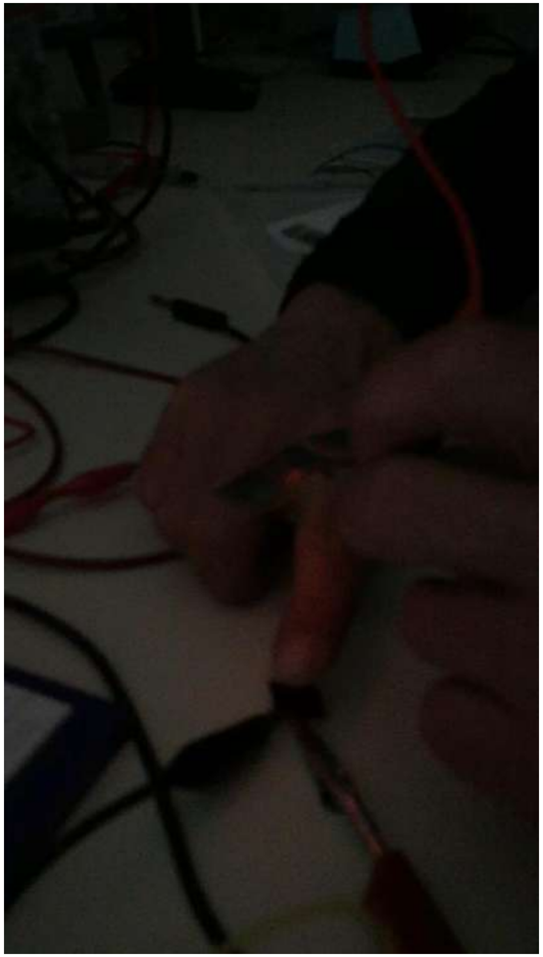
First test: OLED - OPD assembly through the skin

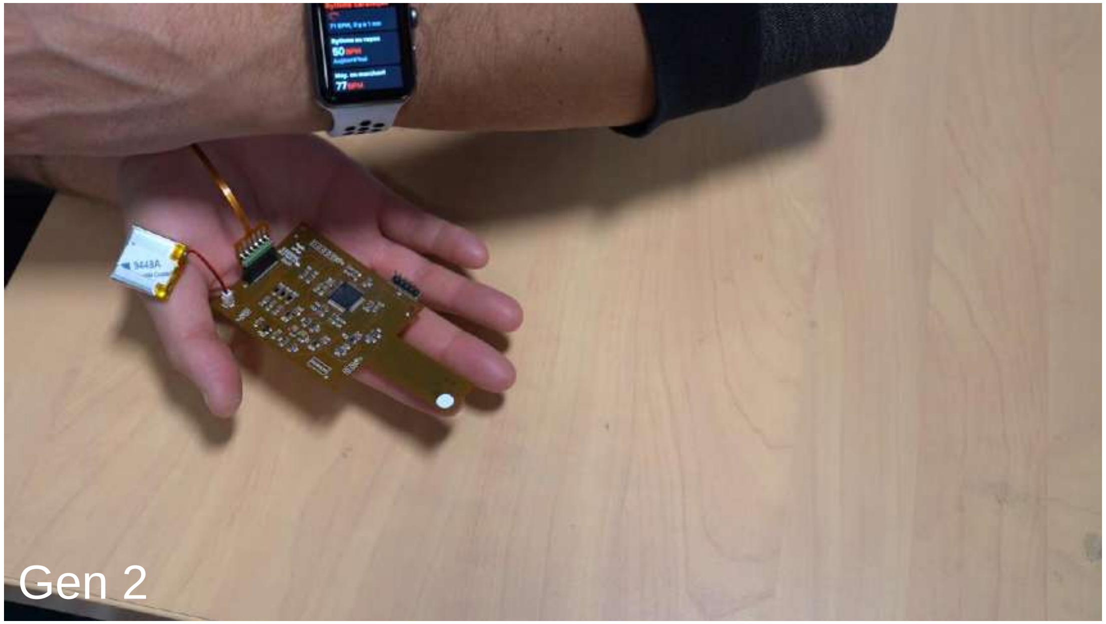


With coll. TECMOLED

MINES Saint-Étienne Une école de l'IMT

Acquisition card design & fabrication
Wireless data transmission

With coll. TECMOLED



Received data (BPM, SpO_2) by wireless.
Directly displayed on smartphone.

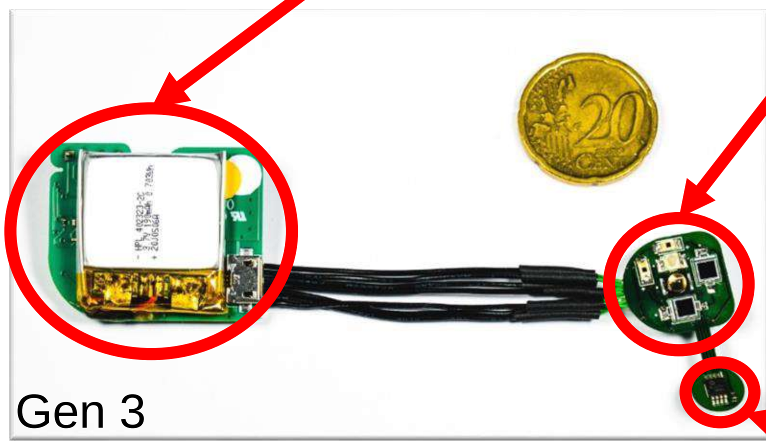
Acquisition card design & fabrication
Wireless data transmission

With coll. TECMOLED

LiPo battery.
USB connector charging.
Signal conditioning

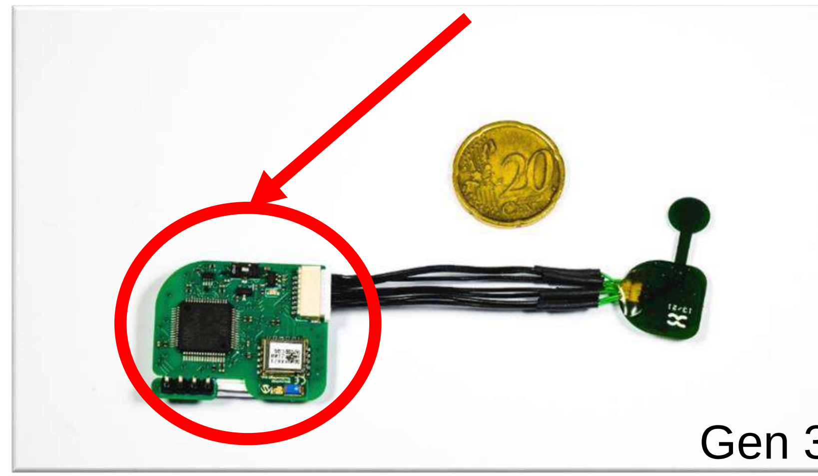
Optoelectronic sensors

Signal Processing.
Wireless transmission.
LEDs controller



Thermal sensor

Face side (in contact with skin)



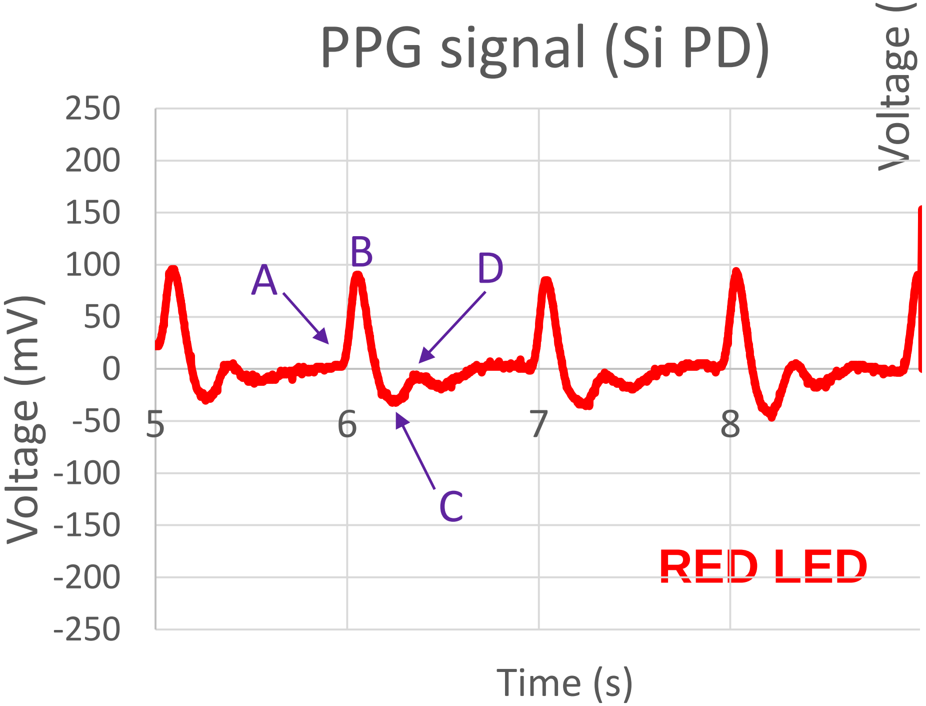
Reverse side

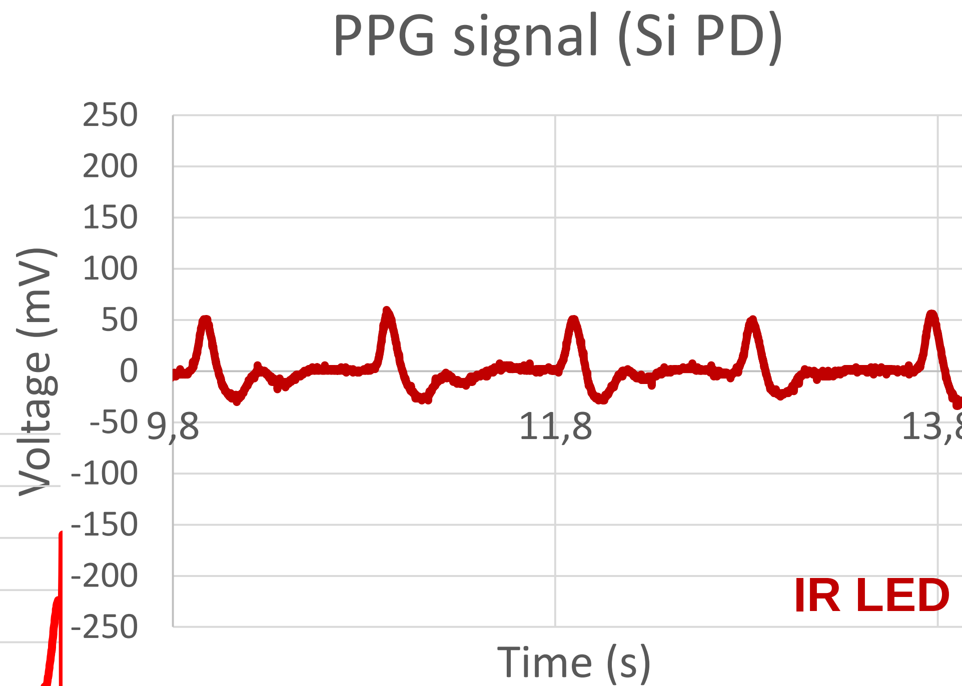
Received data (BPM, SpO_2) by wireless.
Directly displayed on smartphone.

Acquisition card design & fabrication
Wireless data transmission

With coll. TECMOLED

A: dicrotic point
B: systolic point
C: dicrotic notch
D: diastolic point





Wireless received data.
Display on smartphone.

Smartees webinar / Sébastien Sanaur

MINES Saint-Étienne
Une école de l'IMT

Conclusion & Perspectives

- **Inkjet Printing:**
  - for « pixelated » planar devices (i.e 25 x 25 µm² → 500 x 500 µm²),
  - short time between design and fabrication,
  - personalized applications (smart medical patches,…).

- **Devices**
  - Ultra-flexible OTFTs & OECTs (low voltage operation),
  - Skin-cutaneous electrophysiological MEAs (sEMG, ECG, blood oxymetry).

- **Perspectives**
  - Skin-wearables,
  - Readout printed electronics
  - Monolithic integration, compact devices/ circuits

Thank you for your kind attention

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Partnership Contract:

TECMOLED

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