Organic Electrochemical Transistors for Biological Interfacing

Christopher Proctor, George Malliaras
Electrical Engineering Division, University of Cambridge
Electrical recording for epilepsy monitoring

- Affects 1-2% of world population
- Temporal lobe epilepsy (TLE) is most frequent form in adults
- TLE is often drug resistant

Key challenges:
- Improve electrode performance
- Make less invasive recordings
Transistor vs. electrode

Transistor recordings offer higher SNR
Recording neural activity with transistors


Fromherz group, MPI
The organic electrochemical transistor (OECT)

No insulator between channel and electrolyte

Different types of transistors

Volumetric ion transport in PEDOT:PSS

For $d=130$ nm:
$C' \sim 500 \, \mu\text{F/cm}^2$

100× larger than double layer capacitance

Characteristics of PEDOT:PSS OECTs


100x higher than Si transistors
Field-effect vs electrochemical transistor

In vivo recordings using transistors

w/ Christophe Bernard (INSERM)

Transistors enable less invasive recordings

Balance between electronic and ionic transport

$g_m^{SAT} = \frac{W \cdot d/L}{L} \cdot \mu \cdot C^* \cdot (V_T - V_G)$

$\mu \cdot C^*$ of different materials

Double layer capacitance

Capacitance of double layer:

$$C_{DL} = \varepsilon \cdot \varepsilon_0 \cdot A / t$$

Capacitance per unit area:

$$C_{DL}' = C_{DL} / A = \varepsilon \cdot \varepsilon_0 / t$$

$$C_{DL}' \sim 1-10 \ \mu F/cm^2$$
How do we envision this process in PEDOT:PSS?
What does volumetric capacitance mean?

N double layer capacitors in parallel

Where \( N = \frac{L}{\alpha} \)

\[
C = N \cdot C_{DL} = N \cdot \varepsilon \cdot \varepsilon_0 \cdot A/t \Rightarrow 
\]

\[
C^* = \frac{C_{DL}'}{\alpha} 
\]

What values of \( C^* \) do we expect?

\[
C^* = \frac{C_{DL'}}{\alpha}
\]

For flat organic electrodes (HOPG, PPR): \( C_{DL'} = 1-10 \text{ \( \mu \)F/cm}^2 \)

Site density in PEDOT:PSS: \( 1.9 \cdot 10^{20} \text{ cm}^{-3} \)

Average distance between sites: \( \alpha \sim 1.8 \text{ nm} \)

\[
C^* = \frac{C_{DL'}}{\alpha} \sim 6-60 \text{ F/cm}^3
\]

Experimental value within this range!

Denser polymer: values up to 200 F/cm^3

μ·C* of different materials

Molecular engineering of ion injection

w/ Iain McCulloch (Imperial/KAUST), Jonathan Rivnay (Northwestern)

Conclusions

- Organic electrochemical transistors are amplifying transducers. They yield neural recordings with better signal-to-noise ratio than electrodes. They allow to look deeper in the brain.

- PEDOT:PSS is a champion material as it offers high hole mobility coupled with facile ion injection and transport.

- Materials requirements:
  - High electronic carrier mobility
  - High volumetric capacitance

- A winning strategy: efficient π-conjugated backbones with hydrophilic side chains

Acknowledgements

University of Cambridge
Bioelectronics Laboratory
Vincenzo Curto
Christopher Proctor
Alexandra Rutz
Ana Sanchez
Alej Carnicer-Lombarte
Anastasios Polyavras
Tanya Mangoma
Monica Miranda Mugica
Estibaliz Garcia Gaitan
Professor George Malliaras

Ecole des Mines de St. Etienne
Mary Donahue
Esma Ismailova
Rodney O’Connor

Aix Marseille University
Adam Williamson
Pascale Quilichini
Christophe Bernard

KAUST
Sahika Inal
Iain McCulloch

Northwestern University
Jonathan Rivnay

Other collaborators
Dion Khodagholy (Columbia)
Takao Someya (Tokyo)
Georges Hadziioannou (Bordeaux)
High transconductance means high SNR


w/ Christian Benar, Jean-Michel Badier (INSERM)
The human brain contains 100 billion neurons, organized in networks. Their communication holds the key for understanding how the brain works. These networks can be rewired by diseases such as epilepsy, Parkinson’s, ... Cost of neurological disease in the US is $800 billion/year.

Importance of neural interfacing

EEG
ECoG
SEEG

Na⁺, K⁺

Nucleus
Axon
Synapse
Dendrites
Cell body

From Laurent Perrin and Thierry Viéville, "Biologie et civilisation: les chemins de l'intelligence"
OECT figure of merit

\[ g_m^{SAT} = \left( \frac{W \cdot d}{L} \right) \cdot \mu \cdot C^* \cdot (V_T - V_G) \]

Why organics?

Mixed conductivity leads to novel/state-of-the-art devices

Outline

- Importance of neural interfacing
- Organic electrochemical transistors (OECTs)
- Polymer design for OECTs
  - Balance between ionic and electronic transport
  - How can we do better?
- Conclusions