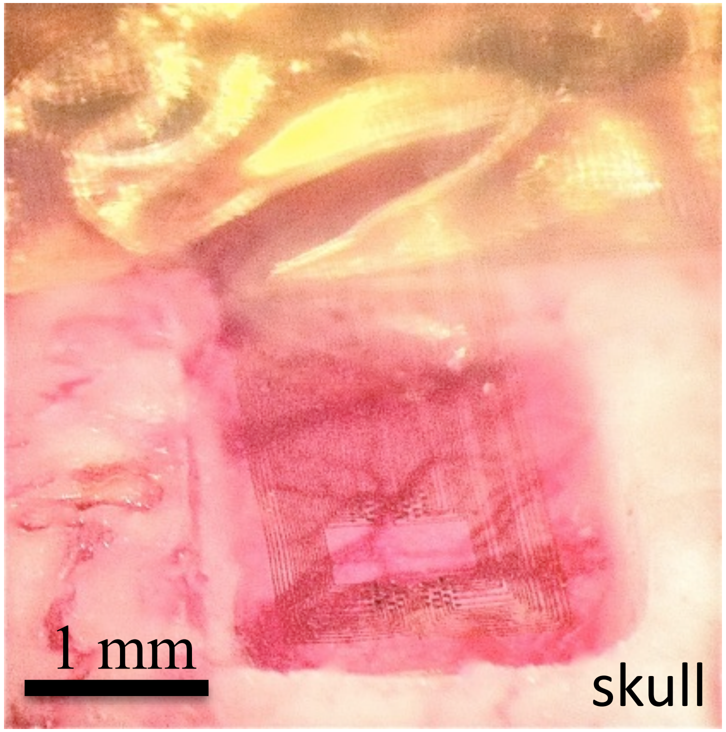
Organic Electrochemical Transistors for Biological Interfacing



Christopher Proctor, George Malliaras

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Department of Engineering

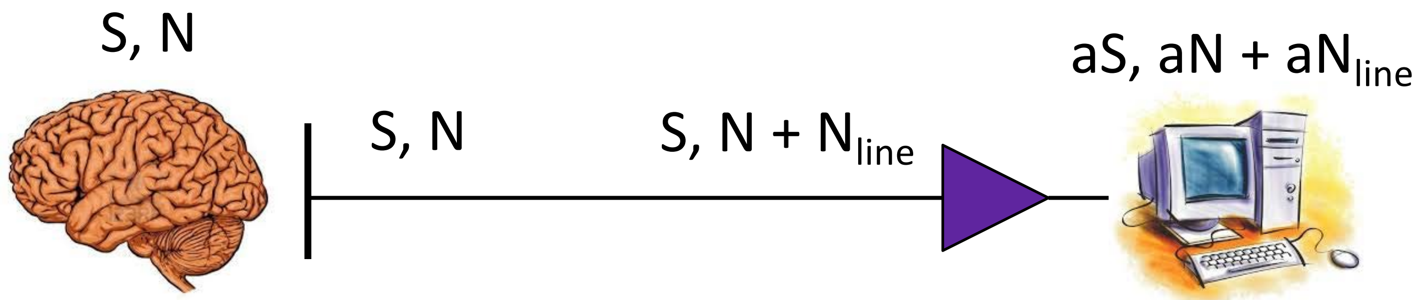
Electrical recording for epilepsy monitoring

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

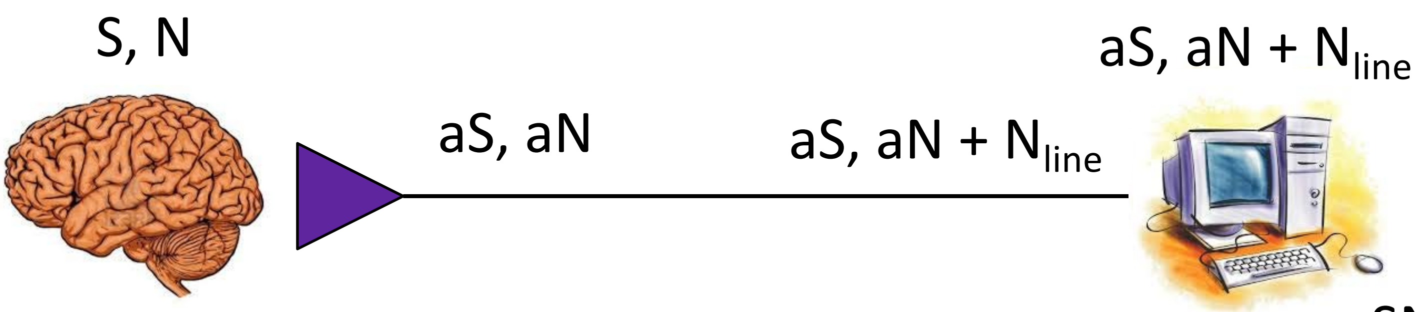
Key challenges:

- Improve electrode performance
- Make less invasive recordings

Transistor vs. electrode



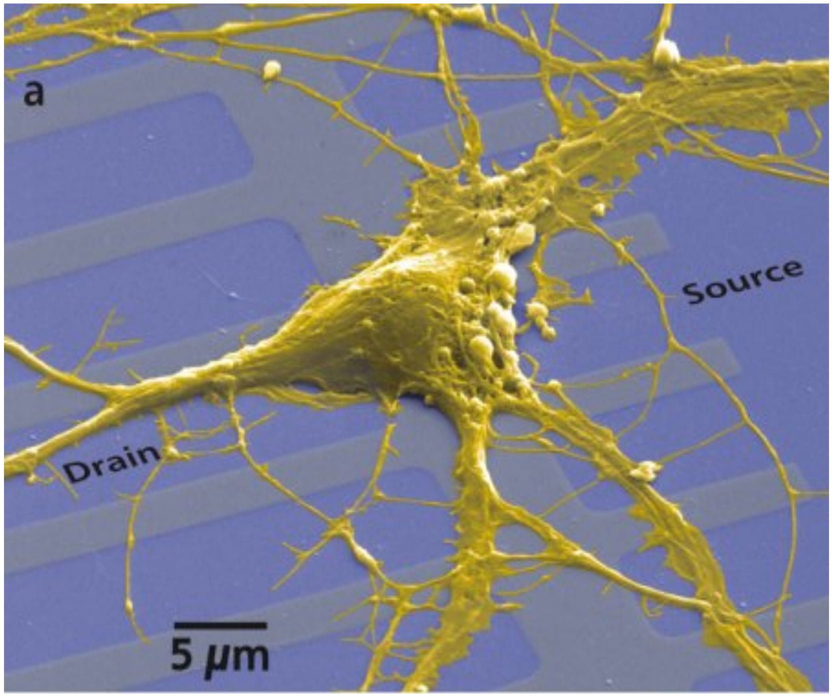
$$\text{SNR} = \frac{aS}{aN + aN_{line}}$$

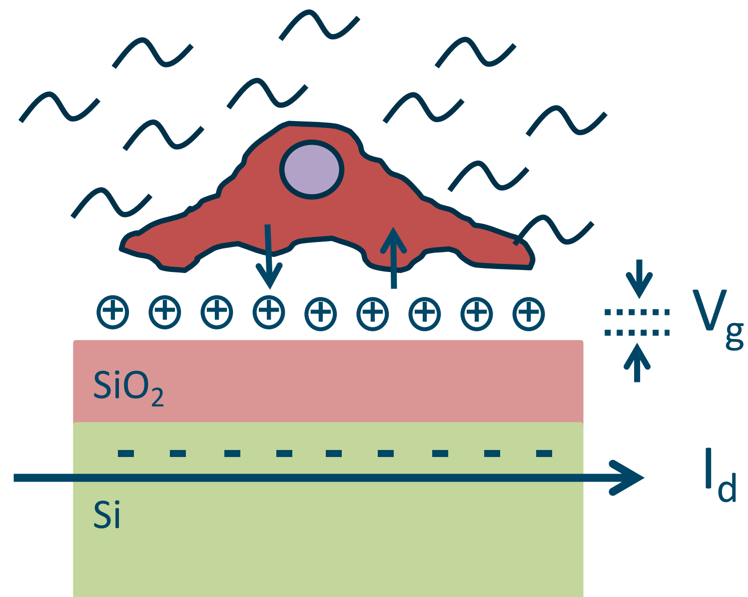


$$\text{SNR} = \frac{aS}{aN + N_{line}}$$

Transistor recordings offer higher SNR

Recording neural activity with transistors

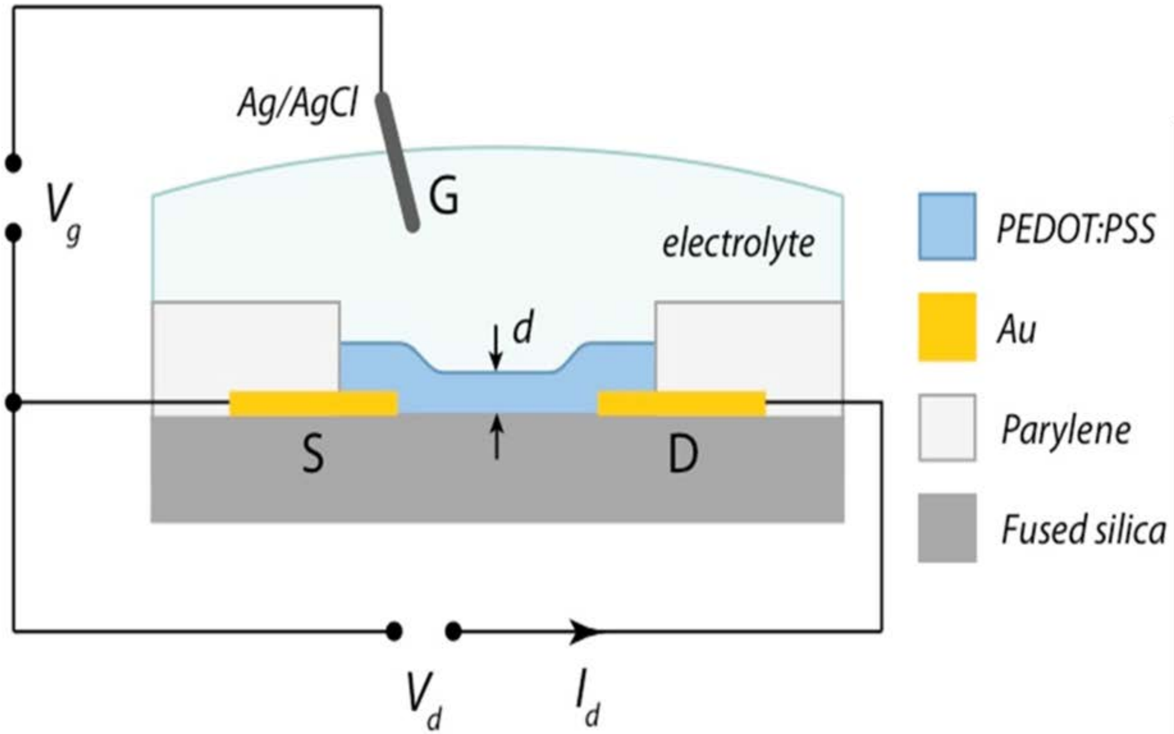




Fromherz group, MPI

Review: M. Voelker and P. Fromherz, *Small* 1, 206 (2005).

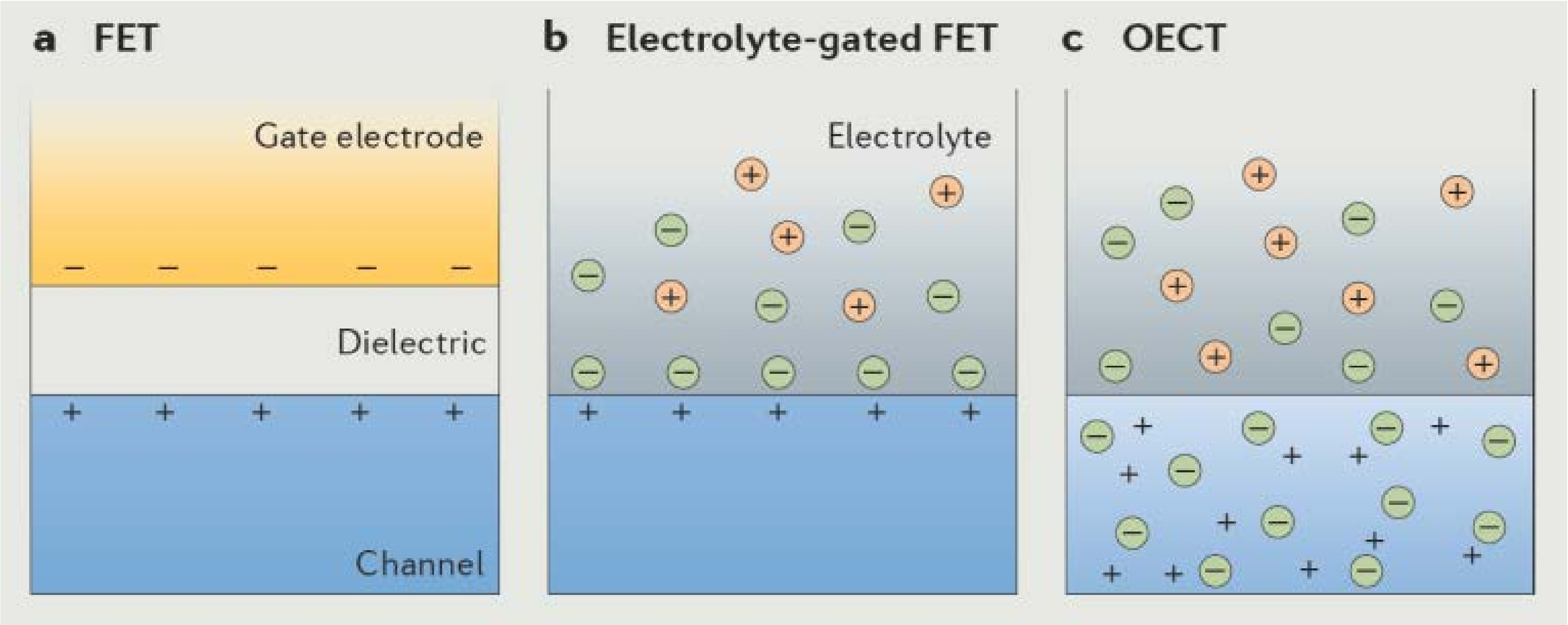
The organic electrochemical transistor (OECT)



No insulator between channel and electrolyte

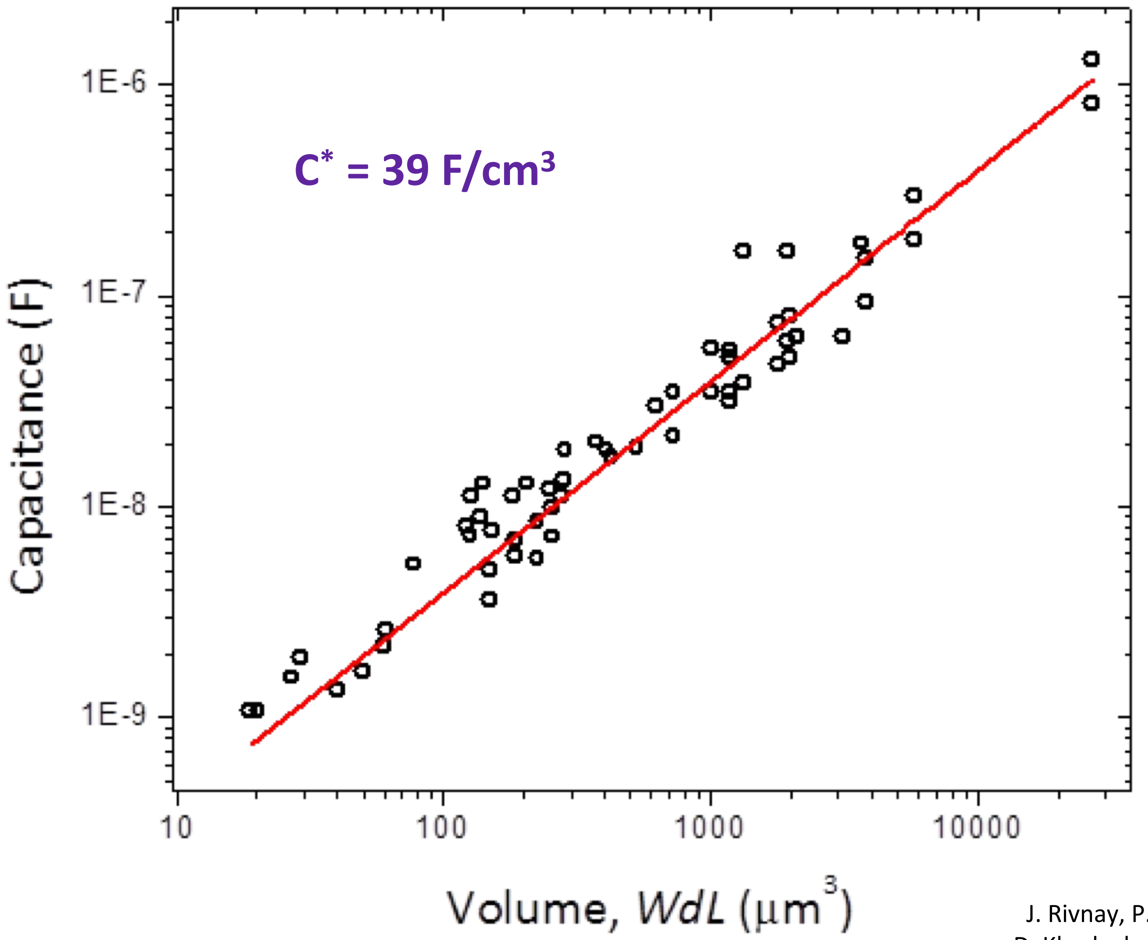
First OECT: H.S. White, G.P. Kittlesen, and M.S. Wrighton, *J. Am. Chem. Soc*. 106, 5375 (1984).

Different types of transistors



J. Rivnay, S. Inal, A. Salleo, R.M. Owens, M. Berggren, and G.G. Malliaras, *Nature Rev. Mater.* 3, 17086 (2018).

Volumetric ion transport in PEDOT:PSS

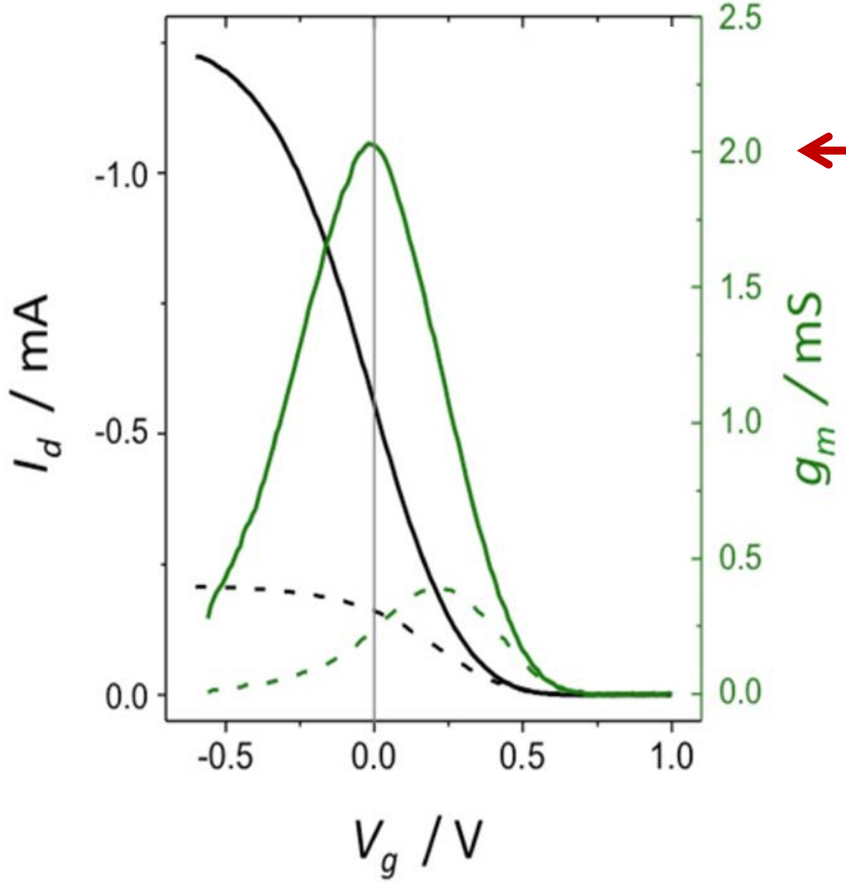


For d=130 nm:
C′ ~ 500 μF/cm²

100× larger than
double layer capacitance

J. Rivnay, P. Leleux, M. Ferro, M. Sessolo, A. Williamson, D.A. Koutsouras, D. Khodagholy, M. Ramuz, X. Strakosas, R.M. Owens, C. Benar, J.-M. Badier, C. Bernard, and G.G. Malliaras, *Science Advances* 1, e1400251 (2015).

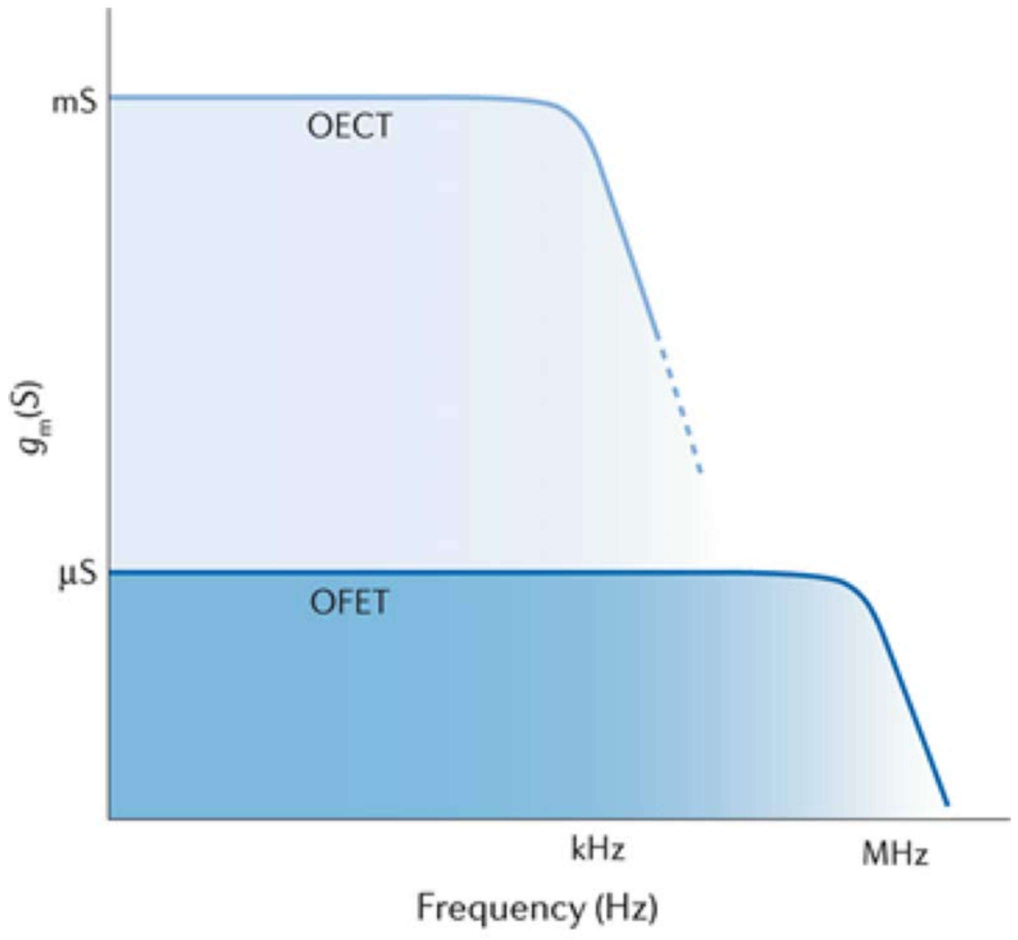
Characteristics of PEDOT:PSS OECTs



100× higher than Si transistors

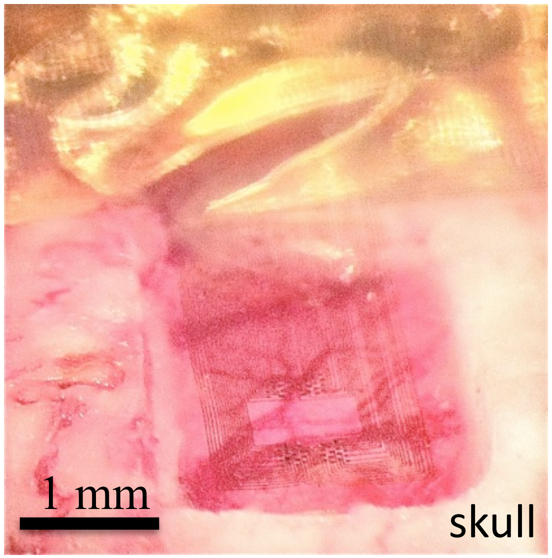
D. Khodagholy, J. Rivnay, M. Sessolo, M. Gurfinkel, P. Leleux, L.H. Jimison, E. Stavrinidou, T. Herve, S. Sanaur, R.M. Owens, and G.G. Malliaras, *Nature Comm.* 4, 2133 (2013).

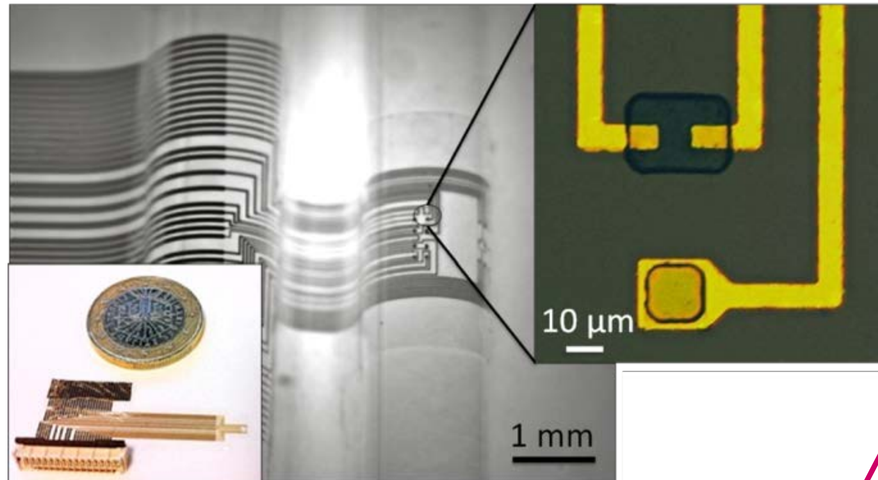
Field-effect vs electrochemical transistor

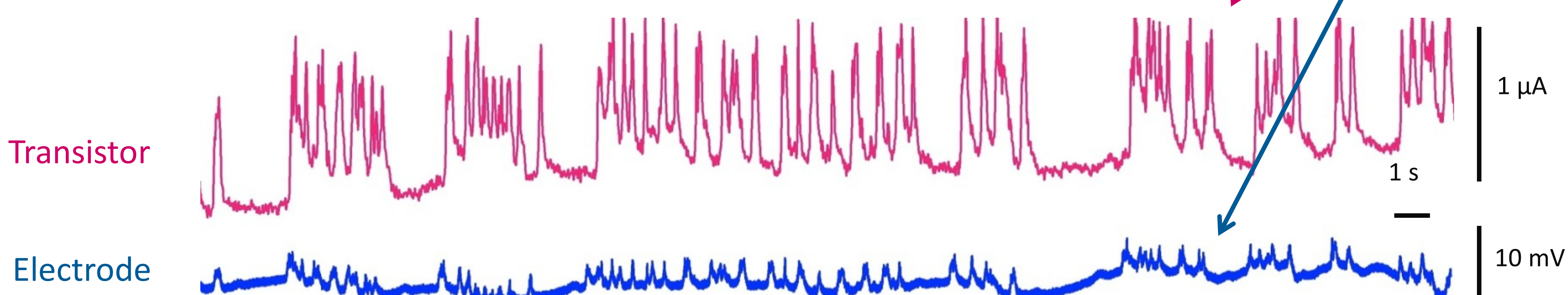


J. Rivnay, S. Inal, A. Salleo, R.M. Owens, M. Berggren, and G.G. Malliaras, *Nature Rev. Mater.* 3, 17086 (2018).

In vivo recordings using transistors







w/ Christophe Bernard (INSERM)

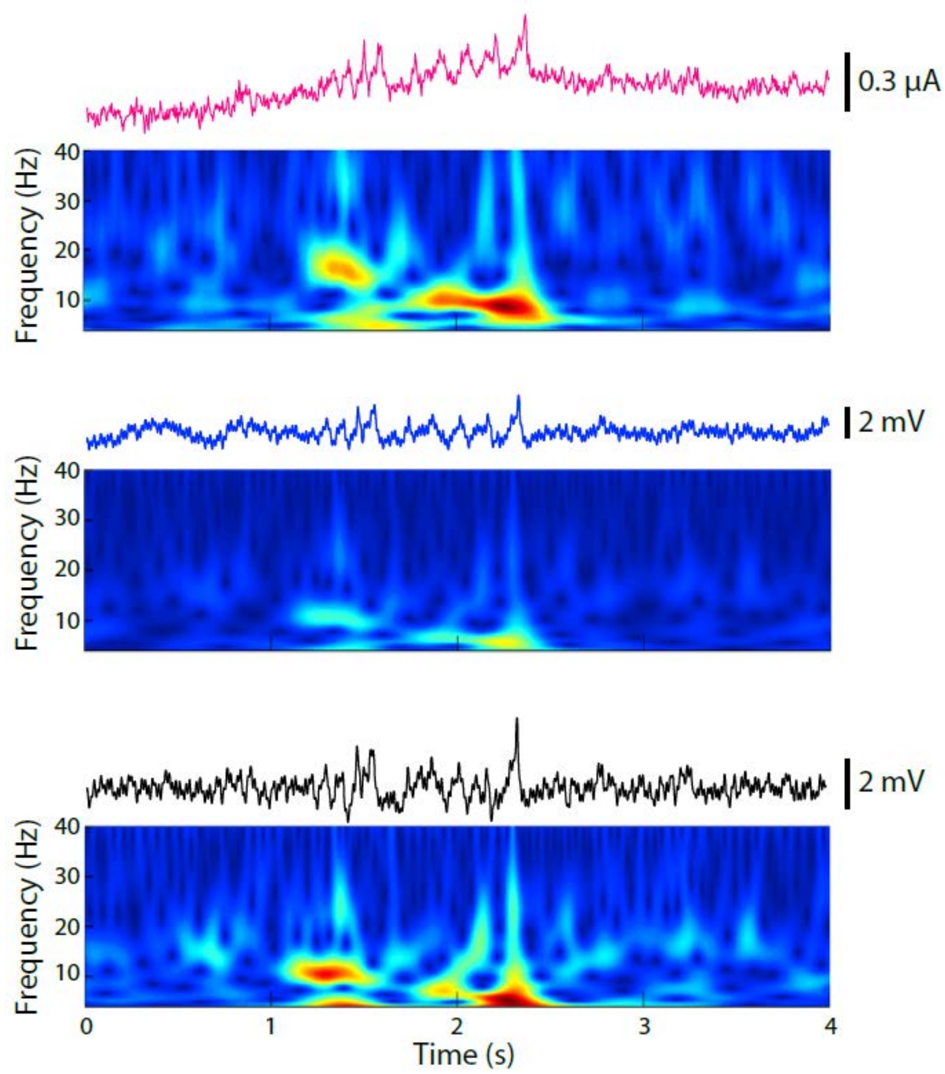
D. Khodagholy, T. Doublet, P. Quilichini, M. Gurfinkel, P. Leleux, A. Ghestem, E. Ismailova, T. Herve, S. Sanaur, C. Bernard, and G.G. Malliaras , *Nature Comm.* 4, 1575 (2013).

Transistors enable less invasive recordings

Transistor

Surface electrode

Depth electrode



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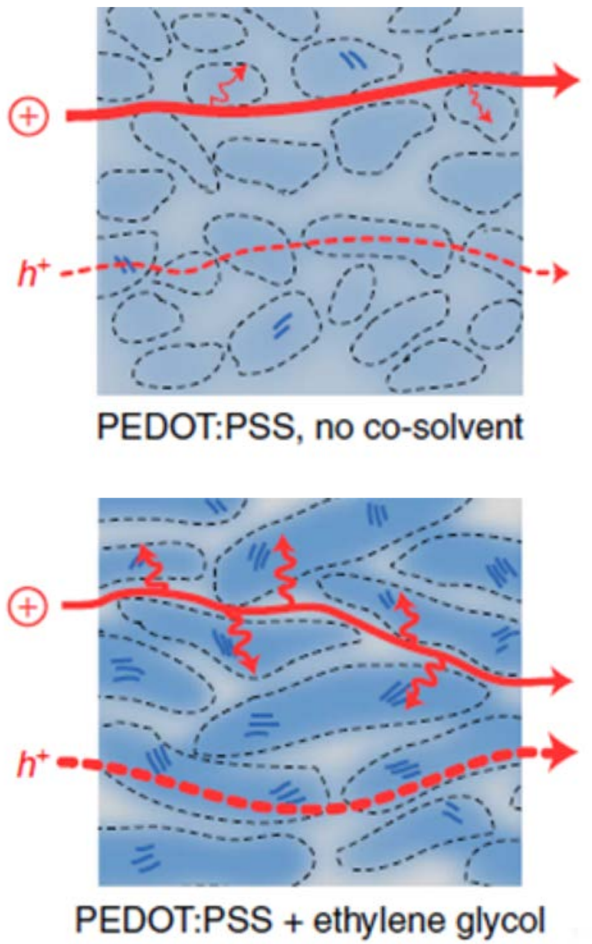
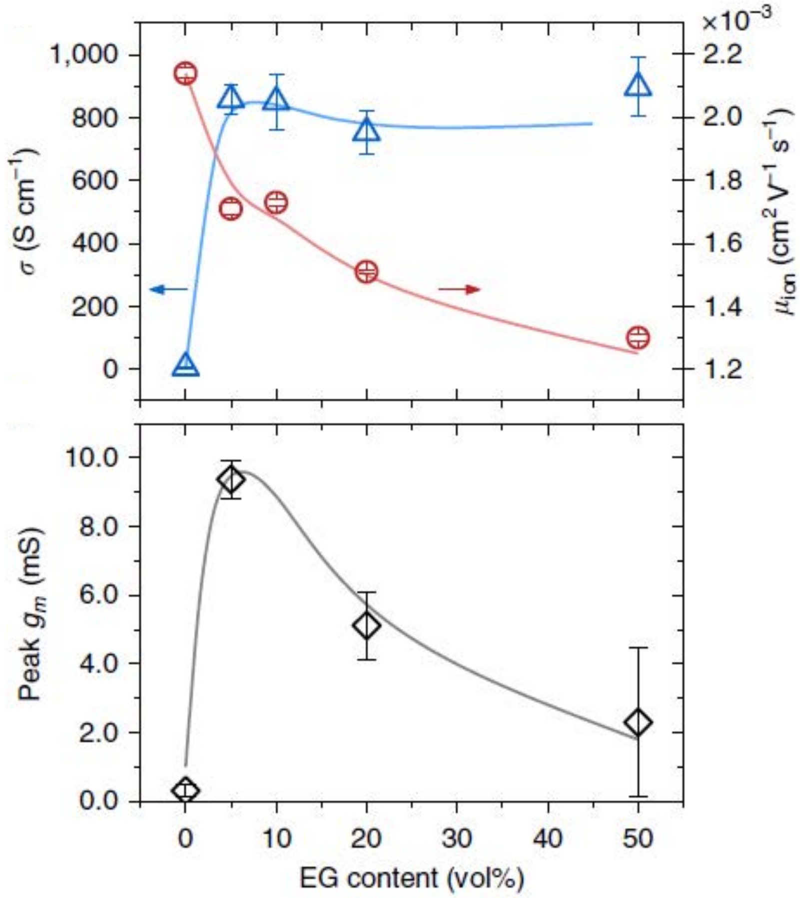
Balance between electronic and ionic transport

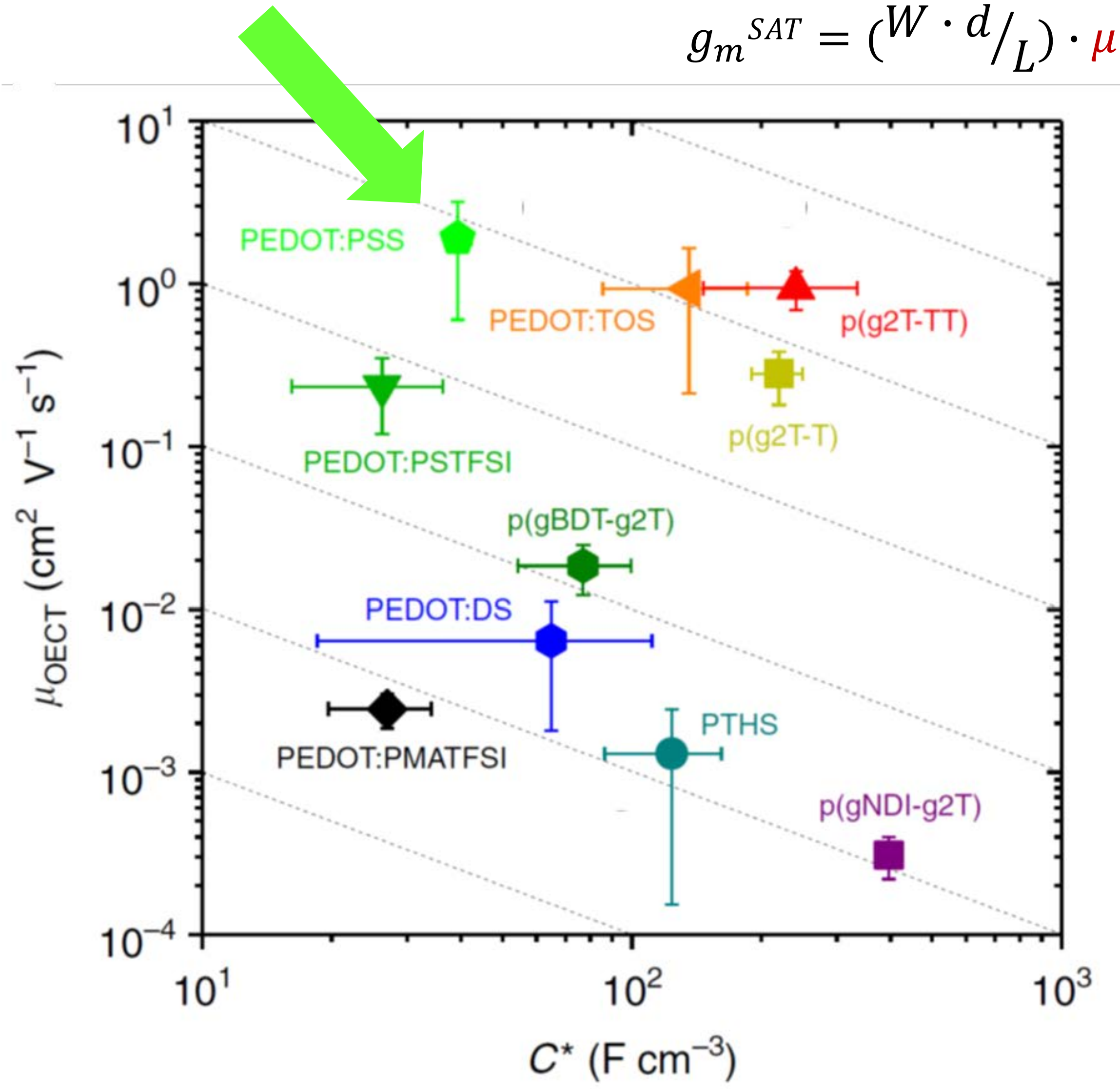




J. Rivnay, S. Inal, B.A. Collins, M. Sessolo, E. Stavrinidou, X. Strakosas, C. Tassone, D.M. Delongchamp, and G.G. Malliaras, *Nature Comm.* 7, 11287 (2016).

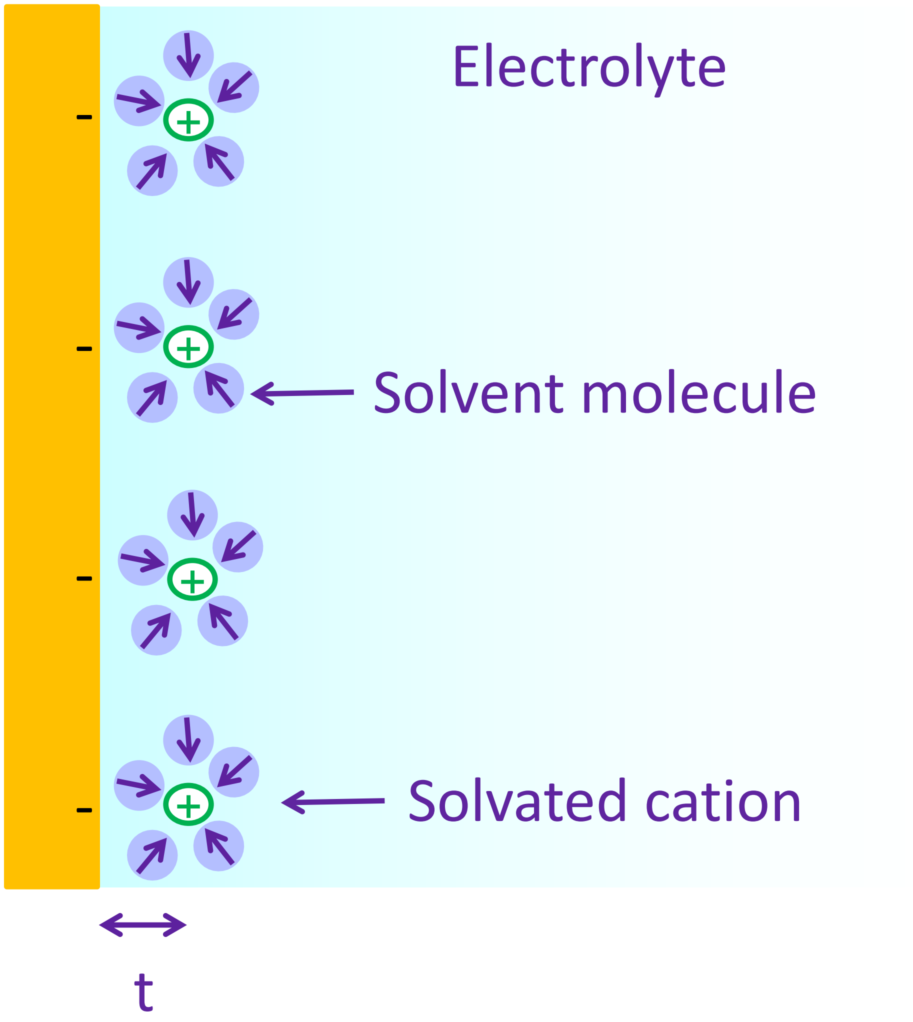
$\mu \cdot C^*$ of different materials

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



S. Inal, G.G. Malliaras, and J. Rivnay, *Nature Comm.* 8, 1767 (2017).

Double layer capacitance



Capacitance of double layer:

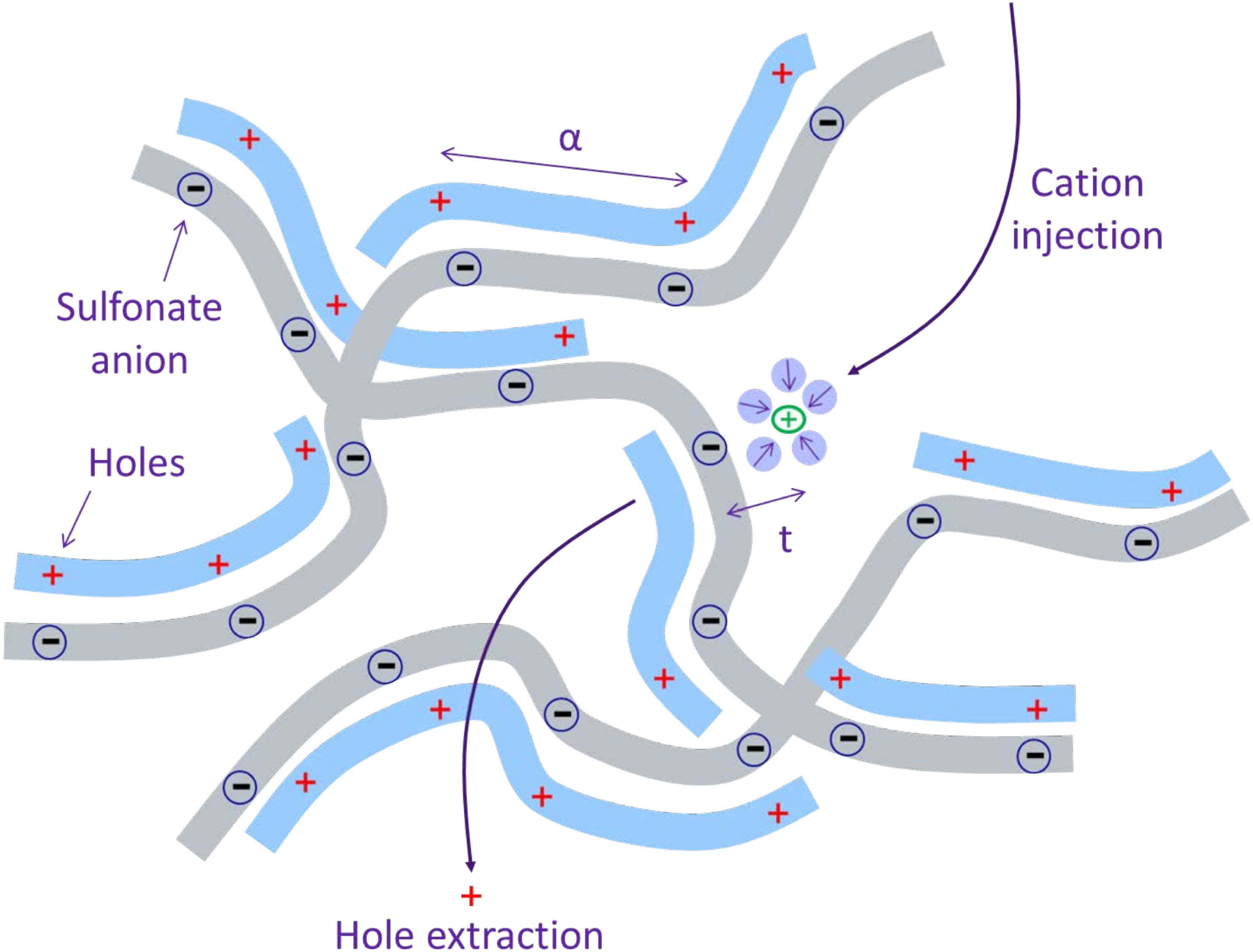
$$C_{DL} = \varepsilon \cdot \varepsilon_0 \cdot A/t$$

Capacitance per unit area:

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

$C_{DL}' \sim 1\text{-}10\ \mu F/cm^2$

How do we envision this process in PEDOT:PSS?



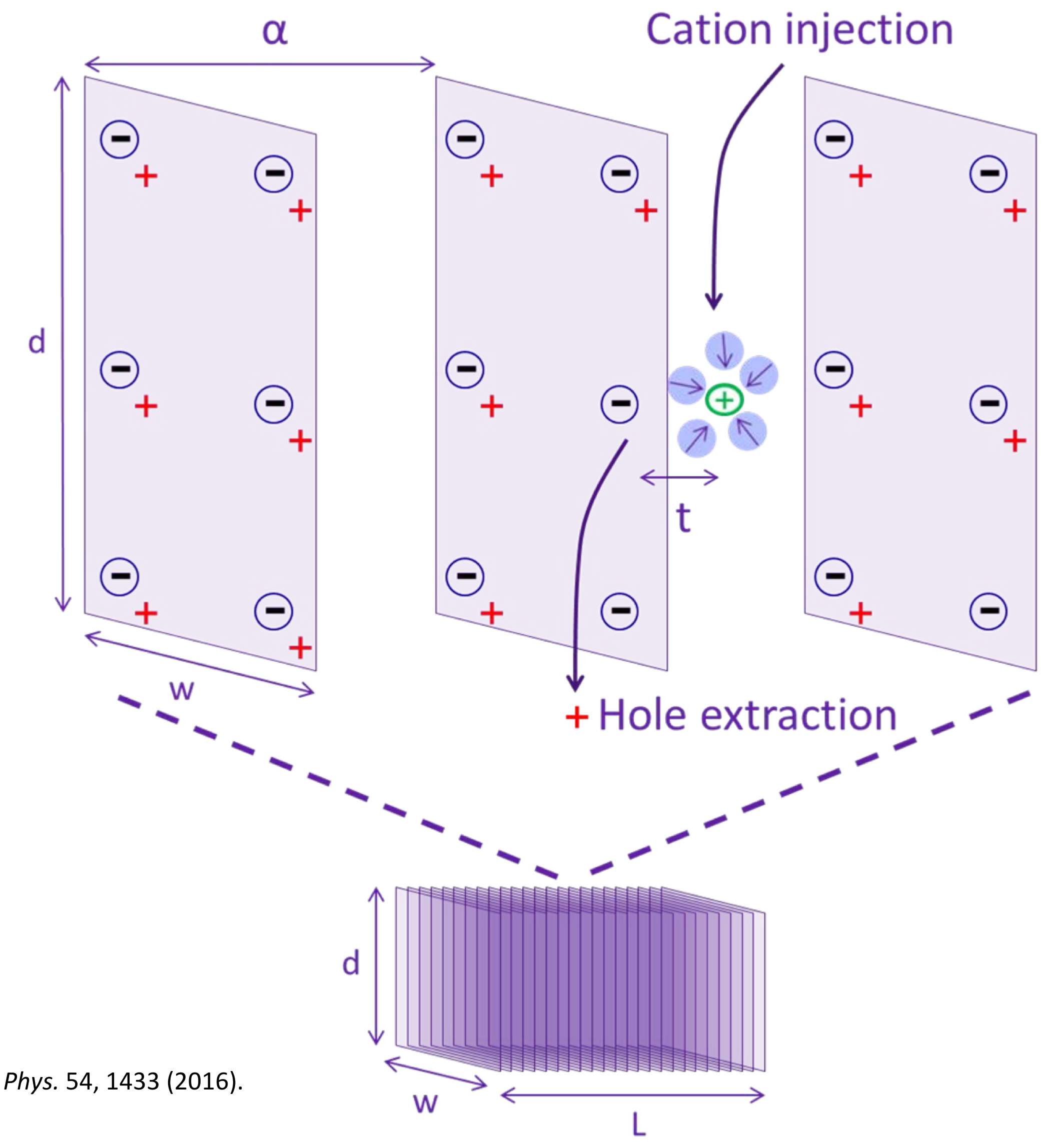
What does volumetric capacitance mean?

N double layer capacitors
in parallel

Where $N = L/\alpha$

$$C = N \cdot C_{DL} = N \cdot \varepsilon \cdot \varepsilon_0 \cdot A/t \;=>$$

$$C^* = C_{DL}'/\alpha$$



C. Proctor, J. Rivnay, and G.G. Malliaras, *J. Polym. Sci., Part B: Polym. Phys.* 54, 1433 (2016).

What values of C^* do we expect?

$C^* = C_{DL}'/\alpha$

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

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

Average distance between sites: $\alpha \sim 1.8\ nm$

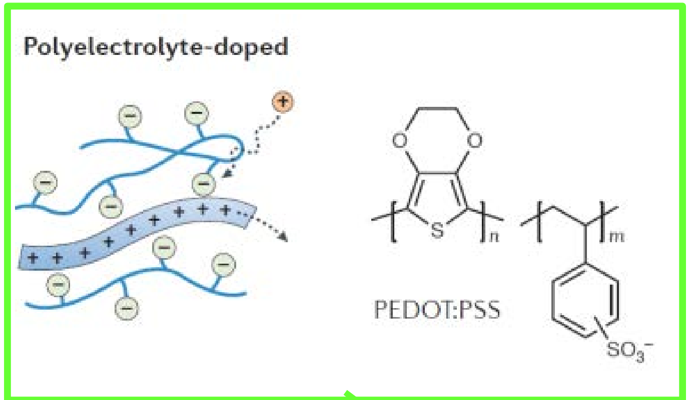
$C^* = C_{DL}'/\alpha \sim 6\text{-}60\ F/cm^3$

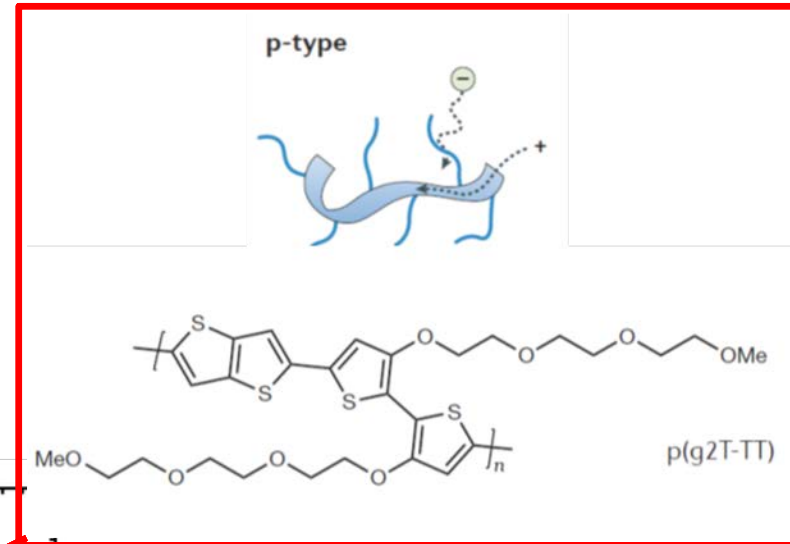
Experimental value within this range!

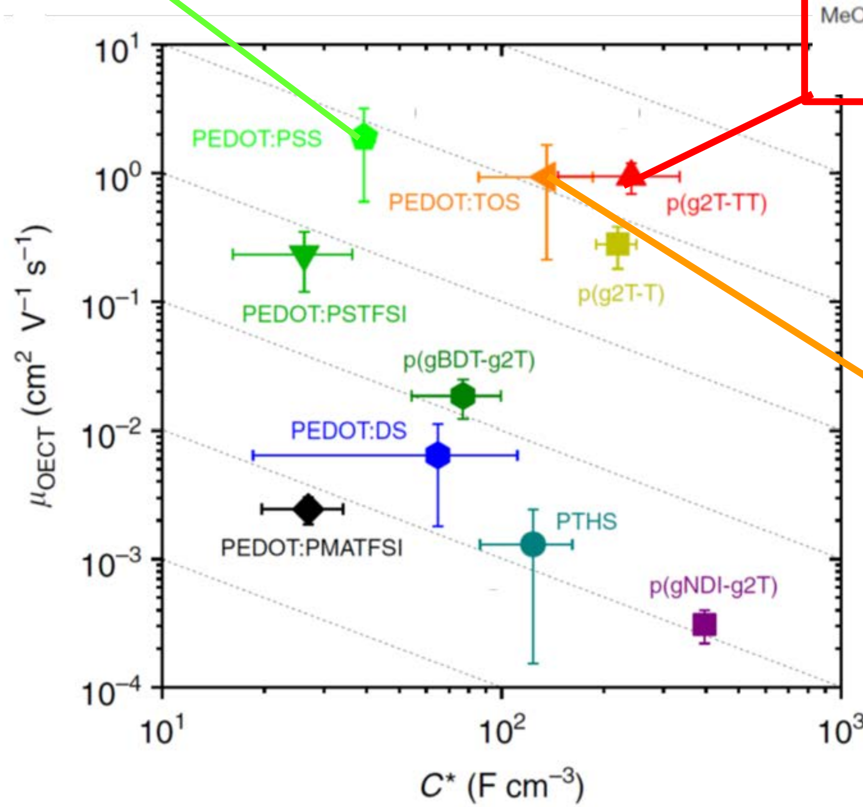
Denser polymer: values up to 200 F/cm^3

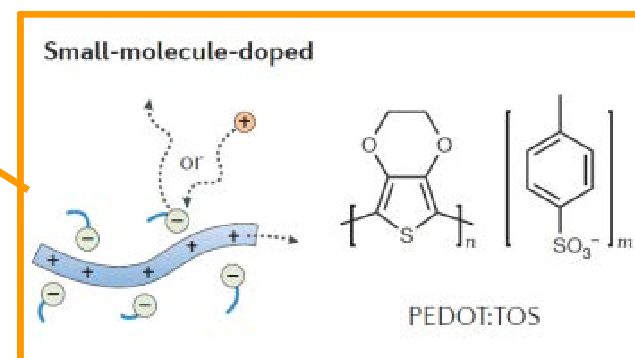
C. Proctor, J. Rivnay, and G.G. Malliaras, *J. Polym. Sci., Part B: Polym. Phys.* 54, 1433 (2016).

μ·C* of different materials



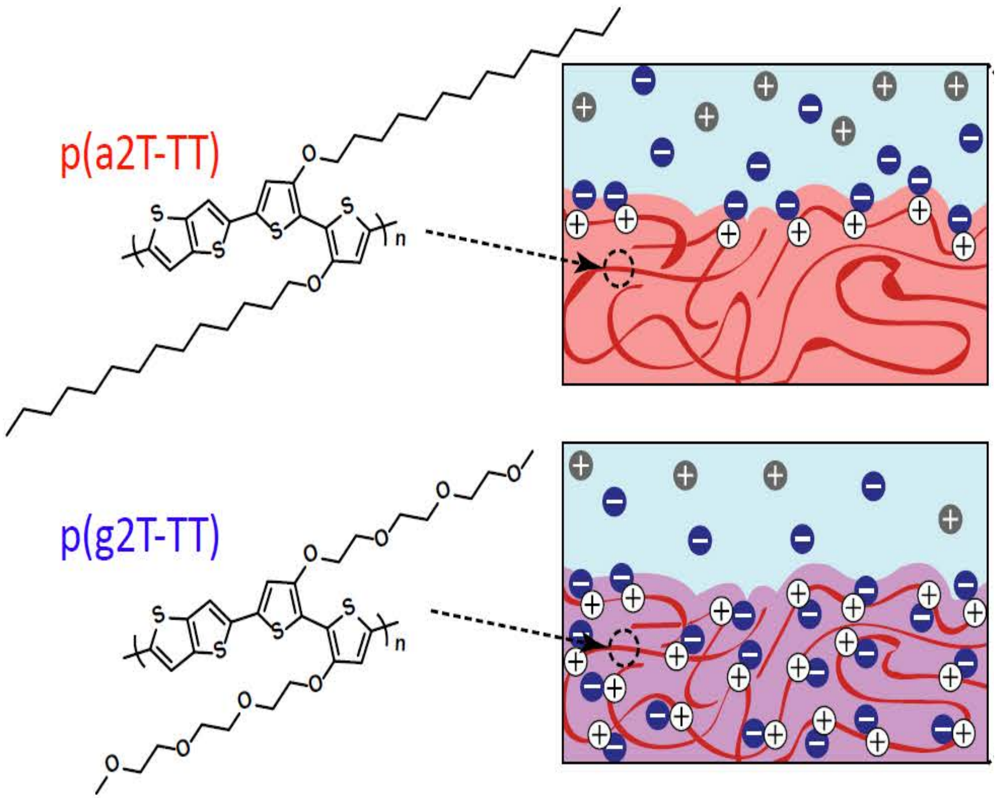


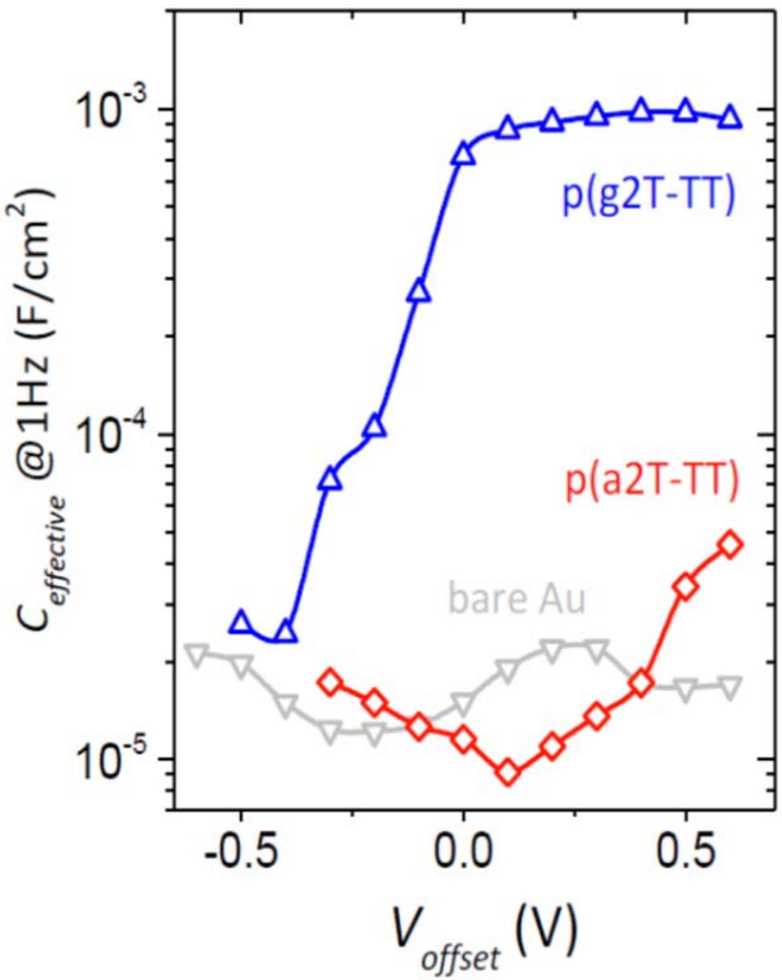




S. Inal, G.G. Malliaras, and J. Rivnay, *Nature Comm.* 8, 1767 (2017).

Molecular engineering of ion injection





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

A. Giovannitti, D.R. Sbircea, S. Inal, C.B. Nielsen, E. Bandiello, D.A. Hanifi, M. Sessolo, G.G. Malliaras, I. McCulloch, J. Rivnay, *PNAS* 113, 12017 (2016).

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**

Recent review: J. Rivnay, S. Inal, A. Salleo, R.M. Owens, M. Berggren, and G.G. Malliaras, *Nature Rev. Mater.* 3, 17086 (2018).

Acknowledgements

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Adam Williamson
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Christophe Bernard

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Northwestern University
Jonathan Rivnay

Other collaborators
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Takao Someya (Tokyo)
Georges Hadziioannou (Bordeaux)

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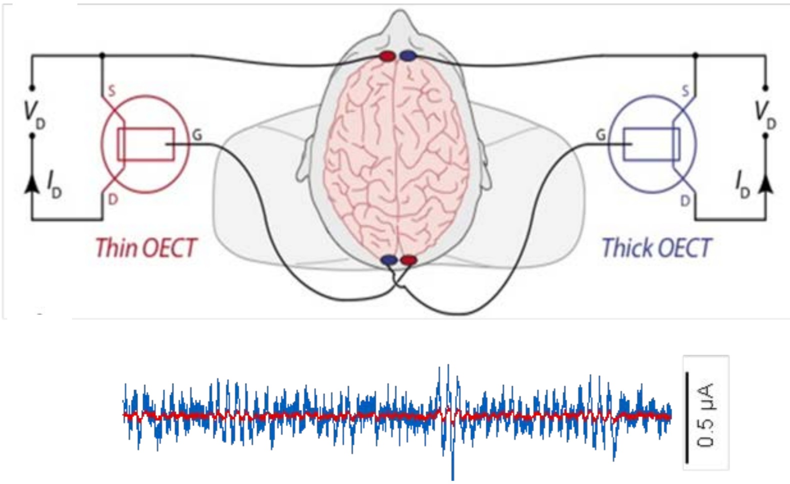
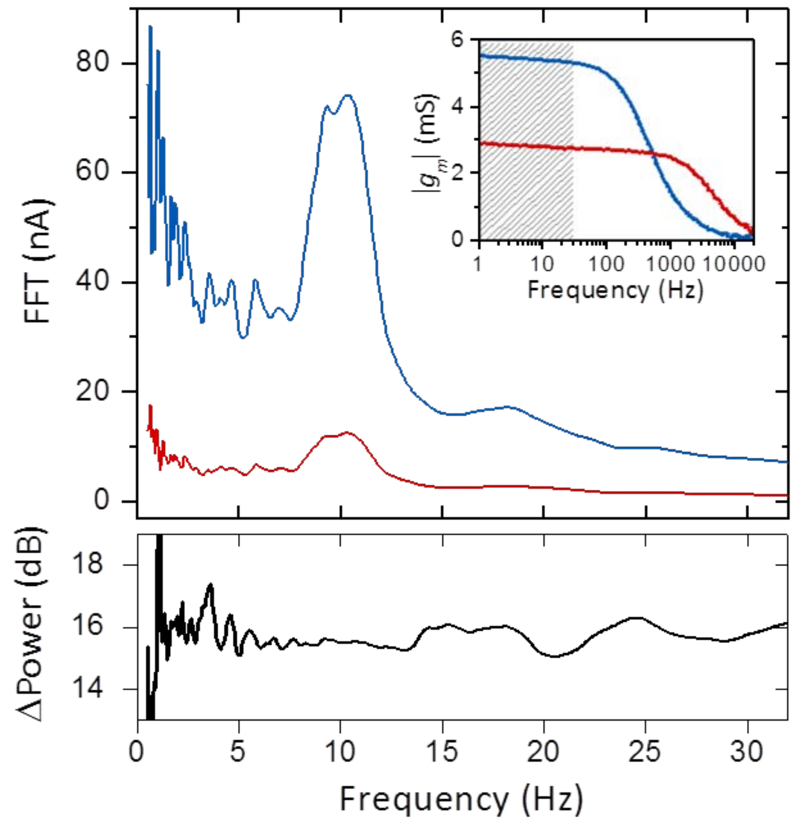
High transconductance means high SNR





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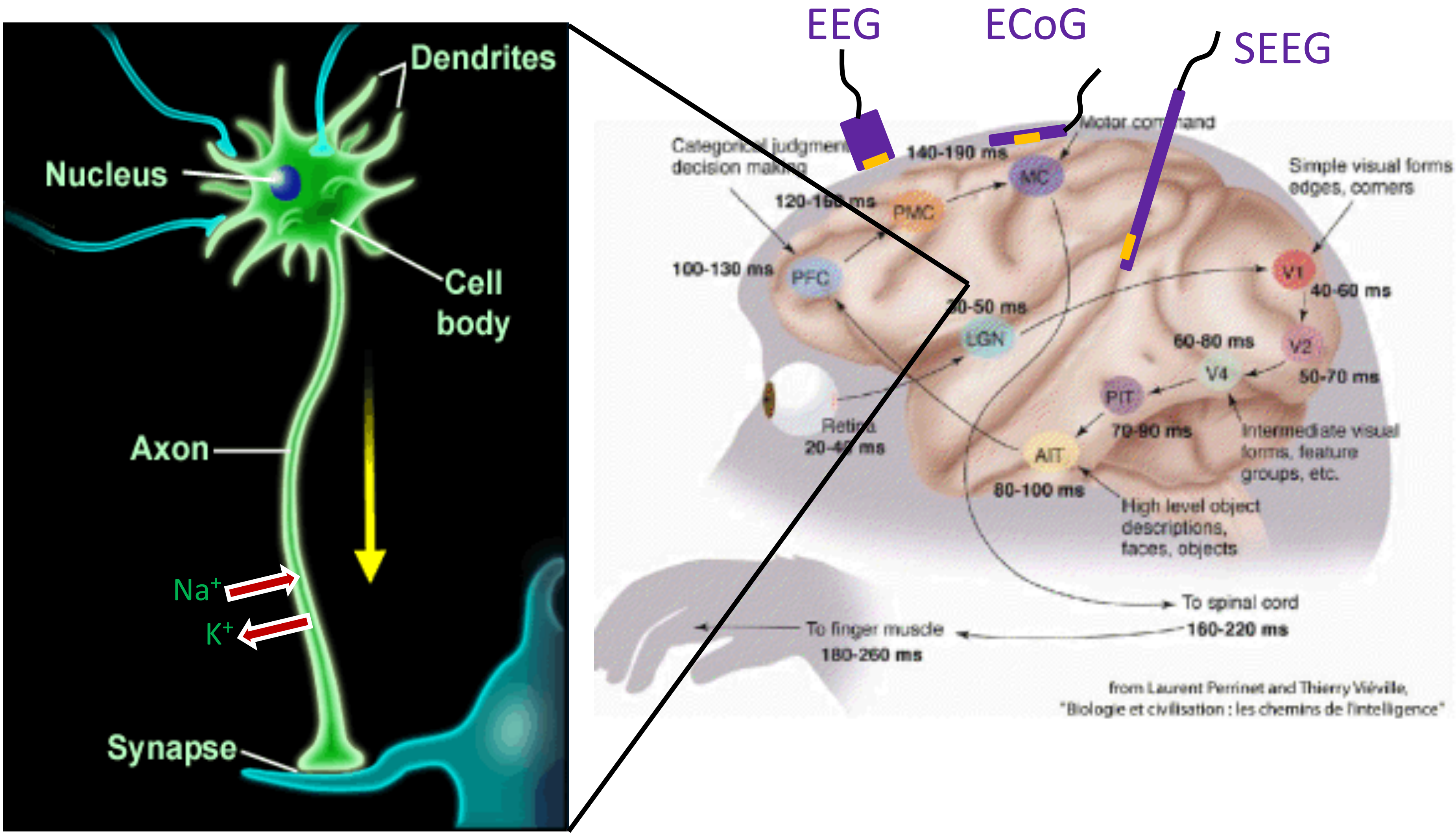
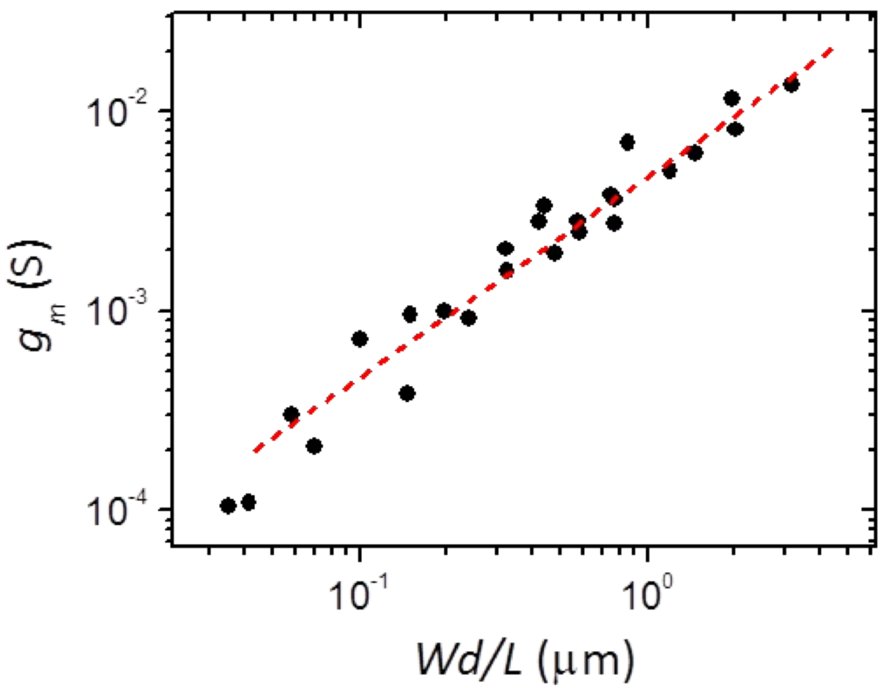
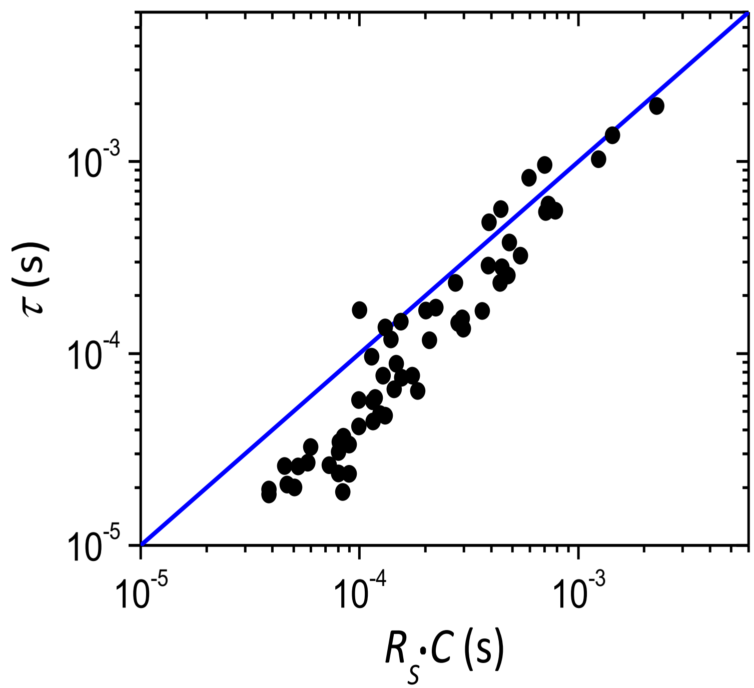
w/ Christian Benar, Jean-Michel Badier (INSERM)

Importance of neural interfacing



OECT figure of merit





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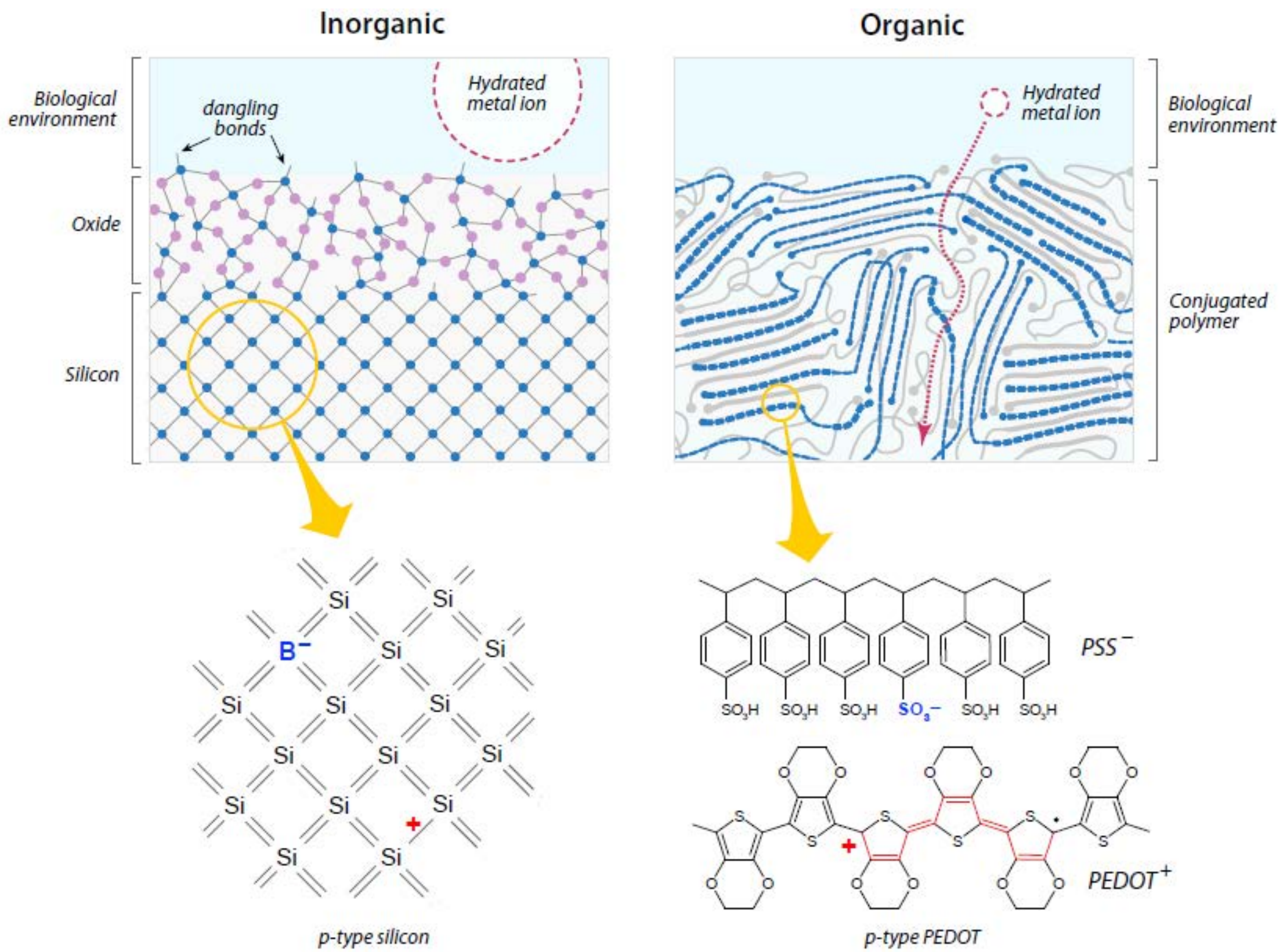
Why organics?



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

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

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**