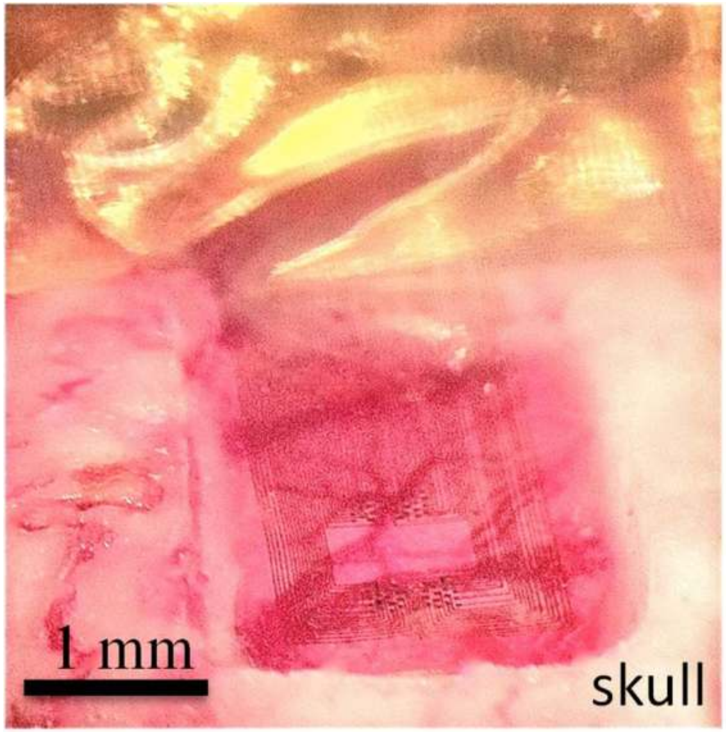
Organic Electrochemical Transistors



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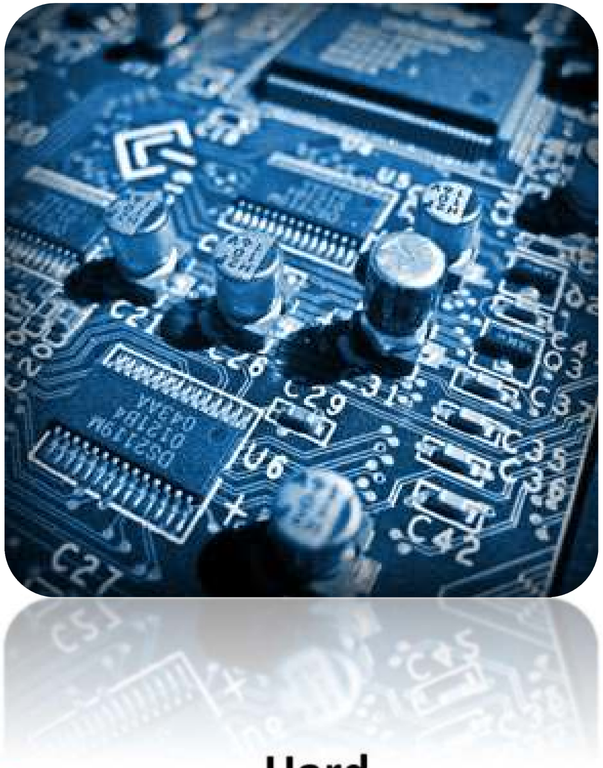
UNIVERSITY OF CAMBRIDGE
Department of Engineering

Bioelectronics Laboratory

Outline

- The organic electrochemical transistor
- Applications in neural recordings
- How do they work?
- Conclusions

Bioelectronics: Coupling biology and electronics



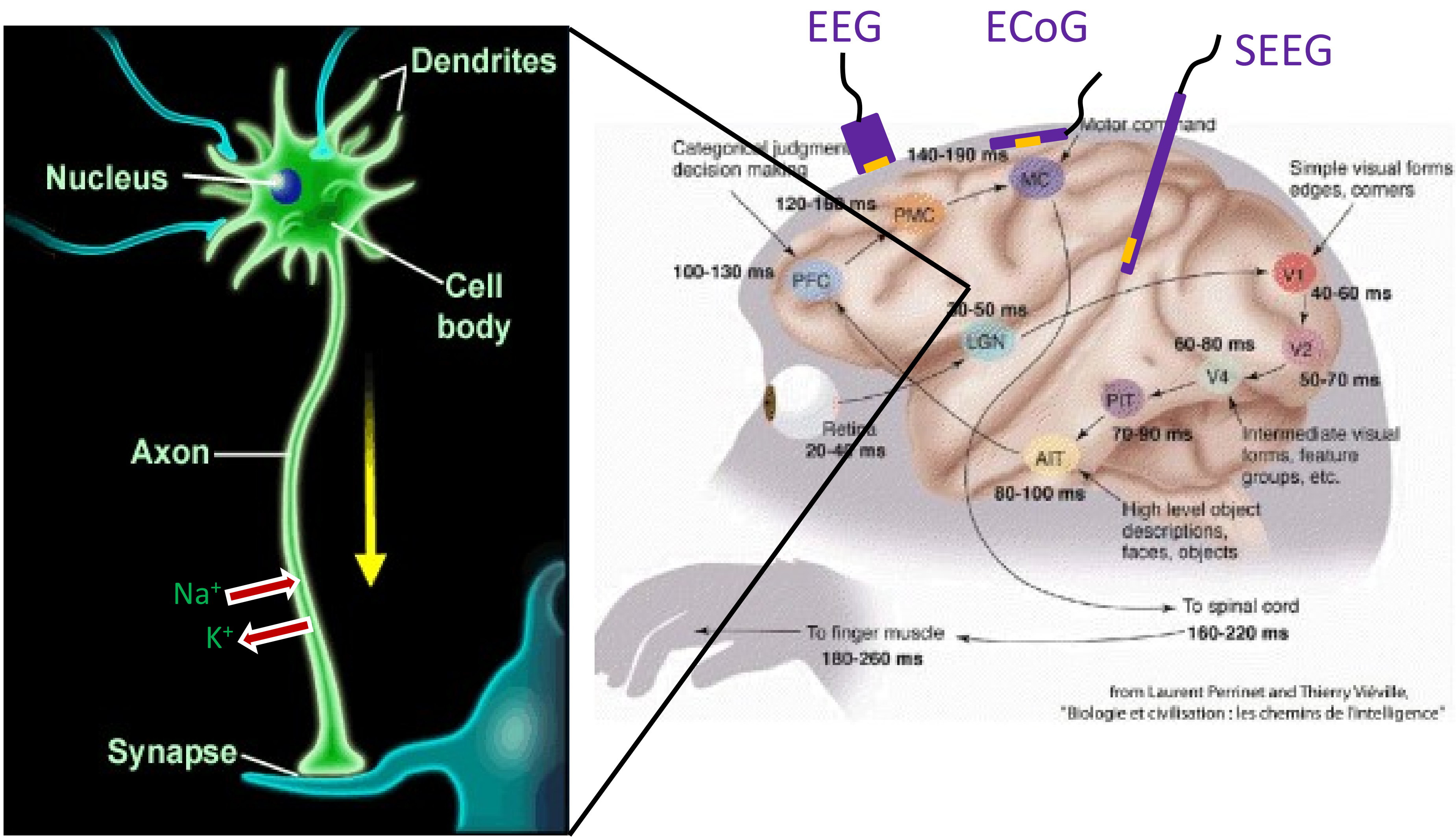
Sensing
Diagnosis

Mostly soft
Complex signaling
Dynamic

Hard
Electrons/holes
Static

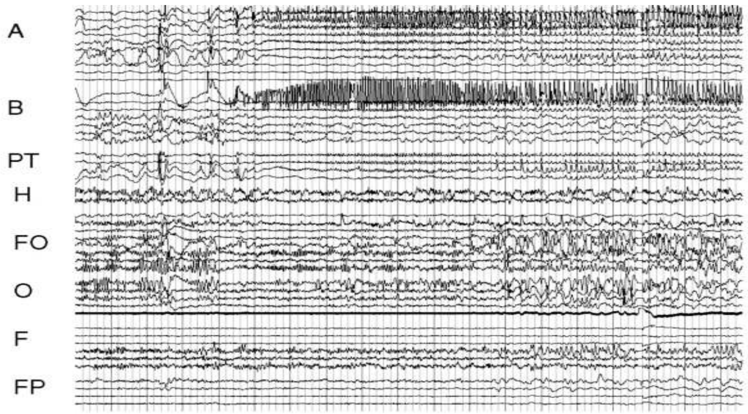
Actuation
Therapy

Importance of neural interfacing



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**



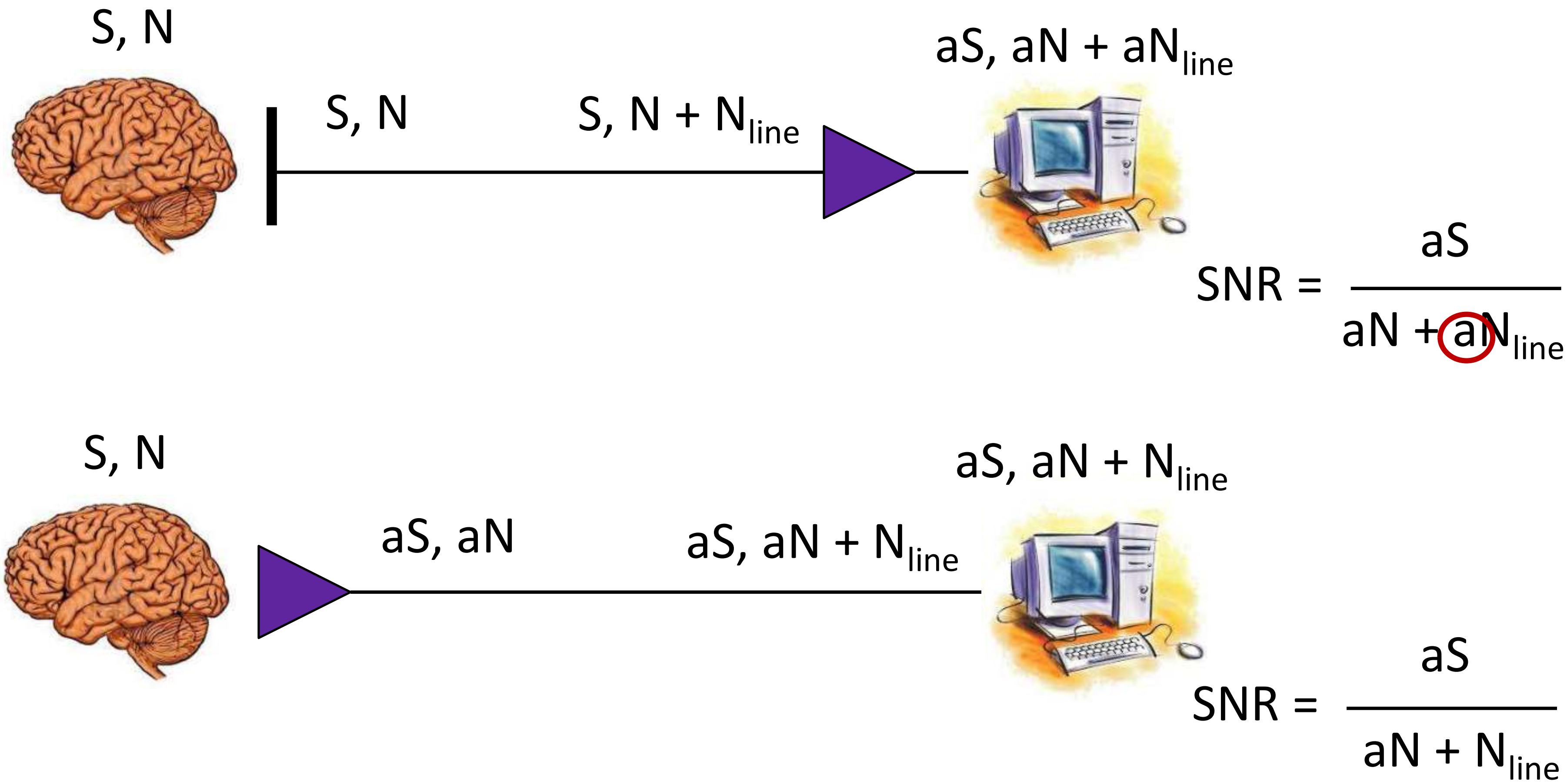
Key challenges:

- **Improve electrode performance**
- **Make less invasive recordings**

Brain-Computer Interfaces

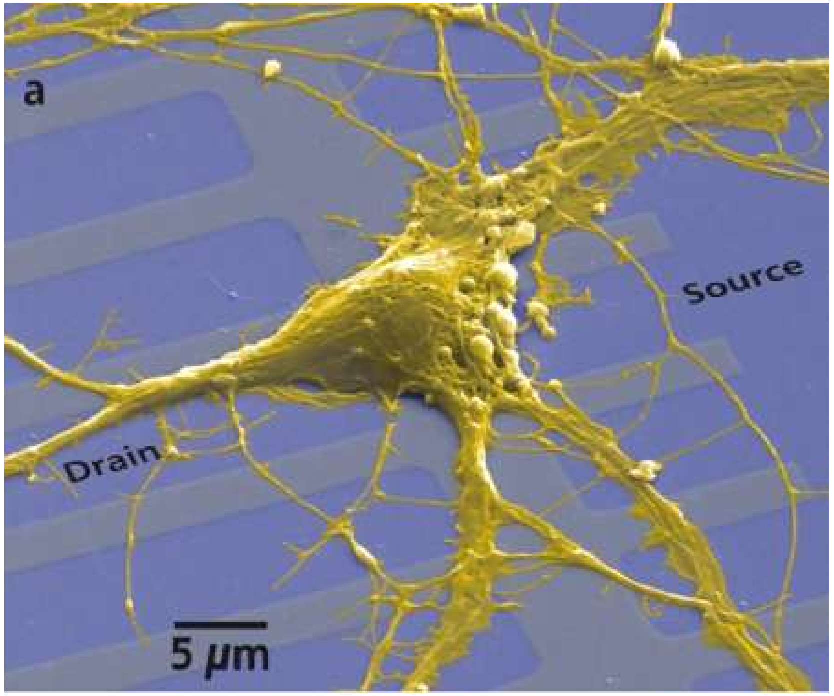
L.R. Hochberg, D. Bacher, B. Jarosiewicz, N.Y. Masse, J.D. Simeral, J. Vogel, S. Haddadin, J. Liu, S.S. Cash, P. van der Smagt, and J. P. Donoghue, *Nature* 485, 372 (2012).

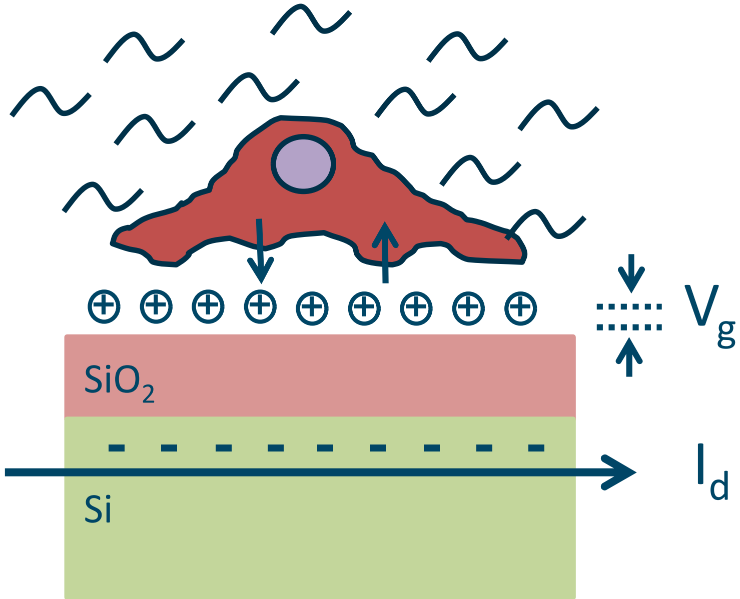
Transistor vs. electrode



Transistor recordings offer higher SNR

Recording neural activity with transistors

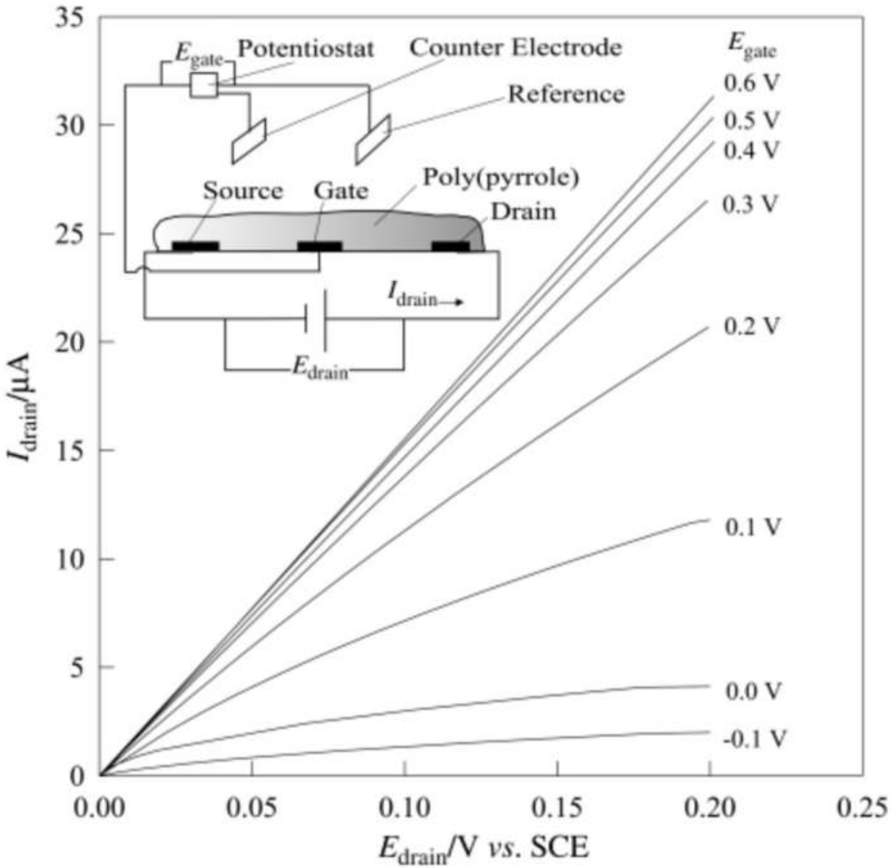




Fromherz group, MPI

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

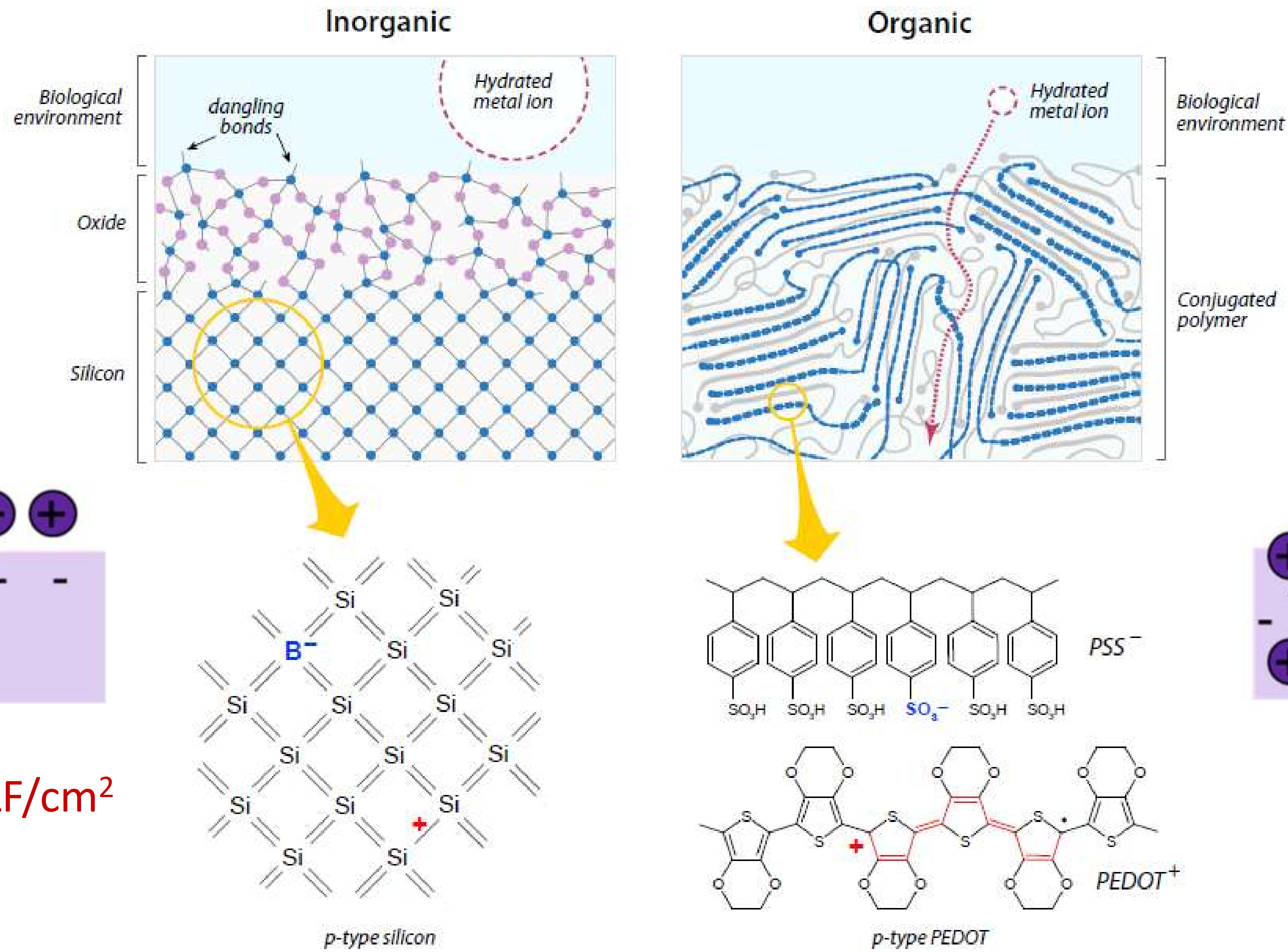
The organic electrochemical transistor (OECT)

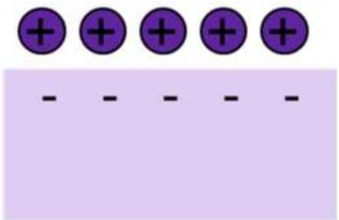


No insulator between channel and electrolyte

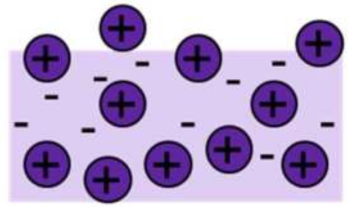
First OECT: H.S. White, G.P. Kittlesen, and M.S. Wrighton, *J. Am. Chem. Soc*. 106, 5375 (1984).

Why organics?





C_{DL}’ ~ 1-10 µF/cm^2

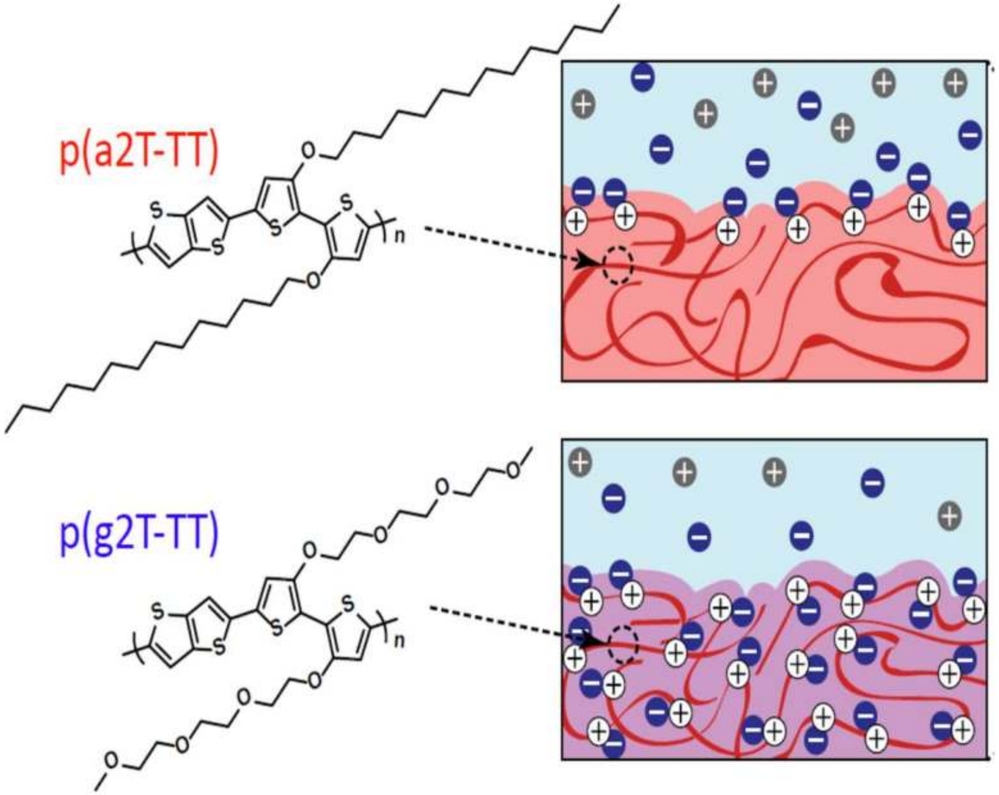


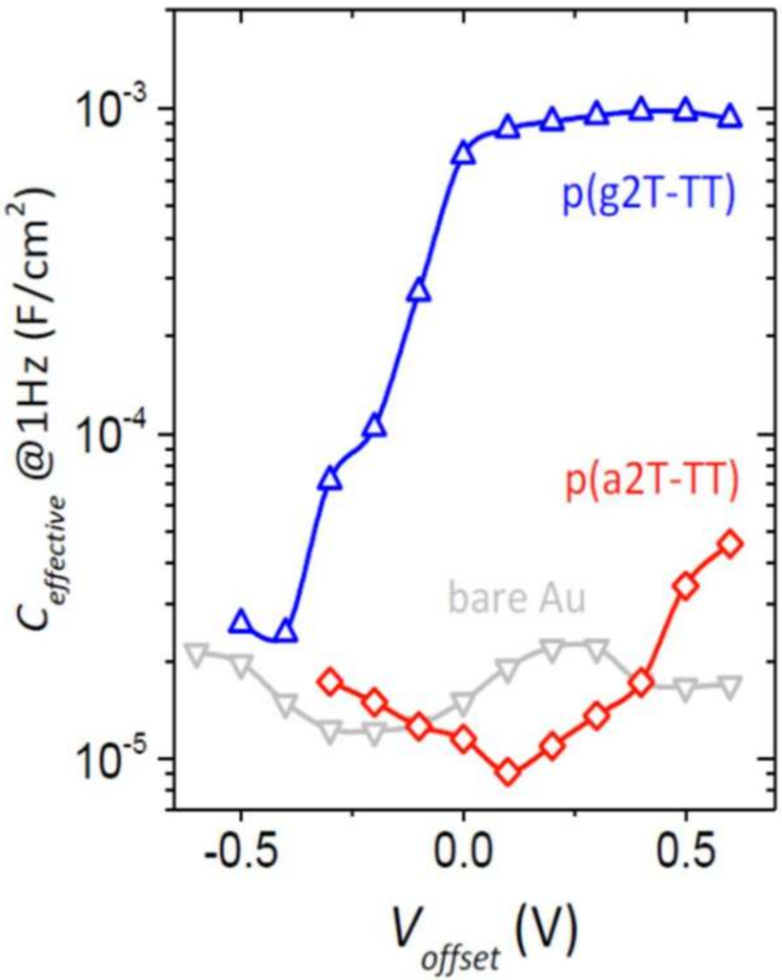
C’>>C_{DL}’

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

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

Molecular engineering of ion injection

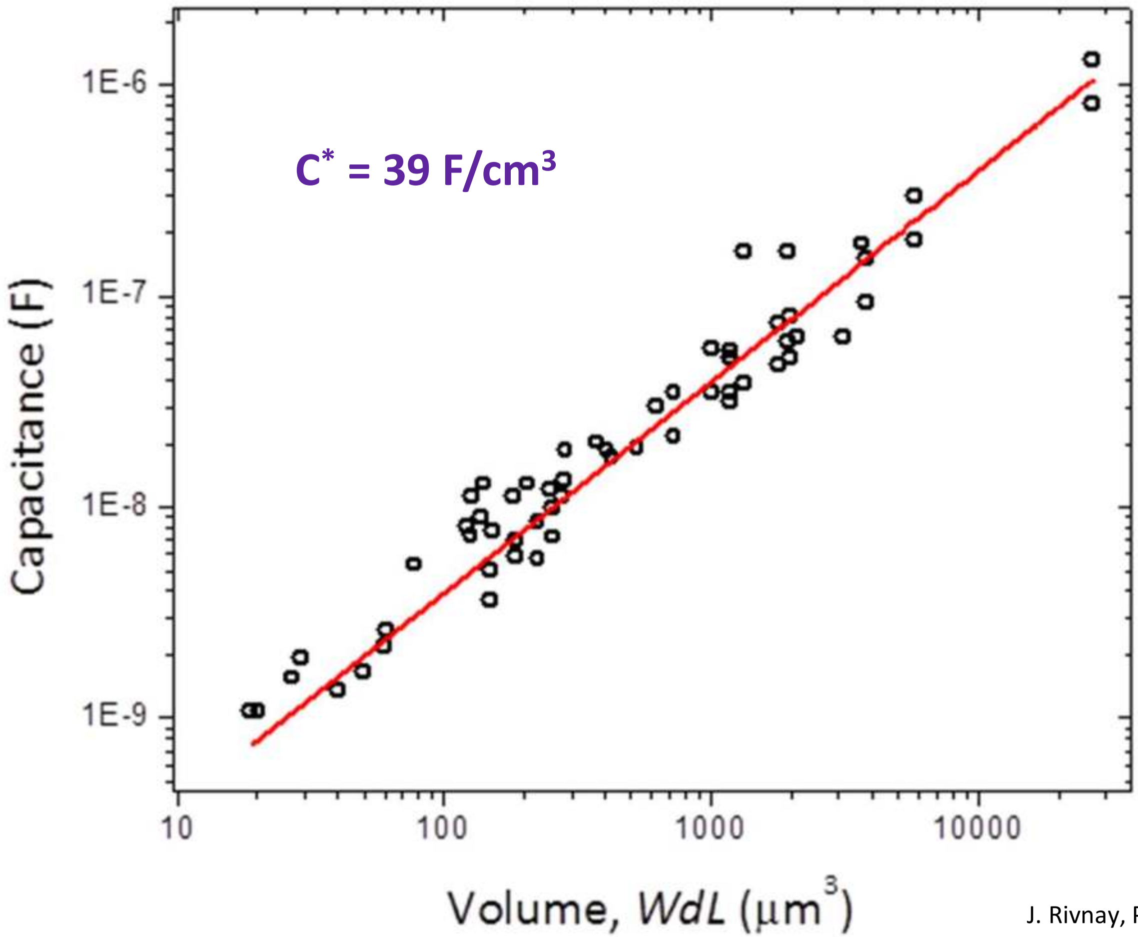




w/ Iain McCulloch (Imperial/KAUST), Jonathan Rivnay (Northwestern)

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).

Volumetric ion transport in PEDOT:PSS

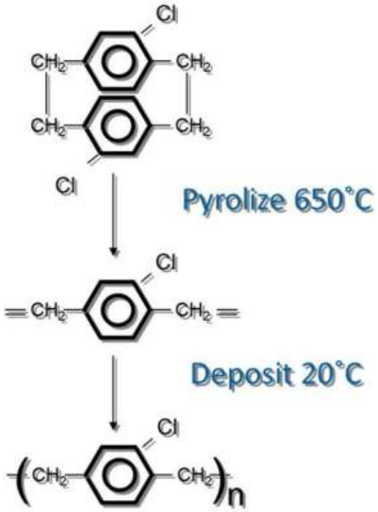


For d=130 nm:
C′ ~ 500 µF/cm^2

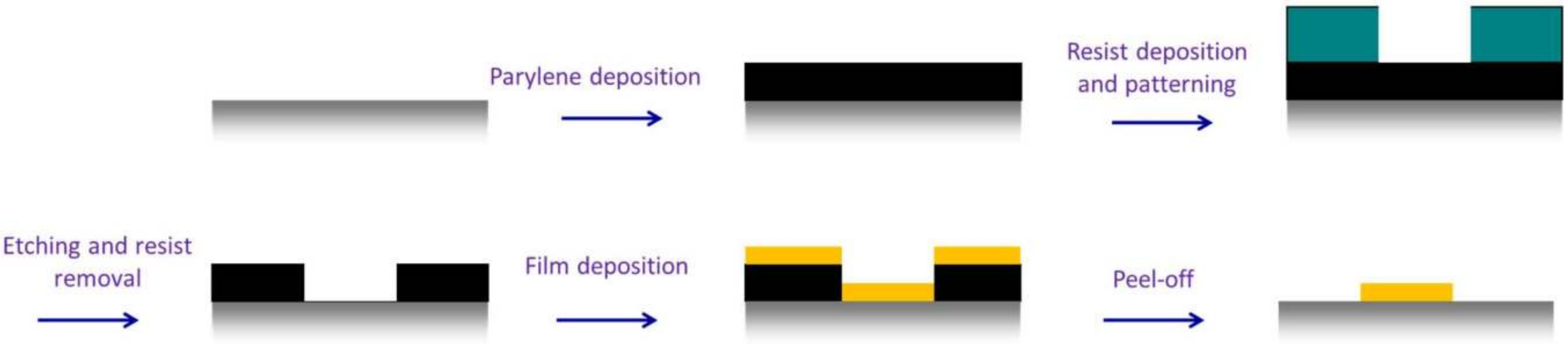
100× larger than double layer capacitance

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).

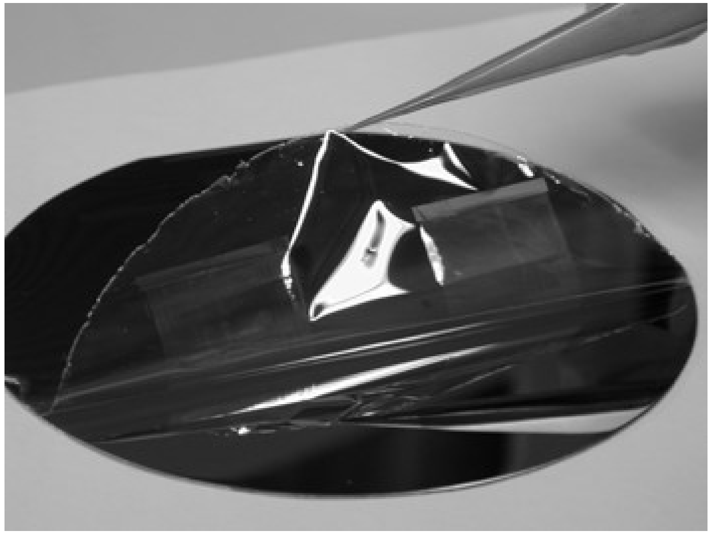
Lithographic fabrication using parylene-C

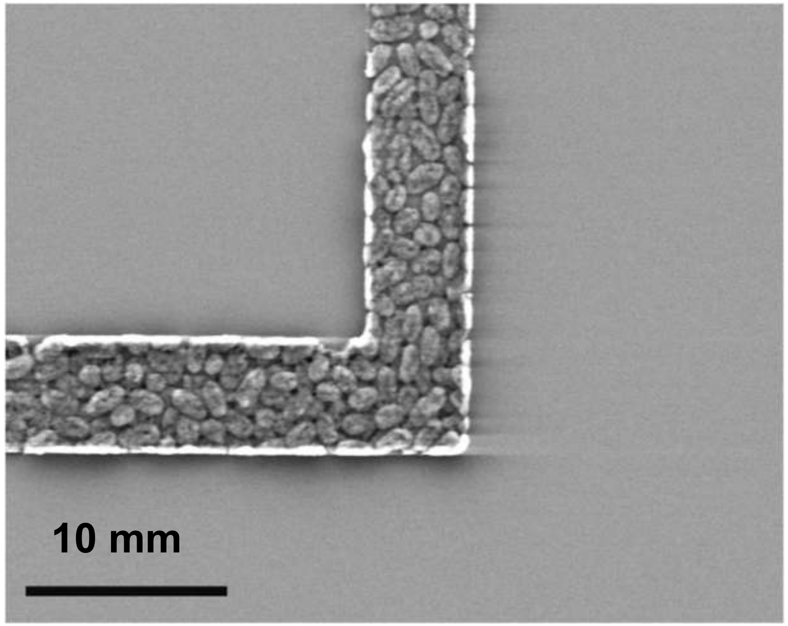


- CVD polymer
- Conformal
- Chemically inert



Lithographic fabrication using parylene-C



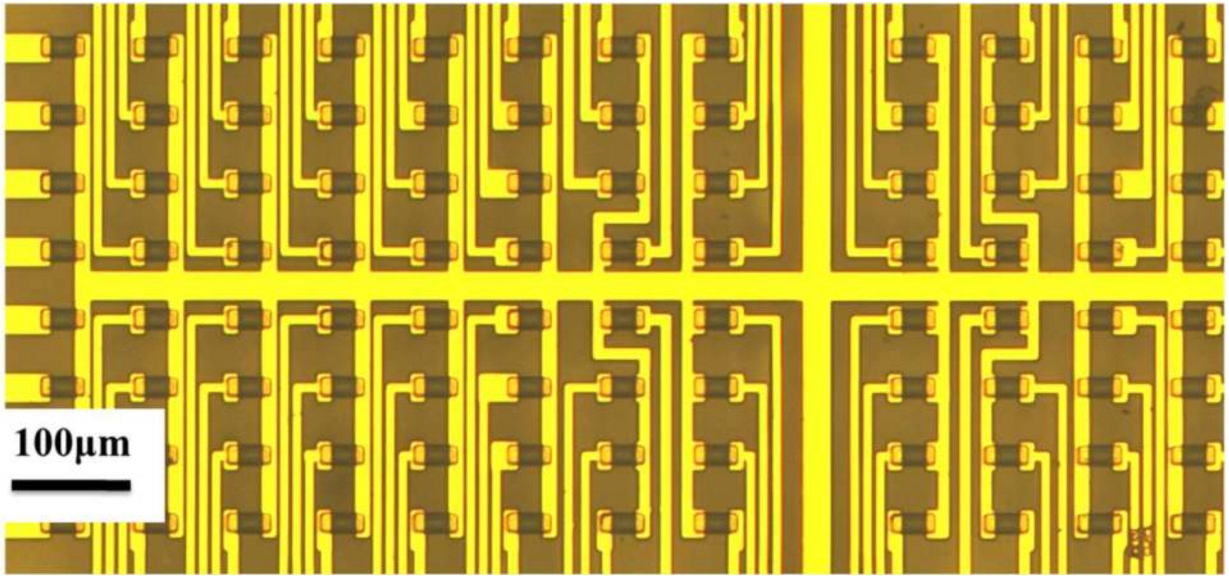


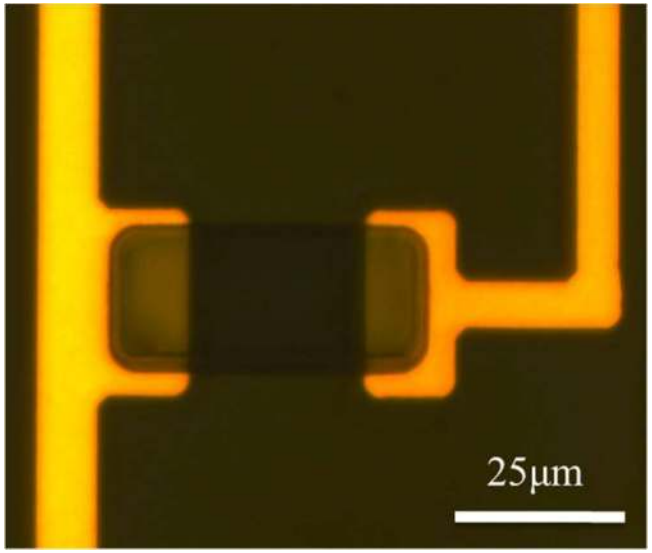
E. Coli

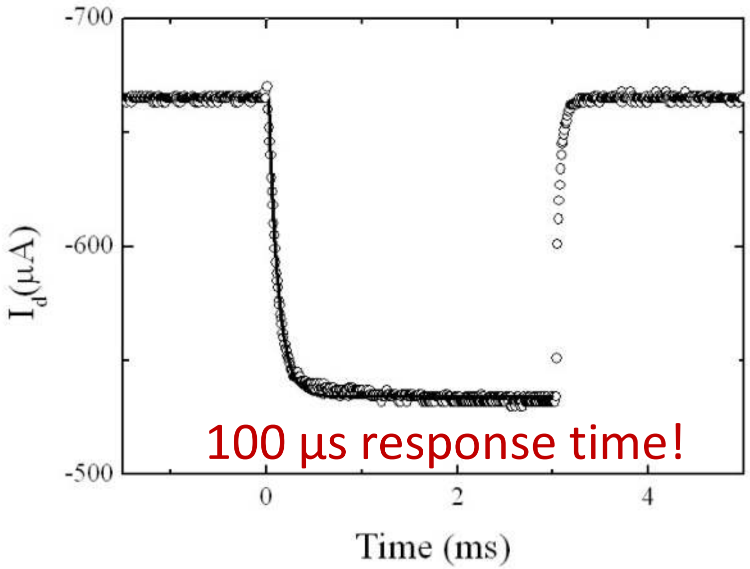
Slide courtesy of Rob Ilic (CNF)

R. Ilic and H.G. Craighead, *Biomedical Microdevices* **2**, 317 (2000).

Microfabricated OECTs

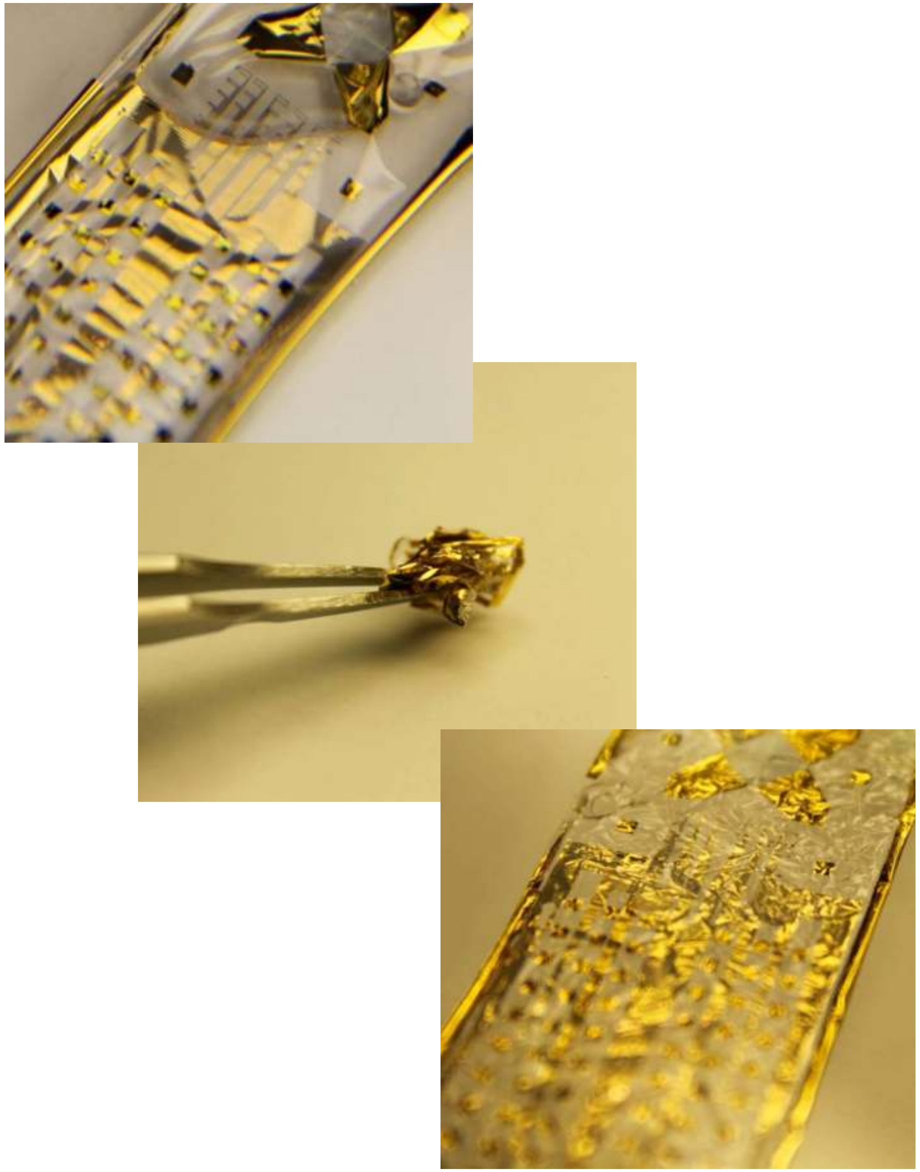


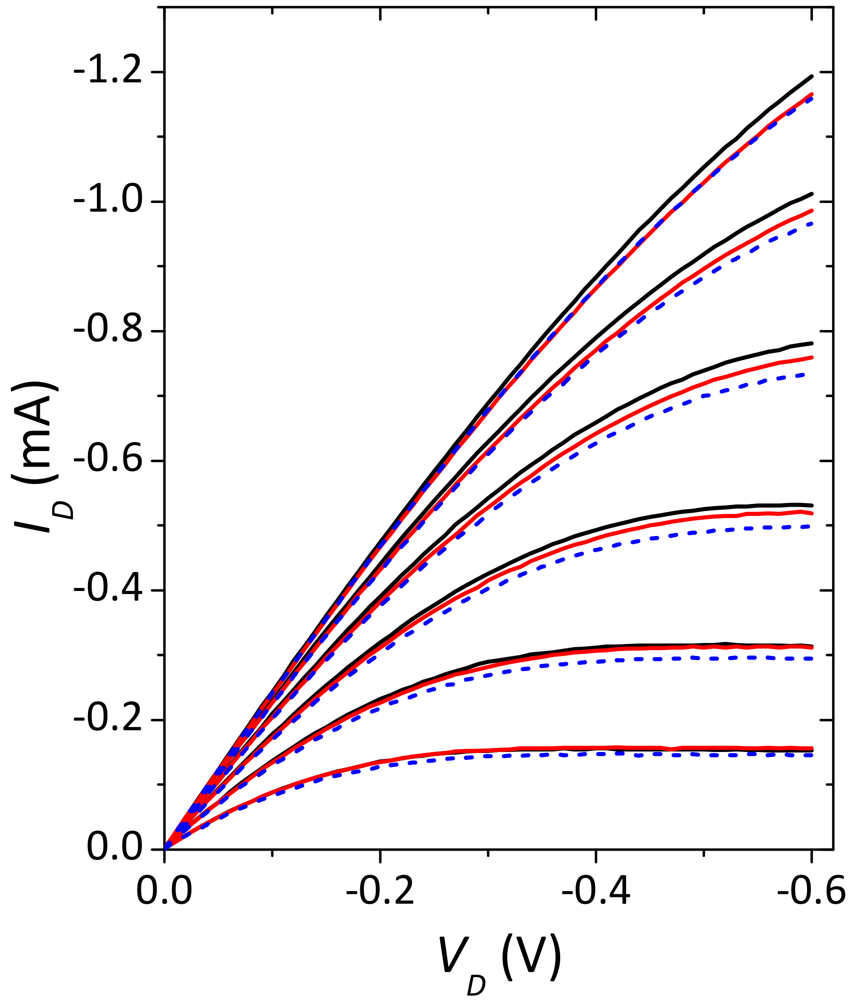




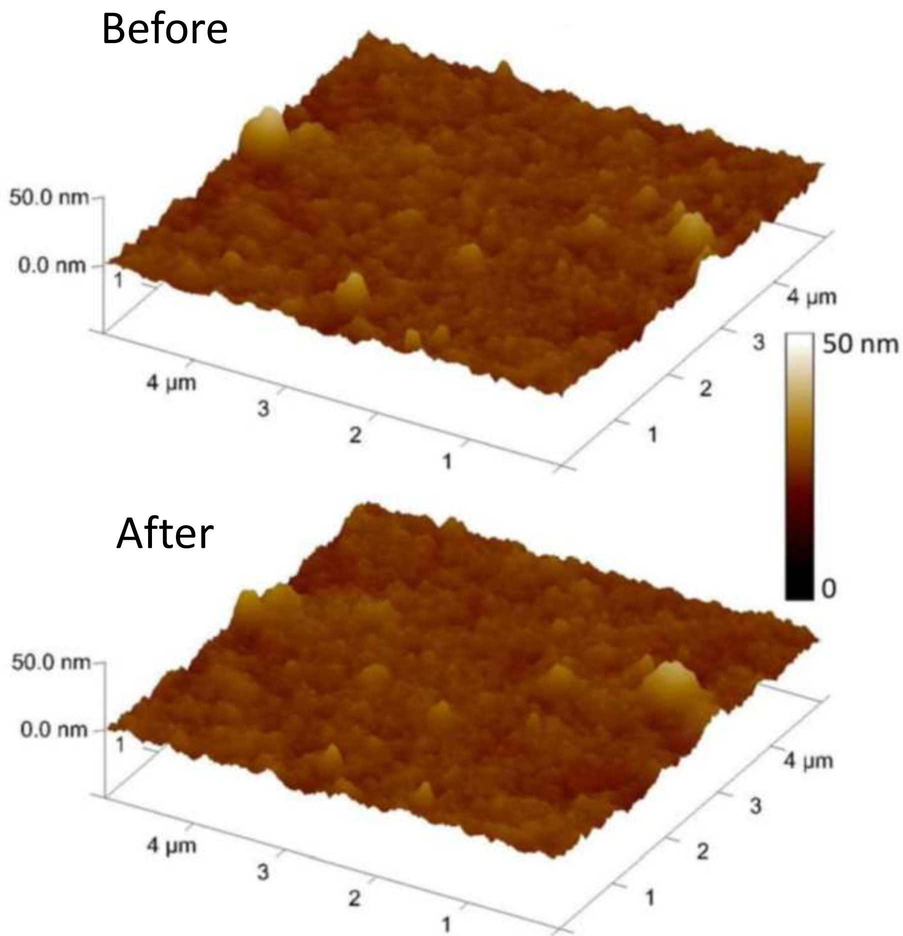
D. Khodagholy, M. Gurfinkel, E. Stavrinidou, P. Leleux, T. Herve, S. Sanaur, and G. G. Malliaras, Appl. Phys. Lett. 99, 163304 (2011).

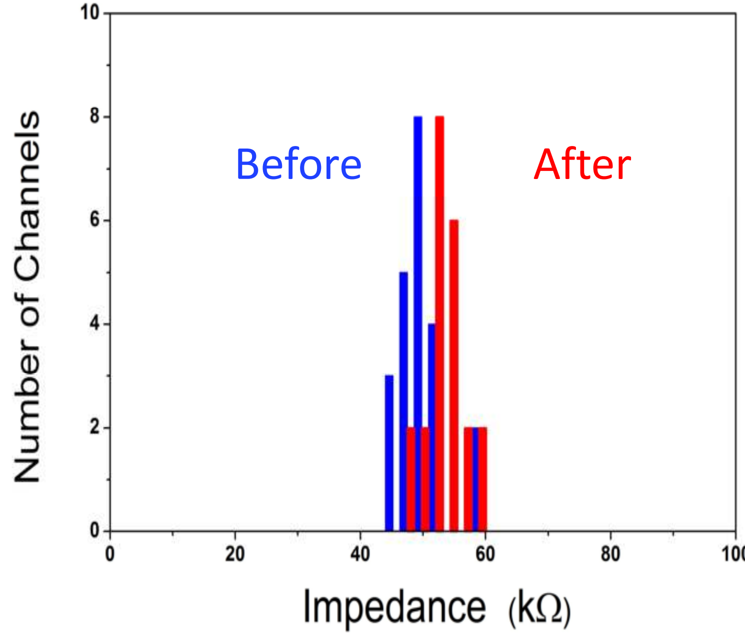
Integration with flexible substrates





Autoclave sterilisation

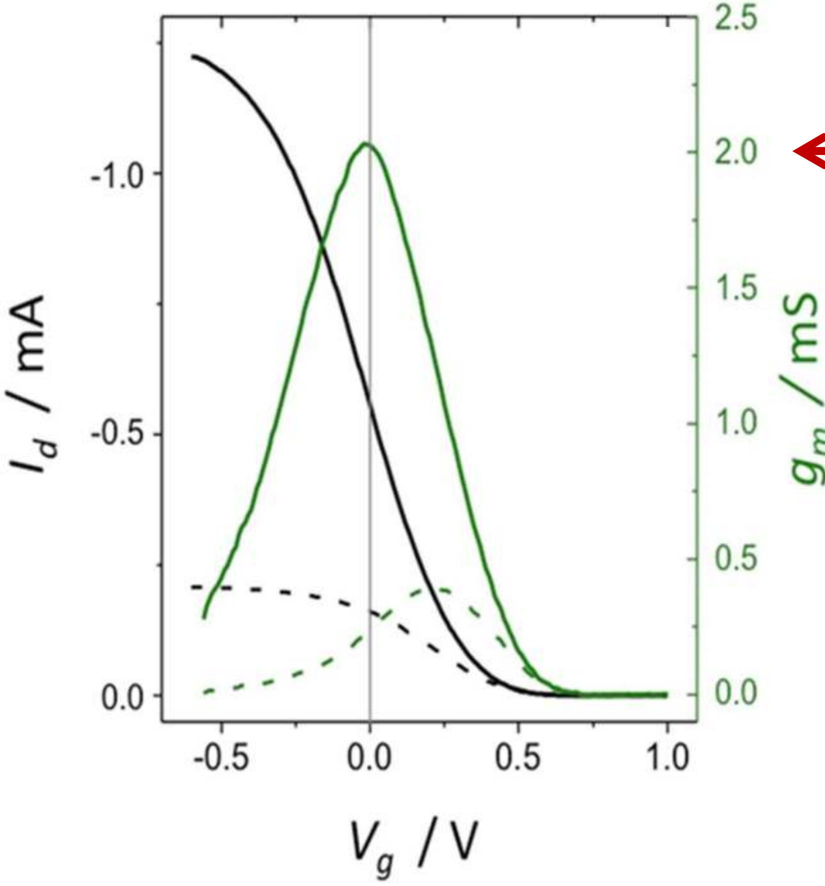




w/ Christophe Bernard (INSERM), Shadi Dayeh (UCSD)

I. Uguz, M. Ganji, A. Hama, A. Tanaka, S. Inal,
A. Youssef, R.M. Owens, S. Dayeh, and G.G. Malliaras,
Adv. Healthcare Mater. 5, 3094 (2016).

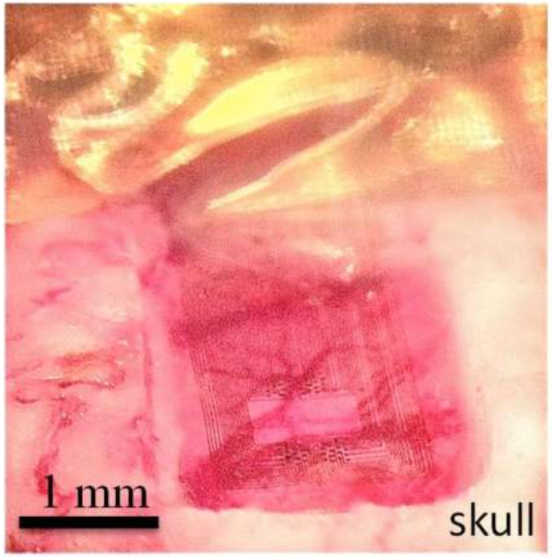
Characteristics of OECTs

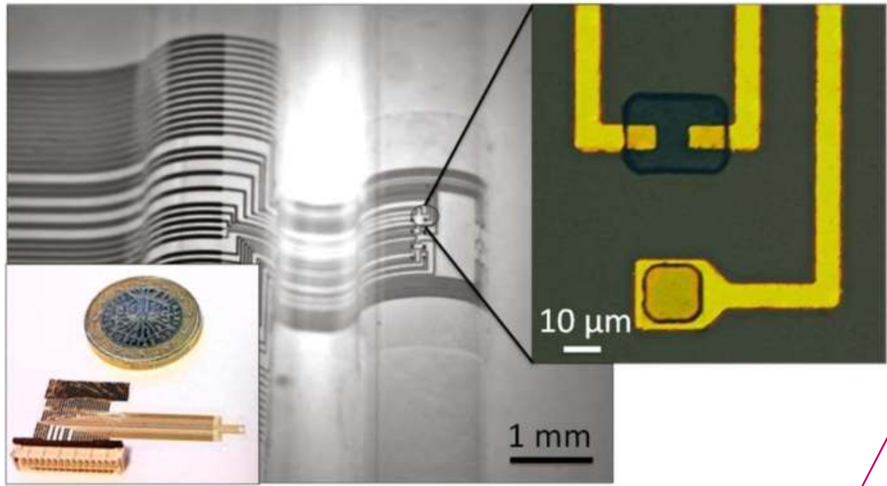


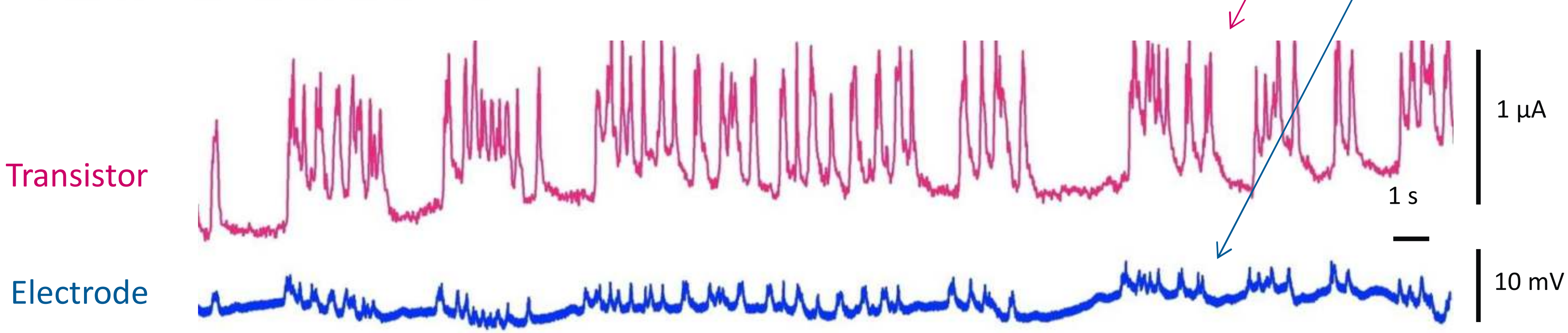
100× higher than
Si transistors

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).

In vivo recordings using transistors







w/ Christophe Bernard (INSERM)

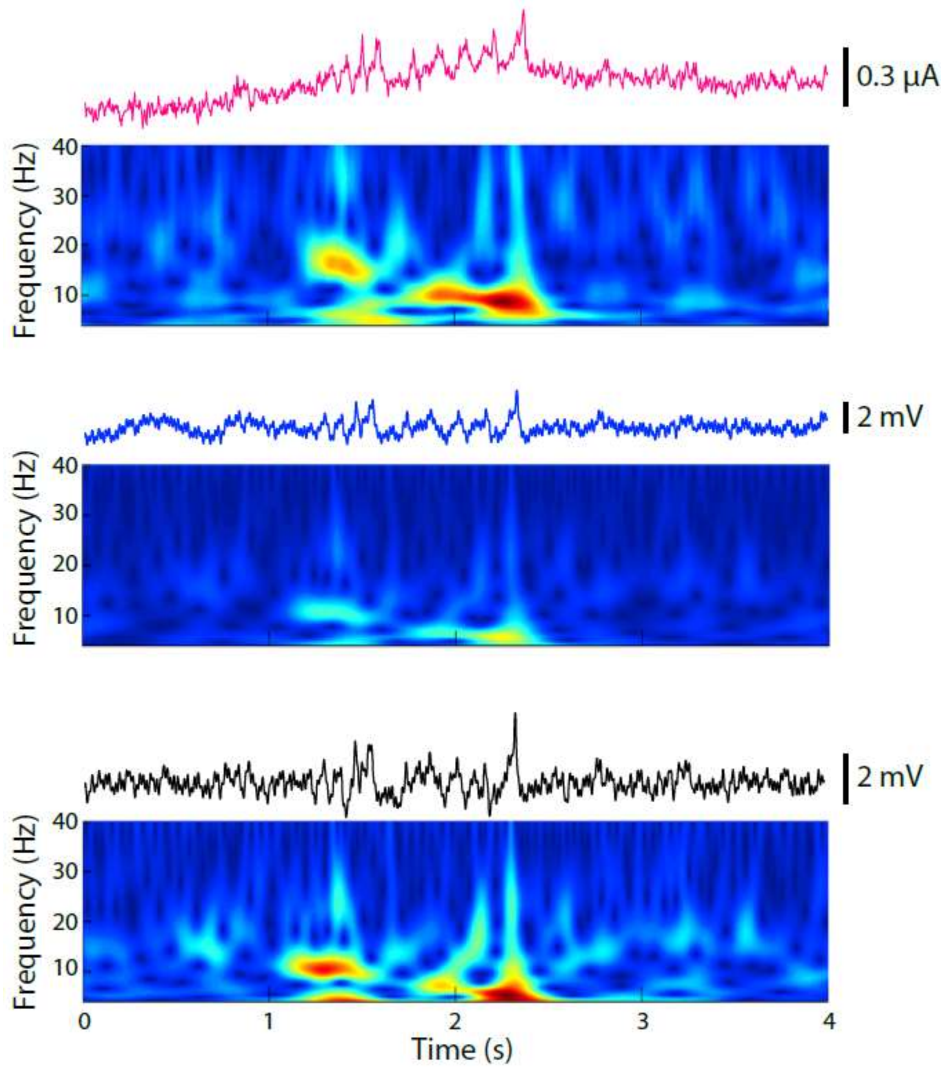
D. Khodagholy, T. Doublet, P. Quilichini, M. Gurfinkel, P. Leleux, A. Ghestem, E. Ismailova, T. Herve, S. Sanaur, C. Bernard, and G.G. Malliaras , *Nature Comm.* 4, 1575 (2013).

Transistors enable less invasive recordings

Transistor

Surface
electrode

Depth
electrode



w/ Christophe Bernard (INSERM)

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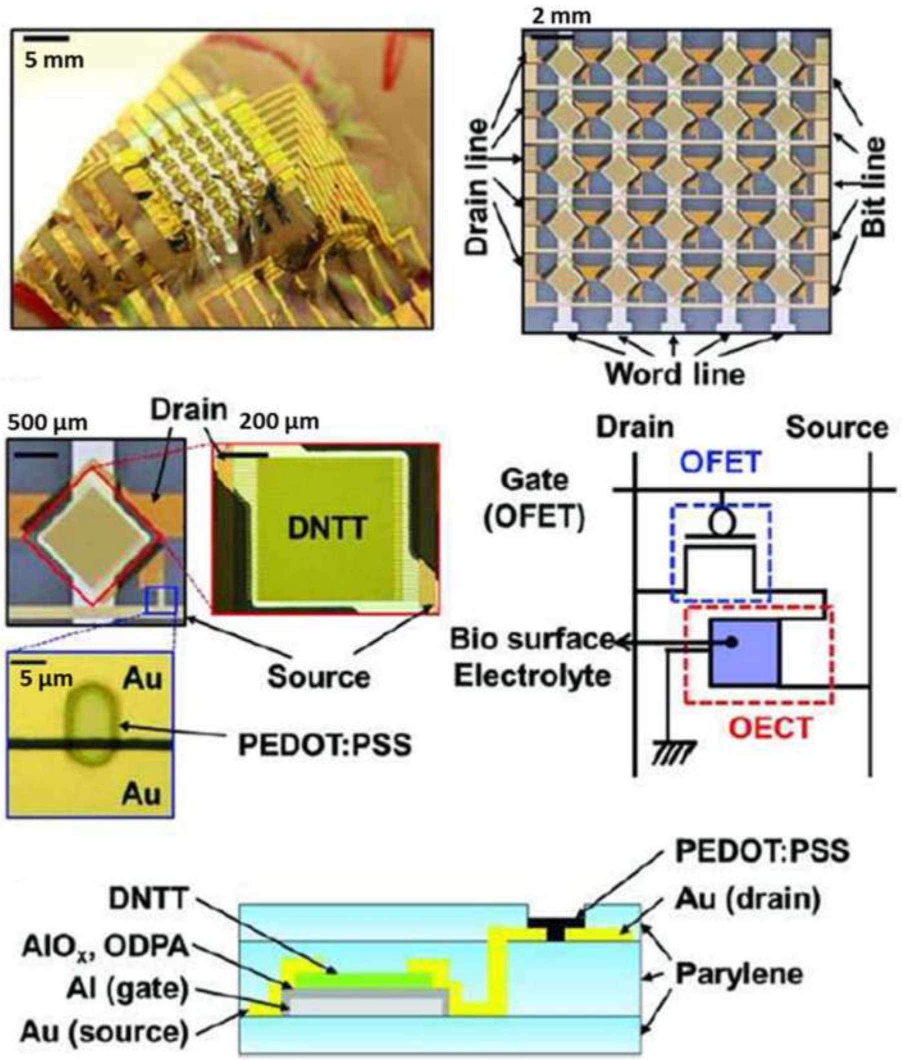
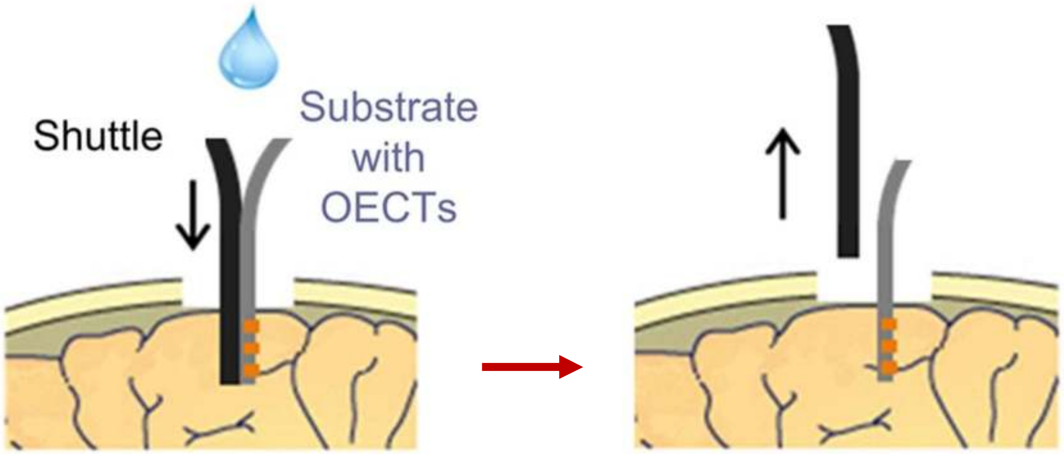
Multiplexed arrays for massive recordings

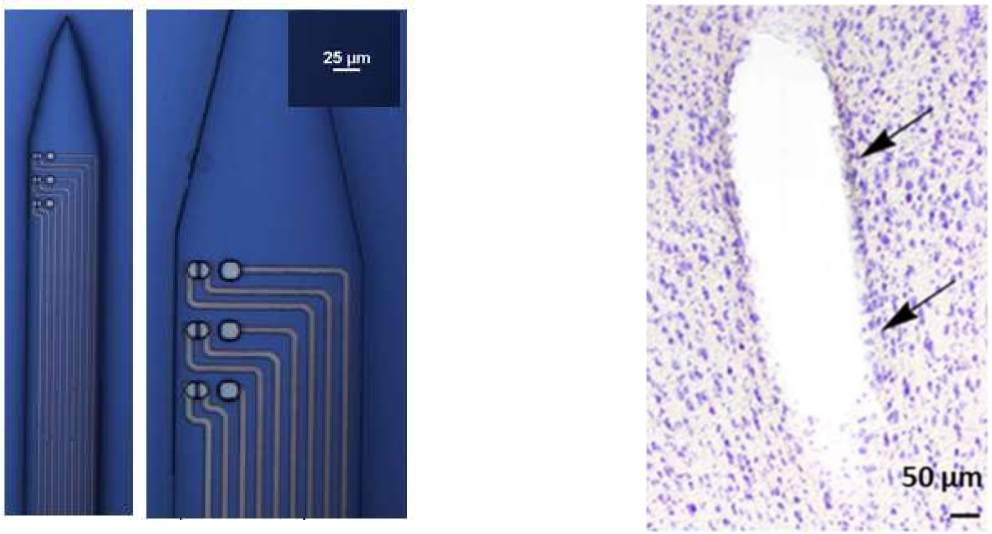


w/ Takao Someya (Tokyo)

- W. Lee, D. Kim, J. Rivnay, N. Matsuhisa, T. Lonjaret, T. Yokota, H. Yawo, M. Sekino, G. Malliaras, T. Someya, *Adv. Mater.* 28, 9722 (2016).
- W. Lee, D. Kim, N. Matsuhisa, M. Nagase, M. Sekino, G.G. Malliaras, T. Yokota, and T. Someya, *Proc. Natl. Acad. Sci.* 114, 10554 (2017).
- W. Lee, S. Kobayashi, M. Nagase, Y. Jimbo, I. Saito, Y. Inoue, T. Yambe, M. Sekino, G.G. Malliaras, T. Yokota, M. Tanaka and T. Someya, Sci. Adv. 4, eaau2426 (2018).

Insertion in the brain using removable shuttles

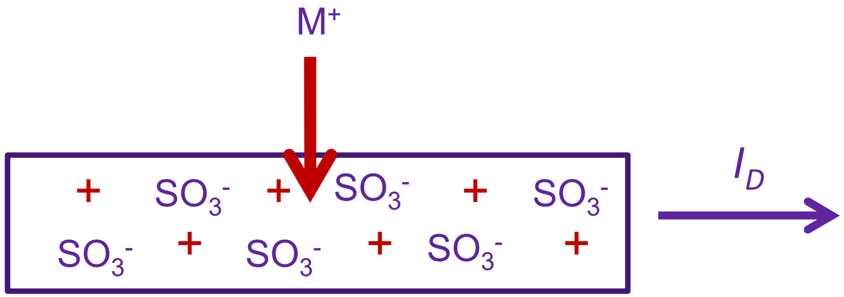




w/ Christophe Bernard (INSERM)

A. Williamson, M. Ferro, P. Leleux, E. Ismailova, A. Kaszas, T. Doublet, P. Quilichini, J. Rivnay, B. Rózsa, G. Katona, C. Bernard, and G. G. Malliaras, Adv. Mater. 27, 4405 (2015).

Model



$$I_D = W \cdot d \cdot e \cdot \mu \cdot p(x) \cdot [dV(x)/dx]$$

↑

$$p(x) = SO_3^- - M^+(x)$$

↑

$$M^+(x) = (C^*/e) \cdot [V_G - V(x)]$$

Integrating I_d over the length of the channel:

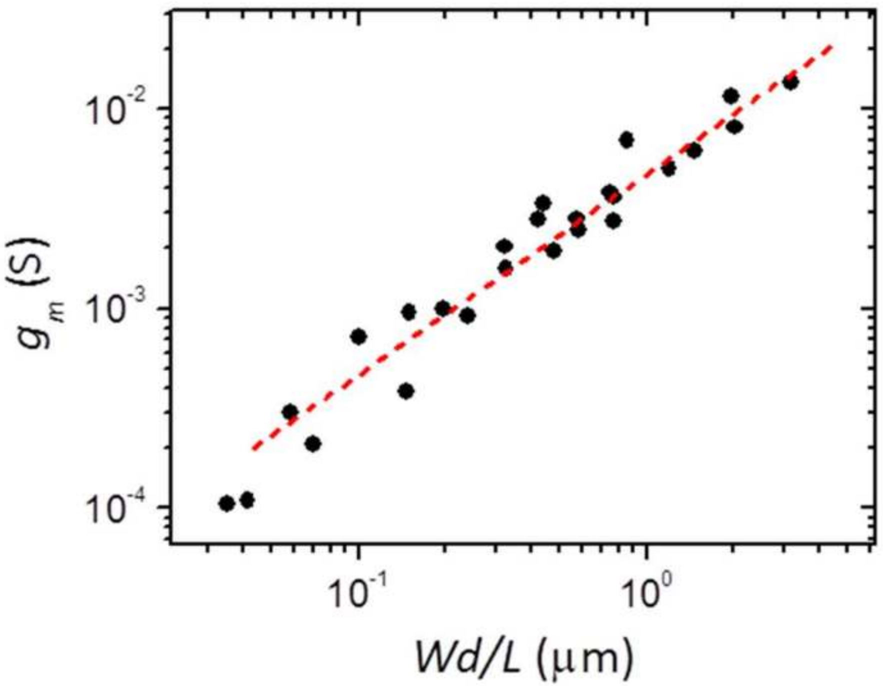
$$I_D = (W \cdot d/L) \cdot \mu \cdot C^* \cdot [V_T - V_G + V_D/2] \cdot V_D$$

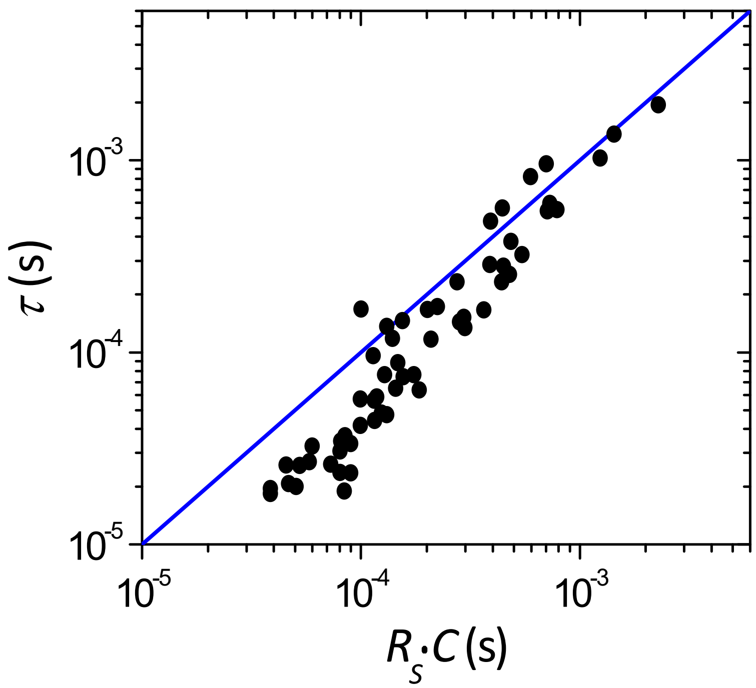
↑

$$V_T = e \cdot SO_3^-/C^*$$

$$I_D^{SAT} = [W/(2 \cdot L)] \cdot d \cdot \mu \cdot C^* \cdot [V_T - V_G]^2$$

Scaling with geometry

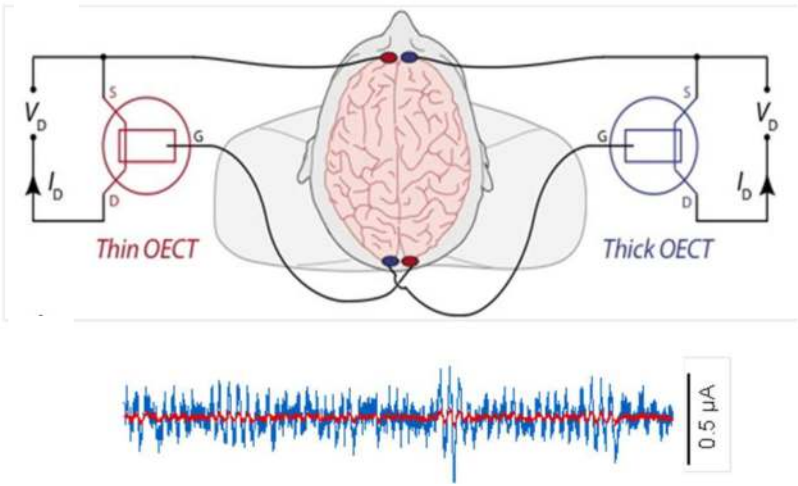


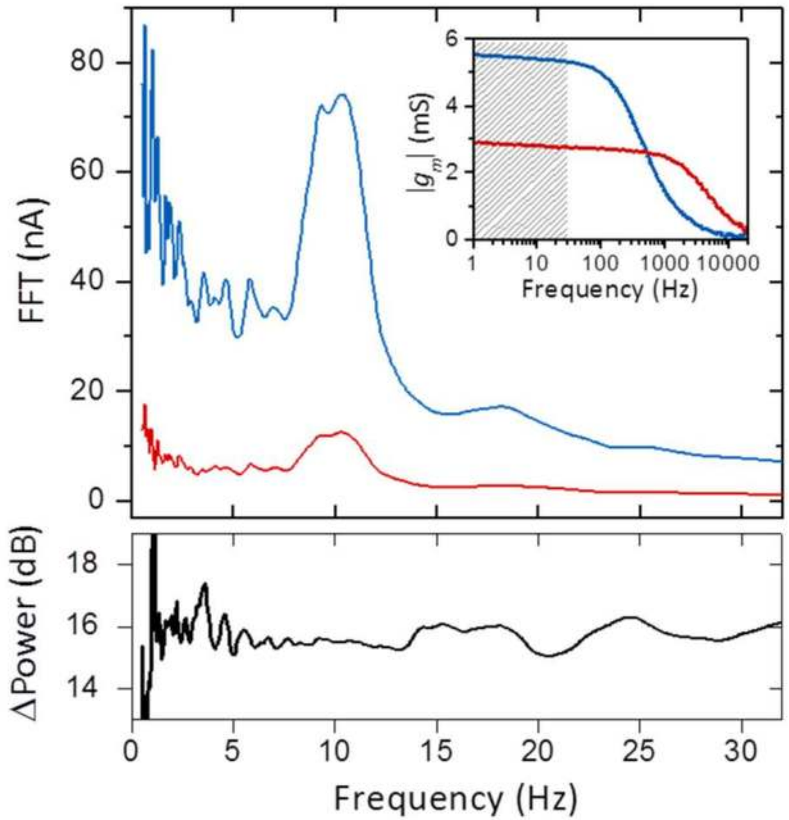


$$g_m{}^{SAT} = \left({}^{W \cdot d}/_{L}\right) \cdot \mu \cdot C^* \cdot (V_T - V_G)$$

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 Advances1, e1400251 (2015).

High transconductance means high SNR

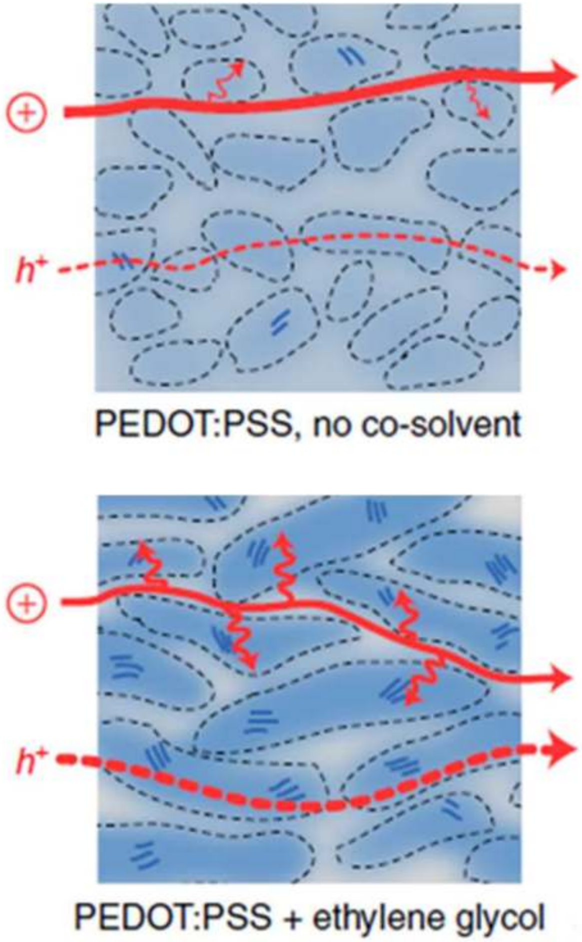


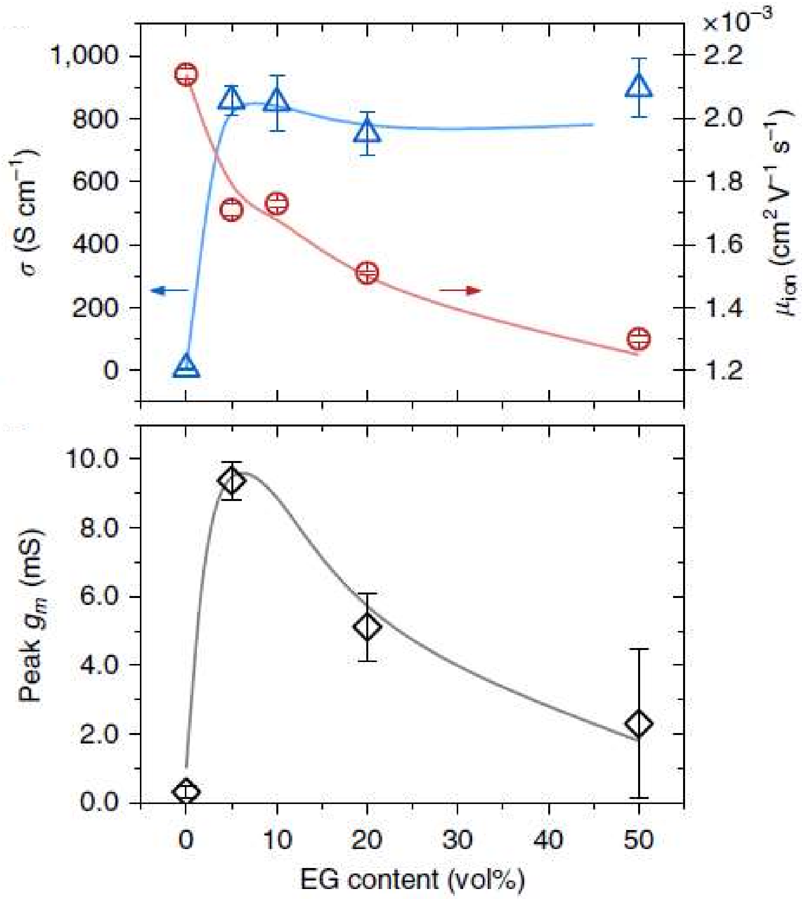


J. Rivnay, P. Leleux, M. Ferro, M. Sessolo, A. Williamson, D.A. Koutsouras, D. Khodagholy, M. Ramuz, X. Strakosas, R.M. Owens, C. Benar, J.-M. Badier, C. Bernard, and G.G. Malliaras, SCIENCE Advances 1, e1400251 (2015).

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

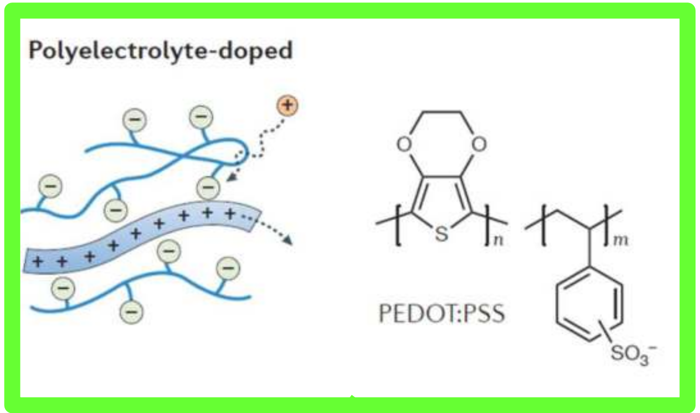
Optimizing by means of materials processing

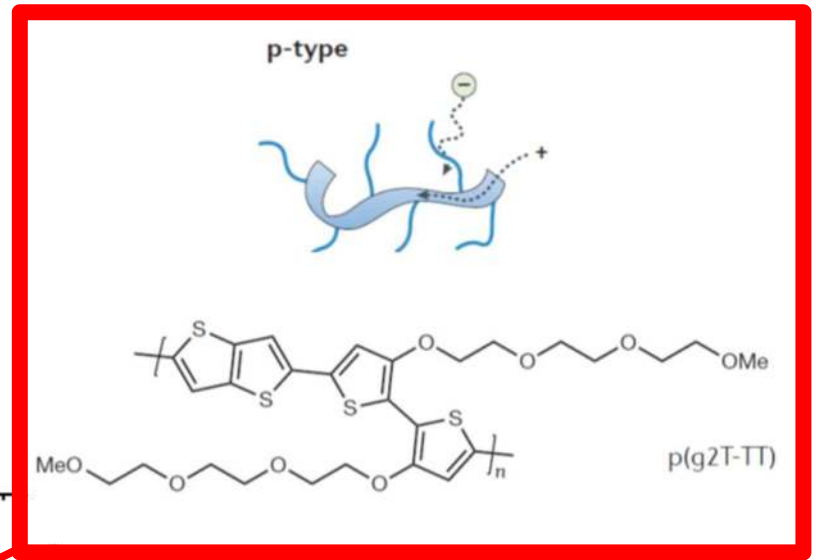


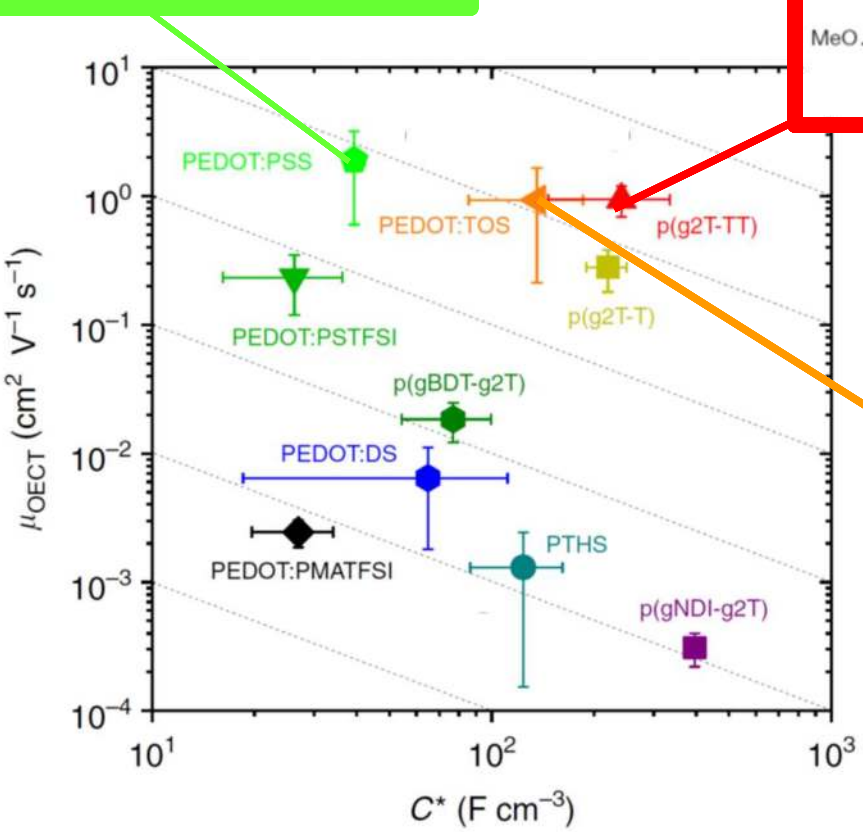


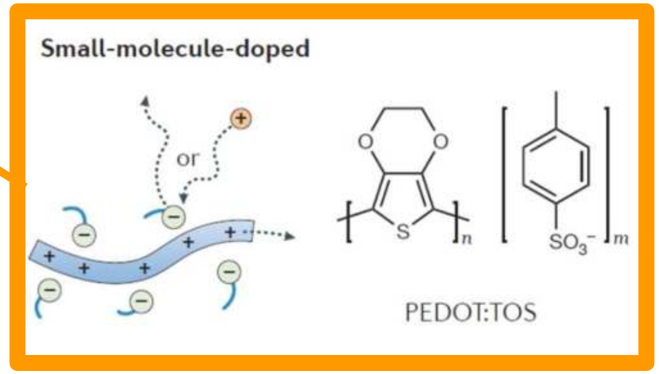
J. Rivnay, S. Inal, B.A. Collins, M. Sessolo, E. Stavrinidou, X. Strakosas, C. Tassone, D.M. Delongchamp, and G.G. Malliaras, *Nature Comm.* 7, 11287 (2016).

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









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

Conclusions

- **Organic electrochemical transistors leverage volumetric ions transport to yield high transconductance.**

- **They are amplifying transducers that yield better signal-to-noise ratio recordings 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. Better materials require:**
  - 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, "Organic electrochemical transistors", Nature Rev. Mater. 3, 17086 (2018).

Bioelectronics Laboratory

Acknowledgements

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Clare Grey (Chemistry)
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Stephen Price (Clinical Neurosciences)
Michael Lee (Medicine)
Richard Gilbertson (Oncology)

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