

FINAL REPORT

Student name: Nicolò Lago

Cycle: XXX

Curriculum: ICT

Supervisor name: Andrea Cester

Thesis title (final): Characterization and simulation of organic field-effect devices for simultaneous stimulation and recording of cellular electrical activity with reference-less EGOFETs

PART 1 - COURSES, CONFERENCES AND MOBILITY

Courses for Ph.D. students

- Physics and operation of heterostructure-based electronic devices (G. Meneghesso)
- Digital Processing of Measurement Information (C. Narduzzi)
- Statistical Methods (L. Finesso)
- Mathematical modeling of cell Biology (M. Pedersen)

Summer schools, short courses, tutorials

- International Summer School on Flexible and Printed Electronics, Brescia, Italy, Jun-Jul. 2015.
- CSNII School on Neurotechniques, Padova, Italy, Feb. 2016.

Seminars

- 11/11/2014 - Green electronics technology. Tecnologie abilitanti per l'internet delle cose. *Relatore:* Dottor Luca Roselli
- 27/11/2015 - Light-emitting diodes and applications. The era of solid-state lighting. *Relatore:* Dottor Matteo Meneghini
- 4/12/2014 - Quantum mechanics in energy and signal transfer processes. *Relatore:* Dottoressa Elisabetta Collini
- 9/12/2014 - Multifunctional organic field-effect transistors as a technological platform for sensing and biondiagnostics. *Relatore:* Dottor Stefano Toffanin
- 16/12/2014 - Polymer Solar Cells: Materials, Processing and Device Architecture. *Relatore:* Dottor Mirko Seri
- 24/10/2015 - GaN- a long way to go from crystal growth to substrates for reliable electronic devices: The effects of structural disturbances on the electrical behavior of GaN from a materials perspective. *Relatore:* Dottoressa Elke Meissner
- 10/12/2015 - Multifunctional organic field-effect transistors as a technological platform for sensing and biondiagnostics. *Relatore:* Dottor Stefano Toffanin
- 16/12/2015 - Polymer Solar Cells: Materials, Processing and Device Architecture. *Relatore:* Dottor Mirko Seri

Participation to International Conferences and Workshops

- European Symposium on Reliability of Electron Devices, Tolosa, France, Oct. 2015.

Other learning activities

- Company visit at OSRAM Opto Semiconductors, Leuven, Belgium, Nov. 2015.
- Company visit at IMEC, Regensburg, Germany, Dec. 2016.

PART 2 - RESEARCH ACTIVITY

My research activity is focused in the study of organic thin-film transistors (OTFTs) for the realization of neural interfaces.

To pursue this goal, in collaboration with the ISMN-CNR of Bologna, the activity was subdivided into two main research lines:

1. Study and characterization of OTFTs featuring different organic semiconductor materials.
2. Characterization and modeling of the organic semiconductor/solution interface.

To master the sensing and amplification properties of the OTFT-based sensors, it is mandatory to gain an intimate knowledge of the single transistors (without any analytes or cells) that cannot be limited to basic characterizations or to general models. Moreover, organic transistors are characterized by different working principles and properties as respect to their inorganic counterpart.

I performed pulsed and transient characterization on different OTFTs (both p-type and n-type) showing that, even though the transistors can switch on and off very fast, the accumulation and/or the depletion of the conductive channel continues for times as long as ten seconds [J5]. Such phenomenon must be carefully considered in the realization of a biosensor and in its applications, since the DC operative point of the device can drift during the recording of the cellular signals, thus altering the collected data.

I further investigate such phenomenon by performing characterizations at different temperatures and by applying the deep level transient spectroscopy (DLTS) technique [J7]. I showed that the slow channel accumulation (and depletion) is due to the semiconductor density of states (DOS) that must be occupied in order to bring the Fermi energy level close to the conduction band. This is a phenomenon that can takes several seconds and I described it by introducing a time-depend mobility. I also proposed a technique to estimate the behavior, in time, of the position of the Fermi energy level as respect to the conduction band.

To understand the electrochemical transduction processes between living cell and organic biosensor, we realized two-electrodes structure (STACKs) where a drop of saline solution is put directly in contact with the organic semiconductor. On these devices, I performed electrochemical impedance spectroscopy (EIS) at different DC polarizations and I presented an equivalent circuit model that describes all the observed phenomena [J6]. In particular, whit the help of surface analysis (ESEM and optical profilometer) I demonstrated that the solution can percolate throw the organic layer and, in the extreme cases, reach and corrode the electrodes.

Lately, I further extended the model by introducing a more general one, able to described a wider range of cases [J9], for instance where surface functionalizations are involved, or when different solutions are used (e.g. NaCl, pure water, ...).

These two different structures (OTFTs and STACKs) were then put together to realize electrolyte-gated field effect transistors (EGOFETs). Hence, the previous studies were used to investigate the physics behind the EGOFET working principle and to understand the transduction of the cells signal. I studied and characterized both p- and n-type EGOFETs, focusing to the later ones since the n-type organic semiconductors need a deeper investigations due to their intrinsic lower stability. To characterized such devices, a custom low-voltage high-speed acquisition board was developed and programmed to emulate a real-time neuron response.

Finally, I developed a model to simulate the entire biosensor-neuron system and to understand how the electronics and biological worlds interact each to the other. Using this model, I was able to explain some data that are present in literature. Moreover, I theorized that EGOFET biosensor can simultaneously stimulate and record the cell activity without the need of any gate or reference electrodes immersed into the bath solution. Thus, EGOFET-based sensors for extracellular recording without any implanted electrodes would be possible, increasing the biocompatibility of the implant and reducing the risk of infections.

PART 3 - PUBLICATIONS

List of publications on international journals

- J1. N. Wrachien, A. Cester, N. Lago, G. Meneghesso, R. D'Alpaos, A. Stefani, G. Turatti, M. Muccini "Stress-induced degradation of p- and n-type organic thin-film-transistors in the ON and OFF states" *Microelectronics Reliability*, vol. 54, no. 9-10, pp. 1638-1642, September-October 2014. DOI: [10.1016/j.microrel.2014.07.065](https://doi.org/10.1016/j.microrel.2014.07.065)
- J2. N. Wrachien, A. Cester, N. Lago, A. Rizzo, R. D'Alpaos, A. Stefani, G. Turatti, M. Muccini, and G. Meneghesso "Reliability study of organic complementary logic inverters using constant voltage stress" *Solid-State Electronics*, vol. 113, no. 11, pp. 151-156, November 2015. DOI: [10.1016/j.sse.2015.05.028](https://doi.org/10.1016/j.sse.2015.05.028)
- J3. N. Wrachien, N. Lago, A. Rizzo, R. D'Alpaos, A. Stefani, G. Turatti, M. Muccini, G. Meneghesso, and A. Cester "Effects of thermal and electrical stress on DH4T-based organic thin-film-transistors with PMMA gate dielectrics" *Microelectronics Reliability*, vol. 55, no. 9-10, pp. 1790-1794, August-September 2015, DOI: [10.1016/j.microrel.2015.06.073](https://doi.org/10.1016/j.microrel.2015.06.073)
- J4. A. Cester, A. Rizzo, A. Bazzega, N. Lago, J. Favaro, M. Barbato, N. Wrachien, S.A. Gevorgyan, M. Corazza, and F.C. Krebs "Effects of constant voltage and constant current stress in PCBM: P3HT solar cells" *Microelectronics Reliability*, vol. 55, no. 9-10, pp. 1795-1799, August-September 2015, DOI: [10.1016/j.microrel.2015.06.082](https://doi.org/10.1016/j.microrel.2015.06.082)
- J5. N. Lago, A. Cester, N. Wrachien, I. Tomasino, S. Toffanin, S. D. Quiroga, E. Benvenuti, M. Natali, M. Muccini, and G. Meneghesso "On the Pulsed and Transient Characterization of Organic Field-Effect Transistors", *IEEE Electron Device Letters*, vol.36 , no.12 , pp. 1359-1362, December. 2015, DOI: [10.1109/LED.2015.2496336](https://doi.org/10.1109/LED.2015.2496336)

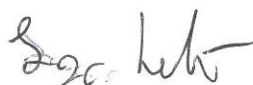
- J6. N. Lago, A. Cester, N. Wrachien, M. Natali, S. D. Quiroga, S. Bonetti, M. Barbato, A. Rizzo, E. Benvenuti, V. Benfenati, M. Muccini, S. Toffanin, and G. Meneghesso "A physical-based equivalent circuit model for an organic/electrolyte interface" *Organic Electronics*, vol. 35, pp. 176–185, August 2016. DOI: [10.1016/j.orgel.2016.05.018](https://doi.org/10.1016/j.orgel.2016.05.018)
- J7. N. Lago, A. Cester, N. Wrachien, E. Benvenuti, S. D. Quiroga, M. Natali, S. Toffanin, M. Muccini, and G. Meneghesso "Investigation of Mobility Transient on Organic Transistor by Means of DLTS Technique" *IEEE Transactions on Electron Devices*, vol. 63, no. 11, pp. 4432–4439, November 2016. DOI: [10.1109/TED.2016.2611142](https://doi.org/10.1109/TED.2016.2611142)
- J8. A. Rizzo, A. Cester, N. Wrachien, N. Lago, L. Torto, M. Barbato, J. Favaro, S. A. Gevorgyan, M. Corazza, and F. C. Krebs "Characterization and modeling of organic (P3HT:PCBM) solar cells as a function of bias and illumination" *Solar Energy Materials and Solar Cells*, vol. 157, pp. 337–345, December 2016. DOI: [10.1016/j.solmat.2016.06.001](https://doi.org/10.1016/j.solmat.2016.06.001)
- J9. N. Lago, M. Buonomo, N. Wrachien, F. Prescimone, M. Natali, M. Muccini, S. Toffanin, and A. Cester "A general equivalent circuit model for an organic/solution interface" *Rivista*. (SUBMITTED)

List of publications on conference proceedings

- C1. N. Wrachien, A. Cester, N. Lago, G. Meneghesso, R. D'Alpaos, A. Stefani, G. Turatti, and M. Muccini "Effects of constant voltage stress on organic complementary logic inverter" *2014 44th European Solid State Device Research Conference (ESSDERC)*, Venice, 2014, pp. 298–301. DOI: [10.1109/ESSDERC.2014.6948819](https://doi.org/10.1109/ESSDERC.2014.6948819)
- C2. M. Natali, N. Lago, M. Brucale, S. D. Quiroga, S. Bonetti, E. Benvenuti, E. Bonaretti, N. Wrachien, M. Muccini, A. Cester, V. Benfenati, and S. Toffanin "Investigation on the Mechanism of Bioelectrical Transduction at the Organic/Electrolyte Interface in Perylene-Based O-CST" *MRS – Fall Meeting*, 2015.
- C3. A. Rizzo, A. Cester, L. Torto, M. Barbato, N. Wrachien, N. Lago, M. Corazza, F. C. Krebs, and S. A. Gevorgyan "Effects of Current Stress and Thermal Storage on polymeric heterojunction P3HT:PCBM solar cell" *2016 IEEE International Reliability Physics Symposium (IRPS)*, Pasadena, CA, 2016, pp. 3C-2-1-3C-2-6. DOI: [10.1109/IRPS.2016.7574523](https://doi.org/10.1109/IRPS.2016.7574523)
- C4. N. Wrachien, L. Torto, N. Lago, A. Rizzo, G. Meneghesso, R. D'Alpaos, G. Generali, G. Turatti, M. Muccini, and A. Cester "Thermal Stress Effects on Organic-Thin-Film-Transistors" *12th International Conference of Organic Electronics ICOE-2016*, Bratislava, Slovakia.

28/08/2017

Student signature



Supervisor signature

