

Tuning Threshold Voltage in Organic Electrochemical Transistors by Varying Doping of the conjugated polymer p(g3T2-T)

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Preface

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Abstract

Organic Electrochemical transistors (OECTs) exhibit advantageous properties, such as high transconductance and steep-slope switching, while operating at very low voltages. Although, their switching speed is comparatively slower than solid-state devices, it remains sufficient for applications in bioelectronics [?]. The gold standard semiconductor for p-type OECTs is PEDOT:PSS. However, its main drawback lies in its depletion-mode operation, which requires power to turn off the device. To minimize power consumption and improve stability, efforts have been made to the design conjugated polymers that allow accumulation-mode devices. One such polymer, 3-(2-(2-(2-methoxyethoxy)ethoxy)ethoxy)thiophene (p(g3T2-T)) has demonstrated negative threshold voltages close to zero and high transconductance [?]. Furthermore, by doping p(g3T2-T) at various levels and drop-casting it as a gate, it has been possible to fine-tune the threshold voltage [?]. This study aims to adapt a microstructuring method for fabricating side-gated OECT devices that comprises different doping levels of F₄TCNQ and F₆TCNNQ in p(g3T2-T) and a solid-state electrolyte [?], the latter is deposited by inkjet printing. Additionally, the study aims to adjust the threshold voltage by utilizing these varying doping levels, while analyzing the stability and performance of the doped devices.

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List of Abbreviations and Symbols

Abbreviations

OEET	Organic Electrochemical Transistor
V _{th}	Threshold Voltage
CV	Cyclic Voltammetry
EIS	Electrical Impedance Spectroscopy
UPS	Ultraviolet Photoelectron Spectroscopy
XPS	X-Ray Photoelectron Spectroscopy

Symbols

c	Speed of light
E	Energy
m	Mass
π	The number pi

Chapter 1

Introduction

The field of organic electronics has witnessed significant advancements in recent years due to its biocompatibility, mechanical compliant, and other application-specific characteristics. Among the numerous types of organic devices, Organic Electrochemical Transistors (OECTs) have attracted considerable attention due to their unique capabilities such as high transconductance and steep-slope switching at low operation voltages, which give them potential for use in energy storage, bioelectronics and neuromorphic devices.

Accumulation-mode transistors, devices that are normally in the OFF state at zero-gate-biased condition, rely on the use of undoped conjugated polymers. In contrast, the ability to precisely control and tune threshold voltage of an OECT can be achieved by manipulating the doping level of the mentioned conjugated polymer [?]. Tan et al. fabricated devices that did not follow a complete microstructuring technique, limiting their integration into circuits.

The primary objective of this research is to address this missing information by developing a microstructuring method to fabricate accumulation-mode OECTs with controlled doping levels and enable their seamless integration into circuits. However, during the pursuit of this objective, it was identified that stability of dopants in an electrochemical environment may pose challenges that need to be addressed as well. Therefore, this research project specifically aims to:

1. Characterize 3-(2-(2-(2-methoxyethoxy)ethoxy)ethoxy)thiophene (p(g3T2-T)) with varying doping levels of F₄TCNQ and F₆TCNNQ. This involves chemically modifying the conjugated polymer with different concentrations of dopant and analyzing their electronic structure, morphology and electrical properties using techniques such as UV-Vis spectroscopy, Ultraviolet Photoelectron Spectroscopy (UPS), Atomic Force Microscopy (AFM), Van Der Pauw method, Electrical Impedance Spectroscopy (EIS) and Cyclic Voltammetry (CV),
2. fabricate OECT devices, which involves utilizing the conjugated polymer at different doping levels, and adapting an existing method that combines electrode patterning techniques, spin-coating, photolithography and inkjet printing. The devices will be carefully optimized to ensure reproducibility and stability,

3. assess doped polymer stability in OECT, which involves performing conductivity measurements over time and selecting an electrolyte composition that allows an stable performance, and
4. investigate the shift in threshold voltage through electrical characterization of the fabricated OECT devices with varying doping levels of F₄TCNQ and F₆TCNNQ.

The thesis is structured as follows: Chapter 1 provides an overview of organic electronics and the importance of the OECT threshold voltage, and outlines the motivation, goals, and structure of the thesis. Chapter 2 presents a comprehensive review of the relevant background information on Organic Semiconductors (OSCs), Organic Mixed Ionic Electronic Conductors (OMIECs), and Organic Electrochemical Transistors, and relevant research on tuning the threshold voltage of OECTs. Chapter 3 illustrates the Experimental Methods used in this research, describes the materials, equipment, software, and procedures to chemically dope the films and characterization method employed in the study. Finally, it outlines the fabrication and characterization process of OECT devices. In Chapter 4, the experimental results obtained are presented, from the characterization of the conjugated polymer at different doping levels and fabricated OECT devices. Analysis of the relationship between the doping level and the shift in threshold voltage. Finally, it discusses the implications of the findings and their relevance to the field. Lastly, Chapter 5 provides a summary of the research objectives and the extent to which they were achieved, suggests future research direction, and potential applications.

By addressing the aforementioned research goals and following the proposed thesis structure, this study aims to contribute in adapting an existing protocol to the conjugated material p(g3T2-T), in understanding the doping-dependent tuning of OECT threshold voltage and establish a foundation for the development of high-performance organic electronic devices.

Chapter 2

Background

2.1 Organic Semiconductors

Semiconducting properties of conjugated polymers built by alternating electron donor and acceptor moieties [1],

2.1.1 Electronic Structure

Since inorganic semiconductors' band theory does not take into consideration the Coulomb and exchange electron-electron interaction, which play a major role in organic semiconductors, it is necessary to add new theoretical approaches. On one hand, the transport properties are better described in terms of a hopping mechanism and the optoelectronic properties are better described by the molecular orbital picture [2]. Since the device under study in this work is a transistor and their transport properties in aqueous and quasi-solid environments, the theoretical approach used will be the hopping mechanism.

2.1.2 Molecular Doping

Use of small molecules Electron-deficient dopants such as 2,3,5,6 tetrafluoro-7,7,8,8-tetracyanoquinodimethane (F₄TCNQ) extract electrons from shallow HOMO p-type OMIECs, increasing hole concentration [3].

2.1.2.1 Measuring techniques to characterize doping

2.2 Organic Mixed Ionic/Electronic Conductors (OMIECs)

Initially investigated for batteries and super capacitors, where the induction of charges was the main objective of a semiconducting material, OMIECs has rapidly grown to include other applications, among them OECTs. [4]

Commonly semiconducting polymers which are redox-active and can simultaneously conduct ions and electrons. Electronic charges accumulated on the conjugated

polymer backbone result in secondary property changes in electrochemical potential and electronic conductivity, allowing OMIECs to be implemented in a variety of devices such as chemical sensors, organic electrochemical transistors, and energy storage electrodes [3].

2.2.1 A widely used material: PEDOT:PSS

Due to its commercial availability, operational stability, and relatively high performance, the conductive polymer poly(3,4-ethylenedioxythiophene) poly(styrene-sulfonate) (PEDOT:PSS) became a standard material for p-type OEECTs. Its main drawback lays in its depletion-mode operation, which requires a voltage to turn off the device (as represented in Figure 1(b)). With the aim of minimizing power consumption, there is a special interest to design semiconducting polymers that would allow accumulation-mode devices (Figure 1(c)) with high performance [5] [3].

2.2.2 Other Thiophene-based polymers

Thiophene is a planar conjugated ring structure consists of six delocalized pi-electrons. The aromatic nature arises from the four pi electrons and one unshared lone pair of electrons of the oxygen as six delocalized pi-electrons. It folow Huckle´s rule. Hene it is aromatic compound

Nielsen et al. reported a series of semiconducting polymers with Ethylene Glycol (EG) side chains designed to elucidate important strcuture-property guidelines for accumulation-mode OEECT operation. They demonstrated that an OEECT with 3-(2-(2-(2-methoxyethoxy)ethoxy)ethoxy)thiophene p(g3T2-T), as seen in Figure , has higher transconductance, and a turn-on voltage close to zero compared to other thiophene-based species [5]. While its backbone design warrant reversibility during electrochemical redox reactions and good electronic transport, the EG side chains enable its stability in aqueous electrolytes and efficient transport of ionic and electronic charge carrier [6]. Moser et al. studied the impact of the length of the EG side chain of this polythiophene backbone on the performance of OEECTs. They reported that reducing chain length would maximize the capacitance, but the increase of length would enhance ion-polymer interaction. Finally, they suggested an optimum length of 3 monomers in side chains over 2, 4 and 6 monomers [7]. The main advantage of p(g3T2-T) over PEDOT:PSS is its higher transconductance [5], the absence of extensive pre- and postprocessing to optimize polymer stability and electrochemical performance in aqueous media and the possibility of an accumulation-mode OEECT with low operation voltages[7].

2.2.3 Electrochemical Doping

2.3 Organic Electrochemical Transistors (OEECTs)

Organic Electrochemical Transistors (OEECTs) consists of metallic source, drain and gate electrodes, an organic semiconductor channel (specifically an OMIEC as

described in previous section) and an electrolyte that couples channel and gate [8]

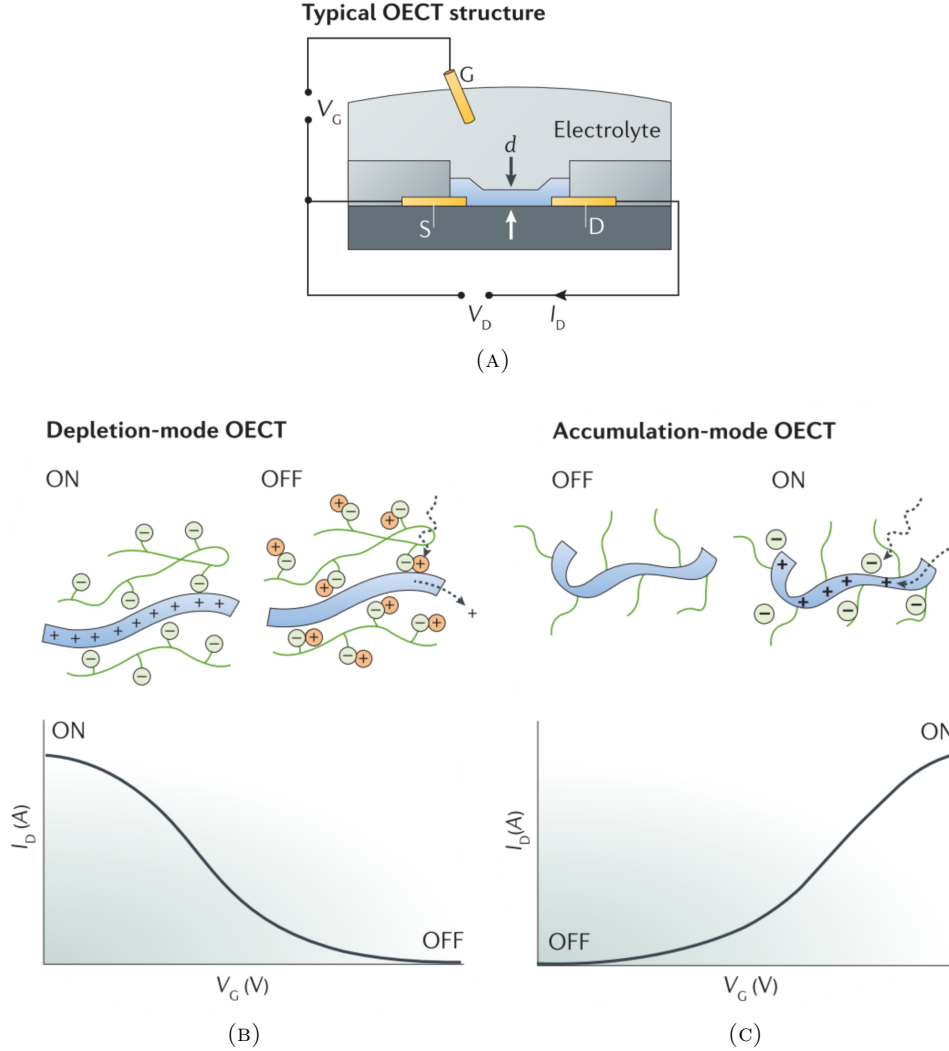


FIGURE 2.1: (a) Typical structure of an organic electrochemical transistor (OECT). (b) Transfer curve showing depletion-mode operation of an OECT with a conducting polymer channel. (c) Transfer curve showing accumulation-mode operation of an OECT with a semiconducting polymer channel. Images extracted from reference[?].

The semiconductor

devices that are mechanically compliant, biocompatible, and are sensitive to biochemical modules [9]

2.3.1 Device Physics

2.3.2 Operation Modes

2.3.3 Important Figures of Merit

2.3.3.1 Transconductance

2.3.3.2 μC^* product

2.3.3.3 Threshold voltage

An approach to shift the operating voltage range for PEDOT:PSS OECTs to lower the channel current, leading to reduced power consumption, is to tune the threshold voltage by de-doping PEDOT:PSS using commercially available amine-based molecular de-dopants [10]. Tan et al., on the other hand, explored a different approach, rather than modifying the doping level of the channel, they tuned the doping level of the gate to shift the threshold voltage. They used p(g3T2-T) and obtained a 400mV change with 60% mol ratio of 2,3,5,6-Tetrafluoro-7,7,8,8-tetracyanoquinodimethane (F4TCNQ) dopant. The advantage over this approach is i) protecting the material from oxidation, since the Fermi level is brought towards the highest occupied molecular orbital (HOMO), and ii) no interference with the channel which helps to leave the transconductance unaffected [11].

2.3.4 Requirements to Avoid Undesirable Side Reactions

Achieving effective charge transfer between the analyte and OMIEC requires appropriate alignment of the electrochemical potential of electrons on the OMIEC electrode and the redox specie. Failure to do so may result in the subsequent transfer of charges to other redox-active sinks in the environment, leading to undesirable side reactions and products that may interfere with the OMIEC's operation. Electrons flow from a region of higher to lower electrochemical potential. Hence, achieving electron transfer from redox-active species to the OMIEC requires the latter to have a deep LUMO (high electron affinity) [9]

2.3.5 Building Block for neuromorphic and bioelectronic applications

Chapter 3

Experimental Methods

3.1 Materials

All reactivities were purchased from commercial suppliers and non further chemical modification or purification was done unless stated before.

- Chromium etchant: Standard, Sigma Aldrich
- Developer: AZ 726 MIF Developer, Merck performance Materials GmbH
- EG: Ethylene glycol, $\geq 95\%$, Sigma Aldrich
- [EMIM][EtSO₄]: (1-Ethyl-3-methylimidazolium ethyl sulfate), $\geq 95\%$, Sigma Aldrich
- Gold etchant: Standard, Sigma Aldrich HHPAA (2-Hydroxy-4'-(2-hydroxyethoxy)-2-methylpropiophenone), 98%, Sigma Aldrich
- MBBAm (N,N'-Methylenebisacrylamide), 99%, Sigma Aldrich
- NIPAm: (N-Isopropylacrylamide), 97%, Alfa Aesar
- Orthogonal Developer: Orthogonal Developer 103a, Orthogonal Inc.
- Orthogonal Photoresist for undoped species: NLOF, Orthogonal Inc.
- Sacrificial layer: Sacrificial Layer (SL), Orthogonal Inc.
- Orthogonal Photoresist for doped species: OSCoR 4020 Photoresist, Orthogonal Inc.
- Orthogonal Stripper: Orthogonal Stripper 900, Orthogonal Inc.
- p(g3T2-T): 3-(2-(2-(2-methoxyethoxy)ethoxy)ethoxy)thiophene
- Dopants: 1,3,4,5,7,8-hexafluorotetracyanonaphthoquinodimethane and 1,3,4,5-tetrafluorotetracyanonaphthoquinodimethane

- Photoresist: AZ 1518 Photoresist, Merck Performance Materials GmbH & Microchemical GmbH
- Silane A174 (3-(Trimethoxysilyl)propyl methacrylate), TCI

3.2 Equipmment

- Baking: All baking steps were carried out on a Stuart SD160 digital hotplate (Stuart Equipment, UK).
- Electrical characterisation (ambient): Device characterisation under ambient conditions was performed on a Everbeing C-6 Probe Station (Everbeing Int'l Corp., Taiwan), connected to a Keithley 4200-SCS Semiconductor Characterisation System (Keithley Instruments, USA).
- Electrical characterisation (glovebox): Device characterisation was performed in a nitrogen-filled glovebox. Probing needles were connected to two Keithley 236 Source Measure Units (Keithley Instruments, USA).
- Impedance measurements: Impedance measurements were carried out by using a Metrohm Autolab PGSTAT302N potentiostat/galvanostat (Metrohm AG, Switzerland).
- Micrographs: Micrographs were taken on a Nikon Eclipse LV100ND microscope, equipped with a DS-Fi2 camera (Nikon, Japan).
- Photolithography: Photolithography was carried out on a SÜSS Microtec MJB4 maskaligner system (SÜSS Microtec AG, Germany).
- Photomasks: Photomasks were custom made by Compugraphics Jena in a 4 inch format (soda-line glass covered with chromium) and held several mask designs (Compugraphics Jena GmbH, Germany).
- Plasma cleaning: O₂-plasma cleaning was performed by using a Harrick PDC-002 plasma cleaner (Harrick Plasma, USA), connected to a Leybold Heraeus Combitron CM 330 Vacuum Gauge Controller (Leybold GmbH, Germany).
- Plasma etching. O₂-plasma etching was performed by using a Diener electronic ATTO plasma cleaner (Diener electronic GmbH & Co. KG, Germany).
- Profilometry. Profilometry was performed on a Veeco Dektak 150 surface profiler (Veeco Instruments Inc., USA).
- UV-Visible Spectroscopy: SolidSpec-3700 UV-Vis-NIR spectrometer from Shimadzu.
- Ultraviolet Photoelectron Spectroscopy (UPS): a helium discharge lamp (UVS10/35, Specs) was used and the main He I excitation line is at $h\nu = 21.22$ eV

- Spincoating. Samples were coated with a SAWATEC SM-180-BT spincoater (SAWATEC AG, Switzerland).

3.3 Software

- Data processing: All data was processed by customised scripts written in the Python programming language. Mathematical computations (e.g. fits, integration) were carried out by employing the Pandas, NumPy, and SciPy libraries. Visualisations were performed using the Matplotlib library.
- Electrical characterisation: Electrical characterisations were performed by controlling SMUs through the in-house developed SweepMe! software ().
- Profilometry: Profilometry was performed by using the Dektak software (Veeco Instruments Inc., USA).

3.4 Photomasks

Photomasks were employed during photolithography to cover or uncover the respective areas of interest, depending on the photoresist employed (positive or negative, respectively). Details are given in Chapter . The employed photomasks for OECT fabrication are shown in Figure , with a labeled close-up scheme of a transistor device given in Figure . All devices were designed in a side-gate structure with the 16 devices each mask comprised differing in channel length and gate distance. An overview of the specific dimensions is provided in Table with the designations assigning the devices (U1 – U8 (Up) and D1 – D8 (Down)). Since investigations on device dimensions were not a direct study object of this work, according assignments were left out. However, all comparisons between different substrates do of course always refer to the very same devices on each individual sample. A device assignment of all plots shown is given in Table S1. It shall be pointed out that the fabrication process did regularly lead to samples with several non-functioning devices. Accordingly, experiments were to be conducted on OECTs that were found working, which accounts for the variation in examined devices. For experiments of Chapter , available photomasks were arranged and covered to yield the setup shown in Figure . For experiments of Chapter , channels of p(g3T2-T) with underlying gold contacts were prepared. The corresponding photomasks are shown in Figure and were printed on plastic foil in a common inkjet printer. As schematically shown in Figure though, the lower big as well as several small gold contacts have not been used during execution. The lowest small gold contact served as source electrode.

3.5 Experimental Procedures

3.5.1 Conjugated polymer films

Unlike in reference [?], where drop cast is used to fabricate devices, in order to perform lithography and being able to do a miniaturization process, homogeneous films are needed. The following procedure has been established:

1. prepare 10mg/mL solution of p(g3T2-T) in chloroform at 60°C,
2. prepare 5, 10 and 20 mg/mL solution of F₄TCNQ in acetonitrile at 60°C,
3. clean substrates with subsequent steps of ultrasonic bath with acetone for 15 minutes, rinse with IPA, drying with N₂ and O₂-plasma,
4. dynamic spin coat 70μL of p(g3T2-T) at 3000RPM for 60s,
5. if preparing a doped sample, dynamic spin coat 140μL of each dopant solvent at different concentrations on top, to yield approximately 70 nm thick layer, and
6. postbake at 80°C.

3.5.2 Fabrication of Organic Electrochemical Transistors

After following the patterning process to obtain Au contacts from reference , undoped and doped p(g3T2-T) was deposited following the procedure described before. After some trials, different patterning process were defined for undoped and doped films.

3.5.2.1 Undoped p(g3T2-T) OECT

1. Sacrificial Layer 1 (SL1, fluoropolymer provided by Orthogonal Inc.) was spincoated (6000 RPM for 60s) and baked for 60s at 113°C.
2. To promote adhesion, sample was placed in plasma (UFO2) for 60s.
3. NLOF 2020 (commercial negative-tone photoresist from Microchemicals) was spincoated (3000 RPM for 60s) and baked for 60s at 113°C.
4. NLOF was exposed for 12s to structure channel and gate (although only channel is used).
5. After postbaking (60s at 113°C), NLOF was developed by rinsing the sample in AZ MIF 726 (commercial developer for NLOF 2020) for 20s and wash off in DI water (carried out extra times if necessary).
6. SL1 was developed using HF 7300 developer for 20s and spin rinsed at 3000RPM (carried out extra times if necessary):
7. Excess p(g3T2-T) was removed by O₂-plasma etching (180s)

8. Finally, the sample was placed in Orthogonal Stripper 902 overnight at room temperature.
9. Ultrasonic bath with stripper is followed if NLOF pattern is still on sample.

3.5.2.2 Doped p(g3T2-T) OECT

1. Orthogonal photoresist OSCoR 4020 (provided by Orthogonal Inc.) was spin-coated (3000 RPM for 60s) and baked for 60s at 103°C.
2. OSCoR was exposed for 20s (increase one extra cycle if using higher dopant concentration) to structure channel and gate (although only channel is used).
3. After postbaking (60s at 103°C), development followed by covering the sample with Orthogonal Developer 103a and removing it by spinning at 3000RPM after 50s (carried out extra times if necessary, if higher dopant concentration is used, start with 30s development).
4. Excess doped p(g3T2-T) was removed by O₂-plasma etching (180s)
5. The sample was placed in Orthogonal Stripper 902 over night at room temperature.
6. Finally, to prepare for measurements, blow off excess of stripper with N₂ and add 20 μ L of solid state electrolyte (SSE) in liquid state.

Chapter 4

Results and Discussion

4.1 Doped Conjugated Polymer films

4.1.1 Polaron and Bipolar formation

4.1.2 Workfunction increase

4.1.3 Redox properties with Solid State Electrolyte Precursor

4.2 Organic Electrochemical Transistors

4.2.1 Channel and gate morphology

4.2.2 Channel conductivity

4.2.2.1 Under inert conditions

4.2.2.2 Under ambient conditions

4.2.3 Threshold voltage shift

The Ag/AgCl gate electrode's work function is reasonably constant, the work function of an OMIEC gate electrode however may vary depending on its processing history and redox reactions with other species present in the electrolyte (e.g. molecular oxygen).²⁸ Applying VGS only determines the potential difference between the gate and channel but does not control the potentials of either electrode (hence the position of the Fermi level) with respect to a reference. This leads to many challenges in operating an OECT with OMIEC gate electrodes.

4.2.4 Important figures of merit

Chapter 5

Conclusion and Outlook

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