

# 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 [1]. The gold standard conjugated polymer 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-methoxyethoxy)ethoxy)thiophene (p(g3T2-T)) has demonstrated negative threshold voltages close to zero and high transconductance [2]. 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 [3]. This study aims to adapt a microstructuring method for fabricating side-gated OECT devices that comprises different doping levels of F<sub>4</sub>TCNQ and F<sub>6</sub>TCNNQ in p(g3T2-T) and a solid-state electrolyte [4], 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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# Chapter 1

## Introduction

The field of organic electronics has witnessed significant advancements in recent years due to its potential 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 as shown by Tan et al. [3]. However, they 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 the polymer and 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 F<sub>4</sub>TCNQ and F<sub>6</sub>TCNNQ. 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), 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,

## 1. INTRODUCTION

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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 F<sub>4</sub>TCNQ and F<sub>6</sub>TCNNQ.

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.

# Chapter 2

## Background

### 2.1 Organic Semiconductors

Unlike inorganic semiconductors, organic semiconductors are lightweight, easy to chemically tune, mechanical flexible, and offer low-cost and low-temperature processing. All of these characteristics are responsible for the increased attention to this type of materials in the field of organic electronics.

#### 2.1.1 Electronic Structure and Transport

Organic semiconductors are  $\pi$ -conjugated molecules that comprise mostly carbon and hydrogen atoms, with alternating multiple ( $sp^2$  hybridization) and single ( $sp$  hybridization) bonds. The wavefunction of the  $sp^2$  orbitals overlap so that electrons can be delocalized. Based on the size of the conjugated system, organic semiconductors can be divided into conjugated polymers and small molecules. The latter has the advantage of being ordered and its synthesis allows to obtain high purity material [5].

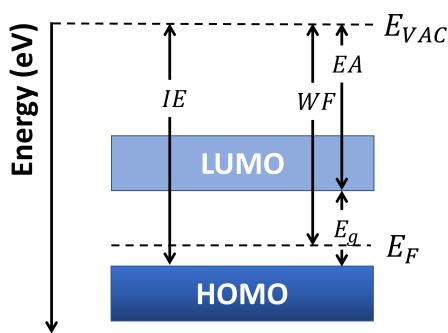


FIGURE 2.1: Energy level diagram of an p-type doped organic semiconductor.

The energy structure of organic semiconductors comprises a highest occupied molecular orbital (HOMO) state and a lowest unoccupied molecular orbital (LUMO) state, which are analogous to the valence and conduction bands, respectively, from

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inorganic semiconductors. The difference between these energy levels corresponds to the energy gap ( $E_g$ ) of the material, as illustrated in Figure 2.1. Additionally, we can define i) the Fermi level ( $E_F$ ) using the material's work function (WF), ii) the ionization energy (IE), also referred as ionization potential (IP), using the HOMO energy, and iii) the electron affinity (EA), using the LUMO energy.

Organic semiconductor materials can also be classified based on whether their ground state is degenerate or non-degenerate. In the former case, the term “degenerate” describes monomers that have equivalent energy states in the ground state. In contrast, in the latter case, the ground state exhibits non-degeneracy, which is commonly observed due to the energy difference of aromatic (benzoid) and quinoid structures [6], as exhibited in Figure 2.2.

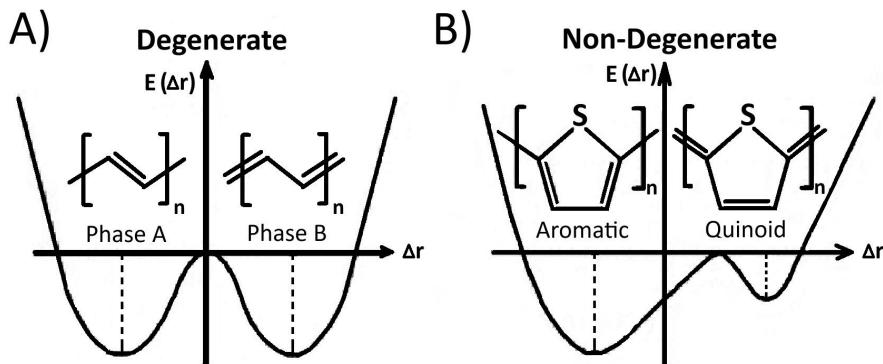


FIGURE 2.2: Potential energy change (electronic plus lattice distortion energy) in A) degenerate and B) non-degenerate ground-state-conjugated polymers. Extracted from reference [7].

In electronic transport theory within organic semiconductors, the concept of polarons is introduced. This quasiparticle effectively captures the alteration of the bond-length alternation pattern induced by the movement of charge carriers (electrons or holes) [8]. This alteration can be observed, for instance, when transitioning from Phase A to Phase B in degenerate molecules, or from aromatic to a quinoid structure in non-degenerate molecules.

### 2.1.2 Molecular Doping

The basic principles of molecular doping are similar than in inorganic materials. A donor or acceptor entity is added to generate electrons or holes, as shown in Figure 2.3. While n-type dopants donate electrons to the lowest unoccupied molecular orbital (LUMO) states, the p-type dopants extract electrons from the highest occupied molecular orbital (HOMO) states, thus creating holes [9]. In other words, the Fermi level  $E_F$  of the polymer will shift towards the LUMO (or HOMO) level when there is n-type (or p-type) doping. This shift can be quantified using spectroscopy techniques such as Ultraviolet Photoelectron Spectroscopy (UPS) at room temperature (RT)

## 2.1. Organic Semiconductors

[10], although it may be somewhat limited by the penetration depth of the incoming electrons.

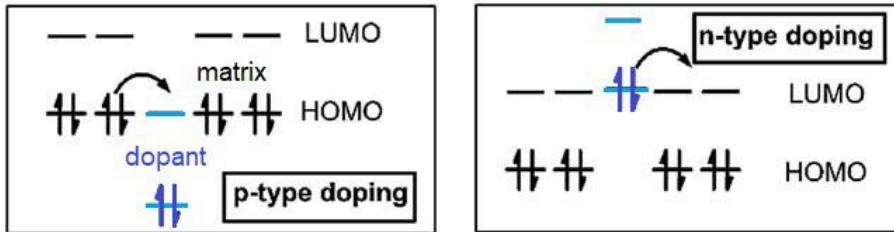


FIGURE 2.3: Schemes for p-type (left) and n-type (right) doping processes. Extracted from reference [9].

When doping occurs, the formation of a new quasiparticle named bipolaron occurs. For instance, if p-type dopants are introduced to a degenerate molecule (as depicted in Figure 2.4), electrons are removed from double bonds. Focusing on a single event, this removal leaves one carbon positively charged, with an adjacent carbon atom possessing an unpaired electron. This unpaired electron moves along the polymer chain until it encounters another unpaired electron from a separate doping event. When they come together, they form a double bond, resulting in the creation of two charged polarons: a bipolaron [11].

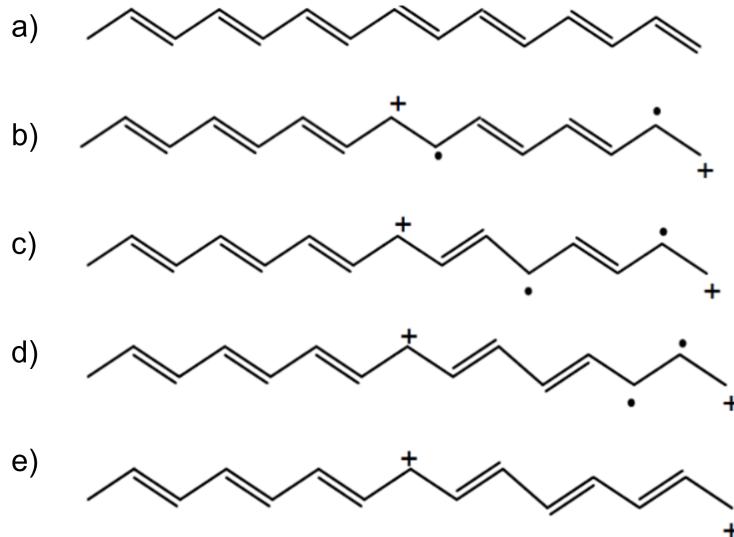


FIGURE 2.4: a) Structure of degenerate molecule. b) Electron extraction via doping. c) Unpaired electron shifting down. d) Unpaired electrons meet. e) Formation of double bond and two charged polarons: bipolaron.

The energy levels generated upon the formation of polarons and bipolarons in non-degenerate molecules are illustrated in Figure 2.5. As the doping density increases, the amount of bipolaron states also increases. Their overlapping leads to

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the formation of bipolaron bands, and the energy difference between the two in-gap states  $i$  and  $i^*$ , as shown from Figure 2.5B to D, decreases.

In addition to these new electronic states, the doped polymer will also exhibit distinct optical transitions that could be revealed through UV-Vis-NIR spectroscopy. In this technique, absorption peaks indicate the presence of these optical transitions. However, these transitions may not be precisely quantified or clearly defined [7].

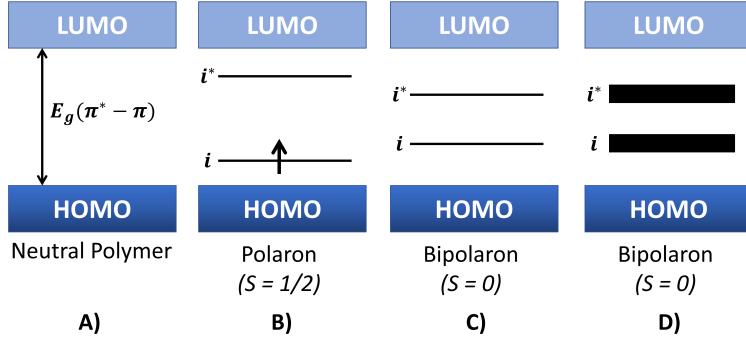


FIGURE 2.5: Potential energy change of aromatic and quinoid in the non-degenerate ground-state A) neutral conjugated polymer, and formation of B) polaron, C) bipolaron, and D) bipolaron bands upon doping. Extracted from reference [7].

The use of small molecules as dopants for organic materials is commonly reported. Some strong acceptor (or electron-deficient) molecules that are widely used include 2,3,5,6 tetrafluoro-7,7,8,8-tetracyanoquinodimethane ( $F_4TCNQ$ ) or 1,3,4,5,7,8 hexafluoro-7,7,8,8-tetracyanonaphthoquinodimethane ( $F_6TCNNQ$ ), both of which are also relevant to this work. The latter exhibits a higher electronic affinity (-5.3 eV) than  $F_4TCNQ$  (-5.2eV), indicating that it can abstract electrons more efficiently, specially from polymers with low ionization potential (less than 5eV) [12].

Among the various methods of molecular doping for conjugated polymers, Jacobs et al. conducted a comparison between solution-mixed and solution-sequential doping of P3HT, a thiophene-based polymer, doped with  $F_4TCNQ$ . These doping methods are considered straightforward and easy, especially when compared to other techniques such as vapour-phase doping [13]. Their research showed that solution-mixed films tend to have considerably rougher surface than solution-sequential films, which can negatively impact their conductivity [14]. The fact that solution-sequential doped films exhibit better homogeneity also makes them more compatible with microstructuring processes such as photolithography. However, this advantage comes at the expense of having less control over the doping levels when compared to solution-mixed films [15].

## 2.2 Organic Mixed Ionic/Electronic Conductors (OMIECs)

Organic Mixed Ionic/Electronic conductors are a class of organic semiconductors that allow the conduction of electrons (or holes) and ions. This feature sets them apart from other organic semiconductors. Commonly designed with polar side chains, OMIECs have been identified as a promising class of materials for the field of bioelectronics [16]. Initially investigated for batteries and super-capacitors [17] [18], where the primary objective was to induce charges in a semiconducting polymer, OMIECs have rapidly expanded their scope to include other applications, among them, our focus: OECTs.

Paulsen et al. classified OMIECs into six different categories based on whether they *intrinsically contain ionic charge* (I, III, V) or not (II, IV, VI), the latter group comprises materials that “*contain polar moieties that can solvate ions*”. Another distinguishing factor among these categories is whether the conjugated system is composed of a single material (homogeneous, type V and VI) or a two-component, more complex systems or block co-polymer materials (heterogeneous, type I, II, III, IV)[19]. A schematic representation is shown in Figure 2.6.

### 2.2.1 Processes in OMIECs

#### 2.2.1.1 Ionic-electronic interactions

The presence of electronic charge in OMIECs requires also the presence of excess ionic charge, so charge in the system remains in balance. In the case of types II, IV, and VI OMIECs, a phenomenon known as stabilizing electrochemical doping is achieved through the presence of mobile ions that act as free charges. Conversely, other types of OMIECs have these stabilizing charges chemically bound and fixed, making them inherently doped.

The degree of coupling between electronic charges and excess ionic charges in OMIECs can be modulated by applying a bias when connected through an electrolyte [19]. This fundamental principle forms the basis of OECTs, which will be discussed further in Section 2.3.

#### 2.2.1.2 Electronic transport

Electronic charge transport mechanisms present in OMIECs include thermally-activated hopping and band-like transport, as depicted in Figure 2.7. These mechanisms are not different from those observed in other conjugated polymers.

Thermally-activated hopping, as its name implies, is driven by thermal energy and is limited by the degree of structural disorder. In this mechanism, weakly-bonded electrons in delocalized  $\pi$ -orbital move along adjacent  $\pi$ -orbitals within the length of the conjugated polymer, or even between molecules where there is sufficient  $\pi$ - $\pi$  overlapping. This mechanism predominates when there is a low electronic charge carrier density and a low density of accessible hopping states, resulting in low mobility and electrical conductivity [19].

## 2. BACKGROUND

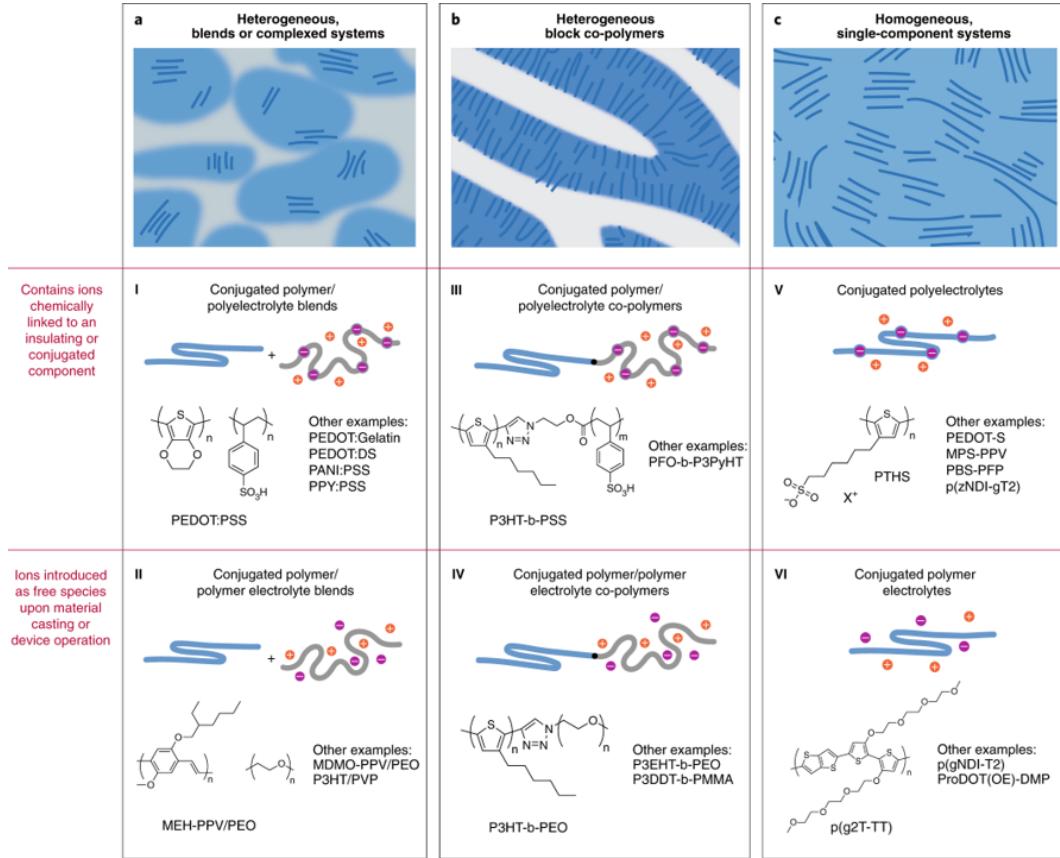


FIGURE 2.6: **OMIECs classes.** a) Heterogeneous blends of a conducting conjugated polymer with (I) a polyelectrolyte or (II) an ion-solvating polymer electrolyte. b) Heterogeneous block copolymers of a conducting conjugated polymer with (III) a polyelectrolyte or (IV) an ion-solvating polymer electrolyte. c) Fully conjugated (V) polyelectrolytes and (VI) ion-solvating polymer electrolytes. Extracted from reference [19].

In contrast, band-like transport, typically occurs in OMIECs with increasing doping levels. In this case, the activation energy of charge hopping decreases, and carrier mobility increases. This leads to diffuse band-like charge transport within the polymer-stacking [20].

### 2.2.1.3 Ionic transport

While the transport of charged anions and cations in OMIECs share some similarities with the transport of electrons and holes, it is a more complex process, since ions can be “*multi-valent, and form pairs and larger clusters; moreover, they are sensitive to solvent and solvation*” [19].

Ion transport in dry OMIECs of type I, III, and V is unipolar because these ions are fixed on a polyelectrolyte. In contrast, in type II, IV, and VI OMIECs,

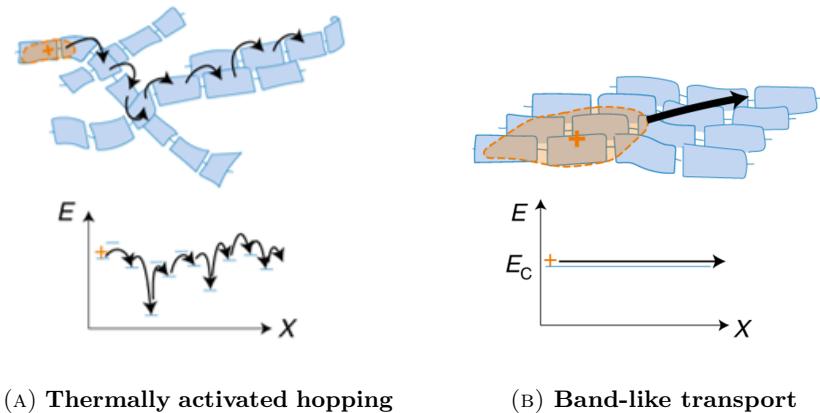


FIGURE 2.7: Schematic representation of electronic charge transport mechanisms: A) Thermally-activated hopping transport and B) band-like transport, where the electronic charge carrier is relatively localized and delocalized, respectively. Extracted from reference [19].

both anions and cations are mobile. When OMIECs come into contact with an electrolyte, they tend to swell, allowing the penetration of excess ions from the electrolyte. Therefore, both mobile anions and cations contribute to ion transport to ensure electroneutrality.

There are two types of ionic charge transport in OMIECs: ion hopping and vehicular solvated-ion transport. In dry or minimally hydrated OMIECs, ion hopping assisted by segmental motion of the OMIEC side chains or backbone is the primary mechanism, as shown in Figure 2.8A. However, when OMIECs are in contact with a solvent or liquid electrolyte, both mechanisms are present, with solvated ion vehicle transport being the predominant mode. For instance, in water-based electrolytes, proton diffusion occurs via the Grotthuss mechanism, where protons within water molecules diffuse through neighboring molecules. This involves a transfer of ionic effects through the hydrogen-bonded network, as shown in Figure 2.8B.

Due to the existing ionic-electronic coupling, both ionic and electronic transport in OECTs and other OMIEC-electrolyte-based applications are not independent but are rather complex and must consider side effects such as hydration and electrolyte swelling [19], as will be further discuss in Section 2.3.

### 2.3 Organic Electrochemical Transistors

Organic Electrochemical Transistors are composed of metallic source, drain and gate electrodes, an organic conjugated polymer channel (specifically an OMIEC as described in previous sections), and an electrolyte that bridges the channel and the gate, as illustrated in Figure 2.10A. OECTs are devices that have received increasingly attention due to their mechanically compliance, biocompatibility, and sensitivity to biochemical signals [21].

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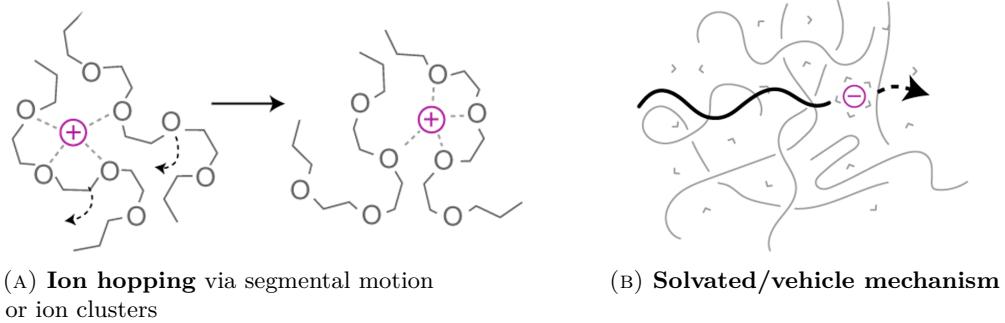


FIGURE 2.8: Schematic representation of ionic charge transport mechanisms: A) Ion hopping via segmented motion and B) vehicular solvated-ion transport. Extracted from reference [19].

### 2.3.1 Device Physics

Although the structural configuration of OECTs differs from conventional metal-oxide-semiconductor field-effect transistors (MOSFETs), understanding the operation of the latter can provide insight into how OECTs function. In contrast to MOSFETs, where an insulator is used, OECTs are coupled with an electrolyte, as shown in Figure 2.9. When a gate voltage is applied, instead of polarizing the dipoles in the insulator and creating a field that causes accumulation of carriers at the interface of the semiconductor/insulator, as is the case with MOSFETs, in OECTs, the gate voltage drives ions to penetrate the bulk of the channel. Consequently, accumulation of carriers occurs throughout the whole volume of the OMIEC film. This mechanism explains the large gate-channel capacitance observed in these devices compared to MOSFETs and why the drain current takes into account a volumetric capacitance [22].

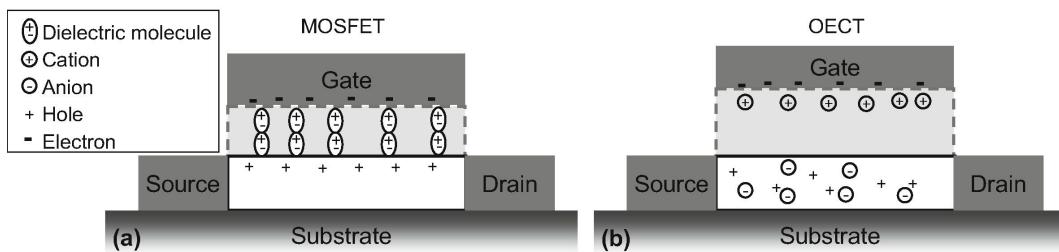


FIGURE 2.9: Comparison of p-type A) MOSFET and B) OECT, where the light-gray region represents an insulator and a electrolyte, respectively. Extracted from reference [22]

Bernards and Malliaras implemented a model based on a p-type depletion-mode OECT (based on PEDOT:PSS as it is widely studies and fabricated material, further discussion in the following section). The model divides the behavior of the OECT into two circuits: an electronic circuit (comprising the source-channel-gate structure)

and an ionic circuit (comprising the gate-electrolyte-channel structure).

The electronic circuit is treated as a *variable* resistor and is thus modeled using Ohm's law. Its variability arises from the fact that when a positive gate voltage is applied, de-doping of the semiconductor occurs, which is analogous to the compensation doping observed in silicon. Cations from the electrolyte penetrate the polymer, compensating for an acceptor.

Meanwhile, the ionic circuit consists of a resistor that represents the flow of ions in the electrolyte, connected in series with a capacitor representing the storage of ions in the channel, as shown in Figure 2.10B [1][23].

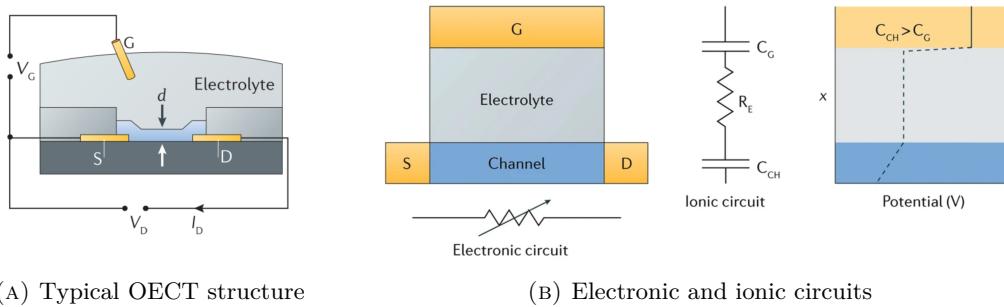


FIGURE 2.10: A) Typical structure of an organic electrochemical transistor (OECT). B) (Left) Electronic circuit modelled as a resistor with a variable resistance. (Right) Ionic circuit consisting of channel ( $C_{CH}$ ) and gate ( $C_G$ ) capacitors, coupled with a resistor corresponding to the electrolyte ( $R_E$ ). Extracted from reference [1].

### 2.3.2 Operation Modes

Analogous to conventional MOSFETs, depending on whether the device requires a gate potential to be turned ON, OECTs exhibit two operation modes: depletion and enhancement (the latter often referred to as accumulation in the context of OECTs). The operation modes are closely linked to the nature of the channel material.

As illustrated in Figure 2.11A and B, the polymer can be either intrinsically doped (conductive) or undoped (insulating). In the first scenario, the OMIEC already possesses anions that induce charges within its backbone. Consequently, to turn off the device, cations need to be injected to counteract this effect. Conversely, for an insulating polymer channel, a zero-gate biased OECT will have no charges induced in its backbone, resulting in the OFF state. To transition to the ON state, a gate voltage is required to drive anions into the polymer and induce charges.

#### 2.3.2.1 Standard material for depletion-mode OECTs

Poly(3,4-ethylenedioxythiophene) poly(styrene-sulfonate) (PEDOT:PSS) is a “*degenerately doped*” [23] or conductive polymer that is widely used in various applications in organic electronics. Classified as type I OMIEC, as seen in Figure 2.6, it is a blend between a conjugated polymer (PEDOT) and a polyelectrolyte (PSS), the latter

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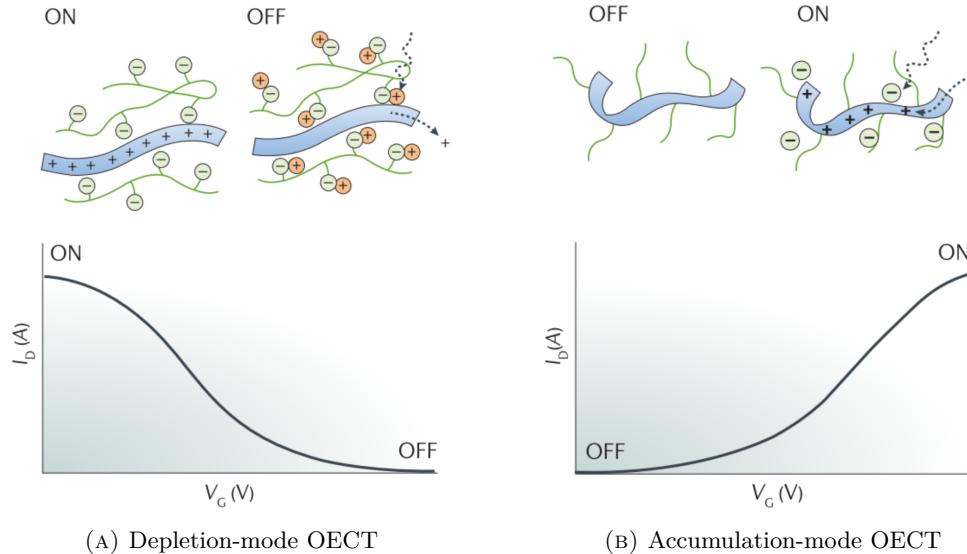


FIGURE 2.11: (A) Transfer curve showing depletion-mode operation of a p-type OECT with a conducting polymer channel. (B) Transfer curve showing accumulation-mode operation of a p-type OECT with a semiconducting polymer channel. Images extracted from reference [1].

possesses chemically linked ions and serves as a polymeric acid template to allow dispersable suspensions [19].

Due to its commercial availability, operational stability, and relatively high performance, PEDOT:PSS became a standard material for p-type OECTs. However, its main drawback lies in its depletion-mode operation.

With the aim of minimizing power consumption, there is a strong interest in fabricating high-performance accumulation-mode devices [2][15][24][25]. These devices offer the advantage of dissipating less static power when the device is not in operation, due to low OFF current [16].

### 2.3.2.2 Prospective materials for accumulation-mode OECTs

PEDOT:PSS has not been ruled out as a possible accumulation-mode OECT, Keene et al. employed a series of amines to de-dope PEDOT:PSS and achieve OECTs with negative turn-on voltages [25]. However, synthetically modifying PEDOT:PSS in a controlled manner remains a challenge.

In parallel to these efforts, researchers are also working on the design of new semiconducting polymers with the aim of not only having accumulation-mode OECTs but enhancing their performance. Nielsen et al. reported a series of semiconducting polymers with triethylene glycol (TEG) side chains, some of which demonstrated good performance. Among the five thiophene- and benzodithiophene-based polymers, they found out that the one with a backbone consisting of 2,2'-bithiophene polymerized

### 2.3. Organic Electrochemical Transistors

with other thiophene molecule (g2T-T), as seen in Figure 2.12, exhibited the highest performance [2].

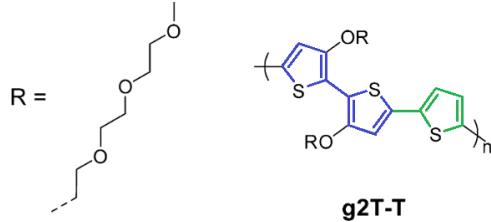


FIGURE 2.12: Chemical structure of polymer with backbone g2T-T, R representing the side chain. Extracted from reference [2].

Moser et al. conducted a study using the same backbone (g2T-T) to investigate the impact of the length of the ethylene glycol (EG) side chain on the performance of OECTs [26]. They found that reducing the side chain length maximized both the capacitance and mobility of the OECTs. However, shorter side chain were less favorable for ion-polymer interaction.

Their research suggested an optimum-side-chain length of 3 monomers, compared to 2, 4 and 6 monomer. OECTs based on 3-(2-(2-methoxyethoxy)ethoxy)thiophene (p(g3T2-T)) exhibited a turn-on voltage close to zero and superior performance compared to other thiophene-based species (as seen in Figure 2.13 and Table 2.1), even surpassing PEDOT:PSS-based OECTs [24].

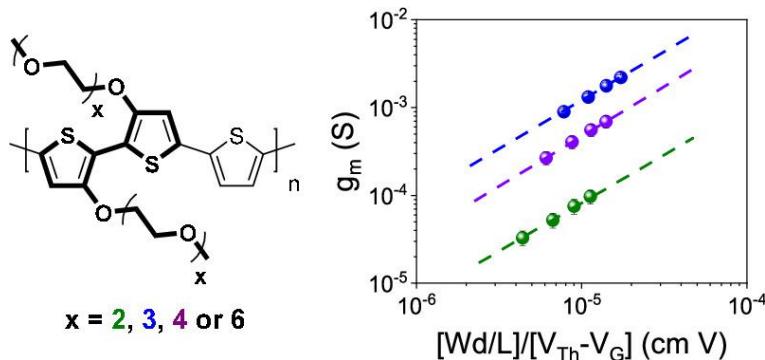


FIGURE 2.13: (Left) Chemical structure of the repeat units for p(gxT2-T). (Right) Transconductance vs channel geometry and operating parameters of p(gxT2-T) for  $x = 2, 3, 4$  and 6. Extracted from reference [26].

The structural tuning of the polymer was designed to have a backbone that warrants reversibility during electrochemical redox reactions and good electronic transport, while the side chains enhance its stability in aqueous electrolytes and facilitate efficient transport of both ionic and electronic charge carrier [27].

Under the classification presented in Figure 2.6, p(g3T2-T) can be categorized as a type VI OMIEC that consists of a conjugated polymer with ions introduced as **free species**. Whereas, PEDOT:PSS contains ions that are **chemically linked** to

## 2. BACKGROUND

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the polyelectrolyte (PSS). This structural distinction results in p(g3T2-T) displaying larger magnitudes of ionic-electronic coupling and volumetric capacitance compared to biphasic OMIECs like PEDOT:PSS [19]. Understanding these structural characteristics is crucial for addressing the challenges associated with achieving stable OECTs.

TABLE 2.1: Volumetric capacitance ( $C^*$ ) of OECTs channel materials including p(g2T2-T), p(g3T2-T), p(g4T2-T) [26] and PEDOT:PSS [24] using a 0.1 NaCl electrolyte and Ag/AgCl pellet electrode.

Polymer	$C^* \text{ (Fcm}^{-3}\text{)}$
p(g2T2-T)	8±2
p(g3T2-T)	211±18
p(g4T2-T)	192±10
PEDOT:PSS	39

### 2.3.3 Important Figures of Merit

#### 2.3.3.1 Transconductance

Transconductance is considered as the most important parameter for measuring the amplification capability of any transistor. It is calculated as the first-order derivative of the output current (drain current) with respect to the input voltage (gate-source voltage), expressed as  $g_m = \partial I_D / \partial V_{GS}$ . Bernards and Malliaras derived this parameter in their mathematical model for depletion-mode p-type OECTs [23], as discussed in Section 2.3.1. When considering both n-type and p-type OECTs, the transconductance can be expressed as follows:

$$g_m = \frac{Wd}{L} \mu C^* |(V_{th} - V_G)|, \quad (2.1)$$

where  $W$ ,  $L$  and  $d$  are the channel width, length, and thickness, respectively,  $\mu C^*$  denotes the product of mobility and volumetric capacitance, while  $V_G$  and  $V_{th}$  stand for the gate voltage and threshold voltage, which will be further discussed in the following subsections.

Typically, the maximum transconductance ( $g_{m,max}$ ) is reported, which falls into the saturation regime. Inal et al. reported the maximum transconductance for various channel materials with different device geometry parameters. They used an Ag/AgCl pellet as reference/gate electrode and 0.1M NaCl as electrolyte. Their results showed that OECTs with polymerized g2T backbones exhibited the best performance, achieving transconductance values ranging from 1 to 30 mS, depending on the geometry (Figure 2.14A) [24].

#### 2.3.3.2 $\mu C^*$ product

The parameter  $\mu C^*$  is considered the most important for benchmarking OECT channel materials because it represents both the ionic and electronic transport

### 2.3. Organic Electrochemical Transistors

properties [24]. It is the product of two important parameters,  $\mu$ , the electronic mobility, and  $C^*$ , the volumetric capacitance, the latter encloses the ion penetration, transport, and storage ability of the OMIEC film.

Along with the transconductance, Inal et al. determined the values of  $\mu C^*$  by calculating the linear slope of the maximum transconductance and channel geometry (Figure 2.14A), using Equation 2.1. They correlated their results with independent calculations of both parameters and found that polymerized g2T backbones exhibited the highest  $\mu C^*$  value of  $261 \pm 29 \text{ F cm}^{-1} \text{ V}^{-1} \text{ s}^{-1}$ . Among the materials that showed a close 1:1 relationship for both methods of calculation of the  $\mu C^*$  product, polymerized g2T backbones stood out (Figure 2.14B) [24].

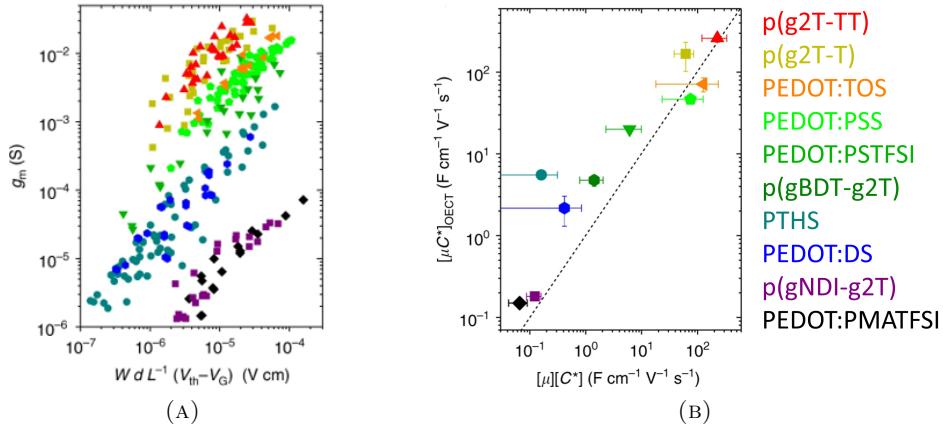


FIGURE 2.14: A) Plot of  $\mu C^*$  product calculated by the linear slope between transconductance and channel geometry. B) Calculated slope from A) in function of the product of independent determination of  $\mu$  and  $C^*$ , dotted line represents the 1:1 relation between both methods of calculation. Extracted from reference [24].

Calculating the electronic mobility ( $\mu$ ) independently is challenging due to the presence of ionic species. This calculation is normally performed in transient regimes, taking advantage of ions' lower mobility, but it is outside the scope of this work.

One method to calculate the volumetric capacitance ( $C^*$ ) is by performing Electrochemical Impedance Spectroscopy (EIS). Equation 2.2 is used to calculate the capacitance ( $C$ ) based on the imaginary part of impedance ( $Z^{img}$ ) at low frequency ranges where the capacitance should describe a plateau. The calculated capacitance is then divided by the film volume to obtain  $C^*$  [28].

$$C = \frac{1}{2\pi \cdot f \cdot |Z^{img}|}, \quad (2.2)$$

It is important to note that the capacitance ( $C$ ) can be potential-dependent when electrochemical doping is modulated in OECTs with an applied bias [24].

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### 2.3.3.3 Threshold voltage

The threshold voltage ( $V_{th}$ ) in an OECT can be determined from the steady-state transfer characteristics ( $I_D$  vs  $V_{GS}$ ). To calculate  $V_{th}$ , you can plot the square root of  $I_D$  as a function of  $V_{GS}$  and extrapolate the linear portion of the slope, where it intersects the x-axis. This value of  $V_{th}$  represents the “film’s readiness for ion penetration” in OECTs [28].

Controlling or shifting the threshold voltage is desirable, specially for integrating transistors into circuits to meet specific requirements for operation, noise margins, and power consumption. There are different approaches to achieve this. One approach is the chemical de-doping of PEDOT:PSS, as discussed in previous sections, which can shift the threshold voltage to negative values characteristic of accumulation-mode OECTs [25].

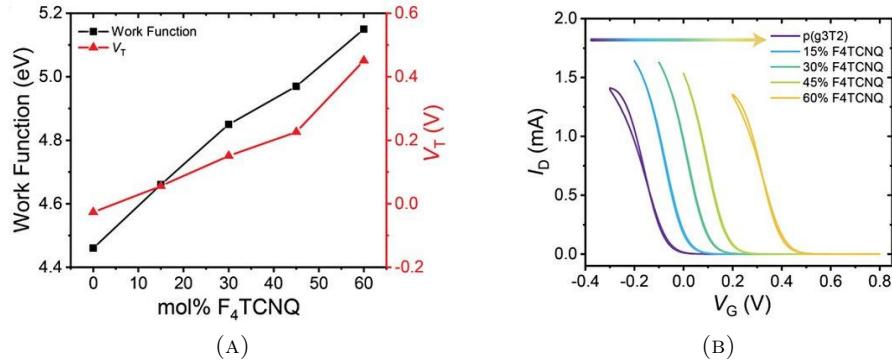


FIGURE 2.15: Controlling OECT threshold voltage by chemical doping of p(g3T2-T) gate electrode with  $F_4TCNQ$ . A) Plot of threshold voltage and gate work function for doped gates of different dopant concentrations. B) Transfer curves of p(g3T2-T) channel OECT with p(g3T2) gates of various  $F_4TCNQ$  dopant concentrations. Extracted from reference [3].

Another approach, explored by Tan et al., involves tuning the doping level of the gate to shift the threshold voltage. They used p(g3T2-T) and achieved a 400mV change in threshold voltage with a 60% molar ratio of 2,3,5,6-Tetrafluoro-7,7,8,8-tetracyanoquinodimethane ( $F_4TCNQ$ ) dopant, as shown in Figure 2.15. This approach offers advantages such as i) protecting the material from oxidation by bringing the Fermi level towards the highest occupied molecular orbital (HOMO), and ii) avoiding interference with the channel which helps to maintain the transconductance unaffected [3].

### 2.3.4 Side Reactions

#### 2.3.4.1 Water uptake and swelling

Water uptake and swelling are important side reactions that occur when OMIECs come into contact with water-based electrolytes. Even in the pursuit of solid-state

OECTs, precursors may contain a certain degree of water content [4][29], making it necessary to understand the impact of water-related side reactions.

Water uptake in OMIECs causes their increase of mass (swelling) and changes in morphology. This water uptake occurs because OMIECs need to compensate for their intrinsic doping, and as a result, “*the effect of doping-induced hydration on the OMIEC morphology must be taken into account when designing OECTs*” [30].

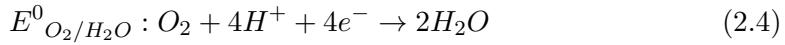
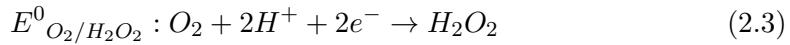
Savva et al. conducted a study to investigate the influence of water on the performance of PEDOT:PSS OECTs. They found that water uptake led to a 10-13% increase in mass under non-biased conditions. Interestingly, the concentration of water played a role in the ionic charging rate. While lower concentrations of water ( $\text{NaCl}_{aq}$  10 mM, 100mM, 1M, and 6M) led to faster ionic charging, the fastest response time was achieved with  $\text{NaCl}_{aq}$  1 M. This was attributed to attractive forces between counter ions, which hindered the drift of anions and delayed the injection of ions from the electrolyte [31].

Another study by Savva et al. showed that a certain level of hydration is necessary for facile ionic transport, but can have a negative impact on electronic charge transport, particularly in glycol-based side chains [30]. These side chains are commonly used in accumulation-mode OECTs, where ionic transport is already enhanced through side-chain engineering [27].

#### 2.3.4.2 Oxygen Reduction Reaction (ORR)

The Oxygen Reduction Reaction (ORR) is a common undesirable side reaction that occurs under environmental conditions, especially in devices fabricated with polymers having low ionization potential (IPs). The use of OMIECs with low IPs is frequent in accumulation-mode OECTs.

The ORR is a non-capacitive faradaic reaction that takes place between the OMIEC and molecular oxygen, involving electron-transfer. This reaction can yield either hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) or water ( $\text{H}_2\text{O}$ ), as described in 2.3 and 2.4, or it can result in the oxidation (p-doping) of the OMIEC which acts as the catalyst [16].



As represented in Figure 2.16,  $\eta_1$  and  $\eta_2$  represent the free energy difference between reactants and the reaction products  $\text{H}_2\text{O}_2$  and  $\text{H}_2\text{O}$ , respectively. If this free energy difference is negative, indicating that the reaction requires an energy input, the ORR is endergonic, while a positive free energy difference makes it exergonic (spontaneous). For instance, to prevent the formation of oxygen peroxide, a polymer with higher IP ( $> 4.9\text{eV}$ ) would be required.

In the context of OECTs, where polymers like PEDOT:PSS and p(g3T2-T) are used, it is important to recognize that these materials exhibit exergonic reactions under environmental conditions. Therefore, it is crucial to consider the impact of

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the ORR on device stability and performance, particularly in applications where long-term reliability is essential.

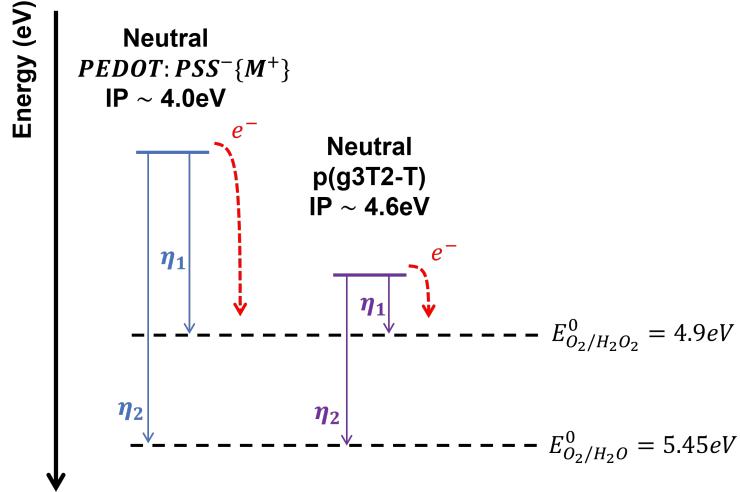


FIGURE 2.16: Simplified mechanism of two- and four-electron Oxygen Reduction Reactions with neutral states of OMIECs: p(g3T2-T) and PEDOT:PSS. The free energy difference between reactant and the reaction products is represented by  $\eta$ . Image adapted from reference [16], where values are defined from cyclic voltammetry measurements using Ag/AgCl as reference electrode and NaCl as electrolyte.

# Chapter 3

# Experimental Methods

## 3.1 Materials

All reactives were purchased from commercial suppliers.

- Chromium etchant: High purity ceric ammonium nitrate, Standard, Sigma Aldrich
- Gold etchant: HHPAA (2-Hydroxy-4'-(2-hydroxyethoxy)-2-methylpropiophenone), 98%, Standard, Sigma Aldrich
- Developer: AZ 726 MIF Developer, Merck performance Materials GmbH
- EG: Ethylene glycol,  $\geq$  95%, Sigma Aldrich
- [EMIM][EtSO<sub>4</sub>]: (1-Ethyl-3-methylimidazolium ethyl sulfate),  $\geq$ 95%, Sigma Aldrich
- MBBAm: (N,N'-Methylenebisacrylamide), 99%, Sigma Aldrich
- NIPAm: (N-Isopropylacrylamide), 97%, Alfa Aesar
- Sacrificial Layer 1: Sacrificial Layer 1 (SL1), Orthogonal Inc
- Photoresist: AZ 1518 Photoresist, Merck Performance Materials GmbH & Microchemical GmbH
- Photoresist for undoped species: NLOF 2020, commercial negative-tone photoresist, Microchemical
- Orthogonal Photoresist for doped species: OSCoR 4020 Photoresist, Orthogonal Inc.
- Developer for SL1: Developer HF 7300, Orthogonal Inc.
- Orthogonal Developer for OSCor 4020: Orthogonal Developer 103a, Orthogonal Inc.

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- Orthogonal Stripper: Orthogonal Stripper 900, Orthogonal Inc.
- p(g3T2-T): 3-(2-(2-methoxyethoxy)ethoxy)ethoxythiophene
- Dopants: 1,3,4,5,7,8-hexafluorotetracyanonaphthoquinodimethane ( $F_6TCNNQ$ ) and 1,3,4,5-tetrafluorotetracyanonaphthoquinodimethane ( $F_4TCNQ$ )
- Adhesion promoter: Silane A174 (3-(Trimethoxysilyl)propyl methacrylate), TCI

## 3.2 Equipment

- Baking: All baking steps were carried out on a Stuart SD160 digital hotplate (Stuart Equipment, UK).
- Electrical characterization (ambient): Device characterization 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 characterization (glovebox): Device characterization was performed in a nitrogen-filled glovebox. Probing needles were connected to two Keithley 236 Source Measure Units (Keithley Instruments, USA).
- Cyclic voltammetry and Impedance measurements: 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-lime glass covered with chromium) and held several mask designs (Compugraphics Jena GmbH, Germany).
- Plasma cleaning:  $O_2$ -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:  $O_2$ -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).

- Film resistance measurements: The film resistance was measured using a linear four-point probe system (Lucas four-point probe connector) connected to a multimeter (Keithley 2010 Multimeter).
- Transmittance and Reflectance measurements: Measurements were performed with UV-Visible-NearInfraRed Spectroscopy on a SolidSpec-3700 UV-Vis-NIR spectrometer using an integral sphere from Shimadzu.
- Energy of HOMO/HBEC cutoff measurements: Measurements were done using Ultraviolet Photoelectron Spectroscopy (UPS) on a PHOIBOS 100 from Specs, a Helium plasma discharge lamp (UVS10/35, Specs).
- Spincoating: Samples were coated with a SAWATEC SM-180-BT spincoater (SAWATEC AG, Switzerland).

### 3.3 Software

- Data processing: All data was processed by customized scripts written in Python. Files import and manipulation was done by using OS [32] and CSV [33] modules. Mathematical computations (e.g. fits, integration) were carried out by employing the NumPy [34], SciPy [35], and PeakDetect [36] libraries. Visualisations were performed using the Matplotlib library [37]. All is compiled in the following GitHub Repository: **marivelasco25/Thesis.git**.
- Electrical characterization: Measurements were performed by controlling SMUs through the in-house developed SweepMe! software (<https://sweep-me.net/>).
- Profilometry: Profilometry was performed by using the Dektak software (Veeco Instruments Inc., USA).
- Cyclic voltammetry: Measurements were performed by using the NOVA software (Metrohm AG, Switzerland). Parameters were fixed and are described in the following table:

TABLE 3.1: Cyclic Voltammetry parameters.

Parameter	Value
Start/Stop potential	0 V
Upper vertex potential	1 V
Lower vertex potential	-1 V
Number of scans	10
Scan rate	0.1 V/s

- Impedance measurements: Measurements were performed by using the NOVA software (Metrohm AG, Switzerland) in potentiostatic mode. Parameters were fixed and are described in the following table:

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TABLE 3.2: Electrochemical Impedance Spectroscopy parameters.

Parameter	Value
Initial frequency	$10^5$ Hz
Final frequency	$10^{-1}$ Hz
Frequencies per decade	10
Amplitude ( $V_{RMS}$ )	0.01 V

## 3.4 Photomask

The employed photolithography mask for OECT fabrication depict a specific layout of gold electrodes, as illustrated in Figure 3.1. Detailed information about the photolithography process is provided in the following section.

This layout accommodates 14 devices, each with a channel length of 70  $\mu\text{m}$  and a 20  $\mu\text{m}$  overlap on both sides. The channel width is set at 190  $\mu\text{m}$ . Additionally, the gate electrode dimensions describes a length of 190  $\mu\text{m}$  and a width of 220  $\mu\text{m}$ , with a gate-channel distance of 30  $\mu\text{m}$ . All 14 devices will be located within a glass sample substrate measuring  $2.5 \times 2.5 \text{ cm}^2$ .

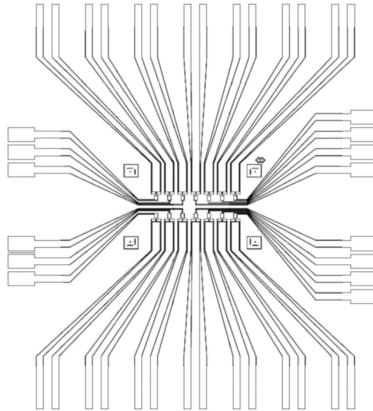


FIGURE 3.1: Used photomask for fabricated OECT gold electrodes.

## 3.5 Experimental Procedures

All fabrication steps were performed under standard cleanroom conditions.

### 3.5.1 Preparation of Films

**Dynamic spin-coating of p(g3T2-T).** In contrast to the approach described in reference [3], which employed drop-casting for the deposition of undoped and doped p(g3T2-T) films, our objective is to enable photolithography and facilitate a miniaturization process. To achieve this, uniform films are needed. The BioSens group members at IAPP had previously established dynamic spin-coating method

### 3.5. Experimental Procedures

due to the high volatility of p(g3T2-T) solvent, chloroform. Substrates were cleaned through sequential steps of ultrasonic bath in acetone for 15 minutes, IPA rinse, N<sub>2</sub> drying, and 5 minutes of O<sub>2</sub> plasma etching (0.3 mbar). Then, 70 $\mu$ L of 10 mg/mL of p(g3T2-T) mixed at 60°C for 20 minutes, was applied using dynamic spin-coating at 3000 RPM for 60s, yielding approximately 70nm thick films. The samples were then dried at 80°C.

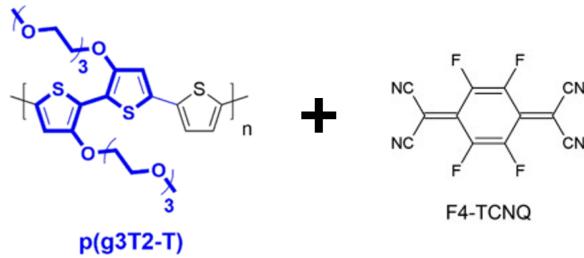


FIGURE 3.2: Chemical structures of the repeat units of p(g3T2-T) and F<sub>4</sub>TCNQ dopant.

**Dynamic spin-coating of F<sub>4</sub>TCNQ dopant.** Different doping levels of p(g3T2-T) were achieved by dynamic spin-coating 140 $\mu$ L of dopants at different concentrations (5, 10 and 20 mg/mL, as seen in Figure 3.3), previously mixed in acetonitrile at 60°C for 20 minutes. The samples were then dried at 80°C.

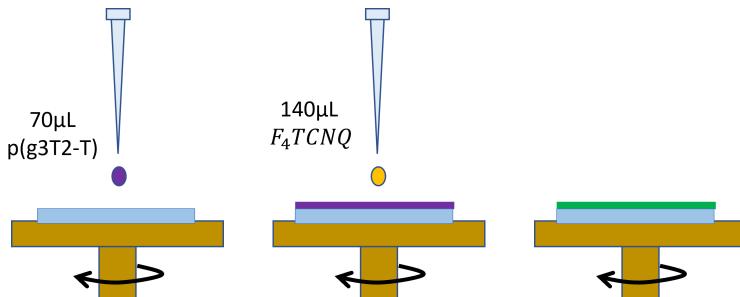


FIGURE 3.3: Dynamic spin-coating process to obtain undoped and doped films of p(g3T2-T)).

#### 3.5.2 Doping Characterization of Films

**Profilometer.** The films were scratched 4 times to remove part of material, and measure the cavity depth to obtain the film thickness.

**Four-point probe.** Sheet resistance and resistivity were calculated following reference [38], via equations:

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$$R_S = \frac{\pi}{\ln(2)} R = 4,53R \quad [\Omega/sq], \quad (3.1)$$

where R is the resistance measured with the four-point probe setup, and

$$\rho = R_s t \quad [\Omega.cm], \quad (3.2)$$

where  $t$  is the thickness of the film.

**UV-Vis-NIR Spectroscopy.** After the preparation of the films onto quartz substrates, transmittance (T) and reflectance (R) was measured using the UV-Vis-NIR Spectrometer in the range of 285 to 1600 nm. Then, absorption (A) was calculated via

$$A = 1 - T - R, \quad (3.3)$$

and normalized with respect to the incoming light [39]. Additional measurements were taken, after some days of storage under ambient conditions to check its stability in air.

**Ultraviolet Photoelectron Spectroscopy.** After the preparation of the films, the energy of the highest occupied molecular orbital cutoff ( $E_{HOMO}$ ) and the high binding energy cutoff  $E_{HBEC}$  was measuring using UPS. The pressure in the chamber during measurements was about  $5 \cdot 10^{-9}$  mbar, while the base pressure is in the range of  $10 \cdot 10^{-10}$  mbar. The workfunction (WF) and ionization energy (IE) are calculated by using the following equations:

$$WF = h\nu - E_{HBEC} \quad [eV], \quad (3.4)$$

$$IE = h\nu - (E_{HBEC} - E_{HOMO}) \quad [eV], \quad (3.5)$$

where  $h\nu = 21.22eV$ , the main He I excitation line of the Helium plasma discharge lamp [40].

#### 3.5.3 Fabrication of Organic Electrochemical Transistors

##### 3.5.3.1 Influence of Doping on OECT Channel

Photolithographically patterned substrates with gold contacts for source, drain and gate were obtained using mask layout illustrated in Figure 3.1. The steps outlined in references [4] and [41] were followed, which is also represented in Figure 3.4.

Then p(g3T2-T) films were deposited following the procedure described in the previous section. The patterning of doped-p(g3T2-T) channel adopted a procedure similar to the one described in references [4][41], which involves the use of PEDOT:PSS. However, some modifications in the exposure and developing times were made. In contrast, the patterning of undoped-p(g3T2-T) samples, required a different protocol. A sacrificial layer is introduced to ensure proper cross-linking with photoresist. Both processes are detailed in the following:

### 3.5. Experimental Procedures

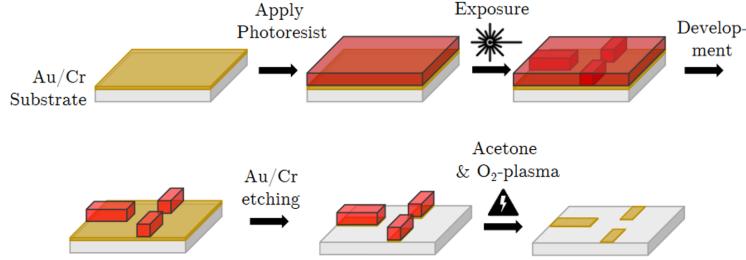


FIGURE 3.4: Visualization of the workflow for Au-contacts patterning. Image modified based on reference [41].

**Patterning undoped-p(g3T2-T).** Patterning of the p(g3T2-T) was achieved with photolithography, as shown in Figure 3.5. First, a fluoropolymer Sacrificial Layer 1 (SL1) was spin-coated at 6000 RPM for 60 s, followed by a baking step for 180 s at 113°C. Before the deposition of photoresist, a O<sub>2</sub> plasma cleaning step was applied for 60 s to promote adhesion. Then, NLOF 2020 photoresist was spin-coated at 3000 RPM for 60 s and baked for another 60 s at 113°C. Exposure of negative resist was performed for 12 s by shadowing all areas except the ones of interest. After post-baking for 60 s at 113°C, NLOF was developed by rinsing the sample in AZ MIF 726 for 20 s and wash off in DI water (carried out extra times if necessary). Next, SL1 was developed using HF 7300 developer for 45 s and spin rinsed at 3000 RPM (carried out extra times if necessary). Excess of p(g3T2-T) was removed by O<sub>2</sub>-plasma etching for 180 s. The sample was placed in Orthogonal Stripper 900 overnight at room temperature, to complete the removal. Finally, ultrasonication in acetone was added for 15 min the next day.

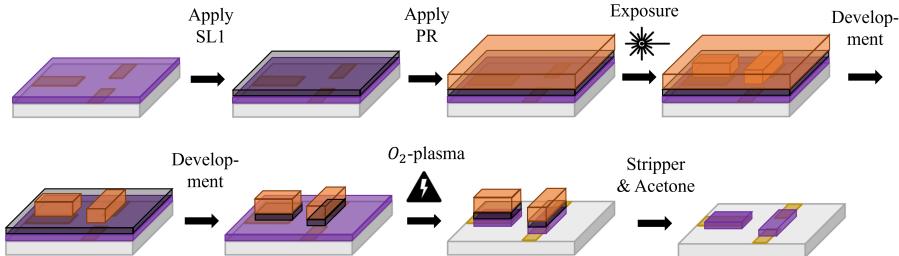


FIGURE 3.5: Visualization of the workflow for patterning undoped p(g3T2-T).

**Patterning doped-p(g3T2-T).** Patterning of the doped-p(g3T2-T) was achieved with photolithography, as shown in Figure 3.6. First, the orthogonal photoresist OSCoR 4020 was spin coated at 3000 RPM for 60 s and baked for another 60 s at 103°C. Exposure of negative resist was performed for 20 s with shadowing all areas except the ones of interest, one extra cycle was added if using higher dopant concentration (10 mg/mL). After post-baking for 60 s at 103°C, OSCoR was

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developed using Orthogonal Developer 103a for 45 s and spin rinsed at 3000 RPM for 60 s (carried out extra times if necessary). Excess of doped-p(g3T2-T) was removed by O<sub>2</sub>-plasma etching for 180 s. The sample was placed in Orthogonal Stripper 900 overnight at room temperature.

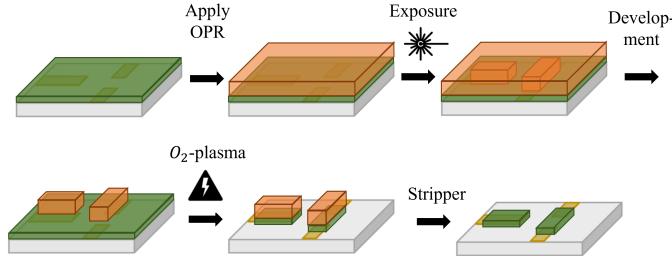


FIGURE 3.6: Visualization of the workflow for patterning doped p(g3T2-T).

**OECT with undoped- and doped-p(g3T2-T) channel.** A solid-state electrolyte precursor was prepared according to the details provided in Table 3.3. Next, 20 $\mu$ L of this precursor were drop-casted to the patterned samples, both undoped and doped, covering all 14 devices in the sample. Finally, a Ag/AgCl pellet was installed and used as gate (Figure 3.7). Transfer characteristics were measured under ambient conditions with a  $V_{GS}$  swept backwards from 1.0 V to -0.8 V.

TABLE 3.3: Composition of the solid-state electrolyte [4].

Component	Amount	Function
H <sub>2</sub> O	1.0 mL	dilution
[EMIM][EtSO <sub>4</sub> ]	1.5 mL	ionic liquid
MBBAm	20 mg	crosslinker
NIPAm	750 mg	monomer
HHPAA	200 mg	photoinitiator
EG	1.5 mL	increase viscosity, ensures good print
Triton	1 drop	surfactant, ensures good print

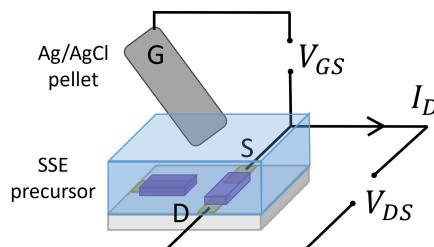


FIGURE 3.7: Representation of experimental setup for measuring threshold voltage shift of a single OECT under ambient conditions. Scheme is not drawn to scale.

### 3.5.3.2 Stability on Air of p(g3T2-T)

In this subsection, stability tests were conducted on both undoped and doped p(g3T2-T) samples. These samples were doped with F<sub>6</sub>TCNNQ, following same procedure described in subsection 3.5.1. The channel conductivity was measured before and after patterning and after contact with SSE while a fixed biased drain-source voltage was maintained, under N<sub>2</sub> and ambient conditions.

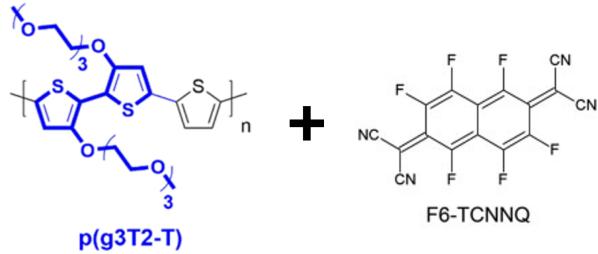


FIGURE 3.8: Chemical structures of the repeat units of p(g3T2-T) and F<sub>6</sub>TCNNQ dopant.

**Channel conductivity measurements.** Undoped-p(g3T2-T) sample was measured in N<sub>2</sub> then ambient conditions immediately after spin-coating onto substrate with patterned gold contacts. Then, sample was measured after patterning process (as described in previous section). Finally, upon drop-casting solid-state electrolyte precursor. The doped-p(g3T2-T) channel was measured after patterning and upon drop-casting solid-state electrolyte precursor.

### 3.5.3.3 Reverse Oxidation of Undoped-p(g3T2-T)

**By electrochemical dedoping.** Undoped-p(g3T2-T) samples onto patterned-gold-contacts substrates were prepared. The solid-state-electrolyte precursor was dropcast onto the 14 devices, one device source-drain was negatively-biased and applied a positive gate voltage. Channel conductivity was monitored. Finally, other devices on the sample were measured to detect any effect of the process.

**By heating.** An undoped-p(g3T2-T) solid-OECT, whose fabrication will be described in the following subsection (3.5.3.4), was exposed to ambient conditions, devices were clearly oxidized. The sample was placed on a hot plate at 120°C, brought back to glovebox, and measured the following day.

### 3.5.3.4 Solid-OECTs using Undoped-p(g3T2-T)

After following the patterning steps for undoped-p(g3T2-T) from Subsection 4.5. Three different methods of applying the solid-state electrolyte precursor were tested. Then, transfer characteristics were measured at a constant V<sub>DS</sub> of -0.1V, and a V<sub>GS</sub> swept backwards from 1.0 V to 1.0 V at a scanning rate of 0.083 V/s. Cyclic

### 3. EXPERIMENTAL METHODS

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voltammetry and electrochemical impedance spectroscopy were performed by short-circuiting source and drain to probe between channel and gate. Parameters were fixed as described in Section 3.3, and measurements were taken one day after the fabrication.

**Application of adhesion promoter.** An adhesion promoter, consisting of reactants detailed in Table 3.4, was applied to the substrate. The sample was placed in a Petri dish at 50°C and covered for 20 min. Subsequently, it was thoroughly rinse with ethanol and dried on a hot plate at 100°C for a minimum of 10 min. The composition and application steps of adhesion promoter was previously established by Biosens group members at IAPP.

TABLE 3.4: Composition of adhesion promoter.

Component	Amount
SilaneA174	30 $\mu$ L
Etolol	3mL
Acetic acid	60 $\mu$ L

**OECT with drop-casted Solid-State Electrolyte.** Solid-state electrolyte precursor was drop-casted and then exposed for 2 cycles of 60 s in a mask aligner, as shown in Figure 3.9A. No adhesion promoter was applied in this sample.

**OECT with photopatternable Solid-State Electrolyte.** After the application of the adhesion promoter, the solid-state electrolyte precursor was drop-casted onto the sample, followed by the placement of a Teflon foil to prevent contact with the mask, which would shadow all areas except the ones of interest in the negative resist. The sample was then exposed for 2 cycles of 60 s in a mask aligner. Removal of excess, non-cross-linked precursor was careful blown off with a N<sub>2</sub> gun, as shown in Figure 3.9B, following references [4][41].

**OECT with inkjet-printed Solid-State Electrolyte.** After the application of the adhesion promoter, the solid-state-electrolyte precursor was ink-jet printed and expose for 2 cycles of 60 s in mask aligner, as illustrated in Figure 3.9C. Parameters and procedure for ink-jet printing was previously established by members of BioSens group at IAPP.

#### 3.5.3.5 Solid-OECTs using Doped-p(g3T2-T)

**OECT with inkjet-printed Solid-State Electrolyte.** After the deposition of films and dopant (F<sub>6</sub>TCNNQ), films were stored in glovebox over the weekend to let dopants soak and dry. Then, the patterning steps for doped-p(g3T2-T) from Subsection 4.5 were followed with no extra cycles in exposure times. Solid-state electrolyte precursor was ink-jet printed as described in the previous subsection.

### 3.5. Experimental Procedures

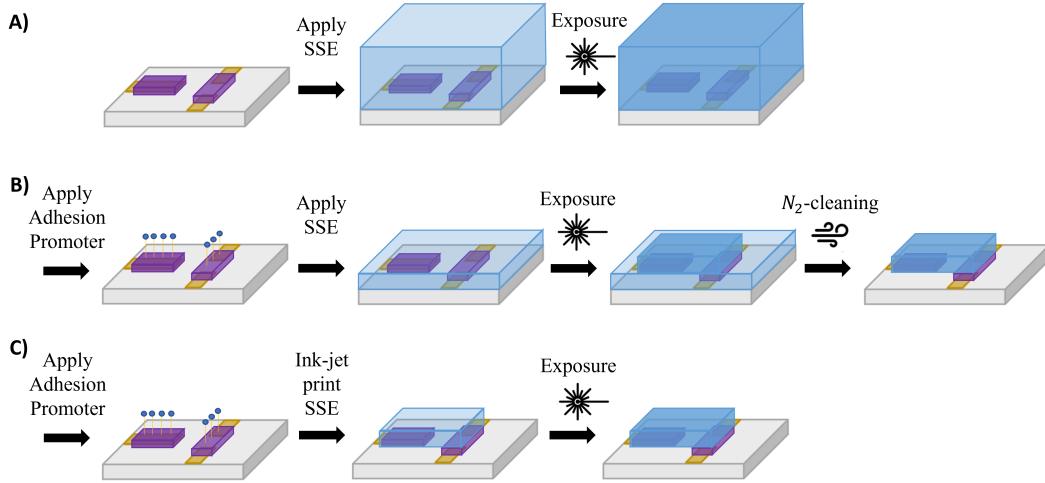


FIGURE 3.9: Visualization of the workflow for solid-OECT fabrication with undoped p(g3T2-T) by A) drop-casting SSE, B) photopatterning SSE, C) ink-jet printing SSE.

Then, transfer characteristics were measured at a constant  $V_{DS}$  of -0.1V, and a  $V_{GS}$  swept backwards from 1.0 V to 1.0 V at a scanning rate of 0.083 V/s. Cyclic voltammetry and electrochemical impedance spectroscopy were performed by short-circuiting source and drain to probe between channel and gate. Parameters were fixed as described in Section 3.3, and measurements were taken one day after the fabrication.

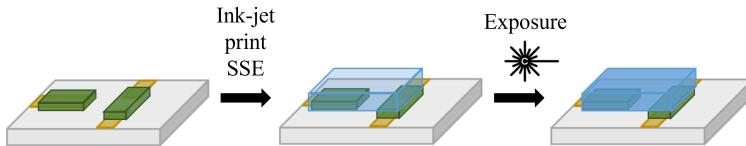


FIGURE 3.10: Visualization of the workflow for solid-OECT fabrication with doped p(g3T2-T) by ink-jet printing SSE.



# Chapter 4

## Results and Discussion

### 4.1 Doping Characterization

Upon increasing the dopant concentration deposited on top of the p(g3T2-T) film and subsequent baking, the reflection hue, as depicted in Figure 4.1 shift toward more yellowish tones.

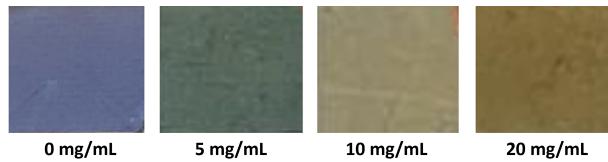


FIGURE 4.1: Color change upon increasing dopant concentration from 0 to 20 mg/mL.

#### 4.1.1 Thickness, Sheet Resistance and Resistivity

Sheet resistance and resistivity, as shown in Table 4.1, were calculated using equations 3.1 and 3.2, respectively, as described in previous chapter. The film thickness was determined through profilometer measurements, resulting in an approximate thickness of 70 nm.

TABLE 4.1: Sheet resistance and resistivity values for undoped and doped films of p(g3T2-T)

	Undoped	5 mg/mL	10 mg/mL	20 mg/mL
$R_S$ ( $\Omega/\text{sq}$ )	6.3M	104.6k	70.7k	49.4k
$\rho$ ( $\Omega\text{cm}$ )	44.1	0.73	0.49	0.35

Upon doping, a substantial decrease is observed in both sheet resistance and resistivity. However, this decrease is not as pronounced when higher dopant levels are introduced, as depicted in Figure 4.2. Nevertheless, when comparing the reduction

## 4. RESULTS AND DISCUSSION

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among doped samples, a clear linear relationship becomes apparent with increasing the dopant concentration.

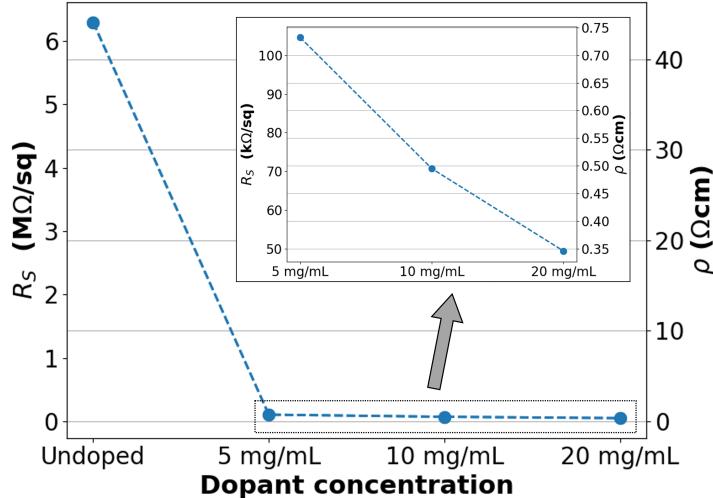


FIGURE 4.2: Sheet resistance and resistivity drop upon doping of p(g3T2-T). Inlet represents the quasi-linear drop of parameters as between doped samples.

### 4.1.2 Absorbance and Dopants Diffusion

The visible color hue shift can be quasi-quantitatively described by examining the absorbance spectra of the samples, as illustrated in Figure 4.3. In the case of undoped-p(g3T2-T), there is a prominent absorption peak at 588 nm (red), which diminishes with increasing doping concentration, indicative of oxidation. Notably, new absorption peaks emerge at around 860 nm, a consequence of polaron generation, leading to new optical transitions, as explained in Chapter 2, Section 2.1.2.

Tan et al. documented the appearance of new absorption peaks within the 300 to 600 nm range. The higher energy (lower wavelength) peak is generated by unreacted neutral dopant species ( $\text{TCNQ}^0$ ), while the second is attributed to the new dopant anions ( $\text{TCNQ}^-$ ), which induce charges in our polymer [3]. Additionally, it is worth noting that, after several days of storage, the initially dominant peak of unreacted neutral dopants diminishes in intensity relative to the anions peak. This observation suggests ongoing diffusion of dopants through the polymer over time.

Absorbance values are directly correlated with the density of states of these new optical transitions [11]. In our spectra, the absorbance value at 860 nm of the lowest-doped p(g3T2-T) sample (5 mg/mL) is relatively higher, around 40%. This might initially appear counterintuitive. However, as the doping concentration increases, the formation of bipolarons and bipolaron bands becomes energetically more favorable [42]. This phenomenon aligns with observations in the higher wavelengths, such as at 1600 nm, where absorbance increases in the more highly doped p(g3T2-T) sample.

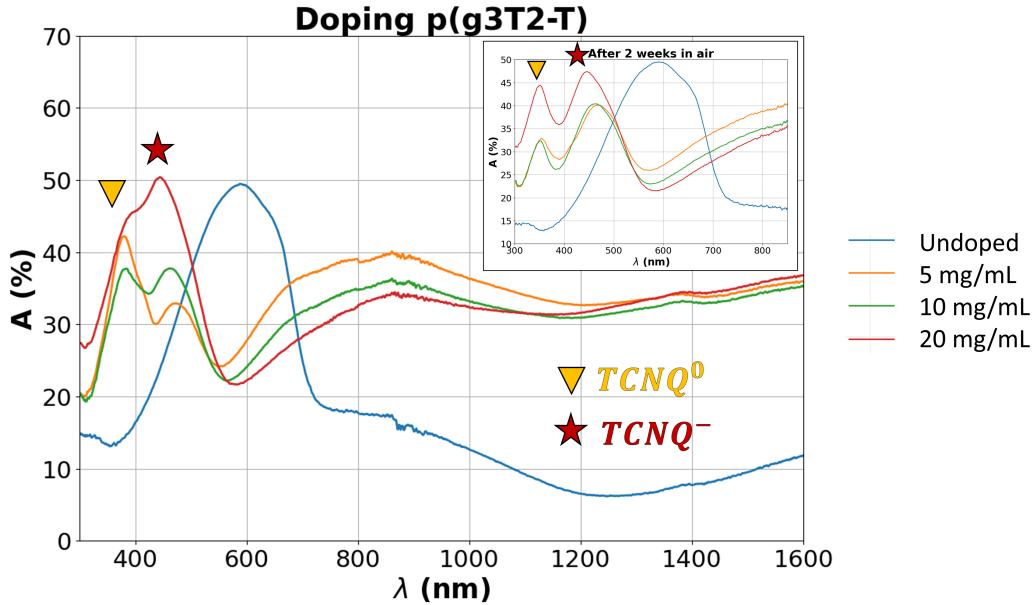


FIGURE 4.3: Spectra of undoped and doped-p(g3T2-T) at different doping levels, corresponding to samples on Figure 4.1. Inlet represents absorbance after two weeks of storage in ambient conditions.

Moreover, Tan et al. reported the formation of bipolaron in this specific context, evidenced by a shift to lower energies in the broad absorbance spectrum within the mid-IR region (wavenumbers 1000-1600 cm<sup>-1</sup>) [3]. Consequently, further analysis of hole bipolaron formation can be conducted with Fourier Transform InfraRed (FTIR) spectroscopy.

#### 4.1.3 Workfunction

While the ideal preparation of films for studying electron energy levels with UPS involves working under inert conditions to prevent contamination, the current fabrication process of OECTs unavoidably exposes our films at ambient conditions. Therefore, measurements were conducted following deposition under these ambient conditions. Yet, it is possible to discern an increase in the workfunction, indicated by a shift of Fermi level of the polymer. This shift towards the HOMO level is more pronounced at higher dopant levels, as depicted in Figure 4.4, which is characteristic of p-type doping. Although some potential contamination prevented the measurement of samples with a dopant concentration of 20 mg/mL, the trend is clearly evident.

It is important to consider that UPS is a surface-sensitive measurement. The penetration depth of the ultraviolet-range electrons in UPS is approximately 2 nm, significantly less than our polymer thickness (approximately 70 nm). Consequently, this technique constrains our understanding of the diffusion of dopants throughout the entire volume of the polymer. While, we gained some insights into this matter in the

#### 4. RESULTS AND DISCUSSION

TABLE 4.2: Workfunction calculation from UPS measurements.

	Undoped	5 mg/mL	10 mg/mL
$E_{HBEC}$ [eV]	17.35	16.47	16.36
$E_{HOMO}$ (vs $E_F$ )	4.28	3.27	3.24
WF [eV]	3.87	4.28	4.86

previous subsection, further analysis could be undertaken using X-Ray Photoelectron Spectroscopy which offers a depth profiling mode.

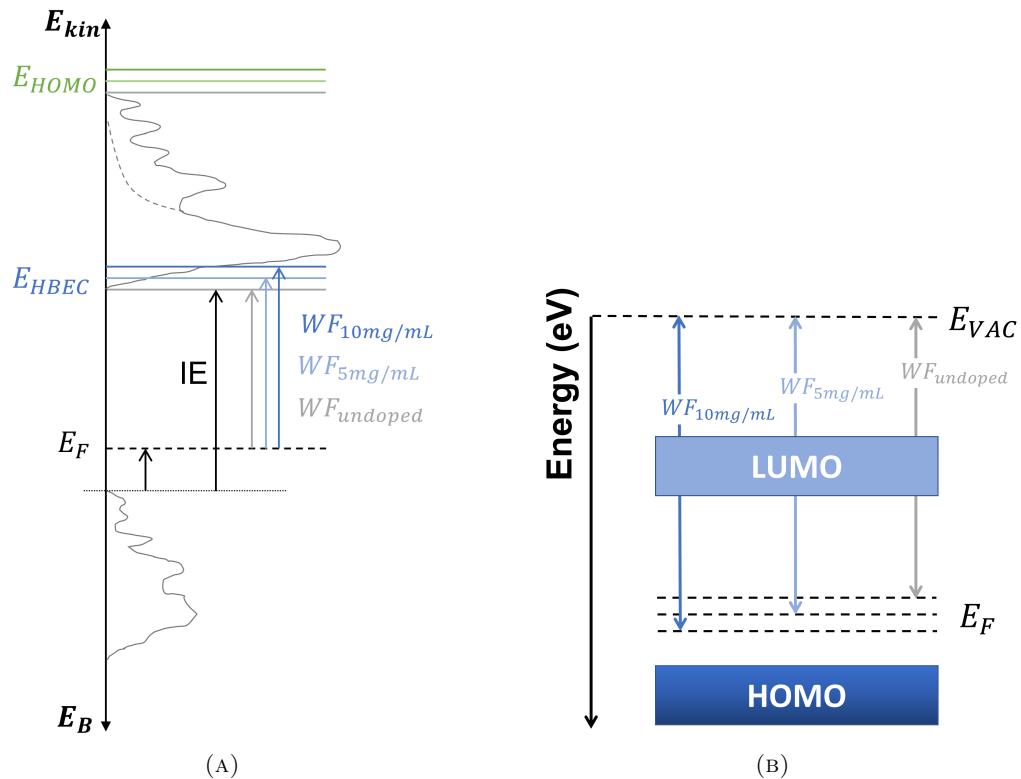


FIGURE 4.4: Graphical representation of A) the relationship between the binding energies  $E_B$  and the kinetic energy of the photoelectrons  $E_{kin}$ , and B) the Fermi level shift, upon doping.

## 4.2 Fabrication of Organic Electrochemical Transistors

### 4.2.1 Influence of Doping on OECT Channel

The fabrication process uses a mask that include a microstructure gate, suitable for studying OECTs with both channel and gate made of the same OMIEC material, commonly PEDOT:PSS. The result of the patterning process is displayed in Figure 4.5.

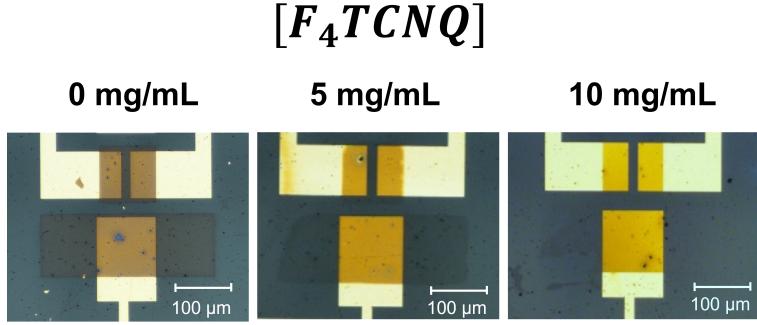


FIGURE 4.5: Micrographs of patterned channel and gate with p(g3T2-T) undoped, 5 mg/mL and 10 mg/mL dopants, following procedures explained in Section .

However, in this section, we will specifically examine only the OMIEC channel (p(g3T2-T)) at various doping levels paired with a non-polarizable Ag/AgCl electrode as gate, and coupled with SSE precursor.

Unfortunately, the sample that used solution with dopant concentration of 20 mg/mL exhibited doping homogeneity issues. While photolithography was still possible, it could not provide a fair basis for comparison with the other devices. Therefore, this sample will be omitted from this analysis.

The results shown in Figure 4.6, Figure 4.7 and Figure 4.8 correspond to the same device and same loop on each sample (undoped, 5 mg/mL and 10 mg/mL dopants). Among the attempts to increase the yields, only 3 or 4 out of the 14 devices were operational on each sample. Further improvements on the development process were needed, and were accomplished as it will be shown in further sections of this chapter. After reporting the findings on these analysis, a more statistical study will be shown within the operating devices on each sample from the same batch of materials.

Transfer characteristics illustrated in Figure 4.6A, C, E correspond to undoped, 5 mg/mL and 10 mg/mL dopants, respectively. A positive turn ON voltage is perceived in the undoped OECT device, which evidenced the fast oxidation (or unwanted doping) of p(g3T2-T) under environmental conditions due to its low IP.

Gate current ( $I_{GS,ON}$ ) is displayed in dotted lines and it is perceive that the drain OFF current ( $I_{DS,OFF}$ ) is dominated by this leakage current in all devices. Figure 4.7 shows doped devices have minimum differences on  $I_{DS,OFF}$ , and higher values were measured in the undoped device at all  $V_{DS}$  values. As it was reported by Hidalgo et al. pristine p(g3T2-T) show oxygen reduction reaction activity in oxygen-saturated conditions, increasing the current within the polymer until reaching saturation [43]. It will be necessary to control the oxidation state of the polymer among the different steps of the photolithography process, and somehow revert the oxidation of p(g3T2-T), this issue will be further discuss in the following sections.

The higher dopant concentration device (10 mg/mL dopant) shows signs of breakage as going to more negative  $V_{DS}$  (Figure 4.6E and Figure 4.7D), therefore, this measurement will be disregard for transconductance and threshold voltage calculation.

#### 4. RESULTS AND DISCUSSION

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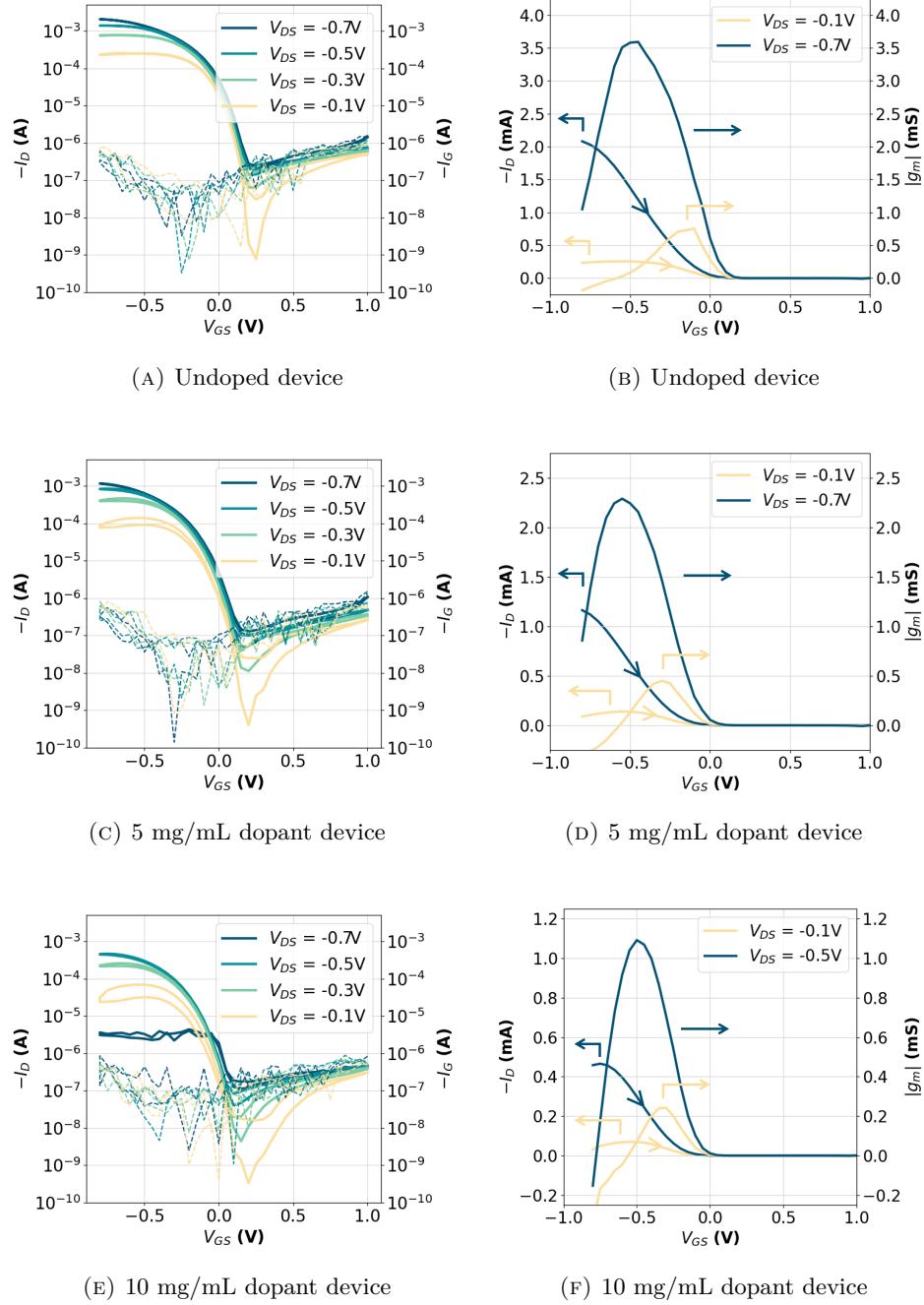


FIGURE 4.6: A), C), E) Transfer characteristics of all measured  $V_{DS}$  including the gate leakage current  $I_G$  B), D), F) Transfer curves (off-switching) with corresponding transconductance. Each group of graphs for undoped, 5 mg/mL and 10 mg/mL doped p(g3T2-T) channel, respectively.

Additionally, it is observed that  $I_{DS,ON}$  decreases while increasing doping levels. This is reflected in the maximum transconductance values displayed in Table 4.3. Additionally to the oxidation of undoped p(g3T2-T) devices that also increased  $I_{DS,OFF}$ . When doping our polymer, we are increasing its conductivity by inducing new charges in its backbone, the introduction of new ionic species will negatively impact the mobility of the induced charges, which explains the decrease in  $I_{DS,ON}$ .

TABLE 4.3: Maximum transconductance values extracted from Figure 4.6

$ g_{m,max} $ [mS] @	Undoped	5 mg/mL	10 mg/mL
$V_{DS} = -0.1$ V	0.75	0.45	0.24
$V_{DS} = -0.3$ V	2.01	1.31	0.74
$V_{DS} = -0.5$ V	2.90	1.97	1.09
$V_{DS} = -0.7$ V	3.59	2.23	

More importantly and counterintuitive, Figure 4.7 and Figure 4.8 showed turn ON voltages and threshold voltages, respectively, **shifted towards negative values** as the dopant concentration increased in all  $V_{DS}$  values. The introduction of ionic species ( $\text{TCNQ}^-$ ) should have created depletion-mode devices, so a higher positive gate biased would have been needed to counteract anions and turn OFF the device, resulting to positive threshold voltage (which is the case of PEDOT:PSS,  $V_{Th}$  of 0.6 - 0.7 V). However, a sort of *compensation doping* happened upon coupling channel and gate with SSE precursor, and as explained in the Background chapter, p(g3T2-T) as a type VI OMIEC, unlike PEDOT:PSS, have ionic species as free carriers and not chemically bonded. Further analysis in the conductivity needs to be done to understand to impact of this coupling in our undoped and doped polymer.

Additionally, threshold values had lower variability among different values of  $V_{DS}$  with higher introduction of dopants (Figure 4.8). This variability could be caused by ORR which should be different at different biased conditions. By bringing the polymer towards its HOMO level by doping, we assured a better stability in air, then although we are impacting mobility and repeatability among loops, the values at different drain biased are maintain.

Moreover, something that it is not shown in this report but it was perceived during analysis, there is higher repeatability of transfer characteristics with undoped OEET devices. This could be explained by considering our environmental conditions as a infinite reservoir of molecular oxygen, until this unwanted doping and ORR reaches saturation, making it stable. In the case of  $\text{F}_4\text{TCNQ}$ , stability is still unclear and further investigation will be done in the next sections.

#### 4.2.2 Stability on Air of p(g3T2-T)

Channel conductivity was measured before and after the patterning process. Immediately after spin-coating unpatterned p(g3T2-T) exhibited a conductivity around  $1 \mu\text{S}$ , after patterning the conductivity increase to three orders of magnitude to the order of  $1 \text{ mS}$ , a clear sign of oxidation after the whole patterning process. Measurements of  $I_D$  at  $-0.3$  V of  $V_{DS}$  and no gate biased in glovebox exhibited a small decrease of

#### 4. RESULTS AND DISCUSSION

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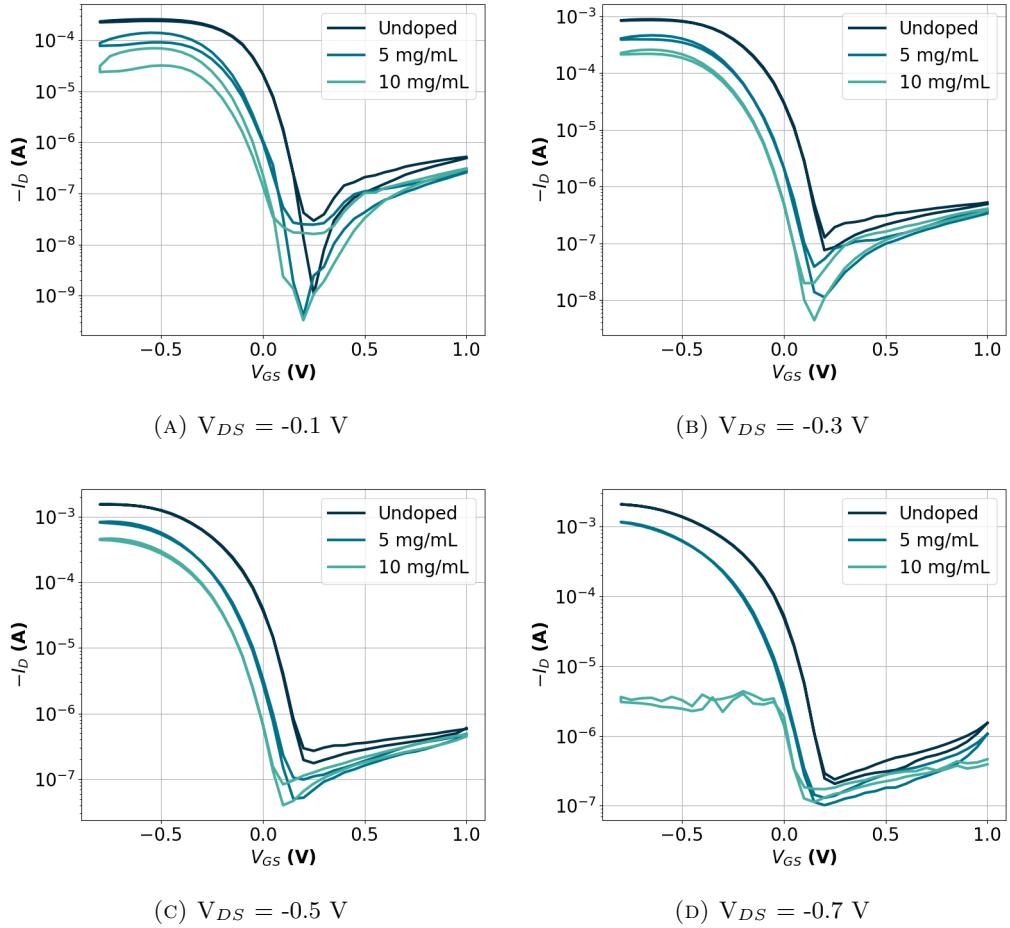


FIGURE 4.7: Transfer characteristics comparing undoped, 5 mg/mL and 10 mg/mL dopants devices, each graph represent a different  $V_{DS}$

4% within two hours, and small increase of 15% within two hours in air exposure, pretty stable after patterning.

Interestingly, upon contact with SSE precursor, conductivity drops significantly, at least six orders of magnitude, as shown in Figure 4.9A. Another device from another sample was tested showing the same result.

Transfer curves were measured from the latter device under environmental conditions with a Ag/AgCl pellet, a clear shift to more negative values of turn ON values are noticed, as reported in Figure 4.9B.

## 4.2. Fabrication of Organic Electrochemical Transistors

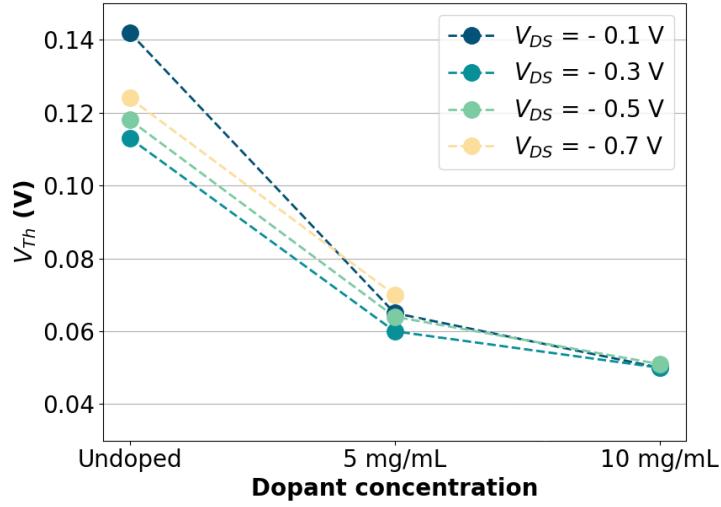


FIGURE 4.8: Threshold shift at different doping levels and  $V_{DS}$ , corresponding from Figure 4.6

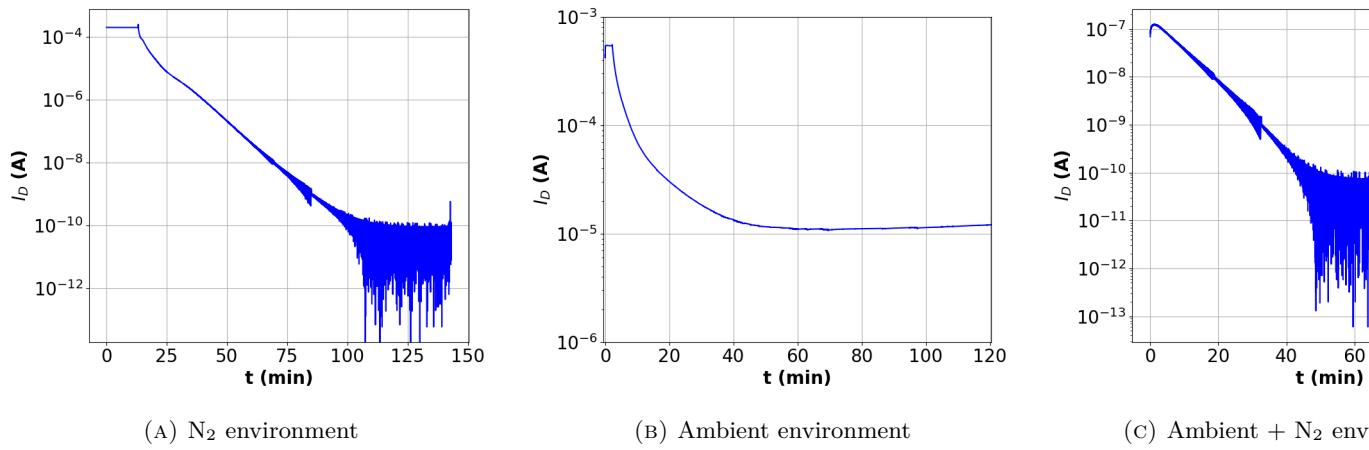


FIGURE 4.9: Transfer characteristics comparing undoped, 5 mg/mL and 10 mg/mL dopants devices, each graph represent a different  $V_{DS}$

#### 4. RESULTS AND DISCUSSION

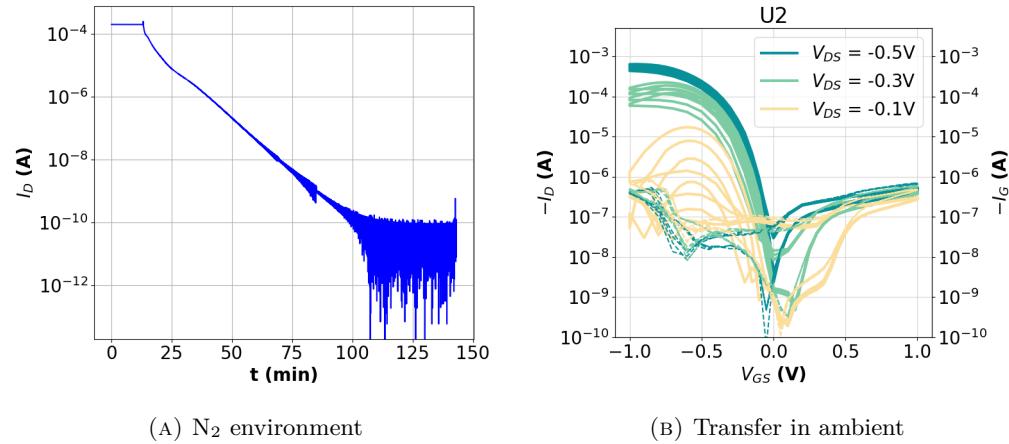


FIGURE 4.10: Transfer characteristics comparing undoped, 5 mg/mL and 10 mg/mL dopants devices, each graph represent a different  $V_{DS}$

#### 4.2.3 Reverse Oxidation of Undoped-p(g3T2-T)

#### 4.2.3.1 By Electrochemical Dedoping

#### 4.2.3.2 By Heating

#### 4.2.4 Solid-OECTs using Undoped p(g3T2-T)

#### 4.2.4.1 Dropcasted Solid-State Electrolyte

#### 4.2.4.2 OECT with Dropcast Solid-State Electrolyte

#### 4.2.4.3 OECT with Photopatternable Solid-State Electrolyte

#### 4.2.4.4 OECT with Inkjet-Printed Solid-State Electrolyte

#### 4.2.5 Solid-OECTs using Doped-p(g3T2-T)

## **Chapter 5**

# **Conclusions and Outlook**



# **Appendices**



## Appendix A

# Absorption of p(g3T2-T) Doped with F<sub>6</sub>T<sub>4</sub>CNNQ

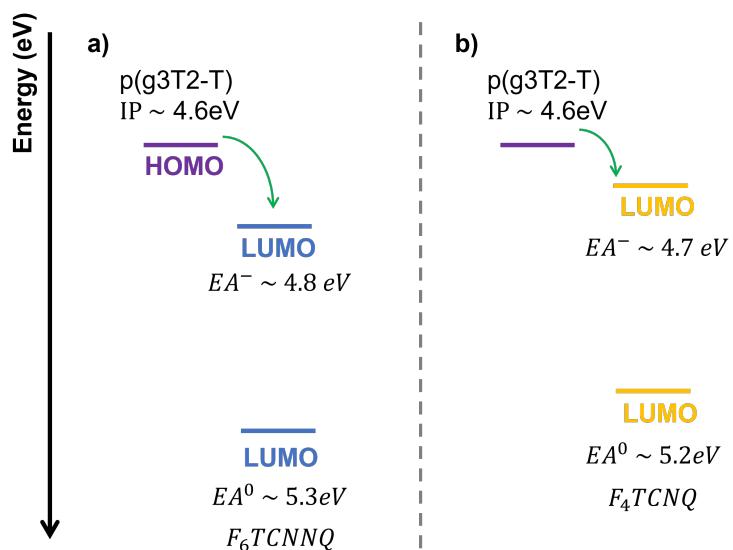


FIGURE A.1: Energy diagram of p(g3T2-T) with a) F<sub>6</sub>T<sub>4</sub>CNNQ and b) F<sub>4</sub>T<sub>4</sub>CNNQ. Ionization potential of p(g3T2-T) extracted from reference [3] and electron affinities of the neutral species (EA<sup>0</sup>) and of the anion (EA<sup>-</sup>) of the dopants are extracted from cyclic voltammetry measurements in reference [12].



## Appendix B

### PEDOT:PSS vs Doped p(g3T2-T) as Channel



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