Anna Solé Huertas

DEVELOPMENT OF CALCIUM MEMBRANES USING ORGANIC ELECTROCHEMICAL TRANSISTORS

Directed and tutored by Dr. Francisco Javier Andrade

BACHELOR THESIS

Degree of Chemistry

UNIVERSITAT ROVIRA i VIRGILI

2022

Tarragona

Table of contents

Acknowledgments

1. Summary……5
2. Objectives……6
3. Introduction……..7
   3.1. Why do we measure calcium?.....8
   3.2. Electrochemical sensors……8
   3.3. Transistors……..…….9
      3.3.1. Organic Electrochemical Transistors…….10
      3.3.2. Semiconductor polymer, PEDOT:PSS……...10
   3.4. Characterization of an OECT……..11
4. Experimental part …….13
   4.1. Instrumentation…….13
   4.2. OECTs manufacturing…….14
   4.3. Addition of the membrane……...15
   4.4. Procedure……..18
      4.4.1. Electrical characterization……...19
      4.4.2. Electrochemical characterization……20
      4.4.3. Calibration……..21
5. Results and discussion……22
   5.1. Electrical characterizations……..22
   5.2. Electrochemical characterizations……..27
   5.3. Calibrations……31
   5.4. Selectivity……...36
6. Conclusions……..38
7. Bibliography……..39

Acknowledgments

I would like to thank several people for their help during those months of learning. First, to my co-worker Ariadna Dasca who taught me all she knew. She has been a research support for me, a reference in the laboratory and a more advanced researcher who has helped me in solving doubts and problems. Thank you for your time and your dedication.

I also want to thank Dr. Pascal Blondeau and Dr. Francisco Javier Andrade to be in this process helping me. It has been a great fortune for me that these two great researchers on the subject have supervised my research work.

Lastly, I want to thank all the team of the laboratory that helped me when I needed it. I am proud to have done my final work in this advanced laboratory. Thanks to all the team of professionals who have been there. I feel lucky to have been part of this great team.

1. Summary

The evolution and expansion of transistors caused a revolution in the electronics field in the last decade. The continuous investigation, research, and development to improve the quality of the systems increased drastically when appeared new semiconductor materials and its application in transistors. The synthesis of those semiconductor polymers created a new generation of transistors, the organic electrochemical transistors (OECTs). In this group the system is done using low-cost substrates as paper and plastic being then possible to arrive anywhere in the world. The reason is because there are undeveloped countries in which many research instruments cannot arrive. This project develops and study how works a calcium membrane using an organic electrochemical transistor. They operate as a transducer from a chemical phenomenon into an electrical signal. This electrical signal is read through its characterization and calibration being able to take different analytical parameters from the response. The ion-selective membrane of calcium makes it only selective to calcium ions decreasing its response to other ions. In this preliminary study is also explained why calcium is analysed and if it is possible or it will be possible to be determined through this methodology in different areas as medicine.

2. Objectives

The aim of this project is to develop and observe the application of a calcium membrane using an organic electrochemical transistor. Also, there are other specific goals, such as:

- To understand how works an organic electrochemical transistor.
- To perform the necessary steps to develop it from the beginning.
- To solve the calculations needed and know how to interpret the resulting analytical data.
- To study the selectivity of the membrane and its permeability among other ions.

3. Introduction

The development of sensors is an important topic in the technological and scientific scale for the society. We are constantly interacting with those devices in our life. For example, in the form of electrical appliances as light, humidity, temperature, and weight; in healthcare as electrocardiograms and glucose detectors. Currently they are most used in phones and other smart devices as cameras and fingerprint detectors, among others[1].

The research to extract information from nature and everything around us allowed the progressive evolution of sensors. Thus allowed the detection of a certain chemical action transmitting it in an electrical signal commonly. They transform the chemical information into an analytically useful signal normally proportional to the concentration of the analyte. The concentration of a specific sample can be very smaller, depending on the type of sensor used[2].

Chemical and biochemical sensors have an important role in the detection and quantification of analytes based on experimental simplification and time reduction without losing sensitivity, selectivity, and precision. Thanks to that, in chemical laboratories it is possible to determine the pH, lower concentrations of ions and different functional groups.

Among the different existing sensor groups, one of the most important in analytical chemistry is the electrochemical sensors. These sensors are a response from an electrical impulse when they are measuring a change of an intrinsic property of a material thanks to the electrode that transduces the information in the presence of an analyte. They are chemical sensors and permit the study of new materials and different natures. Historically, electrochemical sensors appeared at 1950s along the monitoring of industrial oxygen[3].

The latest innovation in sensors has started with the synthesis of conductive polymers that has led to the formation of organic compounds capable of being conductive. They are named organic electrochemical transistors (OECTs) and are made with hydrophobic paper, which makes it much cheaper because paper arrives anywhere in the world, also to the undeveloped countries where some instruments cannot arrive. They have a simple manufacture and production in comparison from other sensors.

3.1. Why do we measure calcium?

Calcium is a key mineral found everywhere such as industry, food, bones, clinical, water, etc. It is the most abundant mineral in the body and essential for its growth and maintenance[4].

Almost all the calcium found in the human's body is stored in the bones and teeth. It can be also found in the blood as free calcium, that is not attached to anything else in the blood; or as bound calcium, that is attached to a protein called albumin or other substances in the blood. There are two types of blood calcium test: one is the total calcium test, which measure both free and bound calcium, and the other is the ionized calcium test, that only measures free calcium[5].

The determination of calcium and total hardness in waters can be carried out with potentiometric sensors, which consists of a series of ion selective electrodes for different ions[6] . With this method it will be possible to measure the hardness of water with an OECT, depending on the resulting range of detection obtained.

3.2. Electrochemical sensors

From an interaction between the analyte and the electrode a signal is obtained. The electrode is the transducer element. They are some of the most used sensors because the devices are more robust, the manufacture is simpler and cheaper, and they obtain a wide range of linearity in a very short response time[7]. There are three different type of electrochemical sensors that are distinguished according to the way of obtaining the information:

- Potentiometric: This sensor measures the difference of potential between two electrodes without applying current. It is produced an equilibrium in the interface, where either the membrane or electrode potential is measured. The signal is based on the Nernst equation[8].
- Amperometric: This sensor measures oxidation or reduction reactions of an electroactive specie, that can be done applying current in a fixed interval between a reference and a working electrode[9].

- Conductometric: This sensor measures the conductivity at a series of frequencies. It is based on changes in the electrical conductivity of a film or a bulk material with the presence of an analyte[10].

With the evolution of the electrochemical sensors have appeared the OECTs, new devices of lower scale without losing effectiveness. These transistors are more sensitive, simple, and cheap.

3.3. Transistors

Transistors are devices that allow the control of the electron flow of a system from the structural doping of a semiconductor. Thanks to the current control those components can be used as signal amplifiers or as controllers of the system, as a switch. Since the first fabrication of a transistor, a lot of improvements and developments have been done in the design and fabrication techniques of these devices[11].

They are semiconductor materials that change its structure improving the conductivity by the addition of impurities, also named doping. There are two types of doping:

- P-type: The doping is done adding atoms that have lower concentration of electrons than the material where is doped generating electronic vacancies, also called holes. These holes are occupied by other electrons from the neighbour atoms and generate a conduction in the system
- N-type: The doping is based on the addition of atoms that have an excess of electrons. Then, there are free electrons in the structure that can move easily through them. It increases the conductivity by increasing the number of available electrons[12].

3.3.1. Organic electrochemical transistors (OECT's)

These transistors are controlled by the migration of ions from an electrolyte into an organic semiconductor channel, where can be modulated the conductivity. They translate chemical signals to electronic signals with high sensitivity. OECTs have high transconductance compared to other transistors[13]. This system has two parts. The first part is a channel where it is doped with a semiconductor polymer, also called PEDOT:PSS. This channel has source (S) and drain (D), joined by the conductive polymer. And the second part is separated from the channel, and it is the gate. Both parts, the channel and the gate are immersed in an electrolyte which connects them[14].

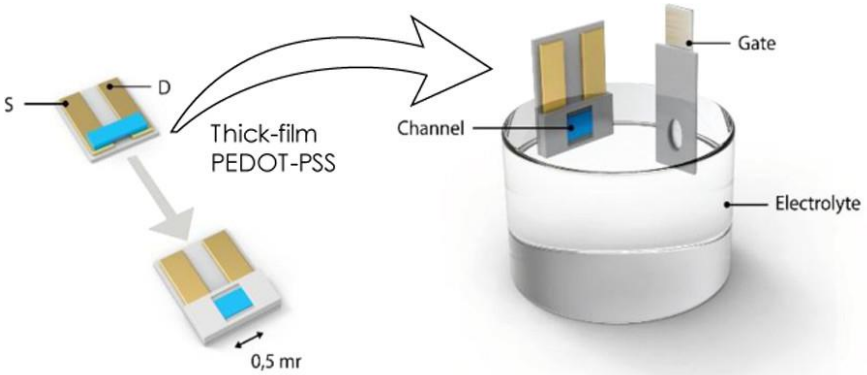

Figure 1: Representation of a High Transconductance Paper-Based Organic Electrochemical Transistor (OECT) [15]

3.3.2. Semiconductor polymer PEDOT:PSS

The semiconductor polymer used is PEDOT:PSS or poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate), that it is a polymer mixture of two ionomers. The PEDOT takes reference of the poly(3,4-ethylenedioxythiophene) and the PSS of the poly(styrene sulfonate). It is a degenerately p-type doped polymer, it turns conductive due to the negative ions. The negative charge of the PSS is compensated by a positively charged hole in the PEDOT backbone, increasing the ionic mobility of the vacancies and consequently also the conductivity. Those negative dopant ions stabilize

the positive holes balancing then the overall charge. The dopant for the PEDOT in that case is the PSS[16].

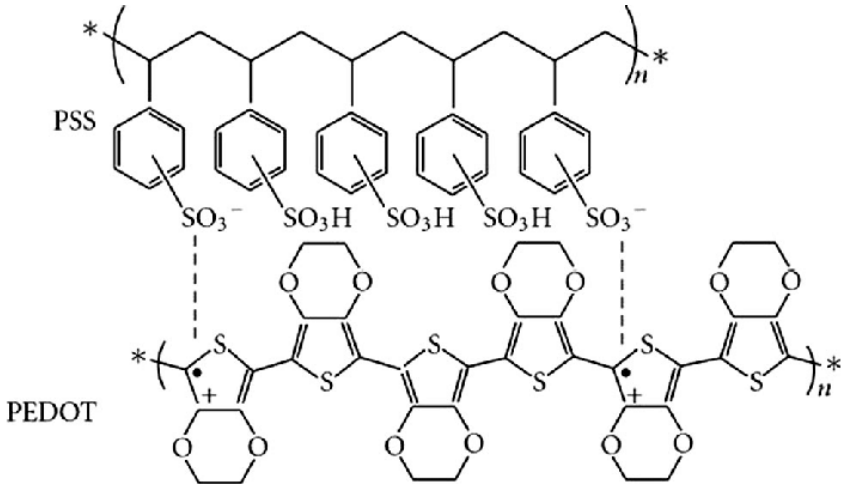

Figure 2: Chemical structure of PEDOT:PSS[17]

The requirement of a polymer to be used in the channel of an organic transistor is to be conductor. Not all the materials or polymers are valid to be used. The material must be able to be doped by the migration of ions, to present a high stability and to be electrochemically active.

3.4. Characterization of an OECT

There are two ways of characterization in organic transistors. One is an electric way, where the system acts as a resistor and the other is an electrochemical way, where it acts as a transistor.

The electric way consists in applying direct voltage producing an electric current. From the magnitudes of intensity and voltage appears the resistance following the Ohm's law.

$$I = \frac{V}{R}$$

Equation 1: Ohm's law

Also, it is important to know that the resistance is the inverse of the conductance.

$$\sigma = \frac{1}{R}$$

Equation 2: Resistance vs Conductance

The electric way of characterization is done with the sensor dry, without solution and with the sensor in contact to the electrolyte, with solution. In both cases it acts as a resistor because direct voltage is applied to it. From the two characterizations it is obtained the dynamic resistance. This dynamic resistance can be compared with the static resistance measured directly with a voltameter.

The electrochemical way is done to obtain the transconductance and occur with the application of a modulating potential to the gate keeping the potential of the drain constant. In that way, the application of an external potential causes a change in the detected current.

$$\varphi = \frac{\Delta Current}{\Delta Vg}$$

Equation 3: Transconductance formula

Where the difference in current is the difference in intensity of the drain and the source and the difference in Vg is the difference in potential of the gate.

The goal of the transconductance is to discover the change in voltage applied that will give the highest difference in current. The highest difference will be the one that has more transconductance. It is a way to study the sensitivity because is correlated to the transconductance. So, when at small additions the difference in current is higher, it means that there is more transconductance and consequently more sensitivity

The electrochemical way of characterization is done in a solution, the electrolyte, connecting the channel and the gate. The gate works driving the electrons and is positively charged related to the sensor, so the calcium ions go to the channel and are placed in the ion-selective membrane (ISM). The key point is the ion migration of the solution to the polymer. Depending on the effective potential of the gate, a different flux of ions will be obtained. For that reason, it is important to study different conditions of the gate and the drain and choose the optimal one for the calibration. The reaction that takes place during that process is the following[18]:

$$PEDOT^{+}:PSS^{-} + M^{+} + e^{-} \leftrightarrow PEDOT^{0} + M^{+}:PSS^{-}$$

Reaction 1: Electrochemical reaction of the polymer

The M^+ is the cation present in the electrolyte and the e^- an electron of the source.

When the gate of the potential is applied, the M^+ that in this case is Ca^{2+} migrate to the PEDOT, where it is reduced from $PEDOT^+$ to $PEDOT^0$. In that case, as the ion is divalent instead of monovalent, but the only difference is that it will need two PSS to stabilize the two positive charges instead of one, the reaction is the same.

The conductivity will decrease because the ions (Ca^{2+}) interact with the sulfonate which is responsible for stabilizing the positive charges of the PEDOT. It is produced an interaction between the calcium ions and the PSS. The negative charge of the PSS interacts with the positive calcium ions that are in the electrolyte solution. Thus, the positive charges of the PEDOT reduces the stabilization giving a lower conductivity.

4. Experimental part

4.1. Instrumentation

The equipment needed to carry out this project are two power supplies, an electrometer, and a computer to read the data and store it.

The main function of the two DC power supplies or also called bench power supplies is give a direct and continuous current to the channel between the source and the drain for one power supply, and the other for the gate[19] .

Figure 3: DC Power Supply[20]

The electrometer is used to find the measure very small voltages and currents. It is a very sensitive device[21].

Figure 4: Electrometer

The computer must be connected through the two DC power supplies and the electrometer to record the obtained current and at the same time is possible to make a graphical representation of the data in Excel. The data obtained can then be converted directly to get the results and conclusions.

4.2. OECT's manufacturing

The transistors are done with a thick film of hydrophobic paper, also called photography paper. The construction of the channel starts doing with the photography paper big circles and attach 0.5 mm strips of Max-tape, leaving the desired space between them. Then, gold is sputtered on the photography paper and the strips are removed. Once the gold is sprayed, to separate them they are cut creating all the time two gold parts separated between the 0.5 mm of the strips and with a length of approximately 2 cm.

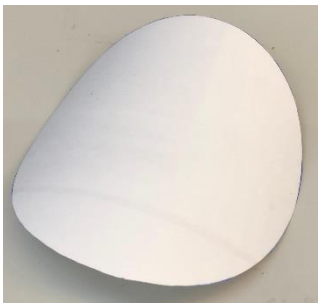

Figure 5: Photography paper

Figure 6: Photography paper with 0.5mm strips

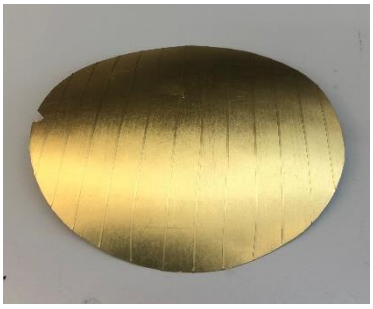

Figure 7: Sputtering of Au in the photography paper with the 0.5 mm strips

Afterwards, two masks of sticky paper with 1.5 cm x 1.5 cm of dimensions are prepared. The upper one has a hole of 3 mm. The two papers stick together with the gold band in the middle and placing the hole on the top where the PEDOT:PSS and the membrane will be added. To ensure it is well attached, glue is added around the sensor without touching the gold.

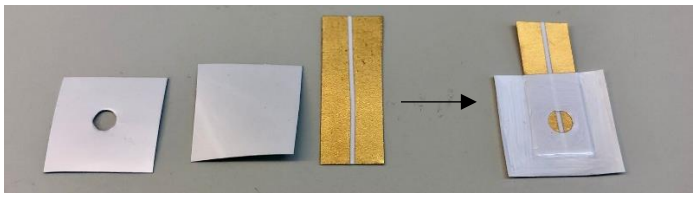

Figure 8: Manufacture of the sensor

The last step to create the channel is with the addition of the PEDOT:PSS, the semiconductor polymer. The deposition of the PEDOT:PSS is carried out by adding 1.5 µl with a micropipette in the hole. This addition is done once. After that the channel is placed in the oven for 20 minutes.

4.3. Addition of the membrane

The deposition of the membrane is done after the addition of the PEDOT:PSS, on the semiconductor polymer. When the PEDOT:PSS is on the sensor, it is important to do a conditioning in a solution of $CaCl_2.2H_2O$ 0.01M during two hours in order to create in the sensor movements of calcium ions between the semiconductor polymer and the solution. After those two hours, the sensors are washed with Milli-Q water (ultra-pure water) during fifteen minutes, changing the water every five minutes. Let the sensors dry for three hours and then the membrane can be added. Fifteen µl of membrane are deposited with a micropipette in total. It is added five µl every five minutes, in total three times. It is deposited in the same hole as the PEDOT:PSS.

The composition of the membrane is the following:

	Component	Wt %
Ion exchange	Potassium tetrakis (4-chlorophenyl)-borate	1.20
Ionophore	calcium ionophore II	2
Matrix	PVC (Poly vinyl chloride)	21.87
Plasticizer	O-NPOE (2-nitrophenyl octyl ether)	43.74
Solvent	THF	2

Figure 9: Composition of the calcium membrane

The ion exchange is a very voluminous ion with a negative charge, the opposite charge of the analyte, and its function is to remove all the negative ions touching the membrane and put the positive ones. When it is in contact with a solution containing ionic species, it is produced an equilibrium state between the membrane and the electrolyte solution. The aim is maintaining the same electrochemical potential of the mobile ionic species in the two phases[22].

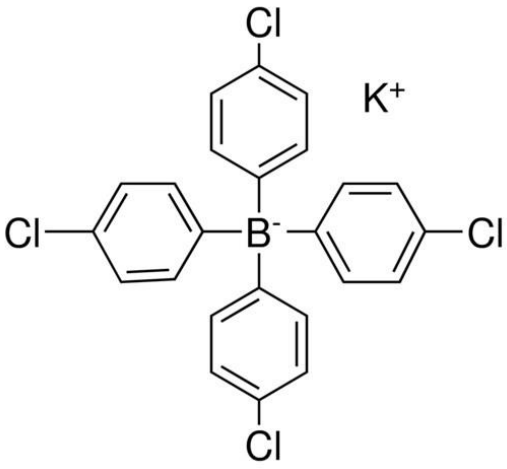

Figure 10: Potassium tetrakis (4-chlorophenyl)-borate

The ionophore is a molecule that permits us to treat the analyte that we want in front of others. They are low molecular weight natural products which dissolve in the membranes and make the membrane permeable to specific ions[23].

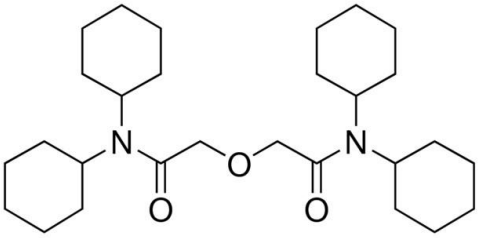

Figure 11: calcium ionophore II

The matrix and the plasticizer are used to give consistency. They make an organic phase that does not dissolve in water, to create a balance between the two types of phases.

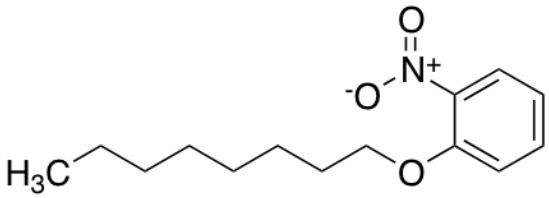

Figure 12: 2-nitrophenyl octyl ether

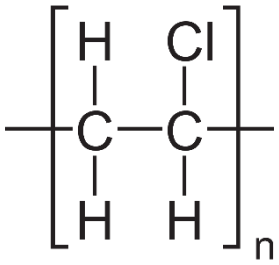

Figure 13: Poly vinyl chloride

When the membrane is applied, the final representation of the OECT is the following:

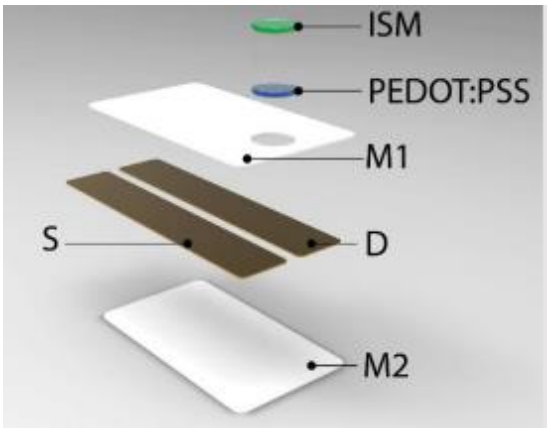

Figure 14: Representation OECT with the addition of the PEDOT and the ISM (Ion Selective Membrane)[31]

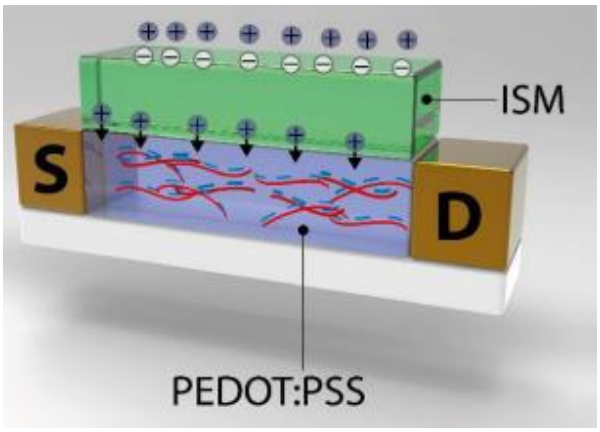

Figure 15: Representation of the ions in channel with the addition of the ISM[31]

In the Figure 15 it is observed the phase boundary potential produced in the upper part of the ISM and in the bottom of the membrane the stabilization of the PEDOT where the negative charge of the PSS is added to the positive ions of calcium.

The phase boundary potential is based on the assumption of local equilibria at the aqueous/organic interface, governs the membrane response. Is the potential created in a surface between the two samples of matter that are in contact, the aqueous phase and the membrane phase. This can be observed in the upper part of the ISM (Figure 15), where the negative ions of the membrane are attracted with the positive of the aqueous solution. When the membrane is in contact with solution creates a local charge separation being the interface at the phase-boundary[24].

4.4. Procedure

The circuit must be electrically closed to perform the measurement and flow the electric current. So, depending on the type of measurement the set up will be connected differently[25]. The setup is always with the two clamps connected one to the source and the other to the drain. Then, depending on the desired potential, if it is negative or positive, the cables will be connected in different ways.

4.4.1. Electrical characterization

In the electrical characterization process is only used the sensor, without a gate. It consist on applying direct voltage producing an electric current that permits us to study how works as a resistor and to obtain the dynamic resistance. To apply a negative potential, one cable from the sensor, is connected to the negative pole of the power supply being then the drain. Through this cable will take place the application of the potential. And the source will be the output, that it is connected to the electrometer closing the circuit. If the desired potential applied it is positive, the cable from the drain is connected to the positive pole.

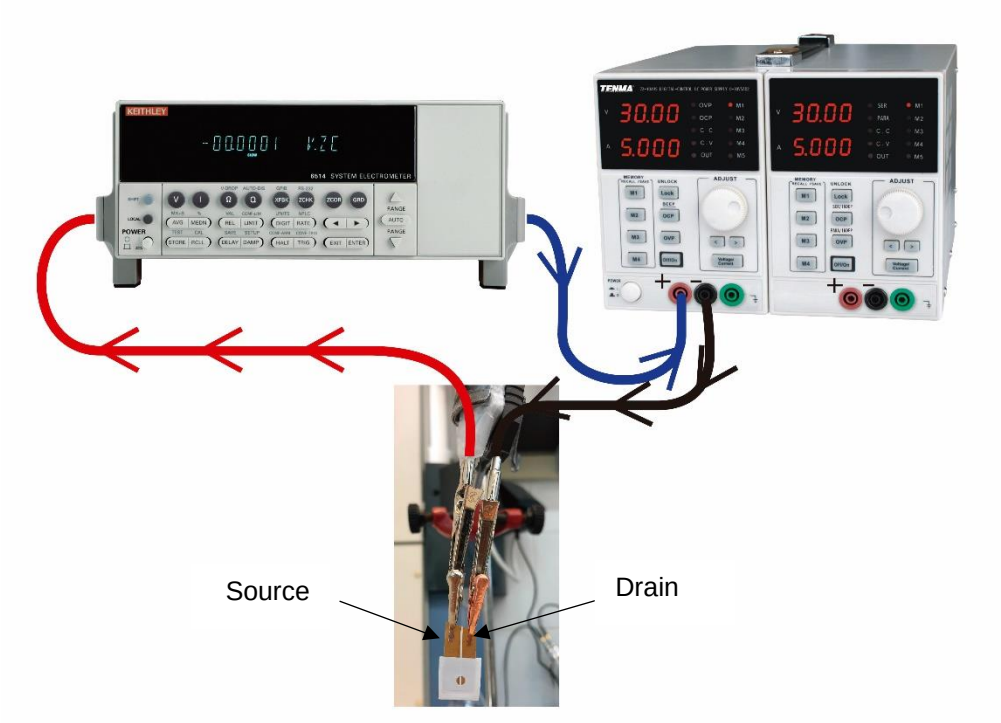

Figure 16: Assembly of the electrical characterization

In this process it is only used one DC power Supply because there is no gate, so the other one now is not connected.

In that case, the voltage of the drain applied is from -0.4 V to 0.4 V. The change of the voltage is done manually by the wheel situated in the power supply and approximately between one hundred seconds every change. This process is done without solution and with solution, that it is the electrolyte. The electrolyte used is Milli-Q water.

4.4.2. Electrochemical characterization

For the electrochemical characterization or transconductance, the connections to the channel are made in the same way as the electrical one, but in that case there is added a gate. To apply an external potential, the cable where it is the gate is connected to the input of the other DC power supply in the corresponding place according to the sign of the voltage desired. The aim is to apply a positive ion promoter in relation to the channel with the purpose that calcium ions are transported to the channel and placed in the ISM. The gate and the channel are connected through a solution of $CaCl_2.2H_2O$ 0.1M, the analyte.

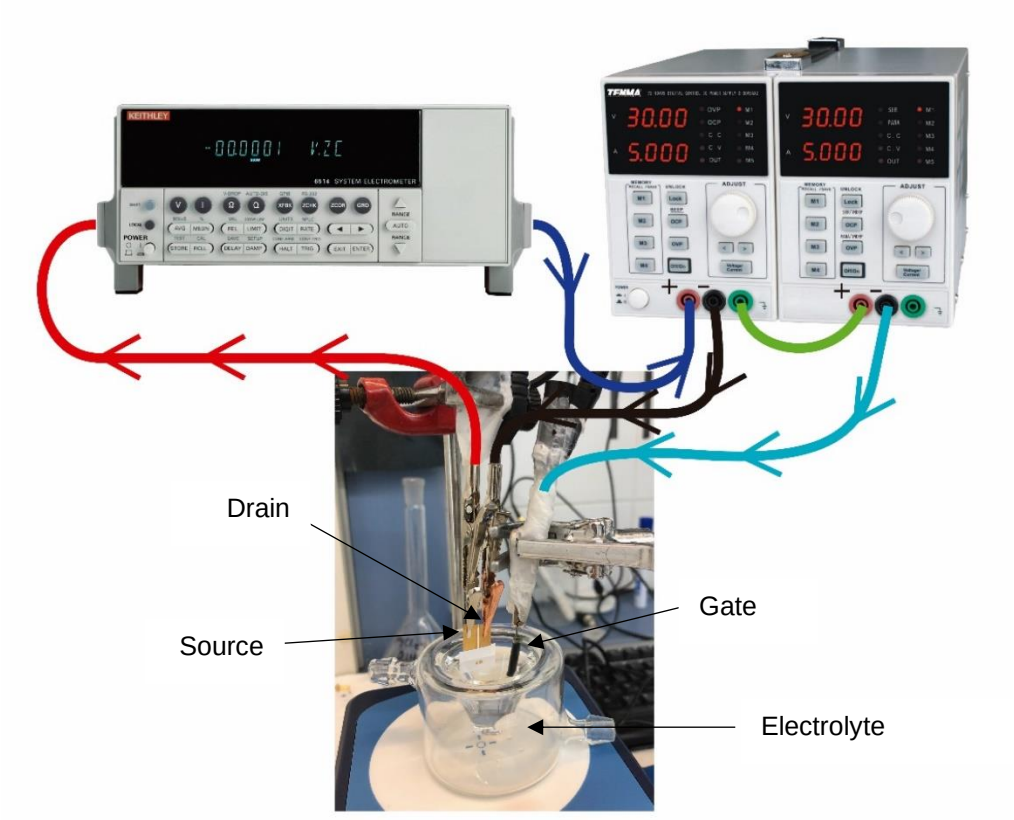

Figure 17: : Assembly of the electrochemical characterization

In this characterization takes place the application of two voltages from different DC power supplies because one is for the gate and the other for the channel. When a voltage is applied it must be always with respect to the ground as it has a potential difference. Both sources must have the same ground in that case because the devices may have a different off-set. And if they have the same ground can be ensure that the applied potential is based on a common value[26].

In the transconductance the voltage of the drain is fixed at -0.4 and then the applied potential of the gate is modulated from -0.3 V at 0.4 V normally. This can be repeated but fixing the drain at -0.3 V, -0.2 V and -0.1 V. More negative voltages in the drain are not applied because there will be so much current, and the channel will melt.

4.4.3. Calibration

The result of the electrochemical characterization indicates which applied voltage give the highest difference in current so, the maximum number of transconductance. The maximum transconductance is where they are more sensitivity. For this reason, the calibration is done at the maximum transconductance, the optimal conditions of the Vg and Vd.

The connections are the same as the electrochemical characterization, but the voltage is fixed. The electrolyte is five millilitres of Milli-Q water and are placed in the cuvette. The additions will be the following:

Log [Ca^{+2}]	Standard solution	Quantity added (µl)
-6	10^{-4} M	50.51
-5	10^{-2} M	4.55
-4	10^{-2} M	45.96
-3	1 M	4.60
-2	1 M	46.41
-1	1 M	515.20

Figure 18: Additions of the calibration

All the standard solutions were prepared from the electrolytic solution used, Milli-Q water.

5. Results and discussion

In this project, for each method applied there are many repetitions. For every method it will be explained one of it. Also, in the manufacture of the OECTs, some of them are done using strips of 0.5 mm and 1 mm. But the final and robust results will be in OECTs of 0.5 mm.

5.1. Electrical characterizations

Before starting the electrical characterization, the static resistance was measured with a digital electrometer. The approximate value provided an idea of the actual resistance of the sensor.

First, the electrical characterization of the sensor is measured only with PEDOT:PSS and without solution, the sensor is dry. The static resistance in that case before start is 7.5 Ω. It is the measure of the resistance in a single point and the dynamic resistance of a system when voltage is applied, both according to the Ohm's law[27].

When the potential it is applied, thanks to the Ohm's Law, it is possible to calculate the relationship between the voltage and the current, that it is the resistance in those electrical circuits[28].

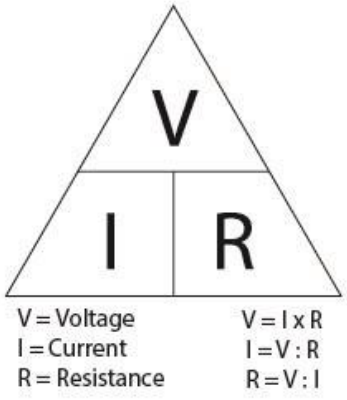

Figure 19: Ohm's Law[29]

Carrying out the electrical characterization it is obtained a time trace where it is possible to observe the variation of current over time when a fixed potential is constantly applied. In each potential change 0.1 V are added. (Figure 20)

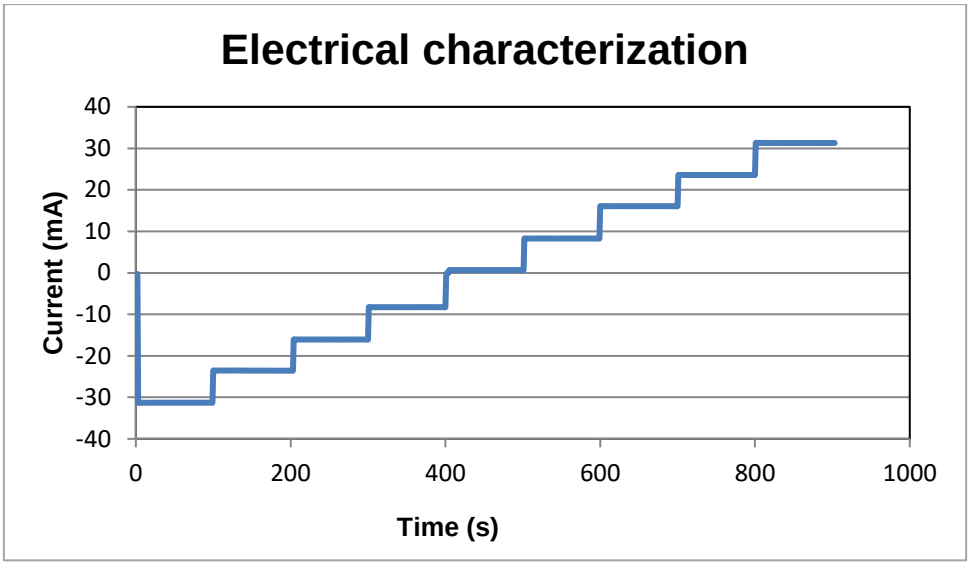

Figure 20: Time trace electrical characterization. Represents the stability of the intensity over time.

A voltage of -0.4 V was applied in the drain obtaining a current value, specifically of -31.29 mA. Thus, the characterization was executed by applying in the drain voltage range from -0.4 V to 0.4V. A constant current was expected in the representation because the supplied potential was fixed and stable during the time. Otherwise, if there were current fluctuations, the system could not be used as it would not have stability over the time and therefore would not offer repeatable and robust results.

Once the current values for the different potentials were found, it was made the Figure 21 where it is represented the relationship of the applied potential according to the measured current.

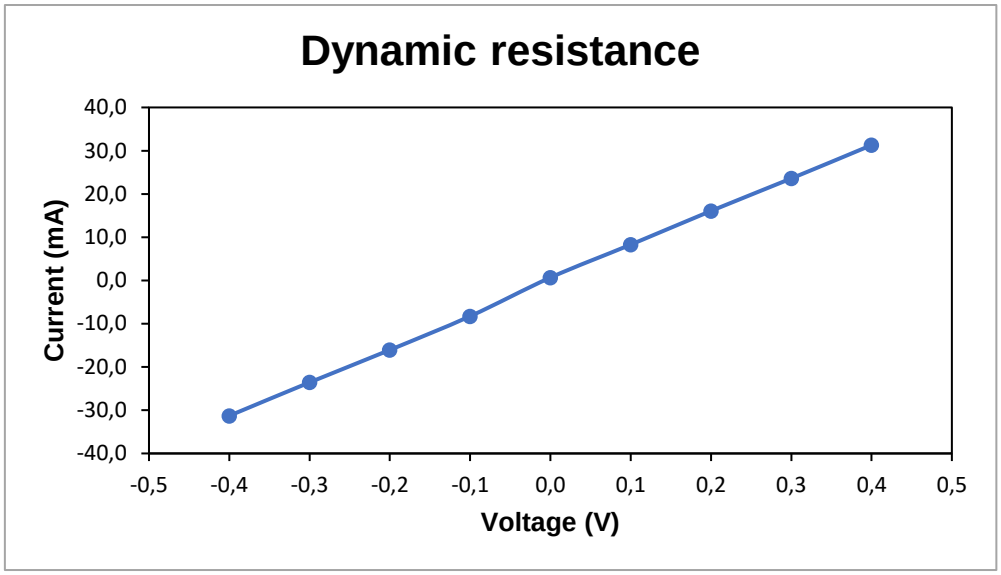

Figure 21: Dynamic resistance. Represents the intensity in function of the applied voltage

From the slope of the Figure 21, the dynamic resistance of the system was calculated. In this case it was 12.7 Ω. This resistance is obtained applying the Ohm's law explained before. The applied voltage (V) is proportional to the current (I) where the resistance (R) is obtained for the relation R = V / I. (Figure 19)

After the electrical characterization with the sensor without solution, the same process is repeated but with the system in a solution of $CaCl_2.2H_2O$ 0.01M. The solution corresponds to the electrolyte. The drain potential range applied and the representations obtained were the same. For that reason, they can be compared.

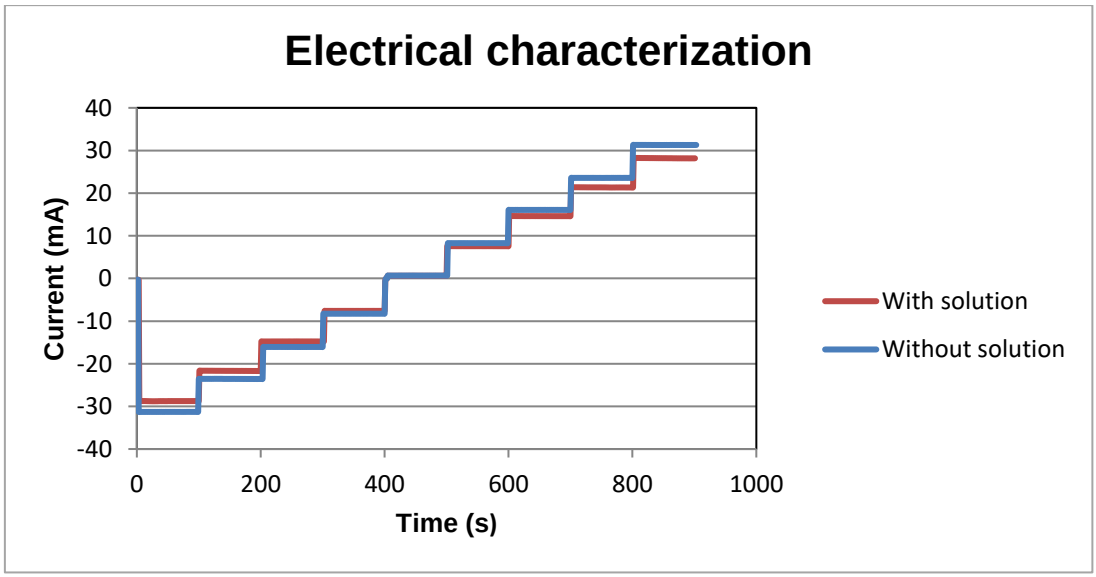

Figure 22: Time trace electrical characterization. Comparing the stability of the intensity over the time between the sensor without and with the electrolyte.

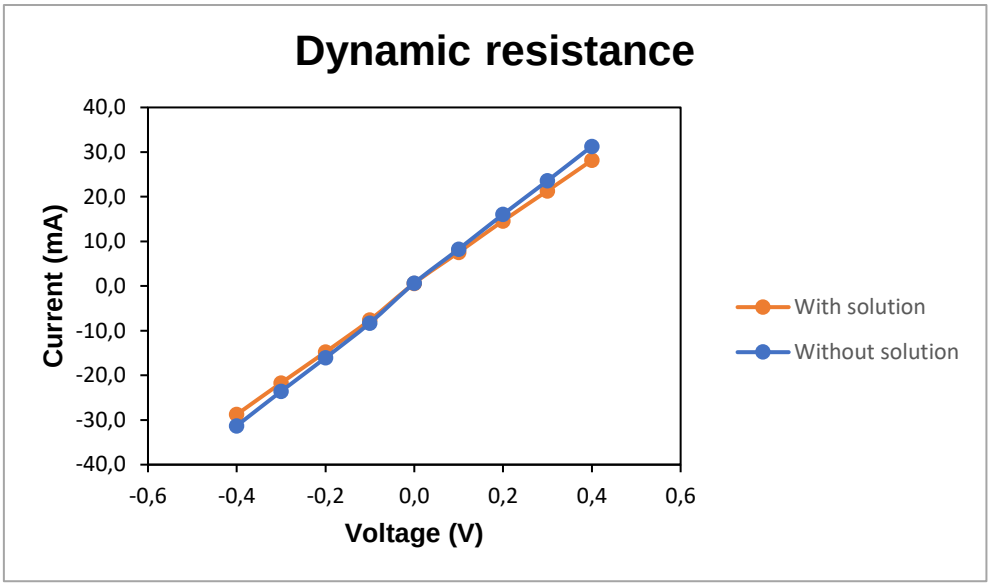

Figure 23: Dynamic resistance. Comparing the intensity in function of the applied voltage between the sensor without and with the electrolyte.

It was observed that for the same potential value almost the same current was obtained when it was measured with solution. The reason of that similar values was due to experimental reasons, for the hydration of the cations. Practically there was no change with and without solution. The difference can be negligible. The resistance is the inverse of the conductance so, the final dynamic resistance obtained was 13.9 Ω, only a little higher than the one without solution as it is observed. (Figure 23)

Then, it was done the electrical characterization but with the membrane added to the system. It was repeated the same procedure, one time without solution and the other immerse in the same electrolyte, a solution of $CaCl_2.2H_2O$ 0.01M. The membrane only made the sensor selective to calcium, but it did not change the electrical characterization because happened the same to it. The static resistance before starting the characterization was 9.1 Ω.

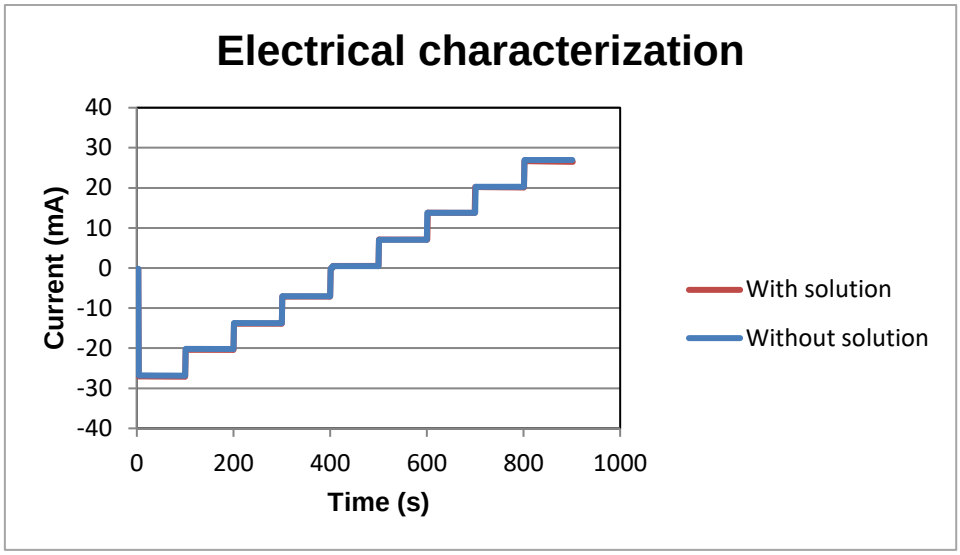

Figure 24: Time trace electrical characterization. Comparing the stability of the intensity over the time between the sensor without and with the electrolyte

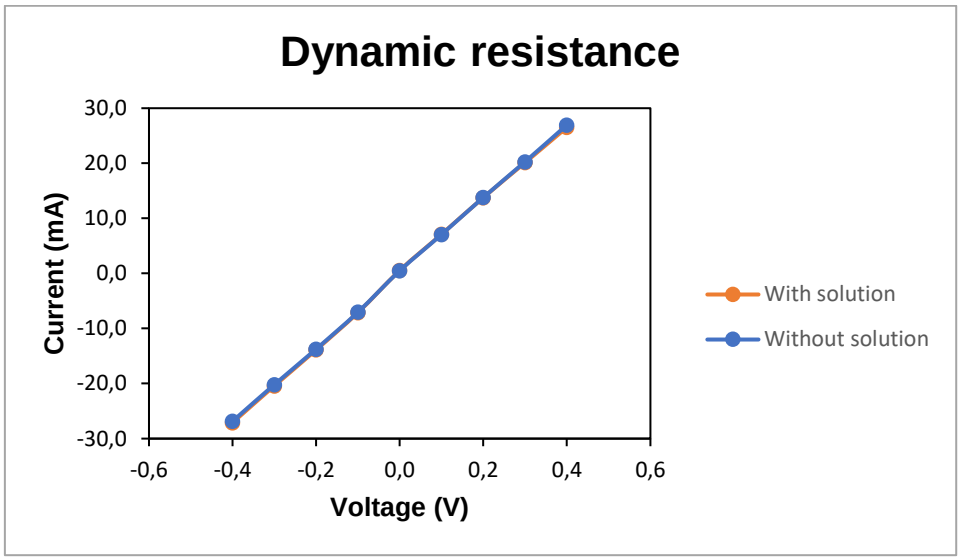

Figure 25: Dynamic resistance. Comparing the intensity in function of the applied voltage between the sensor without and with the electrolyte.

In that case the difference between the sensor without solution and immerse in the electrolyte was lower as it is possible to observe in the Figure 24 and Figure 25. The time trace where it is observed the variation of current over time and the curve of the dynamic resistance are almost overlapped. Applying the same potential, the sensor with solution obtained lower current. The current of the sensor without solution when a voltage of -0.4 V was applied is -26.84 mA and the current with solution applying the same voltage was -27.10 mA. This difference again can be negligible. The dynamic resistance

obtained of the sensor without solution was 14.78 Ω and the one with the electrolyte was 14.79 Ω.

5.2. Electrochemical characterizations

The following step was studying the transconductance doing the electrochemical characterization. In those characterization was used a reference electrode of Ag/AgCl as a gate. The gate with the sensor was connected being both immersed in a solution of $CaCl_2.2H_2O$ 0.1M. The aim of this experiment was evaluating the effect of applying an external potential, the voltage of the gate, to a resistor. A constant voltage of the drain was applied and then, the voltage of the gate changed from -0.3 V to 0.4 V studying then how the system responded when an external voltage was applied. It is important to read the current when it is constant over the time. Therefore, a study of the current over time was performed applying different gate potentials.

First, the sensor without membrane, only PEDOT:PSS, is being explained. The constant voltage of the drain applied was -0.4 V and the voltage of the gate were from -0.3 V to 0.4 V. This was the time trace observed:

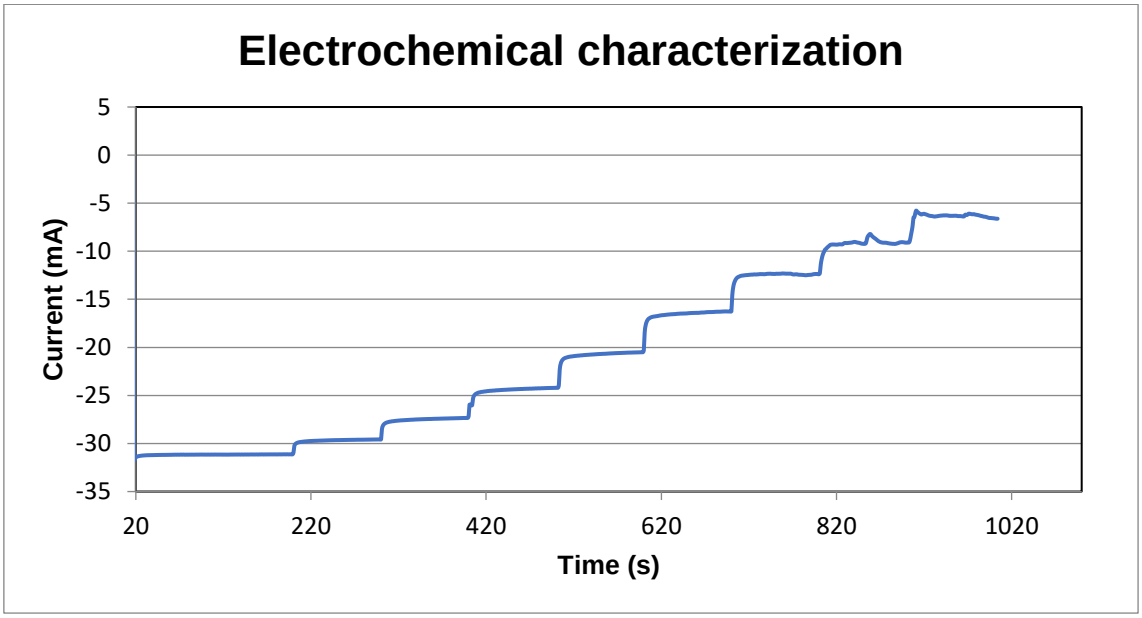

Figure 26: Time trace of the electrochemical characterization. Representation of the stability of the intensity over time.

Regarding the potential of the gate applied it is possible to observe that the higher potential is applied, the lower measured current is, following the Ohm's law.

Then, to know which potential of the gate produced the highest difference in current it was studied the transconductance. The potential that has more current difference made the system more sensitive because sensitivity and transconductance are equivalent. In the Figure 27 the transconductance is the gm and it was expressed in milli siemens.

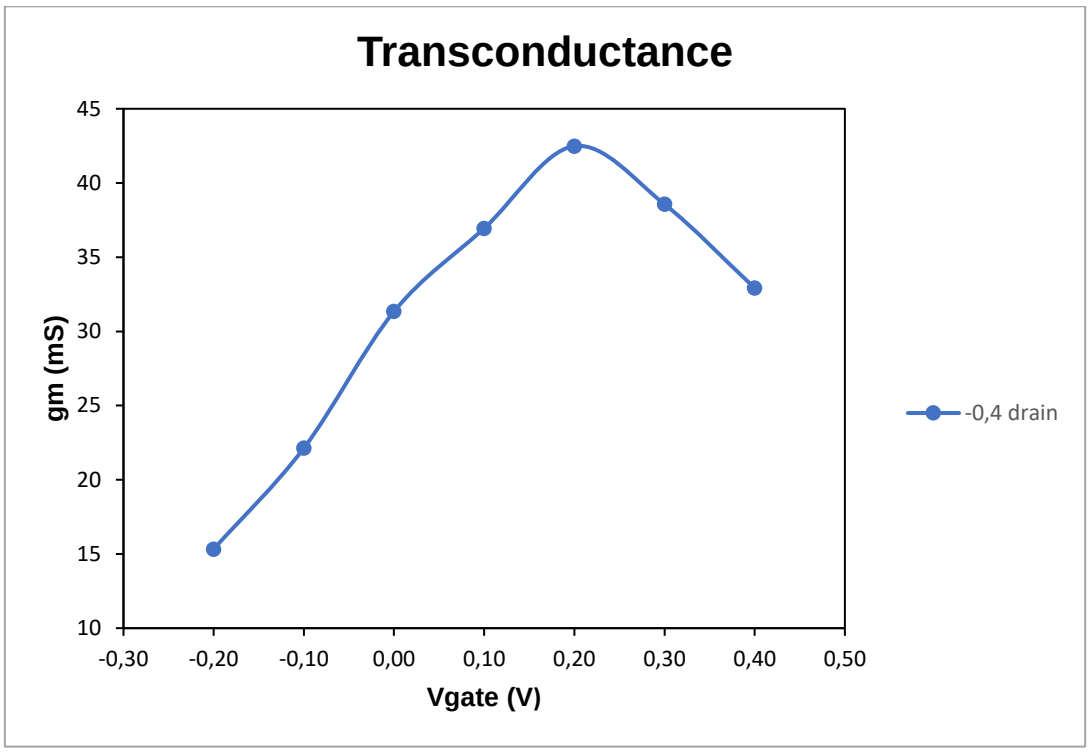

Figure 27: Variation of the transconductance value as a function of the applied gate voltage keeping the applied drain voltage constant

It was observed that the optimal Vgate, that is the external voltage of the gate, provided the highest transconductance and, therefore, the highest sensitivity of the system, where at 0.2 V. The transconductance studied in a sensor with only PEDOT is used to be compared to the one with membrane, that must have different response. If the response of the transconductance of the sensor with membrane is the same than the response without membrane, means that the membrane is not dopped in the correct way or is not properly weighted. The electrochemical characterization is useful to know the optimal conditions, the ones where the sensor is more sensible. The calibrations will be done in those conditions. The membrane is in charge to give response of the different additions.

Now, it is being explained the case of a sensor with membrane. The constant voltage of the drain applied was -0.4 V, -0.3 V and the voltage of the gate were from -0.3 V to 0.4 V. This was the time trace observed:

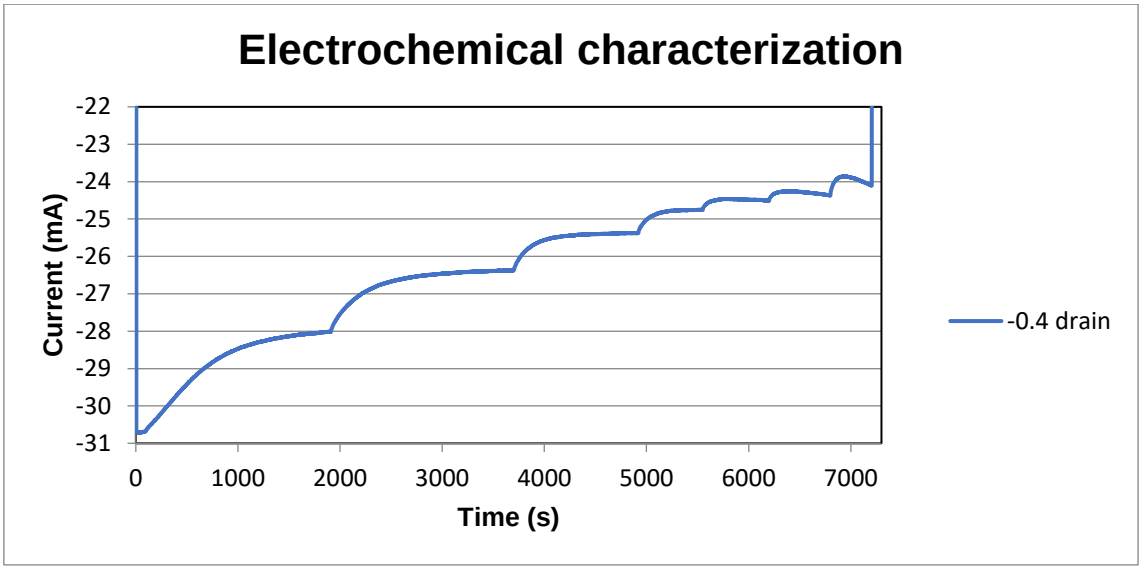

Figure 28: Time trace of the electrochemical characterization with Vd:-0.4 V. Representation of the stability of the intensity over time.

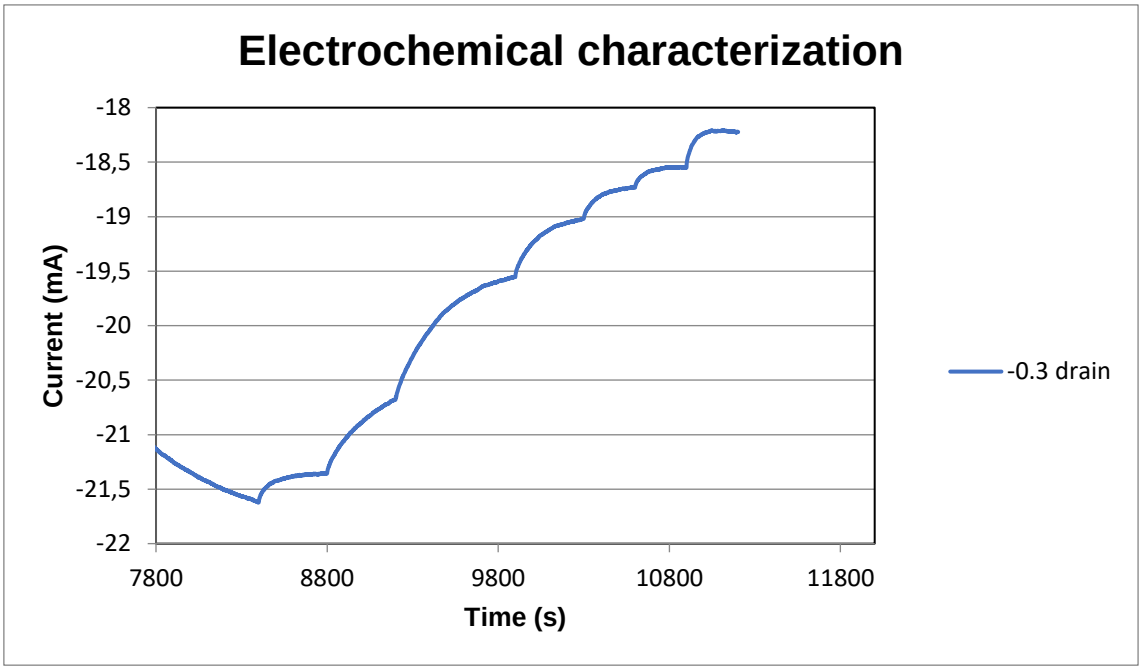

Figure 29: Time trace of the electrochemical characterization with Vd:-0.3 V. Representation of the stability of the intensity over time.

From those two time traces (Figure 28 and Figure 29) the maximum transconductance was studied. The time trace sometimes shows which change has higher difference in current, but to prove it is important to calculate the transconductance.

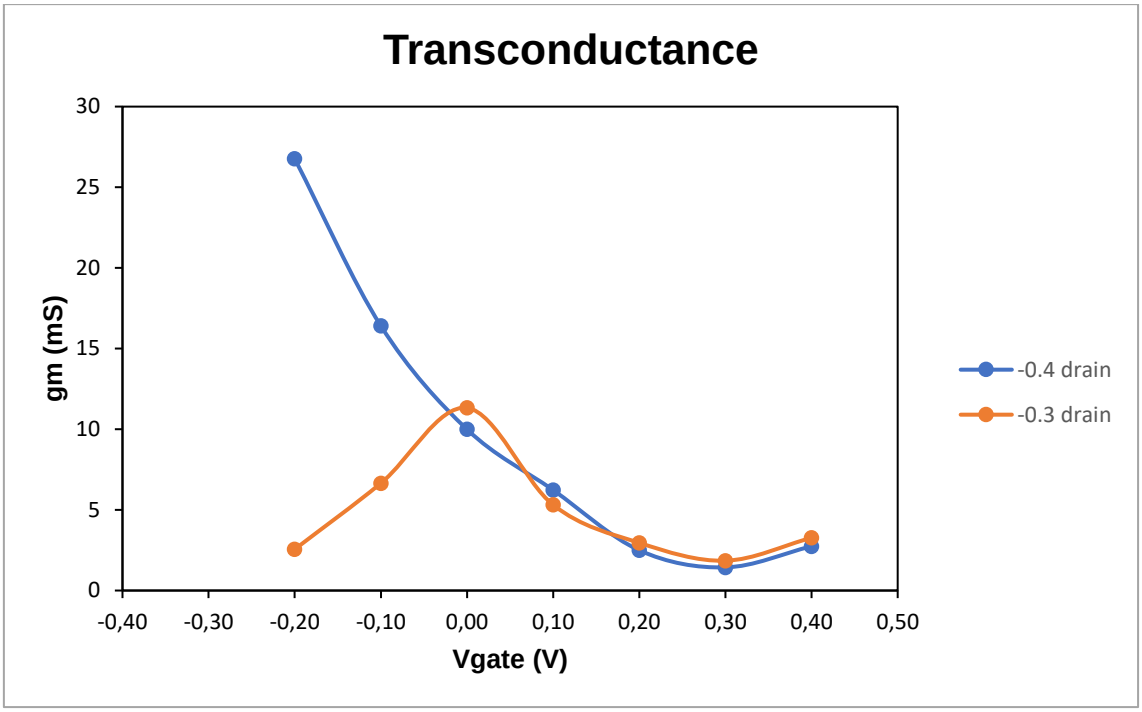

Figure 30: Variation of the transconductance value as a function of the applied gate voltage keeping the applied drain voltage constant at -0.4 V and -0.3 V.

From the Figure 30 it was observed two maximums, two possible values that make the system with higher sensitivity. The maximum point for the voltage of the drain at -0.4 V was with the voltage of the gate at -0.1 V. Until here, is possible to compare it with the transconductance from the system without membrane. The response it was different and that means the addition of the membrane it was good, the values differ. The maximum point for the voltage of the drain at -0.3 V was with the voltage of the gate at 0.0 V.

5.3. Calibrations

Once the applied voltages with the maximum transconductance and sensitivity were found it has been done different calibrations in order to find different analytical parameters as the linear range, the sensitivity, the limit of detection and the coefficient of determination, among others. Calibrations will help us to predict concentrations. When there are a sample that the concentration is unknown, having a previous calibration it is possible to know the concentration that it will have before studying it.

When the drain voltage was applied constantly at -0.4 V and the gate at -0.1 V, the transconductance was in its maxim level. The time trace obtained with the different additions mentioned before was:

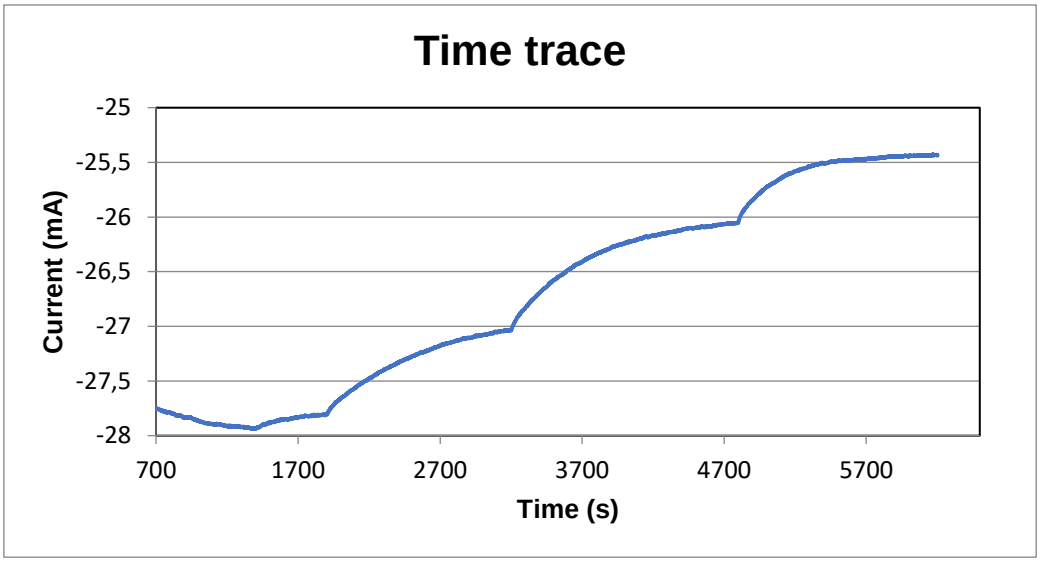

Figure 31: Time trace of the calibration at Vd: -0.4 V and Vg: -0.1 V

The time trace was stable and without noise. From the recorded current it was calculated some analytical parameters and perform the calibration curve of the logarithm of the concentration of calcium in function of the current measured.

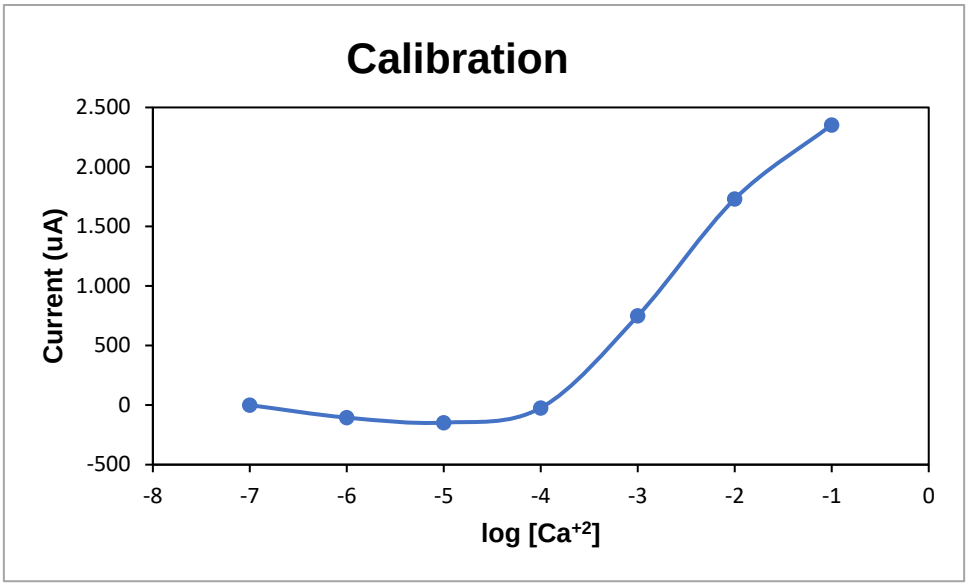

Figure 32: Calibration curve. Represents the logarithm of the concentration in function of the current.

These are the obtained analytical parameters from the calibration curve:

Coefficient of determination (R^2)	0.995
Linear range (L.R)	-4 to -2
Sensitivity (µA/dec)	877,08
Intercept (µA/dec)	3450.63
Limit of detection (L.O.D)	-4.1

Figure 33: Analytical parameters of the calibration at Vd: -0.4 V and Vg: -0.1 V

The limit of detection must be calculated with the linear function of y=a·x+b being the "y" a single point taken from the base line, because the base line is not enough straight. The "a" corresponds to the sensitivity and the "b" to the intercept. With this equation the limit of detection is isolated, "x".

When an addition of calcium ions was applied, it was produced a shielding from the calcium-PSS interaction. The negative charges of the PSS interacted with the positive calcium ions that were in the electrolyte solution. Then, the positive charges of the

PEDOT had a lower stabilization giving a lower conductivity. This happened during the different additions in the calibration. In each addition there were more calcium ions.

Applying a constant and fixed voltage of the drain at -0.3 V and the maximum point in transconductance of the Vgate that it was 0.0 V the following time trace was obtained in response to the different additions of the concentration of calcium:

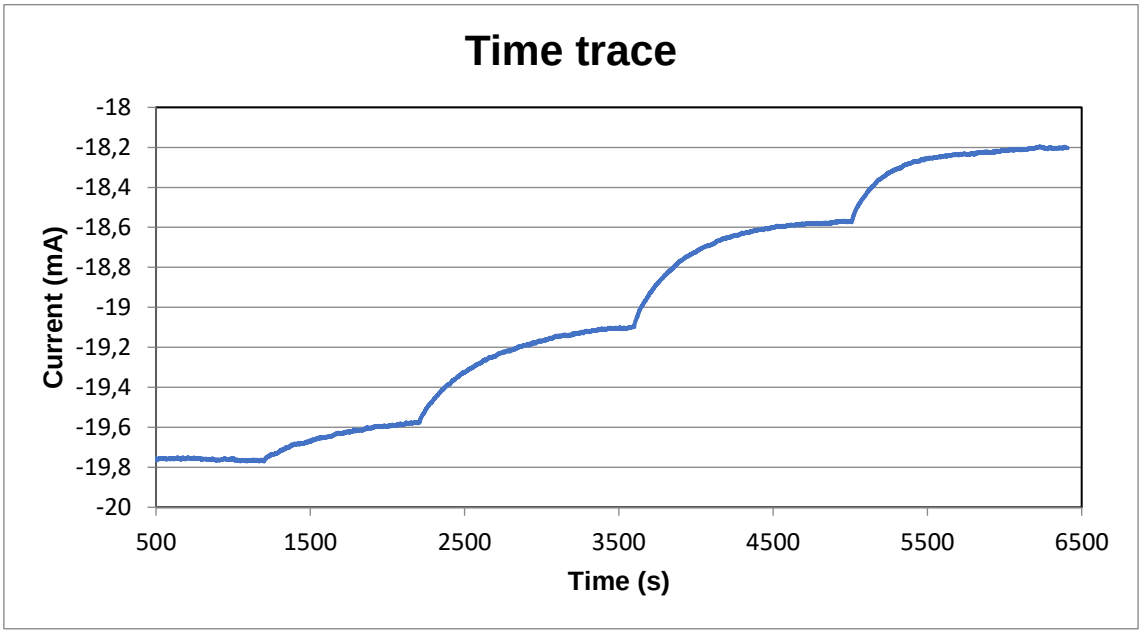

Figure 34: Time trace of the calibration at Vd: -0.3 V and Vg: 0.0 V

In this time trace it is possible to observe the stability of the response and no noise appeared. The difference in current is smaller than the previous calibration.

Again, from the recorded current it was calculated some analytical parameters and obtained the calibration curve of the logarithm of the concentration of calcium in function of the measured current.

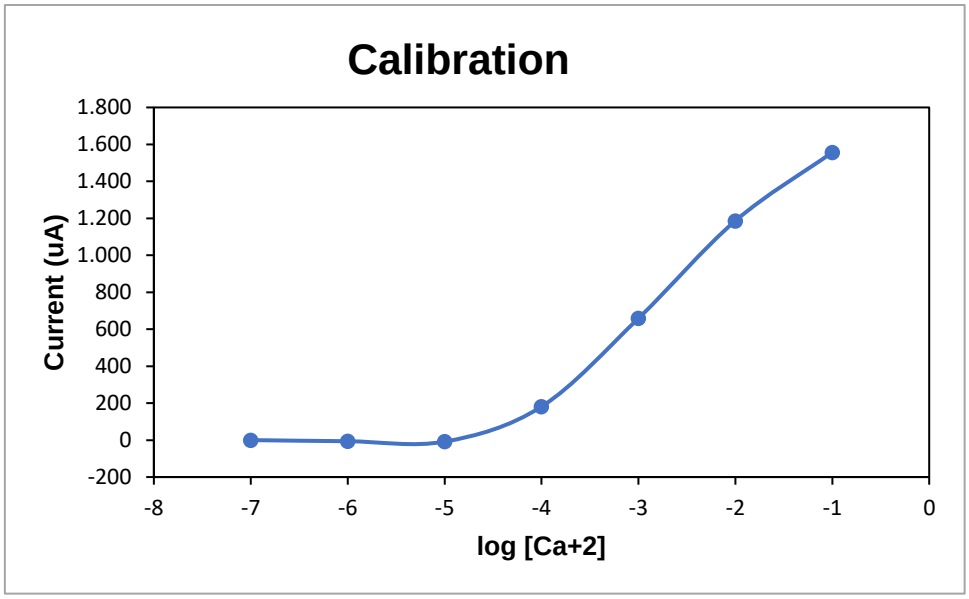

Figure 35: Calibration curve. Represents the logarithm of the concentration in function of the current.

These are the obtained analytical parameters from the calibration curve:

Coefficient of determination (R^2)	0.999
Linear range (L.R)	-4 to -2
Sensitivity (µA/dec)	502.58
Intercept (µA/dec)	2183.19
Limit of detection (L.O.D)	-4.34

Figure 36: Analytical parameters of the calibration at Vd: -0.3 V and Vg: 0.0 V

Finally, at the same sensor where were done the two calibrations with the maximum of transconductance, it was done another calibration but changing then the Vg to see how it affects and how changes. The conditions where the following: a Vd of -0.4 V and a Vg of 0.0 V. The Vd chose was the -0.4V because it gave highest sensitivity.

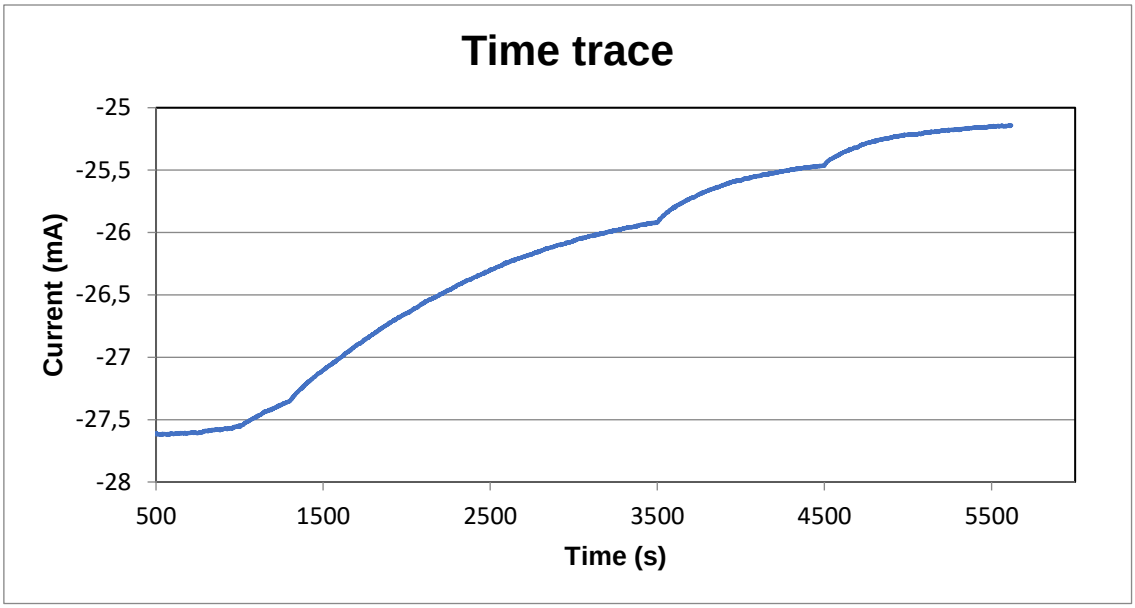

Figure 37: Time trace of the calibration at Vd: -0.4 V and Vg: 0.0 V

In this time trace it was possible to observe a clear big addition that corresponds to the -4. From the recorded current it was calculated some analytical parameters and perform the calibration curve of the current measured in function of the logarithm of the concentration of calcium.

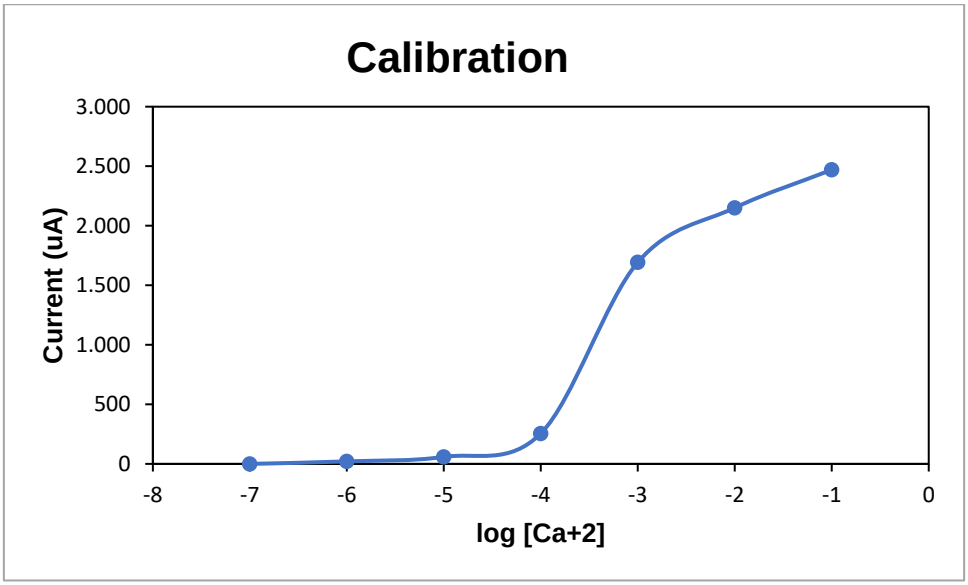

Figure 38: Calibration curve. Represents the logarithm of the concentration in function of the current

In this calibration curve can be seen two possible linear ranges. The one studied is from -4 to -3. These are the obtained analytical parameters from the calibration curve:

Coefficient of determination (R^2)	1
Linear range (L.R)	-4 to -3
Sensitivity (μA/dec)	1437.46
Intercept (μA/dec)	6005.56
Limit of detection (L.O.D)	-4.17

Figure 39: Analytical parameters of the calibration at Vd: -0.4 V and Vg: 0.0 V

In that case, the sensitivity was very high because the linear range its lower also. The other linear range it was not too accurate as the one chose. Taking into account the three calibrations, the optimal conditions were at Vd: -0.4 V and the Vg: -0.1 V because the sensitivity is the highest one in the highest possible range.

5.4. Selectivity

The selectivity is studied in order to know how selective the membrane is to the cation of interest, calcium^{+2} in that case. The membrane should be selective to calcium and give lower response to the other ions that get in contact. The selectivity was done in the same way as the calibrations but changing the salt of the additions, instead of calcium were added other ions. It is important to study the selectivity in an OECT that also was performed a Calibration to compare the calibrations lines. In that case the selectivity was studied with Potassium and Sodium.

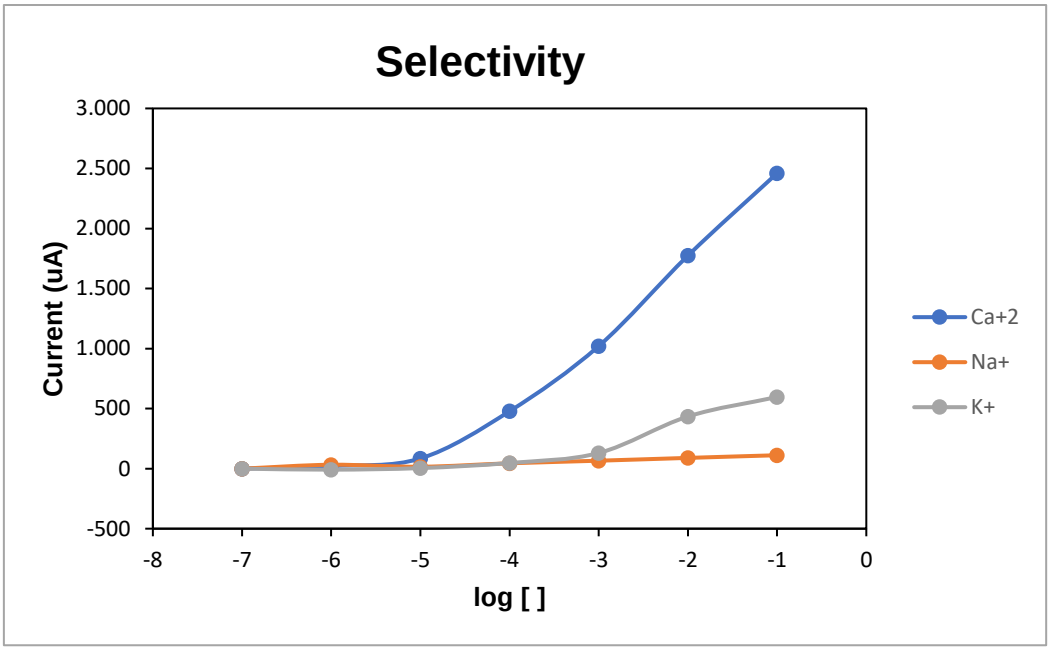

Figure 40: Selectivity of an OECT with a membrane of calcium. Represents the logarithm of the concentration in function of the current.

In the figure 40 it is observed the lower response of the membrane to the addition of the Sodium and Potassium ions compared to the calibration curve of calcium. The calibration done adding Sodium salt specifically gives almost no answer. OECTs can be tuned to detect the desired ion using an ion-selective membrane. Membrane selectivity is determined by the ionophore, specifically[30]. It is the molecule that makes it selective to calcium in that case, it is permeable to specific ions. There are some differences between the ions determined by the ionophore as the charge and the atomic radius. For that reason, the response of calcium is higher being then selective to those ions.

6. Conclusions

This project has allowed to understand how works and the basic concepts of an organic electrochemical transistor with the application of a calcium membrane. The ion-selective membrane used was built to be selective only to calcium and the response was outstanding. The selectivity of the membrane it has been proved in front other ions such as Sodium and Potassium.

The study of the different analytical parameters as the sensitivity, selectivity, linear range, limit of detection, stability, noise, among other, has shown the optimization of the potential of the system in order to offer the maximum sensitivity. The optimal conditions for the calibration of an OECT with a membrane of calcium were a potential of the drain of -0.4 V and the potential of the gate of -0.1 V. The sensitivity in those conditions was the highest obtained, 877.08 μA/dec.

With the different studies that were done in that project, it is possible to conclude that the hardness of water can be studied with those OECTs sensors. The sensitive and rapid monitoring of the hardness in water is very important in numerous environmental and industrial fields. In that case, using an ionophore specific for calcium and for magnesium makes it possible to study the response of these ions through the ion-selective membrane because the sensor can be immersed in the water as it was now in Milli-Q water. The response with a membrane of calcium in the OECT was done in that project.

For the next steps, future improvements in the devices would help to create the OECTs being able to read in the desired linear range for blood and other areas because calcium is found everywhere.

During these months I developed different skills for fieldwork. In the laboratory I carried out documented procedures and studied the proper use of standard chemical instrumentation.

7. Bibliography

(1) Meijer, G. C. M. Smart Sensor Systems. *Smart Sensor Systems* **2008**, 1–385. https://doi.org/10.1002/9780470866931.

(2) Ohashi, T.; Dai, L. C60 and Carbon Nanotube Sensors. *Carbon Nanotechnology* **2006**, 525–575. https://doi.org/10.1016/B978-044451855-2/50018-8.

(3) Zhang, X.; Ju, H.; Wang, J. 13.2 Properties of Transition Metal Hexacyanoferrates. *Electrochemical Sensors, Biosensors and their Biomedical Applications* **2011**, 412–439.

(4) Trailokya, A.; Srivastava, A.; Bhole, M.; Zalte, N. Calcium and Calcium Salts. *Journal of The Association of Physicians of India* ■ **2017**, *65*.

(5) *Calcium Levels Test: High vs. Low vs. Normal Range*. https://www.webmd.com/a-to-z-guides/do-i-need-a-calcium-blood-test (accessed 2022-06-14).

(6) Saurina, J.; López-Aviles, E.; le Moal, A.; Hernández-Cassou, S. Determination of Calcium and Total Hardness in Natural Waters Using a Potentiometric Sensor Array. *Analytica Chimica Acta* **2002**, *464* (1), 89–98. https://doi.org/10.1016/S0003-2670(02)00474-9.

(7) Cano Luna, M. Tesis Doctoral. **2008**.

(8) Javanbakht, M.; Akbari-Adergani, B. Molecularly Imprinted Polymer-Based Potentiometric Sensors for the Determination of Drugs in Pharmaceutical, Biological, and Environmental Samples. *Molecularly Imprinted Sensors* **2012**, 247–273. https://doi.org/10.1016/B978-0-444-56331-6.00011-6.

(9) Rezaei, B.; Irannejad, N. Electrochemical Detection Techniques in Biosensor Applications. *Electrochemical Biosensors* **2019**, 11–43. https://doi.org/10.1016/B978-0-12-816491-4.00002-4.

(10) Stradiotto, N. R.; Yamanaka, H.; Zanoni, M. V. B. Electrochemical Sensors: A Powerful Tool in Analytical Chemistry. *J Braz Chem Soc* **2003**, *14* (2), 159–173. https://doi.org/10.1590/S0103-50532003000200003.

(11) Fjer, M. Strained Si Heterojunction Bipolar Transistors.

(12) *What is a Transistor: How Does It Work » Electronics Notes*. https://www.electronics-

notes.com/articles/electronic_components/transistor/how-does-a-transistors-works-basics-tutorial.php (accessed 2022-06-06).

(13) Rivnay, J.; Inal, S.; Salleo, A.; Owens, R. M.; Berggren, M.; Malliaras, G. G. Organic Electrochemical Transistors. *Nature Reviews Materials 2018 3:2* **2018**, *3* (2), 1–14. https://doi.org/10.1038/natrevmats.2017.86.

(14) Nikolou, M.; Malliaras, G. G. Applications of Poly(3,4-Ethylenedioxythiophene) Doped with Poly(Styrene Sulfonic Acid) Transistors in Chemical and Biological Sensors. *Chem Rec* **2008**, *8* (1), 13–22. https://doi.org/10.1002/TCR.20133.

(15) Ait Yazza, A.; Blondeau, P.; Andrade, F. J. Simple Approach for Building High Transconductance Paper-Based Organic Electrochemical Transistor (OECT) for Chemical Sensing. *ACS Applied Electronic Materials* **2021**, *3* (4), 1886–1895. https://doi.org/10.1021/ACSAELM.1C00116/ASSET/IMAGES/MEDIUM/EL1C00116_M009.GIF.

(16) Strakosas, X.; Wei, B.; Martin, D. C.; Owens, R. M. Cite This. *J. Mater. Chem. B* **2016**, *4*, 4952. https://doi.org/10.1039/c6tb00852f.

(17) Sun, K.; Zhang, S.; Li, P.; Xia, Y.; Zhang, X.; Du, D.; Isikgor, F. H.; Ouyang, J. Review on Application of PEDOTs and PEDOT:PSS in Energy Conversion and Storage Devices. *Journal of Materials Science: Materials in Electronics* **2015**, *26* (7), 4438–4462. https://doi.org/10.1007/S10854-015-2895-5.

(18) Liao, J.; Si, H.; Zhang, X.; Lin, S. Functional Sensing Interfaces of PEDOT:PSS Organic Electrochemical Transistors for Chemical and Biological Sensors: A Mini Review. *Sensors 2019, Vol. 19, Page 218* **2019**, *19* (2), 218. https://doi.org/10.3390/S19020218.

(19) *DC Power Supply: What Is It? Where Is It Used? AC vs. DC*. https://www.iqsdirectory.com/articles/power-supply/dc-power-supply.html (accessed 2022-06-09).

(20) *Dual Output Linear DC Bench Power Supply - 30V, 5A - Tenma | CPC UK*. https://cpc.farnell.com/tenma/72-10495/power-supply-2ch-30v-5a-adjustable/dp/IN06823 (accessed 2022-06-10).

(21) *electrometer | instrument | Britannica*. https://www.britannica.com/technology/electrometer (accessed 2022-06-09).

(22) Gubler, L. Polymer Electrolyte Materials for Electrochemical Energy Devices. *Reference Module in Chemistry, Molecular Sciences and Chemical Engineering* **2018**. https://doi.org/10.1016/B978-0-12-409547-2.14285-4.

(23) Epel, D.; Vacquier, V. D.; Peeler, M.; Miller, P.; Patton, C. Sea Urchin Gametes in the Teaching Laboratory: Good Experiments and Good Experiences. *Methods in Cell Biology* **2004**, *2004* (74), 797–823. https://doi.org/10.1016/S0091-679X(04)74033-9.

(24) Bakker, E.; Bühlmann, P.; Pretsch, E. The Phase-Boundary Potential Model. *Talanta* **2004**, *63* (1), 3–20. https://doi.org/10.1016/J.TALANTA.2003.10.006.

(25) *Closed, Open, and Short Circuits - dummies*. https://www.dummies.com/article/technology/electronics/general-electronics/closed-open-and-short-circuits-141399/ (accessed 2022-06-10).

(26) *Estudi i desenvolupament de transistors orgànics electroquímics per a la detecció de reaccions immunològiques*. http://nportal0.urv.cat:18080/fourrepopublic/search/item/TFG%3A2546 (accessed 2022-06-10).

(27) *Static and Dynamic Resistance*. https://www.electrotechnik.net/2015/02/static-and-dynamic-resistance.html (accessed 2022-06-13).

(28) Brown, P. W.; Musil, S. A. Automated Data Acquisition and Processing. *Environmental Monitoring and Characterization* **2004**, 49–67. https://doi.org/10.1016/B978-012064477-3/50006-0.

(29) *Ohm's Law & circuits - Students 1920*. https://minormakerslab.gitbook.io/students-1920/andrei/andrei/week-2/ohms-law-and-circuit (accessed 2022-06-13).

(30) Sessolo, M.; Rivnay, J.; Bandiello, E.; Malliaras, G. G.; Bolink, H. J. Ion-Selective Organic Electrochemical Transistors. *Advanced Materials* **2014**, *26* (28), 4803–4807. https://doi.org/10.1002/ADMA.201400731.

(31) Clua, M.; Yazza, A. A.; Blondeau, P.; Andrade, F. J. HIGH-PERFORMANCE ION-SELECTIVE ORGANIC ELECTROCHEMICAL TRANSISTORS FOR THE DETERMINATION OF POTASSIUM IN CLINICAL SAMPLES. https://doi.org/10.13039/501100011033.