

Storage of Charge in
Redox Conductive Polymers
Probed with
Electron Spin Resonance Spectroscopy

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| $\vec{e}_x, \vec{e}_y, \vec{e}_z, t$ | Laboratory frame of reference |
| $\vec{\hat{S}} = (\hat{S}_x, \hat{S}_y, \hat{S}_z)$ | Spin operator |
| $h = 6.62607015 \times 10^{-34} \text{ J} \times \text{s}$ | Planck constant |
| $g_e = -2.00231930436118(27)$ | Electron g factor |
| $\mu_B = 9.2740100783(28) \times 10^{-24} \text{ J/T}$ | Bohr magneton |
| $\mu_0 = 1.25663706212(19) \times 10^{-6} \text{ N/A}^2$ | Permeability of free space |
| ε | Relative dielectric permittivity |
| $\vec{B}_0 = B_0 \vec{e}_z$ | Static magnetic field |
| ω_L | Larmor frequency |
| $\vec{B}_1(\vec{r}, t)$ | Microwave field |
| cwEPR | Continuous wave electron paramagnetic resonance |
| pEPR | Pulsed electron paramagnetic resonance |
| DUT | Device under testing |
| ORB | Organic radical battery |
| WE | Working electrode (cathode, "+") |
| CE | Counter electrode (anode, "-") |
| RE | Reference electrode |
| V_{OC} | Open circuit potential |
| SoC | State of charge |
| ESOC | EPR-detected state of charge |
| SoH | State of health |
| CV | Cyclic voltammogram |
| GCD | Galvanostatic charge-discharge |
| TEMPO | 2,2,6,6-tetramethylpiperidine-1-oxyl |
| pDiTS | Poly-di-TEMPO-Salen |
| RCP | Redox conductive polymer |
| pDiTBuS | Poly-di-TEMPO-Butyl-Salen |
| PTMA | Poly-TEMPO-methacrylate |
| EDFS | Echo-detected field sweep |
| ID | Instantaneous diffusion |
| $\langle n \rangle$ | Mean spin concentration |
| C | Local spin concentration |
| T_1 | Spin-lattice relaxation time |
| T_m | Phase memory time |
| t_d | Microwave detector dead time |

Table 1: List of abbreviations

Chapter 1

Introduction

This chapter introduces the concept of an organic radical battery, the electrochemical processes in the battery electrodes, the structures of organic electrode materials based on redox conductive polymers and their electrochemical performance. Necessary electrochemical characterization techniques are described. Charge transport models for particular electro-active conjugated polymers are reviewed.

Energy storage systems such as fuel cells, supercapacitors and batteries are crucial elements for powering portable electronics, vehicles, and for balancing a power grid with a renewable energy source [46]. Stable, capacious and powerful batteries have become of great demand for today's energy driven society [124, 120, 83]. The capacity of installed battery storage systems is predicted to increase upto 400 GWh by 2030 [28]. The advances in lithium ion technology for rechargeable batteries have enabled energy densities that make it possible to battery-power a wearable Internet-of-things device [64, 72], an airplane [50] or a house [19, 42]. Still, the application of lithium ion batteries is limited by irreversible processes [62, 30, 129] that occur upon extreme operating conditions such as high power demand [128, 35] or over-discharge [71]. Such degradation processes limit the performance of a battery by lowering its safe operating power, resulting in lower power density and longer charging times. The challenge to overcome these limitations, together with low abundance of Lithium, Cobalt and rare earth metals [120, 46], the toxicity of the manufacturing process [93, 91] and the bio-hazardous nature of the inorganic electrode materials [12] is motivating research and development of advanced, organic-based battery technologies [17]. This requires understanding of charge transport and degradation pathways in energy storage materials as well as exploring novel materials such as materials based on organic precursors [69, 54].

1.1 Rechargeable Electrochemical Cells

Two opposite electric charges separated from each other can store energy in an electrostatic field. It is possible to accumulate many charges on the plates of a capacitor and store some energy [38], but due to the technological difficulties, electrochemical cells are commonly used instead [28]. An electrochemical cell is an energy storage device and a power source that undergoes a chemical reaction to transfer some electric charge from one of its components to another through an external circuit.

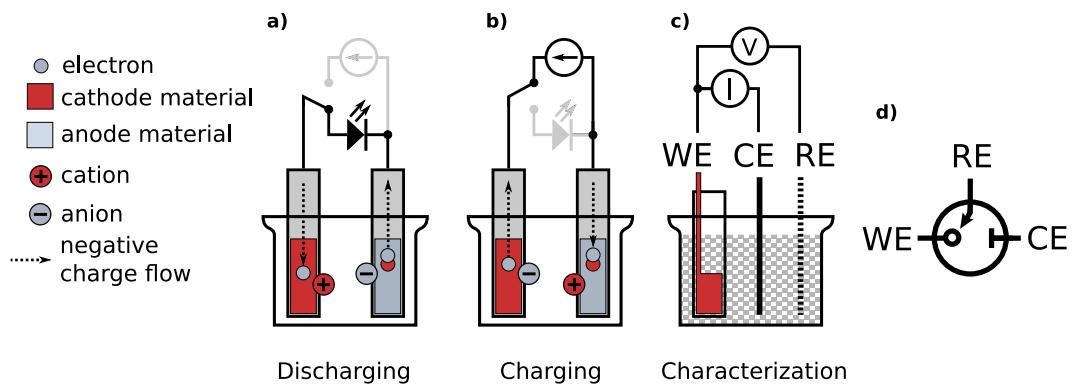


Figure 1.1: Rechargeable electrochemical cell connected to an external circuit for discharging a) and charging b). c): Three-electrode half-cell used for electrochemical characterization and charging of the cathode material. d): symbol for an electrochemical cell used in electric diagrams.

A simple electrochemical cell consists of three elements: two spatially separated materials called electrodes, and a solution of mobile ions between them called electrolyte. The two electrodes have different work functions, or, chemically speaking, reduction-oxidation (redox) potentials. The potential difference between the two electrodes is called the open-circuit potential of the cell, V_{OC} . When the electrodes are connected through an external circuit, as shown in Figure 1.1 a), the charge flows from one electrode to another through the circuit and the ions in the electrolyte rearrange to maintain charge balance [75]. While the cell delivers the electric current to the circuit, a chemical reaction is happening on its electrodes: the positively charged electrode, called cathode, is being reduced, obtaining electrons from the negatively charged anode through the external circuit. At the same time, the anode loses electrons and is being oxidized. If the electrodes can undergo a reversible redox reaction, a current applied to the cell restores its charged state, as shown in Figure 1.1 b).

1.2 Experimental Techniques for Characterizing Battery Materials

1.1.1 Organic Radical Battery

Batteries based on redox conductive polymers containing stable radical fragments as high-capacitance groups represent a promising class of future electrochemical power sources - organic radical batteries (ORB) [76, 81, 118, 95]. ORB combine the advantages of high-power supercapacitors, namely high discharge rates, and the high energy density of conventional lithium-ion technology. In contrast to the lithium-ion battery, the charging of an organic battery does not involve intercalation of metal ions into the electrodes. This reduces the structural change of the electrode upon repeated recharging which allows for a longer cycle life of ORBs. The electrolyte ions in an ORB do not chemically react with the electrodes, but rearrange to compensate the charges in the electrode, that improves the safety and lifetime of ORBs as compared to the Li technology. The amorphous and swollen structure of organic electrodes allows the electrolyte ions to diffuse into the electrode, which allows for oxidizing or reducing the electrode within its volume - this also increases the charge/discharge rates of ORBs [82]. A further beneficial property of organic materials over traditional inorganic materials is their availability and the low cost of the starting materials for the synthesis of the target polymers in conjunction with good mechanical properties [46, 75, 29]. The large knowledge base on polymer processing allows for inkjet printing, roll-to-roll processing and other low-cost manufacturing techniques for making low-cost, flexible and light-weight integrated devices, including flexible plastic batteries [46, 82].

1.2 Experimental Techniques for Characterizing Battery Materials

The flexible molecular design together with questions regarding unresolved charge-transport- and performance limiting mechanisms have inspired a variety of characterization techniques to be developed and applied to both energy storage materials and energy storage devices, operando (during the operation of a device) and ex-situ. Together with electrochemical characterization as the standard method for studying the properties of energy storage materials [4, 109, 127], operando optical microscopy [74], neutron imaging [71], mass spectroscopy [25] and X-ray diffraction [94] were applied to monitor irreversible structural deformations of the components of Li cells during extreme charging conditions.

UV and IR spectroscopy turned out to be particularly useful for studying organic energy-storage materials. For instance, with UV-Vis spectroscopy, it was possible to observe formation of positive polarons in the conductive molecular backbone for ORBs upon its oxidation [20]. Since the electrochemical processes happen within the bulk of the energy storage material and involve changes in the spin states, imaging techniques

based on magnetic resonance [80, 73, 65, 7] can be applied to obtain structural information on the battery electrodes at the molecular level. NMR was used to study dendrite formation, electrolyte dynamics and intercalation of Li ions [60, 34] in Li cells, including operando imaging [103].

Operando continuous-wave electron paramagnetic resonance spectroscopy(cwEPR) was applied to study electron transfer rates and electrolyte decomposition in redox-flow batteries [131], redox kinetics of inorganic battery cathodes [79], radical formation and spin densities in redox polymers [20] and in organic electrochemical cells [44, 57, 51].

Pulsed EPR (pEPR) provides an even more powerful toolbox for material studies with the electron spin as a microscopic structural probe. In particular, pEPR provides access to the dipolar coupling between neighboring electron spins and thus the possibility to determine distances between adjacent redox-active centers using dipolar spectroscopy [97] as in spin-labelled proteins [49, 112]. In addition, the hyperfine coupling between electron and nuclear spins in close vicinity can be measured by the electron spin echo envelope modulation (ESEEM) and the electron nuclear double resonance (ENDOR) techniques and can thus elucidate the degree of delocalization for charge carriers in ORB materials in a similar way as in organic semiconductors [26].

1.3 Organic Electrochemical Cells

1.3.1 Cell Electrodes

The electrode of an ORB is made of a conductive (metallic) lead and a layer of redox active (organic) molecules adsorbed to the metal [8] with a bond that allows for electrical conductivity. The charge transfer between the conductor and the redox active molecule in the electrode can be described in terms of the molecular orbitals of the cathode molecule and the Fermi energy of the electrode [105, 117, 8]. The oxidation potential of a molecule correlates with the energy of its highest unoccupied molecular orbital (HOMO) [108, 117]. A simple organic cathode consists of a metallic lead and one redox active molecule attached to it. When the electric potential V of the metallic lead is set lower than the HOMO of the cathode molecule, and the other end of the molecule is “grounded” with the electrolyte to the anode, an electron can be transferred from the cathode molecule to the lead. The cathode molecule loses an electron, acquires a positive charge and its electronic energy lowers. The induction of a positive charge in the molecule simultaneously attracts a negative ion from the electrolyte. No charge transfer happens between the ion and the charged molecule, but the movement of the ion causes a DC current to flow through the electrochemical cell, closing the electrical circuit shown in Figure 1.1 a). In a cathode containing more than one layer of redox

1.3 Organic Electrochemical Cells

active molecules, together with the polymer-metal charge transfer, an intermolecular charge transfer has to take place in order to oxidize the next molecular layer.

A symmetric reaction on the anode is reducing the anode molecule and changing its state from HOMO to LUMO. These two redox reactions describe the charging of an electrochemical cell. The opposite reaction is discharging. Upon discharging, the cathode is oxidized and the anode is reduced. Excessive charging and discharging may lead to an irreversible chemical reaction in the electrodes and the reactions to the electrolyte, that is undesirable, so the V_{OC} of the cell has to be observed during its operation.

1.3.2 Three-Electrode Cell

It is possible to study the redox reaction only at one electrode of the cell, e.g. the cathode, using a chemically inert second electrode. A cell with only one redox active electrode is called a half-cell. The studied electrode is called the working electrode (WE). The opposite electrode, called the reference electrode (RE), is made of a known material that maintains a constant composition and has a reproducible potential difference at the electrode-electrolyte interface called the standard potential. Any change in the potential difference between the WE and RE of the half-cell setup is therefore attributed to the processes in the WE only [4].

However, when a half-cell is being charged and the current is flowing through the RE, a chemical reaction can take place at the RE, changing its composition and the standard potential. The chemical reaction on the RE changes the parameters of the half-cell and shifts the observed potential difference unpredictably [4, 105]. For this reason, a three-electrode half-cell shown in Figure 1.1 c) is used for characterizing battery electrodes that are designed for significant charging currents.

In the three-electrode half-cell, the charging current is applied between the WE and a chemically inert counter electrode (CE). The oxidation of the WE is accompanied by the formation of a double layer of the electrolyte molecules at the surface of the CE. The electric potential of the WE is measured as a potential difference between the WE and the calibrated RE, inserted in the electrolyte close to the CE. The potential difference between WE and RE is measured with a high impedance voltmeter that ensures minimal charge flow through the RE. That is, RE does not undergo a chemical reaction during the charging of WE, its chemical environment does not change during the experiment and the measured potential difference between WE and RE corresponds to the potential of the WE. Due to the finite dimensions of the electrodes and the finite thickness of the double layer around the CE, the RE cannot be inserted at the position of the CE, so the measured potential has a constant offset as the electrolyte between the points where WE, RE and CE are inserted, acts as a voltage divider [4].

1.3.3 Reference Electrode

The potential E of the cell electrode is measured with respect to a calibrated, inert RE. The potential of the RE is chosen as $E = 0$. A general RE is the standard hydrogen electrode ($\text{Pt}/\text{H}_2/\text{H}^+$), or SHE. The main difference between the various RE is their operation range and a constant potential shift with respect to the SHE depending on the workfunction of the RE material. The couple Ag/AgNO_3 is commonly used in electrochemistry [4]. It exhibits a shift of 0.7991 V vs. SHE. For the couple Ag/AgCl , the shift is 0.2223 V against SHE [4, 105], although these values can only be used if the electrode configuration is strictly equivalent to the one used for determining them. In other cases, like in the case with a thin electrolyte layer in the modified sample tube, the exact shifts of the RE might differ [105].

1.3.4 Electrolyte

Electrolyte is an ionic conductor [4] - an electrically conductive solution of oppositely charged ions that are typically products of dissociation of the corresponding salts. The dissociation of a salt in a solvent implies that the solvent has high enough dielectric constant ϵ to polarize the salt molecule and to separate it into a positive ion (cation) and a negative ion (anion) by creating solvation shells around them. High mobility of the electrolyte ions is needed for the efficient ion diffusion into the battery electrodes, so that the redox reaction can take place along the entire surface of the electrode material that is soaked into the electrolyte. The ionic mobility also influences the Ohmic losses and polarization of electric double layers, governing, together with the electronic properties of the electrodes, the power density of a battery [77].

1.3.5 Characteristics of Rechargeable Batteries

Depending on the redox potentials of the used electrodes, the output voltage of a cell (V_{oc}) ranges between 0 and 5 V [46]. Most applications require higher voltages, so multiple cells are connected in series to form a battery.

Energy and power density, C-rate and State Of Charge The capacity of a cell C is measured in mAh. It is the maximal electric charge that can be stored in it. Different electrode materials can store different amounts of charge depending on their chemical composition and microscopic structure. Due to the unavoidable losses of charge caused by the finite shunting resistance between the cell electrodes, one distinguishes between the charging capacity and the discharging capacity. The capacity of 1 g of an electroactive material is its gravimetric capacity, it is measured in mAhg^{-1} . The volumetric

1.3 Organic Electrochemical Cells

capacity is the corresponding value with respect to the volume of the material that is measured in mAhl^{-1} . The energy stored in a cell is a product of its capacity and its voltage. The ratio of the stored energy to the volume of a cell is its energy density. The energy density of a cell depends on the capacity of the electrodes and the potential difference between the electrodes [67]. The fraction of charge left in a cell with respect to the full charge that can be stored in that cell in percent is called the state of charge or SoC. The SoC of a fully charged battery is 100%.

A battery is typically charged with a constant DC current. The magnitude of the charging (or discharging) current relative to the battery capacity determines the rate at which a battery is charged (or discharged). The charging rate, or C-rate is the charge or discharge current in Amps divided by the battery capacity in Ampere-hours. For a modern rechargeable Li-polymer battery a safe charging C-rate cannot exceed 1 C [128]. That means, the safe charging time for a Li-polymer battery cannot be shorter than 1 hour. The discharge rate of the same battery, however, can be as high as 100 C that corresponds to a discharge current larger than the charging current by a factor of 100. The power that a battery can deliver depends on its maximal discharging C rate and equals to the product of its short-circuit current and its voltage. The organic radical batteries can have charging and discharging C rates close to 3000 C and gravimetric discharge capacities upto 111 mAhg^{-1} [113, 29, 127, 114, 58, 110]. While the capacities of the organic electrode materials are smaller than for the Li metal electrodes (3850 mAhg^{-1}), the organic electrode materials allow for much higher C rates that already exceed the C rate of the conventional inorganic cells by orders of magnitude [19].

State Of Health The capacity of a battery may decrease upon repeated charge-discharge cycling, especially at high C rates [35, 86], over-discharge [71] and extreme environmental conditions [128]. The ratio of the maximum battery charge to its rated as-manufactured capacity expressed in percent is called state of health (SoH). SoH is a measure of the remaining life time of a battery. The decrease in SoH indicates the intensified irreversible processes that take place in an electrochemical cell, such as a physical damage [31], degradation of the electrode material [71, 57], side reactions at the electrode-electrolyte interface [110], or decomposition of the electrolyte [25]. A damaged cell, especially that can store significant amount of charge, represents a major hazard [71]. Accurate measurements of SoH can prevent hazardous battery malfunctions such as explosions.

1.4 Electrochemical Instrumentation

1.4.1 Cyclic Voltammogram

The complete electrochemical behavior of a redox active molecular system can be obtained with a series of transient current responses to potentials, applied step-wise to the electrochemical cell containing the system. However, for a basic electrochemical characterization, a current response during a linearly swept potential is sufficient [4]. During the linear-potential-sweep chronoamperometry, or linear sweep voltammetry, the potential E applied to the electrochemical cell is swept in a linear manner between the values E_{min} and E_{max} , upwards and downwards, with a rate v (mVs^{-1}): $E(t) = E_0 \pm vt$. During the sweep, the current is recorded as a function of the applied potential as shown in Figure 1.2 b).

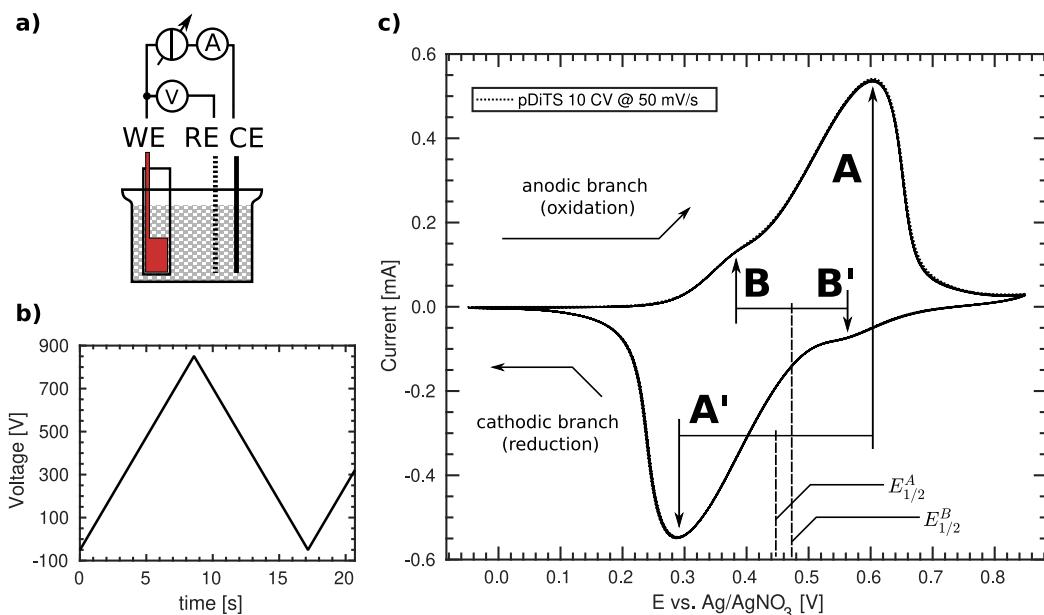


Figure 1.2: a): Electrochemical setup for measuring a cyclic voltammogram. b): Linear voltage sweep at a 50 mVs^{-1} rate. c) Cyclic voltammogram of an electro-active polymer cathode film. Oxidation and reduction of the charge-bearing fragments of the film corresponds to the A and A' redox peaks, respectively. Oxidation and reduction of the conductive polymer backbone of the film corresponds to peaks B and B' . The standard oxidation potential of the charge-bearing fragments, $E_{1/2}^A$, lies close to the standard oxidation potential of the backbone, $E_{1/2}^B$.

The resulting plot $i(E)$ is the cyclic voltammogram (CV). The upward potential sweep corresponds to the anodic, or charging branch of the CV and the downward sweep

1.4 Electrochemical Instrumentation

corresponds to the cathodic, or discharge branch. A CV of a three-electrode electrochemical cell with an electro-active polymer film on the WE is shown in Figure 1.2 c). When E reaches the oxidation potential of the working electrode, charge transfer happens and the current through the cell increases. This corresponds to the oxidation peak in the anodic branch. The width of the peak is determined by the temperature of the cell and the number of electrons n transferred in a single oxidation reaction ($n = 2$ for poly-di-TEMPO-Salen, the redox conductive polymer described in Section 3.2). The negative current peak in the cathodic branch of the CV curve corresponds to the reduction of the WE. The difference between the potentials of the oxidation and reduction peaks arises because of the finite electric capacity of the electro-active film and a finite voltage sweep rate. For higher sweep rates the difference in peak potentials is higher, as the scanning time becomes comparable to the RC time constant of the cell.

The area under the anodic branch can be used to calculate the charge that was transferred from the WE upon its reduction from the fully oxidized state. The applied voltage is swept at a known rate, so the anodic branch $i(E)$ can be plotted vs. time $i(t)$, hence the transferred charge equals to the integral under the curve: $q = \int_{E_{\min}}^{E_{\max}} i(t) dt$. By knowing the q and considering the corresponding chemical reaction (how many electrons are transferred for one molecule) one gets the amount of substance in the electrode $v = qF$ [mol] and the number of electrochemically active molecules $N_{echem} = vN_A$ with $F \approx 9.46853 \times 10^4 \text{ C} \times \text{mol}^{-1}$ for the Faraday constant and $N_A = 6.02214076 \times 10^{23} \text{ mol}^{-1}$ for the Avogadro constant [78]. Given the molecular weight M , the total mass of the electrochemically active molecules of the film can be calculated. Together with the information on the density of the film, its dimensions can be estimated. However, as demonstrated in Section 4.3.3 and in Refs. [114, 57, 58], the number of electrochemically active molecules in a polymer cathode film can be much lower than the total number of molecules in it.

1.4.2 Charge-Discharge Cycling

A constant-current characterization technique called galvanostatic potentiometry [4] can be used in combination with the cyclic voltammetry to study the redox behavior of the electrochemical system quantitatively. The setup for galvanostatic charge-discharge cycling is shown in Figure 1.3 a). The cell is excited with a DC current as shown in Figure 1.3 b) and the potential of the cell is measured as a function of time, as shown in Figure 1.3 c). Upon positive (charging) current, the working electrode of the cell is oxidized. The voltage required to provide the charging current gradually increases, resulting a galvanostatic charging curve shown in Figure 1.3 c). The shape of the charging curve can be approximated by considering two major effects: the Faradic current and the displacement current [4]. The Faradic current is caused by the oxidation of

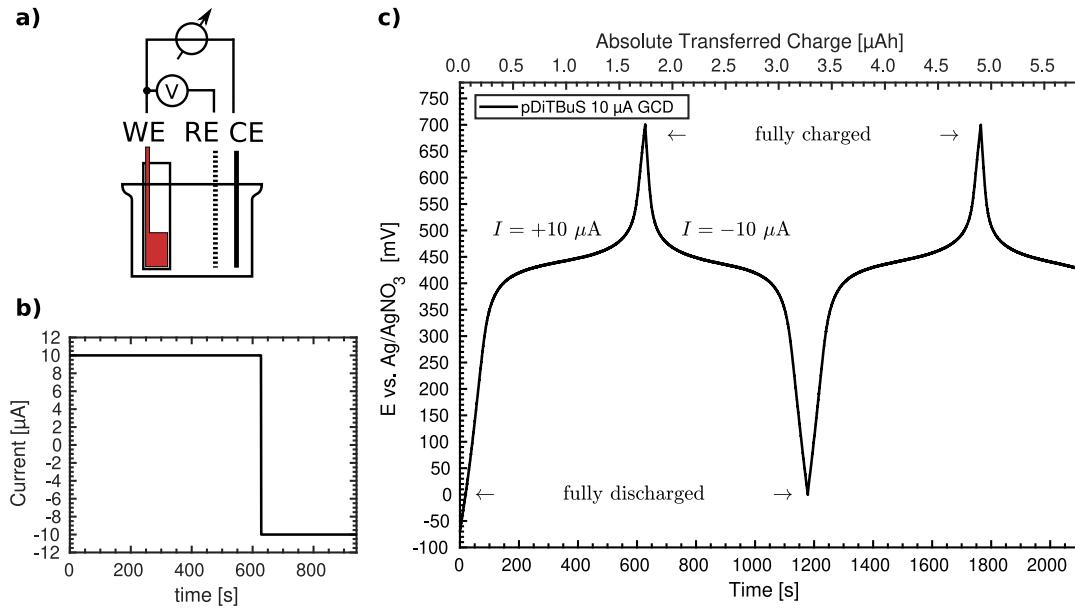


Figure 1.3: a): Electrochemical setup for galvanostatic charge-discharge cycling. b): $\pm 10 \mu\text{A}$ DC current applied to record the cycling. c) Chronopotentiometry of an eelctrochemical cell containing electro-active polymer film cathode. Full charging is recognized by the steep increase of the charging curve after passing the plateau.

the redox active species in the WE. It defines the plateau regions in the middle of the charging and discharging curves. The displacement current is the result of the charging of a double layer around the WE and CE. It explains the capacitor-like response of the charging and discharging curves before and after the plateau region [4]. In this regard the electrochemical cell with only one redox active electrode can be treated as a pseudo-capacitor [38, 114]. When all redox active species of the WE are oxidized, the voltage required for providing the charging current steeply increases, that is seen in the end of the charging curves in Figure 1.3 c) and 3.9. Eventually, upon charging, the potential of the cell grows beyond the oxidation peak of the WE, according to the cyclic voltammogram (Figure 1.2). Then the charging is stopped and the transferred charge is calculated from the charging time. The same strategy is applied for the discharging curve to determine the discharging capacity of the cell. The reproducibility of the charge-discharge curve indicates the stability of the electrochemical cell. SoH of the cell can be estimated by observing the decrease in the period of the charge-discharge curve.

A cell can also be charged by applying a constant voltage to it and by letting the applied current to change upon charging, this mode is called potentiostatic chronoamperometry. A positive voltage applied to a discharged cell will initially result in a large current. Upon potentiostatic charging, the charging current decreases with time, as most

1.5 Redox Conductive Polymers

of the molecules in the electrode are oxidized and the cell voltage approaches the applied voltage.

1.5 Redox Conductive Polymers

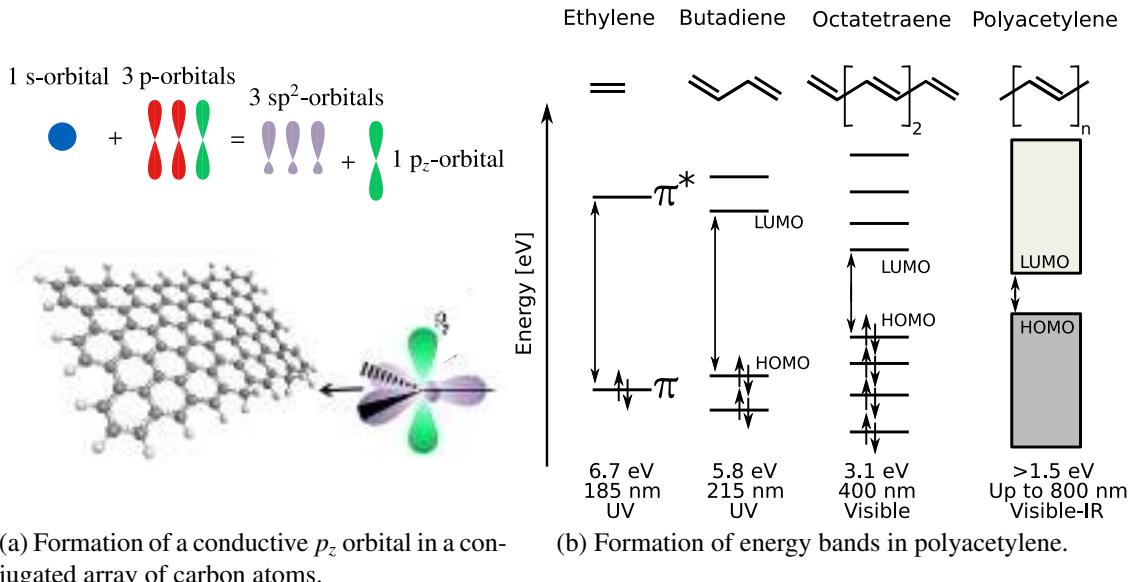
Redox active macromolecules or polymers [106] are known since 1940s due to the works of Lauth and Cassidy [13] on electron exchange polymers. After the discovery of the conductivity of polyacetylene by Shirakawa, Heeger and McDiarmid in 1977 [104], organic semiconducting polymers with sufficient charge carrier mobilities ($\mu > 1 \text{ cm}^2 \text{ V}^{-1} \text{s}^{-1}$) were synthesized [43], and the field of organic electronics had emerged [39, 12]. Electron and hole mobilities in modern organic semiconductors have reached the values as high as $\mu > 10 \text{ cm}^2 \text{ V}^{-1} \text{s}^{-1}$ [43] and, theoretically, can be above $\mu > 100 \text{ cm}^2 \text{ V}^{-1} \text{s}^{-1}$ for organic molecular co-crystals [133], which enables efficient charge transport in fast-switching organic electronic circuits. Organic solar cells [63], organic field effect transistors [55, 122], e-papers [43] and organic electrochemical neurons [37] contain conjugated polymers that have electrical properties of semiconductors, yet can be easily printed in form of thin flexible films without using high temperatures, can be bio-integrated and undergo an environmentally friendly recycling [82]. A combination of conductive polymers with charge-bearing organic radicals [109] has formed the class of redox conductive polymers [12] and lead to the concept of an organic radical battery [95, 81, 76, 119] - the last missing component needed for making an electronic device fully organic.

1.5.1 Semiconducting Polymers

The key for polymer conductivity is the π - conjugated network, a system of overlapping π orbitals of carbon in a chain of alternating single and double carbon-carbon bonds that allows for charge delocalization along the polymer backbone [39, 61, 12]. An example of a π conjugated network is polyacetylene shown in Figure 1.5b. Polyacetylene exhibits a band structure in the electron energy levels (between its band-like π and π^* orbitals) and represents a molecular semiconductor [39].

A simple organic molecule, ethylene, shown in Figure 1.4, contains two carbon atoms and four hydrogens. Each carbon atom has six electrons. The four unpaired electrons of carbon - one at the $2s$ orbital and three at the $2p$ orbital - interact to form two sp^2 - hybridized orbitals and one unhybridized p_z orbital, as shown in Figure 1.5a.

The hybridized sp^2 orbitals form σ bonds between adjacent carbon atoms. The σ bonds keep the carbon atoms together in the molecule. The remaining p_z orbitals interact with each other and form a π bond so that p_z electrons are shared between the

Figure 1.4: Ethylene molecule with σ and π bonds [61].(a) Formation of a conductive p_z orbital in a conjugated array of carbon atoms.

(b) Formation of energy bands in polyacetylene.

Figure 1.5: Formation of a band gap in a conjugated polymer. Figures adapted from [84].

carbon atoms. The interaction between p_z orbitals results in two molecular orbitals, the bonding (π) and the antibonding (π^*) orbitals [18]. A π orbital is described by a symmetric wavefunction and π^* orbital is described by an antisymmetric wavefunction. A π orbital has a lower energy than π^* , as shown in Figure 1.5b. The symmetric π orbital is more energetically favorable, so the electrons occupy it at the equilibrium. Because of that, the π orbital is called the Highest Occupied Molecular Orbital (HOMO) and π^* is the Lowest Unoccupied Molecular Orbital (LUMO). There is a forbidden energy zone between HOMO and LUMO which is equivalent to a bandgap of a semiconductor.

In a longer molecule, the π/π^* states are delocalized over many carbon atoms. This is known as conjugation and the number of conjugated atoms determine the conjugation length. As conjugation length increases, the HOMO and LUMO levels for each pair of carbon atoms in the molecule become slightly different. In a polymer with a very large conjugation length, many energy levels around HOMO and LUMO overlap which

1.5 Redox Conductive Polymers

forms energy bands, as shown in Figure 1.5 [61, 84]. At a finite temperature, there is a non-zero population of electrons above the LUMO level which allows them to move freely along the chain of overlapping p_z orbitals and makes conjugated polymers conductive [39].

Even though conjugated polymers have band-like energy structure and a bandgap, their charge-transport properties are different from crystalline semiconductors. Real polymer chains have finite lengths that brings disorder to an organic semiconductor (Figure 1.6 a). The disorder causes localization of electronic wave functions, that is known as charge carrier trapping, and hinders the electrical transport in semiconductors [123, 73], so when an external electric field is applied, a charge needs additional energy to hop from one localized state to another for electric current to flow (Figure 1.6 b). In Figure 1.6 c) it is shown how a charge moves through a disordered organic semiconductor choosing the optimal path in both energy and space domains. This mode of charge transport is referred to as the hopping transport [111].

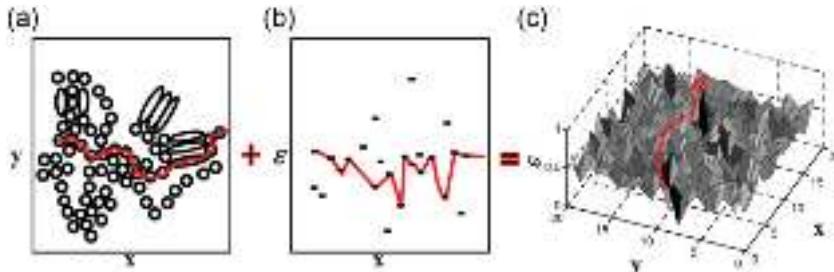


Figure 1.6: Transport of charge through localized energy sites distributed both in space (a) and in energy (b). The line describes a possible path that a charge carrier takes while hopping through a conjugated polymer under an external electric field. The trajectory is affected by the energy distribution (c). The picture is taken from Ref. [111].

Redox conductive polymers (RCP), besides being conductive, are able to store a charge. Typically, a RCP has a large concentration of charge bearing fragments that are interconnected by the polymer backbone [12]. Storage of charge implies that the stored charge carriers are localized and cannot freely move within the polymer, unless the appropriate electric field is applied to release them to the conjugated network. In this regard, the charge bearing fragments of an RCP can be viewed as charge carrier traps. The high concentration of the charge carrier traps in a conductive polymer makes neither the hopping-charge transport model [99], nor the band-like transport model [61] applicable to describe the electric transport in these materials, so alternative models were developed.

1.5.2 Charge Transport in a Polymer Electrode

The charge transfer within a RCP electrode governs the speed, reversibility, physical conditions and release of by-products of the redox reaction in an organic electrochemical cell, that are the key factors that define the charging rate, cycling stability, self-discharge rate and the area of application of the cell.

The transfer of charge between the metallic substrate of the electrode and the surface-bound molecules of the electrode can be described in terms of the electrode workfunction, the HOMO and LUMO levels of the electrode molecule and the applied potential [4]. On the contrary, the transfer of charge between the molecules within the volume of the electrode is a complex process that involves hopping and time-dependent delocalization of the charge carriers in the percolated network of the porous electrode material. Furthermore, the number of available charge bearing groups and the resulting local electric fields in the electrode are changing depending on the state of charge of the electrode, that implies that the conductivity of the RCP strongly depends on its state of charge [130]. The microscopic structure of the electrode affects the diffusion of the electrolyte ions, that also affects the charge transport properties of the electrode [56, 38].

Molecular systems for electrochemical charge storage are inherently disordered materials and the electric performance of a film containing those molecules is strongly dependent on the deposition method, as well as on the molecular structure [119, 130]. Some charge transport models have been developed, that are applicable to certain classes of polymers. The charge transfer between the radicals in non-conductive redox polymers is described with the diffusion cooperation model that involves charge hopping between the charge bearing fragments as well as their Brownian motion [99]. Mixing the non-conductive redox polymers with conductive additives such as activated carbon [114, 15] allows for efficient transport of charges through the conductive additive. The carbon mesh makes it possible to oxidize most of the redox active groups in the electrode and allows for the electrolyte to diffuse into the electrode, but also adds a significant amount of “dead mass” that decreases the specific capacity of such electrodes. In RCPs, the conductive mesh is created by the semiconductor polymer backbone - that reduces the dead mass and allows for higher specific capacities. The transport of charge in such materials includes direct hopping between the charge bearing groups, transfer of charge between the charge-bearing group and the conductive polymer backbone, transport of charge through the backbone, and transport of electrolyte ions inside the polymer mesh. Those many factors affecting the performance of an RCP with a certain molecular structure lead to unexpected results, such as the decrease of the electrode conductivity with the increase of the number of charge-bearing radicals per monomer unit in a Poly (3-hexylthiophene)/TEMPO RCP [130].

Chapter 2

Fundamentals of EPR

In this chapter, the phenomenon of electron paramagnetic resonance is briefly described with details that are required to interpret the spectra of a charging electrochemical cell containing nitroxide radicals attached to a conjugated polymer backbone. After the introduction of the spin Hamiltonian, an experimental procedure to observe the corresponding spin transitions with continuous microwaves is described. The characteristic spectra of nitroxide radicals in various environments are described. Finally, the fundamentals and the experimental techniques of the pulsed EPR spectroscopy are introduced.

2.1 The Spin Hamiltonian

Electron Spin In the Poincaré group of special relativity [92], rotations are considered together with the relativistic boosts [23] and there emerges an additional quantity that is associated with rotation and is preserved together with the orbital angular momentum, yet this quantity is retained for point objects - it is called spin [59]. Spin is quantized [32]; it can take values in integer- or half-integer multiples of the Planck's quantum of action \hbar up to a certain magnitude S . The electron, as a fundamental particle and a fermion, bears a half-integer spin with a magnitude of $S = 1/2$ [32, 96].

An isolated electron has two degenerate spin states - spin-up $|\uparrow\rangle$ and spin-down $|\downarrow\rangle$ - that are eigenfunctions of the square of the spin operator \hat{s}^2 with the same (degenerate) eigenvalue $\hat{s}^2|\uparrow\rangle = \hat{s}^2|\downarrow\rangle = \frac{3}{4}\hbar^2$. The states $|\uparrow\rangle$ and $|\downarrow\rangle$ are also eigenfunctions of the z component of the spin operator, but correspond to different (non-degenerate) eigenvalues $m_s = \pm\hbar/2$ [96]:

$$\begin{aligned}\hat{s}_z|\uparrow\rangle &= +\frac{\hbar}{2}|\uparrow\rangle \\ \hat{s}_z|\downarrow\rangle &= -\frac{\hbar}{2}|\downarrow\rangle\end{aligned}\tag{2.1}$$

g factor Spin combines with the charge of the electron to endow the electron with a magnetic moment $\mu_{spin} = \gamma S$, where $\gamma = \frac{g_e \mu_B}{\hbar} \approx 28 \text{ GHz/T}$ is the gyromagnetic ratio of the electron, $\mu_B = \hbar e/m_e$ is the Bohr magneton and $g_e \approx 2$ is the electron *g* factor [10]. The *g* factor connects the spin of a particle with a magnetic moment that the particle expresses through interactions with external fields [102]. The Dirac quantum theory of the electron predicts $g_e = 2$ [89]. However, up to date, $g_e = 2.00231930436256(35)$ has been measured to the unprecedented accuracy of 0.13 ppt [24]. This measurement lies at the frontier of modern particle physics and the accordance of the measured g_e with the value obtained with quantum electrodynamics [102, 24] is the triumph of the quantum field theory [27].

Depending on the local environment of an electron, its *g* factor can change from g_e due to the spin-orbit coupling that changes the observed magnetic moment of the electron [10]. The magnetic moment of an electron can therefore be used as an extremely sensitive probe of the electron's local environment. The *g* factor of an electron localized in a molecular orbital can be anisotropic, depending on the shape of the orbital. Anisotropic *g* factor is represented by a 3×3 **g** matrix that can almost always be diagonalized [10] by an appropriate rotation of the molecular coordinate system.

Zeeman Splitting When an electron is placed in a static magnetic field $\vec{B}_0 = B_0 \hat{e}_z$, its magnetic moment experiences a torque and precesses in the *xy* plane about the field axis with the Larmor frequency $\omega_L = \gamma B_0$. The magnetic moment of the electron has two possible projections on the magnetic field axis, according to 2.1. The two corresponding eigenvalues $\pm \frac{\hbar}{2}$ define the energy difference between the states $|\uparrow\rangle$ and $|\downarrow\rangle$ when the spin couples to the external magnetic field, that is known as the Zeeman splitting. The energy difference between $|\downarrow\rangle$ and $|\uparrow\rangle$ in a magnetic field is the Zeeman energy.

The energy of an isolated electron placed in the external magnetic field \vec{B}_0 is the energy of the electron's magnetic moment in that field, that is given by the eigenvalue of the spin Zeeman Hamiltonian: $\hat{H}_{EZ} = \frac{\mu_B}{\hbar} \vec{B}_0 g_e \hat{s}$. In the laboratory frame of reference $\vec{B}_0 \parallel \hat{e}_z$, $[\hat{H}_{EZ}, \hat{s}_z] = 0$, so \hat{H}_{EZ} and \hat{s}_z share the two eigenfunctions $|\uparrow\rangle$ and $|\downarrow\rangle$. The energies of the corresponding states are $E_{EZ}^{\pm} = \pm \frac{1}{2} \mu_B g_e B_0$ (see Figure 2.2), and their difference is the Zeeman splitting:

$$\Delta E_{EZ} = \mu_B g_e B_0 \quad (2.2)$$

The measurement of the magnetic moment of an electron can be done by measuring its Zeeman energy. The local molecular environment affects the electron's magnetic moment through spin-orbit coupling which can be seen as a deviation in the electron's *g* factor, and therefore, in the measured Zeeman energy [10].

Nuclear Spin and Nuclear Zeeman Splitting A proton has a half-integer spin $S = 1/2$ that results in a magnetic moment $\mu_p = \mu_e \frac{m_e}{m_p}$, that is $\frac{m_p}{m_e} \approx 1836$ times smaller than

2.1 The Spin Hamiltonian

the electron's magnetic moment. A neutron bears no charge but also has a half-integer spin $S = 1/2$. An atomic nucleus that consists of protons and neutrons has a magnetic moment which is a vector sum of the aligned spins of its protons and neutrons. The spin of a nucleus is defined by the arrangement of its nucleons and by the nuclear charge. A nitrogen nucleus has 7 protons and 7 neutrons that total in a nuclear spin $I = 1$ which, with the g factor for the nitrogen nucleus g_N , results in the nuclear magnetic moment of $\mu_N = \mu_B \frac{m_e}{m_N} g_N I$ that splits each of the electron Zeeman level into three nuclear Zeeman energy sublevels corresponding to the three possible projections of the nuclear spin on the magnetic field axis, $m_I = -1, 0, +1$, analogously to the electron with $m_S = 1/2, -1/2$. The two splittings are shown in the energy diagram in Figure 2.1. The nuclear Zeeman splitting is more than two orders of magnitude weaker than the electron Zeeman splitting because of the difference in the masses of the particles.

Hyperfine Interaction The magnetic moments of an electron and a magnetic nucleus, such as nitrogen, couple in the hyperfine interaction: $H_{HF} = \vec{s}\vec{\mathbf{A}}\vec{I} = H_F + H_{DD}$ with the hyperfine coupling tensor \mathbf{A} . The isotropic part $H_F = a_{iso}\vec{s}\vec{I}$, or the Fermi contact interaction, scales with the probability density of the electron at the position of the nucleus $a_{iso} = \frac{2\mu_0}{3\hbar} g_e \mu_e g_n \mu_n |\psi(0)|^2$ [101]. The anisotropic part $H_{DD} = \vec{s}\vec{\mathbf{T}}\vec{I}$ with the dipolar coupling tensor \mathbf{T} takes into account the anisotropic magnetic dipole coupling between the magnetic moments of the electron and the nucleus. \mathbf{T} depends on the shape of the electron orbital, its 3×3 Cartesian matrix representation depends on the molecular frame of reference and can be diagonalized by rotating the coordinate system. The matrix representation of the hyperfine coupling tensor \mathbf{A} can be written as the sum of its isotropic and anisotropic parts: $\mathbf{A} = a_{iso}\mathbb{1}_3 + \mathbf{T}$ [116]. In its diagonal matrix representation \mathbf{A} reduces to the three principal components $[A_{xx}, A_{yy}, A_{zz}]$. The values of \mathbf{A} are typically given in MHz.

Exchange Interaction In a system of closely placed electrons, such as in a film of densely packed radicals, the electron orbitals may overlap significantly and the radicals may exchange electrons. The energy required to exchange the electrons is called the exchange coupling $H_{exch} = \vec{s}_1 \mathbf{J} \vec{s}_2$, that becomes considerably large at inter-spin distances below $r < 1.5$ nm or with a large spin delocalisation [101]. The positive \mathbf{J} corresponds to a weak coupling between s_1 and s_2 which leads to an antiferromagnetic or antiparallel alignment of spins with a total $S = 0$, whereas the negative \mathbf{J} causes the strong inter-spin coupling which leads to a ferromagnetic alignment with $S = 1$ [101].

Nuclear Quadrupole Moment The nitrogen nucleus has a spin greater than $1/2$ which alters the charge distribution within the nucleus which gives rise to a non-vanishing nu-

clear electrical quadrupole moment Q [101]. The interaction between the asymmetrically distributed charge and the gradient of the electric field at the nucleus is given by the nuclear quadrupole Hamiltonian $H_{NQ} = \vec{I}\vec{\mathbf{P}}\vec{I}$ with the nuclear quadrupole tensor \mathbf{P} that describes the coupling of the nuclear quadrupole moment to the electric field gradient.

The Spin Hamiltonian For the interactions considered in this thesis, the following Hamiltonian will be applied to describe the interactions of unpaired electron spins with their local environments, ranging by their magnitude:

$$H = H_{EZ} + H_{HF} + H_J + H_{NZ} + H_{NQ} \quad (2.3)$$

The electron Zeeman term H_{EZ} defines the requirements on the hardware and sets the range of the magnetic fields used in the spectroscopic experiments. The hyperfine interaction term H_{HF} allows for reconstruction of the hyperfine coupling tensor from the recorded spectra which is used as a marker to identify the molecular structure and dynamics of the mobile molecular fragments that are released during the operation of an electrochemical cell. The exchange interaction term H_J scales with the concentration of the electrons, so the information about \mathbf{J} can be used to characterize the packing of the molecular fragments in the electrode. The nuclear quadrupole interaction term may lead to spectral distortions in a highly charged cathode where electric fields may be sufficiently strong to introduce noticeable nuclear quadrupole couplings to the nitrogen nuclei.

2.1.1 Continuous-Wave Electron Paramagnetic Resonance

First observed in 1945 [126, 125, 98], the phenomenon of electron paramagnetic resonance had quickly become a tool for probing local molecular environments in species that contain unpaired electron spins. A free electron, that does not interact with its environment and has $g = g_e$, experiences a Zeeman splitting of $\Delta E = g\mu_B B_0$, that corresponds to the energy of a photon with a frequency of $\nu = \Delta E/h$. A microwave photon can drive a magnetic dipole transition between the Zeeman-split spin states - this is called electron paramagnetic resonance (EPR). An X band microwave photon (IEEE X band, $\nu = 8 - 12$ GHz, $\lambda = 2.5 - 3.8$ cm, Figure 2.2, left) can drive the magnetic dipole transition between $|\uparrow\rangle$ and $|\downarrow\rangle$ at $B_0 \approx 0.3$ T. In a continuous-wave electron paramagnetic resonance (cwEPR) experiment, the microwave frequency and power is kept constant while B_0 is scanned and the microwave absorption is observed. EPR happens around the B_0 values given by the spin resonance condition:

$$\mu_B g_e B_0 = h\nu \quad (2.4)$$

When B_0 reaches the value that satisfies Eq. 2.4, the sample starts absorbing microwaves. The absorbed microwave power recorded as a function of B_0 is the cwEPR

2.1 The Spin Hamiltonian

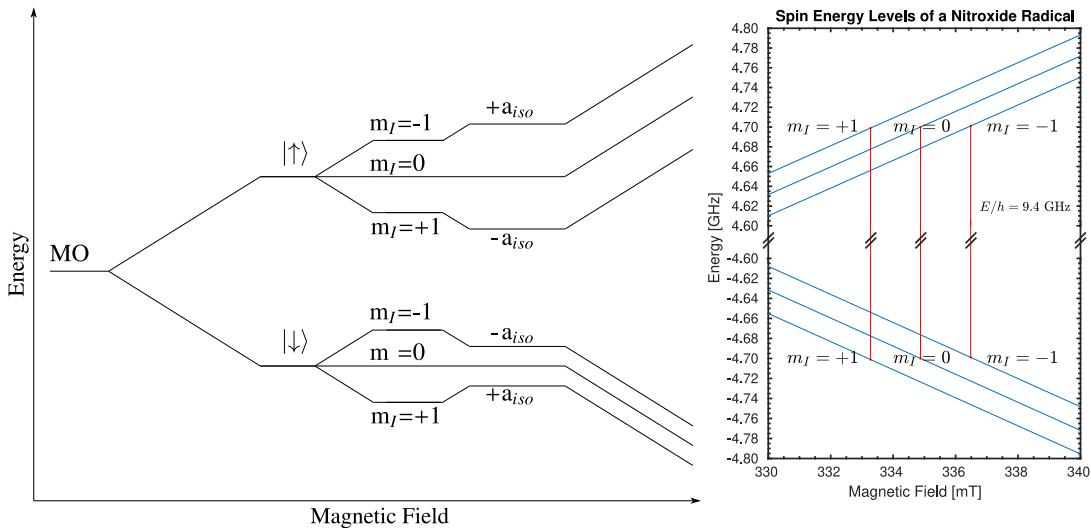


Figure 2.1: Energy diagram of the spin Hamiltonian showing the contributions to the energy level of an unpaired electron in a molecular orbital (*MO*) in the presence of Nitrogen. The energy of the unpaired electron at the molecular orbital (*MO*) splits into two electron Zeeman spin levels $|\uparrow\rangle$ and $|\downarrow\rangle$ in the magnetic field. The electron Zeeman spin levels further split into three nuclear Zeeman sublevels, due to the nuclear Zeeman interaction of the Nitrogen nucleus with three projections of the nuclear spin ($m_I = -1, 0, +1$). The hyperfine interaction between the electron spin and the nuclear spin depend on the relative orientations of the spins of the particles. The parallel alignment adds a_{iso} to the energy level and the anti-parallel alignment subtracts a_{iso} from it. The energy scale for a typical X-band EPR spectrometer is shown on the right. The allowed electron spin transitions corresponding to $\Delta m_s = \pm 1$, $\Delta m_I = 0$ are shown in red vertical lines on the right.

spectrum (Figure 2.2, right, dashed). By construction, cwEPR spectrometers typically record the derivative of the microwave absorption vs. B_0 (Figure 2.2, right, solid). Advanced spin resonance techniques methods that involve coherent spin dynamics and pulsed microwave fields are discussed in Section 2.2.1.

cwEPR spectrometer A basic cwEPR spectrometer consists of a magnet, a microwave source, a resonator and a microwave detector. Figure 2.3 depicts those elements with more details, including the sample - an electrochemical cell that is placed inside the microwave resonator and its SoC controlled with an external potentiostat.

Continuous microwaves are generated with a klystron (MW source in Figure 2.3) and directed towards the resonator (resonating cavity) through the signal arm that contains a variable attenuator and a circulator. The circulator directs the microwaves from the source to the cavity and passes the microwaves reflected from the cavity further to

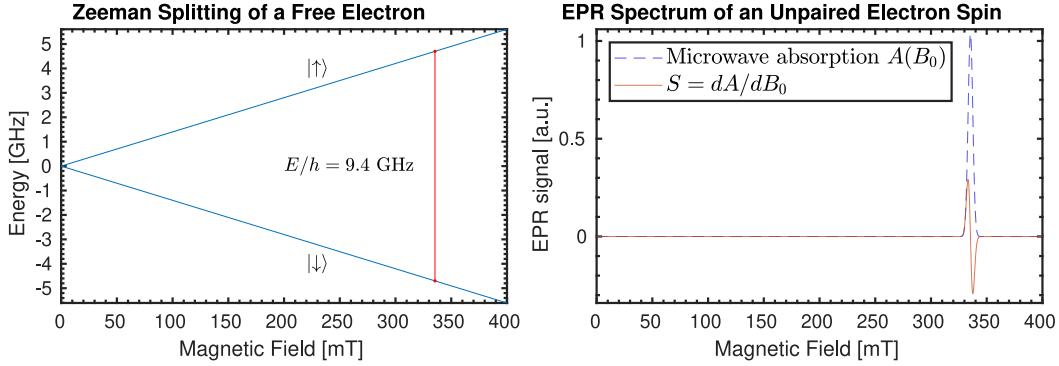


Figure 2.2: Left: Zeeman splitting for the energies of the two states of an isolated electron spin in a static magnetic field computed with EasySpin [107]. Vertical line is the magnetic dipole transition driven by a 9.4 GHz microwave photon. Right: Microwave absorption and its derivative as a function of the static magnetic field for an unpaired electron spin with a 5 mT Gaussian broadening.

the microwave detector. The adjustable coupling iris between the circulator and the resonating cavity allows one to match the impedance of the cavity to the impedance of the signal arm so that minimal microwave power is reflected back from the cavity at a non-resonant field B_0 . That impedance matching is called critical coupling. At the microwave detector, the microwaves reflected from the cavity are compensated by the microwaves with fixed microwave power and an adjustable phase, that pass through the reference arm. The signals from the two arms interfere destructively at the detector, so that there is no signal at the detector for non-resonant B_0 .

When the resonance condition (Eq. 2.4) is met, the incident microwaves are being absorbed by the sample and the resonator's Q factor slightly changes. The change in the Q factor decouples the resonator from the signal arm, that causes additional reflections in the signal arm. The microwaves in the signal arm that are not compensated by the reference arm become detected by the microwave detector - a biased semiconductor diode that has a linearly changing conductivity in the range corresponding to the incident microwave power. A phase sensitive detection with shallow modulation of B_0 increases the signal-to-noise ratio (SNR) and yields the derivative of the microwave absorption profile vs. B_0 . The typically high $Q \gg 1$ factor of the resonator further increases the SNR, as the decoupling of a resonator with higher Q leads to a larger reflected microwave power.

To ensure that only the magnetic component of the microwave is interacting with the sample, a standing microwave is formed in the resonating cavity. In the center of the cavity, the magnetic component of the microwave is maximized and the electric component is quenched. When a small sample is inserted in the center of the cavity, it is mostly the magnetic component of the microwave that is interacting with it. That allows

2.1 The Spin Hamiltonian

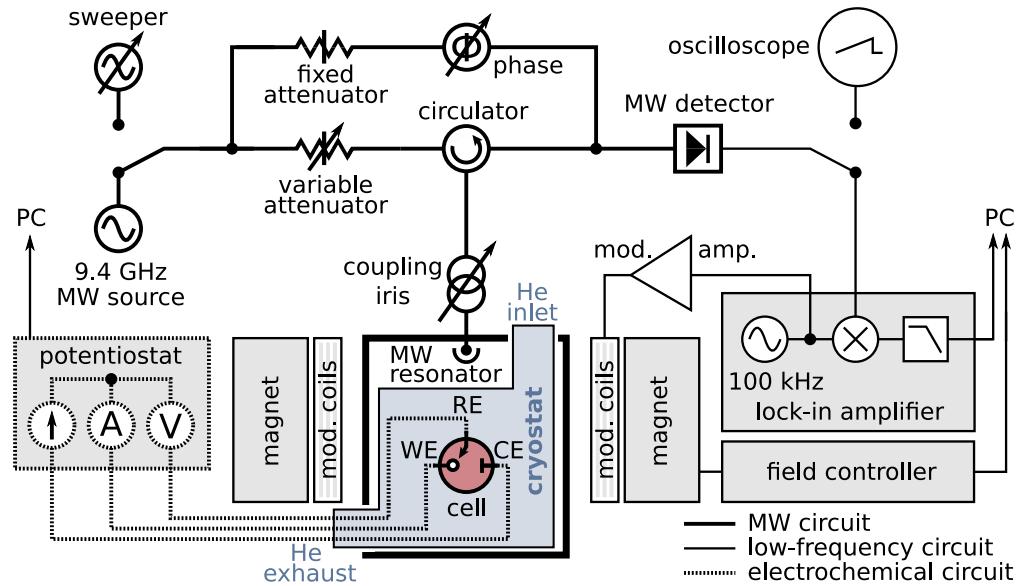


Figure 2.3: Diagram of an X band cwEPR spectrometer combined with an electrochemical setup.

one to drive magnetic dipole transitions without heating up the sample by the electric component. For larger samples as, for example, working electrochemical cells, the separation between the electric and magnetic microwave components does not hold within the full sample volume. Furthermore, the insertion of a cell containing metal electrodes and polar electrolyte into a resonator changes the distribution of the microwave field in it and lead to a non-resonant microwave absorption.

Line Broadening The lines in the EPR spectra have finite widths. The lines of the liquid samples are broadened mostly by the dynamic effects (relaxation, tumbling, chemical exchange), while the lines of solid state samples are broadened by static effects (orientational disorder, unresolved hyperfine splittings, distributions in \mathbf{g} , \mathbf{A} , and \mathbf{D} values) [107].

According to the stochastic, gaussian random modulation theory of exchange narrowing, the width of a strongly exchange narrowed EPR line (HWHM) is given by

$$\Delta B_0 \approx \frac{10}{3} \left(\frac{H_p^2}{H_e} \right) \quad (2.5)$$

and the resonance lineshape is lorentzian. H_p is the mean square dipolar field and H_e is an effective exchange field which is proportional to the mean exchange integral J [85]

2.2 Fundamentals of Pulsed EPR Spectroscopy

2.2.1 Coherent Spin Motion under Pulsed Microwave Field

The motion of the magnetization vector $\vec{M}(t, \vec{r})$ precessing in a static magnetic field B_0 is convenient to consider in the rotating frame of reference that has its \vec{z}' axis fixed to the magnetization vector $\vec{z}' \parallel \vec{M}$ so that the $x'y'$ plane rotates around \vec{M} at the Larmor frequency $\omega_L = \gamma B_0$ when viewed from the laboratory frame $\vec{x}, \vec{y}, \vec{z}$, where γ is the gyromagnetic ratio for electrons described in Section 2.1. In the rotating frame, the macroscopic magnetization stays constant as long as the spin system interacts only with the static field B_0 . When the spin system is excited with a linearly polarized microwave field $\vec{B}_1(t, \vec{r}) \perp \vec{B}_0$, its evolution is described with the set of equations that is known as the Bloch equations (Eq. 2.8). A microwave field of frequency ω_1 and amplitude B_1 propagates along \vec{z} and it is polarized in the xz plane: $\vec{B}_1(t, \vec{r}) = B_1 \vec{x} \cos(\omega_1 t)$. The total magnetic field $\vec{B} = \vec{B}_0 + \vec{B}_1$ then causes a time-dependent torque on the \vec{M} which leads to its precession - this time in the rotating frame of reference.

2.2.2 Bloch Equations

$$\frac{dM_x(t)}{dt} = \gamma (\vec{M}(t) \times \vec{B}(t))_x - \frac{M_x(t)}{T_2} \quad (2.6)$$

$$\frac{dM_y(t)}{dt} = \gamma (\vec{M}(t) \times \vec{B}(t))_y - \frac{M_y(t)}{T_2} \quad (2.7)$$

$$\frac{dM_z(t)}{dt} = \gamma (\vec{M}(t) \times \vec{B}(t))_z - \frac{M_z(t) - M_0}{T_1} \quad (2.8)$$

2.2.3 Refocused Spin Echo

2.2.4 Spin Relaxation Times

2.2.5 Spin Packets

2.3 Pulsed EPR Instrumentation

2.3.1 Pulse Sequences and Measurement Techniques

The Hahn Echo Sequence

The Hahn Echo sequence consists of two pulses, the $\pi/2$ pulse and the π pulse, separated in time by τ : $\pi/2 - \tau - \pi - \tau - echo$. Initially, the macroscopic magnetization of the spin system is aligned along \vec{B}_0 : $\vec{M}_0 = M_Z \vec{e}_Z$. The $\pi/2$ microwave pulse has such

2.3 Pulsed EPR Instrumentation

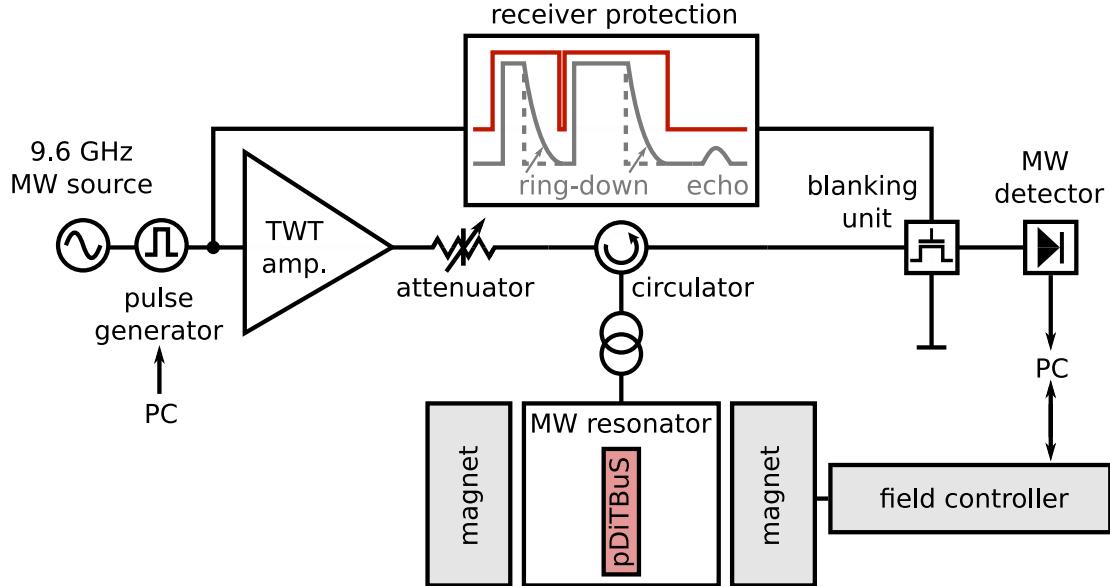


Figure 2.4: Diagram of a pulsed EPR spectrometer.

length $t_{\pi/2}$ and amplitude B_1 that, during the pulse, \vec{M} nutates to the xy plane, where it keeps precessing about \vec{e}_Z after the end of the pulse. The difference in local environments for each individual spins in the spin packet, as well as the interactions between the spins, that make up \vec{M} , leads to slightly different precession frequencies ω_L^i of the spins. After some time τ , the difference in the precession frequencies translates into the differences in phases so that the vector sum of the excited spins averages down to $\vec{0}$ for sufficiently long τ . In other words, the excited spin packet dephases with time. The dephasing due to different local spin environments can be reversible if the deviations of the precession frequencies do not depend on time, as is the case for separated electrons in an inhomogeneous solid. In such case, a π pulse can be applied to the spin system to flip every single spin in the dephased spin packet by 180deg in a plane containing \vec{e}_Z , so that the spins keep precessing in the xy plane, but the direction of precession is inverted for them, leading to the effect that is opposite to the initial dephasing. So a τ after the π pulse excites the spin packet, the accumulated phase differences become the smallest and the packet recovers its macroscopic magnetization \vec{M} that oscillates in the xy plane with $\langle \omega_L^i \rangle$ and can be detected. The recovered \vec{M} at $t = \tau$ after the π pulse is called the refocused spin echo. The difference in ω_L^i leads to a further dephasing of the considered spin packet and to the vanishing of \vec{M} .

Spin Echo Decay and Phase Memory Time

Inversion Recovery and Spin-Lattice Relaxation Time

Chapter 3

Materials and Devices

In this chapter, the redox conductive polymers are presented and a preparation of organic electrochemical half-cells suitable for electron spin resonance spectroscopy is described.

3.1 Electrolytes

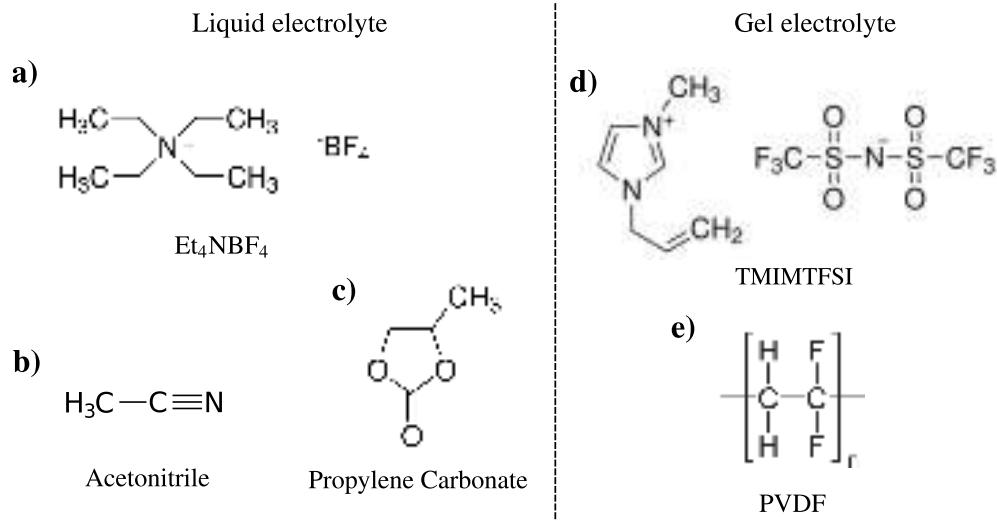


Figure 3.1: Ionic salt (ET_4NBF_4 , a) and the corresponding solvents (Acetonitrile (b) and Propylene Carbonate (c)) for liquid electrolytes. Ionic liquid (TMIMTFSI, d)) and polymer matrix (PVDF, e)) for the gel electrolyte.

Liquid Electrolyte

Tetraethylammonium tetrofluoroborate (Et_4NBF_4 , Figure 3.1 a) is a crystalline salt that dissociates into a Et_4N^+ cation and a BF_4^- anion in polar solvents such as Acetonitrile (CH_3CN , Figure 3.1,b) and Propylene Carbonate ($\text{C}_4\text{H}_6\text{O}_3$, Figure 3.1,c). Et_4NBF_4 is a small molecule with a relatively high dissociation energy, so the solvents have high dielectric constants ($\epsilon \approx 40$ for Acetonitrile and $\epsilon \approx 64$ for Propylene Carbonate). Propylene Carbonate has higher density than Acetonitrile, has higher viscosity and is less volatile. A 100 mM solution of Et_4NBF_4 in Acetonitrile or in Propylene Carbonate ensures sufficient ionic transport for the organic electrochemical cells described later in this section.

Polymer-based Gel Electrolyte

The use of ionic liquids and the suitable polymer matrix allows for fabrication solid-state electrolytes that are used for making organic electrochemical neurons [37] and solid-state Li batteries [90]. PVDF (Figure 3.1 e) was used as a polymer matrix. TMIMTFSI (Figure 3.1 d) was the ionic liquid. The polymer grains were dissolved in Chloroform at 80 $^\circ\text{C}$ and the ionic liquid was mixed in at a ratio 1 : 4 : 20 (polymer : ionic liquid : solvent). The polymer electrolyte was used to manufacture an all-polymer organic radical battery described later in this section.

3.2 Organic Electrode Materials

ORB based on redox polymers containing stable radicals [76] have been shown to compete with or even outperform conventional Li based batteries in terms of power densities [109] with the additional benefit of being free from rare precursors, inheriting mechanical properties of plastics and electrical properties of semiconductors [29, 11, 33]. Advanced molecular design techniques allow for tuning of the electrochemical properties of the redox polymers [47], that brings in a rich variety of organic energy storage materials [119, 114, 48] and creates a large room for their optimization.

3.2.1 TEMPO

TEMPO (2,2,6,6-tetramethylpiperidine-1-oxyl) shown in Figure 3.2 a) is a small molecule and a stable radical that can undergo a fast and reversible redox reaction between TEMPO^\bullet and TEMPO^+ [115], with an electron self-exchange rate constant of $k_{ex} \approx 10^{6-8} \text{ M}^{-1} \text{ s}^{-1}$ [14]. TEMPO is an inexpensive organic compound [114] produced from acetone with liquid ammonia, hydrazine and peroxide [12]. TEMPO radicals are widely used as spin labels in the studies of biological systems with electron spin resonance [9], because the unpaired electron of TEMPO^\bullet has a well defined spectral signature that

3.2 Organic Electrode Materials

changes when the local environment of a TEMPO fragment changes. TEMPOL is a TEMPO with an OH group. It is soluble in many organic solvents and forms crystals. Solutions of TEMPOL with various concentrations can be used for the reference spectroscopic measurements, as by varying the concentration the strength of inter-spin interactions between the neighboring radicals can be adjusted.

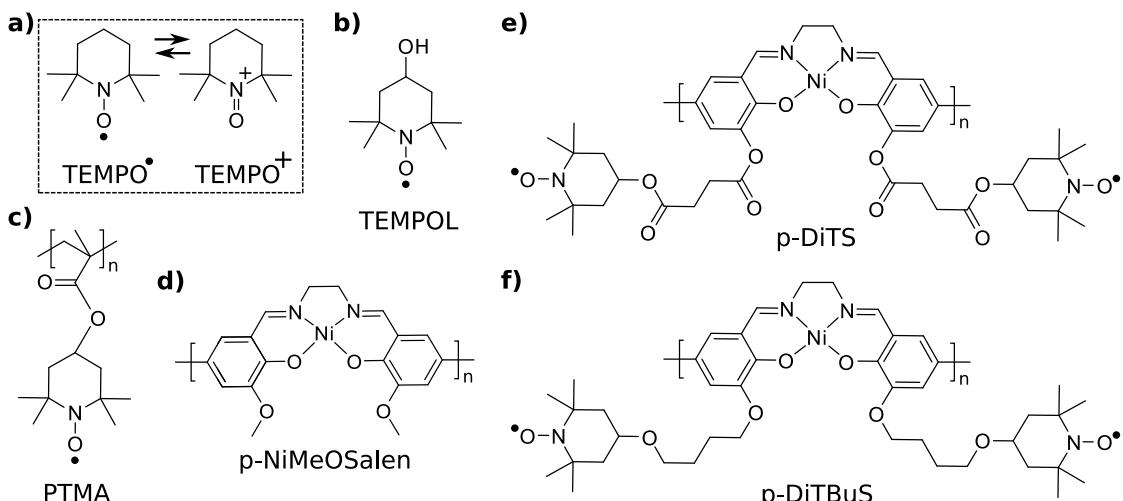


Figure 3.2: Chemical structures of the molecular fragments and polymers that were used for making a battery cathode containing stable nitroxide radicals.

Redox conductive conjugated polymers containing TEMPO redox groups, as pDiTBuS (poly-di-TEMPO-Butyl-Salen) shown in Figure 3.4, demonstrate particularly promising energy and power densities [113]. The pDiTBuS was designed as a cathode material: it is oxidized when the electrochemical cell containing this material is charged. A film of pDiTBuS comprises a high concentration of redox active stable nitroxyl radicals attached to a conjugated polymer backbone that interconnects them as a molecular wire. Such system can be viewed as a highly disordered molecular hole-transporting semiconductor (the poly-NiSalen backbone) that contains a large amount of hole traps (TEMPO groups) attached to it with butyl linkers. When the film is reduced (discharged), the TEMPO groups are in the radical state and act as unfilled traps. Upon oxidation (charging), the TEMPO fragments lose an unpaired electron and acquire a positive charge, so the traps are being filled with holes. The reversible redox reaction in the pDiTBuS film is demonstrated in a cyclic voltammogram shown in Figure 1.2, c) and in the equal charging and discharging capacity of the film in Figure 3.9, c).

While active electrode materials with nitroxide radicals as redox-active groups are ideally suited for organic radical batteries (ORBs) that exhibit high power densities, the broad application of most nitroxide-based materials is limited by their moderate electrical properties. A promising route towards overcoming the conductivity problem is the use of polymers that combine radical-containing moieties and a conductive backbone.

This strategy was successfully followed in a number of studies focusing on different polymers [88, 3, 52, 121, 2, 100]. The standard redox potential of the NiSalen molecular backbone ($E_{1/2}^B$ in the middle of the peaks B and B' in Figure 1.2) lay close to the standard redox potential of the attached nitroxide charge-bearing fragments ($E_{1/2}^A$ in the middle of the peaks A and A' in Figure 1.2) - that ensures an efficient charge transport between the charge-bearing fragments and the conductive backbone and allows for very high charge and discharge rates up to 3000 C [113, 57].

3.2.2 PTMA

A simple organic radical polymer containing TEMPO is poly-TEMPO-methacrylate) (PTMA, Figure 3.2 c). The polymer backbone of PTMA consists of single C-C bonds and therefore is not conductive, so the transport of charge in a PTMA film has to be mediated by adding conductive mesh such as activated carbon. When mixed with conductive carbon additive, PTMA has become a standard cathode material for ORBs and Li-ORBs, providing a discharge cell voltage of $V_{OC} = 3.5$ V (with a Li anode) and a theoretical discharge capacity of $C_{theo} = 111$ mAh/g [15]. PTMA is soluble in acetonitrile (AN), chloroform (CF), tetrahydrofuran and dichlormethane. It is claimed to be insoluble in toluene, ethers, carbonates, and alcohols, however it becomes gel-like with some of these solvents [105].

3.2.3 NiSalen

The molecular backbone of a redox conductive polymer has to conduct electric charge. A NiSalen molecule shown in Figure 3.2 d) is a Schiff complex of Ni that has a conjugated path through it. p-NiMeoSalen is polymerized NiSalen with two methoxy groups, that forms the conductive backbone of the corresponding RCPs in e) and f). The pNiSalen backbone is redox active and can store up to 2 positive charges per monomer unit [20]. The conductivity of p-NiSalen depends on its oxidation state. The oxidized polymer has higher conductivity due to a higher concentration of holes [20]. Upon oxidation of a polymeric NiSalen, the formation of positive polarons and bipolarons was observed in it with UV-Vis and EPR spectroscopy [20], that suggests p-NiSalen is a p-type molecular semiconductor.

3.2.4 Poly-Di-TEMPO-Salens

Redox conductive conjugated polymers containing TEMPO (2,2,6,6-tetramethylpiperidine-1-oxyl) redox groups, as pDiTS [113, 57] (poly-Di-Tempo-Salen) and pDiTBuS [58] (poly-di-TEMPO-Butyl-Salen) shown in Figure 3.2 e) and f), demonstrate particularly promising energy and power densities with charging rates upto 3000 C and gravimetric

3.2 Organic Electrode Materials

capacity upto 91.5 mAh g^{-1} for pDiTS [113] and upto 75 mAh g^{-1} for pDiTBuS [58]. pDiTS and pDiTBuS have similar molecular structures, except for pDiTBuS has no oxygens in the linkers that connect the backbone to the TEMPO fragments, which has led to its higher electrochemical stability and a more efficient electro-polymerization, that allows for growing thicker films. pDiTS is a charge storage material that consists of TEMPO redox active molecular fragments [114, 49, 36] interconnected by a redox conductive conjugated NiSalen backbone [113, 20]. DiTS and DiTBuS monomers were synthesized in the Levin group at the Saint-Petersburg State University.

pDiTS was designed as a cathode material: it is oxidized when the electrochemical cell containing this material is charged. A film of pDiTBuS comprises a high concentration of redox active stable nitroxyl radicals attached to a conjugated polymer backbone that interconnects them as a molecular wire. Such system may be viewed as a highly disordered molecular hole-transporting semiconductor (the poly-NiSalen backbone) that contains a large amount of hole traps (TEMPO groups) attached to it with butyl linkers. When the film is reduced (discharged), the TEMPO groups are in the radical state and act as unfilled traps. Upon oxidation (charging), the TEMPO fragments lose an unpaired electron and acquire a positive charge, so the traps are being filled with holes [58].

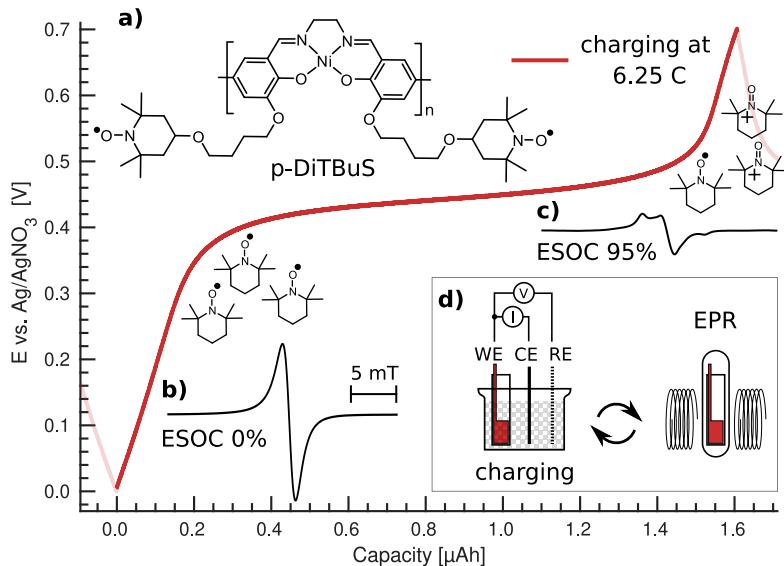


Figure 3.3: Galvanostatic charge-discharge curve for a pDiTBuS cathode film at $10 \mu\text{A}$ (6.25 C), chemical structure of pDiTBuS (a), normalized cwEPR spectral signatures for reduced (b) and oxidized (c) states. Scheme of the ex-situ EPR measurement on the pDiTBuS half cell (d).

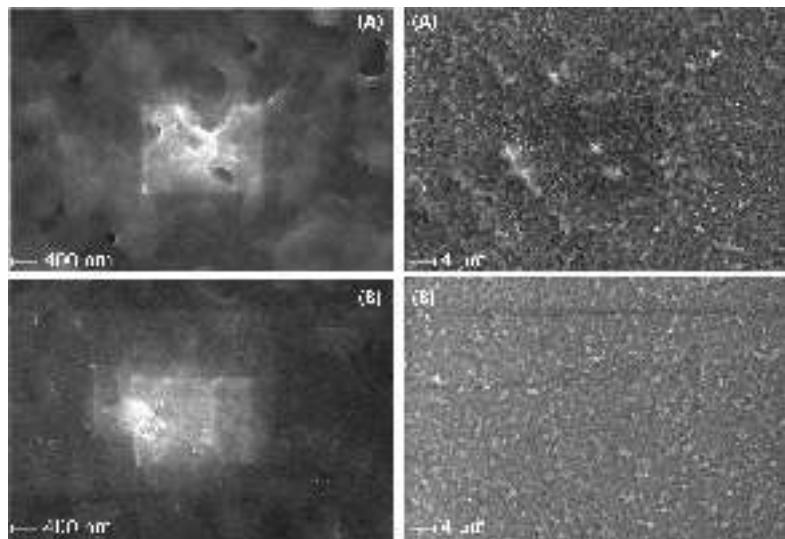


Figure 3.4: Scanning electron microscope images of a pDiTS film in a reduced (a) and oxidized (b) states, image adapted from Ref. [113].

3.2.5 Electro-polymerization of TEMPO-Salens

The process of polymerization is connecting multiple monomer units of one sort to a continuous molecular chain. A polymerization of redox active molecules, such as NiSalen monomer fragments, can be done electrochemically with the setup shown in Figure 3.6. A three-electrode cell is made with a 10 mM solution of NiSalen in the electrolyte. By applying a positive voltage between the WE (Au) and the CE (Pt), NiSalen molecules are adsorbed to the surface of the WE and oxidized. Oxidation of NiSalen leads to a formation of a positive radical in the ring of the NiSalen that can be seen as the opening of the ring, as shown in the diagram in Figure 3.6. The oxidized, open ring attracts the next NiSalen molecule from the solution, then the positive radical is transferred from the ring to the attracted molecule through the conjugated network and the two molecules form a bond [56]. The reaction repeats until the conductivity of the film allows for efficient transfer of the positive radical to its outer surface. Because of charge storing ability of pNiSalen, the film growing from the oxidized monomers has to be periodically discharged to withdraw the positive charges that repel the oxidized monomers and do not allow them to attach to the film. So a pNiSalen film is grown on the WE surface [1, ?].

The electrochemical polymerization of a TEMPO-Salen is done in the same way as for pNiSalen. The electrical screening effect in TEMPO-Salens is much stronger, because the oxidation potential of the charge-bearing TEMPO radicals is close to that of NiSalen and the TEMPO radicals in the film oxidize when the film is oxidized. The

3.3 Ex Situ Electrochemistry

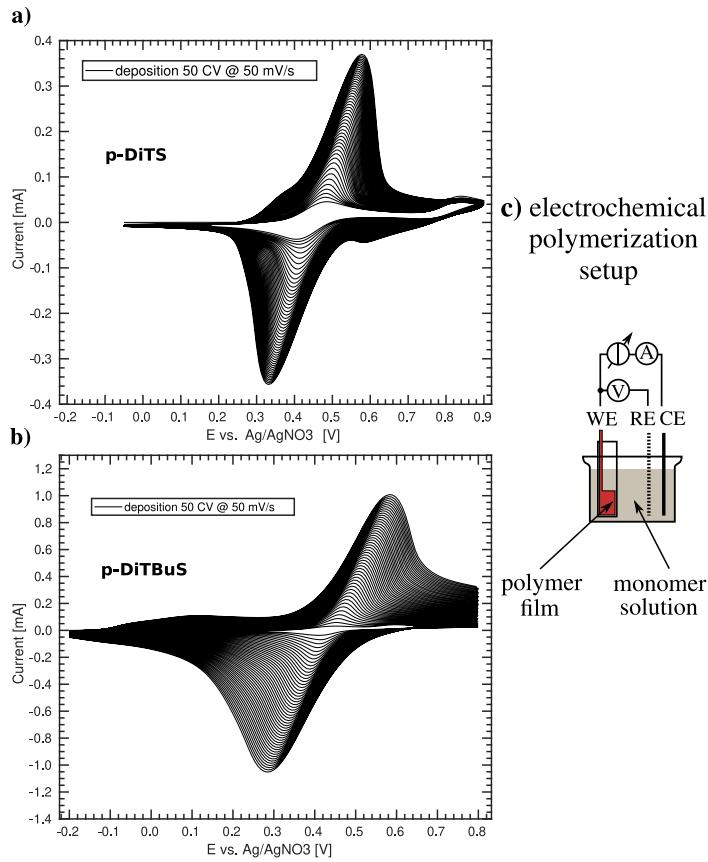


Figure 3.5: Deposition of TEMPO-Salen films with cyclic electrochemical polymerization from 1 mM monomer solutions in the 10 mM Et₄NBF₄ electrolyte at 50 mVs⁻¹ and 50 deposition cycles. a): pDiTS, b): pDiTBU_S. c) setup for electrochemical polymerization

oxidized TEMPO radicals form a strong Coulombic “shield” that repels the TEMPO-Salen monomer fragments in the solution [113]. To discharge the TEMPO fragments, the growing film has to be periodically discharged, so a cycling voltage is applied to perform a cyclic polymerization of pDiTS and pDiTBU_S films [113, 58].

3.3 Ex Situ Electrochemistry

The pDiTBU_S film was brought to the desired oxidation state by galvanostatic discharging with a current of 10 µA in a three-electrode electrochemical cell in a 5 ml beaker with the electrodes and the electrolyte described above. Each potential of the film was reached by first fully charging the cell to 700 mV and then discharging it to the desired

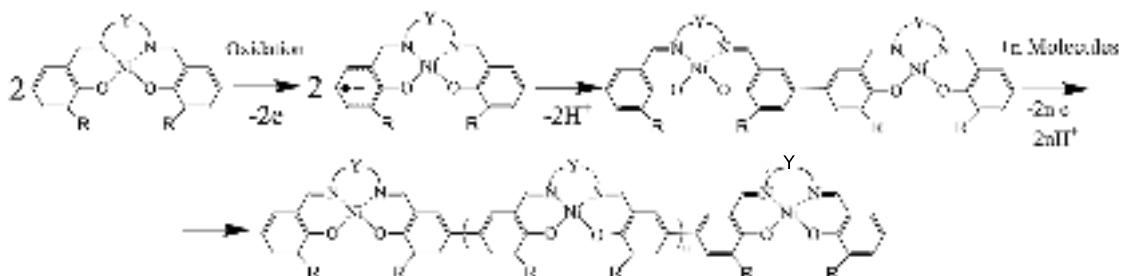


Figure 3.6: A scheme of a two-step cyclic electropolymerization of NiSalen containing electrochemically inactive side groups (R). First, two monomers are oxidized upon application of a positive potential to the cell containing the monomer solution, that induces a cation (hole) in their phenyl rings. The oxidized monomers create a bond by sharing their cations. When the potential is ramped down, the holes are withdrawn from the radicals and they remain connecting by forming a C-C bond instead of closing the bond in their rings.

potential (labeled points in Figure 3.7). When the desired potential was reached, the output relay of the potentiostat was opened so that no current went through the cell after charging. The substrate with the WE and the pDiTBuS film was removed from the charging cell, placed in a 5 mm OD quartz EPR tube, evacuated down to $< 5 \times 10^{-3}$ mbar, filled with He up to a pressure of 500-600 mbar, then flame sealed with a H₂/O₂ burner.

After reaching the fully charged state with 10 μ A (by $t = 0$ in Figure 3.8), a 10 μ A discharge current was applied to reach the four states of charge considered in this study (a-d in Figure 3.8 and in Figure 3.7). Initially, the full charging capacity of the film was 1.48 μ Ah = 5.11 mC (3.29e+16 electrons withdrawn upon the full charging). The charging capacity has decreased by 0.06 μ Ah (4%) after the four temperature cycles between 300 K and 5 K during the cryogenic EPR measurements.

3.3 Ex Situ Electrochemistry

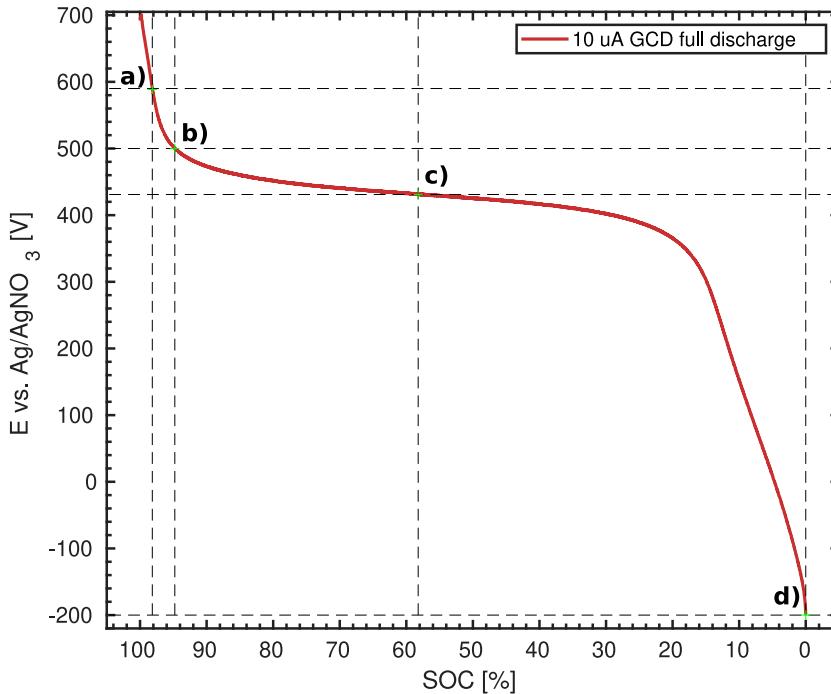


Figure 3.7: Initial galvanostatic discharge curve for the pDiTBuS film with the redox potentials described in the main text. Since the film has lost 12% of its capacity during the temperature cycling, the SoC determined from the potentials mapped to the initial curve are lower than the SoC determined from the individual discharge curves (given in brackets). The SoC values corresponding to the initial (individual) discharge curve are a): SoC 98 (98)%, b): SoC 94 (96)%, c): SoC 57(65)%, d): SoC 0(0)%. (Dis-)charging current: 10 μ A, charging rate: 6.25 C. After this initial discharging, the pDiTBuS film has undergone 10 charge-discharge cycles and 4 temperature cycles.

From the quantitative analysis of the GCD for each SoC, we calculate the number of elementary charges that are transferred to the film (withdrawn from the film) upon charging (discharging). The GCD and the calculated values of the transferred charge are shown in Figure 3.8. During the full discharge from +700 mV down to -200 mV the pDiTBuS film has gained a total charge of 1.355 μ Ah=4.88 mC (d), corresponding to $3.01e+16$ electrons that had been transferred to the film.) The considered SoC correspond to discharging by 0.020 ± 0.005 μ Ah (Figure 3.8 a, $(5 \pm 1) \times 10^{14}$ electrons injected), 0.060 ± 0.005 μ Ah (Figure 3.8 b, $(1.4 \pm 0.1) \times 10^{15}$ electrons injected), 0.480 ± 0.005 μ Ah (Figure 3.8 c, $(1.07 \pm 0.01) \times 10^{16}$ electrons injected) and 1.360 ± 0.005 μ Ah (Figure 3.8 d, $(3.05 \pm 0.01) \times 10^{16}$ electrons injected). The SoC values determined from the respective potentials are different when mapped to the initial discharge curve

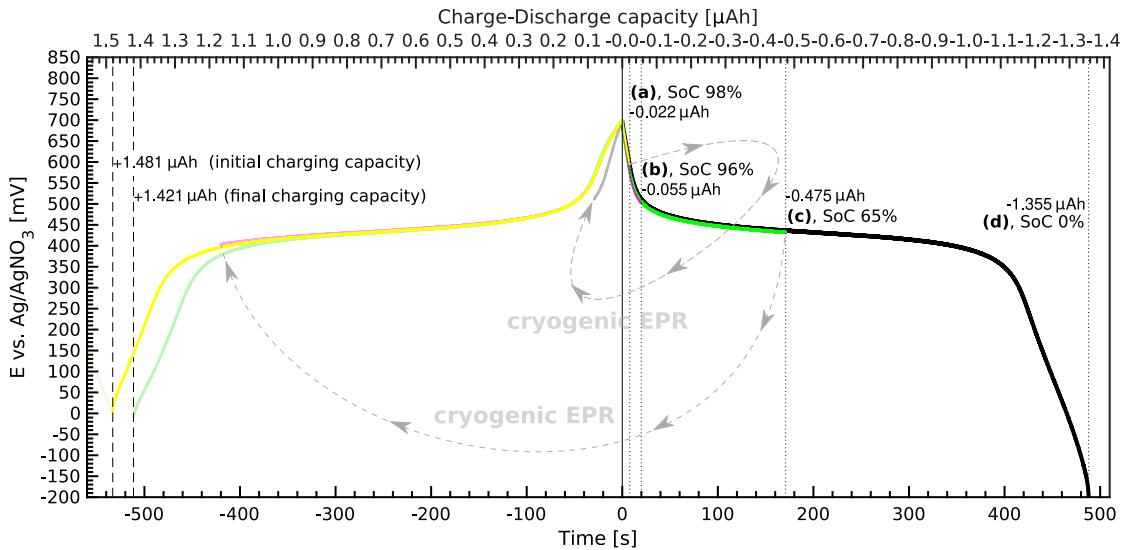


Figure 3.8: Calculation of the number of withdrawn electrons from a pDiTBuS film for the four states of charge. At negative times the pDiTBuS film is charged, corresponding to the withdrawal of electrons from the film. At positive times the film is discharged. The number of transferred electrons during discharging is determined from the four overlaid galvanostatic discharge curves (a-d).

in Fig. 3.7 and when considering the individual discharge curves in Fig. 3.8, as the film was gradually losing its capacity during the temperature cycling, so the discharge curves were reaching the considered potentials at shorter times, leading to a lower Coulomb counting, lower discharge capacity and therefore a lower SoC.

3.4 Electrochemical Cells for Operando cwEPR Spectroscopy

3.4.1 Design of an EPR-Compatible Electrochemical Cell

3.4.2 TEMPO-Salen Films for EPR Spectroscopic Measurements

3.4.3 Reference Electrode

The Ag/AgCl reference (RE) electrode for the EPR-compatible electrochemical cells described in 4.2.1 was formed by coating a layer of AgCl onto a 250 μm Ag wire galvanically from a 1 M aqueous solution of KCl. For that, the Ag wire and a Pt wire were connected as a cathode and an anode respectively to 10 mL of the KCl solution and a DC potential of 500 mV was applied for 7500 s which resulted in a dark AgCl layer

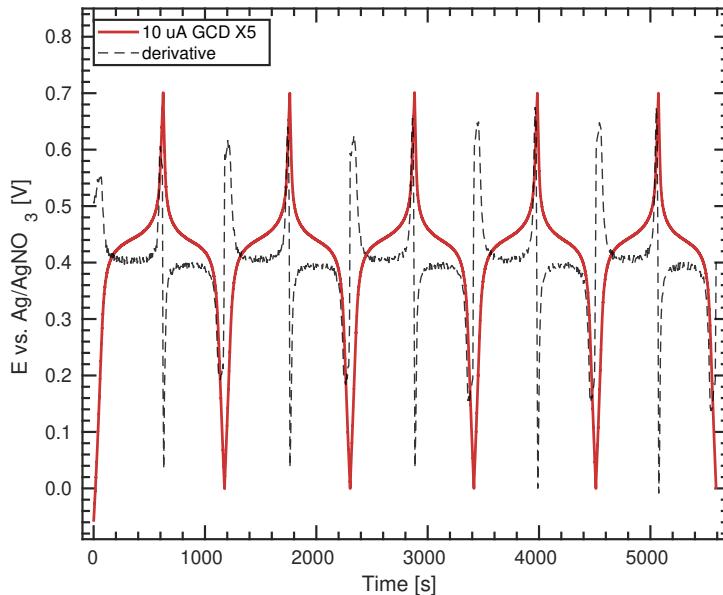


Figure 3.9: Galvanostatic charge-discharge cycling of a pDiTBuS electro-active film with a discharge capacity $C_{DCG} = 1.6 \pm 0.1 \mu\text{Ah}$ recorded with 10 μA charging and discharging current that corresponds to charging and discharging at a C rate of $6.3 \pm 0.4 \text{ C}$.

deposited onto the Ag cathode. In the beginning of the galvanic deposition, the current through the KCl solution was changing in a jumpy manner, that indicated the growth of the AgCl layer. The galvanic process was stopped after the current was stable for at least 300 s.

3.4.4 Electrochemical Cells with a Separator

Two planar substrates were covered with a 7 nm layer of Cr and a 180 nm layer of Au. One substrates was covered with a redox active pDiTBuS film. The other substrate was either covered with pNiSalen (full cell), or was used as is (half cell). The cell preparation is shown in a scheme in Figure 3.9.

3.4.5 Electrochemical Cells with Solid Electrolyte

The electrolyte based on an ionic liquid incorporated in a gel-like polymer matrix has sufficient ionic mobility and diffusion to penetrate the pDiTBuS and pNiSalen surface and allow for partial charging and discharging of the battery electrodes. TEMPO rad-

icals were shown to undergo a redox reaction in ionic liquids with a slightly changed redox potential of the TEMPO[•]-TEMPO⁺ reaction [?].

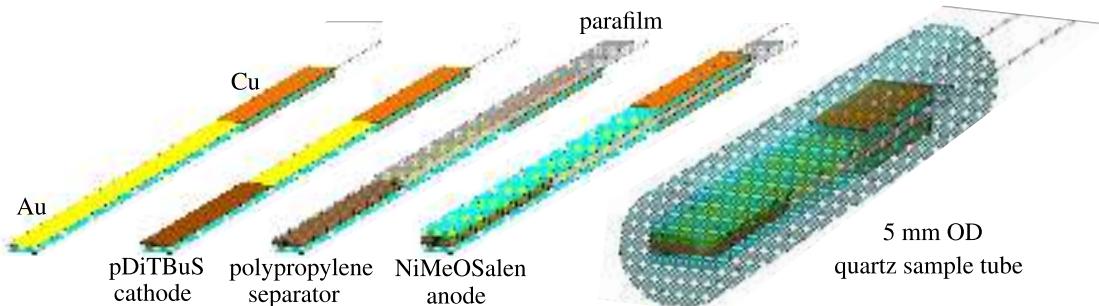


Figure 3.10: Organic radical battery made with two parallel Au-plated substrates and a polypropylene separator soaked in liquid electrolyte.

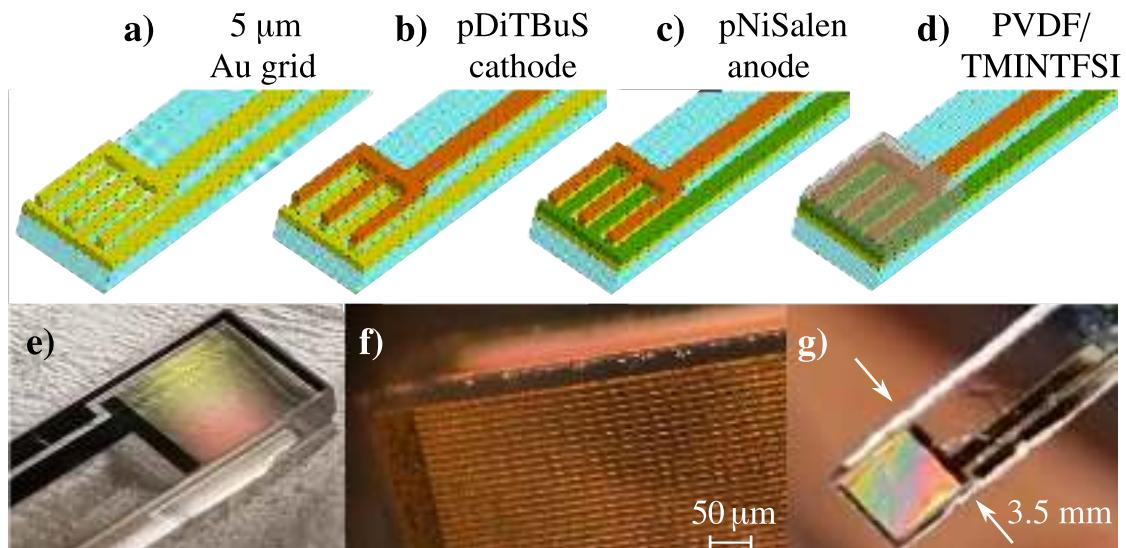


Figure 3.11: All-polymer solid state organic radical battery produced on a 5 μm interdigitated grid.

3.4.6 Energy Diagram of an Electrochemical Half-Cell

The transfer of charges in a TEMPO-Salen electrochemical cell can be described in an energy diagram shown in Figure 3.14. The energy scale of the diagram starts at the vacuum level - the energy of a free electron. The potential energy of an electron in the Au lead in this energy scale is the work function of Au which is 5.1 eV [21]. The energy at which an electron in a material can be found with a 0.5 probability is called the Fermi energy. The Fermi energy of a cathode changes with the SoC of the cell.

3.4 Electrochemical Cells for Operando cwEPR Spectroscopy

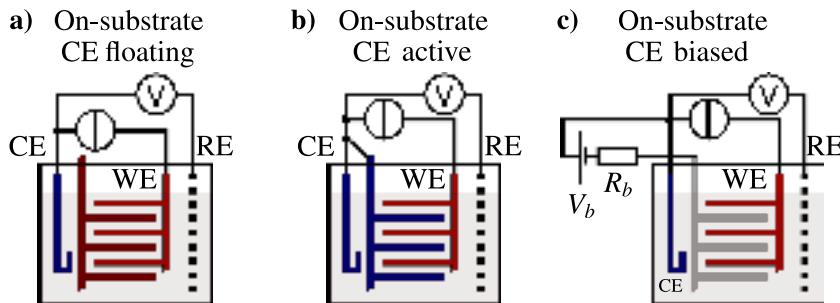


Figure 3.12: Deactivation of the on-substrate CE during the electrodeposition of a pDiT-BuS film on the on-substrate WE of a 5 μm interdigitated grid.

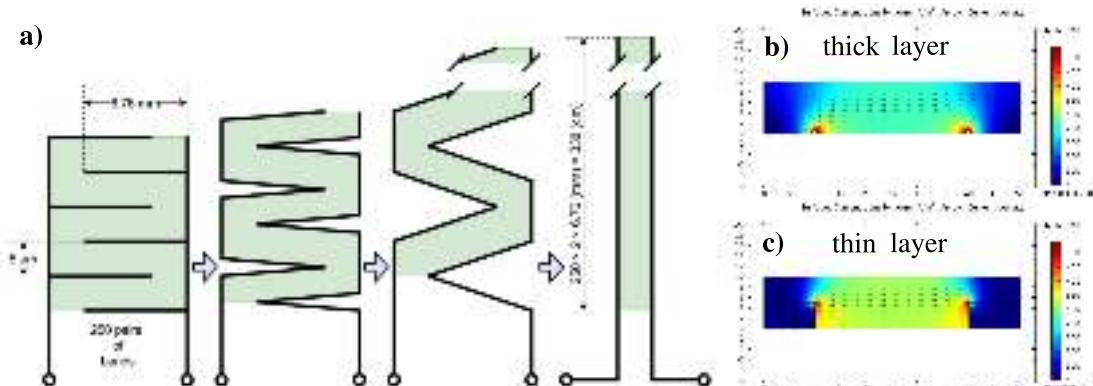


Figure 3.13: Extremely inhomogeneous current density in a closely spaced electrodes of the interdigitated grid. Numerical simulation in Comsol Multiphysics.

The redox potential of TEMPO is 0.812 V vs. SHE [132]. The absolute potential of the SHE is 4.44 V vs the vacuum level. The workfunction of Au is 5.1 eV. The electrochemical window of Acetonitrile is between -3.45 V and +2.35 V vs. SCE (+0.268 V vs SHE) [70].

Electrochemical doping of a semiconducting polymer [45]: Charge transfer, ion insertion. The oxidation and reduction potentials of the ions are separated from the redox potentials of the polymer by several volts, so no charge transfer occurs between the polymer and the electrolyte. The positive charge injected to the polymer from the metal is compensated by the intercalated negative ion. The ionization efficiency in electrochemically doped films is close to 100% [45].

During the charging of a poly-TEMPO-Salen half-cell, its electrochemically active cathode film is being oxidized: positive charges are being injected into it. If the bias potential of the cathode E is higher than the oxidation potential of the polymer (see Figure 3.14 a)), a positive charge is injected to the pNiSalen backbone. The oxidation potential of pNiSalen was adjusted during the molecular synthesis to be close to

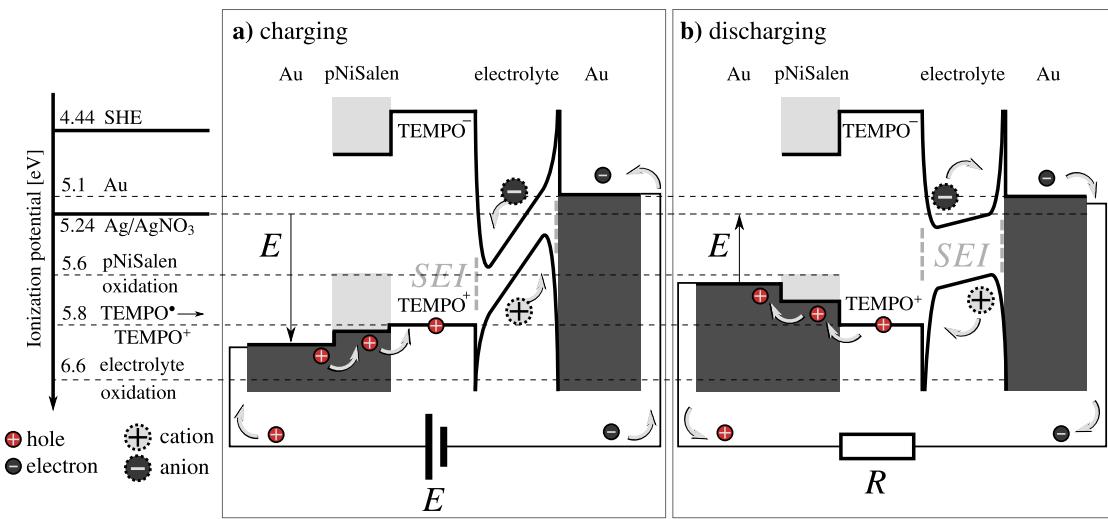


Figure 3.14: Band diagram of a rechargeable electrochemical half-cell with a TEMPO-containing polymer cathode during charging (a) and discharging (b).

the oxidation potential of TEMPO^{\bullet} , so that the oxidation of the backbone would lead to a simultaneous oxidation of the charge bearing groups [113]. If E increases above the oxidation potential of TEMPO^{\bullet} and the polymer backbone connecting the metal and the TEMPO^{\bullet} fragment is oxidized, the injected hole reaches the TEMPO^{\bullet} fragment and oxidizes it to TEMPO^+ . The charge transfer process during the charging of the half-cell is shown in Figure 3.14 a). The oxidation TEMPO^{\bullet} leads to a creation of an electric double layer [6] of A negative BF_4^- ion is attracted from the electrolyte solution to the positively charged backbone.

The hole injected into the polymer backbone propagates in the direction of the Fermi energy gradient within the biased polymer until it encounters the unpaired electron on a TEMPO^{\bullet} group and recombines with it. During the recombination, the hole disappears from the backbone and the electron disappears from the TEMPO^{\bullet} . The charge bearing group oxidizes to TEMPO^+ . This process can be seen as the hole hopping from the backbone to the TEMPO radical. The TEMPO radicals therefore serve as hole traps.

The consequent oxidation of the redox active groups during the biasing of the polymer cathode is shown in Figure 3.15.

3.4 Electrochemical Cells for Operando cwEPR Spectroscopy

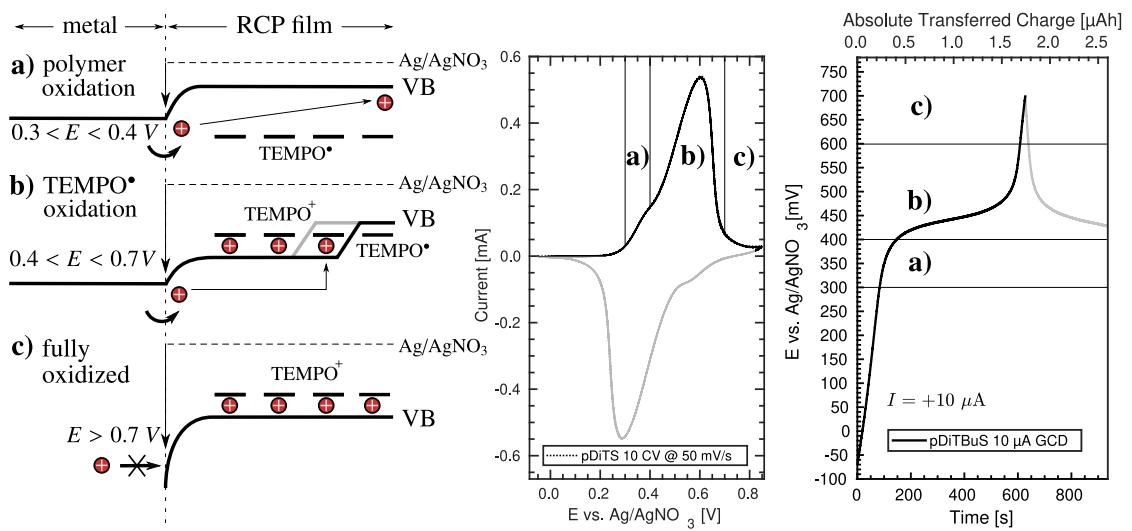


Figure 3.15: Charging of a poly-TEMPO-Salen film by injecting positive charge carriers at different biasing conditions. The Fermi energy for holes in the film is lowering during its electrochemical p-doping. a) $0.3 < E < 0.4$ V - the biasing potential is above the oxidation potential of the backbone and below the oxidation potential of TEMPO[•]. b): $0.4 < E < 0.7$ V - the biasing potential is in the range of the oxidation potentials of TEMPO observed as a current peak in a cyclic voltammogram (middle plot) and a voltage plateau in a galvanostatic charging curve (right plot). c): $E > 0.6...0.7$ V - the biasing potential is above the oxidation potential of all TEMPO groups in the film. Bending of the conduction band edge at the metal-semiconductor interface due to the Coulomb shielding by the ions stabilizing the TEMPO⁺ fragments.

Chapter 4

EPR Spectroscopy of TEMPO-Salen Electrochemical Cells

Here the EPR spectra of TEMPO-Salen electrochemical cells are shown under operating conditions and ex situ, for various states of charge, as well as the spectra of the materials that were used to construct the cells. That information is used to decompose the complex spectra of a charging cell and to perform its quantitative analysis to identify the state of charge of the cell and the by-products that are being released during the cell operation.

4.1 cwEPR Spectroscopy of TEMPO Containing Molecular Fragments

The stable TEMPO[•] radical is widely used in the EPR spectroscopy as a spin probe and particularly in the EPR studies of TEMPO containing ORB materials [76, 81, 3, 2, 53, 130]. The spin density at the TEMPO[•] radical is localized within the N-O bond [87] and partially resides on the $I = 1$ ^{14}N nucleus, so to describe the EPR spectrum of an isolated TEMPO[•] one has to take into consideration the electron Zeeman term H_{EZ} , the nuclear Zeeman term H_{NZ} and the hyperfine coupling term H_{HF} . The unpaired electron spin on TEMPO[•] has anisotropic g value, because of the asymmetry of its molecular orbital, so the \mathbf{g} matrix and the \mathbf{A} hyperfine coupling tensor are both anisotropic. \mathbf{g} is diagonal in the molecular frame of reference shown in Figure 4.1. Its principal values are $[g_{xx} = 2.009, g_{yy} = 2.006, g_{zz} = 2.002]$ [68, 9]. The principal values of \mathbf{A} in the same frame are $[A_{xx} = 20, A_{yy} = 20, A_{zz} = 100]$ MHz [68, 9].

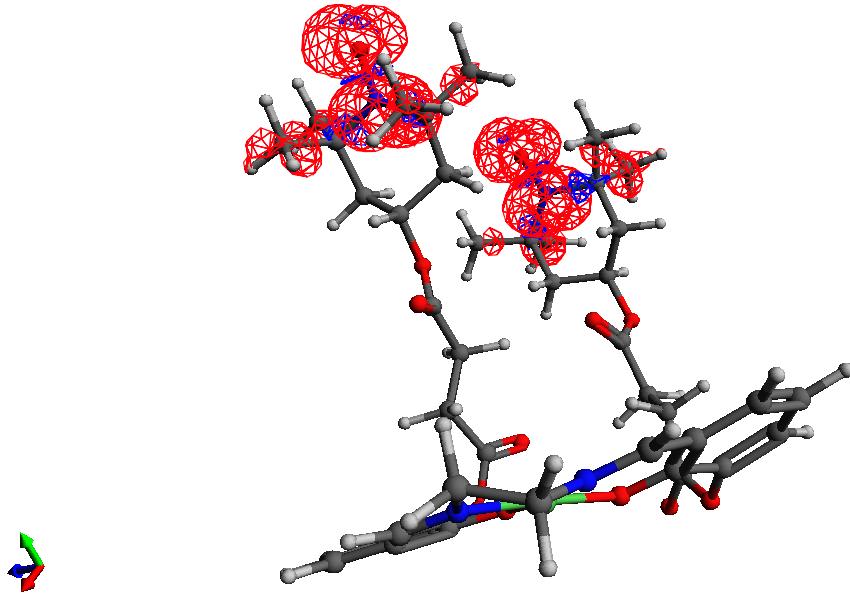


Figure 4.1: Spin density in a DITS monomer with unoxidized TEMPO groups computed with density functional theory. The spin density localized on two neighboring TEMPO radicals, around the Nitrogen nuclei that gives rise to the hyperfine coupling. Calculation by Marcel Gauglitz in ORCA [?] at the high-performance computing cluster Curta of the Free University of Berlin [5]. The def2-TZVP functional basis set was used for the geometry optimization and for the calculations of the spin density.

4.1.1 Room Temperature Spectra of TEMPO[•] Solutions

Solution spectra of radicals are showing averaged values of g and A because of the fast molecular tumbling [68, ?]. The observed g value for a tumbling TEMPO[•] is the average of the principal values of the \mathbf{g} matrix: $g = 1/3(g_{xx} + g_{yy} + g_{zz})$. The anisotropic part of the hyperfine coupling tensor for the tumbling TEMPO[•] also averages to zero, so only the isotropic hyperfine constant a_{iso} determines the observed hyperfine coupling. CwEPR spectra of a 0.1 mM solution of TEMPOL measured at room temperature are shown in Figure 4.2. The spectral simulation performed with EasySpin [107] yields $g = 2.0055$ and $a_{iso} = 43.8$ MHz.

A biradical molecule like Di-Tempo-Salen (Figure 3.2 e) and f)) has two paramagnetic species that are close to each other and therefore exchange electrons. When the exchange coupling between the radicals J is comparable to the hyperfine coupling A of each radical to its 'host' nucleus, the superhyperfine interaction [?] takes place, in which

4.1 cwEPR Spectroscopy of TEMPO Containing Molecular Fragments

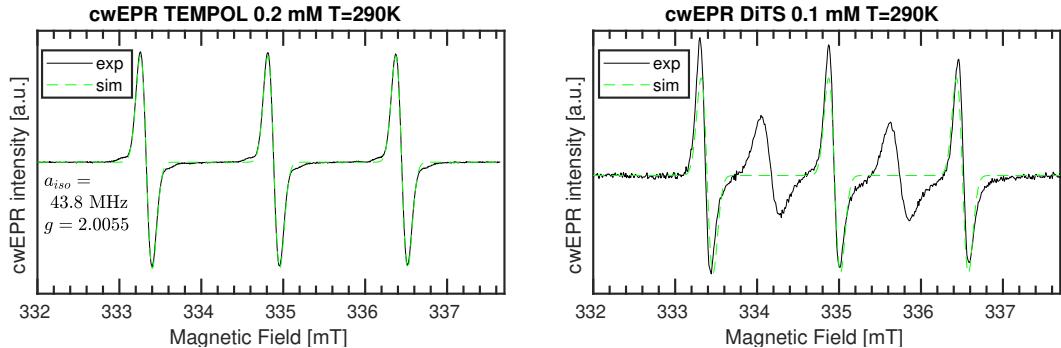


Figure 4.2: Room temperature cwEPR spectra of a low-concentration solutions containing mono- and di-TEMPO molecular fragments. Left: TEMPOL, Right: Di-Tempo-Salen.

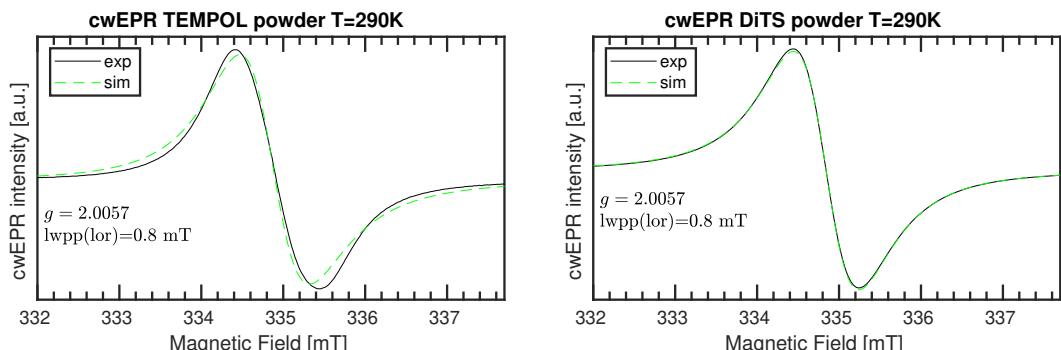


Figure 4.3: Room temperature cwEPR spectra of pure TEMPO-containing powders. Left: TEMPOL, Right: Di-Tempo-Salen.

the radical is interacting to the nucleus of the neighboring radical [22]. Solutions of biradical molecules with magnetic nuclei show more features in cwEPR spectra when the electron-electron exchange coupling J between the two radicals within the molecule becomes comparable to the hyperfine coupling between the radical and its 'host' ^{14}N nucleus. tumbling of the molecule and the restricted motions of each radical within the molecule cause a complex molecular motion that affects the dipolar and exchange couplings between the radicals and causes "spectra with alternating linewidths" [22, 10]. A solution of Di-TEMPO-Salen shows a five-line cwEPR spectrum with alternating linewidths (Figure 4.2, right) with the three most intense lines corresponding to the three hyperfine sublevels of TEMPO^\bullet . The five-line structure in the cwEPR spectrum indicates the presence of a di-TEMPO biradical in the solution.

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If the TEMPO groups are far away from each other, their cw-EPR signal consists of three lines that are due to the hyperfine interaction between the electron spin and the

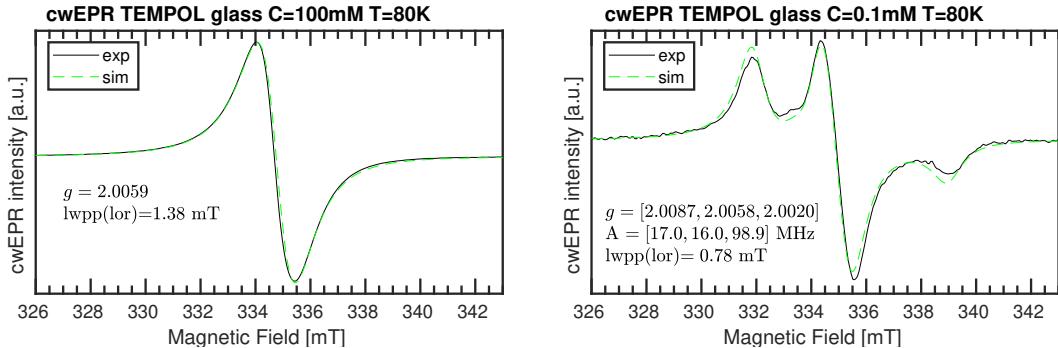


Figure 4.4: Cryogenic cwEPR spectra of TEMPOL at high and low concentration in a Dichloroethane/Acetonitrile glass. Left: 100 mM, Right: 0.1 mM.

spin of the Nitrogen nucleus. When the TEMPO groups are brought closer to each other, their electron orbitals start to overlap, and the exchange interaction (J) between the electrons grows. That splits the signal into more lines as it was shown by [10] and represented in Fig. 7. In the case of strong exchange interaction the spectrum consists of five lines with relative ratios 1:2:3:2:1. In the absence of the exchange interaction the spectrum contains only three hyperfine lines of equal intensities. In DiTS, a sum of a three-line spectrum and a five-line spectrum was observed. This may be the evidence that TEMPO-bearing linkers are sufficiently long to allow TEMPO groups to move freely in space around the organometallic complex. That can yield to different J values depending on the relative orientation of the linkers, similar to [10]. In theory, there are several possible positions of TEMPO groups relative to each other that can change the EPR spectrum. Depending on the angle between the linkers (from π to 0), J may vary from its minimal to maximal value, that should yield a three- and five-line structures respectively. Since the process of movement is dynamic, we can explain the observed picture as a combination of several positions in space [10]. The five-line structure suggests different preferred conformations of the TEMPO fragments and dynamic interconversion between these states with different exchange coupling J leads to the observed spectrum.

4.1.2 Spectra of $\text{TEMPO}^\bullet/\text{TEMPO}^+$ Films

A film made of a TEMPO-containing polymer can be brought to a certain oxidation state, depending on how many of the TEMPO groups are in the radical (TEMPO^\bullet) state and how many are in the oxidized (TEMPO^+) state. The densely packed TEMPO^\bullet fragments in the film cannot be considered as isolated molecules anymore, and the interactions between the radicals become significant. Microcrystals of TEMPOL are densely packed TEMPO^\bullet with a concentration of ??? mM. The cwEPR spectrum of TEMPOL microcrystals in Figure ?? is one broad line centered at $g = 2.0055$. A powder of DiTS

4.1 cwEPR Spectroscopy of TEMPO Containing Molecular Fragments

monomers is showing the same cwEPR spectrum in Figure ???. It is the matter of concentration of the paramagnetic TEMPO fragments that changes the cwEPR spectral shape. In Figure ?? cryogenic (80 K) cwEPR spectrum of a 100 mM solution of TEMPOL in Dichloroethane/Acetonitrile is presented. With a slight shift in g factor due to the polar molecular environment of the frozen solvent [?] and a broader lineshape due to a weaker exchange narrowing, the spectrum consists on one dipolar-broadened Lorentzian line. In contrast, when the concentration of the solution is lowered to 0.1 mM (Figure ??) - the inter-molecular interactions become weak enough to resolve the A and g anisotropy of the nitroxide radical, so the spectrum consists of three lines that can be simulated with the known A and g parameters.

A redox-active film containing TEMPO radicals, like the TEMPO-Salen cathode film, shows different cwEPR signatures depending on its redox state. Figure 4.5 represents two cryogenic cwEPR spectra of a $d \approx 2.2 \mu\text{m}$ DiTBuS cathode film that was discharged to $E = -50$ mV and charged to $E = +900$ mV vs. the Ag/AgNO₃ RE as described in Section 1.4.2. The spectral intensities were normalized to represent the signal shape not the magnitude. The discharged film shows one broad cwEPR line in Figure 4.5, left, that reflects on the strong interactions between the non-oxidized TEMPO[•] in the discharged cathode. The linewidth of the discharged film spectrum is smaller than the linewidth of the DiTS monomer spectrum, suggesting a smaller exchange interaction between the TEMPO fragments in the film [113].

The oxidized film in Figure 4.4, right, shows a well resolved spectrum of an isolated nitroxide, similar to the low-concentrated solution of TEMPOL (Figure ??). A series of powers was recorded for both redox states of the film to observe possible microwave saturation effects that are crucial for the pulsed EPR experiments discussed in Chapter 2.2.1.

4.1.3 Spectra of NiSalen Films

The molecular backbone of pDiTS and pDiTBuS is the pNiSalen, a conjugated polymer that exhibits redox behavior [20, 113, 1]. The observations of electrochromicity of pNiSalen films with UV-VIS spectroscopy [20] have revealed the formation of polarons and antiferromagnetically coupled (with total spin S=0) bipolarons in the oxidized state of pNiSalen. A series of cwEPR spectra recorded for a pNiSalen film in various redox states is shown in Figure 4.9. Operando cwEPR spectra of a cell containing a pNiSalen cathode is shown in Figure 4.10.

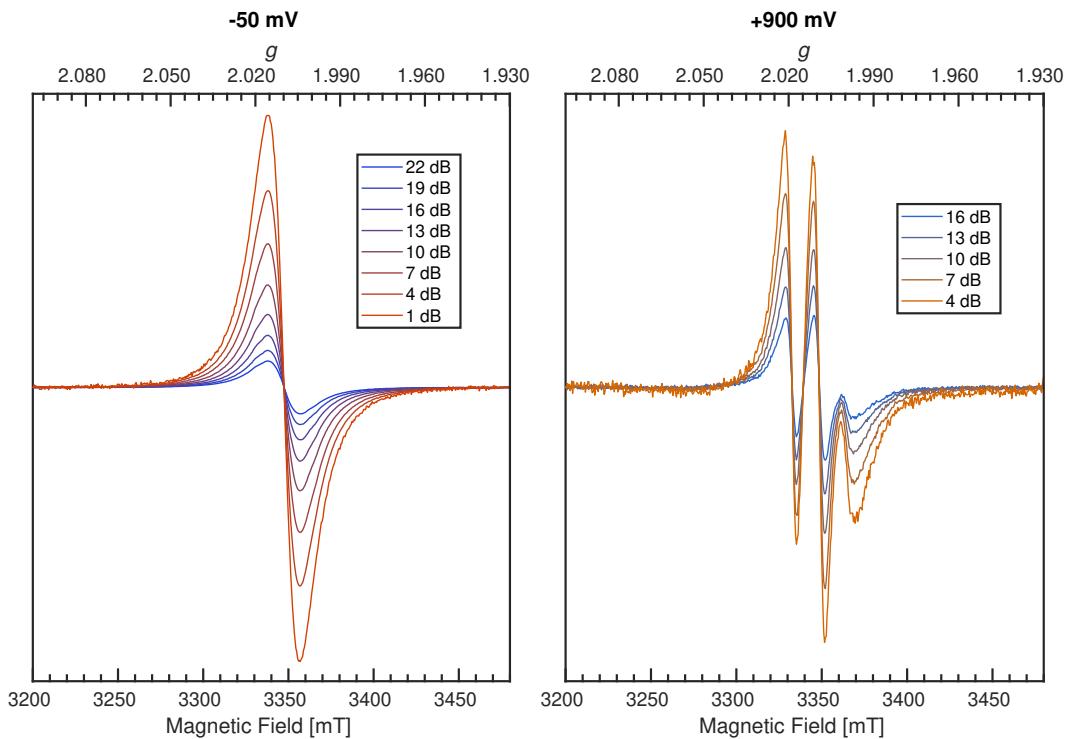


Figure 4.5: Cryogenic (80 K) cwEPR spectra of a pDiTBuS film grown with 200 deposition cycles. Left: discharged film, -50 mV vs. Ag/AgNO₃ RE. Right: Fully charged film, 900 mV vs. Ag/AgNO₃ RE.

4.2 Electrochemical Cells for EPR spectroscopy

4.2.1 Cells Based on a Modified EPR Sample Tube

An electrochemical cell was constructed inside an X band EPR sample tube.

4.2.2 Versatile electrode setup for ex-situ and in-situ spectroelectrochemical EPR

One significant drawback with SEC EPR is the fact that microwave resonators suffer from substantial microwave damping as a result of introducing metal electrodes, polar solvents and ionic salts (i.e., the electrolyte) needed for successful electrochemistry.[?] Microwave damping can be significantly reduced by our novel on-substrate electrode design (see Fig. 4.11) as this limits the amount of metal that is introduced into the resonator, while still allowing us to have electrode surface areas large enough to deposit sufficient material of interest to observe EPR signals.

The on-substrate electrodes are produced as follows. Cleaned quartz substrates are

4.2 Electrochemical Cells for EPR spectroscopy

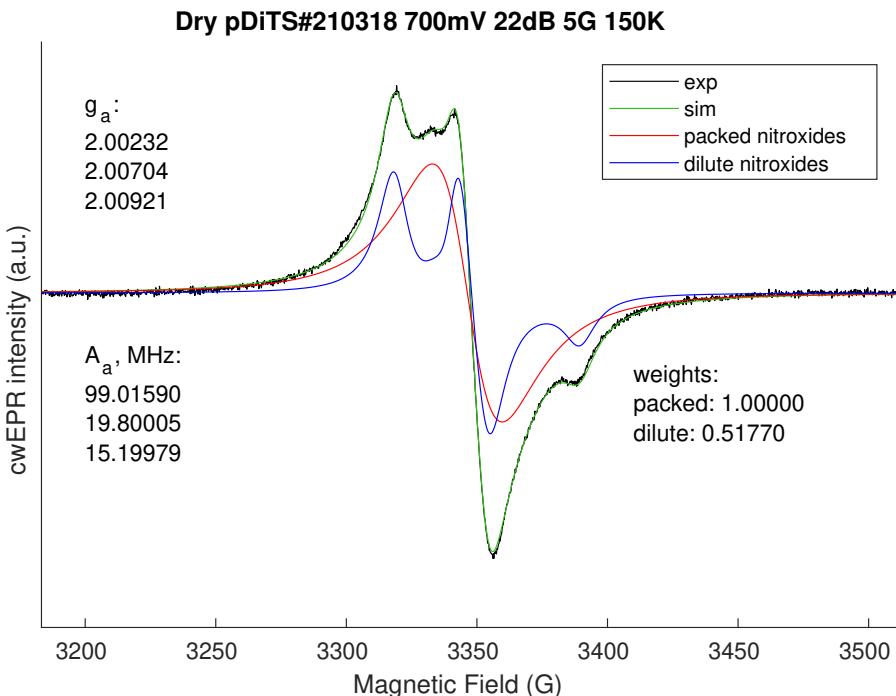


Figure 4.6: A pDiTS film in the intermediate state of charge (700 mV vs. Ag/AgNO₃) showing a composition of two spectral signatures. The single-line signal from the densely packed nitroxide radicals coexists with the signal of the isolated nitroxide radicals. Two-component simulation.

placed inside a holder and covered with shadow masks. The assembly is transferred into a vacuum chamber equipped with a thermal evaporator (MBraun ProVap 5G PVD System). At a pressure of 7×10^{-7} mbar, 10 nm of Chromium (Cr) adhesion layer is evaporated, followed by 180 nm of Gold (Au). In this way the on-substrate working and counter electrodes are formed (WE and CE respectively). The reference electrode (RE) is not evaporated on substrate for electrochemical stability reasons. Instead, a 250 µm Ag wire is used, either as is or, for additional stability, coated galvanically with a AgCl layer.^[?] See Section ?? in the ESI† for details of the sample preparation.

The above procedure provides a WE active area of 12.0 mm² which allows one to deposit an electrochemically active film that is large enough to yield a clear EPR signal. The flat electrode design provides the possibility to increase the WE area for samples with particularly small EPR signals while still maintaining certain film thicknesses. This also allows for studying EPR properties as a function of film thickness. In cases where the electrochemical process is thought to deposit material on both the WE and CE, the distance between the on-substrate electrodes can be adjusted such that only one of the electrodes is positioned in the active volume of the microwave resonator, allowing for

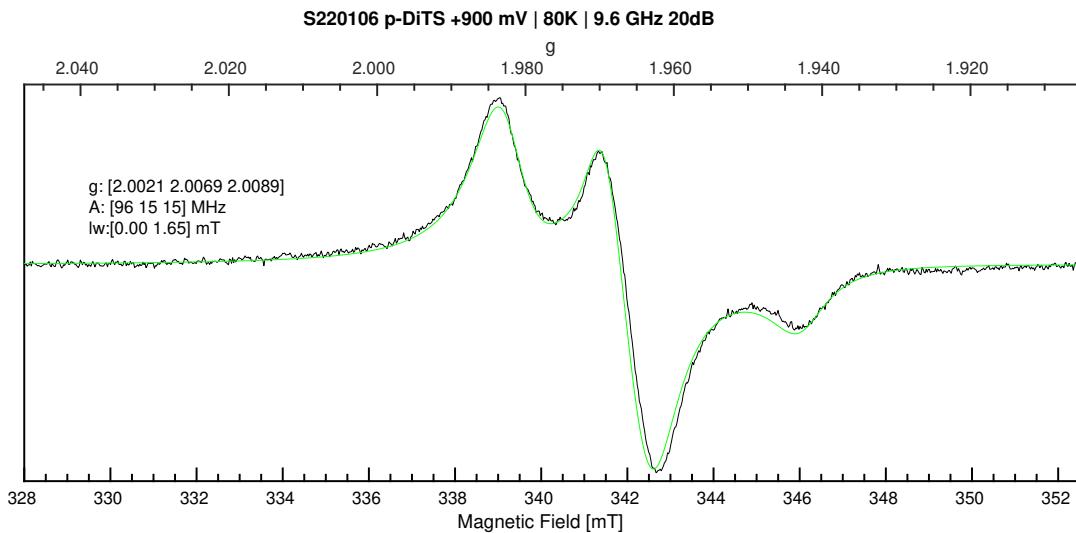


Figure 4.7: Cryogenic (80 K) cwEPR spectrum of an oxidized pDiTBuS film grown with 200 deposition cycles showing a signature of the isolated nitroxide radical with the standard g and A parameters, revealed with a simulation.

selective EPR probing of either of the electrodes.

The on-substrate electrodes reduce microwave damping. However, a substantial amount of microwave damping occurs due to the electrolyte, made of polar solvent and ionic salts. Therefore, we further optimize our setup by modifying conventional 5 mm outer diameter (OD) quartz EPR tubes by flattening the bottom 1.3–1.6 cm (cf. Fig. 4.11b and Section 4.12 in the ESI†), thereby reducing the active electrolyte volume needed to submerge both the WE and CE on the substrate as well as the RE wire, from $\sim 120 \mu\text{L}$ to $\sim 60\text{--}70 \mu\text{L}$.

The flattened tube and the thin-film electrode setup have an additional benefit in that the sample is moved away from the maximum of the electric field distribution in the Bruker ER 4122-SHQE resonator (TE_{011} mode cavity for cwEPR), thereby further increasing the resonator quality factor (Q-factor, given by $Q = \frac{\nu_{res}}{\Delta\nu}$, ν_{res} = resonance frequency, $\Delta\nu$ = FWHM of the resonance dip) and hence sensitivity. Further improvements can be made using the flat electrode setup in a TM_{110} mode cwEPR cylindrical cavity such as a Bruker ER 4103-TM (developed for studying samples exhibiting high dielectric constants), where the flattened cell can be aligned to further reduce coupling to the microwave electric field. The modified tube is compatible with commercial Bruker ER 4118X-MD5 resonators, most commonly used for advanced pulse EPR measurements at X-band frequencies ($\nu = 9\text{--}10 \text{ GHz}$).

4.2 Electrochemical Cells for EPR spectroscopy

4.2.3 Fabrication of the modified tube

The volume of the cell used in this study had to be minimized, as the high dielectric constant of the electrolyte does not allow for the critical coupling of the resonator. The volume of the electrolyte was minimized by flattening the tip of the quartz (melting point $T_m = 1660 - 1710^\circ\text{C}$) tube accommodating the cell. For that, a tungsten (W, $T_m = 3420^\circ\text{C}$) rod of a 3.70×1.35 mm rectangular cross section, narrowing to the bottom of the tube at a wedge angle of $\alpha \approx 5^\circ$, was inserted into the tube (Fig. 4.12). The tube was evacuated and filled with He to a pressure of 100 mbar. The tip of the evacuated tube was molten around the thermally expanded rod with a Hydrogen-Oxygen burner ($T_f = 3080^\circ\text{C}$). The modified tube was then connected to atmosphere and the cooled, contracted rod was removed and later reused for modifying other tubes. The tungsten rod was fabricated from an electrode of a flash lamp of a pulsed Nd:YAG laser.

The modification of the tip of the tube provided a decrease in the volume of the electrolyte down to $45 \mu\text{L}$, while the cylindrical part of the tube allowed for fitting the substrate connector and the wiring in. That allowed for the room temperature EPR measurements on the electrochemical cell during charging and discharging. Extensive care had to be taken to reproduce the cv curve in the modified tube as the limited volume of the electrolyte was distributed over the large surface area. That caused poor ionic transport in the electrolyte layer.

To establish the extent to which the modified tube improves the resonator Q-factor (Q) and therefore sensitivity of the cwEPR experiment, cwEPR spectra and associated Q-factors were recorded for a flat-electrode p-DiTS cell assembled in two different sample tubes. For both cell setups we used enough electrolyte to submerge all three electrodes. This required $100 \mu\text{L}$ for the standard tube and $70 \mu\text{L}$ for the modified tube. The effect of the two tubes on the cwEPR spectrum and on the Q-factor was studied for a range of heights (H) measured from the center of the microwave resonator to the middle of the WE.

4.2.4 Q-factors and cwEPR spectra for p-DiTS in standard and modified tube

We determine $Q \approx 7800$ for the empty resonator. Inserting the tube-based cells initially at $H = 24$ mm reduces the Q-factor for both cases, but more significantly for the standard tube ($Q_{\text{standard tube}} \approx 4200$, $Q_{\text{modified tube}} \approx 5400$, see Fig. 4.13). At $H = 18$ mm the Q-factor drops for both, again more significantly for the standard tube to $Q_{\text{standard tube}} \approx 300$ while for the modified tube it is still $Q_{\text{modified tube}} \approx 1200$, a factor of 4 difference. This difference between the two tubes shows the benefit of using the modified tube and flat electrode geometries for SEC EPR. When the modified tube is inserted as deep

as $H = 14$ mm, the $Q_{\text{modified tube}}$ is around 400, which still allows for EPR measurements. Coupling the resonator not possible for $H < 18$ mm (standard tube) and $H < 14$ mm (modified tube).

The decreasing Q-factor is not the only effect of a high-dielectric sample in an EPR resonator. The interaction between the sample and the electric field distribution of the resonator causes a mixture of absorption and dispersion signals, leading to asymmetric lineshapes in the cwEPR spectra. This makes double integration of the derivative cwEPR signal more complex, thereby making a quantitative analysis more difficult. This effect can be seen in the cwEPR spectra of p-DiTS (Fig. 4.13) measured in the standard 5 mm tube for $H = 18$ mm where the cwEPR signal is asymmetric. The modified tube yields symmetric lineshapes at the same sample heights. Further details are presented in the following subsection.

The electrochemical cells based on the modified tube allow for higher EPR signals as compared to the normal X-band EPR tube. Fig. 4.14 represents two sets of measurements that describe the enhancement of the EPR signal for the modified tube. When the cell is inserted closer to the resonator's center, the Q factor of the resonator lowers and the EPR signal increases, because the intensity of the magnetic component of the microwave field B_1 is higher in the center of the resonator. When the cells were inserted closer to the center of the resonator, the Q factor went from ≈ 6000 down to ≈ 400 , so that the microwave bridge could not be critically coupled to the resonator and no EPR measurements were possible. Depending on the volume of the electrolyte in the cell, it can be inserted more or less deep into the resonator.

The modified tube could be inserted 7 mm deeper into the microwave resonator (see Fig. 4.14). The EPR signal in the modified tube is increased as compared to the normal tube at the same height.

The modified tube also allows for larger cwEPR signal intensities as it can be inserted closer to the resonator center. The signal-to-noise ratio (S/N) for the modified tube is increased by a factor of ≈ 6 as compared to the standard tube, both inserted at $H = 18$ mm. At the maximum sample insertion, the S/N is improved by a factor of ≈ 8 for the modified tube.

Using the modified tube we see three major benefits. Firstly, it results in much higher Q-factors and therefore sensitivity when comparing Q-factors for the same sample height. Secondly, the modified tube allows for insertion of the tube closer to the resonator center, allowing for a larger S/N and therefore requiring less averaging time for each cwEPR measurement. This is especially useful for samples where holding the potential for long periods causes unwanted effects or degradation. Thirdly, cwEPR measurements with the modified tube give symmetric cwEPR lineshapes (using the conventional procedure for critically coupling the microwave cavity, the standard tube gives an asymmetric lineshape) which allows for more straightforward quantitative analysis (spin counting), especially useful for in-situ cwEPR with varying redox potentials.

4.3 cwEPR Spectroscopy of a Charging Electrochemical Cell

There is a number of difficulties when it comes to an EPR experiment on a working electrochemical cell. The cell must contain mobile ions between its electrodes - cations and anions. The ions are normally produced as products of dissociating salts. To overcome the ionic bond in a salt and to break it into the ions, a solvent with large dipole moment is needed. Solvents with large dipole moments, as acetonitrile (CH_3CN , $\epsilon \approx 37.5$) or water ($\epsilon \approx 78.4$), have large dielectric constants which results in a non-resonant absorption of microwaves. A cell containing liquid electrolyte absorbs microwaves and lowers the sensitivity of the EPR experiment. Furthermore, due to a finite dimension of cell, not only the magnetic component of the microwave is interacting with the electrolyte, but also the electric one - this results in heating of the electrolyte in a similar fashion as in a microwave oven. The heating of the electrolyte leads to a faster degradation of the cell and does not allow for long systematic measurements.

Another general issue with the operando EPR and EDMR experiments is that the device under testing (DUT) has to have metal electrodes that deliver current to it. Metals, placed in a microwave cavity, change the distribution of the electromagnetic field in it - that weakens the magnetic component at the device and at the same time strengthens the electric component. It is the magnetic dipole transition that is causing the magnetic resonance, so the weakening of the magnetic component by introducing the metal electrodes further decreases the magnetic resonance response. The increased electric component causes heating to temperatures that can be critical for the DUT operation.

4.3.1 cwEPR Spectra During a Charge-Discharge Cycle

There are four characteristic cwEPR signatures of an electrochemical cell containing di-TEMPO-Salen polymer cathode. The well known signature of a freely tumbling TEMPO[•] exhibits three narrow lines corresponding to the three nuclear sublevels of nitrogen: $m_I = -1, 0, +1$.

EPR spectra of electrochemical cells with p-DiTS as active-electrode material can exhibit a variety of different signals. Before presenting and discussing the experimental results, we will provide an overview about the various characteristic cwEPR lineshapes associated with nitroxides in different environments.

Fig. 4.15a shows the spectrum expected for a *densely packed p-DiTS film* with all nitroxides in the EPR-active reduced state. The broad unstructured line results from the strong dipolar and exchange interaction between both nitroxides of each DiTS monomer as well as between the nitroxides of different monomers. The exchange interaction can lead to either line narrowing or broadening depending on the strength of the interaction,[?] while the dipolar interaction causes broadening. In consequence, the

overall cwEPR line width depends on the spin concentration in the film.

Dilute mono-TEMPO fragments dissolved in the electrolyte, each containing only one nitroxide, give rise to a three-line spectrum (cf. Fig. 4.15b) which is well known from nitroxide-based spin labels in solution.[68] Tumbling of the molecules in the liquid electrolyte results in an averaging of the anisotropic interaction between the electron spin and the nitrogen nuclear spin ($I = 1$) as well as of the g anisotropy, leaving only the isotropic part of the hyperfine coupling and the isotropic g value.

Dilute DiTS monomers in the electrolyte generally give a spectrum consisting of five narrow lines (cf. Fig. 4.15c), if each monomer contains two interacting EPR-active nitroxides. The spectrum depends on dynamic effects, specifically the modulation of the exchange interaction between both radicals of each monomer. Thus, depending on the solvent and temperature, the spectrum can be indistinguishable from the three-line spectrum of mono-TEMPO fragments.

The fully charged (oxidized) p-DiTS film can contain electrically isolated domains in which the nitroxides are not connected to the electrode and cannot be oxidized or reduced. These electrically inactive *immobilized DiTS monomers* in the oxidized film display a spectrum as shown in Fig. 4.15d. In contrast to the densely packed p-DiTS film, the dipolar and exchange interactions between neighboring radicals are much weaker. The anisotropy of the nitroxide's hyperfine tensor adds features to the cwEPR spectrum in d) as compared to a). Yet, there is some remaining line broadening that does not allow one to distinguish between immobilized DiTS monomers with either one or two paramagnetic nitroxides.

We note that the oxidized NiSalen backbone can contribute to the spectrum as well. Its EPR signature, which is not shown in Fig. 4.15, is clearly different from the nitroxide/TEMPO-related spectra discussed above.

4.3.2 Spectral Simulations

4.3.3 Quantitative Analysis of Potential-Dependent EPR Spectra

The number of spins at each SoC was determined with quantitative cwEPR from the double integral of the cwEPR intensity calculated with the SpinCounting Toolbox [?] for Matlab [?]. The cwEPR spectra in Figure 4.17 were measured in a Bruker Elexsys E580 spectrometer equipped with an ER 4118 X-MD5 dielectric ring resonator with an unknown Q factor. To calibrate the intensity of the measured cwEPR signals and to determine the absolute number of spins in the film, we measured the cwEPR spectrum of the fully discharged film (SoC 0%) with a calibrated spectrometer. The calibrated spectrometer is a lab-built X-band cwEPR spectrometer equipped with a 9.4 GHz, 200 mW microwave source and a 4122-SHQE resonator. With $Q = 6095$, the absolute number of spins in the pDiTBuS film at SoC 0% was measured to be $N = (6.9 \pm 0.4) \times 10^{15}$. We used N to get the number of spins for other SoC from the spectra measured with the

4.4 EPR-Detected State Of Charge

uncalibrated spectrometer. We assumed that the Q factor of the resonator remains the same for different SoC [?] and computed the corresponding numbers of spins from the doubly integrated spectral intensities.

The doubly integrated cwEPR spectral intensities for the pDiTBuS film in the four considered SoC relate to each other as 100:51:15:6 with the absolute number of spins of $(6.9 \pm 0.4) \times 10^{15}$, $(3.5 \pm 0.2) \times 10^{15}$, $(1.1 \pm 0.1) \times 10^{15}$ and $(3.8 \pm 0.4) \times 10^{14}$, respectively. The respective ESOC are therefore $(0 \pm 5)\%$, $(49 \pm 3)\%$, $(85 \pm 2)\%$ and $(95 \pm 1)\%$. Spin concentrations in the film are $(5.3 \pm 2.7) \times 10^{20}$, $(2.7 \pm 1.4) \times 10^{20}$, $(0.8 \pm 0.4) \times 10^{20}$ and $(0.3 \pm 0.2) \times 10^{20} \text{ cm}^{-3}$, respectively. Integration of the cyclic voltammogram yields $(2.3 \pm 0.8) \times 10^{16}$ electrons in the reduced state.

4.4 EPR-Detected State Of Charge

The SoC of the film determined with Coulomb counting were compared to quantitative cwEPR to directly relate the number of charges, injected into the film upon charging, to the number of paramagnetic centres in it. We refer to the fraction of spins removed from the fully discharged film to reach a given SoC as the EPR-detected state of charge, or ESOC. The fully discharged film has the maximum number of spins and its ESOC is 0%. ESOC at other SoC are determined as the fraction of the missing spins with respect to ESOC 0%. ESOC of 95% thus corresponds to the oxidation state where only 5% of the initially present spins are left in the film. The cwEPR spectra were recorded for the listed SoC, and the corresponding numbers of spins were calculated from the double integrals of the spectra. The integrated spectra and the experimental details are shown in the ESI, Section ???. The injected charges, detected spins and ESOC values are counted for each SoC in Table 4.1. The average spin concentration in the film $\langle n \rangle$ at each ESOC was calculated from the corresponding number of spins and the estimated volume of the film of $(1.3 \pm 0.6) \times 10^{-5} \text{ cm}^3$.

4.4.1 Formation of Singlet Spin States in a Reduced Cathode Film

The number of electrons left in the film were determined with the Coulomb counting from the galvanostatic discharge curves shown in Figure 3.8. The number of electron spins detected with cwEPR is close to the Coulomb counting for high SoC, that corresponds to lower spin concentrations. However, for low SoC, the difference in the number of electrons measured with the Coulomb counting and with quantitative cwEPR is dramatic: up to 70% of the electrons in the discharged film are EPR silent. The absence of cwEPR signal from the majority of the electrons indicates that their spins pair up in singlet ($S=0$) EPR silent states. The singlet spin pairs follow Bose statistics and can oc-

| E [mV] | SoC | ESOC | capacity drawn [μAh] | charges injected | spins detected | n_C [cm ⁻³] | $\langle n \rangle$ [cm ⁻³] | C [cm ⁻³] |
|----------|-----|-----------|----------------------|----------------------------------|--------------------------------|--------------------------------|---|------------------------|
| 590 ± 5 | 98% | (95 ± 1)% | 0.020 ± 0.005 | (5 ± 1) × 10 ¹⁴ | (4 ± 1) × 10 ¹⁴ | (3 ± 2) × 10 ¹⁹ | (3 ± 2) × 10 ¹⁹ | > 1 × 10 ¹⁹ |
| 500 ± 5 | 96% | (85 ± 2)% | 0.060 ± 0.005 | (1.4 ± 0.1) × 10 ¹⁵ | (1.1 ± 0.1) × 10 ¹⁵ | (1.0 ± 0.5) × 10 ²⁰ | (8 ± 4) × 10 ¹⁹ | > 3 × 10 ¹⁹ |
| 430 ± 5 | 65% | (49 ± 3)% | 0.480 ± 0.005 | (1.07 ± 0.01) × 10 ¹⁶ | (3.5 ± 0.2) × 10 ¹⁵ | (8 ± 4) × 10 ²⁰ | (3 ± 2) × 10 ²⁰ | — |
| -200 ± 5 | 0% | (0 ± 5)% | 1.360 ± 0.005 | (3.05 ± 0.01) × 10 ¹⁶ | (6.9 ± 0.4) × 10 ¹⁵ | (2 ± 1) × 10 ²¹ | (5 ± 3) × 10 ²⁰ | — |

Table 4.1: EPR-detected state of charge, Coulomb counting and the corresponding spin concentrations in a galvanostatically discharging pDiTBuS film with $I = -10 \mu\text{A}$. The electric potential of the film E was measured with respect to the Ag/AgNO₃ RE. The number of injected (negative) elementary charges and the corresponding concentration of charges n_C were determined from the drawn capacity. The average spin concentration $\langle n \rangle$ is the ratio between the number of spins measured with quantitative cwEPR and the volume of the film determined by integrating the cyclic voltammogram. C is the local spin concentration in the film estimated with pEPR as described in text.

cupy the same quantum state which is favorable for the charge transport. The formation of singlet states was detected only in low SoC.

4.5 Monitoring of Degradation Processes

The operando monitoring of EPR spectra in pDiTS cells has revealed that the amount of paramagnetic species reduces upon the cycling. The cwEPR spectra during one charge-discharge cycle of two different pDiTS cells are shown in Figure 4.20. Both datasets show a significant amount of the three-line structure in the oxidised (fully charged) state, that corresponds to the release of dilute nitroxide radicals from the polymer film to the electrolyte. The fact that the released species exhibit a 3-line structure and not a 5-line structure excludes the release of the di-TEMPO (DiTS) monomers and suggests that individual TEMPO[•] fragments are being detached from the film. Therefore, it was found that it is the molecular degradation of DiTS that is responsible for the loss of cell's capacity and not the decomposition of the polymer film into the monomer fragments. The overall EPR signal intensity decreases for both samples after the charge-discharge cycle. The spectral deconvolution with quantitative analysis of the individual components has revealed that the released fragments do not explain the overall loss of the signal intensity after the cycle.

4.6 Monitoring of Self Discharge

Organic Radical Batteries have a tendency to self-discharge, as the organic electrochemically active layer partially dissolves in polar electrolytes. Particularly for the TEMPO containing ORB, the dissolved, mobile TEMPO fragments serve as redox shuttles that carry the charge between the battery electrodes and cause a self discharge. The amount

4.7 Low Temperature Measurements

of unoxidized TEMPO[•] shuttles can be measured with cwEPR spectroscopy as the mobile fragments have distinct spectra as compared to the fragments tightly packed in the electrode. Further in this subsection operando spectra of a TEMPO containing electrochemical cells are shown. Quantitative analysis of the released fragments during a charge-discharge cycle allows for a description of the self-discharge process in an ORB. The charge state of a battery is monitored with cwEPR and, additionally, with a potentiometric measurement to identify the self-discharge rate and to connect it with the concentration of diffusing redox shuttles. Figure 4.22 represents a gradual change in the cwEPR intensity of a self-discharging tube-based cell with a pDiTS cathode. The cell was initially discharged to $V_{OC} = 350$ mV and then charged to $V_{OC} = 1300$ mV, at that point the minimal cwEPR intensity was registered. The cell was left under the open circuit condition. After $t = 500$ s, the cwEPR signal of the cell has fully recovered, that corresponds to the complete reduction of the electrochemically active nitroxide radicals in the cathode film.

4.7 Low Temperature Measurements

4.8 Pulsed EPR spectroscopy of a Cathode Film

4.8.1 Pulsed EPR Spectra of TEMPOL solutions

In a glassy, frozen solution of TEMPOL, the distance between the TEMPO radicals is controlled by the concentration of the solution. With the increasing concentration, the relaxation times shorten significantly, as the distance between the radicals decreases, which intensifies the inter-spin interactions and leads to a faster in-plane dephasing of the excited spins.

4.9 Pulsed EPR Spectroscopy of a charged pDiTBuS Cathode film

4.9.1 Field Swept Echo of a charged pDiTBuS Cathode film

4.9.2 Instantaneous Diffusion in Charged pDiTBuS

We have seen that the ESOC has a strong influence on the shape of the EDFS spectra. Furthermore, the EDFS spectra of pDiTBuS are quite different from the reference spectrum of TEMPOL in a dilute frozen solution.

In Section /// it is shown that in a densely packed radical system, as in a TEMPO-Salen cathode film, the phase memory time can be shorter than $T_m \leq 100$ ns. That is, the spin echo is decaying by $e \approx 3$ times at $t = 100$ ns. The short phase memory time limits the duration of the pulse sequence at which the echo is detectable. For a $\pi/2 - \tau - \pi - \tau - \text{echo}$ sequence, with a hardware limitation on $\tau \geq t_d \approx 100$ ns, the shortest realizable pulse sequence becomes longer than $t > 200$ ns. By this time, the spin echo decreases by $e^2 \approx 7$ times and may be comparable to noise. The limitations imposed by the finite T_m and t_d force one to use shorter microwave pulses.

A short microwave pulse may have a spectral width comparable to the width of the observed spectrum. According to the Fourier theorem, the spectral width of a pulse is inversely proportional to the pulse length: $\Delta\omega \sim 1/t_p$. A spectrum of a 100 ns long rectangular pulse shown in Figure /// is ///MHz wide (FWHM).

4.9 Pulsed EPR Spectroscopy of a charged pDiTBuS Cathode film

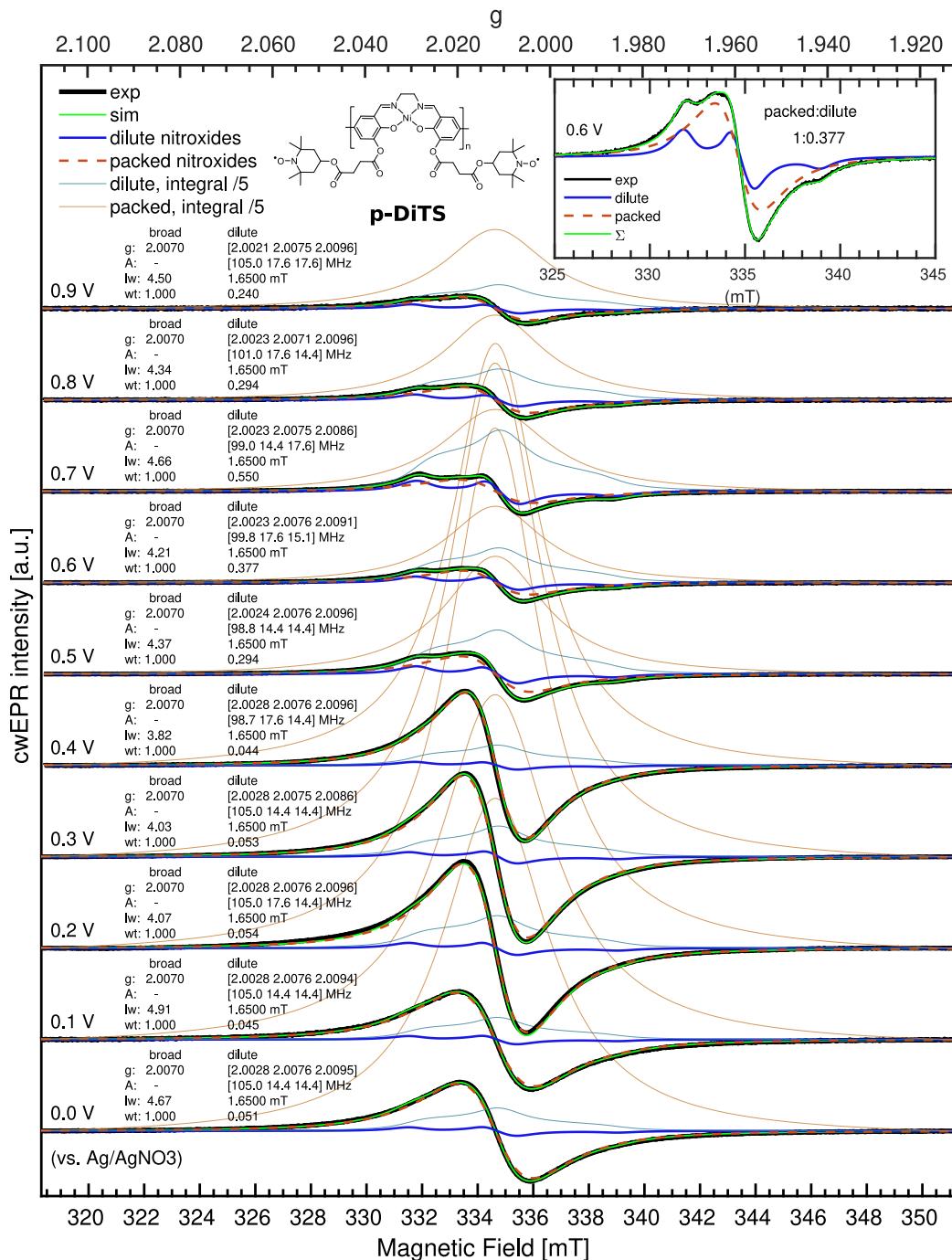


Figure 4.8: Ex-situ SEC cwEPR measurements ($\nu = 9.4$ GHz) on a dry p-DiTS film at 150 K. Decomposition of spectra into two components with numeric simulations using EasySpin [?]: a broad Lorentzian line ($g = 2.0070$, $Iw = 4.63 \pm 1.00$ mT) and a dilute component with a hyperfine coupling to ^{14}N ($I = 1$, $g = [2.00231 2.00711 2.00912]$, $A = [100 15 15] \pm 5 2 2$ MHz, Lorentzian broadening with $Iw = 1.65$ mT). The absorption profiles are shown with the integrals of the EPR signals. The ratio between the simulated components for each potential is shown by the double integrals of the components. Inset: sum of the broad and dilute components that reproduce the line shape at 0.6 V.⁶³

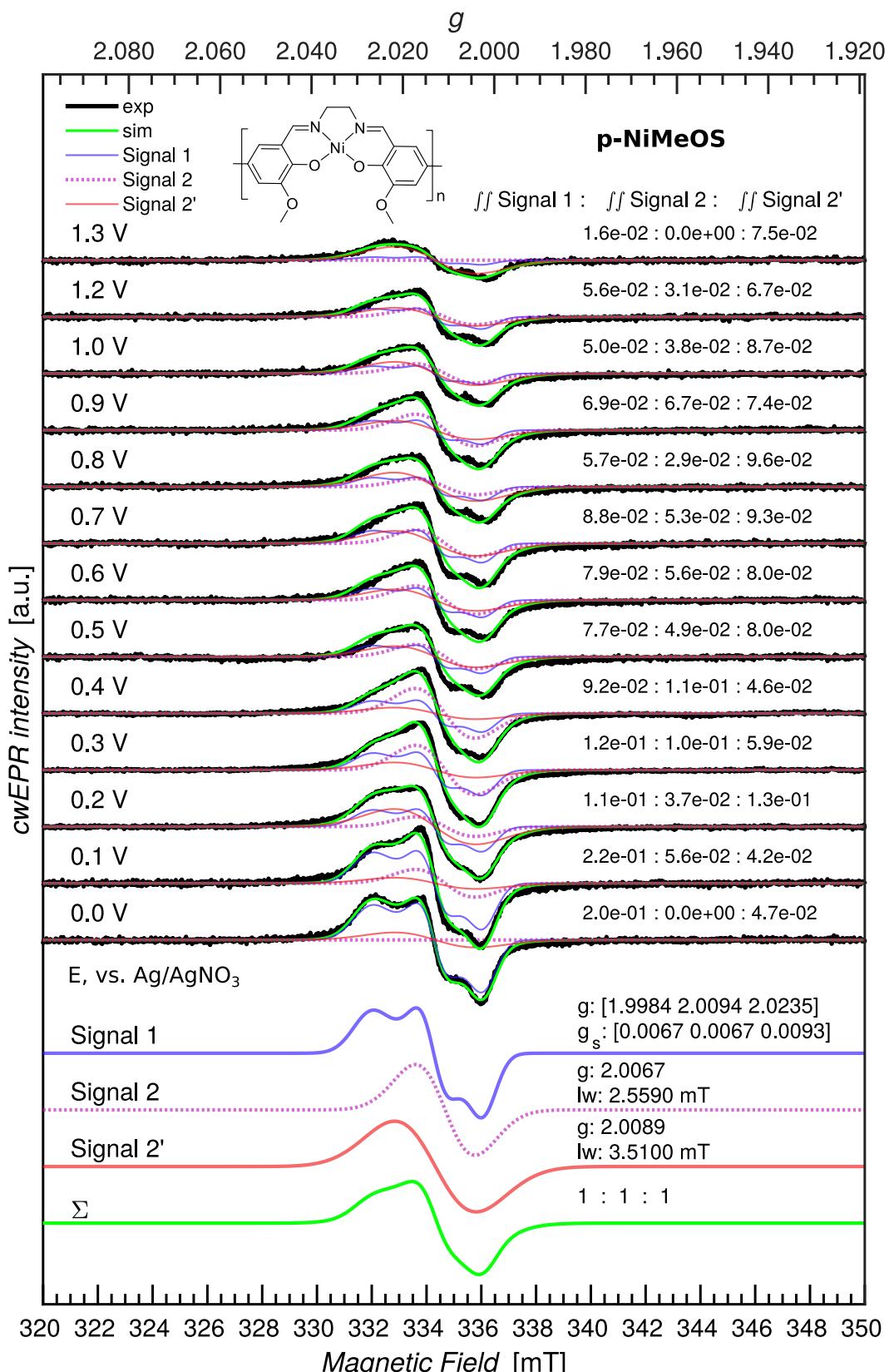


Figure 4.9: Potential-dependent cwEPR spectra of a NiMeOSalen film measured at 150 K. Simulation of the spectra with three components reported by the Timonov group.

4.9 Pulsed EPR Spectroscopy of a charged pDiTBuS Cathode film

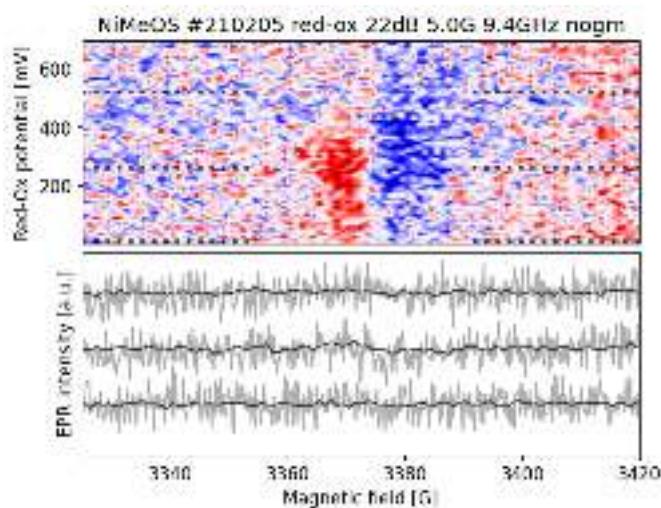


Figure 4.10: Potential-dependent operando cwEPR spectra of a NiMeOSalen cathode film measured at room temperature.

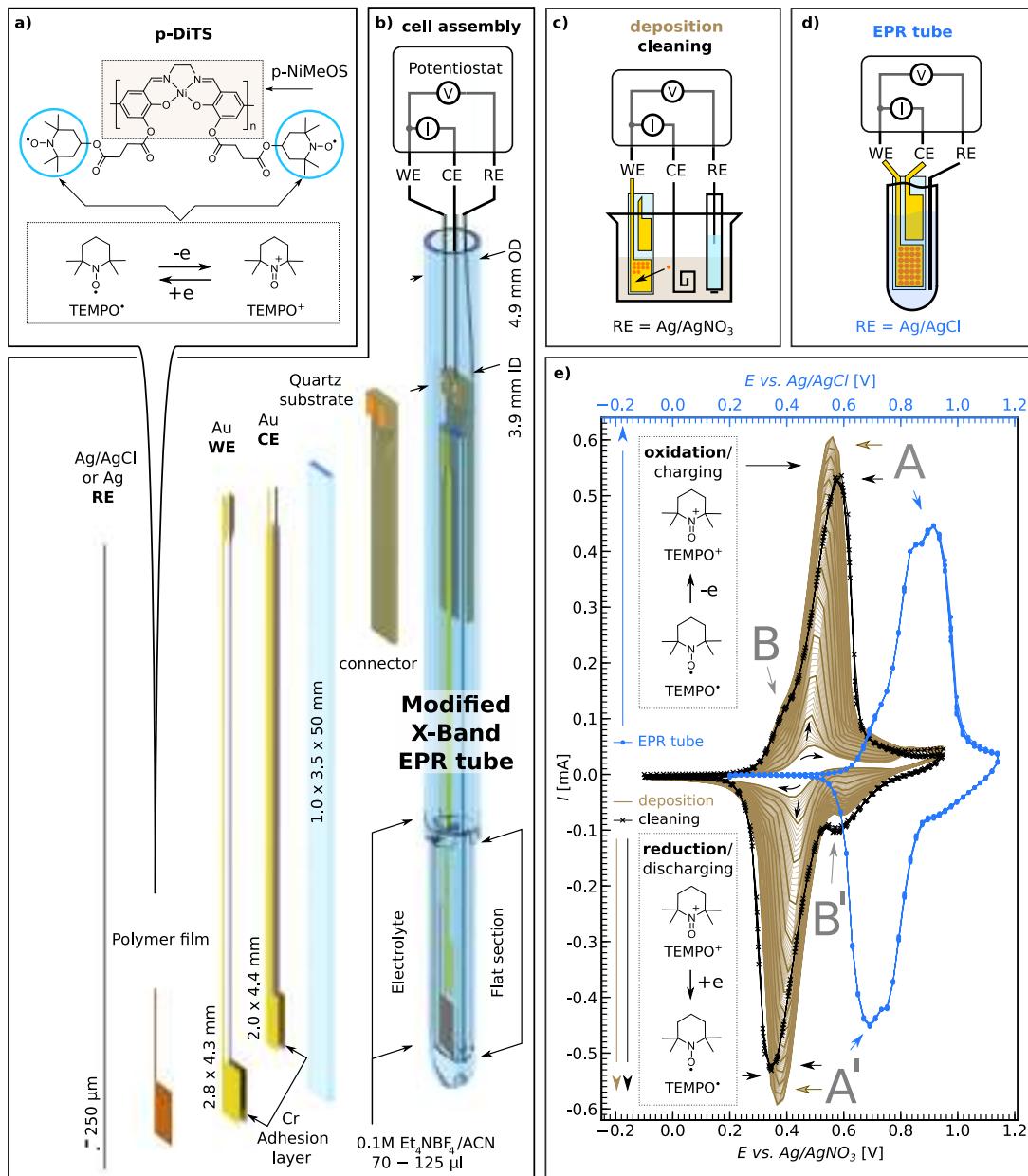


Figure 4.11: Schematic diagram of the electrode design and assembly of the electrochemical cell based on a modified X-band EPR quartz tube. a): Molecular structure of p-DiTS, with the redox reaction of its charge-bearing TEMPO groups; highlighted is the backbone, p-NiMeOSalen. b): Photograph of the modified tube with a flattened bottom section, with the on-substrate electrochemical setup assembled inside, and the process of forming the modified tube. c): Electrochemical setup for deposition and cleaning of polymer films. d): Tube-based electrochemical setup. e): Cyclic voltammograms of a growing p-DiTS film during 100 electropolymerization cycles (solid-brown), during the cleaning process (crossed-black) and in the tube-based setup (dotted-blue). Peaks A/A', B/B' correspond to the oxidation and reduction of the TEMPO fragments and of the p-NiSalen backbone, respectively. All CV were recorded at 50 mV s⁻¹.

4.9 Pulsed EPR Spectroscopy of a charged pDiTBuS Cathode film

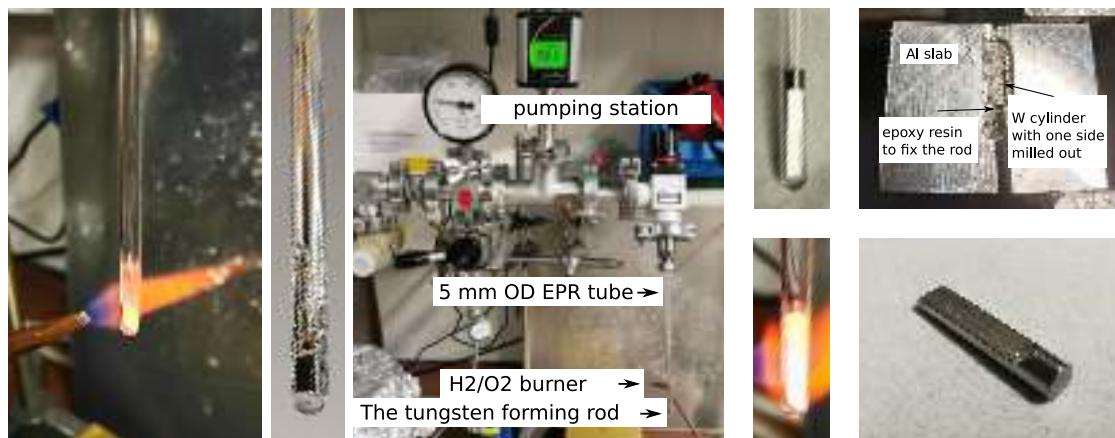


Figure 4.12: Modifying the tip of the standard 5 mm OD quartz EPR sample tube by melting it around a Tungsten (W) forming rod with a H₂/O₂ burner in an evacuation setup.

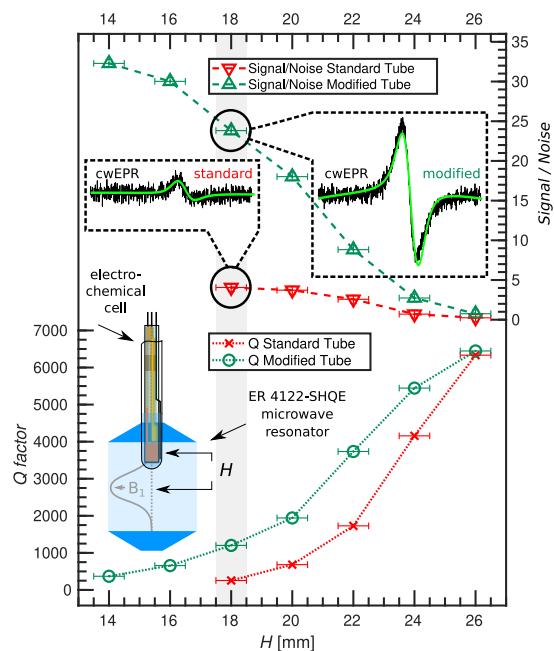


Figure 4.13: Signal-to-noise ratio of the cwEPR spectrum of p-DiTS and the Q-factor of the Bruker ER4122-SHQE microwave resonator measured for an electrochemical cell based on a standard X-band EPR sample tube and for an electrochemical cell based on the modified tube. Data for various heights H from the center of the resonator. Insets: Representative cwEPR spectra at $H = 18$ mm, where the signal for the standard tube is the strongest.

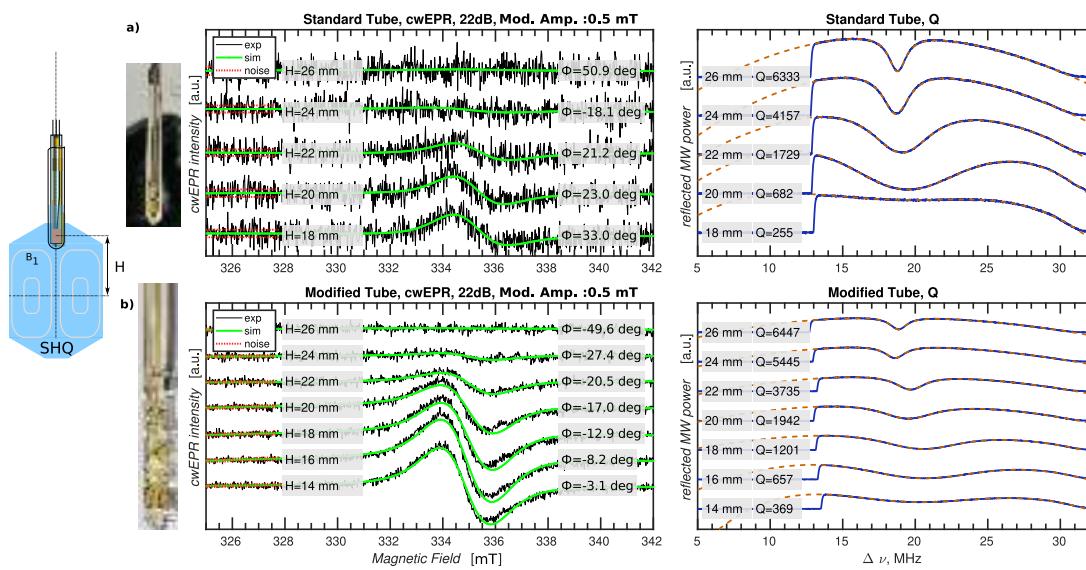


Figure 4.14: cwEPR signal intensity and Q factors for the standard 5 mm OD quartz EPR sample tube and for the modified tube at different heights from the center of the Bruker ER 4122-SHQE resonator. $\nu = 9.4$ GHz. Simulations of the cwEPR spectra with adjusted microwave phase. Noise analysis.

4.9 Pulsed EPR Spectroscopy of a charged pDiTBuS Cathode film

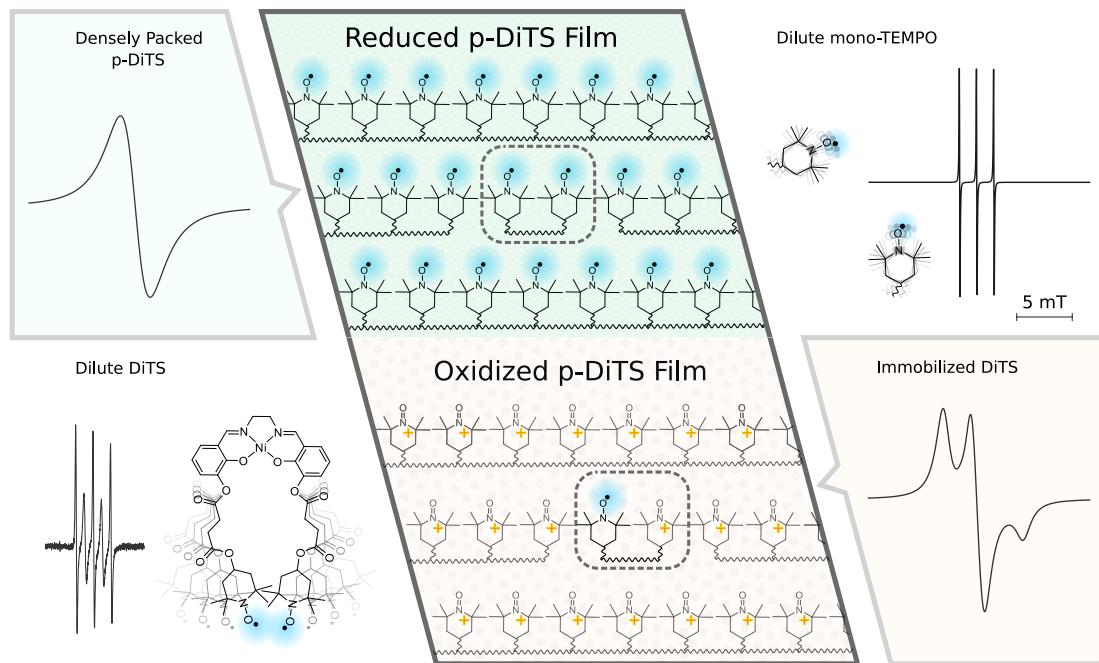


Figure 4.15: Classification of the nitroxide cwEPR spectra observed for p-DiTS under different conditions and in different environments. a): Densely packed nitroxide film with dipolar broadening and exchange narrowing or broadening giving a single derivative line. b): Typical spectrum of dilute mono-nitroxide in solution, three-lines due to $S = 1/2$, $I = 1$ ^{14}N hyperfine interaction (described by isotropic g -factor and isotropic hyperfine (A) interaction). c): Typical spectrum of tumbling di-nitroxide in solution where dynamic changes in the nitroxide – nitroxide distance modulate the exchange interaction yielding a five-line structure with alternating line width (measured cwEPR of DiTS monomers in solution at room temperature). d): Immobilized nitroxide spectrum with both g and A anisotropy.

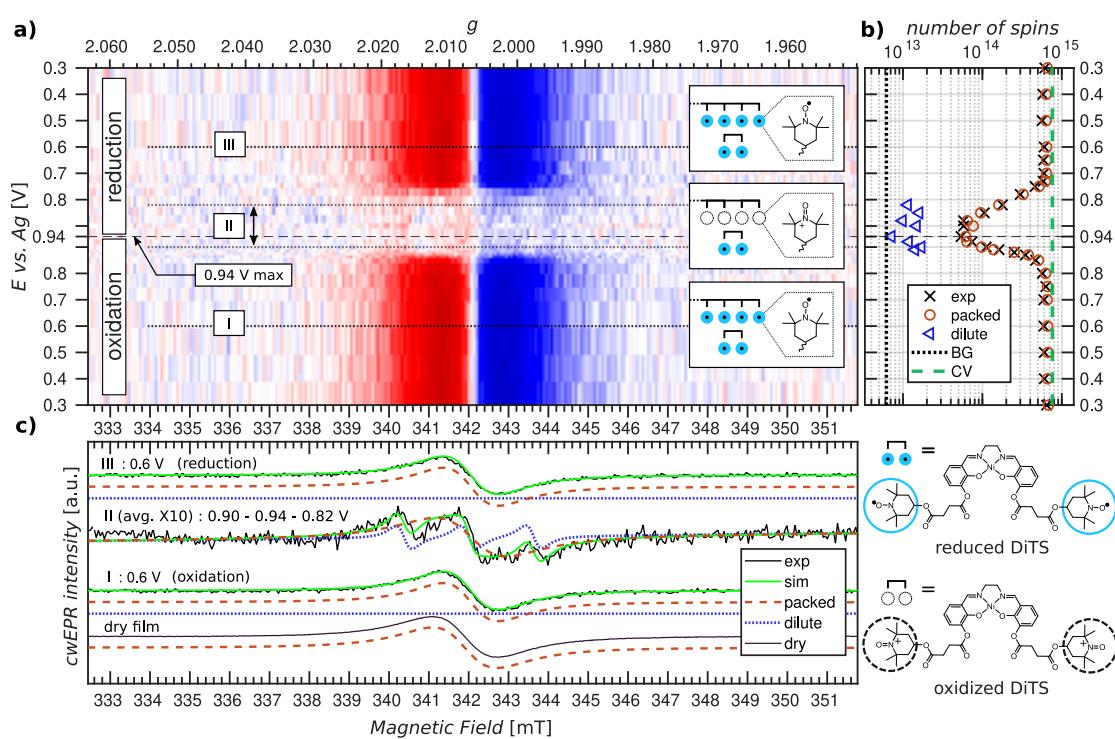


Figure 4.16: XXX

4.9 Pulsed EPR Spectroscopy of a charged pDiTBuS Cathode film

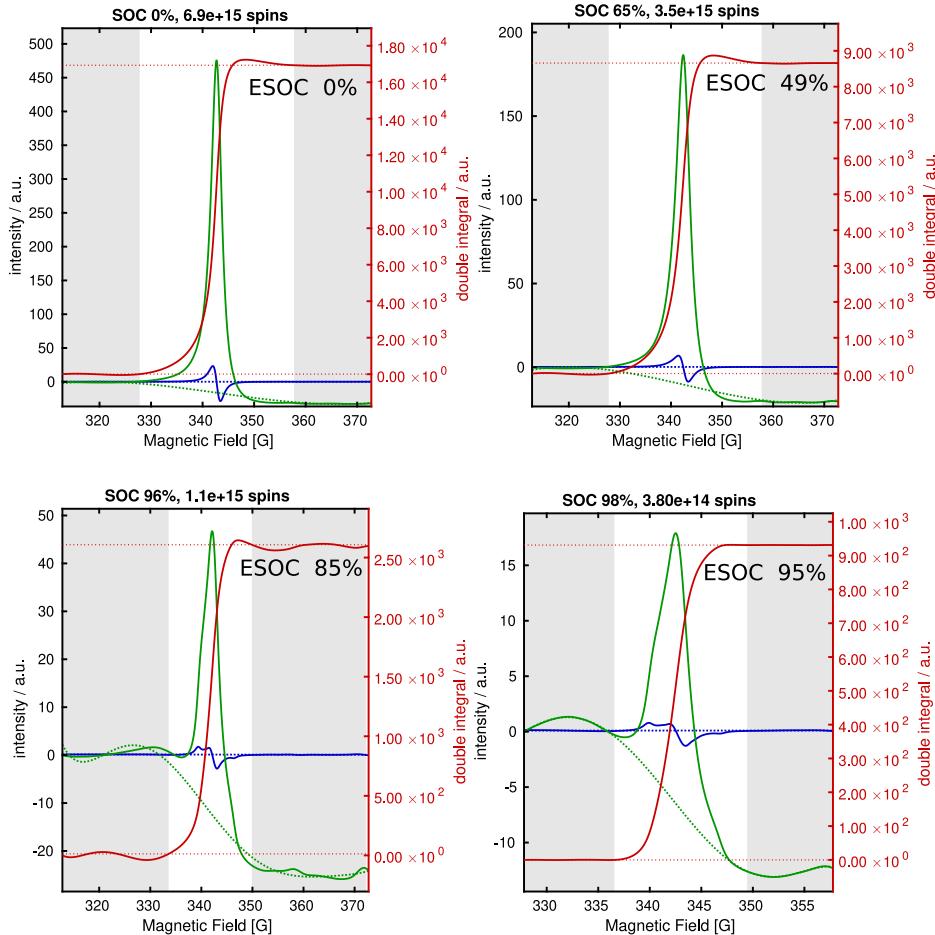


Figure 4.17: cwEPR spectra for a pDiTBuS film in four charge states. Single and double integrals of the signal. Spin count is proportional to the end value of the double integral. Temperature: 80 K, $\nu \approx 9.6$ GHz, field modulation: 5 G at 100 kHz. ER 4118 X-MD5 dielectric ring resonator.

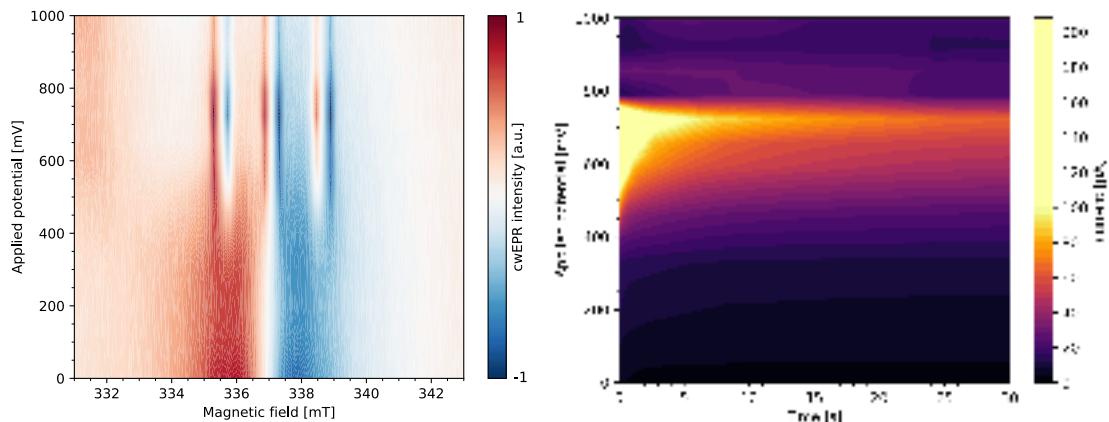


Figure 4.18: Operando cwEPR spectra of a pDiTS electrochemical cell showing irreversible release of charge-bearing fragments and decomposition of the device upon potentiostatic charging with currents up to $I < 0.2 \text{ mA} \approx 125 \text{ C}$.

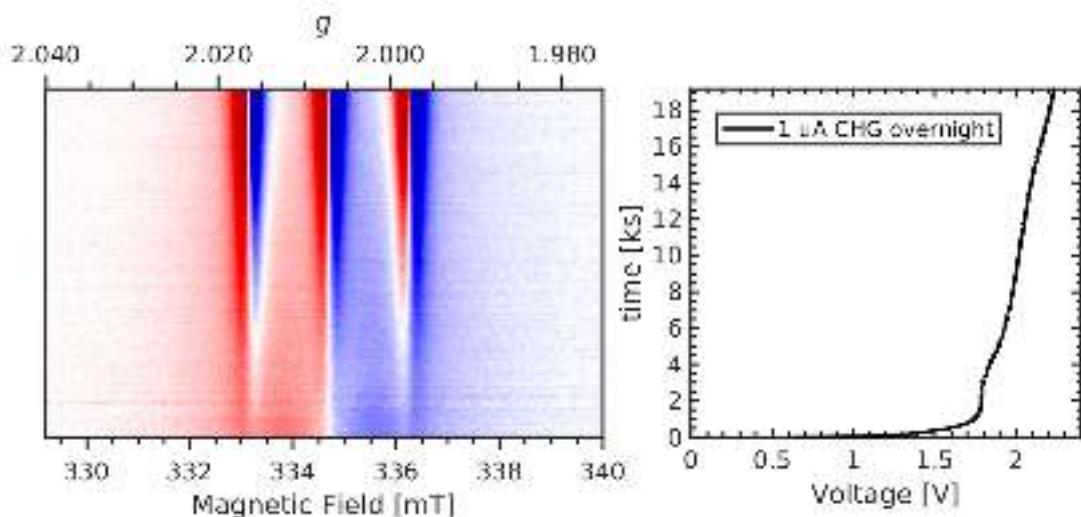


Figure 4.19: Operando cwEPR spectra of a pDiTS electrochemical cell showing irreversible release of charge-bearing fragments upon moderate charging currents.

4.9 Pulsed EPR Spectroscopy of a charged pDiTBuS Cathode film

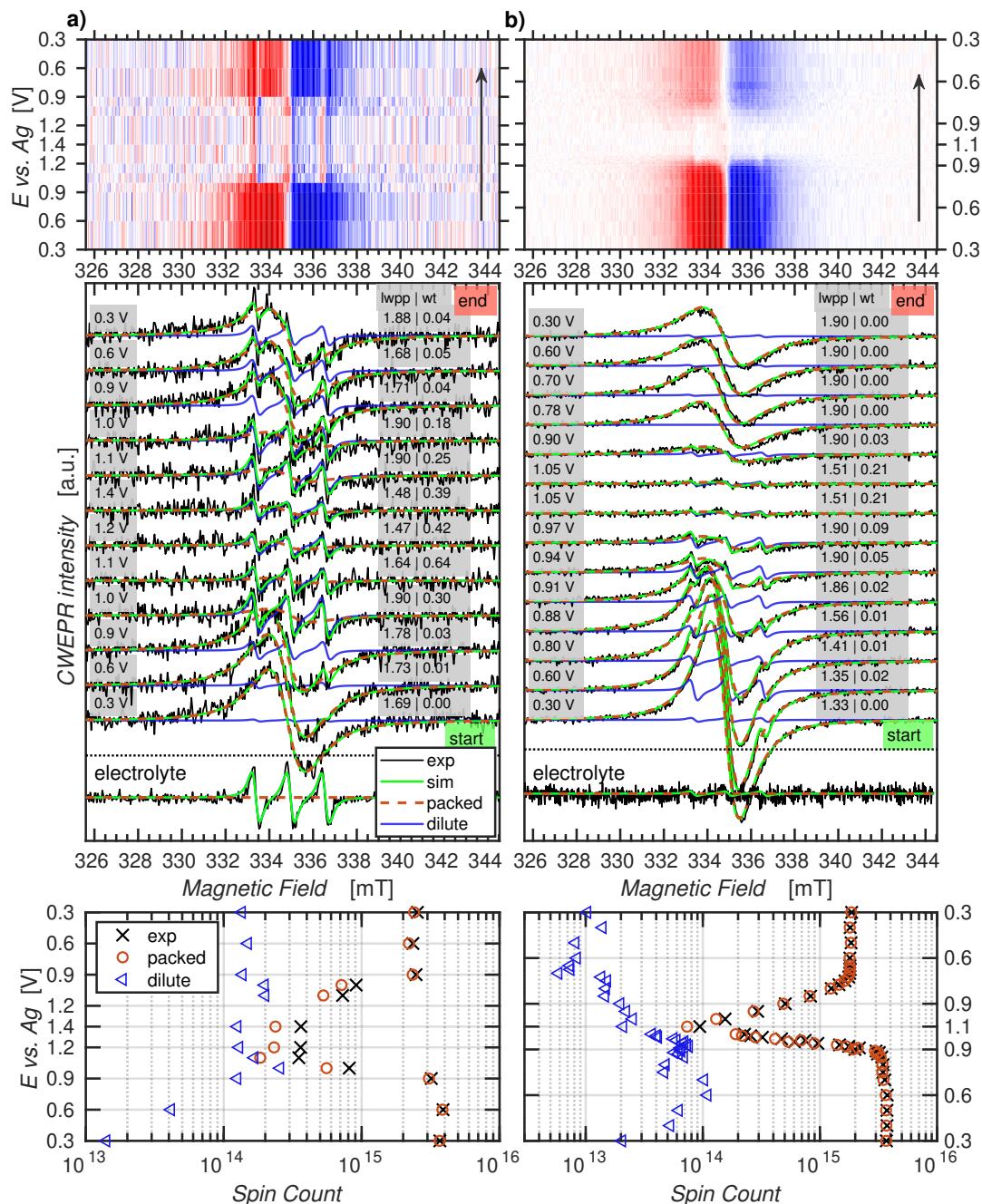


Figure 4.20: Operando cwEPR spectra of two pDiTS electrochemical cells showing release of charge-bearing fragments upon the charge-discharge cycle.

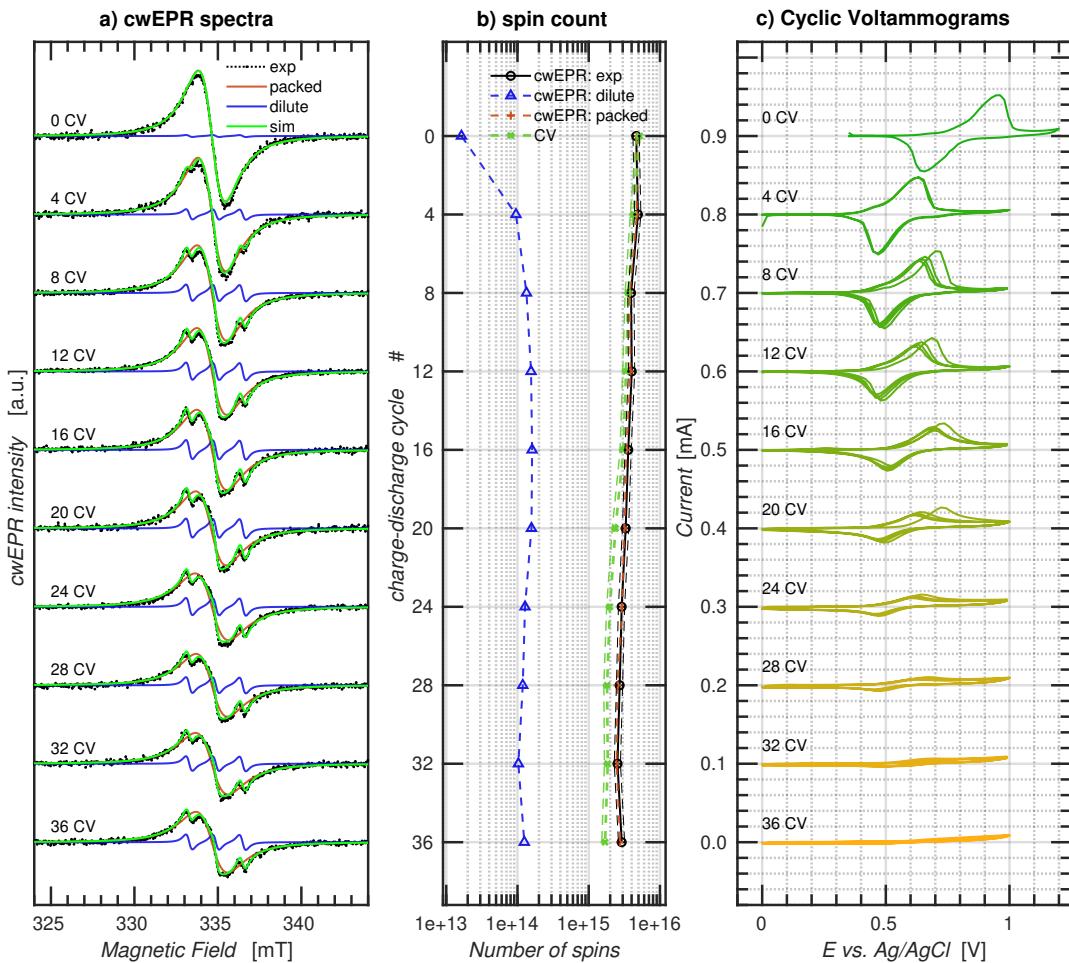


Figure 4.21: a): Evolution and component decomposition of cwEPR spectra for a tube-based, 150 CV p-DiTS ORB upon 36 charge-discharge cycles. b): Quantitative analysis of the separated spectral components. $\nu = 9.4$ GHz, Mod. Amp: 0.5 mT. Quantitative analysis of the CV curves. c): Cyclic voltammograms of the cell, recorded with respect to Ag/AgCl RE at a rate of 5 mV s^{-1} in between the EPR scans, in the modified tube inside the microwave resonator. The CV were taken at 5 mV s^{-1} , which is 10 times slower than the CV curves taken in the larger beaker, because limited amount of the electrolyte in the modified tube was found to strongly affect the shape and positions of the CV peaks at higher speeds of cycling.

4.9 Pulsed EPR Spectroscopy of a charged pDiTBuS Cathode film

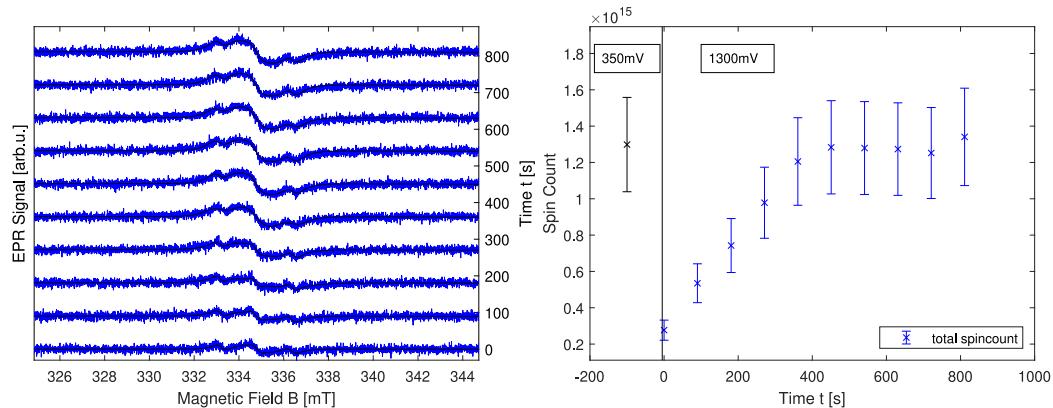


Figure 4.22: cwEPR monitored self-discharge of a tube-based cell containing a pDiTS film made with 50 deposition cycles. Left: Development of the EPR spectra of the oxidised sample over time from bottom to top; Right: Development of the spincount of the oxidised sample over time and comparison to the reduced state. [105]

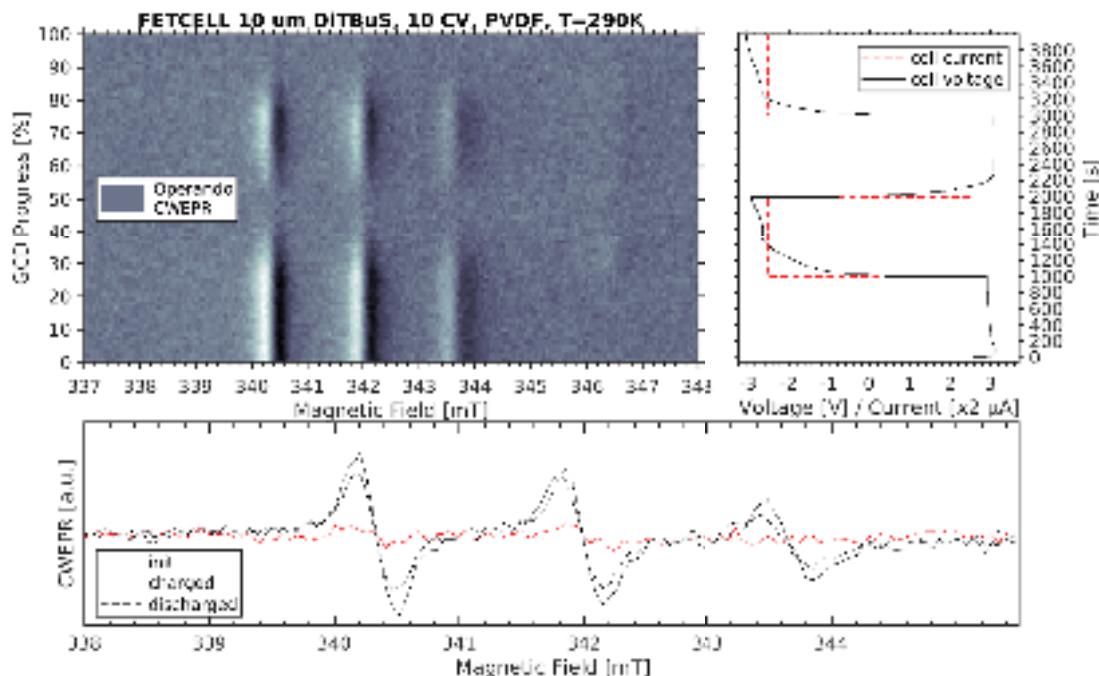


Figure 4.23: Operando cwEPR on an all-polymer organic radical battery made on a 5 μm grid with a PVDF/TFSI gel electrolyte.

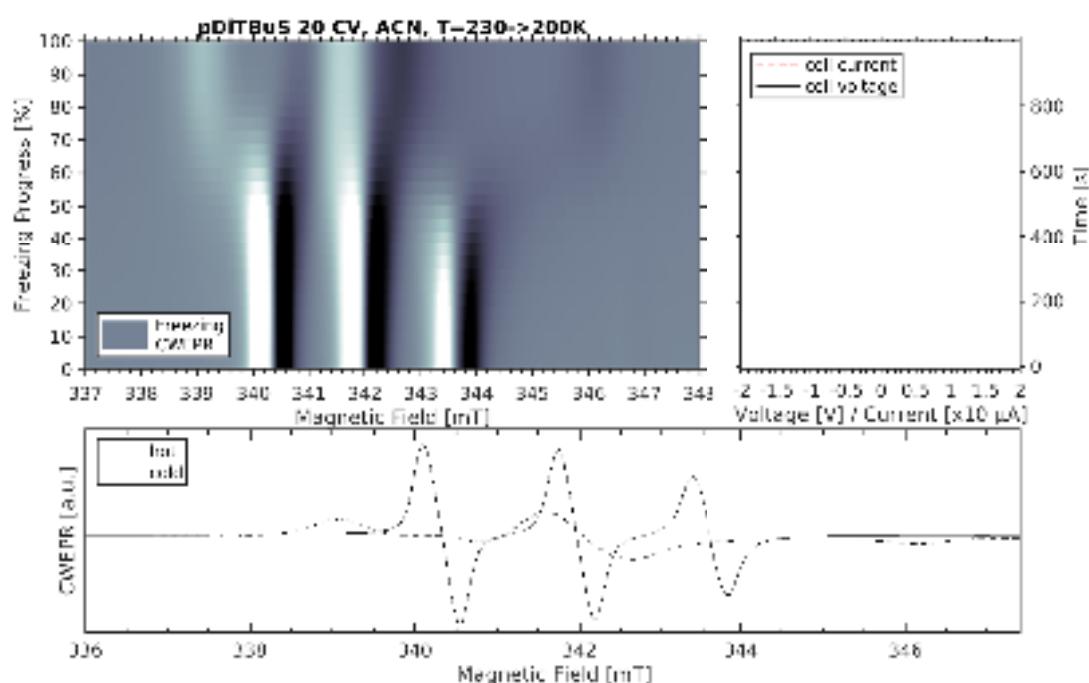


Figure 4.24: Freezing a pDiTBuS cell

4.9 Pulsed EPR Spectroscopy of a charged pDiTBuS Cathode film

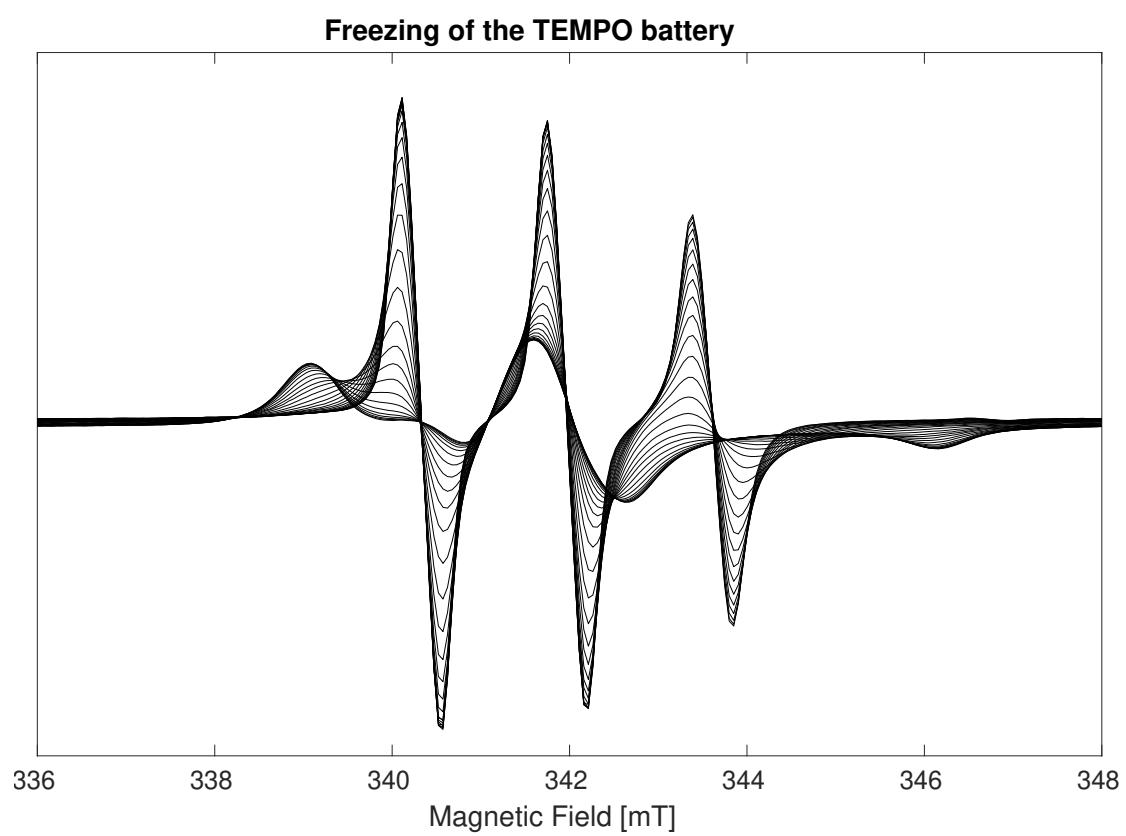


Figure 4.25: Freezing a pDiTBuS cell

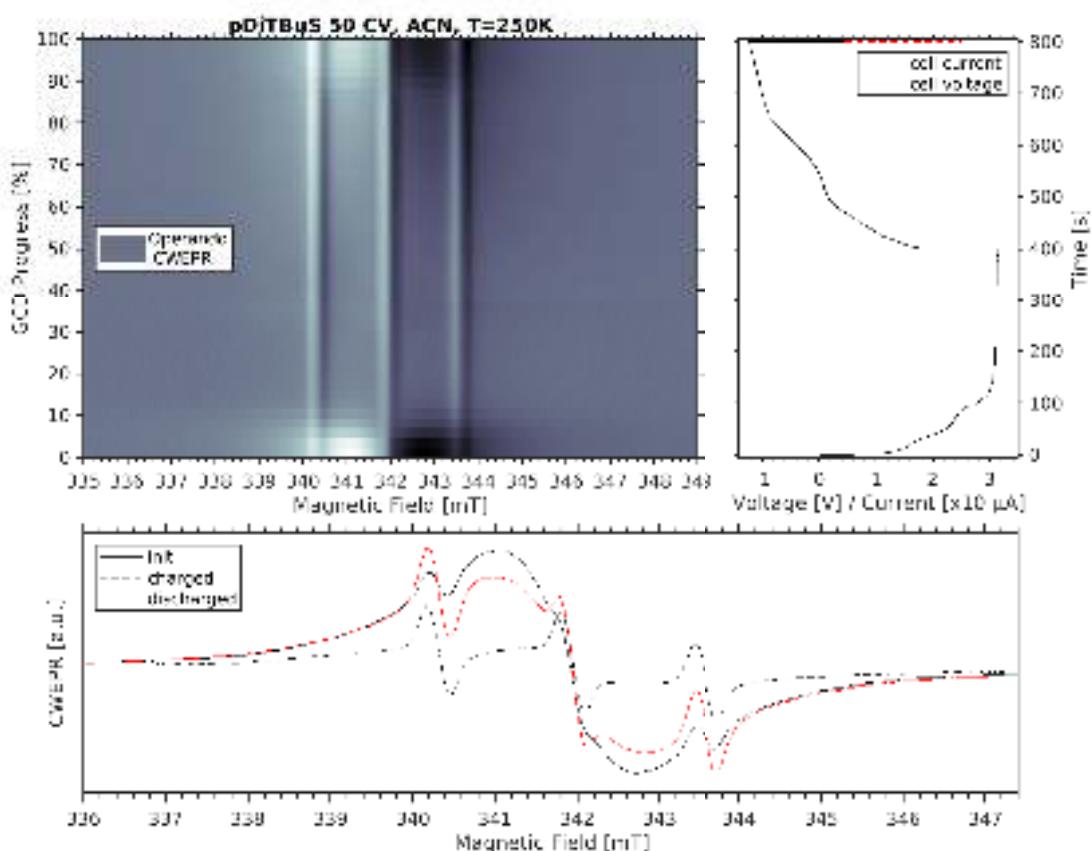


Figure 4.26: XXX

4.9 Pulsed EPR Spectroscopy of a charged pDiTBuS Cathode film

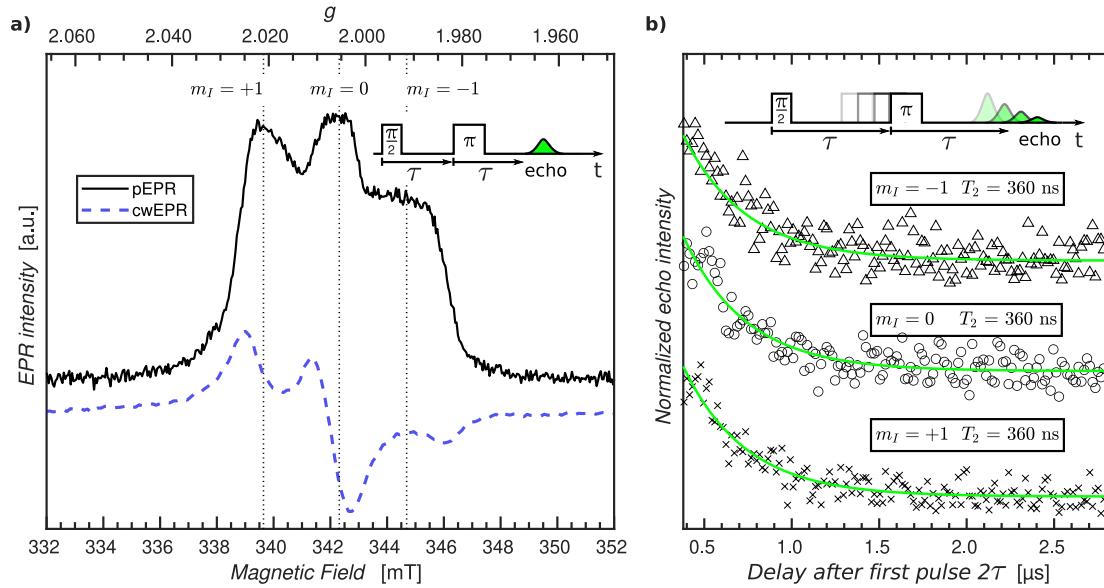


Figure 4.27: X

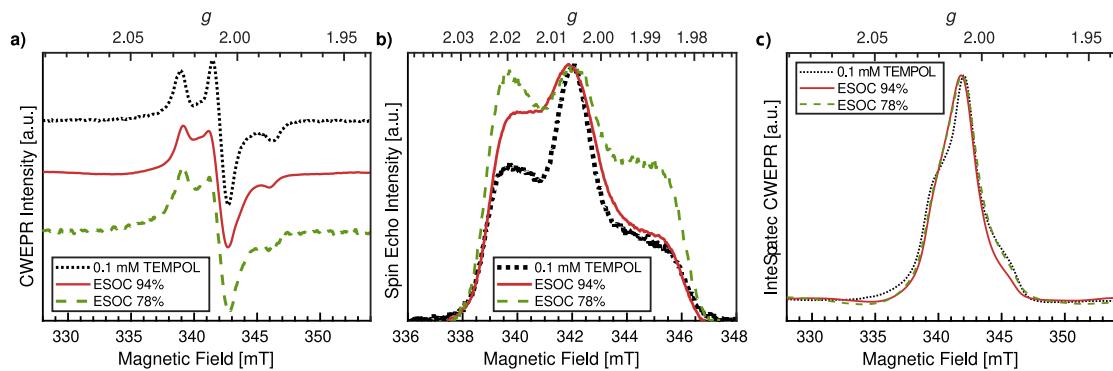


Figure 4.28: a): cwEPR spectra for pDiTBuS charged to 95% and 85%, and for a frozen 0.1 mM solution of TEMPOL. Normalized intensities. Temperature 80 K. b): Corresponding pEPR spectra measured at 5 K. Intensities scaled by the $m_I = 0$ central peak. c): Integrated cwEPR intensities show similar spectral shapes. Temperature: 80 K, microwave frequency: 9.6 GHz, field modulation: 5 G at 100 kHz. ER 4118 X-MD5 dielectric ring resonator.

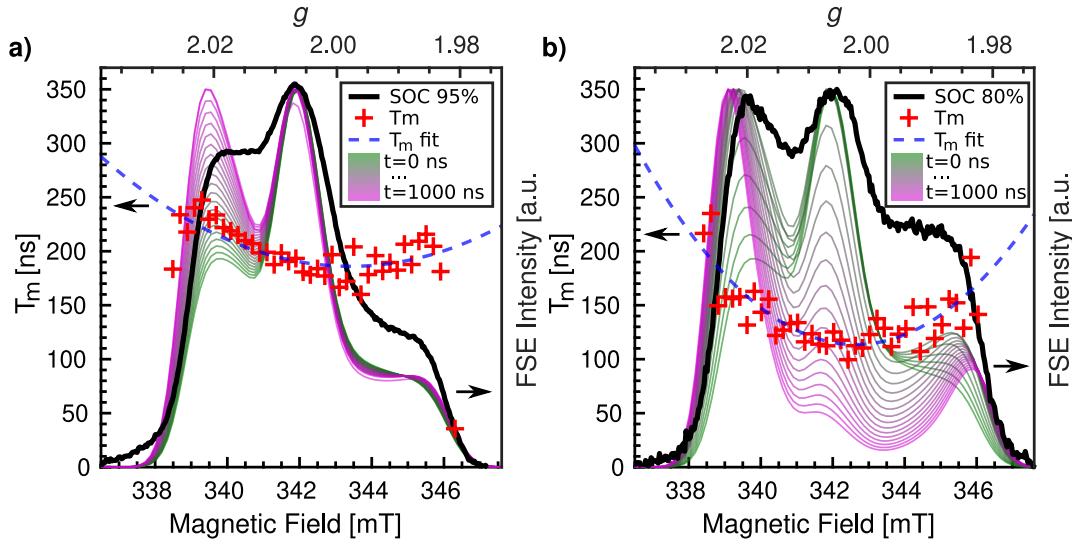


Figure 4.29: X

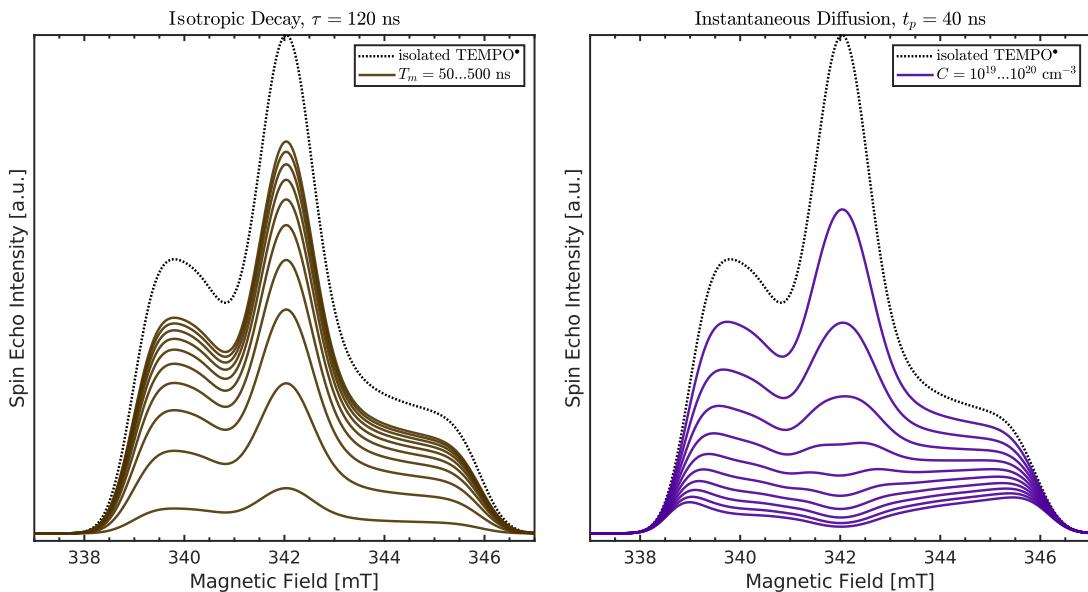


Figure 4.30: Distortions of a nitroxide FSE spectrum caused by isotropic spin relaxation (left) and instantaneous diffusion (right).

Chapter 5

Results and Discussion

5.1 Instantaneous Diffusion in pDiTS

High spin concentration in a pDiTBuS electrode suggests strong inter-spin dipolar couplings which cause instantaneous diffusion when probed with short (broad-band) microwave pulses [112], as it was observed in a PTMA/carbon mixture [16]. Instantaneous diffusion caused by a broad-band microwave pulse shown in Figure 5.1, dashed-red, manifests itself in an additional field-dependent spin relaxation factor $V(B_0)$, that alters the relative peak intensities in the echo-detected spectrum. For spins uniformly distributed in space, $V(B_0)$ is described [112] by Equation 5.1:

$$V(B_0, 2\tau, C) = V_0(2\tau) \exp\left(-2\tau \frac{4\pi^2}{9\sqrt{3}} \gamma^2 \hbar C \langle \sin^2(\theta/2) \rangle\right) \quad (5.1)$$

with

$$\langle \sin^2(\theta/2) \rangle = \frac{\int \frac{B_1^2}{(B-B_0)^2+B_1^2} \sin^2\left(\frac{\gamma t_p}{2} \sqrt{(B-B_0)^2 + B_1^2}\right) g(B) dB}{\int g(B) dB} \quad (5.2)$$

where B_0 is the static magnetic field, C is the concentration of spins, τ is the time between the first and second pulses in the microwave pulse sequence, γ is the gyromagnetic ratio of the electrons at resonance, t_p is the duration of the second microwave pulse, B_1 is the amplitude of the second microwave pulse, $g(B)$ is the EDFS spectrum at $\tau = 0$ that is not affected by the instantaneous diffusion. As the resulting spectral shape depends on the spin concentration, comparing spectra simulated according to Equation 5.1

and measured spectra thus allows us to provide information about the local spin concentrations. Since the spin echo of the most densely packed and thus quickly relaxing spins is not detectable with the given t_d , the regions of the highest spin concentration do not contribute to the EDFS spectrum. Thus, C is lower than the true concentration of spins in the densely packed domains and can also be lower than the average spin concentration $\langle n \rangle$ measured with cwEPR that is most sensitive to the quickly relaxing spins.

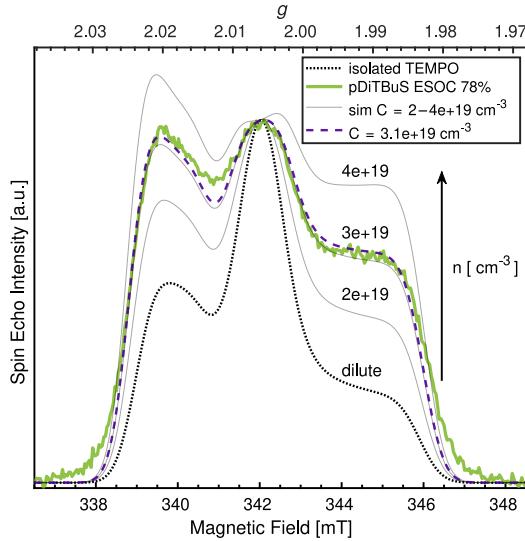


Figure 5.1: EDFS spectrum of p-DiTBuS at ESOC 85% (solid-green) affected by instantaneous diffusion with $t_p = 40$ ns. Simulation of the spectrum with spin concentration $C = 3.1 \times 10^{19} \text{ cm}^{-3} = 52 \text{ mM}$ as a fit parameter (dashed-purple). Simulated spectrum of non-interacting TEMPO with $g=[2.0099, 2.0055, 2.0026]$, $A=[21.99, 21.43, 96.27]$ MHz and 0.812 mT (lwpp) Gaussian line shape as the starting values for the simulation (dashed-black). Excitation profile of the 40 ns pulse at $B_0 = 340$ mT is shown in dashed red.

We have used a 50 mM solution of TEMPOL as a model system to explore how the excitation bandwidth affects instantaneous diffusion for nitroxides (see Section 5.2.1, ESI). The EDFS spectrum recorded with $t_p = 40$ ns and $\tau = 120$ ns shows a distortion that corresponds to $C = 9 \text{ mM}$, while for $t_p = 1000$ ns no effect of instantaneous diffusion is observed. We simulated the undistorted EDFS spectrum of TEMPOL using the Easyspin toolbox [107] for Matlab and obtained the g matrix and the hyperfine coupling tensor A (for simulation details see Section ??, ESI). Then we simulated the EDFS spectrum for pDiTBU, ESOC 85%, using the obtained parameters and Equation 5.1 with $t_p = 40$ ns and the concentration C as a fit parameter. The result of the simulation with $C = 3.1 \times 10^{19} \text{ cm}^{-3} = 50 \text{ mM}$ is shown in Figure 5.1. At the same time, quantitative cwEPR yields a higher spin concentration for ESOC 85%: $\langle n \rangle = (8 \pm 4) \times 10^{19} \text{ cm}^{-3}$

5.2 Simulations of the EDFS Spectra Considering Instantaneous Diffusion

= 130±70 mM.

The ESOC 95% spectrum cannot be simulated with Equation 5.1 because of the increased intensity of the low-field peak. The ratio of the two remaining peaks at ESOC 95% corresponds to $C = 1.2 \times 10^{19} \text{ cm}^{-3} = 20 \text{ mM}$ (see ESI, Section 5.2.4), while cwEPR again yields a higher $\langle n \rangle = 3 \pm 2 \times 10^{19} \text{ cm}^{-3} = 50 \pm 30 \text{ mM}$.

5.2 Simulations of the EDFS Spectra Considering Instantaneous Diffusion

We used Equation 5.1 from the main text with varying C to fit the EDFS spectra affected by ID.

5.2.1 EDFS in 50 mM TEMPOL Measured with Narrow-Band Pulses

The EDFS spectrum of a 50 mM frozen solution of TEMPOL measured with long (selective, narrow band) microwave pulses shows no asymmetry with $t_P = 1000 \text{ ns}$ and $\tau = 1000 \text{ ns}$. The spectrum was deconvoluted into the broad ('packed') and the narrow ('dilute') components. The narrow component is an Easyspin simulation with the typical g and A tensors for a nitroxide radical (see Figure caption for parameters). The broad spectral component might correspond to densely packed agglomerates in the not perfect glass. The fit is shown in Figure 5.2 a.

5.2.2 EDFS in 50 mM TEMPOL Measured with Broad-Band Pulses

The EDFS spectrum of a 50 mM solution of TEMPOL in Figure 5.2 b shows asymmetry when measured with shorter, $t_P = 40$ and $\tau = 120 \text{ ns}$ pulses with a microwave power attenuation 11 dB. The spectrum has a stronger contribution of the broad component which in this case was calculated as the weighted integral of the cwEPR spectrum. The asymmetric dilute component was simulated considering the anisotropic relaxation of the 'standard' TEMPOL spectrum which was caused by instantaneous diffusion using Equation 5.1 in the main text. The fit of the EDFS spectrum of 50 mM TEMPOL was done with a concentration $C = 5.6 \times 10^{18} \text{ cm}^{-3}$ or 9.3 mM as a fit parameter, $t_P = 40 \text{ ns}$, $\tau = 120 \text{ ns}$ and $\gamma = -1.76 \times 10^{11} \text{ rad/T}$ (for $g = g_e$). The spin concentration determined from the instantaneous diffusion simulation is only 19% of the molecular concentration that was used to prepare the TEMPOL solution. The presence of the broad component in the EDFS spectrum suggests that the concentration of TEMPOL was not homogeneous within the sample.

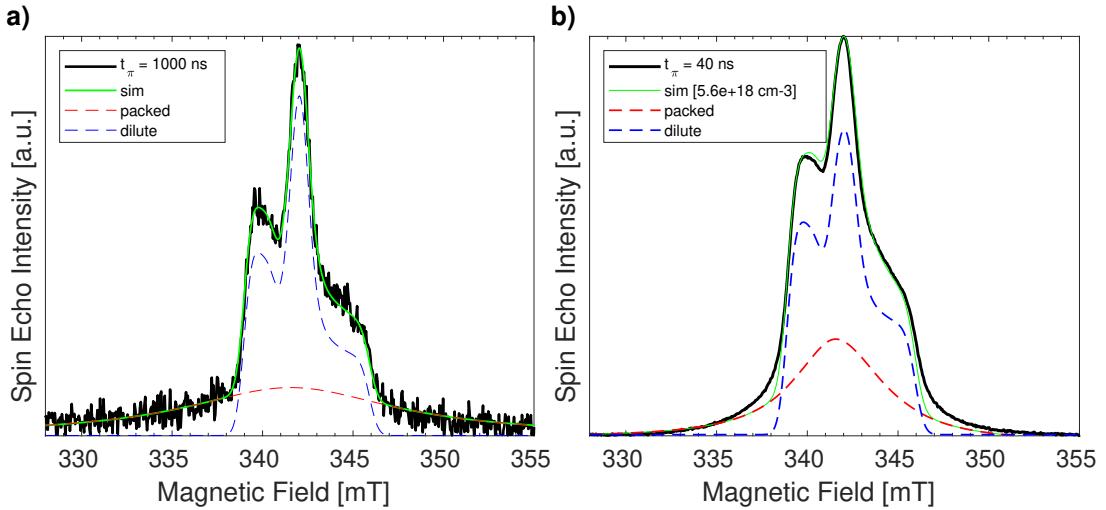


Figure 5.2: a): EDFS of 50 mM TEMPOL in Acetonitrile/Dichloromethane glass measured with long (selective, narrow-band) microwave pulses. $t_P = 1000$ ns, $\tau = 1000$ ns, microwave frequency: 9.6 GHz, microwave power attenuation: 36 dB. Temperature: 5 K. 2-component spectral simulation. Dilute component: $\mathbf{g}=[2.0099 \ 2.0055 \ 2.0026]$ and $\mathbf{A}=[21.9850 \ 21.4260 \ 96.2707]$ MHz. Broad component: $\mathbf{g}=2.0082$, $lwpp=8.08$ mT (Lorentzian). No effect of instantaneous diffusion is detectable with the long pulses. b): Same, measured with short (non-selective, broad-band) microwave pulses. $t_P = 40$ ns, $\tau = 120$ ns, microwave frequency: 9.6 GHz, microwave power attenuation: 11 dB. Temperature: 5 K. 2-component spectral simulation. Dilute component: same as in (a), but affected by the instantaneous diffusion with $C = 5.6 \times 10^{18} \text{ cm}^{-3}$. Broad component: integrated cwEPR spectrum.

5.2.3 EDFS in PDiTBuS at ESOC 85% Affected by Instantaneous Diffusion

The quick echo decay in pDiTBuS necessitates the usage of short microwave pulses that lead to ID. The asymmetric EDFS spectrum of pDiTBuS at 85% ESOC was simulated considering the distortion of the standard TEMPO spectrum caused by the ID. The anisotropic relaxation of the spectral components is given by the equation 5.1 in the main text. The fit of the EDFS spectrum of pDiTBuS at 85% ESOC was done with a concentration $C=3.1 \times 10^{19} \text{ cm}^{-3} = 50 \text{ mM}$ as a fit parameter, $t_P = 40$ ns, $\tau = 120$ ns and $\gamma = -1.76 \times 10^{11} \text{ rad/T}$. The fit was done with $\mathbf{g}=[2.00987, 2.0055, 2.0026]$, $\mathbf{A}=[22.0 \ 21.5 \ 96.3]$ MHz, 0.81 mT ($lwpp$) Gaussian line shape, Figure 5.3.

5.2 Simulations of the EDFS Spectra Considering Instantaneous Diffusion

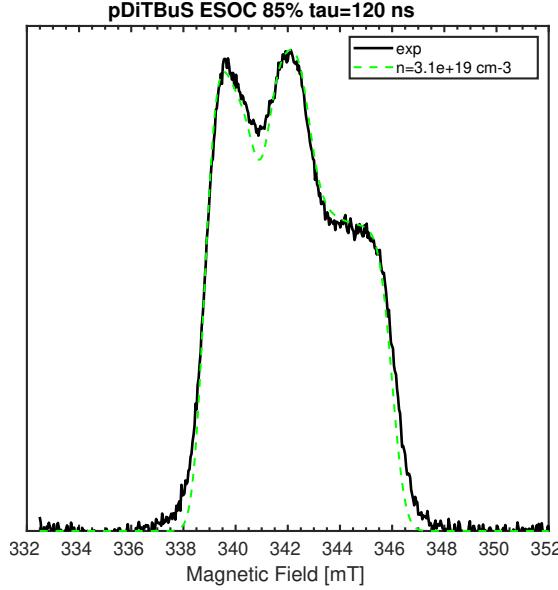


Figure 5.3: EDFS spectrum of pDiTBuS at 85% ESOC (solid-black). Spectral simulation with $\mathbf{g}=[2.00987, 2.0055, 2.0026], \mathbf{A}=[22.0 \ 21.5 \ 96.3]$, 0.81 mT (lwpp) Gaussian line shape and anisotropic relaxation caused by instantaneous diffusion (dashed-green). Relative peak intensities correspond to $C=3.1e19 \text{ cm}^{-3}$ or 52 mM. Microwave frequency: 9.6 GHz, $\pi/2 = 20$ ns, $\tau=120$ ns. Temperature: 5 K.

5.2.4 EDFS in PDiTBuS at ESOC 95% Affected by Instantaneous Diffusion

The asymmetric EDFS spectrum of pDiTBuS at 95% ESOC could not be simulated considering the distortion of the standard TEMPO spectrum caused by the ID given by Eq. 5.1 in the main text. The spectrum and the attempted fit are shown in Figure 5.4. The low-field peak has a much higher relative intensitiy than expected from the ID model. The observed spectrum may be a superposition of a dilute species that do not experience instantaneous diffusion and the densely packed species that is affected by ID.

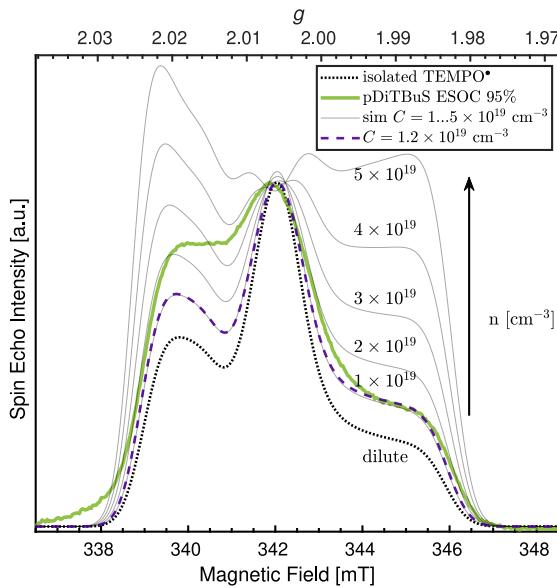


Figure 5.4: EDFS spectrum of pDiTBuS at ESOC 95% (solid-green). Spectral simulation with $\mathbf{g}=[2.0099, 2.0055, 2.0026]$, $\mathbf{A}=[21.9850 \ 21.4260 \ 96.2707]$ MHz, 0.24 mT (lwpp) Lorentzian line shape and anisotropic relaxation caused by instantaneous diffusion (dashed-blue). Relative peak intensities correspond to $C= 1.2 \times 10^{19} \text{ cm}^{-3}$ or 22 mM. Microwave frequency: 9.6 GHz, $\pi/2 = 20$ ns, $\tau=120$ ns. Temperature: 5 K.

5.2.5 Estimation of Local Spin Concentrations with Instantaneous Diffusion

5.3 Spin Relaxation in a charged pDiTBuS Cathode Film

As we have shown in Section 4.9.2, the reason for the distorted spectral shape in pDiTBuS at ESOC 85% is instantaneous diffusion that manifests itself in anisotropic spin relaxation which alters the relative peak intensities. However, the spectrum for ESOC 95% cannot be simulated assuming just instantaneous diffusion (cf. Figure 5.4, ESI). In order to gain additional information about the processes that may influence the shape of the EDFS spectra, we performed field-dependent measurements of the spin relaxation times.

Figure 5.5a shows the EDFS spectra of pDiTBuS for 85% and 95% ESOC as well as a reference sample (50 mM solution of TEMPOL in Dichloromethane:Acetonitrile (3:1) glass) measured at $T = 5$ K. The spectra reveal markedly different intensities of the three hyperfine components.

The changed relative peak intensities in pDiTBuS may be the result of a magnetic field-dependent spin relaxation mechanism that manifests itself in a field-dependent

5.3 Spin Relaxation in a charged pDiTBuS Cathode Film

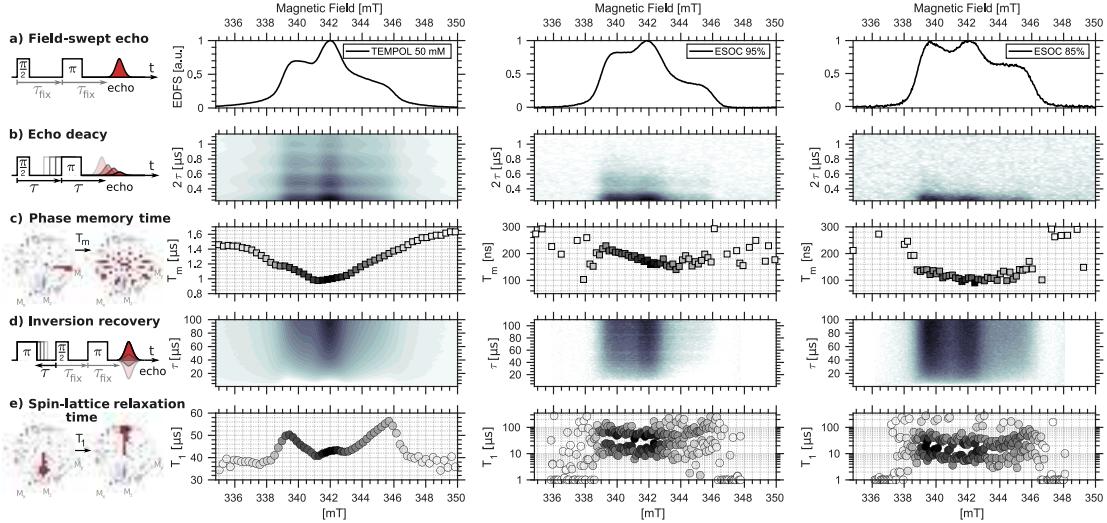


Figure 5.5: Field-swept echo (a), echo decay transients (b), phase memory times T_m (c), inversion recovery (d) and spin-lattice relaxation times T_1 (e) measured in 50 mM frozen electrolyte solution of TEMPOL (left) and in dry pDiTBuS film charged to ESOC 95% (center) and to ESOC 85% (right). Temperature 5 K. Grayscale represents the intensity in b)–e).

phase memory time T_m [101]. The T_m for pDiTBuS and for TEMPOL was probed in a field-swept echo decay experiment. The echo decay transients for the three samples are shown in Figure 5.5b. A Hahn echo pulse sequence was used with a $\pi/2$ pulse length of 20 ns and variable pulse separation time $\tau \geq 120$ ns. Spin echo was detected at 2τ after the $\pi/2$ pulse. Periodic oscillations in the echo decay transients correspond to the ESEEM effect from protons [101] with $\Delta\omega_L \approx 15$ MHz, which are particularly pronounced for TEMPOL.

If the sample contains several different species (i.e. nitroxide radicals in different environments and/or different local concentration) with distinct spin-spin relaxation times, the echo decay transients may contain multiple decay components, so more than one T_m can correspond to each field point. This effect is not considered when simulating the effect of instantaneous diffusion using Equation 5.1. To determine the number of decay components in the echo decay transients, we studied the poles of the Padé approximation of the Taylor expansion of the Laplace transforms of the transients that is known as the Padé-Laplace method [40] (see ESI, Section 5.4.1 for details). This analysis revealed only monoexponential spin echo decays for both 95% ESOC and 85% ESOC. We therefore assumed a monoexponential spin echo decay for pDiTBuS, though some faster relaxing components with $T_m < t_d$ might have decayed by the earliest achievable τ , as shown in Section 5.3.2, ESI. The detected decay times $T_m(B_0)$, extracted from

fits of the background-corrected echo-decay curves, are shown in Figure 5.5c as filled squares with the grayscale representing the amplitude of the corresponding fit component. As expected, T_m is significantly larger for 95% than for 85% ESOC, consistent with the weaker spin-spin couplings in the fully charged film. Further, we note that the field-dependence of T_m is more pronounced for 95% ESOC, with $T_m \geq 200$ ns for the $m_I = +1$ hyperfine component. This anisotropy in T_m results in an increased intensity of the low-field peak, which is in line with the observation that we cannot describe the 95% ESOC spectrum assuming only instantaneous diffusion (see Section 4.9.2). The transient fits and the residuals are shown in Section 5.4.1, ESI.

We attempted to reproduce the pDiTBuS spectra from a standard nitroxide spectrum by considering anisotropic transient decay of the spectral intensity at $t = \tau = 120$ ns for each B_0 with the measured $T_m(B_0)$. However, this approach did not allow us to reconstruct the pDiTBuS spectra for neither 85%, nor 95% ESOC.

It was recently shown, that densely packed TEMPO radicals in a TEMPO-containing, non-conductive polymer PTMA, intermixed into an amorphous carbon mesh, show multiple spin-lattice relaxation times T_1 because of different types of contact between the TEMPO radicals and the conductive additive in the TEMPO/carbon composite [16]. In order to find out whether such behavior can also be observed for the porous pDiTBuS film, we measured spin-lattice relaxation times T_1 with an inversion-recovery pulse sequence ($\pi - \tau - \pi/2 - \tau_{fix} - \pi - \tau_{fix} - echo$) with variable τ (Figure 5.5d). The Padé-Laplace analysis yielded one decay component for TEMPOL and two decay components for pDiTBuS both at 85% ESOC and 95% ESOC (see ESI, Section 5.4.1 for details). The T_1 for charged pDiTBuS is on the same order as for TEMPOL and splits in two rather broad distributions with similar intensities (Figure 5.5e). Similar as in the case of T_m , also T_1 is larger for 95% than for 85% ESOC. Irrespective of the ESOC there is no significant field dependence of T_1 , in contrast to what is observed for the TEMPOL reference sample.

Daniel et al. [16] concluded that separate distributions of T_1 correspond to different binding between TEMPO and the carbon mesh, representing the quality of electrical contact between TEMPO and the conductive additive. With the observed distribution of T_1 and considering the two-component cwEPR spectral contributions for charged pDiTBuS (“broad” and “dilute” components, cf. Section ??, ESI), we suggest that two types of domains could exist in a partially charged pDiTBuS film as well. These two morphologies may correspond to “conductive” domains with shorter T_1 , where TEMPO[•] are close to the conductive pNiSalen backbone, and “non-conductive” domains with longer T_1 , where TEMPO[•] are separated from pNiSalen. We note, however, that based on the experimental data presented here, this interpretation is rather speculative. The

5.3 Spin Relaxation in a charged pDiTBuS Cathode Film

detected T_1 values for pDiTBuS may also correspond to one distribution, as the separation between the T_1 values is comparable to the widths of their distributions.

5.3.1 Temperature Dependence of Pulse Spectra of Charged pDiTBuS

Spin relaxation times usually depend on temperature[101]. We measured EDFS of charged pDiTBuS at 5 K and at 80 K to see how faster spin relaxation affects the spectral shape. Figure 5.6 shows EDFS spectra for pDiTBuS charged to ESOC 95% (a) and to ESOC 85% (b) at 80 K (solid) and at 5 K (dashed). At 80 K an overnight scan was required to obtain a satisfactory signal-to-noise ratio, whereas at 5 K the spectrum was recorded in a few minutes. The spectral intensities at different temperatures were scaled such that the high-field $m_l = -1$ peak has the same intensity. Figure 5.6 clearly shows that the relative intensities of the peaks change with temperature for both ESOC. At higher temperatures the EDFS spectrum of pDiTBuS has a peak ratio closer to that of dilute TEMPOL that corresponds to a lower spin concentration, according to Equation 5.1. The influence of the temperature increase on the spectral shape is stronger for the lower, 85% ESOC.

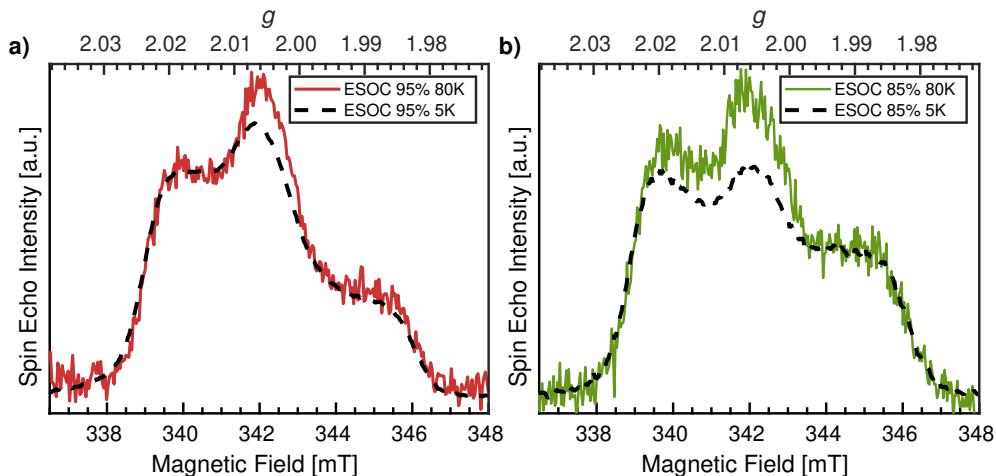


Figure 5.6: EDFS spectra for pDiTBuS charged to 95% ESOC (a) and to 85% ESOC (b) measured at 5K and at 80K.

The overall relaxation times in the film decrease with increasing temperature, but the dead time of the spectrometer ($t_d = 120$ ns) does not change. Therefore, at a given temperature, only spins with $T_m > t_d$ contribute to the signal. At higher temperature only the weakly coupled spins (with the longest T_m) are detectable, which results in a spectral shape that is less affected by instantaneous diffusion and thus closer to a dilute

nitroxide solution.

5.3.2 Limitation on Shortest Detectable T_m by the Spectrometer Dead Time

If a system exhibits multiple phase memory times T_m , the spin echo from the species with short memory times may decay below the noise level at a given pulse separation τ . Figure 5.7 illustrates the spin echo intensity in a two-component system with $T_m^1 = 100$ ns and $T_m^2 = 25$ ns in dependence on the pulse separation τ . The fast relaxing component with $T_m^2 = 25$ ns decays below the noise level after the dead time of $t_d = 100$ ns.

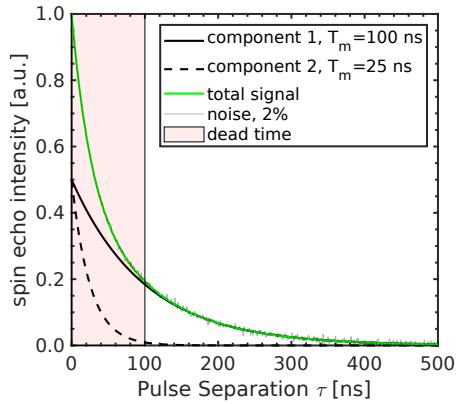


Figure 5.7: Simulated echo decay transient of a spin ensemble exhibiting two distinct phase memory times $T_m^1 = 100$ ns and $T_m^2 = 25$ ns. The 100 ns dead time, during which the spin echo detection is not possible, is marked in red. After the dead time, the sum of the two components is indistinguishable from the slowly relaxing component within the 2% noise.

5.4 Padé-Laplace Deconvolution of Polyexponential Decay Signals

The echo decay and inversion recovery transients measured in the corresponding experiments may contain multiple exponential decay components. The conventional method of determining the distribution of the decay components in a transient decay is the Laplace inversion, where the signal in the time domain $s(t)$ is converted into its Laplace image $L(p) = \int_0^{+\infty} s(t)e^{-pt}dt$ in the time-constant domain $p = 1/t$, where the peaks of

5.4 Padé-Laplace Deconvolution of Polyexponential Decay Signals

$L(p)$ give the decay constants that make up the signal. However, for the noisy signal, the direct calculation of the Laplace transform brings in artifacts that drastically vary with the noise. The signal-to-noise ratio (SNR) of the recorded data makes it difficult to apply the Laplace inversion to determine the number of the decay components, as the Laplace transform is unstable at that SNR.

The Padé-Laplace method comes useful for analyzing noisy polyexponential decays as it was demonstrated in Ref. [41]. The idea of the Padé-Laplace method is to analyze the Padé approximation of the Taylor expansion of the $L(p)$ in the vicinity of one of the expected decay constants p_0 , rather than considering the $L(p)$ fully. This way of signal decomposition is stable against the noise for SNR<10 (see Figure 5.8). The number of exponents detected by the Padé-Laplace method as well as their locations in the p space may vary depending on the expansion point p_0 . We considered $p_0 = 1/t_{1/2}$ where $t_{1/2}$ is the time at which the signal amplitude halves.

We implemented the following algorithm to detect the number of exponents in the decaying transient $s(t)$:

First, a point $p_0 = 1/t_{1/2}$ was chosen, at which $s(t)$ halves.

Then, 11 coefficients of the Taylor expansion of the Laplace transform $L(p)$ were calculated in the vicinity of $p \rightarrow p_0$

$$L(p)|_{p \rightarrow p_0} = \sum_{n=0}^{11} d_i(p - p_0)^i \quad (5.3)$$

with

$$d_i = \frac{1}{i!} \left(\frac{d^{(i)} L}{dp^{(i)}} \right)_{p=p_0} \quad (5.4)$$

where the derivatives $\frac{d^{(i)} L}{dp^{(i)}}$ are computed numerically at the point $p = p_0$ from the discrete signal $s(t) = (t_j, f_j)$, $j = 1 \dots M$:

$$\frac{d^{(i)} L}{dp^{(i)}} = \sum_{j=2}^{M-1} (-t_j)^i e^{(-p_0 t_j)} f_j + \frac{1}{2} \left((-t_1)^i e^{(-p_0 t_1)} f_1 + (-t_M)^i e^{(-p_0 t_M)} f_M \right) \quad (5.5)$$

Then the Taylor expansion for $L(p)$ was approximated in the vicinity of p_0 with the Padé polynomials $a(p)$ and $b(p)$ of orders $n = 5$ and $n = 6$ respectively:

$$L(p)|_{p \rightarrow p_0} = d_0 + d_1(p - p_0) + \cdots + d_{11}(p - p_0)^{11} = \frac{a_0 + a_1(p - p_0) + \cdots + a_5(p - p_0)^5}{1 + b_1(p - p_0) + \cdots + b_6(p - p_0)^6} \quad (5.6)$$

The equation 5.6 is multiplied by the denominator and the prefactors at $(p - p_0)^n$ for $n = 6 \dots 11$ are compared. This defines a system of linear equations on coefficients b_i :

$$\begin{pmatrix} d_5 & d_4 & d_3 & d_2 & d_1 & d_0 \\ d_6 & d_5 & d_4 & d_3 & d_2 & d_1 \\ d_7 & d_6 & d_5 & d_4 & d_3 & d_2 \\ d_8 & d_7 & d_6 & d_5 & d_4 & d_3 \\ d_9 & d_8 & d_7 & d_6 & d_5 & d_4 \\ d_{10} & d_9 & d_8 & d_7 & d_6 & d_5 \end{pmatrix} \begin{pmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \\ b_5 \\ b_6 \end{pmatrix} = \begin{pmatrix} -d_6 \\ -d_7 \\ -d_8 \\ -d_9 \\ -d_{10} \\ -d_{11} \end{pmatrix} \quad (5.7)$$

From 5.7, b_i are found. The coefficients a_i are found from d and b .

Finally, the Padé approximation $P = \frac{a}{b}$ is constructed and its poles are analyzed. The position of the poles reveal the decay constants. The residues at the poles may give the amplitudes of the decay components, but this was not used in the present study.

5.4 Padé-Laplace Deconvolution of Polyexponential Decay Signals

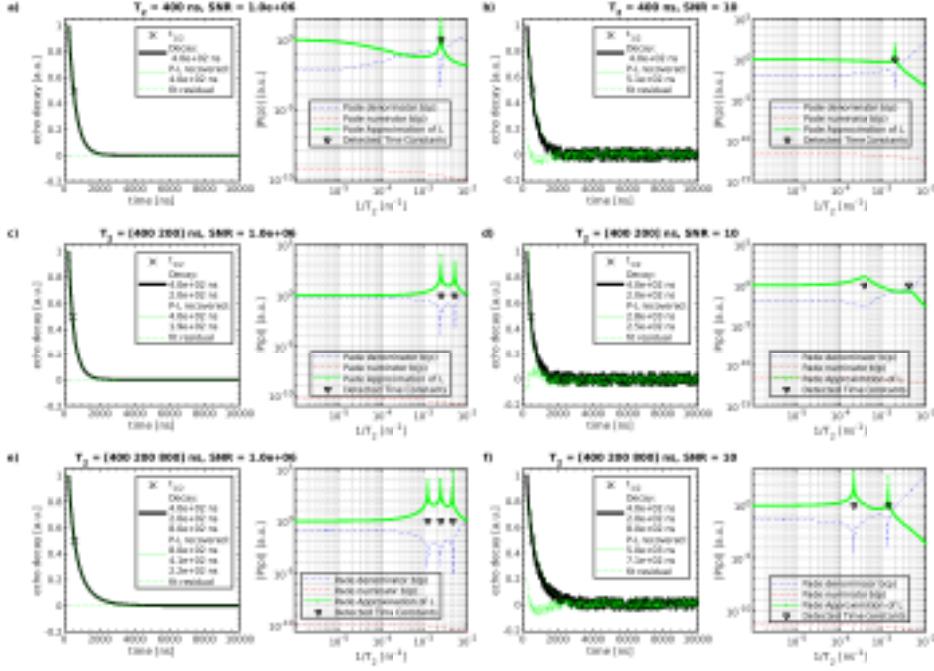


Figure 5.8: Padé-Laplace deconvolution of the mock data containing two decay constants with various signal-to-noise (SNR) ratios.

5.4.1 Padé-Laplace Deconvolution of the Echo-Decay and Inversion-Recovery Transients

We used the Padé-Laplace method to determine the number of the decay constants in the signals and used multiexponential fits to adjust the decay constants and their amplitudes. For the echo decay transients the best fits were monoexponential fits, even though the Padé-Laplace analysis initially showed biexponential behavior for pDiTBuS with major contribution from the fast decay constants in the order of the detector's dead time. All recorded echo decay transients contain oscillations due to the ESEEM effect. The oscillations were excluded from the analysis as shown in the 'fit area' on the plots in Figure 5.10, Figure 5.12 and Figure 5.14.

Echo Decay in 50 mM TEMPOL

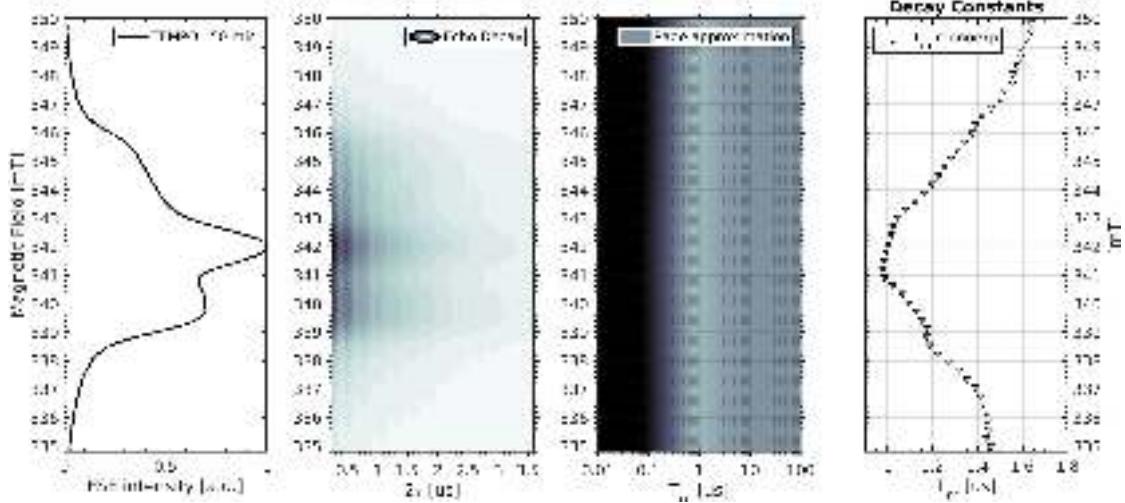


Figure 5.9: Padé-Laplace deconvolution of the field-swept spin echo decay in a frozen 50 mM solution of TEMPOL in Dichloromethane:Acetonitrile glass (3:1). One decay component detected with Padé-Laplace (triangles, right panel). Monoexponential fit (squares for faster component, circles for slower component, right panel). Temperature 5K.

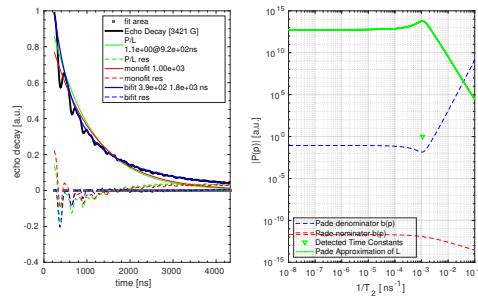


Figure 5.10: Fits of the echo decay transient in the frozen 50 mM TEMPOL solution at the central spectral peak ($m_I = 0$, 342 mT). Padé-Laplace deconvolution the transient vs. free monoexponential fit vs biexponential fit. Temperature 5K. Data was fit in the 'fit area' region. ESEEM oscillations were excluded from the data for fit and Padé-Laplace analysis.

Echo Decay in DiTBuS 95% ESOC

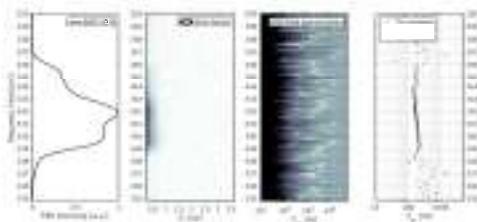


Figure 5.11: Padé-Laplace deconvolution of the field-swept spin echo decay in the pDiTBuS film at 95% ESOC. Temperature 5K.

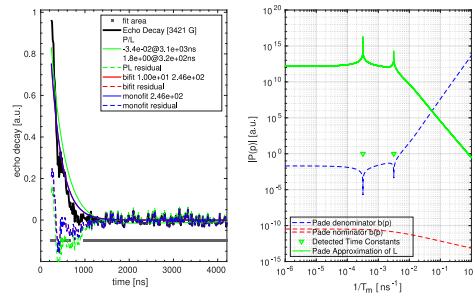


Figure 5.12: Fits of the echo decay transient in the pDiTBuS film at 95% SoC at the central spectral peak ($m_I = 0$, 342 mT). Padé-Laplace deconvolution the transient vs. free monoexponential fit vs biexponential fit. Temperature 5K. Data was fit in the 'fit area' region. ESEEM oscillations were excluded from the data for fit and Padé-Laplace analysis.

Echo Decay in DiTBuS 85% ESOC

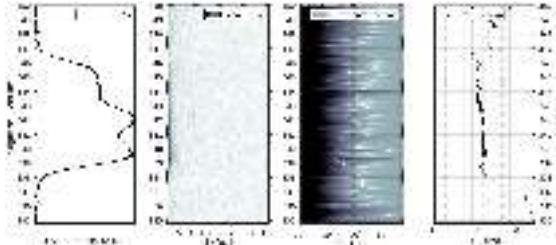


Figure 5.13: Padé-Laplace deconvolution of the field-swept spin echo decay in a pDiTBuS film at 85% ESOC. Temperature 5K.

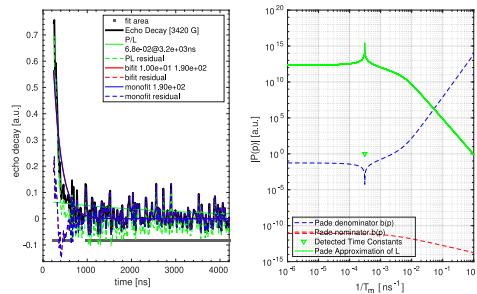


Figure 5.14: Padé-Laplace deconvolution, biexponential and monoexponential fits of the spin echo decay in a pDiTBuS film at 85% SoC at the $m_I = 0$ spectral position. Temperature 5K. Data was fit in the 'fit area' region. ESEEM oscillations were excluded from the data for fit and Padé-Laplace analysis.

Inversion Recovery in 50 mM TEMPOL

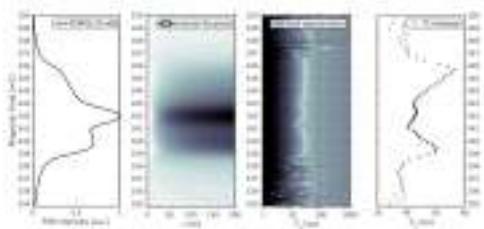


Figure 5.15: Padé-Laplace deconvolution of the field-swept inversion recovery in a frozen 50 mM solution of TEMPOL in the Dichloromethane:Acetonitrile glass (3:1). Two decay components detected with Padé-Laplace (separated poles in the Padé-Laplace approximation, third panel). Biexponential fit (circles for faster component, squares for slower component, right panel). Temperature 5K.

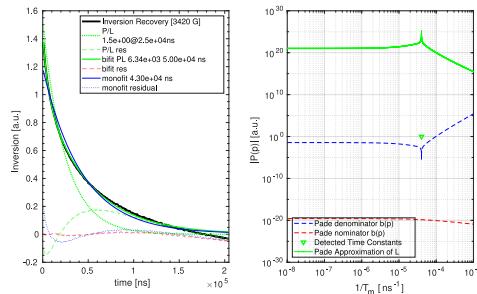


Figure 5.16: Fits of the inversion recovery transient in the frozen 50 mM TEMPOL solution at the central spectral peak ($m_I = 0$, 342 mT). Padé-Laplace deconvolution the transient and a biexponential fit. Temperature 5K.

Inversion Recovery in DiTBuS 95% ESOC

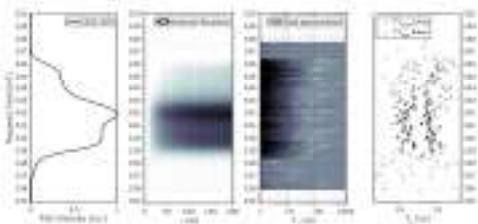


Figure 5.17: Pade-Laplace deconvolution of the field-swept inversion recovery in a pDiTBuS film at 95% ESOC. Temperature 5K.

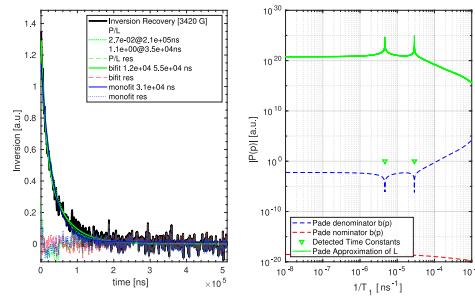


Figure 5.18: Fits of the inversion recovery transient in the 95% ESOC pDiTBuS film at the central spectral peak ($m_I = 0$, 342 mT). Padé-Laplace deconvolution the transient and a biexponential fit. Temperature 5K.

Inversion Recovery in DiTBuS 85% ESOC

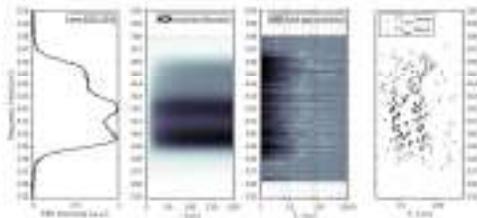


Figure 5.19: Padé-Laplace deconvolution of the field-swept inversion recovery in a pDiTBuS film at 85% ESOC. Temperature 5K.

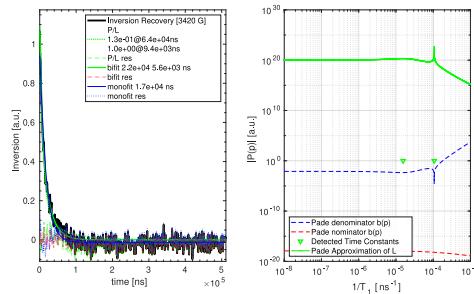


Figure 5.20: Padé-Laplace deconvolution and biexponential fit of the inversion recovery in a pDiTBuS film at 85% ESOC at the $m_I = 0$ spectral position. Temperature 5K. Data is inverted and scaled before fitting.

5.4.2 Detection of Domains with Poor Conductivity

5.4.3 Towards Electron Resonance Imaging of Spin Concentrations in Battery Electrodes

The local spin concentrations that are present in an electrode film can be obtained by the time-constant-domain analysis of the echo decay transients, as it was described in 5.4.2. One can extend this characterization technique and obtain a spatially resolved image of the spin concentrations inside the battery electrode by encoding the position at which the sample is excited with a gradient of the magnetic field. A strongly asymmetric ferromagnetic wedge [32] can be used to superimpose a gradient of B_0 in a chosen direction so one can not only measure the spin concentrations that are present in the electrode, but also to locate the electrochemically inactive domains and to visualize the conductive paths throughout the electrode, analogously to the NMR imaging. The

difficulty on the way to apply this visualization technique lies in the large excitation bandwidth of the pulse sequence.

Let the cathode film of width l be oriented along the static magnetic field so that B_0 lies in the film plane. Let the B_0 be fixed at the maximum intensity of the FSE spectrum, say, $B_0 = B_0^{res} = 342$ mT. Let B_0 be homogeneous within the film length, which is normally the case for the EPR resonator. Let the film contain a distribution of spin concentrations within its length $C_{min} < C(z) < C_{max}$. With the homogeneous B_0 , the microwave pulse will excite the entire film length and the spin echo signal will contain spin echoes from all length elements of the film, that correspond to all $C(z)$. The inversion recovery transient will contain the time constants from all length elements of the film $T_1(z)$. With the Padé-Laplace analysis one recovers the distribution of the concentrations within the film C_i , but since the B_0 is homogeneous, the information on the position z_i at which the domains are located, is lost.

Let now the B_0 to be linearly increasing from $B_0(z = -l/2) = B_0^{res} - \Delta B_0$ at one side of the film to $B_0(z = l/2) = B_0^{res} + \Delta B_0$ by the other side of the film, so that for a given length element dl the inhomogeneity of B_0 is $dB/dl = \frac{B(z=l/2)-B(z=-l/2)}{l}$. In the center of the film (at $z = 0$) the B_0 is resonant and the spin echo signal will be generated, while from the other positions of the film the magnetic field will be non-resonant and no spin echo signal will be generated. Let the width of the EPR spectrum be $\Delta B_{FWHM} = 8$ mT and that to define the probed length element Δl with the given B_0 gradient. $\frac{\Delta B_{FWHM}}{\Delta l} = \frac{B(z=l/2)-B(z=-l/2)}{l}$, so the spatial resolution is

$$\frac{\Delta l}{l} = \frac{\Delta B_{FWHM}}{B(z = l/2) - B(z = -l/2)} \quad (5.8)$$

With the spectral width of $\Delta B_{FWHM} \leq 8$ mT and the film width of $l \leq 3 \times 10^{-1}$ cm to get 256 points per film length one needs a B_0 gradient of $dB/dl \geq 256 * 8/0.3 \geq 6.8$ [T/cm] which is a realistic value for a typical Stern-Gerlach apparatus [32, 66].

Chapter 6

Conclusions and Outlook

It is possible to perform a cwEPR experiment on a working organic radical battery. Degradation of electric capacity of a polymer electrode was attributed to a formation of electrochemically disconnected domains in the electrode upon repeated recharging.

The significant difference in the number of elementary charges and the number of electron spins in a discharged electrode implies that the closely packed radicals in the discharged electrode pair up into S=0 states. Therefore, a formation of two-particle charge storing unit was observed. The transport of such two-particle units through the electrode film may be more efficient than the single-particle transport, as the total S=0 spin state allows them to recombine with the bipolarons in the NiSalen backbone without obeying the Pauli exclusion principle. The formation of paired spin states between the charge-bearing radicals is increasing the speed of the charge transfer and explains the high charging and discharging rates of TEMPO-Salen RCPs.

cwEPR monitoring of the degradation in pDiTS has shown the extensive release of the mono-nitroxide fragments which indicated that the decomposition of the pDiTS electrode upon is due to the breaking of the Salen-TEMPO linkers. The improved molecular structure of the Salen-TEMPO linkers in pDiTBuS by adding the oxygen atoms to the chains has improved the electrochemical stability of the material and also lead to a more efficient electropolymerization, allowing to grow thicker films that have larger capacity and more intense cwEPR signals.

Study of self-discharged have demonstrated the possibility to measure the concentration of the released mono-nitroxide shuttles and allowed to connect the concentration of the shuttles to the self-discharge rate.

Short spin relaxation times are limiting the application of pulse EPR techniques. Discharged cathode films have high spin concentrations that lead to spin dephasing on

a timescale shorter than the dead time of the microwave detector. This limitation can be overcome using longitudinal detection of magnetization.

Spectral distortions caused by the instantaneous diffusion due to the broad-band excitation were simulated numerically and used to estimate the local spin concentrations in the cathode. The incomplete spectral information due to the finite dead time of the detector allows to only give the lower estimate of the local spin concentration.

The echo decay and inversion recovery transients were shown to be polyexponential signals, with individual components corresponding to certain spin concentrations within the electrode. It was possible to do an analytic deconvolution of the devay signals into its exponential components without specifying the number of components, by using the Pade-Laplace analysis.

The observation of distribution of the inversion recovery times with longitudinal detection may further increase the sensitivity of the method for detecting the electrically inactive domains in the film. Combining the polyexponential analysis of the inversion recovery transients with the spatially resolved spectroscopic measurements may enable the electron resonance imaging of spin concentrations in a battery cathode. However, the existence of the $S=0$ states in the discharged cathodes makes this method applicable only to higher states of charge, where the charges are mostly in the $S=1/2$, EPR active state.

EPR-compatible, polymer electrochemical cells with solid electrolyte were fabricated. These devices are shown to be more stable and longer charging with smaller current can be used to detect spin-dependent charge transport processes in them, by using the electrically detected magnetic resonance techniques.

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Appendix A:

Electron Magnetic Resonance

Environment

A python-based interactive program EMRE (Electron Magnetic Resonance Environment) was developed to interconnect and control the EPR spectrometer and to simultaneously operate the electrochemical device under testing. The program allows one to perform electrochemical measurements such as cyclic voltammetry and galvanostatic charge-discharge cycling and to simultaneously record cwEPR spectra with customizable, lab-built and commercial EPR spectrometers. Most of the redox conductive films considered in this thesis were manufactured using EMRE. Some of the potential-dependent spectra and degradation studies were carried out using EMRE. The source code of the program and the documentation is available at the remote repository:
<https://github.com/rst030/EMRE>.

Appendix B: Calculations of Spin Density in DiTS

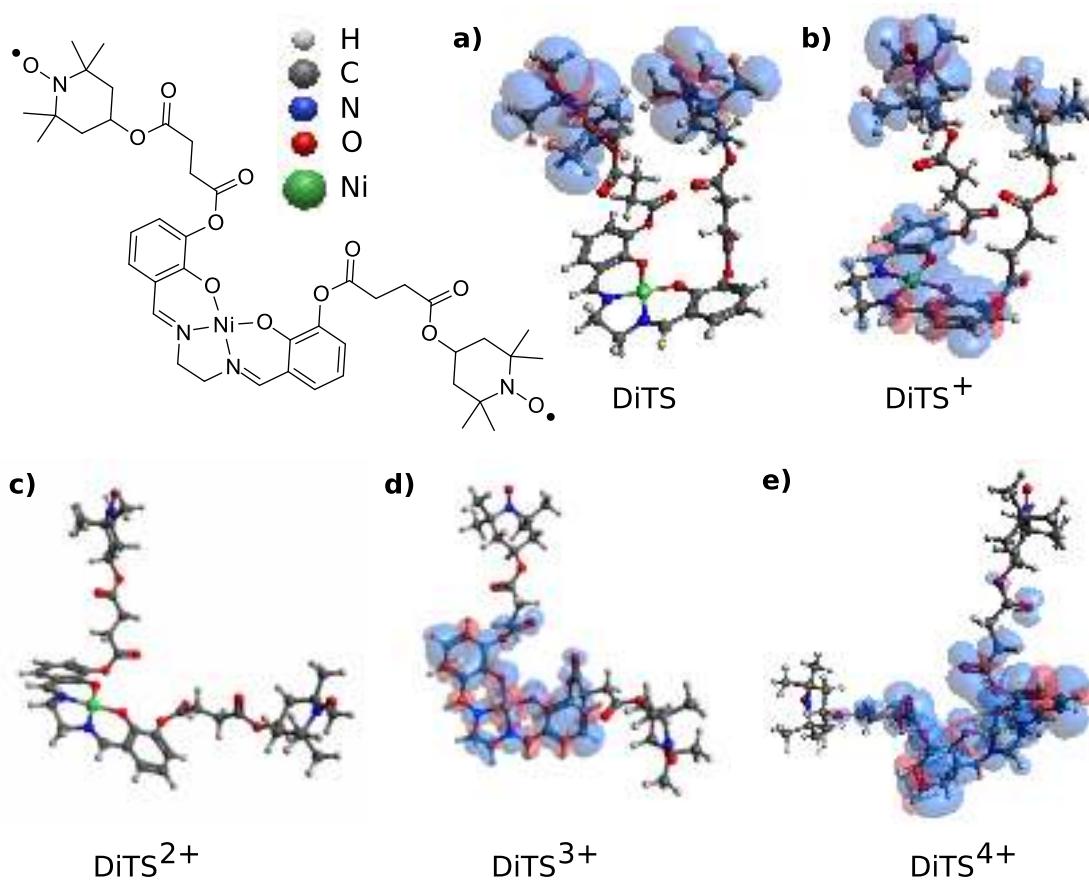


Figure 6.1: Spin density in a single DiTS monomer unit for various oxidation states (isovalue: 0.01) calculated with density-functional theory in ORCA [?], using the def2-TZVP functional basis set for the geometry optimization and the calculations of the spin density. The calculations were carried out at the high-performance computing cluster Curta of the Free University of Berlin [5]. a): neutral DiTS with two TEMPO radicals, b) singly oxidized DiTS (one hole injected), b) doubly oxidized DiTS showing no spin density, c) DiTS³⁺ showing a positive polaron localized on the NiSalen backbone, d) DiTS⁴⁺ showing increased spin density on the backbone. Calculations performed by Marcel Gauglitz.