

CHAPTER II

LITERATURE SURVEY

2.1 Conductive Polymers

Conductive polymers are a recently new class of polymers; they are organic materials that are generally comprised of C, H and simple heteroatoms such as N and S and consisting of unique π -conjugation electrons. These materials differ from other typical organic polymers due to their unique π -conjugation electrons properties, which impart higher electrical conductivity at room temperature on oxidation or reduction than ordinary polymers that are usually insulating materials relative to metals such as copper (Chandrasekhar, 1999; Deependra *et al.*, 2004).

The discovery of conductive polymers began nearly a quarter of a century ago, when Shirikawa and coworkers (Kumar and Sharma, 1978) accidentally discovered and developed an electrically conductive polymer namely polyacetylene which was found to exhibit an increase in electrical conductivity when exposed to iodine vapor. Polyacetylene remains the most crystalline conductive polymer but was not the first conductive polymer to be commercialized due to its ease in oxidation by the oxygen in air and its sensitivity to humidity. Other conductive polymers studied extensively since the early 1980s include polypyrrole, polythiophene (and various polythiophene derivatives), polyphenylenevinylene and polyaniline, as shown in the schematic in Figure 2.1. Polypyrrole and polythiophene differ from polyacetylene in that they may be synthesized directly in the doped form and are very stable in air (Kumar and Sharma, 1998; Chandrasekhar, 1999; Deependra *et al.*, 2004).

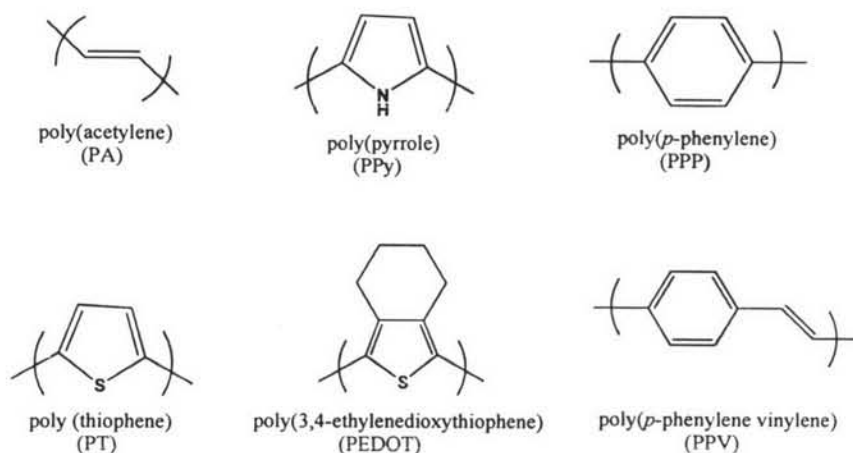


Figure 2.1 Schematic diagrams of conjugated polymers in their neutral forms.

The common electronic feature of pristine (undoped) conducting polymers is the π -conjugated system, which is formed by the overlap of carbon p_z orbitals, with alternating single and double bonds on polymer backbones, as shown in the schematic diagram of Figure 2.2. The incorporation of the conjugation along the backbone is important because it provides a pathway for electrons to migrate along a polymer chain and to jump from one chain to another chain (Deependra *et al.*, 2004; Mark *et al.*, 1996). This process provides conversion from an insulating polymer (conductive range 10^{-10} to 10^{-5} S.cm $^{-1}$) to a conductive polymer with near metallic conductivity (conductive range 1 to 10^4 S.cm $^{-1}$) (Salaneck *et al.*, 1993).

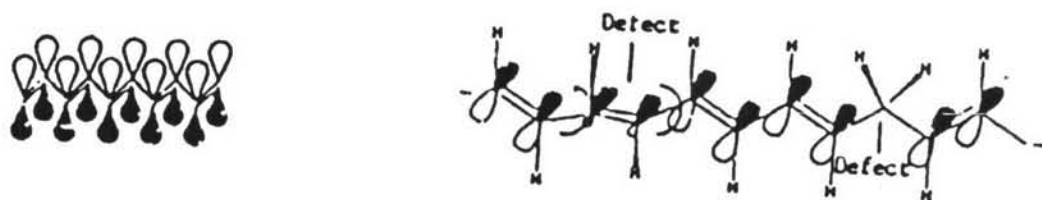


Figure 2.2 Schematic diagrams of π -conjugation in the poly(acetylene).

Left: Basic schematic Right: 3-dimensional, including defect.

Conductive polymers are widely used in a great number of applications because of their several advantages: low density and cost, ease of processing, relative robustness, and lightweight. Applications of conductive polymers which have been developed commercially include gas sensing, light-emitting cells and diodes, rechargeable batteries, electronic cells, controlled-release applications, actuators, and polymeric electronics such as transistors (Van Vught *et al.*, 2000).

2.2 Conduction Mechanism

Materials in the world can be classified into three broad categories according to their room temperature conductivity properties: Insulators, Semiconductors and Conductors (Chandrasekhar, 1999). Conduction is the transport of charge from one point to the other and is governed by charge carriers that move through a specimen. In general, electrical conductivity, σ , [$\text{S}\cdot\text{cm}^{-1}$] is a function of the number of charge carriers, n , [cm^{-3}], the charge carried by the carrier, q , [$\text{A}\cdot\text{s}$], and the mobility of the charge carriers, μ , [$\text{cm}^2\cdot\text{V}^{-1}\cdot\text{s}^{-1}$] as followed; (Van Vught *et al.*, 2000).

$$\sigma = |q| \cdot n \cdot \mu \quad [\text{S}\cdot\text{cm}^{-1}] \quad (2.1)$$

Conduction in solids can be described with the band model which is shown in the schematic diagram of Figure 2.3. In this model, two molecular orbitals, both with half filled orbitals, are brought close enough to each other until overlapping occurs. The overlapping of individual molecular electronic states in all these materials produces electronic bands; valence electrons overlap to produce a valence band which is a low-energy band, while the electronic levels immediately above these levels also coalesce to produce a conduction band which is a high-energy band. The energy difference between the newly formed bands is called the energy gap. The extent of occupation of the energy bands and the energy gap between them determines the conductivity of a material. If the valence band is only partially filled by available electrons, or if the energy gap vanishes,

an overlap between the valence and conduction bands occurs. When electrical potential is applied, some of electrons as charge carriers rise into empty levels where they can possess freedoms of movement ($\mu = \infty$). This leads to the metallic conduction. In semiconductor and insulators, the valence band is completely filled ($\mu = 0$) and the conduction band is empty ($n = 0$); both bands are separated by an energy gap. Therefore, electrical conduction can only take place when charge carriers are excited from the valence band to the conduction band. For insulators, if the energy gap is too large it is difficult for charge carriers to be excited into the conduction band. If the energy gap for semiconductors becomes smaller, charge carriers can be easily excited into the conduction band by means of thermal excitation, vibrational excitation, or excitation by photons (Kumar and Sharma, 1998; Chandrasekhar, 1999; Deependra *et al.*, 2004; Van Vught *et al.*, 2000).

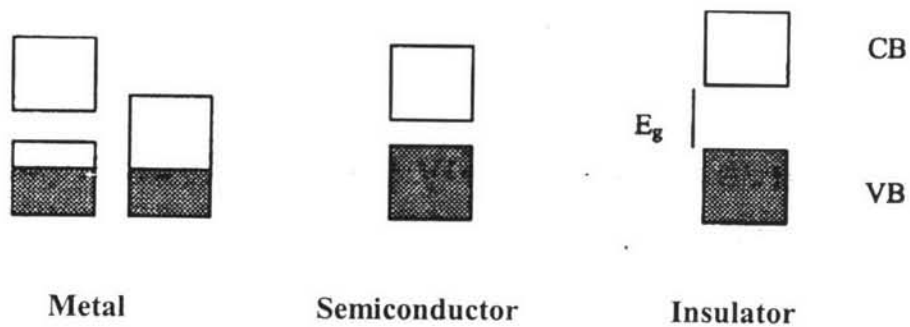
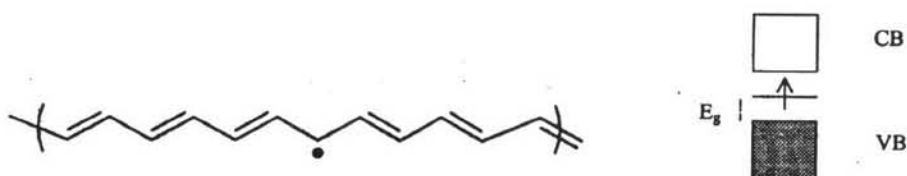


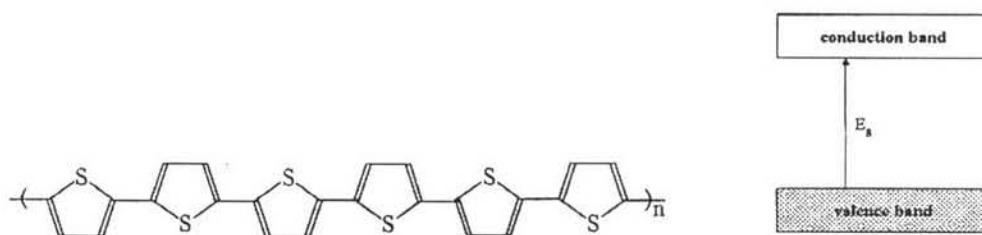
Figure 2.3 Schematic diagram of the band structure of metals, semiconductors, and insulators (E_g is the energy gap between the valence band (VB) and the conduction band (CB)).

The band model concepts can be used to describe conductive polymers behaviors. A characteristic of all conductive polymers is the conjugated structure. The conjugation length is an important parameter influencing the conductivity due to the carrier mobility (which is related to conductivity); it increases with increasing conjugation length. The conduction mechanism of all conductive polymers is divided into two paths: charge carriers move along the extent of the π -conjugated system backbone (intrachain conductivity); or they move between the individual molecules (interchain conductivity).

The conjugational defects or charge carriers are formed through solitons, polarons or bipolarons in the polymer chain when these conductive polymers are exposed to oxidation/reduction condition as shown in the schematic diagram of Figure 2.4. These defects or the charge carriers generate localized electronic states in the middle of the energy gap between the valence band and the conduction band. This effectively reduces the energy gap and the charge carriers can jump into conduction band and electrical conductivity is enhanced (Kumar and Sharma, 1998; Chandrasekhar, 1999; Van Vught *et al.*, 2000).

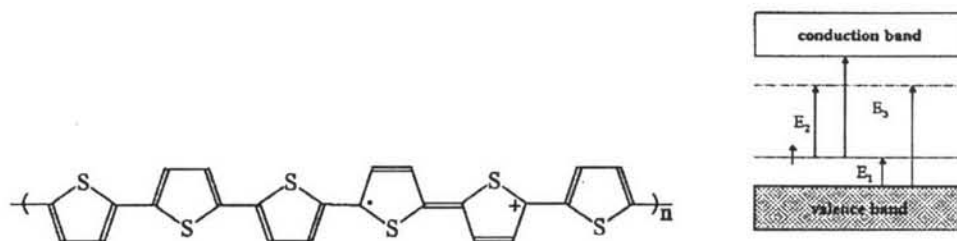


Soliton in trans-polyacetylene (left) and electronic state induced between the VB and CB by the soliton (right)

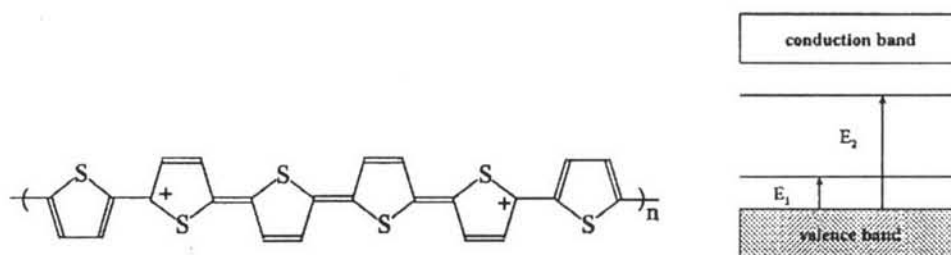


Neutral form of poly(thiophene) (left) and the electronic state of neutral form (right)

Figure 2.4 Schematic diagram of soliton of polyacetylene, and polaron, bipolaron of poly(thiophene).



The oxidative doping of poly(thiophene) in form polaron (left) and electronic state induced between the VB and CB by the polaron (right)



The oxidative doping of poly(thiophene) in the bipolaron form (left) and the electronic state induced between the VB and CB by the bipolaron (right)

Figure 2.4(cont.) Schematic diagram of soliton of polyacetylene, and polaron, bipolaron of poly(thiophene).

2.3 Concept of Doping

The naturally π -conjugated electrons systems on conductive polymer backbone are not sufficient to render them highly conductivity; trans-polyacetylene possesses only 10^{-6} S.cm⁻¹. The high electrical conductivity is achieved by the process called the "doping process". This process was firstly discovered by Shirakawa and Ikeda by

doping of polyacetylene (PA) with iodine, and conductivity increases by 9-13 orders of magnitude (Kumar and Sharma, 1998).

Doping of pristine (undoped) conductive polymer can be accomplished by the chemical method of a direct exposure of the conjugated polymer to a charge transfer agent (called dopant) in a solution or in vapor phase, or by the electrochemical oxidation or reduction. Dopants are either strongly reducing agents or strongly oxidizing agents. They may be neutral molecules, compounds or inorganic salts, which can easily form ions. Organic dopants are, for example ClO_4^- or Na^+ . Polymeric dopants are poly(styrene sulfonic acid) or poly(vinyl sulfonic acid), for example. During the doping process, charge carriers can be generated by the oxidation or the reduction of the polymer. The conductivity of either insulator or semiconductor (typically in the range 10^{-10} to 10^{-5} S.cm^{-1}) is raised to the metallic conduction (typically in the range 1 to 10^4 S.cm^{-1}) by controlling addition of doping level or the extent of oxidation/reduction. Increasing doping level leads to increasing conductivity, via the creation of more mobile charges carriers. The maximum doping levels achievable vary and depend on the conductive polymers and the dopants, as shown in Table 2.1.

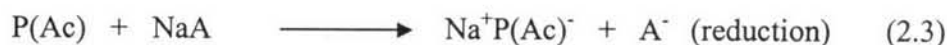
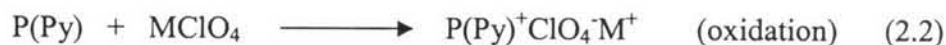
Table 2.1 The dopants and maximum doping levels attainable for specific conductive polymers (Chandrasekhar, 1999)

Dopant		Doping level (Typical range)
For Ppy, P(aromatic amines), P(bi/thiophenes) as dopant electrolyte, chemical/electrochemical		
(tetrafluoroborate)	BF_4^-	5% to 33%
(hexafluorophosphate)	PF_6^-	5% to 33%
(perchlorate)	ClO_4^-	4% to 30%
(hydrogen sulfate)	HSO_4^-	2% to 30%
(fluorosulfonate)	SO_3F^-	5% to 15%

Table 2.1(cont.) The dopants and maximum doping levels attainable for specific conductive polymers (Chandrasekhar, 1999)

Dopant		Doping level (Typical range)
For Ppy, P(aromatic amines), P(bi/thiophenes) (cont.)		
as dopant electrolyte, chemical/electrochemical		
(tri-F-methane sulfonate)	CF_3SO_3^-	4% to 31%
(benzene sulfonate)	$\text{C}_6\text{H}_5\text{SO}_3^-$	2% to 33%
(Br-benzene sulfonate)	$\text{BrC}_6\text{H}_4\text{SO}_3^-$	2% to 33%
(trifluoroacetate)	CF_3COO^-	4% to 25%
(sulfate)	SO_4^{2-}	5% to 22%
(chloride)	Cl^-	3% to 42%
(chloroferrate)	FeCl_4^-	3% to 42%
(poly(styrene sulfonate))	PSS^{n-}	3% to 15%
Nafion(DuPont membrane fluoro-polymer)	Naf^{n-}	1% to 15%
Poly(acrylic acid)	PAcrA^{n-}	2% to 20%
For Poly(di/acetylenes), P(Ac), anionic (p-type)		
from vapor phase :		
I ₃ - (iodine), I ₂ Cl ⁻ , Br ⁻ , I ₂ Br ⁻		2% to 25%
(Se, Te, mo, W, U, Re, Os, It, Ru)F ₆ ⁻ , BiF ₅		2% to 19%
from toluene solution :		
MoCl ₅ , WCl ₆ , (Ta, Nb, Zr)Cl ₅		2% to 7%
In(I, Cl) ₃ , (Sn, Ti, Zr)Cl ₄ , TiI ₄		0.3% to 7%
HSO ₄ ⁻ from NOHSO ₄		1% to 12%
(Ce, Dy, La, Pr, Sm, Yb)nitrates		0.9% to 2.2%
For P(Ac), P(phenylene), cationic(n-type)		
from THF or pentane solution :		
Na ⁺ , from NaC ₁₀ H ₈ , Na ₂ Ph ₂ CO		4% to 28%
Li ⁺ , from LiPh(CH ₂) ₆ Ph		6% to 44%

Removal or addition of electrons may also be accomplished through the introduction of a dopant which imparts higher conductivity. If the oxidation in the polymer occurs, it extracts electrons from the valence band (electrons from the polymer to the dopant), creating "holes" in the valence band, which is then known as "p-doping". It generates a positively charged conductive polymer and an associated anion. When the reduction on the polymer occurs, it adds electrons to the conduction band (electrons from the dopants to the polymer), increasing conducting electrons in this band, which is known as the "n-doping". This generates a negatively charged conductive polymer with an associated cation. These processes are summarized in the schematic below, where M and A are the cation and the anion, respectively:



In order to maintain charge neutrality, counter-ions (associated ions) are also incorporated. The interaction between counter-ions and the charge carriers on the conjugated polymer can influence the mobility of the charge carriers which is known as pinning effect (Van Vught *et al.*, 2000). This effect becomes less when the size of counter-ions is larger and the degree of charge delocalization is stronger. This means that the stability of the conductivity can be affected by the size of the counter-ions.

Doping of a conductive polymer results in the formation of new, neutral solitons, polarons or bipolarons in conjugated polymers. The doping with n-type dopants, anion conductive polymer is formed which is highly unstable in air and water. So, the conductivity which is generated by n-type dopants e.g. Na, Li is less stable than by p-type dopants e.g. I₂, AsF₅, FeCl₃, HClO₄. Therefore p-type dopants are more frequently used (Kumar and Sharma, 1998; Chandrasekhar, 1999; Van Vught *et al.*, 2000).

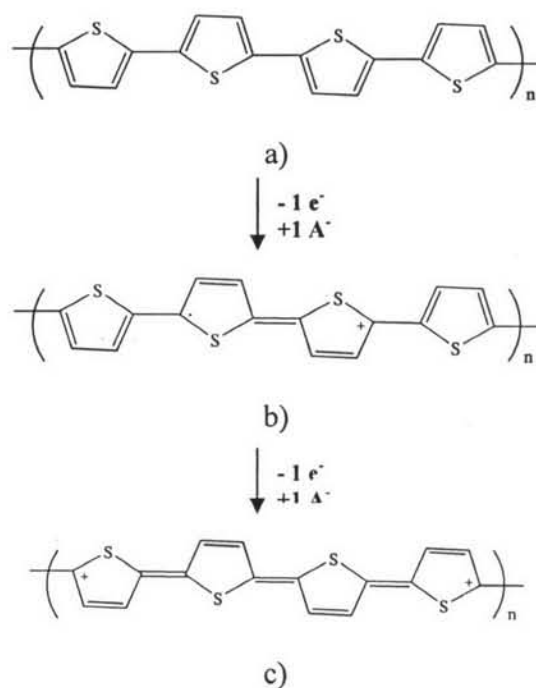


Figure 2.5 p-Type doping of polythiophene: a) Neutral form; b) Polaron form; c) Bipolaron form.

2.4 Overview of Poly(3,4-ethylenedioxythiophene)

Scientists at the Bayer AG research laboratories in Germany developed a new polythiophene derivative called poly(3,4-ethylenedioxythiophene) (Bayer AG, 1988). PEDOT for short was initially thought to be insoluble in any organic solution. The polymer was found to have a conductivity of 400-600 S/cm, and it was found to be transparent in thin oxidized films (Jonas *et al.*, 1995). The polymer is also an intrinsic p-type organic semiconductor. PEDOT possesses several advantageous properties as compared to other polythiophene derivatives: it combines a low oxidation potential and moderate band gap with good stability in the oxidized state (Jonas *et al.*, 1992; Heywang and Jonas, 1992; Winter *et al.*, 1995; Dietrich *et al.*, 1994). Unfortunately, PEDOT itself is an insoluble polymer. This drawback can be circumvented by the introduction of substituents (alkyl, alkoxy, or alkoxy-sulfonate groups), or by polymerization in

combination with a water-dispersible polyelectrolyte such as PSS. In addition to a high conductivity (ca. 400-600 S/cm, for both chemically and electrochemically prepared samples), thin oxidized films of PEDOT are highly transparent in the visible region of the spectrum, but show a broad, strong absorption band that starts at about 1.5 eV and extends into the infrared (Chang *et al.*, 1999).

2.4.1 Synthesis of 3,4-ethylenedioxythiophene

To develop PEDOT, the ethylenedioxythiophene (EDOT) monomer must be developed first. The first synthesis starts with thiodiglycolic acid, and after subsequent decarboxylation using a copper salt, can lead to EDOT in five steps (Coffey, 1996) shown in Figure 2.6.

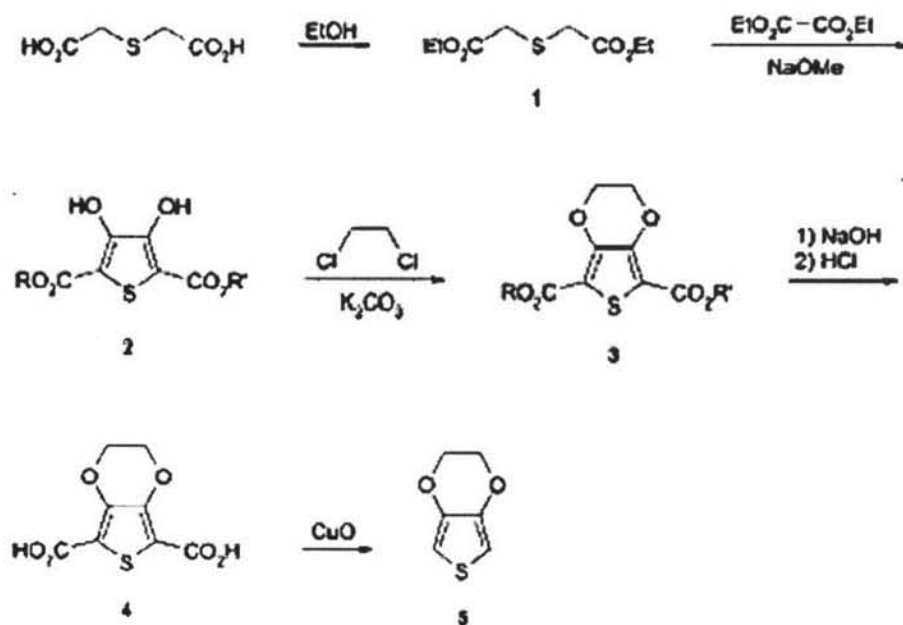


Figure 2.6 Synthesis of EDOT ($\text{R}, \text{R}' = \text{Me}$ or Et).

2.4.2 Different Types of Synthesis of Poly(3,4-ethylenedioxythiophene)

The synthesis of PEDOT can be done in several ways depending on how conductive the polymers are needed to be and what type of byproducts are contained in the polymer chain itself (Yamamoto, 1999).

There are three general ways of synthesizing PEDOT:

- Oxidative chemical polymerization of the EDOT-based monomers.
- Electrochemical polymerization of the EDOT-based monomers.
- Transition metal-mediated coupling of dihalo derivatives of EDOT.

The first type of synthesis deals with using several types of oxidants to create the polymer PEDOT chain. This is the way the synthesis is conducted for the experiments discussed in this thesis. The reason that the oxidative polymerization is used over the other forms of polymerization of PEDOT is because the reaction can take place at room temperature and depending on the oxidation agent will make the reaction occur at a much faster pace.

2.4.2.1 *Iron Ferrite Core Synthesis*

The classical oxidizing agent is FeCl_3 or $\text{Fe}(\text{OTs})_3$. This method of synthesis will result in a black insoluble and infusible compound. The PEDOT will become insoluble in organic solvents when the FeCl_3 to monomer ratio becomes greater than five. This is due to crosslinking (Kumar and Reynolds, 1996). Figure 2.7 shows the synthesis of EDOT to PEDOT using the $\text{Fe}(\text{OTs})_3$ oxidizing agent. EDOT is oxidized by the $\text{Fe}(\text{OTs})_3$ to create the PEDOT polymer. The conductivity exhibited by this polymerization method is as high as 550 S/cm (Pettersson *et al.*, 1998).

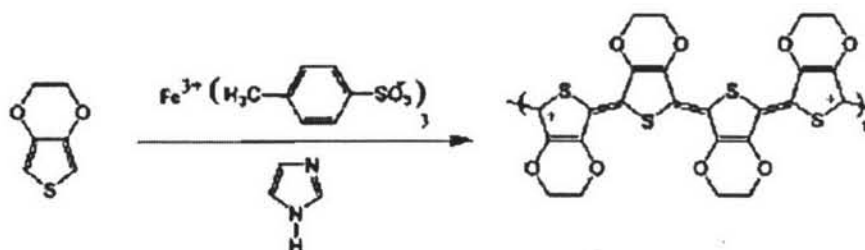


Figure 2.7 Chemical polymerization of EDOT as developed by de Leeuw (Leeuw *et al.*, 1994).

2.4.2.2 Bayer AG Synthesis

The most useful way that PEDOT is created is the method developed by Bayer AG called Baytron P (Bayer AG, 1988). This method utilizes the fact that EDOT can polymerize in aqueous polyelectrolyte which is a polystyrene sulfonic acid (PSS) solution. Sodium persulfate ($\text{Na}_2\text{S}_2\text{O}_8$) is used as the oxidizing agent. This reaction can be done at room temperature and results in a dark blue PEDOT/PSS dispersed in an aqueous solution. The properties of Baytron P process result in a compound that is highly conductive, transparent, mechanically durable, and insoluble in any common solvent film. PEDOT/PSS is shown in Figure 2.8, where the top polymer chain is PSS crosslinked to the PEDOT polymer chain below. These polymer chains are connected by a valence, or weak bond connection.

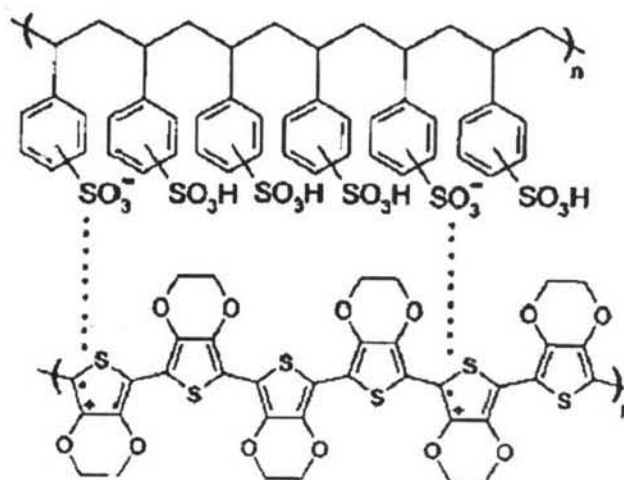
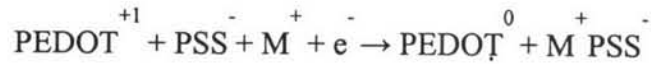


Figure 2.8 PEDOT/PSS blend.

PEDOT/PSS was initially created for antistatic applications in the photographic industry. Using electrical and vibration spectroscopy, it was discovered that the material is created from a conjugated polymer and is easily oxidized due to its electron rich character. Using X-ray diffraction, it was concluded that the material, PEDOT/PSS, is very anisotropic and there is a limited amount of crystalline order in thin films (Aasmundtveit *et al.*, 1999). This means that PEDOT/PSS can be characterized by an anisotropic metal. Considering that the reaction can be conducted at room temperature and the synthesis created by Bayer has only three chemicals makes it an ideal synthesis of PEDOT to use in these experiments.

2.4.3 Poly(3,4-ethylenedioxythiophene) Properties

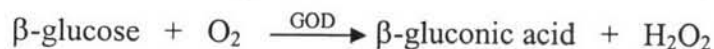
The PEDOT used in the experiments is synthesized by the Baytron P method. The reaction that makes PEDOT/PSS conductive is:



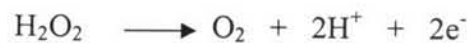
Where M^{+} is a cation (sodium usually) and PSS is a passive counterion. The color of PEDOT is a dark blue. The different weight ratios of ingredients used will control the tone of the blue from light blue green to a dark royal blue. PEDOT after being synthesized also has a viscosity approximately that of water. (<http://www.orgel.itn.liu.se/index.html/research/modelling.html>)

2.5 Electrically Conductive Polymer Composite

Conducting polyaniline-polyisoprene (PANI-PIP) composite film was synthesized electrochemically (Shen *et al.*, 2001). The film was used to immobilize glucose oxidase (GOD) forming glucose biosensor. When being used for the determination of glucose, the enzyme electrode reaction as followed:



The amount of H_2O_2 was detected by the amperometric current method during electrode oxidation:



This PANI-PIP/GOD biosensor had good operational stability. The electrochemical activity of this biosensor remained unchanged after 5 months. This biosensor had high permselectivity, which can determine H_2O_2 with high selectivity against the in the electroactive interferent ascorbic acid. When the PIP content in the composite was increased, the selectivity of the biosensor was improved. The PIP content in the composite reached 28.6%, the interference from ascorbic acid was eliminated effectively, which may be due to slow diffusion of the substrate (glucose) and product (H_2O_2).

Polydimethylsiloxane (PDMS)/polythiophene (Pth)/carbon fiber (CF) composites was synthesized by the electrochemical polymerization using tetrabutylammoniumtetrafluoroborate (TBAFB) as supporting electrolyte and acetonitrile as solvent was studied by Küçükyavuz *et al.* (2002). Electrical, thermal and mechanical properties of the composites were investigated. They found that conductivities of the composites were in the range of 2-5 S/cm depending on contents of material (PDMS, Pth, carbon fiber). Conductivities of these composites were environmentally stable. From the thermal analysis, these composites still remained more than 50% weight at 900°C. They concluded that the composites were more stable than both PDMS and carbon fiber. In mechanical tests, it was observed that higher percent elongation was obtained by increasing PDMS content whereas tensile strength and modulus of composites increased with increasing carbon fiber content. Knite *et al.* (2004) fabricated electrically conductive polymer composite (ECPC). The composite are acts as large-size flexible pressure and stretch sensors for detecting of dangerous deformations and vibrations of vehicle parts. Reversible change of resistance of electro-conductive polymer nanocomposite depended on stretch and pressure. All the composites were examined; the best results were obtained on samples with 10 mass fractions of carbon nano-particles, which belonged to the region of percolation phase transition. Electrical resistance of the samples was changed by more than four orders upon a 40% stretch and more than three orders upon a 0.30 MPa pressure. The resistance returned to its previous value after the samples were relaxed but in the case of micro-size carbon filler was irreversible. This nanocomposite exhibited a weak semiconductor-like thermal dependence of resistivity. The tenzoresistive and piezo-resistive effects were thermally stable within the region of 20-70°C. The increase of electrical resistance with uniaxial stretch and pressure can be explained as a result of destruction of the structure of the carbon electro-conductive nano-size channel network. At large deformations, the destruction of the conductive network and decreased of the number of conducting pathways occurred.

Faez *et al.* (2001) prepared the electrically conductive heterogeneous binary polymer blends based on ethylene-propylene-diene-monomer (EPDM) and polyaniline (PAni), doped with dodecylbenzene sulfonic acid (PAni-DBSA). They

studied the effect of the doping method on mechanical and electrical properties of these blends. Different doping methods were used: solution (EPDM/PAni-DBSA-S), grinding in a mortar (EPDM/PAni-DBSA-M) and reactive processing (EPDM/PAni-DBSA-R). They observed from the optical micrographies that the EPDM/PAni-DBSA-S blends PAni was homogeneously dispersed into EPDM but the EPDM/PAni-DBSA-M and EPDM/PAni-DBSA-R blends formed non-miscible blends with EPDM. However, the swelling measurements for all blends showed that in the EPDM/PAni-DBSA-R blends the EPDM was partially soluble. This phenomenon observed indicates that entanglements or chemical reaction occurred between the components. Young modulus increased with PAni-DBSA concentration independently of the doping method was related with the reinforcement effect of PAni-DBSA but the less pronounced for EPDM/PAni-DBSA-S due to the low viscosity of these blends. The conductivity values of PAni-DBSA changed with the doping method, being higher for PAni-DBSA doped by the reactive processing and increased linearly with PAni-DBSA concentration, independently of the PAni doping method, until 30% (w/w).

Electrically conductive heterogeneous binary polymer blends based on ethylene-propylene-diene-monomer (EPDM) and polyaniline (PAni) doping with dodecylbenzene sulfonic acid (PAni-DBSA) were prepared (Faez *et al.*, 2002). They studied the effect of the crosslinking method for EPDM rubber on mechanical and electrical properties of this blends. Two difference crosslinking methods, which were phenolic resin and electron beam irradiation, were studied. They found that the electron beam irradiation vulcanization was not precluded by the presence of an acid from doping substance but the phenolic resin vulcanization occurred. The mechanical properties such as the tension and the elongation at break as a function of amount of conducting polymer loading and type of crosslinking method. The tension at break for all blends increased with PAni-DBSA loading increased until 30%(w/w). This indicates that the reinforcement effect of the conducting polymer. Above 30 % (w/w) loading, the tension of blends dropped due to the large PAni-DBSA agglomerated so the absence of phase adhesion between conducting polymer particles and polymer chain matrix occurred. The conductivity increased with PAni-

DBSA loading and polymer blends, which were crosslinked by electron beam irradiation, produced high conductivity due to some ionic species that were generated.

2.6 Advantages of Poly(Dimethyl Siloxane) Based Electroactive Polymers

PDMS, a fairly transparent polymer having high elasticity and low stiffness, is a polymer composed of an alternating backbone of silicon and oxygen atoms with two organic functionalities attached to each silicon atom. The absence of a chromophore within alkyl-substituted polysiloxanes results in a polymer with high stability towards ultraviolet radiation. Also, the silicon-oxygen backbone gives polysiloxanes high resistance towards oxidation and chemical attack. The high torsional mobility about the silicon-oxygen bond results in the dimethyl substituted polysiloxane having one of the lowest glass transition temperatures of any polymer (-123 °C), thus allowing a large temperature window from -100°C to over 200 °C of operation and showing stable behavior even for harsh environments. Owing to the combination of these properties with its adaptable molecular composition and excellent process-ability, PDMS systems attract attention for a variety of actuation applications like robotics, android heads, MEMS. Moreover, PDMS is used as a base polymer because a stable electroactive blend can be obtained by attaching not only cyanophenyl as the dipolar moiety but several other functional groups like nitro, fluoro or other group that have either a permanent or induced dipole moment and can be crosslinked to the poly (dimethyl siloxane) oligomer. Thus, making PDMS the base of the electrostrictive EAP and tailoring it with dipolar entities is a step towards implementation of the applications.

2.7 Actuators

Zrínyi *et al.* (2000) studied a novel gel actuator containing TiO₂ particles operated under static electric field. They prepared poly(dimethylsiloxane) gels (PDMS gels) and TiO₂ particles were embedded in this gels. The crosslinking reaction occurred in a plastic tube. After the gelation was completed, the gel cylinders were removed from the tubes and were suspended in silicon oil to study the

elastic response of the gels to an electric field. The filler-loaded gel cylinders showed significant and rapid bending toward the cathode, when an external electric field was applied. When positive and negative electrodes were changed, this behavior was reversible. The displacement of the free bottom end of the gel cylinders depended on the strength of the electric field. These results showed that in an external electric field the gel accumulated positive charges. The large deflection has been observed due to the interaction of the applied external electric field with the charged gel.