



**UNIVERSITI PUTRA MALAYSIA**

**PREPARATION AND CHARACTERIZATION OF  
POLYPYRROLEPOLYETHYLENE  
GLYCOL CONDUCTING POLYMER COMPOSITE FILMS**

**LIM MEI YEE**

**FS 2007 32**



**PREPARATION AND CHARACTERIZATION OF POLYPYRROLE-  
POLYETHYLENE GLYCOL CONDUCTING POLYMER COMPOSITE FILMS**

**By**

**LIM MEI YEE**

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in  
Fulfilment of the Requirement for the Degree of Master of Science**

**August 2007**



## DEDICATION

To my beloved parents Lim Tet Yoong and Lau Mau Ching

For their endless love and concern.....

To my beloved Wan Kee Peng

For his romantic love, support, understanding and care.....

To my supervisor Prof. Dr. Anuar bin Kassim, PhD

For his guidance, advice, understanding and endless support.....

To my co-supervisors Prof Mohd. Zobir Hussein, PhD and Professor Wan

Mahmood Mat Yunus, PhD

For their kindly advice and indispensable support.....

To my senior H. N. M. Ekramul Mahmud, PhD

For his wonderful encouragement and support.....

To my friends

For their wonderful love and generous moral support.....

Abstract of the thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

**PREPARATION AND CHARACTERIZATION OF POLYPYRROLE-POLYETHYLENE GLYCOL CONDUCTING POLYMER COMPOSITE FILMS**

By

**LIM MEI YEE**

**August 2007**

**Chairman: Professor Anuar Kassim, PhD**

**Faculty: Science**

Polypyrrole-polyethylene glycol (PPy-PEG) conducting polymer composite films were electrochemically prepared on Indium Tin Oxide (ITO) glass electrode from an aqueous solution containing pyrrole monomer, *p*-toluene sulfonate dopant and poly(ethylene glycol) as an insulating polymer. The PPy-PEG composite films prepared from different process conditions were characterized by Fourier Transform infrared (FT-IR) spectroscopy, electrical conductivity measurement, photoacoustic spectroscopy, X-ray diffraction (XRD) analysis and optical microscopy. The FT-IR study of PPy-PEG composite films shows the evidence of the incorporation of PEG in PPy structure forming PPy-PEG composite films.

The highest electrical conductivity of 61 S/cm and thermal diffusivity of  $7.88 \times 10^{-7} \text{ m}^2\text{s}^{-1}$  were shown by the PPy-PEG composite film prepared from 0.20 M pyrrole, 0.10 M *p*-toluene sulfonate and  $1 \times 10^{-3}$  M PEG at 1.20 volt (vs SCE) at room temperature among all the PPy-PEG composite films produced. The conductivity data of PPy-PEG shows that with the increase in PEG concentration in the pyrrole



solution, the electrical conductivity of the prepared PPy-PEG film increased up to certain level due to the increase in conjugation length and later it decreased with further increase in PEG concentration, which is again linked with the decrease in conjugation length.

The measured values of thermal diffusivity and electrical conductivity for the PPy-PEG composites films showed that there was a correlation between thermal diffusivity and electrical conductivity. Both thermal diffusivity and electrical conductivity showed a similar peak for the same process condition in respective composite films.

The XRD results of PPy-PEG composite films showed that the films were amorphous with very little order. The optical micrographs of PPy-PEG showed the globular surface morphology. The changes in globular surface morphology with the change in process condition of the film preparation indicated that the process parameters used to prepare the composite films had a strong influence over the surface morphology.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia  
sebagai memenuhi keperluan untuk ijazah Master Sains

**PENYEDIAAN DAN PENCIRIAN UNTUK POLIPIROL-POLIETILENA  
GLIKOL FILEM KOMPOSIT POLIMER PENGALIR**

Oleh

**LIM MEI YEE**

**Ogos 2007**

**Pengerusi : Professor Anuar Kassim, PhD**

**Fakulti : Sains**

Filem komposit polimer pengalir bagi pasangan polipirol-polietilena glikol (PPy-PEG) dan telah disediakan melalui kaedah elektrokimia di atas elektrod kaca Indium Stanum oksida (ITO) daripada larutan akueus yang mengandungi monomer pirol, dopan *p*-toluena sulfonat dan polietilena glikol sebagai polimer selulosa penebat. Filem komposit bagi PPy-PEG telah disediakan melalui keadaan proses yang berlainan dan langkah pencirian telah dilakukan melalui penyerapan infra merah (FT-IR), penentuan kekonduksian elektrik, spektrokopi fotoakustik, pengimbasan analisis sinar-X, dan mikroskopi optikal. Kajian FT-IR ke atas filem komposit PPy-PEG nyata menunjukkan kemasukan PEG ke dalam struktur PPy berkaitan dengan pembentukan filem komposit PPy-PEG.

Filem komposit PPy-PEG yang memberi nilai konduktiviti elektrik tertinggi dan nilai resapan terma iaitu 61 S/cm dan  $7.88 \times 10^{-7} \text{ m}^2\text{s}^{-1}$  berbanding dengan yang lain telah disediakan daripada larutan 0.20 M pirol, 0.10 M *p*-toluena sulfonat dan  $1 \times 10^{-3}$  M PEG pada keupayaan 1.20 v (melawan SCE) pada suhu bilik. Data

kekonduksian elektrik, PPy-PEG menunjukkan dengan penambahan kepekatan PEG dalam larutan pirol, kekonduksian elektrik filem PPy-PEG turut bertambah ke satu paras tertentu disebabkan penambahan panjang konjugatan dan nilai kekonduksian elektrik berkurangan dengan penambahan PEG berlebihan iaitu berkaitan langsung dengan panjang konjugatan yang berkurangan.

Nilai resapan terma dan konduktiviti elektrik untuk filem komposit PPy-PEG menunjukkan satu hubungan pertalian secara bersistem di antara resapan terma dan konduktiviti elektrik. Kedua-dua nilai resapan terma dan konduktiviti elektrik esapan terma dan konduktiviti elektrik menyatakan kesamaan puncak daripada keadaan proses yang sama dalam komposit filem masing-masing.

Keputusan XRD menunjukkan bahawa filem komposit PPy-PEG adalah bersifat amorfus dengan mempunyai sedikit sifat ketertiban. Mikrograf optikal PPy-PEG menunjukkan sifat morfologi permukaannya yang berbentuk sfera. Perubahan keadaan penyediaan turut mengubah morfologi permukaan sfera jelas menunjukkan bahawa parameter dalam proses penyediaan mempunyai kesan untuk mempengaruhi sifat permukaannya.

## ACKNOWLEDGEMENT

The completion of this project is not a one-man work. It is a project, which could only get completed on time with the help of many parties. Therefore I would like to take this opportunity to express my gratitude to all of them to show my appreciation for their support.

First and foremost, I wish to thank Professor Anuar Kassim, PhD for being such a good supervisor and personal tutor. His guidance leads me to some solution, which I would never come across by myself. He was always there to provide everything I needed in the laboratory.

I would also like to express my sincere thanks to my co-supervisors Professor, Mohd. Zobir Hussein, PhD and Professor Wan Mahmood Mat Yunus, PhD for their guidance, support, and encouragement throughout my study period. Special word of appreciation to H. N. M. Ekramul Mahmud, PhD for his guidance, suggestion, innovative ideas and also invaluable advice with patients.

I am also indebted to the staff of the Department of Chemistry and Physics, Universiti Putra Malaysia, for their help and cooperation.

A deep acknowledgment is also extended to Mrs Yusmawati Wan Yusof, Mrs Rusnani, Miss Yusnita Osman, and Mrs Saliana for their kindness to allow me to use supportive apparatus such as FT-IR, XRD, optical microscopy and photoacoustic



spectroscopy. Special thanks are extended to my lab members Miss Masnizaayu, Mrs. Rozita Yahya, and Mr. Fariz Adzmi who helped me in every possible way and providing a congenial and enthusiastic atmosphere in the laboratory.

Last but not least, special greetings and thanks to my beloved family for their wonderful love and generous moral support.

I certify that an Examination Committee met on 3<sup>rd</sup> August, 2007 to conduct the final examination of Lim Mei Yee on her Master of Science thesis entitled “Preparation and Characterization Conducting Polymer Composite Films: Polypyrrole-Polyethylene Glycol” in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

**Gwendoline Ee Cheng Lian, PhD**

Associate Professor  
Faculty of Science  
Universiti Putra Malaysia  
(Chairman)

**Asmah Hj Yahya, PhD**

Associate Professor  
Faculty of Science  
Universiti Putra Malaysia  
(Internal Examiner)

**Abdul Halim Bin Abdullah, PhD**

Associate Professor  
Faculty of Science  
Universiti Putra Malaysia  
(Internal Examiner)

**Rusli Daik, PhD**

Associate Professor  
Faculty of Science and Technology  
Universiti Kebangsaan Malaysia  
(External Examiner)

---

**HASANAH MOHD. GHAZALI**

Professor and Deputy Dean  
School of Graduate Studies,  
Universiti Putra Malaysia

Date:



This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee are as follows:

**Anuar Kassim, PhD**

Professor  
Faculty of Science  
Universiti Putra Malaysia  
(Chairman)

**Mohd. Zobir Hussein, PhD**

Professor  
Faculty of Science  
Universiti Putra Malaysia  
(Member)

**Wan Mahmood Mat Yunus, PhD**

Professor  
Faculty of Science  
Universiti Putra Malaysia  
(Member)

---

**AINI IDERIS, PhD**

Professor and Dean  
School of Graduate Studies  
Universiti Putra Malaysia

Date:



**DECLARATION**

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

---

**LIM MEI YEE**

Date: 19 December 2007

## TABLE OF CONTENTS

	<b>Page</b>
<b>DEDICATION</b>	ii
<b>ABSTRACT</b>	iii
<b>ABSTRAK</b>	v
<b>ACKNOWLEDGEMENTS</b>	vii
<b>APPROVAL</b>	ix
<b>DECLARATION</b>	xi
<b>LIST OF TABLES</b>	xv
<b>LIST OF FIGURES</b>	xvi
<b>LIST OF ABBREVIATIONS</b>	xix
<b>CHAPTER</b>	
<b>I      INTRODUCTION</b>	
Conducting Polymers	1
History of Conducting Polymers	6
Research Objectives	14
<b>II     LITERATURE REVIEW</b>	
Monomer	15
Counter ion or Dopant	16
Insulating Polymer	18
Solvent	19
Polypyrrole as a Conducting Polymer	21
Mechanisms of Pyrrole Electropolymerization- Role of Doping	23
Mechanisms of Pyrrole Electropolymerization	25
Applications of Polypyrrole Conducting Polymers	
Batteries	35
Polypyrrole Microactuators	36
Condenser	36
Transparent Loudspeakers	37
Electromagnetic Interference (EMI)	38
Shielding Material	
Brilliant	38
Microelectronics	39
<b>III    MATERIALS AND METHODS</b>	
Electrochemical Synthesis	41
Electrode	41
Monomer, Electrolyte and Insulating Polymer	42
Preparation of PPy-PEG Composite Films	43

Characterization of the PPy-PEG Composite Films	
Electrical Conductivity	44
Fourier Transform Infrared Spectrometry (FT-IR)	45
X-ray Diffraction (XRD)	46
Optical Microscopy	46
Open Photoacoustic Technique	47
<b>IV RESULTS AND DISCUSSION</b>	
Electrochemically Prepared Polypyrrole Composite Films	48
Molecular Structure of PPy-PEG Composite Films	50
Electrical Conductivity of PPy-PEG Composite Films	54
Effect of PEG Concentration on the Electrical Conductivity of PPy-PEG Composite Films	55
Effect of Pyrrole Concentration on the Electrical Conductivity of PPy-PEG Composite Films	57
Effect of Dopant Concentration on the Electrical Conductivity of PPy-PEG Composite Films	58
Effect of Applied Voltage on the Electrical Conductivity of PPy-PEG Composite Films	60
Thermal Diffusivity of PPy-PEG Composite Films	63
Effect of PEG Concentration on the Thermal Diffusivity of PPy-PEG Composite Films	64
Effect of Pyrrole Concentration on the Thermal Diffusivity of PPy-PEG Composite Films	66
Effect of Dopant Concentration on the Thermal Diffusivity of PPy-PEG Composite Films	68
Effect of Applied Voltage on the Thermal Diffusivity PPy-PEG composite films	70
The Relation Between Electrical Conductivity and Thermal Diffusivity of PPy-PEG Composite Films	72
Molecular Order in PPy-PEG Composite Films	79
Effect of PEG Concentration on the Molecular Order of PPy-PEG Composite Films	83
Effect of Pyrrole Concentration on the Molecular Order of PPy-PEG Composite Films	87
Effect of Dopant Concentration on the Molecular Order of PPy-PEG Composite Films	89

Effect of Applied Voltage on the Molecular Order PPy-PEG Composite Films	91
Morphological Study of PPy-PEG Composite Films	92
Effect of PEG Concentration on the Morphology of PPy-PEG Composite Films	92
Effect of Pyrrole Concentration on the Morphology of PPy-PEG Composite Films	99
Effect of Dopant Concentration on the Morphology of PPy-PEG Composite Films	103
Effect of Applied Voltage on the Morphology PPy-PEG Composite Films	107
<b>VI CONCLUSIONS</b>	<b>110</b>
Future Studies	111
<b>REFERENCES/BIBLIOGRAPHY</b>	<b>113</b>
<b>APPENDICES</b>	<b>123</b>
<b>BIODATA OF THE AUTHOR</b>	<b>126</b>
<b>LIST OF PUBLICATIONS</b>	<b>127</b>



**LIST OF TABLES**

<b>Table</b>		<b>Page</b>
1.1	Conducting polymers: preparation methods and conductivities	8
2.1	Examples of copolymer prepared from pyrrole functional polymers	16
2.2	Polypyrrole films with different anions	18
2.3	Physical properties of polypyrrole with $\rho$ -toulenesulfonate films	20
3.1	The parameter used to synthesize PPy-PEG composite films prepared from various process conditions	43
4.1	Physical observation of PPy-PEG Composite films	48
4.2	Diffraction orders for stretch-aligned polypyrrole (Warren, 2001)	82

## LIST OF FIGURES

<b>Figure</b>		<b>Page</b>
1.1	The conductivity of materials (Przyluski, 1991)	4
2.1	Pyrrole is synthesized into polypyrrole with the dopant ( $A^-$ )	17
2.2	Simple band picture explaining the difference between an insulator, a semiconductor and a metal	24
2.3	First part of the reaction mechanism of polypyrrole film formation	26
2.4	Second part of the reaction mechanism of polypyrrole film formation	30
2.5	Third part of the reaction mechanism of polypyrrole film Formation	33
3.1	The experimental set-up for the electrochemical preparation of PPy-PEG composite films	42
3.2	Circuit used for conductivity measurements	45
4.1	FT-IR spectra of PPy-PEG composite film, PPy film, PEG and <i>p</i> -toluene sulfonate	52
4.2	The formation of PPy-PEG composite film from pyrrole, monomer, <i>p</i> -toluene sulfonate dopant and PEG	53
4.3	Electrical conductivity of PPy-PEG composite films versus PEG concentration used to prepare the PPy-PEG composite films	56
4.4	Electrical conductivity of PPy-PEG composite films against pyrrole concentration	58
4.5	Electrical conductivity of PPy-PEG composite films against different <i>p</i> -toluene sulfonate concentration	60
4.6	Electrical conductivity of PPy-PEG composite films against different applied voltage (vs SCE).	62
4.7	Thermal diffusivity of PPy-PEG composite films versus PEG concentration used to prepare the PPy-PEG composite films	65

4.8	Thermal diffusivity of PPy-PEG composite films versus pyrrole concentration used to prepare the PPy-PEG composite films	67
4.9	Thermal diffusivity of PPy-PEG composite films against different <i>p</i> -toluene sulfonate concentration	69
4.10	Thermal Diffusivity of PPy-PEG composite films against different applied voltage (vs SCE)	71
4.11	The electrical conductivity and thermal diffusivity of PPy-PEG composite films against different PEG concentration	75
4.12	The electrical conductivity and thermal diffusivity of PPy-PEG composite films against different pyrrole concentration	76
4.13	The electrical conductivity and thermal diffusivity of PPy-PEG composite films against different <i>p</i> -toluene sulfonate concentration	77
4.14	The electrical conductivity and thermal diffusivity of PPy-PEG composite films against different applied voltage	78
4.15	Stacked lamellae	80
4.16	Fringed mycelles	80
4.17	XRD diffractograms of PPy-PEG composite films prepared from various concentrations of PEG	84
4.18	The XRD diffractograms of PEG	86
4.19	The XRD diffractograms of PPy	86
4.20	The XRD diffractograms of PPy-PEG composite film	86
4.21	XRD diffractograms of PPy-PEG composite films prepared from various concentrations of pyrrole	88
4.22	XRD diffractograms of PPy-PEG composite films prepared from various concentrations of <i>p</i> -toluene sulfonate	90
4.23	XRD diffractograms of PPy-PEG composite films prepared from various applied voltage	91

4.24	The optical micrographs of the solution side of PPy-PEG composite films produced from using (a) $5 \times 10^{-4}$ M, (b) $1 \times 10^{-3}$ M, (c) $3 \times 10^{-3}$ M, (d) $5 \times 10^{-3}$ M, (e) $7 \times 10^{-3}$ M and (f) $9 \times 10^{-3}$ M PEG in the pyrrole solution (Magnification: 20x)	93
4.25	The optical micrographs of the electrode side of PPy-PEG composite films produced from using (a) $5 \times 10^{-4}$ M, (b) $1 \times 10^{-3}$ M, (c) $3 \times 10^{-3}$ M, (d) $5 \times 10^{-3}$ M, (e) $7 \times 10^{-3}$ M and (f) $9 \times 10^{-3}$ M PEG in the pyrrole solution (Magnification: 20x)	95
4.26	The optical micrographs of the solution side of (a) only PPy film and (b) PPy-PEG composite film (magnification: 20x)	97
4.27	The optical micrographs of the electrode side of (a) only PPy film and (b) PPy-PEG composite film (magnification: 20x)	98
4.28	The optical micrographs of the solution side of PPy-PEG composite films produced from using (a) 0.10 M, (b) 0.20 M, (c) 0.30 M and (4) 0.40 M pyrrole (magnification: 20x)	101
4.29	The optical micrographs of the electrode side of PPy-PEG composite films produced from using (a) 0.10 M, (b) 0.20 M, (c) 0.30 M and (4) 0.40 M pyrrole (magnification: 20x)	102
4.30	The optical micrographs of the solution side of PPy-PEG composite films produced from using (a) 0.05 M, (b) 0.10 M, (c) 0.20 M and (d) 0.30 M $\rho$ -toluene sulfonate (Magnification: 20x)	104
4.31	The optical micrographs of the electrode side of PPy-PEG composite films produced from using (a) 0.05 M, (b) 0.10 M, (c) 0.20 M and (d) 0.30 M $\rho$ -toluene sulfonate (Magnification: 20x)	106
4.32	The optical micrographs of the solution side of PPy-PEG composite films produced from using (a) 0.80 volt (vs SCE), (b) 1.20 volt (vs SCE) and (c) 1.50 volt (vs SCE) (Magnification: 20x)	108
4.33	The optical micrographs of the electrode side of PPy-PEG composite films produced from using (a) 0.80 volt (vs SCE), (b) 1.20 volt (vs SCE) and (c) 1.50 volt (vs SCE) (Magnification: 20x)	109



**LIST OF ABBREVIATIONS**

InSb	Indium Antimonide
AsF <sub>5</sub>	Arsenic Pentafluoride.
TTF	Tetrathiafulvalene
TCNQ	Tetracyanoquinodimethane
CH	Methyl
T <sub>c</sub>	Glass transition temperature
Ch	Chemical preparation
EP	Electropolymerization
Pt	Platinum
Py	Pyrrole
PPy	Polypyrrole
PEG	Polyethylene Glycol
FT-IR	Fourier Transform Infrared Spectrometry
XRD	X-ray diffraction analysis
vs	Versus
PMMA	Poly (methyl methacrylate)
PTHF	Polytetrahydrofuran
PCL	Polycaprolactone
PDMS	Poly (dimethyl siloxane)
A <sup>-</sup>	Dopant/ counter-ions
BS	Benzenesulfonate
PTS	sodium <i>p</i> -toluenesulfonate



EBS	sodium 4-ethylbenzenesulfonate
MXS	sodium m-xylene-4-sulfonate
MSS	sodium mesitylnesulfonate
OBS	sodium 4-n-noctylbenzenesulfonate
DBS	sodium dodecylbenzenesulfonate
ET <sub>4</sub> NPTS	tetraethylammonium <i>p</i> -toulenesulfonate
mA	Mega ampere
H <sub>2</sub> O	Hydrogen oxide
CH <sub>3</sub> CN	Methyl Cyanide
psi	Per square inch
$\sigma$	Conductivity
R	Monomer
R <sup>+</sup>	Cation radical
ITO	Indium-tin-oxide
SCE	Saturated calomel electrode
V	Voltage
dc	Direct current
$\mu\text{m}$	Micrometre
cm	Centimeter
Hz	Hetze
2 $\theta$	2 Theta
<i>p</i> -TS	<i>p</i> -toluene sulfonate
DMA	Dynamic mechanical analysis
EMI	Electromagnetic interference



## CHAPTER I

### INTRODUCTION

#### Conducting Polymers

Polymers are long chain giant organic molecules assembled from many smaller molecules called monomers. Polymers consist of many repeating monomer units in long chains. The interlinking of many units has given the polymer its name, *poly* meaning 'many' and *mer* meaning 'part' (in Greek) (Gowariker *et al.*, 1987). A polymer is analogous to a necklace made from many small beads (monomers). These monomers react together chemically to give a variety of molecular architectures ranging from linear structures to a three dimensional network of polymer chains.

Another common name for many synthetic polymers is plastic which comes from the Greek word "plastikos", suitable for molding or shaping. Many objects in daily use from packing, wrapping, and building materials include half of all polymers synthesized. Plastics are polymers, molecules that form long chains, repeating themselves like pearls in a necklace. In becoming electrically conductive, a polymer has to imitate a metal, that is, its electrons need to be free to move and not bound to the atoms. The first condition for this is that the polymer consists of alternating single and double bonds, called conjugated double bonds (Said *et al.*, 2000).

Conducting polymer are polymers which can exhibit significant level of electrical conductivity. The electrical conductivity exhibited by conducting polymers is



attributed to the presence of “free electrons” within the body of the specimen. Conducting polymers are usually polyconjugated structures which are insulators in the pure state but when treated with an oxidizing or a reducing agent can be converted into polymer salts with electrical conductivities comparable to metals. Conducting polymeric materials possess great design flexibility together with a number of characteristics that are desirable for a number of specific applications in the fields of catalysis, conversion and storage of energy, chemical and biochemical sensing, microelectronics and optoelectronics (Skotheim, 1998).

Supercapacitors are attracting great attention because of their high capacitance and potential applications in electronic devices. There has been more interest in two types of supercapacitors, the double layer supercapacitors and the redox supercapacitors with different charge storage modes. The redox supercapacitor involves faradic process due to redox reaction. Due to versatility of structure and low cost compared to noble metal oxides, electronically conducting polymers represents a promising class of active materials for electrodes of the redox supercapacitors (Hughes *et al.*, 2002).

For most of the history of polymer technology, one of the most valued properties of synthetic polymers has been their ability to act as excellent electrical insulators both at high voltages and at high frequencies. In spite of this there has been an interest for many years in the possibility of producing electrically conducting polymers. The obvious attraction is to combine in one material the electrical properties and the high added value applications of a semiconductor or a metal with the advantages of a polymer.



Approximately two decades ago, it has been discovered that polyacetylene, which is a type of polymer containing conjugated single and double bonds in its structure, could become highly conductive after carrying out a structural modification process called “doping” (Shirakawa *et al.*, 1977). During the doping process, an organic polymer, either an insulator or a semiconductor having a small conductivity typically in the range of  $10^{-10}$  to  $10^{-5}$  S/cm, is converted to a polymer, which is in the metallic conducting regime ( $1-10^{-4}$  S/cm). Figure 1.1 shows the conductivity range of metals, semiconductors and insulators.

