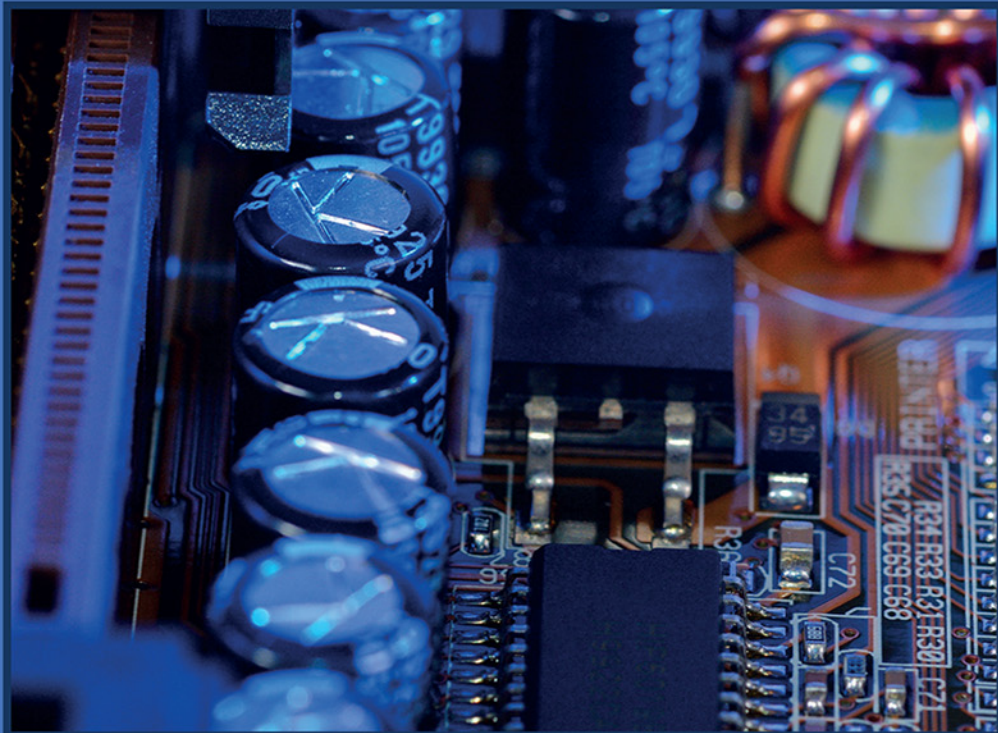


WOODHEAD PUBLISHING SERIES IN ELECTRONIC AND OPTICAL MATERIALS



CONJUGATED POLYMERS FOR NEXT-GENERATION APPLICATIONS

SYNTHESIS, PROPERTIES AND
OPTOELECTROCHEMICAL DEVICES

VOLUME 1



Edited by
VIJAY KUMAR, KASHMA SHARMA,
RAKESH SEHGAL, SUSHEEL KALIA

Woodhead Publishing Series in Electronic and
Optical Materials

Conjugated Polymers for Next-Generation Applications, Volume 1

**Synthesis, Properties and
Optoelectrochemical Devices**

Edited by

Vijay Kumar

Kashma Sharma

Rakesh Sehgal

Susheel Kalia



WP

WOODHEAD
PUBLISHING

An imprint of Elsevier

Contents

List of contributors	xiii
About the editors	xix
Preface	xxiii
1 Conjugated polymer-based fibers: synthesis, properties, and applications	1
<i>Krishnendu Nath and Narayan Chandra Das</i>	
1.1 Introduction	1
1.2 Synthesis of conjugated polymer -based fibers and properties	7
1.3 Application of conjugated polymer-based fibers	15
1.3.1 Electromagnetic interference shielding	15
1.3.2 Sensor devices	19
1.3.3 Photovoltaic/solar cells	23
1.3.4 Electrochemical supercapacitors/electrical storage device	25
1.3.5 Other applications of conjugated polymers	30
1.4 Conclusion	34
References	34
2 Techniques for designing patterned conducting polymers	39
<i>Muhammad Faiz Aizamddin, Mohd Muzamir Mahat, Nazreen Che Roslan, Dania Adila Ahmad Ruzaidi, Ayu Natasha Ayub, Nurul Ain Najihah Asri and Awis Sukarni Mohmad Sabere</i>	
2.1 Introduction	39
2.2 Synthesis of conducting polymer	41
2.2.1 Chemical oxidation	41
2.2.2 Electrochemical oxidation	42
2.3 Patterning of conducting polymer	43
2.3.1 Coating technique	43
2.3.2 Spin coating technique	44
2.3.3 Printing technique	47
2.3.4 Inkjet printing	49
2.3.5 Photolithography	54
2.3.6 Direct laser writing	62
2.3.7 Laser lithography of conducting polymers	63
2.4 Conclusion	68
References	69

3	Synthetic approaches of conducting polymer nanocomposites	79
	<i>Y.T. Ravikiran, CH.V.V. Ramana, R. Megha, R.S. Dubey and M. Prashantkumar</i>	
3.1	Introduction	79
3.2	Hydrothermal synthesis-based conducting polymer nanocomposite	81
	3.2.1 Synthesis	82
	3.2.2 Characterization	83
3.3	Sol–gel based conducting polymer nanocomposite	87
	3.3.1 Synthesis	90
3.4	Solid template-based conducting polymer nanocomposite	91
	3.4.1 Synthesis	93
	3.4.2 Characterization	93
3.5	In situ synthesis-based conducting polymer nanocomposite	100
	3.5.1 Synthesis	100
	3.5.2 Characterization	101
3.6	Summary	105
	Acknowledgment	107
	References	107
4	Mechanical properties of conjugated polymers	113
	<i>Rameshwar Adhikari, Bidit Lamsal, Tika Ram Bhandari, Shankar P. Khatiwada and Goerg H. Michler</i>	
4.1	Introduction and overview	113
4.2	Structure–properties correlation in polymers	114
4.3	Morphological diversities in conjugated polymers	118
4.4	Methods of mechanical characterization	121
	4.4.1 Tensile testing	122
	4.4.2 Dynamic mechanical analysis	122
	4.4.3 Micro- and nanoindentation methods	122
	4.4.4 In situ techniques	122
4.5	Factors affecting mechanical properties of conjugated polymers	127
	4.5.1 Molecular weight	127
	4.5.2 Temperature	129
	4.5.3 Regioregularity	131
	4.5.4 Polymer blends, composites, architectures, and fibers	131
4.6	Concluding remarks	133
	Acknowledgement	135
	References	135
5	Porous carbon from conducting polymers for electrochemical applications	147
	<i>Ashish Kumar, Chandra Jeet Verma, Manish Kumar Singh and Rajiv Prakash</i>	
5.1	Introduction	147
5.2	Control of porosity: a case study for pore formation	150

5.3	Source of porous carbon	152
5.3.1	Porous carbon from biomass	152
5.3.2	Porous carbon from conducting polymers	154
5.3.3	Porous carbon from metal–organic framework	158
5.3.4	Porous carbons form organic molecules	160
5.4	Porous carbon for electrochemical applications	161
5.4.1	Porous carbon for electrocatalysis	164
5.4.2	Porous carbon for charge storage	169
5.4.3	Porous carbon for electrochemical sensing	170
5.5	Summary and perspectives	172
	References	172
6	Conjugated polymers and graphene-based composites for flexible electrochemical energy storage devices: synthesis to device fabrication	181
	<i>Jun Ma, Junaid Ali Syed, Dongyun Su and Xiangkang Meng</i>	
6.1	Introduction	181
6.1.1	Conjugated polymers in flexible electrochemical energy storage devices	183
6.1.2	Graphene in flexible electrochemical energy storage devices	184
6.2	Conjugated polymers and graphene-based composites in supercapacitors	185
6.2.1	Polyaniline and graphene-based composites in supercapacitors	185
6.2.2	Polypyrrole and graphene-based composites in supercapacitors	192
6.2.3	Poly(3,4-ethylenedioxythiophene) and graphene-based composites in Supercapacitors	198
6.3	Graphene as a battery/lithium-ion storage	204
6.4	Conclusions/outlook	208
	References	209
7	Biobased conducting polymer composites for electromagnetic interference shielding and electronics applications	215
	<i>Rhiya Paul, P.A. Parvathy, Sreelakshmi P. Vijayan, Ben John and Sushanta K. Sahoo</i>	
7.1	Introduction	215
7.2	Intrinsic conducting polymers	216
7.3	Conducting polymer composites	217
7.3.1	Polymer matrices	217
7.3.2	Conductive polymer composites	219
7.3.3	Preparation of conducting polymers and composites	221
7.3.4	Applications	223
7.4	Biobased conducting polymer composites	225
7.4.1	The need of biobased conducting polymers	225

7.4.2	Preparation of biosourced conductive composites	226
7.4.3	Polymer composites for photovoltaics	230
7.4.4	Electromagnetic interference shielding and electronics applications	232
7.5	Conclusion	233
	References	233
8	Conjugated polymers in bioelectronics	239
	<i>Aparna Guchait, Anubhav Saxena, Santanu Chattopadhyay and Titash Mondal</i>	
8.1	Introduction	239
8.2	Basic mechanism associated in conjugated polymer and living organism	241
8.2.1	Conduction mechanism in conjugated polymers	241
8.2.2	Bioelectricity in living organisms	243
8.3	Synthesis of different conjugated polymers	245
8.3.1	Chemical oxidation polymerization	245
8.3.2	Vapor phase oxidation polymerization	245
8.3.3	Oxidative chemical vapor deposition	247
8.3.4	Electrochemical polymerization	247
8.3.5	Transition-metal-catalyzed polycondensation	248
8.3.6	Overview of commonly used conjugated polymers in bioelectronics	249
8.4	Application of conjugated polymers in bioelectronics	252
8.4.1	Tissue engineering and regenerative engineering	252
8.4.2	Drug delivery	256
8.4.3	Biosensor	259
8.5	In vivo studies	260
8.6	Concluding remarks	261
	References	262
9	Conjugated polymers-based sensors for detection of water pollutants	273
	<i>T. Senthil, Kingshuk Dutta, Duraisami Dhamodharan, Nidhin Divakaran and Lixin Wu</i>	
9.1	Introduction	273
9.2	A brief overview of the major water contaminants and their detection techniques	278
9.2.1	Heavy metal ions	278
9.2.2	Pesticides	281
9.2.3	Fertilizers	284
9.2.4	Pharmaceuticals	286
9.3	Use of conjugated polymers as sensor materials for water pollutants	288
9.3.1	Detection of heavy metal ions	288
9.3.2	Detection of pesticides and herbicides	293
9.3.3	Detection of fertilizers	295
9.3.4	Detection of harmful organic compounds and solvents	296

9.3.5	Detection of other water contaminants	299
9.4	Summary and future directions	299
	References	300
10	Conducting polymer-based textile materials	325
	<i>Nazreen Che Roslan, Muhammad Faiz Aizamddin, Dania Adila Ahmad Ruzaidi, Ayu Natasha Ayub, Nurul Ain Najihah Asri, Nur Aimi Jani, Saiful' Arifin Shafiee and Mohd Muzamir Mahat</i>	
10.1	Introduction	325
10.2	Overview of conducting polymer	327
10.3	Fabrication techniques	329
10.3.1	Dip coating	329
10.3.2	Wet-spinning technique	333
10.3.3	Electrospinning	340
10.4	Application of conducting polymers-based textiles as energy generators	346
10.4.1	Piezoelectric generators	346
10.4.2	Triboelectric nanogenerators	348
10.4.3	Thermoelectric generators	349
10.5	Challenges and future outlook	351
10.6	Conclusions	352
	References	352
11	Current trends on flexible and wearable mechanical sensors based on conjugated polymers combined with carbon nanotubes	361
	<i>Anthony Palumbo and Eui-Hyeok Yang</i>	
11.1	Introduction	361
11.2	Structure and properties	363
11.2.1	Conjugated polymers	363
11.2.2	Carbon nanotube	366
11.2.3	Conjugated polymers with carbon nanotubes	368
11.3	Synthesis	371
11.3.1	Conjugated polymers	371
11.3.2	Carbon nanotubes	372
11.3.3	Conjugated polymers with carbon nanotubes	373
11.3.4	Combining carbon nanotube and conjugated polymers toward flexible mechanical sensors	374
11.3.5	Substrates and dimensionality toward flexible mechanical sensors	381
11.4	Applications of conjugated polymers/carbon nanotubes as flexible mechanical sensors	387
11.4.1	Demonstrated durability toward wearable applications	389
11.4.2	Demonstrated functionalities toward wearable applications	391
11.5	Summary and future perspectives	393
	References	395

12	Conjugated polymers-based biosensors	401
	<i>Prakash Sengodu</i>	
12.1	Introduction	401
12.2	Conjugated polymers in biosensors	402
12.2.1	Immobilization methods for biosensors	403
12.3	Fabrication methods of conjugated polymers	408
12.4	Advantages and disadvantages of conjugated polymers in biosensors	413
12.5	Real-time application of conjugated polymers in biosensors	415
12.5.1	Bioelectronic noses and tongues	415
12.5.2	Aptasensors	416
12.5.3	Immunosensor	419
12.5.4	Glucose biosensors	422
12.5.5	H ₂ O ₂ biosensors	424
12.5.6	Photo bioimaging sensors	425
12.5.7	Photoelectrochemical biosensors	426
12.5.8	Other biochemical sensors (dopamine, ascorbic acid, and uric acid)	426
12.5.9	Pathogen sensors	427
12.6	Conclusion and outlook	430
	Acknowledgments	430
	References	430
13	π-Conjugated polymers for application in proton exchange membrane fuel cells	447
	<i>Kingshuk Dutta</i>	
13.1	Introduction	447
13.2	Recent advances in the use of π -conjugated polymers in different proton exchange membrane fuel cells	448
13.2.1	Hydrogen fuel cells	448
13.2.2	Direct methanol fuel cells	457
13.2.3	Direct ethanol fuel cells	464
13.2.4	Enzymatic fuel cells	467
13.2.5	Microbial fuel cells	469
13.3	Summary and future directions	478
	References	480
14	Conductive polymer-based composite photocatalysts for environment and energy applications	505
	<i>Jagdeep Singh, A.S. Dhaliwal, Kashma Sharma, Rakesh Sehgal and Vijay Kumar</i>	
14.1	Introduction	505
14.2	The mechanism of photocatalytic degradation of organic pollutants	507
14.3	The mechanism of photocatalytic hydrogen generation	510
14.4	Synthesis of conducting polymers	511

14.5	Conducting polymer-based nanocomposites	512
14.6	Conducting polymer for environment and energy applications	515
14.7	Conducting polymer-based composite for water treatment applications	516
14.8	Conducting polymer-based composite for photocatalytic H ₂ generation	519
14.9	Conclusion	523
	References	523
15	Conjugated polymers for electrochromic applications	539
	<i>Zhuang Mao Png, Ming Hui Chua, Qiang Zhu and Jianwei Xu</i>	
15.1	Introduction of electrochromics	539
15.2	Conjugated polymers for electrochromics	541
	15.2.1 Homo-polymers	541
15.3	Donor–donor and donor– π type copolymers for electrochromics	554
	15.3.1 Thiophene-based copolymers	554
	15.3.2 Fluorene-based copolymers	557
	15.3.3 Carbazole-based copolymers	558
15.4	Donor–acceptor type polymers for electrochromics	558
	15.4.1 Benzothiadiazole and analogues as acceptors	560
	15.4.2 Benzotriazole and analogues as acceptors	561
	15.4.3 Quinoxaline acceptors	563
	15.4.4 Diketopyrrolopyrrole acceptors	564
15.5	Conclusion and outlook	566
	Acknowledgment	568
	References	568
	Index	575

Conductive polymer-based composite photocatalysts for environment and energy applications

14

Jagdeep Singh¹, A.S. Dhaliwal¹, Kashma Sharma², Rakesh Sehgal³ and Vijay Kumar^{4,5}

¹Department of Physics, Sant Longowal Institute of Engineering and Technology, Longowal, Punjab, India, ²Department of Chemistry, DAV College, Chandigarh, India, ³Department of Mechanical Engineering, National Institute of Technology Srinagar, Jammu and Kashmir, India, ⁴Department of Physics, National Institute of Technology Srinagar, Jammu and Kashmir, India, ⁵Department of Physics, University of the Free State, Bloemfontein, South Africa

14.1 Introduction

Environmental pollution and deficiency of energy are two major problems faced by all the countries of the world. Overpopulation, industrialization, agricultural practices, and urbanization have led to various types of environmental pollutions such as air, water, and soil pollution [1,2]. Water is a significant natural resource and vital thing on earth for the survival of mankind. But human beings contaminate it by numerous activities such as household products, industrial wastage, medical waste, municipals, etc. Various types of contaminants viz. synthetic dyes, heavy metal ions, and different organic and inorganic substances cause water pollution [3–7]. The usage of contaminated water causes a wide range of harmful, poisonous, mutagenic, and carcinogenic effects [8,9]. Hence, to minimize the health hazards and to save the environment, the purification of wastewater is of major concern, and many water treatment techniques such as ion exchange [10], membrane filtration [11], chemical precipitation [12], advanced oxidation process [13], and electrochemical degradation [14,15] are available in the literature. Photocatalyst has a unique part and it can be employed as an encouraging candidate for wastewater purification applications [16].

Electricity production is not enough to make both ends meet of global energy demand in the present decades [17]. The 85% of energy originates by burning of fossil fuels such as coal, natural gas, and oil which lead to the emission of CO₂ greenhouse gases [18,19]. To reduce carbon emissions renewable energies will be a more reasonable option in the future. Even many countries have begun to install