

Contents

Preface xi

Part I Electrical Conductive Materials: General Aspects 1

- 1.1 **The Compromise Between Conductivity and Transparency** 3
Alicia de Andrés, Félix Jiménez-Villacorta, and Carlos Prieto
- 1.1.1 Introduction 3
- 1.1.2 Relevant Parameters for Transparent Electrodes 5
- 1.1.2.1 Transmittance 5
- 1.1.2.2 Transmittance and Absorption Coefficient: Experimental Aspects 6
- 1.1.2.3 Electronic Transport Parameters 7
- 1.1.2.4 Figure of Merit 9
- 1.1.3 Spectroscopies 11
- 1.1.3.1 Raman and Infrared Spectroscopies 11
- 1.1.3.2 X-ray Absorption Spectroscopies 13
- 1.1.3.3 UPS and XPS 15
- 1.1.4 Transparent Conducting Materials 17
- 1.1.4.1 Oxide Electrodes: Amorphous Films 17
- 1.1.4.2 Metallic Nanowires and Grids 18
- 1.1.4.3 Graphene and Graphene Oxide 19
- 1.1.4.4 Graphene Doping with Atoms and Nanoparticles 21
- 1.1.5 Conclusions and Forecast 24
- References 25

Part II Inorganic Conductive Materials 31

- 2.1 **Metallic Oxides (ITO, ZnO, SnO₂, TiO₂)** 33
Klaus Ellmer, Rainald Mientus, and Stefan Seeger
- 2.1.1 Introduction 33
- 2.1.2 Basic Bulk Properties 35
- 2.1.2.1 ITO 38
- 2.1.2.1.1 Crystallographic Structure 38

2.1.2.1.2	Electrical Properties	39
2.1.2.1.3	Optical Properties	40
2.1.2.2	ZnO	42
2.1.2.2.1	Crystallographic Structure	43
2.1.2.2.2	Electrical Properties	44
2.1.2.2.3	Optical Properties	46
2.1.2.3	SnO ₂	47
2.1.2.3.1	Crystallographic Structure	48
2.1.2.3.2	Electrical Properties	48
2.1.2.3.3	Optical Properties	48
2.1.2.4	TiO ₂	50
2.1.2.4.1	Crystallographic Structure	50
2.1.2.4.2	Electrical Properties	53
2.1.2.4.3	Optical Properties	55
2.1.3	Thin Film Properties	57
2.1.3.1	ITO	57
2.1.3.2	ZnO	59
2.1.3.3	SnO ₂	60
2.1.3.4	TiO ₂	63
2.1.4	Conclusions	67
	References	68
2.2	Chemical Bath Deposition	81
	<i>Peter Fuchs, Yaroslav E. Romanyuk, and Ayodhya N. Tiwari</i>	
2.2.1	Introduction	81
2.2.2	Principles of Chemical Bath Deposition	81
2.2.3	Material Examples	82
2.2.3.1	ZnO	82
2.2.3.2	SnO ₂	90
2.2.3.3	In ₂ O ₃	92
2.2.3.4	CdO	93
2.2.4	Low-temperature Post-deposition Treatment	93
2.2.5	Implementation of CBD TCOs in Devices	94
2.2.6	Conclusions and Outlook	96
	References	97
2.3	Metal Nanowires	105
	<i>Chao Chen and Changhui Ye</i>	
2.3.1	Synthesis of Metal Nanowires	108
2.3.2	Fabrication of Transparent Conductive Films on the Basis of Metal Nanowires	110
2.3.3	Patterning Metal Nanowire Transparent Conductive Films	112
2.3.4	Performance of Metal Nanowire Transparent Conductive Films	114
2.3.4.1	Transparency and Conductivity	115
2.3.4.2	Haze Factor	117
2.3.4.3	Color	119
2.3.4.4	Uniformity	120

2.3.4.5	Roughness	121
2.3.4.6	Adhesiveness	123
2.3.4.7	Stability	124
2.3.5	Concluding Remarks	126
	References	127

Part III Organic Conductive Materials 133

3.1	Carbon Nanotubes	135
	<i>Félix Salazar-Bloise</i>	
3.1.1	Introduction	135
3.1.2	Some Simple Carbon Structures	136
3.1.3	Graphene in the Context of Nanotubes	137
3.1.4	Fundamentals of Nanotubes	142
3.1.4.1	Structure of Carbon Nanotubes	142
3.1.4.2	Electronic Properties of Carbon Nanotubes	146
3.1.5	Mechanical Properties	151
3.1.6	Thermal Properties	152
3.1.7	Some Techniques for Producing Nanotubes	155
3.1.7.1	Arc-discharge Method	155
3.1.7.2	Laser Ablation	156
3.1.7.3	Chemical Vapor Deposition (CVD)	156
	References	156
3.2	Graphene	165
	<i>Judy Z. Wu</i>	
3.2.1	Introduction	165
3.2.2	Physical Properties of Intrinsic Graphene Transparent Conductors (GTCs)	167
3.2.3	Synthesis and Characterization of Graphene Transparent Conductors	169
3.2.3.1	Synthesis of Graphene	169
3.2.3.1.1	Solution Synthesis of Graphene	169
3.2.3.1.2	Chemical Vapor Deposition of Graphene on Metal Foils	170
3.2.3.1.3	Direct Growth of Graphene on Dielectric Substrates	171
3.2.3.2	Characterization of GTC Properties	174
3.2.3.3	GTC Interface with Other Materials in Heterostructures	175
3.2.3.3.1	Engineering Work Function of Graphene	175
3.2.3.3.2	Efficient Charge Transfer Across van der Waals Heterojunction Interface	176
3.2.4	Applications of Graphene Transparent Conductors	178
3.2.4.1	Photodetectors	178
3.2.4.2	Photovoltaics	180
3.2.4.2.1	Dye Sensitizer Solar Cells on GTC	180
3.2.4.2.2	Organic Solar Cells on GTC	181
3.2.4.2.3	Inorganic PV on GTC	182

3.2.4.3	Other Applications	182
3.2.5	Conclusion and Future Remarks	183
	Acknowledgments	183
	References	183
3.3	Transparent Conductive Polymers	193
	<i>Jose Abad and Javier Padilla</i>	
3.3.1	Introduction	193
3.3.1.1	About the Figure of Merit (FoM)	194
3.3.2	Polyaniline (PANI) and Polypyrrole (PPy)	195
3.3.2.1	Polyaniline (PANI)	196
3.3.2.2	Polypyrrole (PPy)	198
3.3.2.3	Other Polymers	198
3.3.3	Poly(3,4-dioxythiophene)-PEDOT	200
3.3.3.1	Oxidative Polymerization	200
3.3.3.2	In Situ Polymerization	200
3.3.3.3	Vapor-phase Polymerization (VPP)	201
3.3.3.4	Oxidative Chemical Vapor Deposition (o-CVD)	201
3.3.3.5	Electrochemical Polymerization	201
3.3.4	PEDOT:PSS	202
3.3.4.1	Solvents and Additives	203
3.3.4.2	Acids	204
3.3.4.3	Salts, Ionic Liquids, and Zwitterions	204
3.3.4.4	Other Approaches	207
3.3.4.5	PSS Substitution	207
3.3.5	Polymer-Metal Composites	208
3.3.5.1	Ag Grid/PEDOT:PSS	208
3.3.5.2	AgNW/PEDOT:PSS	210
3.3.5.3	Other Film Composites	212
3.3.6	Carbon-based Composites	212
3.3.6.1	Carbon Nanotubes (CNTs)	213
3.3.6.2	Graphene Oxide (GO) and Graphene (G)	215
3.3.7	Applications	216
3.3.8	Summary and Perspectives	217
	References	219

Part IV Characterization of Transparent Conductive Films 245

4.1	Characterizations of Electrical Properties by the van der Pauw Method	247
	<i>Yuichi Sato and Toru Matsumura</i>	
4.1.1	Introduction	247
4.1.2	Measurements of Electrical Properties by the van der Pauw Method	248

4.1.3	Effects of Positions, Sizes, and Shapes of the Electrical Contacts Mounted on Various Shapes of Measuring Samples on the van der Pauw Measurement Values	249
4.1.3.1	Effect of Positions and Sizes of the Electrical Contacts Mounted on a Circular Shape Measuring Sample	249
4.1.3.2	Effects of Conditions of the Electrical Contacts in Square-shaped Measuring Samples	250
4.1.4	Effect of Inhomogeneity Existing in Measuring Samples on the van der Pauw Measurement Values	252
4.1.4.1	Estimations of Errors in the van der Pauw Measurement Values Concerning Inhomogeneous Materials	254
4.1.4.2	Incorrect Determinations of the Carrier Type in the van der Pauw Measurements of Inhomogeneous ZnO	259
4.1.5	Conclusions	260
	References	261

Part V Applications 263

5.1	Electrochromic Oxide-based Materials and Devices for Glazing in Energy-efficient Buildings	265
	<i>Claes G. Granqvist</i>	
5.1.1	Introduction	265
5.1.2	Characterization of Optical Properties	267
5.1.3	Functional Principles and Materials	268
5.1.4	The Role of Nanostructure	270
5.1.5	Optical Properties	272
5.1.6	Case Study: Flexible Electrochromic Foil	275
5.1.7	Recent Development: Durability Assessment and Rejuvenation of Electrochromic Thin Films	282
5.1.8	Some Conclusions and Perspectives	285
	References	286
5.2	Transparent Electrodes for Organic Light-emitting Diodes	301
	<i>Shigeki Naka</i>	
5.2.1	Introduction	301
5.2.2	Transparent Electrodes for Anode	303
5.2.3	Conducting Polymers	304
5.2.4	Dielectric/Metal/Dielectric Electrodes	304
5.2.5	Buffer Layer for Anode	308
5.2.6	Transparent Electrodes for Cathode	309
5.2.7	Buffer Layer for Cathode	310
5.2.8	Carrier Injection at Organic/Electrode Interface	311
5.2.9	Issue of Transparent Electrode for OLEDs	312
5.2.10	Conclusions	314
	References	314

5.3	Dye-sensitized Devices: Photovoltaic and Photoelectrolytic Applications	<i>José A. Solera-Rojas, Marisol Ledezma-Gairaud, and Leslie W. Pineda</i>
5.3.1	Introduction	317
5.3.2	Properties of Titanium Dioxide	319
5.3.2.1	Structural Properties	319
5.3.2.2	Electronic Considerations	320
5.3.2.3	Optical Features	322
5.3.3	Surface Modification of TiO ₂	323
5.3.3.1	Chemical Modifications	324
5.3.3.1.1	Doping	324
5.3.3.1.2	Chemical Modification at the TiO ₂ Surface	324
5.3.3.1.3	Organometallic Dyes for Sensitization	324
5.3.4	Bridge-like Molecules to Immobilize Sensitizer Molecules in Nanoparticulate TiO ₂	326
5.3.5	Applications for the Development of Photoelectrochemical Cells in Water Oxidation Reaction	329
5.3.6	Concluding Remarks	331
	Acknowledgments	331
	References	332
5.4	Smart Windows Based on Liquid Crystal Dispersions	<i>Erick Castellón and David Levy</i>
5.4.1	Introduction	337
5.4.2	Liquid Crystals	337
5.4.3	Liquid Crystal Dispersion Materials as Smart-window Devices	342
5.4.4	Parameters of Electrooptical Performance in LC-dispersion-based Smart Windows	345
5.4.5	Polymer-dispersed Liquid Crystals	346
5.4.5.1	Colloidal Method	347
5.4.5.2	Solvent-induced Phase Separation	348
5.4.5.3	Temperature-induced Phase Separation	348
5.4.5.4	Polymerization-induced Phase Separation	348
5.4.6	Polymer-stabilized Liquid Crystals	351
5.4.7	Gel-glass-dispersed Liquid Crystals	352
5.4.7.1	Sol–Gel Chemistry	352
5.4.7.2	Liquid Crystal Dispersions in Sol–Gel Materials	353
5.4.8	Other Liquid Crystal-dispersion Devices	355
5.4.9	Conclusion	356
	References	357
	Concluding Remarks	367
	<i>Castellón Erick and David Levy</i>	
	Index	369