

Contents

About the Author *ix*

Preface *xi*

Acknowledgments *xiii*

1 Introduction *1*

1.1 Electrochromism: A Brief Note on the History and Recent Evolution *1*

Part I Materials *7*

2 Electrochromic Materials *9*

2.1 Inorganic Electrochromic Materials *11*

2.1.1 Transition Metal Oxide Cathodic Materials *12*

2.1.2 Transition Metal Oxide Anodic Materials *23*

2.1.3 Anodic and Cathodic – Transition Metal Oxide Materials: V_2O_5 *28*

2.2 2D Materials *31*

2.2.1 2D Transitional Metal Oxides *32*

2.2.2 Graphene *35*

2.3 Organic Electrochromic Materials *36*

2.3.1 Prussian Blue *36*

2.3.2 Viologens: Small Molecules, Polyviologens, and Hybrid Composite Materials *38*

2.3.3 Semiconducting Polymers *45*

3 Mixed Ionic and Electronic Conductors *55*

3.1 Semiconducting Polymers and Small Molecules *57*

3.2 Structure–Property Relationship and Charge Transport in Disordered Organic Materials *62*

3.3 Potential Impact of Mixed Conductors on the Design of New EC and Multifunctional Devices *65*

4 Electrolytes *67*

4.1 Liquid Electrolytes *68*

4.2 Polymer Electrolytes: From Gel to Solid Polymers *69*

4.2.1	Ionic Conductivity and Transport Properties in Polymer Electrolytes	81
4.3	Inorganic Electrolytes	85
5	Electrodes	89
5.1	Transparent and Conducting Oxides	89
5.2	Carbon-Based Electrode Materials	91
5.3	Metal Nanowires and Metal Grids	93
6	Critical Material Issues	99
 Part II Devices 105		
7	Device Structure: The Key Role of the Interfaces in the Device Design	107
7.1	Electrochromic Devices	108
7.1.1	All-Solid-State Double-Substrate Electrochromic Device	110
7.1.2	Monolithic Single-Substrate Electrochromic Device	116
7.2	Electrochromic Multifunctional Devices	121
7.2.1	Photoelectrochromic and Photovoltachromic: Device Architectures	122
7.2.1.1	Power Supply of Photoelectrochromic Devices: Semitransparent Silicon, DSSC, Polymers, and Perovskite PV Cell	128
7.2.2	Electrochromic and Electroluminescent Devices: ECOLEDs and ECLECs	140
7.2.2.1	Electroluminescence, Electrofluorescence, and Electrochromism: Multifunctional Devices Based on Thereof	151
7.2.3	Electrochromic Energy Storage Devices	156
7.2.4	Self-Rechargeable Electrochromic Transparent Battery and Self-Powered Photovoltaic Electrochromic Energy Storage Devices	163
8	Thin-Film Processing Technologies	169
8.1	Chemical Deposition	170
8.1.1	Spin Coating, Dip Coating, Spray Coating, and Inkjet Printing	170
8.1.2	Sol-Gel Method	172
8.1.3	Electrochemical Deposition	173
8.1.4	Langmuir-Blodgett Film Deposition	174
8.1.5	Chemical Vapor Deposition	175
8.2	Physical Depositions	176
8.2.1	Thermal and Electron-Beam Evaporation	177
8.2.2	Sputtering Deposition	178
8.2.3	Pulsed Laser Deposition	178
8.2.4	Molecular Beam Epitaxy	179
9	Analysis of Device Performance	181
9.1	Optical Spectroscopy	182
9.1.1	UV-Vis Spectroscopy and Optical Properties	182
9.1.2	Infrared Spectroscopy	186

- 9.2 Electrochemical Analysis 187
 - 9.2.1 Cyclic Voltammetry 188
 - 9.2.2 Chronoamperometry 194
 - 9.2.3 Electrochemical Impedance Spectroscopy: Interface Properties and Ion Diffusion Constants 196
 - 9.2.4 Cyclic Stability and Long-Term Durability 199
- 9.3 Chemical and Physical Methods for Electrochromism and Analysis of Material Properties 209
 - 9.3.1 X-Ray Photoemission Spectroscopy 210
 - 9.3.2 FTIR and Raman Spectroscopy 214
 - 9.3.3 Nuclear Magnetic Resonance Spectroscopy 216
 - 9.3.4 X-Ray Diffraction Analysis 218
- 9.4 Characterization of Mixed Ionic and Electronic Conduction Materials 222
 - 9.4.1 Direct Measurement of Ion Mobility in OMIECs 225

Part III Scale-Up, Energy and Environment, and Next-Generation Technologies 231

- 10 Construction of Smart Windows: From Laboratory to Industry Scale 233**
 - 10.1 Manufacturing Processes: Materials and Deposition Techniques 234
 - 10.2 Scale-Up Procedures: Electrochromic Windows and Large-Area Photovoltaic Modules 248
 - 10.3 Laminated Smart Windows and Adhesive Electrochromic Smart Films 261
- 11 Energy-Efficient Electrochromic Glazings for Green Buildings 263**
 - 11.1 Energy Demand and Consumption in Buildings: Energy Saving of Electrochromic Glazings 267
 - 11.2 Effect of Electrochromic Glazings on Visual Comfort: Usable UDI and DGI 270
- 12 Emerging and Next-Generation Technologies for Fabrication of Dynamic Tintable Windows 273**
 - 12.1 Smart Photoelectrochromic and Thermochromic Windows: Green Technologies Toward More Sustainable Buildings 273
 - 12.2 Emerging and Next-Generation Technologies 283
 - 12.3 The New Era of Artificial Intelligence: Toward Immersive Reality and Invisible Technologies 291

References 299

Index 337

