

Contents

Preface XIII

Author List XV

I Introduction 1

1 Organic Transistors 3

Gilles Horowitz

1.1 Introduction 3

1.2 Overview of the Organic Thin-film Transistor 4

1.2.1 Are Organic “Semiconductors” Real Semiconductors? 4

1.2.2 Thin-film Transistor Architecture 7

1.2.3 Operating Mode 8

1.2.4 Thickness of the Channel 10

1.3 Contact Resistance 15

1.3.1 Contact Resistance Extraction 15

1.3.2 Origin of Contact Resistance 19

1.4 Charge Transport 20

1.5 Fabrication Techniques 21

1.6 The Materials 23

1.6.1 Polymers 23

1.6.2 Small Molecules 24

1.6.3 n-Type Semiconductors 25

1.6.4 Single Crystals 26

1.6.5 Insulators 27

1.7 Concluding Remarks 28

Acknowledgements 29

References 29

II	Advanced Materials for Organic Electronics	33
2	High-performance Pentacene Transistors	35
	<i>Tommie Kelley</i>	
2.1	Introduction	35
2.2	Routes to Performance Improvement	38
2.2.1	Purification	38
2.2.2	Device Evolution	39
2.2.3	Structural Perfection	39
2.2.4	Device Architecture	41
2.2.5	Interfacial Control	45
2.3	Structure–Property Relationships	48
2.4	Continuing Reports of High Mobilities	51
2.5	Performance in Practice	52
2.6	The Future of High-performance Organic Transistors	53
	References	54
3	Engineered Pentacenes	58
	<i>John E. Anthony</i>	
3.1	Introduction	58
3.2	Reversible Functionalization	59
3.3	2,3,9,10-Tetrasubstituted and 2,3-Disubstituted Pentacenes: End-substituted Derivatives	60
3.4	<i>Peri</i> -functionalized Pentacene	63
3.5	Pentacene Functionalized at Both <i>peri</i> and End Positions	68
3.6	Heteropentacenes	69
3.7	Conclusion	72
	References	72
4	Organic Semiconductors Based on Polythiophene and Indolo[3,2-<i>b</i>]carbazole	75
	<i>Beng S. Ong, Yiliang Wu, and Yuning Li</i>	
4.1	Introduction	75
4.2	Issues and Challenges	76
4.3	Structural Considerations	79
4.4	Polythiophene Semiconductors	80
4.4.1	High-performance Polythiophene Design	81
4.4.2	Polydialkylterthiophenes	82
4.4.3	Polydialkylquaterthiophenes	87
4.4.4	Polythiophene Nanoparticles	90
4.4.5	Inkjet Patterned TFT Arrays	94
4.5	Indocarbazole Designs	95
4.6	Summary and Prospects	103
	Acknowledgements	105
	References	105

5	Electrical and Environmental Stability of Polymer Thin-film Transistors	108
	<i>Alberto Salleo and Michael L. Chabinyc</i>	
5.1	Introduction	108
5.2	Charge Trapping in TFTs	109
5.2.1	General Considerations	109
5.2.2	Bias Stress in Organic Transistors	111
5.3	Bias Stress in Polyfluorene and Polythiophene TFTs	112
5.3.1	Reversible Bias Stress	113
5.3.2	Long-lived Bias Stress	115
5.3.3	Dependence of Bias Stress on Operating Conditions; Lifetime Predictions	116
5.3.4	A Microscopic Theory of Bias Stress	118
5.4	Chemical Effects on Stability – Defects and Impurities	119
5.4.1	Introduction	119
5.4.2	Defects in Molecular Structure	120
5.4.2.1	Defects from Synthesis	120
5.4.2.2	Photo-induced Defects	121
5.4.3.1	Thermochemical Analysis	123
5.4.3.2	Oxygen	124
5.4.3.3	Water	126
5.4.3.4	Organic Solvents	127
5.4.3.5	Inorganic Impurities	127
5.4.3	Impurities	123
5.4.4	Studies of TFT Lifetime	128
5.5	Conclusion	129
	Acknowledgments	129
	References	129
6	Gate Dielectrics	132
	<i>Marcus Halik</i>	
6.1	Introduction	132
6.2	The Impact of Gate Dielectrics on the Electrical Functionality of Organic TFTs	133
6.3	Insulating Materials – An Overview	135
6.3.1	Inorganic Gate Dielectrics	136
6.3.2	Polymer Gate Dielectrics	137
6.3.3	Self-Assembled Monolayer Gate Dielectrics	138
6.3.4	Multi-layer and Multi-component Gate Dielectrics	139
6.3.5	Multifunctional Dielectrics	140
6.4	Application-related Aspects of Dielectrics	140
6.4.1	Poly-4-vinylphenol Dielectrics	141
6.4.2	The Self-assembled Monolayer Approach	153
	References	161

7	Advanced Flexible Polymeric Substrates	163
	<i>William A. MacDonald</i>	
7.1	Introduction	163
7.2	Polyester Substrates	163
7.3	Properties of Base Substrates	165
7.3.1	Optical Properties	165
7.3.2	Birefringence	166
7.3.3	Thermal Properties	166
7.3.4	Solvent Resistance	167
7.3.5	Surface Quality	170
7.3.6	Mechanical Properties	172
7.3.7	Summary of Key Properties of Base Substrates	173
7.4	Multilayer Structures	174
7.5	Film in Application	177
	Acknowledgments	178
	References	178
III	Manufacturing for Organic Electronics	181
8	Reel-to-reel Vacuum Metallization	183
	<i>Roland Treutlein, Martin Bergsmann, and Carl J. Stonley</i>	
8.1	Reel-to-reel Vacuum Metallization	183
8.1.1	The Metallization Process	184
8.1.1.1	Evaporation Sources	184
8.1.1.2	Pretreatment and Cleaning of the Web Substrate	186
8.1.1.3	PVD Process Flow	186
8.1.1.4	Typical Process Times, Rates, and Quantities	189
8.1.1.5	Transfer Metallization	190
8.1.1.6	Pattern-evaporated Layers	191
8.1.2	Properties of the Evaporated Layer	191
8.1.2.1	Structure	191
8.1.2.2	Layer Thickness (Conductivity)	192
8.1.2.3	Barrier	195
8.1.2.4	Light Barrier	197
8.1.3	Environmental Benefits of Vacuum Evaporated Layers	198
8.1.4	Applications of Metallized Films	199
8.1.4.1	Barrier Packaging	199
8.1.4.2	Decorative Applications	199
8.1.4.3	Functional Layers	199
8.1.4.4	Polymer Electronic Substrates	200
8.1.5	Market Analysis	201
	References	202

9	Organic Vapor Phase Deposition	203
	<i>Michael Heuken and Nico Meyer</i>	
9.1	Introduction	203
9.1.1	The Principle of OVPD	203
9.1.2	Close Coupled Showerhead Technology	204
9.2	Deposition of Organic Thin Films	207
9.2.1	Process Control in OVPD	207
9.2.2	Co-deposition and Doping in OVPD	211
9.2.3	Controlled Morphology and Layer Interfaces in OVPD	213
9.3	Electronic Devices by OVPD	215
9.3.1	OLEDs Made by OVPD	215
9.3.2	Organic Photovoltaics by OVPD	220
9.3.3	Organic Thin-film Transistors by OVPD	221
9.4	Full-color OLED Displays	222
9.4.1	Micropatterning by use of Shadow Masks	222
9.4.2	Mask-less Processes	224
9.5	Material Properties of Organic Molecules for Use in OVPD	225
9.6	Summary	226
	Acknowledgment	229
	References	229
10	Thermal Imaging and Micro-contact Printing	233
	<i>Hee Hyun Lee, John Rogers, and Graciela Blanchet</i>	
10.1	Introduction	233
10.2	Building Blocks	233
10.3	Printing and Patterning Techniques	235
10.3.1	Thermal Imaging	235
10.3.2	Printed Devices: From TFTs to Large-area Backplanes	236
10.4	Printable Materials	240
10.4.1	Polyaniline Nanotube Composites: A High-resolution Printable Conductor	240
10.5	Micro-contact Printing	245
10.5.1	Contact Printing with High-resolution Stamps	245
10.5.1.1	High-resolution Stamps	246
10.5.2	Micro-contact Printing	247
10.5.3	Nanotransfer Printing	251
10.6	Large Area Stamps, Molds, and Photomasks for Soft Lithography	259
10.6.1	Micro-contact Printing: A Path to Reel-to-reel Electronics	259
10.6.2	Inexpensive Approaches to Large-area Printing	259
10.6.3	Registration Using the Lock-and-key Mechanism in Soft Imprinting	264
10.7	Conclusions	266
	Acknowledgments	268
	References	265

11	Thin-film Transistor Fabrication by Digital Lithography	271
	<i>William S. Wong, Jürgen H. Daniel, Michael L. Chabinyk, Ana Claudia Arias, Steven E. Ready, and René Lujan</i>	
11.1	Introduction	271
11.2	Jet-printed Patterning for Thin-film Transistor Processing	272
11.2.1	Introduction	272
11.2.2	Jet-printed Phase-change Etch Masks	273
11.3	Digital Lithography	276
11.3.1	Digital Lithography for TFT Device Fabrication	276
11.3.2	Thin-film Transistor Device Structures	277
11.3.2.1	Amorphous Silicon TFTs	277
11.3.2.2	Polymeric TFTs by Digital Lithography	279
11.3.3	Thin-film Transistor Device Characteristics	282
11.3.3.1	a-Si:H TFTs	282
11.3.3.2	Printed Polymeric TFTs	284
11.4	TFTs on Flexible Substrates	285
11.4.1	Introduction	285
11.4.2	TFT Pixel Design Considerations	285
11.4.3	Digital Lithography for Flexible Backplanes	287
11.5	Display Applications with Print-patterned Backplanes	290
11.6	Conclusions	291
	Acknowledgments	291
	References	291
12	Manufacturing of Organic Transistor Circuits by Solution-based Printing	294
	<i>Henning Sirringhaus, Christoph W. Sele, Timothy von Werne, and Catherine Ramsdale</i>	
12.1	Introduction to Printed Organic Thin Film Transistors	294
12.2	Overview of Printing-based Manufacturing Approaches for OTFTs	297
12.2.1	Screen Printing	298
12.2.2	Offset Printing	299
12.2.3	Gravure Printing	300
12.2.4	Flexography	300
12.2.5	Inkjet Printing	301
12.2.6	Laser-based Dry-printing Techniques	302
12.2.7	Other Nonlithographic Manufacturing Approaches	302
12.3	High-resolution, Self-aligned Inkjet Printing	304
12.3.1	Self-aligned Printing by Selective Surface Treatment	305
12.3.2	Self-aligned Printing by Surface Segregation	307
12.3.3	Self-aligned Printing by Autophobic	308
12.4	Performance and Reliability of Solution-processed OTFTs for Applications in Flexible Displays	314
12.5	Conclusions	318
	Acknowledgments	319
	References	319

IV	Devices, Applications, and Products	323
13	From Transistors to Large-scale Integrated Circuits	325
	<i>Gerwin H. Gelinck, Erik van Veenendaal, Eduard J. Meijer, Eugenio Cantatore, H. Edzer A. Huitema, Pieter van Lieshout, Fred J. Touwslager, Alwin W. Marsman, and Dago M. de Leeuw</i>	
13.1	Introduction	325
13.2	Discrete Devices	326
13.2.1	Basic Device Operation of Organic Transistor	326
13.2.2	Current–Voltage Characteristics	327
13.2.3	Capacitance–Voltage Characteristics	328
13.3	Fabrication and Characterization of Integrated Circuits	330
13.3.1	Fabrication	331
13.3.2	Modeling	333
13.3.3	Analysis of Inverters	336
13.3.4	Analysis of Integrated Circuits	340
	Acknowledgments	342
	References	342
14	Roll-up Active-matrix Displays	344
	<i>H. Edzer A. Huitema, Gerwin H. Gelinck, Erik van Veenendaal, Fred J. Touwslager, and Pieter J. G. van Lieshout</i>	
14.1	Introduction	344
14.1.1	Non-rigid Display Research and Development Overview	345
14.2	Rollable Active-matrix Backplane Technology	346
14.3	Roll-up Active-matrix Backplane Design	349
14.3.1	Field-effect Mobility Effects	351
14.3.2	Leakage Current Effects	353
14.4	The Electronic Ink Film	354
14.5	Roll-up Display Integration	355
14.6	Functional Active-matrix Roll-up Displays	355
14.7	Roll-up Display Device Concepts	358
14.8	Towards a System-on-plastic: Driver Integration	358
14.8.1	Row Driver Integration	358
14.8.2	Stand-alone Shift Registers	360
14.8.3	Integrated Shift Registers	362
	Acknowledgment	364
	References	364
15	Active-matrix Light-emitting Displays	367
	<i>Shelby F. Nelson and Lisong Zhou</i>	
15.1	Introduction	367
15.2	OLED Pixel Differences from LCDs	369
15.3	Complex Pixel Design	369
15.4	Practical Design	370

15.5	AIM–SPICE Simulation of Pentacene TFT-driven OLEDs	372
15.6	Fabrication Process	375
15.7	Device Passivation	376
15.8	PVA and Parylene	380
15.9	Pentacene TFT Uniformity	381
15.10	Stability	383
15.11	Integration of TFTs and OLEDs	384
15.12	Flexible OLED Display	386
15.13	Substrate Selection and Mounting	387
15.14	Thermal Dimensional Stability	387
15.15	Surface Quality	388
15.16	Chemical Resistance	389
15.17	Fabrication Process	390
15.18	Display Results	390
15.19	Conclusion	391
	References	392
16	Large-area Detectors and Sensors	395
	<i>Takao Someya and Takayasu Sakurai</i>	
16.1	Introduction	395
16.2	Large-area Pressure Sensors	396
16.3	Organic Transistor-based Integrated Circuits	398
16.4	Bending Experiments of Organic Transistors	400
16.5	High-temperature Operation of Organic Transistors	401
16.6	Sheet Image Scanners	402
16.7	Three-dimensional Integrated Circuits	405
16.8	Future Prospects of Large-area Electronics	407
16.9	Remaining Issues	407
16.10	Conclusions	408
	Acknowledgments	409
	References	409
17	Organic Semiconductor-based Chemical Sensors	411
	<i>Howard E. Katz and Jia Huang</i>	
17.1	Background	411
17.2	Inorganic and Nanostructured Semiconductor Sensors	412
17.3	Sensitive Organic Field-effect Transistors	414
17.4	Mechanistic Rationale	416
17.5	Conclusion	418
	References	419
	Index	422