

Contents

List of Contributors *xiii*

1	Printing Technologies for Nanomaterials	1
	<i>Robert Abbel and Erwin R. Meinders</i>	
1.1	Introduction	1
1.2	Ink Formulation Strategies	4
1.3	Printing Technologies	6
1.3.1	Inkjet Printing	7
1.3.1.1	Toward 3D Printing	10
1.3.2	Laser-Induced Forward Transfer	11
1.3.2.1	Toward 3D Printing	13
1.3.3	Contact Printing Technologies	13
1.3.4	Photopolymerization	17
1.3.5	Powder Bed Technology	19
1.4	Summary and Conclusions	20
	References	20
2	Inkjet Printing of Functional Materials and Post-Processing	27
	<i>Ingo Reinhold</i>	
2.1	Introduction	27
2.2	Industrial Inkjet	28
2.3	Postprocessing of Metal-Based Inks for Conductive Applications	30
2.3.1	Mechanisms in Solid-State Sintering	32
2.3.2	Influence of Drying and Wet Sintering	34
2.3.3	Thermal Sintering	35
2.3.4	Chemical Sintering	35
2.3.5	Plasma Sintering	36
2.3.6	Sintering Using Electromagnetic Fields	37
2.3.6.1	Impulse Light Sintering	39
2.3.6.2	Microwave Sintering	40
2.3.6.3	Influence of the Substrate	41
2.4	Conclusion	42
	References	43

3	Electroless Plating and Printing Technologies	51
	<i>Yosi Shacham-Diamand, Yelena Sverdlov, Stav Friedberg, and Avi Yaverboim</i>	
3.1	Introduction	51
3.2	Electroless Plating – Overview	54
3.2.1	Electroless Plating – Brief Overview	55
3.3	Seed Layer Printing	57
3.4	Electroless Plating on Printed Parts	57
3.4.1	Methods and Approaches	59
3.4.1.1	Printed Pd Seed	59
3.4.1.2	Printed Ag Ink	60
3.4.1.3	Preseed Surface Modification	60
3.4.2	Electroless Metal Integration: Examples	60
3.5	Summary and Conclusions	63
	References	64
4	Reactive Inkjet Printing as a Tool for <i>in situ</i> Synthesis of Self-Assembled Nanoparticles	69
	<i>Ghassan Jabbour, Mutalifu Abulikamu, Hyung W. Choi, and Hanna Haverinen</i>	
4.1	Introduction to Reactive Inkjet Printing	69
4.2	RIJ of Self-Assembled Au NPs	70
4.3	Parameters Influencing the Growth of Au NPs	74
4.4	Simplifying the Approach (Single Cartridge) Using Single Cartridge Step	77
4.5	Further Progress toward Reduction of Fabrication Time (1 min)	77
4.6	Conclusion	79
	References	79
5	3D Printing via Multiphoton Polymerization	83
	<i>Maria Farsari</i>	
5.1	Multiphoton Polymerization	84
5.2	The Diffraction Limit	85
5.3	Experimental Setup	86
5.4	Materials for MPP	88
5.4.1	Introduction	88
5.4.2	Photoinitiators	88
5.4.3	Organic Photopolymers	89
5.4.4	SU-8	90
5.4.5	Hybrid Materials	90
5.4.6	Applications	91
5.4.6.1	Metamaterials	91
5.4.6.2	Biomedical Applications	94
5.5	Conclusions	96
	References	96

6	High Speed Sintering: The Next Generation of Manufacturing	107
	<i>Adam Ellis</i>	
6.1	The Need for the Next Generation of Additive Manufacturing	107
6.2	High Speed Sintering	109
6.3	Machine Setup & Parameter Control	109
6.4	Materials & Properties	112
6.5	HSS for High-Volume Manufacturing	113
6.6	Case Study: From Elite to High Street	115
6.7	Opening the Supply Chain	115
6.8	The Future of HSS and the Benefits of Inkjet	116
	References	116
7	Metallic Nanoinks for Inkjet Printing of Conductive 2D and 3D Structures	119
	<i>Alexander Kamyshny and Shlomo Magdassi</i>	
7.1	Introduction	119
7.2	Metallic Nanoinks: Requirements and Challenges	120
7.3	Synthesis and Stabilization of Metal NPs for Conductive Nanoinks	121
7.3.1	Synthesis	121
7.3.2	Stabilization	122
7.3.2.1	Stabilization Against Aggregation	122
7.3.2.2	Stabilization Against Oxidation	124
7.4	Formulation of Conductive Metallic Nanoinks	125
7.5	Formation of 2D Conductive Structures: Printing and Sintering	127
7.6	3D Printing of Conductive Patterns: Formation and Sintering	134
7.7	Applications of Metallic Inkjet Nanoinks in Printed Electronics	135
7.7.1	RFID Tags	136
7.7.2	Thin-Film Transistors	136
7.7.3	Electroluminescent Devices and Light-Emitting Diodes	136
7.7.4	Transparent Conductive Electrodes	137
7.7.5	Organic Solar Cells	138
7.8	Outlook	139
	References	140
8	Graphene- and 2D Material-Based Thin-Film Printing	161
	<i>Jiantong Li, Max C. Lemme, and Mikael Östling</i>	
8.1	Introduction	161
8.2	Printing Procedures	162
8.2.1	Ink Formulations	162
8.2.2	Jetting and Patterns	166
8.2.3	Drying	166

8.2.4	Posttreatments	171
8.3	Performance and Applications	172
8.3.1	Transparent Conductors	173
8.3.2	Micro-Supercapacitors	173
8.3.3	Photodetectors	174
8.3.4	Solar Cells	176
8.4	Discussion and Outlook	177
	Acknowledgments	178
	References	178
9	Inkjet Printing of Photonic Crystals	183
	<i>Minxuan Kuang and Yanlin Song</i>	
9.1	Introduction	183
9.2	Inkjet Printing of Photonic Crystals	184
9.2.1	Process of Inkjet Printing	184
9.2.2	Inkjet Printing of Fine Controlled PC Dots and Lines	186
9.2.2.1	Influence of the Ink Formulation	186
9.2.2.2	Influence of Substrate Wettability	188
9.2.2.3	Suppression of "Coffee-Ring" Effect	193
9.3	Application of Printing of Photonic Crystals	196
9.3.1	Photonic Crystal Patterns	196
9.3.2	Printing Patterned Microcolloidal Crystals with Controllable 3D Morphology	199
9.3.3	Inkjet-Printed PCs Applied in Vapor Sensors	201
9.3.4	Inkjet-Printed PCs Applied in Chemical Detection	201
9.4	Outlook	203
	References	204
10	Printable Semiconducting/Dielectric Materials for Printed Electronics	213
	<i>Sunho Jeong and Jooho Moon</i>	
10.1	Introduction	213
10.2	Printable Materials for Semiconductors	213
10.3	Printable Materials for Dielectrics	219
10.4	Conclusions	223
	References	224
11	Low Melting Point Metal or Its Nanocomponents as Functional 3D Printing Inks	229
	<i>Lei Wang and Jing Liu</i>	
11.1	Introduction of Metal 3D Printing	229
11.2	Low Melting Point Metal Ink	230
11.2.1	Liquid Metal Printing Ink	230
11.2.2	Nanoliquid Metal	232

- 11.3 Liquid-Phase 3D Printing 234
 - 11.3.1 Fabrication Scheme 234
 - 11.3.2 Forming Principle of Metal Objects in Cooling Liquid 235
 - 11.3.3 Liquid-Phase Printing of Metal Structures 236
 - 11.3.4 Factors Affecting the Printing Quality 237
 - 11.3.5 Comparison Between Liquid-Phase Cooling and Gas-Phase Cooling 238
 - 11.3.6 Vision of the Future Liquid-Phase Printing 240
- Acknowledgment 241
- References 241

- 12 Inkjet Printing of Conducting Polymer Nanomaterials 245**
Edward Song and Jin-Woo Choi
 - 12.1 Introduction 245
 - 12.2 Inkjet Printing of Polyaniline Nanomaterials 246
 - 12.2.1 Introduction 246
 - 12.2.2 Chemical Structure, Electrochemical Properties, and Conductivity of Polyaniline 246
 - 12.2.3 Inkjet-Printed Polyaniline Nanomaterials 249
 - 12.2.4 Applications of Inkjet-Printed Polyaniline Nanomaterials 250
 - 12.3 Polypyrrole 251
 - 12.3.1 Properties and Synthesis of Polypyrrole (Ppy) Nanomaterials 251
 - 12.3.2 Inkjet Printing and Applications of Ppy Nanomaterials 254
 - 12.4 Polythiophene (Pth) and Poly(3,4-Ethylenedioxythiophene) (PEDOT) 258
 - 12.4.1 Properties and Synthesis of Pth and PEDOT Nanomaterials 258
 - 12.4.2 Inkjet Printing and Applications of Pth Nanomaterials 258
 - 12.5 Conclusions and Future Outlook 258
 - References 260

- 13 Application of Printed Silver Nanowires Based on Laser-Induced Forward Transfer 265**
Teppei Araki, Rajesh Mandamparambil, Jinting Jiu, Tsuyoshi Sekitani, and Katsuaki Suganuma
 - 13.1 Introduction 265
 - 13.2 Ag NW Transparent Electrodes 266
 - 13.2.1 Background 266
 - 13.2.2 Transparent Electrodes Formed from Ultra-Long Ag NWs 267
 - 13.3 Printed Ag NW Electrodes 269
 - 13.3.1 Fabrication and Properties of Stretchable Electrodes 269
 - 13.3.2 Ag NWs Printing by LIFT 269
 - 13.4 Summary 271
 - References 271

14	Inkjet Printing of Functional Polymers into Carbon Fiber Composites	275
	<i>Patrick J. Smith, Elliot J. Fleet, and Yi Zhang</i>	
14.1	Inkjet Printing	275
14.2	Carbon Fiber Composites	276
14.3	Mechanical Tests	276
14.4	Printing and Sample Preparation	277
14.5	Carbon Fiber Composites that Contain Inkjet-Printed Patterns Composed of PMMA Microdroplets	278
14.6	Carbon Fiber Composites that Contain Inkjet-Printed Patterns Composed of PMMA and PEG Microdroplets	283
14.7	Morphology of the Printed PMMA and PEG Droplets	284
14.8	Printed Polymers for Intrinsic Repair of Composites	286
14.9	Conclusions	288
	Acknowledgments	289
	References	289
15	Inkjet-Printable Nanomaterials and Nanocomposites for Sensor Fabrication	293
	<i>Niamh T. Brannelly and Anthony J. Killard</i>	
15.1	Introduction	293
15.2	Metallic Inks	294
15.2.1	Gold	294
15.2.2	Silver	296
15.2.3	Copper, Nickel, and Alumina	296
15.2.4	Metal Oxides	297
15.3	Conductive Polymers	298
15.3.1	Polyaniline	299
15.3.2	Polypyrrole	300
15.3.3	Prussian Blue	301
15.3.4	PEDOT	302
15.4	Carbon Nanomaterials	302
15.4.1	Graphene Oxide	302
15.4.2	Carbon Nanotubes	304
15.5	Future Outlooks and Conclusions	308
	References	308
16	Electrochromics for Printed Displays and Smart Windows	317
	<i>Pooi See Lee, Guofa Cai, Alice L.-S. Eh, and Peter Darmawan</i>	
16.1	Overview on Electrochromics	317
16.1.1	Electrochromics for Green Buildings	318
16.1.2	Electrochromics for Displays	320
16.1.2.1	Solution Processing of Electrochromics	322
16.1.2.2	Printing Techniques in Electrochromics	324
16.2	Screen Printing	324
16.3	Inkjet Printing	326

16.4	Flexographic Printing	329
16.5	Roll-to-Roll Printing	329
16.6	Other Printing Methods	329
16.7	Conclusions and Perspectives	330
	References	332
	Index	341