

# **Flexible Flat Panel Displays**

---

*Edited by*

**Gregory P. Crawford**

*Brown University, USA*



**John Wiley & Sons, Ltd**

# Contents

---

<b>List of Contributors</b>	xvii
<b>Foreword</b>	xxiii
<b>Series Editor's Foreword</b>	xxv
<b>Preface</b>	xxvii
<b>1 Flexible Flat Panel Display Technology</b>	1
<i>Gregory P. Crawford</i>	
1.1 Introduction	1
1.2 Manufacturing	4
1.3 Enabling Technologies	5
1.3.1 Flexible substrates	6
1.3.2 Barrier layers	6
1.3.3 Inorganic conducting layers and mechanical properties	7
1.3.4 Organic conducting layers and mechanical properties	7
1.3.5 Optical coatings	7
1.3.6 Thin film transistors	7
1.3.7 Electro-optic materials	8
1.3.8 Flexible display prototypes	8
1.3.9 Markets	8
1.4 Conclusions	9
References	9
<b>2 Engineered Films for Display Technologies</b>	11
<i>Bill A. MacDonald, Keith Rollins, Duncan MacKerron, Karl Rakos, Robert Eveson, Katsuyuki Hashimoto, and Bob Rustin</i>	
2.1 Introduction	11
2.2 Polymer Substrates	12
2.3 Properties	13
2.3.1 Optical properties	13
2.3.2 Birefringence	14
2.3.3 Thermal properties	14
2.3.4 Moisture and solvent resistance	19
2.3.5 Surface treatment	20

2.3.6	Barrier	23
2.3.7	Mechanical properties of the composite structure	24
2.4	Polyester Films in Application	27
2.4.1	Novel low-temperature processes for building silicon-based TFTs	28
2.4.2	Adapting existing silicon processes to reasonably low temperature	29
2.4.3	Organic-based TFTs with processing temperatures below 200 °C	30
2.4.4	Use of Teonex in flexible displays	30
2.5	Concluding Remarks	31
	Acknowledgements	31
	References	31
<b>3</b>	<b>Flexible Glass Substrates</b>	<b>35</b>
	<i>Armin Plichta, Andreas Habeck, Silke Knoche, Anke Kruse, Andreas Weber, and Norbert Hildebrand</i>	
3.1	Introduction	35
3.2	Display Glass Properties	36
3.2.1	Overview of display glass types	36
3.2.2	Glass properties	37
3.3	Manufacturing of Thin “Flexible” Glass	41
3.3.1	Float and downdraw technology for special glass	41
3.3.2	Limits	42
3.4	Mechanical Properties	45
3.4.1	Thin glass and glass/plastic substrates	45
3.4.2	Mechanical test methods for flexible glasses	45
3.5	Improvement in Mechanical Properties of Glass	48
3.5.1	Reinforcement of glass substrates	48
3.6	Processing of Flexible Glass	50
3.6.1	Cleaning	51
3.6.2	Separation	51
3.7	Current Thin Glass Substrate Applications and Trends	53
3.7.1	Displays	53
3.7.2	Touch panels	53
3.7.3	Sensors	54
3.7.4	Wafer-level chip size packaging	54
	References	55
<b>4</b>	<b>Barrier Layer Technology for Flexible Displays</b>	<b>57</b>
	<i>Gordon L. Graff, Paul E. Burrows, Rick E. Williford, and Robert F. Praino</i>	
4.1	Introduction	57
4.2	Development of Thin Film Vapor Barrier Systems	58
4.2.1	Organic electronics: packaging needs	59
4.2.2	Single-layer gas barrier films on polymeric substrates	59
4.2.3	Multilayer gas barrier films for OLEDs	60
4.3	Measurement Techniques	61
4.3.1	Steady-state transmission tests	61
4.3.2	The calcium test	62
4.3.3	Defect characterization	63
4.4	Theories of Vapor Barrier Permeation	63

4.5	Deconvolution of Experimental Data	64
4.5.1	Transient and steady-state permeation models	65
4.5.2	Methods to determine in situ properties	67
4.5.3	Implications for multilayer barrier systems	72
4.6	Discussion	73
4.7	Conclusions	74
	Acknowledgements	75
	References	75
<b>5</b>	<b>Transparent Conducting Oxide Materials and Technology</b>	<b>79</b>
	<i>David C. Paine, Hyo-Young Yeom, and Burag Yaglioglu</i>	
5.1	Introduction	79
5.2	Materials Selection and Characterization	80
5.2.1	Transparent conducting materials classes: why oxides?	80
5.2.2	Transparent conducting oxides: general considerations	81
5.3	Indium-Based Binary Oxides	84
5.3.1	Background	84
5.3.2	Crystalline indium tin oxide	86
5.3.3	Amorphous indium tin oxide	90
5.3.4	Amorphous indium zinc oxide	92
5.4	Future Directions for Transparent Conducting Oxides	94
5.4.1	Novel materials	94
5.4.2	Manufacturing considerations	95
5.5	Summary	96
	References	97
<b>6</b>	<b>Mechanics of ITO on Plastic Substrates for Flexible Displays</b>	<b>99</b>
	<i>Piet C. P. Bouten, Peter J. Slikkerveer, and Yves Leterrier</i>	
6.1	Introduction	99
6.1.1	Plastic substrates contain thin brittle layers	99
6.1.2	Thermoelastic properties of thin films	100
6.1.3	Mechanical loading and internal stresses	101
6.1.4	Failure modes of thin brittle films	102
6.2	Failure of Brittle Layers under Tensile Stress	103
6.2.1	Mechanical test methods	103
6.2.2	Characteristic failure modes	104
6.2.3	Experimental analysis of uniform layers	104
6.2.4	Experimental analysis of patterned layers	108
6.2.5	Discussion on failure mechanics	109
6.3	Failure of Brittle Layers under Compressive Stress	112
6.3.1	Some pictures of characteristic failure modes	112
6.3.2	Mechanism of buckling failure	113
6.3.3	Buckling strain	114
6.3.4	Discussion	115
6.4	The Failure Situation in a Display	117
6.4.1	Summary of the failure results	117
6.4.2	More complex situations	118
6.4.3	What does it mean for a product?	118
6.5	Conclusions	119
	Acknowledgements	119
	References	120

<b>7 Stability of Externally Deformed ITO Films</b>	<b>121</b>
<i>Jeong-In Han</i>	
7.1 Introduction	121
7.2 Mechanical Properties of Thin Films	122
7.2.1 Numerical analysis of mechanical stress induced by bending force	123
7.2.2 Experimental results for bending-induced mechanical stress	127
7.3 Conclusions	131
References	132
<b>8 Conductive Polymers</b>	<b>135</b>
<i>L. "Bert" Groenendaal</i>	
8.1 Introduction	135
8.2 Historical Overview	138
8.3 Overview of Polymerization Methods	139
8.3.1 Chemical oxidative polymerizations	139
8.3.2 Chemical reductive polymerizations	140
8.3.3 Polymerizations based on organometallic cross-coupling reactions	141
8.3.4 Electrochemical polymerizations	144
8.4 Overview of Conductive Polymer Types	145
8.4.1 Polyacetylene and derivatives	145
8.4.2 Polyaniline and derivatives	148
8.4.3 Polypyrrole and derivatives	151
8.4.4 Polythiophene and derivatives	153
8.4.5 Other conductive polymers	156
8.5 Applications for Conductive Polymers	156
8.6 Outlook	158
References	159
<b>9 Mechanical Reliability of Conductive Polymers for Rollable Display Applications</b>	<b>163</b>
<i>Darran R. Cairns</i>	
9.1 Introduction	163
9.2 Electromechanical Properties of Transparent Anodes	165
9.2.1 ITO-coated PET in tension	166
9.2.2 PEDOT:PSS in tension	169
9.2.3 Cyclic loading in tension	169
9.3 Environmental Degradation of PEDOT:PSS	171
9.4 Cyclic Mandrel Loading of Flexible Anodes	172
9.5 Conclusions	174
References	175
<b>10 Optical and Functional Coatings for Flexible Displays</b>	<b>179</b>
<i>Matthew E. Sousa and Gregory P. Crawford</i>	
10.1 Introduction	179
10.2 Thin Film Polarizers	180
10.2.1 Thin crystal film polarizers	180
10.2.2 Cholesteric film polarizers	182

10.3	Thin Film Retarders	184
10.3.1	Thin crystal film retarders	184
10.3.2	Reactive mesogen retarders	185
10.4	Color Filters	186
10.5	Alignment Layers	188
10.5.1	Linear polymerized photopolymer alignment layers	189
10.5.2	Multidomain linear polymerized photopolymer alignment layers	189
10.6	Antireflective Coatings	190
10.7	Summary	191
	References	191
<b>11</b>	<b>Patterning Techniques and Semiconductor Materials for Flexible Electronics</b>	<b>195</b>
	<i>John A. Rogers and Graciela Blanchet</i>	
11.1	Introduction	195
11.2	Large-Area Patterning Techniques	197
11.2.1	Contact printing with high-resolution stamps	197
11.2.2	Thermal transfer printing	202
11.2.3	Combining contact and thermal transfer printing	204
11.3	Printable Semiconductors and Devices	205
11.3.1	Conventional organic semiconductors	205
11.3.2	New printable semiconductors for flexible circuits	209
11.4	Prototype Circuits and Systems	212
11.5	Conclusions	214
	Acknowledgements	214
	References	215
<b>12</b>	<b>Printed Organic Electronics</b>	<b>219</b>
	<i>Raj B. Apte, Robert A. Street, Ana Claudia Arias, Alberto Salleo, Michael Chabinyc, William S. Wong, Beng S. Ong, Yiliang Wu, Ping Liu, and Sandra Gardner</i>	
12.1	Introduction	219
12.2	System Requirements	220
12.3	Transistor Requirements	222
12.3.1	Fabrication methods	224
12.3.2	Contact resistance	224
12.3.3	Short-channel effects	226
12.3.4	Bias stress and chemical stability	226
12.4	Organic Semiconductors	229
12.4.1	High-performance polythiophene designs	231
12.4.2	Poly(dialkylterthiophene)	232
12.4.3	Poly(dialkylquaterthiophene)	235
12.5	Digital Lithography	237
12.5.1	Subtractive printing	237
12.5.2	Additive printing	238
12.6	Prospects	240
	Acknowledgements	240
	References	241

<b>13</b>	<b>Rollable Active Matrix Displays with Organic Electronics</b>	<b>245</b>
	<i>Edzer Huitema, Gerwin Gelinck, Erik van Veenendaal, Fred Touwslager, and Pieter van Lieshout</i>	
13.1	Introduction	245
13.2	Flexible Display Overview	246
13.3	Organic Electronics Technology	247
13.4	Display Design and Processing	248
13.5	Transistor Requirements	249
13.5.1	Field-effect mobility effects	250
13.5.2	Leakage current effects	252
13.6	Transistor Characteristics	253
13.7	Functional Displays	255
13.8	Driver Integration	256
13.8.1	32-Stage shift registers	258
13.8.2	120-Stage shift registers	259
	Acknowledgement	260
	References	260
<b>14</b>	<b>Mechanics of TFT Technology on Flexible Substrates</b>	<b>263</b>
	<i>Sigurd Wagner, Helena Gleskova, I-Chun Cheng, James C. Sturm, and Z. Suo</i>	
14.1	Introduction	263
14.2	Deformation of a TFT Backplane	264
14.2.1	Mechanical stresses introduced during shaping	264
14.2.2	Mechanical stresses introduced during fabrication	265
14.3	Stress, Strain and Curvature of a Film/Substrate Couple	267
14.3.1	Stiff substrate	267
14.3.2	Compliant substrate	268
14.3.3	Bending by externally applied moment	269
14.4	Effects of Mechanical Strain on a-Si TFTs	270
14.5	Shaping of TFT Backplanes by Plastic Deformation	272
14.6	Case Studies of Stiff TFT Films on Organic Polymer Substrates	275
14.6.1	Evaluating built-in stress in a device film	275
14.6.2	Controlling mask overlay alignment by adjusting built-in stress	279
14.6.3	Determining Electrical Failure of a-Si TFTs after Bending	280
14.7	Summary and Outlook	281
	References	282
<b>15</b>	<b>OLED Displays on Plastic</b>	<b>285</b>
	<i>Mark L. Hildner</i>	
15.1	Introduction	285
15.2	PLED Basics	286
15.2.1	Conjugated polymers	286
15.2.2	Light-emitting diodes	287
15.2.3	OLED display types	289
15.3	Plastic Substrates for OLED	289
15.3.1	Substrate requirements	289
15.3.2	Plastic base film	290

15.3.3	Barrier	291
15.3.4	Composite substrate	292
15.4	Substrate Processing Issues	293
15.4.1	Processing issues	293
15.4.2	Film stress	294
15.4.3	Dimensional stability	295
15.4.4	Substrate fixturing	298
15.5	Passive Matrix Display Fabrication	298
15.5.1	PMOLED structure	298
15.5.2	Substrate patterning	299
15.5.3	Active material application	302
15.5.4	Cathode and encapsulation	303
15.5.5	Device operation	304
15.6	Active Matrix for OLED on Plastic	304
15.6.1	Structure	304
15.6.2	TFT requirements	305
15.7	Conclusion	307
	Acknowledgements	308
	References	308
<b>16</b>	<b>Encapsulated Liquid Crystal Materials for Flexible Display Applications</b>	<b>313</b>
	<i>Gregory P. Crawford</i>	
16.1	Introduction	313
16.2	History of Encapsulated Liquid Crystals	314
16.3	Encapsulation Techniques	318
16.4	Conformed Polymer-Dispersed Liquid Crystals	319
16.5	Holographic Polymer-Dispersed Liquid Crystals	321
16.6	Prefabricated Templates Impregnated with Liquid Crystal	325
16.7	Summary	325
	References	326
<b>17</b>	<b>Cholesteric Liquid Crystals for Flexible Displays</b>	<b>331</b>
	<i>J. William Doane and Asad Khan</i>	
17.1	Introduction	331
17.2	Basic Properties of Cholesteric Displays	332
17.2.1	Cholesteric domains	334
17.2.2	Display brightness and view angle	335
17.2.3	Degree of circular polarization and brightness	336
17.2.4	Effect of cell thickness: brightness versus contrast	337
17.2.5	Drive voltage threshold and multiplexing	338
17.3	Drive Schemes, Chips and Circuitry	341
17.3.1	Conventional drive	341
17.3.2	Dynamic drive	341
17.3.3	Cumulative drive	342
17.3.4	Active matrix drive	342
17.4	Power Consumption	342
17.5	Full Color	343
17.5.1	Stacked color displays	344

17.5.2	Color patterning	345
17.5.3	Black and white	345
17.6	Droplet Dispersions for Flexible Displays	345
17.6.1	Emulsification	346
17.6.2	Droplet morphology	347
17.6.3	Phase separation	347
17.7	Toward Flexible Displays	350
17.7.1	Displays from emulsions	350
17.7.2	Displays from PIPS processes	351
17.7.3	Conducting polymer electrodes	352
17.8	Conclusions	352
	References	352
<b>18</b>	<b>Paintable LCDs: Single-Substrate LCDs Produced by Photoenforced Stratification</b>	<b>355</b>
	<i>Roel Penterman, Stephen I. Klink, Joost P. A. Vogels, Edzert A. Huitema, Henk de Koning, and Dirk J. Broer</i>	
18.1	Introduction	355
18.2	Photoenforced Stratification	356
18.3	Experimental Procedures	357
18.4	Single UV Exposure	359
18.5	Two-step UV Exposure	359
18.6	Paintable Displays	362
18.7	Improved Paintable LCD Technology	364
18.8	Conclusion	367
	Acknowledgements	367
	References	368
<b>19</b>	<b>Electrophoretic Imaging Films for Electronic Paper Displays</b>	<b>369</b>
	<i>Karl Amundson</i>	
19.1	Introduction	369
19.2	Scattering Imaging Films for Displays	370
19.3	Electrophoresis and Electrophoretic Imaging	372
19.3.1	Electrophoretic switching speed	373
19.3.2	Image stability and waveforms	374
19.3.3	Integration of films into displays	374
19.3.4	Failure modes and their remedies	377
19.4	Current Electrophoretic Display Development Efforts	378
19.4.1	Microencapsulated electrophoretic displays	378
19.4.2	Microcellular air-gap electrophoretic displays	383
19.4.3	In-plane electrophoretic displays	385
19.5	Flexible and Conformable EPID Displays	387
	References	389
<b>20</b>	<b>Gyricon Materials for Flexible Displays</b>	<b>393</b>
	<i>Nicolas Sheridan</i>	
20.1	Introduction	393
20.2	Electro-Optical Response	394
20.3	Image Storage	396

20.4	Brightness and Contrast	398
20.5	Addressing Methods	401
20.5.1	Multiple fixed-image addressing with printed circuit boards	402
20.5.2	Linear electrode array (stylus wand) addressing	403
20.6	Fabrication	405
20.7	Conclusions	406
	References	406
<b>21</b>	<b>Roll-to-Roll Manufacturing of Flexible Displays</b>	<b>409</b>
	<i>Abbie Gregg, Lara York, and Mark Strnad</i>	
21.1	Background	409
21.1.1	Some Challenges	410
21.2	Objective	411
21.3	Device Scenario	411
21.4	Product Design	412
21.4.1	Process and tool tables	412
21.5	Tools	414
21.5.1	Tools for roll-to-roll processing	414
21.5.2	Develop, etch, strip	416
21.6	Device Inspection	416
21.6.1	Darkfield technologies	417
21.6.2	Batch web coater for EB deposition	417
21.7	Die Punch for Alignment and Registration	418
21.8	Evaporator: Thermal Cathode for LEP Device	418
21.9	Evaporator: OLED	418
21.10	Exposure: Proximity	419
21.11	Exposure: Step and Repeat	419
21.12	Inkjet Deposition	420
21.12.1	Litrex 140L inkjet system	420
21.13	Lamination	420
21.13.1	Preco 2430 P	420
21.13.2	Schmid CSL 4000	421
21.14	Laser Processing	421
21.15	Roll Coater: Photoresist	421
21.15.1	Toray model 1-2	421
21.15.2	Systronic RC 4000	421
21.16	Screen Printer	422
21.16.1	Preco	422
21.17	Oven for Low-Temperature Curing	422
21.17.1	Gruenberg model 4/MM6H100.83M	422
21.18	Sputtering	422
21.19	Materials Discussion	423
21.19.1	PEFT substrate	423
21.20	Thermal Budget for Plastic Substrates	424
21.21	Interleaf or Slip Sheet	424
21.22	Materials List	424
21.23	Processing Issues	424
21.23.1	Moisture and oxygen resistance	424
21.23.2	Cleanliness and particles	425
21.23.3	Defects and yield	425

21.24 Material Handling in Roll-to-Roll Processing	425
21.24.1 Lift cart	426
21.24.2 Leader material	427
21.24.3 Loading new rolls of material	428
21.24.4 Resist coater	429
21.24.5 Web edge in photoresist process	429
21.24.6 Cleanliness	429
21.24.7 Throughput of handling equipment	429
21.24.8 Tension control	429
21.24.9 Intermittent processing and alignment	431
21.24.10 Punch	431
21.24.11 Roll-to-roll optical alignment	431
21.24.12 Price of interleaf handling	432
21.24.13 Corrosion prevention: wet process	433
21.24.14 Lamination with prepunched windows	433
21.24.15 Integration of vision systems for alignment	434
21.24.16 Minienvironment enclosures	434
21.24.17 Web handling	435
21.24.18 Tension control systems	436
21.24.19 Web transport systems	437
21.24.20 Advanced roll-to-roll processing	438
21.25 Results from the Cost Model	439
21.25.1 Glossary of modelling terms	439
21.25.2 Yields	440
21.25.3 Cost results	441
21.25.4 Cost components	441
21.25.5 Cost by category	442
21.25.6 Factory size issues	442
21.25.7 Tool spacing limitations	443
21.25.8 Minimum realistic capital investment	443
21.25.9 Summary of results	443
21.25.10 Obstacles, technical issues and concerns	444
Bibliography	445
<b>22 High-Resolution Full-Color Flexible TFT LCDs Based on Amorphous Silicon</b>	<b>447</b>
<i>Jin Jang, Sung Hwan Won, Bo Sung Kim, Mun Pyo Hong, and Kyu Ha Chung</i>	
22.1 Introduction	447
22.2 Effect of He Dilution on SiN <sub>x</sub> Deposition	450
22.3 a-Si:H TFT on Plastic with an Organic Gate Insulator	452
22.4 Fabrication of an a-Si:H TFT Array on Plastic	456
22.5 a-Si:H TFT LCD on Plastic	459
22.5.1 Color filter on plastic	459
22.5.2 LC cell	460
22.5.3 Driver IC bonding and driving	460
References	461
<b>23 All-Plastic Color TFT LCDs Based on Low-Temperature Poly-Si</b>	<b>463</b>
<i>Akihiko Asano</i>	
23.1 Introduction	463

23.2	Overview of the Process	465
23.2.1	TFT device process	465
23.2.2	Transfer process	466
23.2.3	Cell process	467
23.3	Results of the Transfer Process	467
23.3.1	Transferred device pattern	467
23.3.2	Influence on TFT characteristics	468
23.4	Changes in TFT Characteristics with Substrate Bending	470
23.5	Display Properties of Plastic LCDs	473
23.5.1	Specification and structure	473
23.5.2	Display performance	474
23.5.3	Displayed image on curved LCD	475
23.6	Problems to Solve	475
23.7	Summaries and Future Prospect	477
	Acknowledgements	477
	References	477
<b>24</b>	<b>TFT Transfer Technology</b>	<b>479</b>
	<i>Sumio Utsunomiya, Satoshi Inoue, and Tatsuya Shimoda</i>	
24.1	Introduction	479
24.2	TFT Transfer Process Sequence	481
24.3	Transfer Mechanism	483
24.4	TFT Performance	485
24.5	Applications	487
24.5.1	SUFTLA TFT LCD	487
24.5.2	SUFTLA TFT OLED	489
24.6	Summary	493
	References	493
<b>25</b>	<b>Markets and Applications of Flexible Displays</b>	<b>495</b>
	<i>Kimberly Allen</i>	
25.1	Introduction	495
25.2	Why Flexible?	496
25.2.1	Lightweight displays	497
25.2.2	Rugged displays	497
25.2.3	Curved displays	497
25.2.4	Roll-up displays	497
25.2.5	Roll-to-roll manufacturing	498
25.3	Supporting Technologies	498
25.3.1	Substrate materials	499
25.3.2	Semiconductor material classes	501
25.3.3	Processing transistors on plastic	502
25.3.4	Flexible display manufacturing processes	505
25.4	Flexible Display Technologies	506
25.4.1	Liquid crystal displays	506
25.4.2	Organic light-emitting diode displays	507
25.4.3	Electrophoretic displays	508
25.4.4	Other types of display	509
25.5	Market Forecast	510
25.5.1	Top-level market view	511

**xvi      CONTENTS**

25.5.2	Market by display technology	512
25.5.3	Market by application	513
25.6	Regional Development	518
25.7	Investment and Commitment	519
25.8	What Will it Take?	520
25.8.1	New substrate material	520
25.8.2	Full-color process	521
25.8.3	A “champion” leading to critical mass	521
25.8.4	Compelling applications	521
25.8.5	Ultra low cost production	522
25.9	Conclusion	522
	References	523
	<b>Index</b>	<b>525</b>