

# Contents

Preface .....	v
---------------	---

---

## Part I Fabrication

---

### 1 Micro-Structuring and Ferroelectric Domain Engineering of Single Crystal Lithium Niobate

S. Mailis, C.L. Sones, R.W. Eason .....	3
1.1 Introduction.....	3
1.2 Other Methods .....	4
1.3 Differential Chemical Etching .....	5
1.3.1 $z$ -Faces .....	5
1.3.2 $y$ -Faces .....	9
1.3.3 Microstructures.....	11
1.4 Summary and Future Work .....	17
References.....	18

### 2 Fabrication and Characterization of Self-Assembled Ferroelectric Linear and Nonlinear Photonic Crystals: GaN and LiNbO<sub>3</sub>

L.-H. Peng, H.-M. Wu, A.H. Kung, C.-M. Lai .....	21
2.1 Introduction.....	21
2.2 Micro-Domain Engineering with Conventional Poling Electrode Design .....	23
2.2.1 Internal Field Effect in the Poling of Congruent-Grown LiNbO <sub>3</sub> or LiTaO <sub>3</sub> .....	23
2.2.2 Origin of the Fringe Field .....	24
2.2.3 Poling Issues with Doped or Stoichiometric LiNbO <sub>3</sub> and LiTaO <sub>3</sub> .....	26
2.3 From Micron to Submicron Domain Engineering with Improved Electrode Design .....	27
2.3.1 Charged Potential Barrier Method .....	27
2.3.2 Stack of High- $k$ Dielectric Poling Electrode Method .....	36

2.3.3 Submicron Domain Engineering with Self-Assembly Type of Poling Electrodes .....	40
2.3.4 Submicron Domain Engineering in Ferroelectric Semiconductors .....	44
2.4 Conclusion .....	47
References.....	48
<b>3 Sub-Micron Structuring of LiNbO<sub>3</sub> Crystals with Multi-Period and Complex Geometries</b>	
<i>S. Grilli, P. Ferraro</i> .....	53
3.1 Introduction .....	53
3.2 Overview of the Etching Techniques Applied to Lithium Niobate .....	53
3.3 Electric Field Poling and Overpoling .....	59
3.4 Holographic Lithography .....	61
3.5 Periodic Sub-Micron Structuring .....	63
3.5.1 Overpoling Applied to One-Dimensional Michelson Resist Gratings .....	63
3.5.2 Overpoling Applied to Two-Dimensional Michelson Resist Gratings .....	65
3.5.3 Overpoling Applied to Two-Beams Resist Gratings at Sub-Micron Scale .....	66
3.5.4 Complex Surface Structures by Moiré HL .....	67
3.6 Double-Face Sub-Micron Surface Structures .....	72
3.7 Possible Applications for Novel Photonic Crystal Devices .....	73
References .....	76
<b>4 Nonlinear Optical Waveguides in Stoichiometric Lithium Tantalate</b>	
<i>M. Marangoni, R. Ramponi</i> .....	79
4.1 Material Properties .....	81
4.1.1 Physical Properties .....	81
4.1.2 Optical Properties .....	83
4.2 Waveguide Fabrication through Reverse-Proton-Exchange .....	85
4.2.1 Fabrication and Characterization Procedures .....	87
4.2.2 Modelling .....	88
4.3 Second-Harmonic Generation in RPE-PPSLT Waveguides .....	93
4.3.1 Highly Confining Waveguides .....	93
4.3.2 Weakly-Confining Waveguides .....	95
References .....	97
<b>5 3-D Integrated Optical Microcircuits in Lithium Niobate Written by Spatial Solitons</b>	
<i>E. Fazio, M. Chauvet, V.I. Vlad, A. Petris, F. Pettazzi, V. Coda, M. Alonso</i> .....	101
5.1 Review of Waveguide Fabrication Techniques .....	101
5.2 Theory of Photorefractive–Photovoltaic Spatial Solitons in Biased LiNbO <sub>3</sub> .....	102

5.2.1 Photorefractive Model . . . . .	102
5.2.2 Time Dependent Electric Field Distribution . . . . .	103
5.2.3 PR Space Charge Field . . . . .	104
5.2.4 Soliton Solutions . . . . .	105
5.2.5 Dark Solitons . . . . .	106
5.2.6 Bright Solitons . . . . .	110
5.3 Photorefractive Bright Soliton Observation . . . . .	112
5.4 Waveguiding in Soliton Channels/Strips . . . . .	115
5.4.1 Experimental Observation . . . . .	115
5.4.2 Fixing Soliton Waveguides and Circuits in Lithium Niobate Crystals . . . . .	116
5.4.3 Waveguide Characteristics . . . . .	117
5.5 Optical Microcircuits with Soliton Waveguides . . . . .	117
5.5.1 Passive . . . . .	117
5.6 Optical Microcircuits with Solitons Waveguides . . . . .	119
5.6.1 Passive . . . . .	119
5.6.2 Active . . . . .	122
5.7 Three-Dimensional Optical Micro-Circuits with SWGs . . . . .	129
References . . . . .	132

## Part II Characterization

---

### 6 Light Aided Domain Patterning and Rare Earth Emission Based Imaging of Ferroelectric Domains

<i>V. Dierolf, C. Sandmann</i> . . . . .	137
6.1 Introduction and Background . . . . .	137
6.1.1 Overview . . . . .	137
6.1.2 Rare Earth Ions in LiNbO <sub>3</sub> . . . . .	137
6.1.3 Combined Excitation Emission Spectroscopy . . . . .	139
6.1.4 Confocal Microscopy and Spectroscopy . . . . .	141
6.2 Application of RE Spectroscopy to the Imaging of Integrated Optical Devices in Lithium Niobate . . . . .	143
6.2.1 Rare Earth Ions as Probes . . . . .	144
6.2.2 Imaging of Waveguides . . . . .	144
6.2.3 Imaging of Ferroelectric Domains and Domain Wall Regions . . . . .	147
6.2.4 Imaging of Periodically Poled Waveguide Structures . . . . .	151
6.3 Light Induced Domain Inversion . . . . .	153
6.3.1 Methods . . . . .	153
6.3.2 Build-Up of Charge under Focussed Laser Irradiation . . . . .	154
6.3.3 Influence of Light on Domain Inversion and Growth . . . . .	155
6.3.4 Direct Writing of Domain Patterns . . . . .	158
6.4 Summary and Conclusions . . . . .	162
References . . . . .	163

<b>7 Visual and Quantitative Characterization of Ferroelectric Crystals and Related Domain Engineering Processes by Interferometric Techniques</b>	
<i>P. Ferraro, S. Grilli, M. Paturzo, S. Nicola</i> . . . . .	165
7.1 Introduction . . . . .	165
7.2 Measuring the Refractive Indices and Thickness of Lithium Niobate Wafers . . . . .	166
7.3 Visualization and <i>In-Situ</i> Monitoring of Domains Formation . . . . .	171
7.3.1 Digital Holography and Experimental Configuration for <i>In-Situ</i> Investigation of Poling . . . . .	174
7.3.2 Investigation of the Electro-Optic Effect and Internal Fields . . . . .	192
7.3.3 Evaluation of Optical Birefringence at Ferroelectric Domain Wall in LiNbO <sub>3</sub> . . . . .	201
References . . . . .	204
<b>8 New Insights into Ferroelectric Domain Imaging with Piezoresponse Force Microscopy</b>	
<i>T. Jungk, A. Hoffmann, E. Soergel</i> . . . . .	209
8.1 Introduction . . . . .	209
8.1.1 Ferroelectrics . . . . .	209
8.1.2 Lithium Niobate (LiNbO <sub>3</sub> ) . . . . .	210
8.2 Principles of Scanning Force Microscopy (SFM) . . . . .	211
8.2.1 Tip-Cantilever-Surface Interactions . . . . .	211
8.2.2 Cantilever Movements . . . . .	212
8.2.3 Cross-Talk . . . . .	213
8.2.4 Calibration . . . . .	213
8.3 Principles of Piezoresponse Force Microscopy (PFM) . . . . .	214
8.3.1 PFM Setup & Standard Settings . . . . .	214
8.3.2 System-Inherent Background in PFM Measurements . . . . .	216
8.3.3 Vectorial Description . . . . .	216
8.4 Consequences of the System-Inherent Background . . . . .	218
8.4.1 Background-Induced Misinterpretations . . . . .	218
8.4.2 Background-Free PFM Imaging . . . . .	220
8.5 Quantitative Piezoresponse Force Microscopy . . . . .	221
8.5.1 Amplitude of the PFM Signal . . . . .	222
8.5.2 Domain Wall Width . . . . .	222
8.6 Ferroelectric Domain Imaging by Lateral Force Microscopy . . . . .	223
8.6.1 Origin of the Lateral Signal . . . . .	224
8.6.2 Application to PPLN . . . . .	224
8.7 Conclusions . . . . .	226
References . . . . .	226

<b>9 Structural Characterization of Periodically Poled Lithium Niobate Crystals by High Resolution X-Ray Diffraction</b>	
<i>M. Bazzan, N. Argiolas, C. Sada, P. Mazzoldi</i>	229
9.1 Introduction	229
9.2 The Principle of the XRD Technique	232
9.2.1 The Theory of High Resolution X-Ray Diffraction	233
9.2.2 The HRXRD Applied to PPLN Crystals	239
9.3 Experimental Set-Up for Structural Characterization by HRXRD	242
9.4 Applications	246
9.4.1 Investigation of Sub-Micrometric PPLN Crystals	246
9.4.2 Investigation of Micrometric PPLN Crystals with Bent Domain Walls	249
9.5 Conclusions	253
References	254
<hr/>	
<b>Part III Applications</b>	
<b>10 Nonlinear Interactions in Periodic and Quasi-Periodic Nonlinear Photonic Crystals</b>	
<i>A. Arie, A. Bahabad, N. Habshoosh</i>	259
10.1 Introduction	259
10.2 Wave Equations in NLPC	261
10.3 Analysis of a Periodic Nonlinear Photonic Crystal	263
10.3.1 The Real Lattice	263
10.3.2 The Reciprocal Lattice	265
10.3.3 Conversion Efficiency for Specific Types of 2D Periodic Structures	266
10.4 Analysis of a Quasi-Periodic Nonlinear Photonic Crystal	272
10.4.1 Statement of the Problem	272
10.4.2 Solution by Quasiperiodic Lattices	273
10.4.3 Establishing an Orthogonality Condition	274
10.4.4 Tiling the Quasi-Periodic Lattice by the Dual Grid Construction	275
10.4.5 The Fourier Transform of the Quasi-Periodic Lattice	276
10.4.6 From Lattice to a Nonlinear Photonic Crystal	277
10.4.7 A One-Dimensional Example – The Three Wave Doubler	278
10.5 Discussion and Summary	282
References	283
<b>11 Domain-Engineered Ferroelectric Crystals for Nonlinear and Quantum Optics</b>	
<i>M. Bellini, P. Cancio, G. Gagliardi, G. Giusfredi, P. Maddaloni, D. Mazzotti, P. Natale</i>	285
11.1 Introduction	285

11.1.1 Classification of Nonlinear Processes . . . . .	285
11.1.2 Phase Matching . . . . .	286
11.2 Nonlinear Optics for Spectroscopic Applications . . . . .	287
11.2.1 Coherent Sources for mid-IR Spectroscopy and Metrology . . . . .	287
11.2.2 OFCS Extension to the mid-IR . . . . .	288
11.2.3 Future Perspectives . . . . .	295
11.3 Structured Nonlinear Crystals for Quantum Optics . . . . .	296
11.3.1 Quantum Light Sources . . . . .	297
11.3.2 Single-Photon Detectors . . . . .	301
References . . . . .	303
<b>12 Photonic and Phononic Band Gap Properties of Lithium Niobate</b>	
<i>M.P. Bernal, M. Roussey, F. Baida, S. Benchabane, A. Khelif, V. Laude</i> . . . . .	307
12.1 Introduction . . . . .	307
12.2 Photonic Crystals . . . . .	309
12.2.1 Band Structure Theory and Slow Light . . . . .	309
12.2.2 Fabrication and Examples . . . . .	313
12.2.3 Experimental Procedure . . . . .	314
12.2.4 Measurement of a PBG in a LN Photonic Crystal . . . . .	318
12.2.5 LN PtC Waveguides: Transmission and SNOM Characterization . . . . .	319
12.2.6 A LN PtC Intensity Modulator . . . . .	321
12.3 Phononic crystals . . . . .	323
12.3.1 Theory . . . . .	323
12.3.2 Fabrication and Examples . . . . .	326
12.4 Conclusion . . . . .	332
References . . . . .	334
<b>13 Lithium Niobate Whispering Gallery Resonators: Applications and Fundamental Studies</b>	
<i>L. Maleki, A.B. Matsko</i> . . . . .	337
13.1 Introduction . . . . .	337
13.2 Modulators . . . . .	338
13.2.1 Principle of Operation . . . . .	340
13.2.2 Performance . . . . .	340
13.3 Tunable Filters . . . . .	341
13.3.1 First-Order Filter . . . . .	341
13.3.2 Third-Order Filter . . . . .	342
13.3.3 Fifth-Order Filter . . . . .	344
13.3.4 Insertion Loss . . . . .	345
13.4 WGRs Made of Periodically Poled Lithium Niobate . . . . .	346
13.4.1 Optical Frequency Doubling . . . . .	347
13.4.2 Calligraphic Poling . . . . .	350
13.4.3 Reconfigurable Filters . . . . .	351
13.5 Photorefractive Damage . . . . .	352

13.5.1 Congruent LiNbO <sub>3</sub> . . . . .	354
13.5.2 Magnesium Doped Congruent LiNbO <sub>3</sub> . . . . .	356
13.5.3 Crossings and Anticrossings of the Modes . . . . .	358
13.5.4 Holographic Engineering of the WGM Spectra . . . . .	359
13.6 Infrared Transparency and Photorefractivity of Lithium Niobate Crystals: Theory . . . . .	359
13.6.1 Rate Equations . . . . .	362
13.6.2 Solution of the Rate Equations . . . . .	365
13.6.3 Absorption of the Light and Initial Concentration of the Filled Traps . . . . .	368
Appendix A: Basic Properties of WGMs . . . . .	371
Appendix B: Lithium Niobate Impurities: A Short Review of Existing Results . . . . .	372
B.1 Small Polarons . . . . .	373
B.2 Bipolarons . . . . .	374
B.3 Iron . . . . .	375
Appendix C: Photorefractivity in Red: A Short Review of the Existing Results . . . . .	376
C.1 Light Induced Change of Refractive Index . . . . .	376
C.2 Light Induced Change of Absorption . . . . .	377
Appendix D: Numerical Values of the Basic Rates Characterizing the Impurities . . . . .	377
References . . . . .	380
<b>14 Applications of Domain Engineering in Ferroelectrics for Photonic Applications</b>	
<i>D.A. Scrymgeour</i> . . . . .	385
14.1 Introduction . . . . .	385
14.2 Ferroelectrics and Domain Engineering . . . . .	385
14.3 Applications of Domain Engineered Structures . . . . .	387
14.3.1 Frequency Conversion . . . . .	387
14.3.2 Electro-Optic Devices . . . . .	390
14.4 Challenges of Domain Engineered Ferroelectric Devices . . . . .	396
14.5 Conclusions . . . . .	397
References . . . . .	398
<b>15 Electro-Optics Effect in Periodically Domain-Inverted Ferroelectrics Crystals: Principles and Applications</b>	
<i>J. Shi, X. Chen</i> . . . . .	401
15.1 Introduction . . . . .	401
15.2 Basic principle . . . . .	402
15.2.1 Electro-Optic Effect in Crystals . . . . .	402
15.2.2 Electro-Optical Effect for Crystals of 3m Symmetry Group . . . . .	404
15.2.3 Electro-Optical Effect in Periodically Domain-Inverted Crystals with 3m Symmetry . . . . .	407

15.3 Applications .....	413
15.3.1 Devices Based on Bragg Diffraction Grating Structure .....	413
15.3.2 Devices Based on Solc-Layered Structure .....	416
15.3.3 Other Application Devices .....	418
References .....	419