Contents

1 Introduction: Overview of Agile Microwave Technologies 1
1.1 Introduction 1
1.2 Ferroelectrics: The Main Material Properties 2
1.2.1 Ferroelectric Properties 3
1.2.2 Dielectric Properties 4
1.2.3 Acoustic Properties 5
1.2.4 Typical Microwave Paraelectrics 6
1.3 Microwave Applications 7
1.3.1 Historical Overview 7
1.3.2 Current Status 8
1.3.3 Potential and Trends 11
1.4 Other Agile Microwave Technologies 15
1.5 Conclusions 18
References 18

2 Physics of the Tunable Ferroelectric Devices 21
2.1 Introduction 21
2.2 Crystal Structure, Non-Polar (Paraelectric) and Polar (Ferroelectric) Phases 22
2.3 Dielectric Models of the Ferroelectric and Paraelectric Phases 24
2.3.1 Phenomenological (Thermodynamic) Theory 24
2.3.2 Microscopic Theory 27
2.4 Engineering Models of the Dielectric Permittivity 29
2.4.1 Barrett's Formula. Bulk Single Crystals 29
2.4.2 Rupprecht–Bell–Silverman Model. Bulk Single Crystals 30
2.4.3 Vendik's Model. Bulk Single Crystals 31
2.4.4 Granular Ceramics and Composites 32
2.4.5 Columnar Thin Film Ceramics and Composites 34

2.5 Models of the Loss Tangent 37
2.5.1 Loss Mechanisms and Early Models of the Loss Tangent 37
2.5.2 Models of the Main Loss Mechanisms 39
2.6 Dielectric Nonlinearities 44
2.6.1 Nonlinear Performance of Paraelectrics 44
2.6.2 Nonlinearity and Power Handling Capability 45
2.7 Thin Films vs. Bulk 46
2.7.1 Thin Film vs. Bulk Single Crystal 46
2.7.2 Strain 48
2.7.3 The Effects of the Strain on Dielectric Properties of the Thin Films 50
2.8 Electro-Acoustic Properties 52
2.8.1 Electrostriction 52
2.8.2 Piezoelectricity and Electrostriction 52
2.8.3 Electric Field Induced Piezoelectricity in Paraelectric Films 54
2.9 Bulk Conductivity 56
2.10 Conclusions 57
References 57

3 Fabrication of Ferroelectric Components and Devices 61
3.1 Introduction 61
3.2 Fabrication of Devices Using Single Crystals 63
3.2.1 Growth Techniques of Single Crystals 63
3.2.2 Structural Characterization 64
3.2.3 Bulk Single Crystal Devices 65
3.2.4 Thin Film Single Crystal Capacitors 66
3.3 Fabrication of Devices Using Bulk Ceramics 68
3.3.1 Ceramic Processes 68
3.3.2 Bulk Ceramic Device Fabrication 68
3.3.3 Structure of the Bulk Ferroelectric Ceramics 73
3.4 Thick Film, HTCC and LTCC Technologies 74
3.4.1 Fabrication of Devices Using Thick Film Technology 74
3.4.2 Fabrication of HTCC and LTCC Devices 76
3.4.3 Structure of Thick and HTCC/LTCC Films 78
3.5 Fabrication of Thin Ferroelectric Films 80
3.5.1 Chemical Deposition Methods 81
3.5.2 Physical Deposition Methods 87
3.6 Thin Film Device Processing 98
3.6.1 Coplanar-Plate Configuration 99
3.6.2 Parallel-Plate Configuration 101
3.7 Substrate Micromachining and Passivation 106
3.7.1 Substrate Micromachining 106
3.7.2 Substrate Passivation 107

3.8 Conclusions 108
References 109

4 Substrates, Varactors and Passive Components 115
4.1 Introduction 115
4.2 Substrates 116
4.2.1 Common Substrates 116
4.2.2 Silicon as a Microwave Substrate 118
4.2.3 High Resistivity Silicon 119
4.3 Varactors. Basic Designs and Figure of Merit 125
4.3.1 Basic Designs of Ferroelectric Varactors 125
4.3.2 Figure of Merit, Structure and Performance of Ferroelectric Films 128
4.3.3 Correlation of the Design with the Film Structure 129
4.3.4 Varactor Design Issues 134
4.4 Equivalent Circuit Model of the Varactors 139
4.4.1 Equivalent Circuit 139
4.4.2 Impedance of Parallel-Plate Varactors 143
4.5 Low Frequency and Tuning Performances 144
4.5.1 C-V and P-V Performances 144
4.5.2 I-V Performance 146
4.5.3 Tuneability and Response Time 149
4.6 Microwave Performance 151
4.6.1 Parallel-Plate Varactors 151
4.6.2 Coplanar-Plate Varactors 156
4.6.3 Distributed Varactors 161
4.7 Power Handling Capability and High Power Varactors 162
4.7.1 Parallel-Plate Varactors 163
4.7.2 Coplanar-Plate Varactors 164
4.8 Ferroelectrics in Passive Devices as High Permittivity Dielectric 165
4.8.1 High Density Capacitors 165
4.8.2 MEMs with Ferroelectric Spacers 167
4.8.3 MOS Transistors with Ferroelectrics as Gate Dielectric 168
4.9 Conclusions 169
References 170

5 Ferroelectric Devices 175
5.1 Introduction 175
5.2 Tunable Delay Lines and Delay Line Type Phase Shifters 176
5.2.1 Figure of Merit 176
5.2.2 Periodically Loaded Lines 177
5.2.3 Uniformly Loaded Delay Lines 182
5.2.4 Other Delay Lines 186

5.3 Phase Shifters 187
5.3.1 Figure of Merit of an Analog Phase Shifter 187
5.3.2 Periodically Loaded Line Phase Shifters 188
5.3.3 Reflection Type Phase Shifters 192
5.3.4 Phase Shifters Based on All Pass Filter Topology 192
5.3.5 Other Phase Shifters 194
5.4 Tunable Filters 196
5.4.1 Tunable Resonators 196
5.4.2 Bandpass Filters 199
5.4.3 Notch Filters 203
5.5 Matching Networks (Impedance Tuners) 204
5.6 Power Splitters 206
5.7 Antennas 207
5.8 Nonlinear Devices 208
5.8.1 Harmonic Generators 208
5.8.2 Frequency Up-Converters 208
5.8.3 Power Limiters 209
5.8.4 Pulse Shapers 210
5.8.5 Parametric Amplifiers 211
5.9 TFBARs 212
5.9.1 Basic Designs and Resonant Frequencies 212
5.9.2 Tunable TFBARs 213
5.10 Conclusions 217
References 217

6 Circuit and System Applications of Tunable Ferroelectric Devices .. 225
6.1 Introduction 225
6.2 Voltage Controlled Oscillators 226
6.3 Amplifiers 229
6.4 Steerable Phased Array and Beam Antennas 231
6.4.1 Phased Arrays 231
6.4.2 Steerable Beamformers and Phased Arrays 232
6.4.3 Nontraditional and Lens Type Steerable Beamformers ... 236
6.5 Conclusions 241
References 242

7 Modeling 245
7.1 Introduction 245
7.2 Coplanar-Plate Transmission Lines 246
7.2.1 The Equivalent Circuit of the Lines 246
7.2.2 Coplanar-Strip Waveguides 249
7.2.3 Coplanar Waveguides 259
7.3 Multilayer Substrate Coplanar-Plate Capacitors 260
7.3.1 Coplanar Plate Capacitors with the Straight Gap (Slot) ... 260
7.3.2 Interdigital (IDC) Coplanar-Plate Capacitors 265

7.4 Parallel-Plate Capacitor 267
7.5 Conclusions 271
Appendix A 273
Appendix B 276
Appendix C 280
Appendix D 285
References 285

8 Measurements of the Dielectric Properties 287
8.1 Introduction 287
8.2 Resonant Techniques 289
8.2.1 Disk Resonator Technique 289
8.2.2 Courtney Resonator 291
8.2.3 Composite Resonator Method 295
8.2.4 Split-Post Dielectric Resonator Method for Thick and Thin Films 297
8.2.5 Open Resonator Technique 299
8.2.6 Resonant Technique for on Wafer Characterization of the Ferroelectric Varactors and Films 302
8.2.7 Transmission Line Resonator Method 306
8.2.8 Near Field Scanning Microscope 308
8.2.9 Uncertainty of Resonant Measurements 311
8.3 Broadband Techniques 317
8.3.1 Transmission/Reflection Method. Bulk Samples in Waveguides 317
8.3.2 Film Measurements Using Coplanar Waveguide (CPW) 321
8.3.3 Film Measurements Using Coupled Microstrip Lines 325
8.3.4 Measurements Using Test Varactors 326
8.4 Nonlinear Measurements of Ferroelectrics 330
8.5 Switching Time of Ferroelectric Films 332
8.6 Conclusions 334
Appendix E 336
Appendix F 343
Appendix G 346
References 347

9 Potentials and Perspectives 351
9.1 Introduction 351
9.2 Multiferroics 352
9.3 Ferroelectric Nanotubes. Ferromagnetic Nanowires 354
9.4 Metamaterials 357
9.5 Bridging the “THz Gap” 360
9.6 Other Tunable Materials 361
9.6.1 Pyrochlores 362

9.6.2 Resistive Switching in Oxides 364
9.6.3 High Temperature Superconductors (HTS) 367
9.6.4 Liquid Crystals 367
9.7 Other/New Effects 370
9.7.1 Resistivity Switching in Doped $SrTiO_3$ 370
9.7.2 Nanoscale Effects 372
9.7.3 Integration with Semiconductors 372
9.8 Conclusions 373
References 374

10 Concluding Remarks 379
10.1 Introduction 379
10.2 Stabilization of the Temperature Dependences 379
10.2.1 Intrinsic Temperature Dependences of Permittivity and Tuneability 380
10.2.2 Materials and Device Design Based Methods of Stabilization 381
10.3 Nonlinearity and Power Handling Capability 384
10.4 Hysteresis, Retention, Long Term Stability and Noise 384
10.5 Reliability 387
10.6 Integration Trends 388
References 389

Index 391