Contents

1 Introduction to mm-Wave Silicon Devices, Circuits, and Systems 1
Ali M. Niknejad and Hossein Hashemi
1.1 Introduction 1
1.2 Why mm-Waves? 3
1.3 The Birth of Silicon mm-Wave 5
1.3.1 Why CMOS? 8
1.3.2 True Cost of Silicon mm-Wave 10
1.4 Communication in the 60 GHz Band 12
1.4.1 Beam Forming 13
1.5 Unique mm-Wave Applications 17
1.5.1 mm-Wave Spectrum 17
1.5.2 Automotive Radar 18
1.5.3 mm-Wave Imaging for Medical Applications 22
1.5.4 Collaborative Distributed MIMO 23
1.6 Overview of Book 24
References 24

2 Silicon Technologies to Address mm-Wave Solutions 25
Andreia Cathelin and John J. Pekarik
2.1 Why Silicon? 25
2.1.1 Performance 26
2.1.2 Cost, Integration [3] 27
2.1.3 Manufacturing Capacity 27
2.2 Modern SiGe and CMOS Technology 28
2.2.1 Lithography 28
2.2.2 Low-K Dielectrics and Copper Wiring 30
2.2.3 Mobility and Strain Engineering 30
2.2.4 Metal Gates & High-K Dielectrics 32
2.3 Active Devices on Recent Bulk and SOI Technologies 32
2.3.1 Bipolar Devices 33
2.3.2 CMOS devices 34

2.3.3 SOI CMOS devices . . . 41
2.3.4 Current Density Scaling for CMOS and Bipolar Devices . 46
2.3.5 Comparison Between State-of-the-Art HBT and CMOS Devices . . . 46
2.4 Impact of the Back-End of Line on mm-Wave Design . . . 49
2.5 Conclusion . . . 55
2.6 Acknowledgements: . . . 55
References . . . 56

3 Design and Modeling of Active and Passive Devices . . . 59
Ali M. Niknejad, Sohrab Emami, Chinh Doan, Babak Heydari, Mounir Bohsali
3.1 Passive Devices . . . 59
3.1.1 Transmission Lines . . . 59
3.1.2 Inductors . . . 70
3.1.3 Capacitors . . . 72
3.1.4 Transformers . . . 75
3.1.5 Resonators . . . 77
3.2 Active Devices . . . 79
3.2.1 Modeling . . . 79
3.2.2 Active Device Design . . . 80
3.2.3 Small-Signal Model . . . 89
3.2.4 Large-Signal Model . . . 90
3.2.5 FET Noise Model . . . 97
3.3 Conclusion . . . 105
References . . . 107

4 Amplifiers and Mixers . . . 109
Ali M. Niknejad, Brian A. Floyd, Sohrab Emami, Babak Heydari, Ehsan Adabi, Bagher Afshar
4.1 60 GHz Low-Noise Amplifiers: What's Different? . . . 109
4.1.1 Transistors Closer to Cutoff . . . 109
4.1.2 Small Wavelengths . . . 110
4.1.3 Parasitics at 60 GHz . . . 111
4.2 Low-Noise Amplifier Design Methodology . . . 111
4.2.1 Input Match Optimization for Noise and Power . . . 112
4.2.2 Transistor Noise Parameters . . . 113
4.2.3 Common-Base vs. Common-Emitter . . . 115
4.3 Low-Noise Amplifier Examples . . . 117
4.3.1 Bipolar LNA (v1), Common-Base Input . . . 117
4.3.2 Bipolar LNA (v2), Common-Emitter Input . . . 121
4.3.3 CMOS Common Source Amplifiers . . . 122
4.3.4 CMOS Common Gate Amplifiers . . . 126
4.3.5 Differential Pair Amplifiers . . . 127
4.3.6 Multi-Stage Amplifier Design . . . 129
4.3.7 A Two-Stage 30 GHz Amplifier . . . 135

4.4 Mixers and Frequency Translation 137
4.4.1 Single Transistor Mixers 137
4.4.2 Dual Gate Mixers 141
4.4.3 Gilbert Cell Mixers 144
4.5 Examples of Integrated Front-Ends 147
4.5.1 CMOS 130nm 60 GHz Front-End 147
4.5.2 SiGe Transceiver Chipset 150
4.6 Conclusion 155
References 156

5 Voltage-Controlled Oscillators and Frequency Dividers 159
Jri Lee
5.1 Considerations of VCOs 159
5.2 Cross-Coupled Oscillators 162
5.3 Colpitts Oscillator 169
5.4 Other Topologies 173
5.4.1 mm-Wave Oscillators 174
5.4.2 Push-Push Oscillators 176
5.4.3 Distributed Oscillators 177
5.5 Considerations of Dividers 178
5.6 Static Dividers 180
5.7 Regenerative (Miller) Dividers 183
5.8 Injection-Locked Dividers 187
5.9 Case Study 190
5.9.1 52-GHz LO Signal Generator 191
5.9.2 60-GHz PLL in 0.15-μm GaAs 192
5.9.3 A 75-GHz PLL in 90-nm CMOS 195
References 199

6 Power Amplifiers at 60GHz and Beyond 201
Ehsan Afshari and Abbas Komijani
6.1 Motivation and Challenges 201
6.2 Passive Components 202
6.2.1 Substrate-Shielded Coplanar Waveguide Structure 202
6.2.2 Characterization of the Substrate-Shielded CPW Structure 204
6.2.3 Conductor-Backed Coplanar Waveguide as the Transmission Line Structure 207
6.2.4 Wirebond and Pad Parasitic Effects 209
6.3 Power Transistors 209
6.3.1 Single-Transistor Power Gain and Stability 210
6.3.2 Stability of the Cascode Pair 212
6.3.3 Relationship of Breakdown Voltage and Cut-off Frequency 214
6.4 Power Combining Techniques 215
6.4.1 Basic Principle 215

6.4.2 Distributed Active Transformer 216
6.4.3 Electrical Funnel 220
6.4.4 Circuit Implementation 228
6.5 Case Studies 229
6.5.1 A 77GHz Amplifier for Automotive RADAR Application 230
6.5.2 A Broadband Amplifier at 85GHz 233
6.6 Summary 238
References 240

7 Integrated Beamforming Arrays 243
Harish Krishnaswamy and Hossein Hashemi
7.1 Introduction 243
7.2 What is a Phased Array? 245
7.2.1 Case Study: A 60GHz WPAN Link Budget 248
7.3 Phased Arrays versus Timed Arrays 249
7.4 Conventional Phased Array Architectures 253
7.4.1 RF Phase-shifting 254
7.4.2 LO Phase-shifting 263
7.4.3 Digital Arrays 269
7.4.4 Comparative View of the Conventional Architectures 269
7.5 The VPRO-PLL Phased Array Architecture 271
7.5.1 VPRO Concept 271
7.5.2 Transmit Mode 272
7.5.3 Receive Mode 273
7.6 The Effect of Mismatch in Phased Arrays 277
7.6.1 Beam-pointing Error 278
7.6.2 Sidelobe Rejection Ratio 280
7.6.3 Implications on Array Packaging 281
7.6.4 Array Calibration 282
7.7 Quantization Error in Phased Arrays 283
7.8 Multi-Beam Antenna Arrays 285
7.9 Antenna Arrays and Multiple Input Multiple Output (MIMO) Transceivers 290
7.10 Concluding Remarks 291
References 293

Index 297