Smart Sensors, Measurement and Instrumentation

Volume 34

Series Editor

Subhas Chandra Mukhopadhyay, School of Engineering, Macquarie University, Sydney, NSW, Australia

The Smart Sensors, Measurement and Instrumentation series (SSMI) publishes new developments and advancements in the fields of Sensors, Instrumentation and Measurement technologies. The series focuses on all aspects of design, development, implementation, operation and applications of intelligent and smart sensors, sensor network, instrumentation and measurement methodologies. The intent is to cover all the technical contents, applications, and multidisciplinary aspects of the field, embedded in the areas of Electrical and Electronic Engineering, Robotics, Control, Mechatronics, Mechanical Engineering, Computer Science, and Life Sciences, as well as the methodologies behind them. Within the scope of the series are monographs, lecture notes, selected contributions from specialized conferences and workshops, special contribution from international experts, as well as selected Ph.D. theses.

Indexed by SCOPUS and Google Scholar.

More information about this series at http://www.springer.com/series/10617

Mladen Božanić · Saurabh Sinha

Systems-Level Packaging for Millimeter-Wave Transceivers

Springer

Mladen Božanić
University of Johannesburg
Johannesburg, Gauteng, South Africa

Saurabh Sinha
Faculty of Engineering and the Built Environment
University of Johannesburg
Johannesburg, Gauteng, South Africa

ISSN 2194-8402 ISSN 2194-8410 (electronic)
Smart Sensors, Measurement and Instrumentation
ISBN 978-3-030-14689-4 ISBN 978-3-030-14690-0 (eBook)
https://doi.org/10.1007/978-3-030-14690-0

Library of Congress Control Number: 2019933849

© Springer Nature Switzerland AG 2019
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

The world, as we know it today, at the end of the second decade of the twenty-first century, is a world in which everybody and everything is connected. In the past several years, the amount of Internet traffic has increased momentously and so has the need for wireless transmission. It is estimated that by 2020, 20 to 50 million devices will be connected to the Internet, necessitating the emergence of the Internet of things (IoT) concept. Wireless connectivity technologies, as well as data sensing and processing technology, now need to adapt fast to cater for the increased rate of change. The obvious solution is then to concentrate the research efforts on the part of the spectrum that is not as congested. One of the areas of investigation since the turn of the century has been transmission in the millimeter-wave regime, part of the spectrum ranging from 30 to 300 GHz, where there is an abundance of bandwidth.

Even though millimeter-wave transmission received increased research attention in at least the past 15 years, the world is still waiting for widespread adoption of millimeter-wave transceivers. One of the contributors to this situation is the lack of research into millimeter-wave device packaging. In electronics, the packaging forms a bridge between the integrated circuit (IC) or a single device (e.g., a resistor) and the rest of the electronic system, encompassing all technology between the two. Even the best performing state-of-the-art millimeter-wave transmitter or a receiver IC can be deemed completely inoperable if packaged in an inadequate package. Packaging material and shape are not the only considerations; what becomes important at millimeter-wave frequencies is how the package interacts with millimeter-wave circuitry inside and outside the package boundary. As such, the package must be treated on the system level.

A packaged IC system can be referred to as a system-on-chip (SoC). While system-on-board remains appealing for simple at-home solutions not requiring portability, SoCs are suitable for mass production and remain the best and least costly solution for many commercial applications. In certain applications, e.g., power electronics or RF transmission, several components still have to be placed on the board outside of the chip. Examples of such components are high-power capacitors, in the case of power electronics, or antennas, in the case of transceivers.

The challenge of millimeter-wave transceiver research thus requires reconsideration of what is packaged and what remains outside the package. In a simple example, a power amplifier IC could be packaged into a small package, where the output of the power amplifier is connected to a bonding pad, which is then connected via a bond wire to the package lead. This signal line is then connected to an antenna. On the other hand, the antennas used in the millimeter-wave range are fairly compact, so another option would be to place this antenna inside the package, removing the need for the bonding pad, bonding wire, and the package lead altogether. In fact, a power amplifier could be fabricated in one technology (e.g., a high-power technology), and it could be connected to the modulation circuitry fabricated in another low-power technology while making use of high-quality discrete inductors; all of this could be mounted onto a small board and packaged inside the same enclosure. This would effectively lead to the system-on-package approach (SoP). SoP is thus a system concept in which the device, package, and system board are miniaturized into a single-system package with all the needed system functions.

In a millimeter-wave regime, the decision on the specific packaging strategy is often a difficult one and depends on the circuit complexity, intended use, choice of passives and available transistor technologies and their costs. In many instances, SoC will be the preferred approach because of its simplicity. An inexpensive technology such as silicon-germanium, for example, allows many different types of circuitry to be fabricated on the same chip die. A requirement for a complex device is likely to be best suitable for the SoP strategy. Many approaches that can be classified as somewhere between SoC and SoP are also possible. This book thus looks at different packaging strategies and puts them into the context of the millimeter-wave regime and unique challenges that are associated with this transmission approach. To be able to make a packaging decision, researchers need to understand the concepts of transmission bands, antennas and propagation, integrated and discrete substrates, materials and technologies, passive and active components, as well as the advantages and disadvantages of various packages and packaging approaches, appropriate selection of packages, package-level modeling and simulation, and thinking about the package from the perspective of testing. Material research is particularly important, and although typically associated with substrates and integrated technologies, materials also need to be understood from the perspective of interconnects.

The book is thus organized as follows: Chapter 1 presents the introduction to the topic of research of this book. The importance of millimeter-wave systems packaging is underlined, which allows for a research gap to be found and research questions to be proposed. Chapter 2 presents an overview of the research challenges that are unique to the millimeter-wave regime. Topics include the millimeter-wave regime itself, channels, the importance of wavelength, propagation of millimeter waves, and millimeter-wave antennas. This chapter also includes extensive treatment of millimeter-wave considerations such as losses, uncertainty, component sizing, coupling, design rules, bonding, and behavior of physical packaging at millimeter-wave frequencies. In Chap. 3, the behavior of active and passive devices at millimeter-wave frequencies is looked at. Solid-state active devices are looked at

first, where the different transistor types are described with the focus on the change in their behavior as frequencies increase. The remaining sections of this chapter look at different options of implementation of passives, including transmission lines, waveguides, resistors, capacitors, inductors, transformers, baluns, couplers, and transitions. Chapter 4 is dedicated to transistor technologies. Si CMOS and various BiCMOS and HEMT technologies are all examined. This chapter also describes how established technologies can be improved to make them more suitable for millimeter-wave applications, typically by deploying small processing modifications. Methods to compare different transistor technologies are also discussed in this chapter. In Chap. 5, discrete substrates are described. Substrates are the foundation for any package option or packaging strategy. Important substrate properties are discussed, such as their thermal, electrical, and mechanical properties. This chapter also presents a classification of substrates and describes the advantages and disadvantages of different substrate types. Ceramics, polymers, hybrids, or even laminates can all be made suitable for millimeter-wave packaging, provided that the materials are selected carefully and the processing is done in a way that is suitable for the required application. Means of comparing substrates and their selection are likewise discussed for discrete substrates.

The remaining chapters focus on different packaging strategies and state-of-the-art examples. Chapter 6 discusses the traditional approach to the least expensive SoC strategy. Different SoC packages suitable for millimeter-wave applications are discussed, in conjunction with suitable means for making first-level interconnects. The economics of the SoC approach is also considered in this chapter. Modeling, simulation, and testing of packaged SoCs also comprise one of the topics. Chapter 7 discusses multi-chip packaging, including 3D packaging and how these packages can be made to perform reliably. This chapter in addition discusses the materials suitable for multi-chip packaging, making interconnects inside these packages (horizontal and vertical transitions), as well as, once again, modeling, simulation, and testing. Many 3D-related challenges, such as 3D wafer processing, wafer thinning, via insertion, heat buildup, and reliability, are the central focus of this chapter. Chapter 8 focuses on the state-of-the-art approach—the SoP strategy. Advantages and challenges of SoP for millimeter-wave are discussed. Various SoP alternatives of various complexities are listed in this chapter, and substrates and other materials suitable for SoP integration are discussed. Methods of integration of different components, such as passives, sensors, and antennas, are also explored. Modeling, simulation, and testing challenges associated with SoP are expanded on here. Furthermore, this chapter discusses the key considerations for package selection and successful packaging execution, as well as the economics of this ultimate packaging strategy. Finally, Chap. 9 summarizes the book by looking at how research questions have been answered. The chapter moreover investigates remaining research gaps in packaging research for the millimeter-wave regime, as well as exploring future directions.

The authors would like to thank Azoteq, (PTY) Ltd., from Pretoria, South Africa, for providing chip samples used in this book.

The authors would further like to recognize Dr. Riëtte de Lange, former Director: Research Productivity and Improvement of Staff Qualifications, Strategic Initiatives and Administration, University of Johannesburg, South Africa, as well as Ms Noluthando Nkosi, for research administration and coordination.

Furthermore, the authors would like to recognize the support of technical peer review process, research review, as well as language and graphic editors, who have all contributed to the book compiling process. We value the system of scholarly peer review and the approach that this adds to the production of research text that adds to the body of scientific knowledge.

Johannesburg, South Africa
January 2019

Mladen Božanić
Saurabh Sinha

Contents

1 Research Impact of System-Level Packaging for Millimeter-Wave Transceivers 1
1.1 Significance of Device Packaging at Millimeter-Wave Range and Systems Approach 5
1.2 Research Contextualization: A Modern Communication System 5
1.2.1 Transmitter 6
1.2.2 Transmitting and Receiving Antennas 10
1.2.3 The Receiver 10
1.2.4 Example of State-of-the-Art Transceiver 14
1.3 Other Considerations: Substrates, Active Devices and Passives 16
1.4 Practical Research Focus: Applications of Millimeter-Wave Systems 17
1.5 Identifying Research Gaps: Packaging Techniques and Technologies 19
1.5.1 Traditional Approach—A One-Chip Solution 19
1.5.2 A Two-Chip Solution 20
1.5.3 Packaging Multiple Dice 20
1.5.4 The Ultimate Goal: System Optimization Through Improved Packaging 22
1.5.5 The Packaging Decision 23
1.6 Research Questions: Packaging for Millimeter-Wave Applications 24
1.7 Contribution to the Body of Knowledge 25
1.8 Content Overview 26
References 27

2 Millimeter-Wave Research Challenges 31
2.1 Wavelength Significance 31
2.2 The Millimeter-Wave Part of the Spectrum 32
2.3 Propagation of Millimeter Waves 35
2.4 Antennas for Millimeter-Waves 37
2.4.1 General Antenna Theory 38
2.4.2 Millimeter-Wave Antennas 40
2.5 Millimeter-Wave Considerations 43
2.5.1 Losses 43
2.5.2 Uncertainty 44
2.5.3 Feasibility of Component Values 45
2.5.4 Interconnects and Component Sizing 46
2.5.5 Coupling and Shielding 46
2.5.6 Layout Dependency 47
2.5.7 Bonding 49
2.5.8 Package Leads 50
2.5.9 Concluding Remarks 51
References 52

3 Behavior of Active and Passive Devices at Millimeter-Wave Frequencies 55
3.1 Solid-State Active Devices 56
3.1.1 Metal-Oxide Transistors 56
3.1.2 MOSFET Operation at Millimeter Wave Frequencies . . . 61
3.1.3 Bipolar Transistors 63
3.1.4 HBT Operation at Millimeter Wave Frequencies 66
3.1.5 Noise Figure in HBTs and MOSFETs 68
3.2 Transmission Lines 68
3.2.1 Q-Factors of Passive Devices 69
3.2.2 Introduction to Transmission Lines 69
3.2.3 Types of Transmission Lines 70
3.2.4 General Transmission Line 71
3.2.5 The Quarter-Wave Transformer 73
3.2.6 Substrate Integrated Waveguides 75
3.2.7 Slow Co-planar Waveguides 76
3.3 Resistors 80
3.4 Capacitors 82
3.4.1 Parallel-Plate Capacitors 82
3.4.2 Transmission-Line Capacitors 83
3.4.3 Other Capacitors 84
3.5 Inductors 86
3.5.1 Wound Inductors 86
3.5.2 Integrated Inductors 88

3.5.3 Embedded Inductors . . . 94
3.5.4 Bond Wires . . . 96
3.5.5 Transmission-Line Inductors . . . 96
3.5.6 RF Chokes . . . 98
3.6 Transformers and Baluns . . . 98
3.7 Concluding Remarks . . . 101
References . . . 101

4 Integrated Substrates: Millimeter-Wave Transistor Technologies . . . 105
4.1 Means for Comparison of Technologies . . . 107
4.2 CMOS Technology . . . 108
4.2.1 Important Characteristics . . . 108
4.2.2 State-of-the-Art CMOS Technologies . . . 109
4.3 High-Electron Mobility Transistor Technology . . . 109
4.3.1 Important Characteristics . . . 109
4.3.2 State-of-the-Art High-Electron Mobility Technologies . . . 111
4.4 Heterojunction Bipolar Transistor Technology . . . 111
4.4.1 Important Characteristics . . . 112
4.4.2 State-of-the-Art Heterojunction Bipolar Technologies . . . 112
4.5 Other Technologies . . . 113
4.6 Comparative Analysis . . . 114
4.7 Advanced Fabrication Techniques . . . 116
4.8 Concluding Remarks . . . 125
References . . . 125

5 Discrete Substrates: Package Foundation . . . 129
5.1 Classification of Substrates . . . 131
5.2 Important Substrate Properties . . . 132
5.2.1 Dielectric Constant . . . 133
5.2.2 Loss Tangent . . . 134
5.2.3 Electrical Conductivity . . . 135
5.2.4 Skin Depth . . . 135
5.2.5 Thermal Properties . . . 135
5.2.6 Reliability . . . 137
5.2.7 Dielectric Breakdown . . . 138
5.2.8 Substrate Thickness . . . 138
5.2.9 Other Properties . . . 138
5.3 Laminate Substrates . . . 139
5.4 Ceramics . . . 140
5.4.1 Thin-Film Ceramics . . . 141
5.4.2 Thick-Film Ceramics . . . 141

5.4.3 Low-Temperature Co-fired Ceramics and High-Temperature Co-fired Ceramics 142
5.4.4 Composite Ceramics 144
5.5 Organic Substrates 145
5.6 Silicon as a Discrete Substrate 147
5.7 Other Materials 148
5.8 Substrate Performance Comparison and Substrate Choice 150
5.9 Concluding Remarks 152
References 154

6 Traditional Approach: System-on-Chip 157
6.1 Main Characteristics and Challenges of the System-on-Chip Approach to Packaging 157
6.2 Traditional Packages and Bonding 160
6.3 Flip Chip Packaging 162
6.3.1 Flip Chip Advantages for Millimeter-Wave Regime 164
6.3.2 Flip Chip Challenges 165
6.3.3 Flip Chip Packaging Options 166
6.4 Electromagnetic Coupling as the First-Level Interconnect 167
6.5 Circuit Reusability 168
6.6 On-Chip Sensors 169
6.7 Transceiver/Antenna Co-design and Antennas on Chip 170
6.7.1 Main Considerations of Antennas on Chip 171
6.7.2 State-of-the-Art On-Chip Antennas 174
6.8 Simulation and Design of Packaged SoCs and System-Package Co-design 176
6.9 State-of-the-Art Millimeter-Wave System-on-Chip Examples 180
6.9.1 A 60 GHz System-on-Chip Transmitter with Built-in Memory and an On-Chip Antenna 180
6.9.2 A 120–145 GHz Heterodyne Receiver for Atmospheric Passive Sensing 181
6.9.3 A 122 GHz Radar System-on-Chip 183
6.9.4 60 GHz Low-Power Receiver for a Monolithic Wireless Sensor Without a Battery 184
6.10 Economics of System-on-Chip 186
6.11 Testing of System-on-Chip 188
6.12 Concluding Remarks 189
References 189

7 Multi-chip Modules and Multi-chip Packaging 193
7.1 Multi-chip Packaging Options 195
7.2 Main Characteristics and Challenges of the Multi-chip Packaging Approach 199
7.3 3D Packaging 200

7.3.1 Processing and Stacking of 3D Wafers . . . 201
7.3.2 Wafer Thinning . . . 202
7.3.3 3D Wafer Bonding . . . 203
7.3.4 Heat and Cooling . . . 205
7.3.5 Reliability . . . 208
7.3.6 Coupling and Shielding . . . 210
7.4 Interconnects . . . 210
7.4.1 Chip-to-Substrate Interconnects . . . 210
7.4.2 Horizontal Transitions . . . 212
7.4.3 Vertical Transitions . . . 213
7.5 Simulation of Multi-chip Modules and 3D Packages . . . 218
7.6 State-of-the-Art Multi-chip Module Examples . . . 219
7.6.1 3D IC Test Vehicle on the 300 mm Multi-project Wafer . . . 220
7.6.2 Stochastic Flash Analog-to-Digital Converter for Integration with an Ultrasound Transducer Array . . . 222
7.7 Testing of Multi-chip Modules . . . 222
7.8 Economics of Multi-chip Modules . . . 224
7.9 Concluding Remarks . . . 225
References . . . 226

8 State-of-the-Art Approach: System-on-Package . . . 229
8.1 Main Characteristics, Advantages and Challenges of the System-on-Package Approach . . . 231
8.2 Popular System-on-Package Technologies . . . 233
8.2.1 Embedded Wafer Level Ball Grid Array Packaging . . . 234
8.2.2 Low-Temperature Co-fired Ceramics System-on-Package . . . 235
8.2.3 Liquid-Crystal Polymer System-on-Package . . . 235
8.2.4 System-on-Package for Micro-Electro-Mechanical Systems . . . 236
8.2.5 Glass Substrate System-on-Package . . . 237
8.2.6 Silicon Substrate System-on-Package . . . 238
8.2.7 Other System-on-Package Technologies . . . 240
8.3 System-on-Package Design Challenges . . . 241
8.3.1 Interconnects and Transitions . . . 242
8.3.2 Material Mix in System-on-Package . . . 246
8.3.3 System Reliability . . . 248
8.4 High-Quality Passives . . . 248
8.4.1 Inductors . . . 248
8.4.2 Capacitors . . . 250
8.4.3 Resistors . . . 250
8.5 In-Package Sensors and Smart ICs . . . 250

8.6 Antennas on Package . . . 251
8.6.1 Advantages of Antennas on Package . . . 251
8.6.2 State-of-the-Art Antennas on Package . . . 253
8.7 System-on-Package Topology Decision . . . 254
8.8 Simulation Challenges of System-on-Package . . . 256
8.9 Design for Test Challenges of System-on-Package . . . 258
8.10 Economics of System-on-Package . . . 259
8.11 State-of-the-Art Millimeter-Wave System-on-Package Examples . . . 260
8.11.1 LTCC Amplitude-Shift-Keying Receiver for 60 GHz Applications . . . 260
8.11.2 LTCC-Based Monolithic SoP for 60 GHz Applications . . . 261
8.11.3 E-Band Antenna-on-Package System in eWLB Technology . . . 262
8.11.4 Four-Chip Package with 64-Antenna Array for W-Band Phased-Array Transceivers on an Organic Substrate . . . 264
8.11.5 160 GHz System-on-Package in EWLB Technology for Short-Range Millimeter-Wave Applications . . . 265
8.12 Keys to Package Selection and Successful Packaging . . . 267
8.13 Concluding Remarks . . . 268
References . . . 268

9 Assessment of Completed Work and Future Directions in Millimeter-Wave Research . . . 273
9.1 Evaluation of Research Questions . . . 273
9.1.1 Research Question 1 . . . 273
9.1.2 Research Question 2 . . . 274
9.1.3 Research Question 3 . . . 274
9.1.4 Research Question 4 . . . 275
9.1.5 Research Question 5 . . . 275
9.2 Remaining Research Gaps and Opportunities for Enhancement . . . 276
9.3 Future Directions . . . 277

About the Authors

Mladen Božanić Ph.D. (Eng.), SMIEEE, obtained his B.Eng. (with distinction), B.Eng. (Hons) (with distinction), and Ph.D. degrees in electronic engineering from the University of Pretoria (UP) in 2006, 2008, and 2011, respectively. In 2008, he joined Azoteq, a fabless IC design company originating in South Africa where he has been responsible for the silicon-level design and simulation characterization design for testability (DFT) of various analog, RF, digital, and mixed-mode circuits. While actively working in the industry, he also participates in research activities, currently with the University of Johannesburg (UJ) where he is serving as Senior Research Fellow. Since 2011, he has been fulfilling the role of Specialist Editor of South African Institute of Electrical Engineers (SAIEE). He is a recipient of SAMES Award and CEFIM Fellowship Award, and an author or co-author of over 20 peer-reviewed journal and conference articles, one chapter, and three books.

Saurabh Sinha Ph.D. (Eng.), Pr.Eng., SMIEEE, FSAIEE, FSAAE, obtained his B.Eng. (with distinction), M.Eng. (with distinction), and Ph.D. degrees in electronic engineering from the University of Pretoria (UP). As an established researcher, rated by the National Research Foundation (NRF), he has authored or co-authored over 110 publications in peer-reviewed journals and at international conferences. He served UP for over a decade—his last service being as Director of the Carl and Emily Fuchs Institute for Microelectronics, Department of Electrical, Electronic, and Computer Engineering. On October 1, 2013, he was appointed as Executive Dean of the Faculty of Engineering and the Built Environment (FEBE) at the University of Johannesburg (UJ). As of December 1, 2017, he is UJ Deputy Vice-Chancellor: Research and Internationalization. Among other leading roles, he also served IEEE as Board of Director and IEEE Vice-President: Educational Activities.