Jacopo Iannacci

Practical Guide to RF-MEMS
Related Titles

Hierold, C. (ed.)
**Carbon Nanotube Devices**
Properties, Modeling, Integration and Applications
2008
Print ISBN: 978-3-527-31720-2, also available in electronic formats.

Bechtold, T., Schrag, G., Feng, L. (eds.)
**System-level Modeling of MEMS**
2013
Print ISBN: 978-3-527-31903-9, also available in electronic formats.

**Inkjet-based Micromanufacturing**
2012
Print ISBN: 978-3-527-31904-6, also available in electronic formats.

Ramm, P., Lu, J.J., Taklo, M.M. (eds.)
**Handbook of Wafer Bonding**
2012
Print ISBN: 978-3-527-32646-4, also available in electronic formats.

Garrou, P., Bower, C., Ramm, P. (eds.)
**Handbook of 3D Integration**
Volumes 1 and 2: Technology and Applications of 3D Integrated Circuits
2012
Print ISBN: 978-3-527-33265-6

Garrou, P., Koyanagi, M., Ramm, P. (eds.)
**Handbook of 3D Integration Volume 3: 3D Process Technology**
2014
Print ISBN: 978-3-527-33466-7, also available in electronic formats.

Baltes, H., Brand, O., Fedder, G.K., Hierold, C., Korvink, J.G., Tabata, O. (eds.)
**Enabling Technologies for MEMS and Nanodevices**
Advanced Micro and Nanosystems
2013
Print ISBN: 978-3-527-33498-8

Baltes, H., Brand, O., Fedder, G.K., Hierold, C., Korvink, J.G., Tabata, O. (eds.)
**CMOS-MEMS**
2013
Print ISBN: 978-3-527-33499-5

Kockmann, N. (ed.)
**Micro Process Engineering**
Fundamentals, Devices, Fabrication, and Applications
2013
Print ISBN: 978-3-527-33500-8

Tabata, O., Tsuchiya, T. (eds.)
**Reliability of MEMS**
Testing of Materials and Devices
2013
Print ISBN: 978-3-527-33501-5
Jacopo Iannacci

Practical Guide to RF-MEMS
Intellectual honesty is like a breeze for a sailor. It is invisible and intangible, but it makes a difference.

Intelligence is not all you need in life. You should be intelligent enough to practice it too.

*J. Iannacci, June 2012.*

Happiness only real when shared.

*C.J. McCandless, August 1992.*

To my parents, and to their unconditional presence.
Contents

Foreword XI
Preface XV

1 RF-MEMS Applications and the State of the Art 1
1.1 Introduction 1
1.2 A Brief History of MEMS and RF-MEMS from the Perspective of Technology 2
1.3 RF-MEMS Lumped Components 3
1.3.1 Variable Capacitors 4
1.3.2 Inductors 10
1.3.3 Ohmic and Capacitive Switches 12
1.4 RF-MEMS Complex Networks 20
1.4.1 Reconfigurable Impedance-Matching Networks 20
1.4.2 Reconfigurable RF Power Attenuators 23
1.4.3 Reconfigurable Phase Shifters and Delay Lines 26
1.4.4 Reconfigurable Switching Matrices 26
1.5 Modeling and Simulation of RF-MEMS Devices 28
1.5.1 The Finite Element Method Approach 28
1.5.2 Compact Modeling of RF-MEMS 28
1.5.3 Mixed-Domain Electromechanical Simulation Environment 30
1.6 Packaging of RF-MEMS 31
1.7 Brief Overview of Exploitation of RF-MEMS in RF Systems 33
1.8 Conclusions 38

2 The Book in Brief 41
2.1 Introduction 41
2.2 A Brief Introduction to the FBK RF-MEMS Technology 42
2.3 An RF-MEMS Series Ohmic Switch (Dev A) 44
2.4 RF-MEMS Capacitive Switches/Varactors 49
2.4.1 Design 1 (Dev B1) 49
2.4.2 Design 2 (Dev B2) 50
2.4.3 RF-MEMS Ohmic Switch with Microheaters (Dev C) 50
2.4.4 MEMS-Based Reconfigurable RF Power Attenuator (Dev D) 52
2.4.5 MEMS-Based Reconfigurable Impedance-Matching Network (Dev E) 55
2.5 Conclusions 55

3 Design 57
3.1 Introduction 57
3.2 Design Rules of the Fondazione Bruno Kessler RF-MEMS Technology 58
3.3 Design of an RF-MEMS Series Ohmic Switch (Dev A) 60
3.4 Generation of 3D Models Starting from the 2D Layout 77
3.5 Conclusions 83

4 Simulation Techniques (Commercial Tools) 85
4.1 Introduction 85
4.2 Static Coupled Electromechanical Simulation of the RF-MEMS Ohmic Switch (Dev A) in ANSYS Multiphysics™ 86
4.2.1 Block 1: Definition of the Geometry and Properties of the Material 88
4.2.2 Block 2: Meshing of the Structure 92
4.2.3 Block 3: Generation of the Elements for the Electromechanical Coupling 93
4.2.4 Block 4: Definition of the Mechanical Boundary Conditions 95
4.2.5 Block 5: Definition of the Simulation 97
4.2.6 Block 6: Simulation Execution 99
4.2.7 Block 7: Postprocessing and Visualization of Results 99
4.3 Modal Analysis of the RF-MEMS Capacitive Switch (Dev B2) in ANSYS Multiphysics 101
4.4 Coupled Thermoelectromechanical Simulation of the RF-MEMS Ohmic Switch with Microheaters (Dev C) in ANSYS Multiphysics 104
4.5 RF Simulation (S-parameters) of the RF-MEMS Variable Capacitor (Dev B1) in ANSYS HFSS™ 121
4.6 Conclusions 130

5 On-Purpose Simulation Tools 133
5.1 Introduction 133
5.2 MEMS Compact Model Library 134
5.2.1 Suspended Rigid Plate Electromechanical Transducer 134
5.2.2 Flexible Beam 140
5.2.3 Simulation Validation of a MEMS Toggle Switch 144
5.3 A Hybrid RF-MEMS/CMOS VCO 149
5.4 Excerpts of Verilog-A Code Implemented for MEMS Models 151
5.4.1 Anchor Point 152
5.4.2 Force Source 154
5.4.3 Flexible Beam 157
5.5 Conclusions 165

6 Packaging and Integration 167
6.1 Introduction 167
6.2 A WLP Solution for RF-MEMS Devices and Networks 168
Contents

6.2.1 Package Fabrication Process 169
6.2.2 Wafer-to-Wafer Bonding Solutions 173
6.3 Encapsulation of RF-MEMS Devices 177
6.3.1 The Issue of Wafer-to-Wafer Alignment 178
6.3.2 Hybrid Packaging Solutions for RF-MEMS Devices 180
6.4 Fabrication Run of Packaged Test Structures 181
6.5 Electromagnetic Characterization of the Package 185
6.5.1 Validation of the S-parameter Simulations of Packaged Test Structures 186
6.5.2 Parameterized S-parameter Simulation of Packaged Test Structures 187
6.6 Influence of Uncompressed ACA on the RF Performance of Capped MEMS Devices 191
6.7 Conclusions 194

7 Postfabrication Modeling and Simulations 195
7.1 Introduction 195
7.2 Electromechanical Simulation of an RF-MEMS Varactor (Dev B2) with Compact Models 196
7.3 RF Modeling of an RF-MEMS Varactor (Dev B2) with a Lumped Element Network 202
7.4 Electromechanical Modeling of an RF-MEMS Series Ohmic Switch (Dev A) with Compact Models 213
7.5 Electromagnetic Modeling and Simulation of an RF-MEMS Impedance-Matching Network (Dev E) for a GSM CMOS Power Amplifier 218
7.5.1 Introduction 219
7.5.2 Electromagnetic Design and Optimization of the RF-MEMS Impedance-Matching Network 219
7.5.3 Deign of a Reconfigurable Class E PA 224
7.5.4 Experimental Results for the Hybrid RF-MEMS/CMOS PA 227
7.6 Electromagnetic Simulation of an RF-MEMS Capacitive Switch (Dev B1) in ANSYS HFSS™ 229
7.7 Electromagnetic Simulation of a MEMS-Based Reconfigurable RF Power Attenuator (Dev D) in ANSYS HFSS 234
7.8 Conclusions 238

Appendix A Rigid Plate Electromechanical Transducer (Complete Model) 241
A.1 Introduction 241
A.2 Mechanical Model of the Rigid Plate with Four DOFs 242
A.3 Extension of the Mechanical Model of the Rigid Plate to Six DOFs 249
A.3.1 Placement of Nodes along the Edges of a Rigid Plate 253
A.4 Contact Model for Rigid Plates with Four and Six DOFs 255
A.5 Electrostatic Model of the Rigid Plate 258
A.5.1 The Four DOFs Condition 258
A.5.2 Extension to the Case of Six DOFs 262
A.5.3 Curved Electric Field Lines Model 266
A.6 Electrostatic Model of the Plate with Holes 268
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.7 Electrostatic Model of the Fringing Effect</td>
<td>272</td>
</tr>
<tr>
<td>A.7.1 Fringing Effect on the Vertical Faces of the Plate</td>
<td>278</td>
</tr>
<tr>
<td>A.8 Viscous Damping Model</td>
<td>281</td>
</tr>
<tr>
<td>A.8.1 Squeeze-Film Viscous Damping of the Rigid Plate with Holes</td>
<td>281</td>
</tr>
<tr>
<td>A.8.2 Viscous Damping Model for Lateral Movements</td>
<td>284</td>
</tr>
<tr>
<td>A.8.3 Effect of the Mean Free Path of Gas Molecules</td>
<td>285</td>
</tr>
<tr>
<td>A.9 Conclusions</td>
<td>286</td>
</tr>
<tr>
<td><strong>Appendix B</strong> Flexigble Straight Beam (Complete Model)</td>
<td>287</td>
</tr>
<tr>
<td>B.1 Mechanical Model of the Flexible Beam with Two Degrees of Freedom</td>
<td>287</td>
</tr>
<tr>
<td>B.1.1 The Stiffness Matrix</td>
<td>288</td>
</tr>
<tr>
<td>B.1.2 The Mass Matrix</td>
<td>290</td>
</tr>
<tr>
<td>B.2 Mechanical Model of the Flexible Beam with 12 DOFs</td>
<td>292</td>
</tr>
<tr>
<td>B.2.1 The Stiffness Matrix for 12 DOFs</td>
<td>293</td>
</tr>
<tr>
<td>B.2.2 The Mass Matrix for 12 DOFs</td>
<td>297</td>
</tr>
<tr>
<td>B.3 Complete Mechanical Model of the Euler Beam with 12 DOFs</td>
<td>302</td>
</tr>
<tr>
<td>B.4 Electrostatic Model of the Euler Beam with 12 DOFs</td>
<td>304</td>
</tr>
<tr>
<td>B.4.1 Fringing Effect Model</td>
<td>310</td>
</tr>
<tr>
<td>B.5 Viscous Damping Model</td>
<td>312</td>
</tr>
<tr>
<td>B.6 Conclusions</td>
<td>315</td>
</tr>
<tr>
<td>References</td>
<td>317</td>
</tr>
<tr>
<td>Index</td>
<td>331</td>
</tr>
</tbody>
</table>
Foreword

The world, as we all know it, has three dimensions. Some of us enjoyed playing with construction bricks as a child, and some still enjoy building stuff, as a hobby or for work. Through the years different branches of engineering have studied how to build complex, efficient, reliable, 3D structures, either movable or still. Indeed, the progress made in the fields of mechanical and civil engineering in recent decades is impressive, making possible the construction of amazing bridges and buildings that literally fight against the force of gravity. In parallel, the achievements obtained by electronic engineering have been continuously changing our lifestyles and deserve a quick recap. Since the invention of the planar fabrication process at the end of the 1950s by Jean Hoerni, and the successive demonstration of the first CMOS circuit by Frank Wanlass at the beginning of the 1960s, the evolution of microelectronic fabrication technologies has literally exploded, pushing to a few nanometers the lithographic resolution achievable nowadays, and making it possible to integrate tens of millions of transistors in a few square millimeters. However, as already mentioned, we live in a 3D world, so why not exploit the advantages offered by the planar fabrication process to build 3D, even movable structures with dimensions well below the millimeter scale? It is likely that Harvey Nathanson had the same question, and in 1964 with his team at Westinghouse he answered it by producing the first batch-fabricated electromechanical device. The device, a resonant transistor, joined for the first time a mechanical component and electronic circuitry. In other words, he gave birth to the first microelectromechanical system (MEMS). The term “microelectromechanical system” (MEMS) originated in the United States and was followed by “microsystem technology” in Europe and “micromachining” in Japan. Despite the different terminology, the essence is the demonstration that it is possible to co-integrate electrical and 3D mechanical components with dimensions (well) below 1 mm using a fabrication process to produce microelectronic devices. A couple of decades since the first MEMS demonstration, the field has experienced a huge expansion. Nowadays, extremely complex MEMS, such as high-resolution accelerometers and gyroscopes, are commonly implemented in many portable guidance and entertainment systems, and in state-of-the-art automotive and avionic applications. This is very exciting from an engineering point of view and, from a business perspective, we are speaking about multi-billion-dollar markets. In parallel to those and other kinds of successful micromachined
Foreword

sensors/actuators, there has been great interest in the last two decades in developing 3D devices for radio frequency (RF) applications. Good examples are transmission lines, suspended inductors, ohmic/capacitive switches, varactors, resonators, and so on. Given the superior performance demonstrated by MEMS compared with traditional solid-state/fully mechanical technologies, such as higher linearity and frequency bandwidth, smaller volume occupancy and weight, ultralow power consumption, and lower batch production cost and fabrication process complexity, it has been straightforward to exploit such kinds of devices in next-generation portable and regular telecommunications systems. As said before, these are exciting and remunerative markets! Given the great interest in the field, many books have appeared on the design of MEMS. Many of them were meant to give the reader a deep theoretical understanding of the working principles of devices. Fewer works preferred to investigate the field of reliability, showing how it is easy to damage, or even destroy, these wonderful, little, 3D movable structures if they are not properly protected from potentially critical electrical, mechanical, or environmental overstress.

The monograph of Iannacci is different from what has already been presented in the literature, filling the gap between pure theoretical books and experimental ones. Indeed, this book takes the reader by the hand, showing how to fabricate, design, simulate, and characterize electrostatic-based MEMS for RF applications. The starting point is the introduction of the Fondazione Bruno Kessler MEMS process flow and a design software tool (L-Edit) in the first chapters, with an easy to follow and practical approach. But the design and optimization of any new device requires spending some time on structure simulation. Any RF design engineer knows very well the importance of a good design and the considerable amount of time it can take to predict the response of the device. Playing with 3D movable devices, everything is complicated by the need to couple the electromechanical physics with electromagnetism. Iannacci did not forget this often cumbersome problem, and has devoted ample space to introduce the reader to many finite element method and RF simulation tools, always with a “from the scratch” approach, and always comparing simulation results with experimental data. In the end, it is worth remembering that you will sell actual devices, not just simulation data. And the differences with previous literature continue. Instead of simply introducing the basic blocks of MEMS, Iannacci provides a full description of two MEMS-based, complex systems: a GSM MEMS-based power amplifier and an RF-MEMS-based reconfigurable power attenuator. These examples can be definitely beneficial to experienced “solid-state” engineers, who can easily compare the pros and cons offered by a 3D technology, as well as to students, who can understand the possible problems in integrating different technologies, including differences and problems encountered in MEMS packaging. Despite the practical approach of the book, theory has not been forgotten, and in the appendices Iannacci describes the theoretical basis behind the electromechanical actuator, the heart of each electrostatic-based MEMS, as well as the flexible beam, that is, the suspension of the MEMS movable structure. In conclusion, the field of RF-MEMS is so ably described by Iannacci that both professionals and students, experienced or newbies, will benefit from his presenta-
tion and experimental point of view. As a last, personal, comment, I really enjoyed reading the book of my friend Jacopo. Actually, I just realized I have never called him by his surname so often as in this foreword!

Pittsburg, USA

May 2012

Augusto Tazzoli
Preface

Microelectromechanical systems (MEMS) technology is characterized by great flexibility, making it suitable for sensor and actuator applications spanning from the biomedical to the automotive sector. A rather recent exploitation of MEMS technology which emerged in the research community about 15 years ago is in the field of radio frequency (RF) passive components. RF-MEMS devices – RF-MEMS is an acronym identifying microsystem-based RF passive components – range from lumped components, such as microrelays, variable capacitors (i.e., varactors), and inductors, to complex elements based on a combination of the previously listed basic components, such as tunable filters, phase shifters, and impedance-matching tuners. All the RF-MEMS components mentioned are characterized by very high performance, for example, low loss, high quality factor (Q factor), and good isolation, as well as by wide reconfigurability. Such characteristics offer the potential to extend the operability and to boost the performance of RF systems, such as transceivers, radar systems, cell phones, and smartphones, and this is the main reason for which significant effort is now being expended (at the research and industrial level) in order to solve the issues still impeding the full integration of MEMS technology in standard RF circuits, they being mainly reliability, packaging, and integration.

Given the wide interdisciplinary behavior of MEMS and RF-MEMS devices, the aspects to be faced as well as the knowledge required to handle their development are multiple, regardless of the specific phase – design, simulation, fabrication, testing – one is dealing with. For example, the proper design of an innovative RF-MEMS component implies propaedeutic knowledge of the physics of semiconductors, structural mechanics, dynamics, electrostatics, and electromagnetism. Consequently, MEMS/RF-MEMS being a novel discipline demanding a straightforward definition of its pertinence, several remarkable handbooks and textbooks were written in the last decade, covering both the comprehensive discussion of the field as a whole and the close examination of specific device development phases, such as modeling, simulation, microfabrication, and packaging.

Since it would have made no sense to publish another text containing the theory of RF-MEMS that, in the best case, could have been as good as already existing texts, a different approach was chosen and pursued in the preparation of this book. The philosophy behind it can be summarized as follows: if relevant books dealing with
the theory of RF-MEMS and hands-on texts already exist, why not aim at something in between? And this is it.

This book covers some of the most critical phases that have to be faced in order to develop novel RF-MEMS device concepts according to a very practical approach, it being the one followed by the author in the research activities he pursued in the last decade. A very limited set of RF-MEMS devices – including both lumped components and complex networks – is chosen at the beginning of the book as reference examples, and they are then discussed from different perspectives while progressing from the design to the simulation, packaging, testing, and postfabrication modeling. Theoretical bases are introduced when necessary, while several practical hints are reported concerning all the development steps discussed, providing the book with an engineering flavor.

In conclusion, given its practical approach, this book is meant to give a helping hand to a wide audience, ranging from scientists and researchers directly involved in the RF-MEMS field, to those who want to gain insight into what working in the field of microsystems for RF applications means.

Trento, Italy
June 2012

Jacopo Iannacci
RF-MEMS Applications and the State of the Art

Abstract: This introductory chapter provides a comprehensive overview of the state of the art in radio frequency (RF) microelectromechanical systems (MEMS) technology and its applications. The exploitation of MEMS technology in the field of RF circuits and systems (i.e., RF-MEMS) represents a rather recent exploitation of microsystems if compared with the field of sensors and actuators, and can be framed in the last 10–15 years. Firstly, the chapter discusses some of the history of MEMS technology, focusing on the development of suitable and appropriate technological steps for the manufacturing of microsystems. Subsequently, the focus is moved to RF-MEMS technology, and a comprehensive scenario of the most relevant devices manufactured with such a technology is provided. The discussion of microsystem-based RF passive components is arranged according to an increasing complexity fashion, with the basic passive lumped components, namely, switches, variable capacitors, and inductors, being presented first. Then, the potential of RF-MEMS technology is framed by showing how such basic elements can be combined in order to realize complex functional RF subblocks, such as phase shifters and filters, characterized by large reconfigurability and very high performance. To conclude this introductory chapter, information about the state of the art in modeling and packaging of RF-MEMS devices is provided, while other relevant aspects, such as testing and reliability, are not described in detail as they will not be treated in this work. A brief overview of the exploitation of RF-MEMS devices in RF systems is also given.

1.1 Introduction

What is the relationship, if it truly exists, between the progress of technology and the progress of human kind? This is one of those complicated questions that do not admit a unique answer; in fact, it is a question with no answer, according to the point of view of an engineer. Nonetheless, trying for a very short while not to be a scientist, but just a human being, which is the basis of a scientist, as well as of a lawyer, a worker, a secretary, and so on, one can maybe address, even though partially, the initial question. The intricacy between the progress of human kind
1 RF-MEMS Applications and the State of the Art

and that of technology is clearly bidirectional. The advancements in technology, and their influence on the daily life of people, definitely improved, and are seamlessly improving, our conditions of life. Let us think about how radio, television, cell phones, and other equipment have brought about a revolution in our lifestyle as well as in our habits, both of which concern ourselves and our social life. Nevertheless, the same advancements have generated a series of negative consequences for human kind, outlining a fundamental paradox. What is the point if the improvement of one aspect of life causes the degradation of other traits? The point is that positive and negative consequences of each change, including the no-change option, are unavoidable. Consequently, real progress is not represented by the sole boost given by technology, but rather by the conscious evaluation of all the aspects and consequences that the employment of a new solution will cause. And this delicate aspect is not solved by the ultimate step forward taken by technology, as it is a responsibility resting on the shoulders of human beings. This is the perspective within which the progress of technology can really become progress also for human kind. These considerations apply to all the changes we have faced, are facing, and will face in the future, in technology as well as in society (concerning laws, regulations, health, etc.), and, of course, also apply to radio frequency (RF) microelectromechanical systems (MEMS) technology, which is the real topic of this book. In other words, it is time for a human being to remember to be an engineer after all.

1.2 A Brief History of MEMS and RF-MEMS from the Perspective of Technology

MEMS are, by definition, submillimeter systems (i.e., microsystems) fabricated by means of the same technological steps used in the manufacturing of integrated circuits (ICs). If we focus on the most important electronic component, namely, the transistor, its manufacture is the result of a sequence of steps in which different doses of dopant are selectively implanted or diffused within a substrate (typically silicon) in order to locally obtain certain electrical properties. The same implantation/diffusion, or alternatively the digging of deep trenches, can be used in order to enhance the isolation and reduce the cross talk between adjacent devices. Moreover, conductive and insulating layers are selectively deposited/grown, or deposited/grown everywhere and then selectively removed, in order to redistribute the electrical signals from the intrinsic devices to the external world.

The most important steps in the manufacturing of ICs are ion implantation, diffusion, epitaxial growth, chemical vapor deposition/physical vapor deposition and their variations, wet and dry etching, sputtering, evaporation, and electrodeposition of metals. The selection of the areas that have to undergo one or more of the previously listed steps is always performed by means of lithography [1].

MEMS devices and components are manufactured using the same steps as just discussed, despite the fact that their number and sequence are different. The transistor is a device built into the silicon substrate, and the insulating and metal layers
1.3 RF-MEMS Lumped Components

The progress and maturation of the technology processes mentioned above enabled the realization of a large variety of MEMS-based devices and components that can be successfully exploited for various sensor and actuator applications. The same consideration applies to RF-MEMS devices, as the technology platforms for the fabrication of microsystems empowered, in the past decade, the manufacturing of...
MEMS components for RF applications. Among the wide variety of RF-MEMS, two main categories can be identified, namely, lumped components, such as tunable reactive elements (capacitors/inductors) and microswitches, and complex networks, such as reconfigurable filters and phase shifters, which are based on a suitable combination of the basic RF-MEMS components belonging to the first category. This section will discuss RF-MEMS lumped components in more details, while the next one will focus on the implementation of complex networks and functional RF subblocks based on RF-MEMS devices.

### 1.3.1 Variable Capacitors

Capacitors are passive components playing an important role in the realization of bandpass and bandstop filters [18], matching networks, and more generally, the large part of telecommunication systems [19]. The most important characteristics that lumped capacitors exhibit are the tuning range and the quality factor (Q factor), which both should be as large as possible. A wide tunability range for the capacitance enables a correspondingly large reconfigurability of the functional block that employs it [18]. On the other hand, a large Q factor ensures a high selectivity concerning passive filters, and more generally, better performance in terms of low losses [20]. Variable capacitors (i.e., varactors) are widely realized in standard semiconductor technology by reverse biasing of diodes [21], with some limitations in terms of performance. A significant alternative solution to obtain varactors with better performance and characteristics is to fabricate them with MEMS technology, and this possibility has been widely investigated at the research level in the past decade [22]. The concept of a varactor realized with MEMS technology is based on having (at least) one of the two capacitor plates movable with respect to the other. The displacement of one electrode modifies the distance between the two plates and, in turn, tunes the capacitance of the entire passive element. The displacement of the movable plate can occur in multiple ways. Electrostatic, piezoelectric, thermal, and magnetic actuation are the commonest ones [23]. A typical implementation of a variable capacitor based on MEMS technology is based on two parallel plates, the lower one being fixed and the one on top being movable [24]. The latter is kept suspended by means of flexible parts (e.g., slender beams or folded deformable structures), and when a DC bias is applied between the two plates, the one on top starts to move toward the fixed (bottom one), because of the electrostatic attraction force, increasing, in turn, the capacitance. The schematic in Figure 1.1 shows a typical geometry for an RF-MEMS electrostatically controlled tunable component (or capacitive switch).

Looking at the cross section of the schematic reported in Figure 1.2, we can better understand the working principle of an electrostatically controlled RF-MEMS component. When no bias is applied between the movable membrane and the underlying electrode, the MEMS structure is in the rest position, as Figure 1.2a shows. In this case, the distance between the two electrodes is the maximum possible, and the capacitance, in turn, assumes the minimum value. On the other hand, when a
1.3 RF-MEMS Lumped Components

Figure 1.1 An electrostatically controlled radio frequency (RF) microelectromechanical system (MEMS)-based variable capacitor based on an electrode kept suspended by deformable slender beams over a fixed electrode.

Figure 1.2 Cross section of the variable capacitor in Figure 1.1 when (a) the switch is in the rest position, (b) the applied bias is smaller than the pull-in voltage \((V < V_{\text{PI}})\), and (c) the applied bias is larger than the pull-in voltage \((V \geq V_{\text{PI}})\).

Bias (i.e., a DC voltage) is applied between the two electrodes, the electrostatic attraction force causes the suspended plate to move toward the underlying electrode, as it is anchored to flexible suspensions.

A scanning electron microscopy (SEM) photograph [25] of an anchoring point for a slender beam flexible suspension of an RF-MEMS device based on the concept reported in the schematic in Figure 1.1 is shown in Figure 1.3.

The smaller the distance between the suspended and the fixed electrode, the larger is the capacitance realized by the RF-MEMS variable capacitor. By increasing the applied voltage, one can further increase the capacitance. However, the whole distance \(d_0\) cannot be used to tune seamlessly the capacitance. Indeed, when the downward displacement of the suspended plate reaches \(d_0/3\) (i.e., one-third of the initial air gap), the balance between the attractive electrostatic force and the restoring mechanical force, induced by the deformed suspensions, reaches a condition of instability, and the plate collapses onto the underlying surface. This phenomenon is known as pull-in, and the bias level causing such an abrupt snap down of the movable membrane is referred to as pull-in voltage \((V_{\text{PI}})\) [26]. Figure 1.2b shows the movable plate configuration when the applied bias is smaller than the pull-in
Figure 1.3 Scanning electron microscopy (SEM) photograph of an anchoring point to which a flexible and suspended straight beam is anchored in a physical RF-MEMS device based on the concept in Figures 1.1 and 1.2.

Typically, the difference between the values the capacitance can assume when it is tuned before the pull-in and after it occurs is rather large (up to two to three orders of magnitude). This means that an RF-MEMS device, like the one depicted in Figures 1.1 and 1.2, can be exploited as a variable capacitor with a small and continuous tuning range [27]. Additionally, it can also be exploited as a two-state capacitor, with a large difference between the two capacitance values, that is, rest position and pulled-in position [28]. In the latter case, the RF-MEMS device could also be exploited as a capacitive switch for RF signals. Indeed, if the variable capacitor is inserted in shunt-to-ground configuration on the RF line, when the MEMS is pulled in, its large capacitance to ground realizes a low-impedance path for the RF signal, which is shorted to ground, and consequently does not reach the output termination (i.e., open switch) [29]. After the pull-in has been reached, if the applied bias starts to decrease, the device approaches the pull-out level, which is the critical voltage causing the release of the MEMS switch [23]. After the RF-MEMS release, if the applied bias is further decreased, the vertical position of the movable membrane will smoothly approach the initial rest position (corresponding to no bias applied). The measured vertical position of the movable suspended RF-MEMS device, similar to the one discussed in the previous figures, in response to an applied varying controlling voltage is reported in Figure 1.4. As is visible in the plot at the top of this figure, the applied controlling signal is a zero mean value triangular symmetric pulse with a period of 50 ms (i.e., frequency of 20 Hz).

The voltage ranges between ±20 V (Figure 1.4, top plot), and the plot at the bottom of Figure 1.4 shows the response of the RF-MEMS device concerning the vertical position of the movable membrane. The initial applied bias, that is, −20 V, is
Figure 1.4 Triangular symmetric zero mean value controlling bias applied to an RF-MEMS variable capacitor/switch (a). The frequency of the signal is 20 Hz and the voltage varies in the ±20 V range. Response of the RF-MEMS device (i.e., vertical displacement of the movable membrane) to the applied triangular bias (b). Pull-in and pull-out transitions are visible in both the positive and the negative range of the applied voltage, and they are $V_{PI} \approx 15 \text{ V}$, $V_{PO+} \approx 8 \text{ V}$, $V_{PI-} \approx -15 \text{ V}$, and $V_{PO-} \approx -8 \text{ V}$, respectively.

larger than the RF-MEMS pull-in voltage, and the movable membrane collapses onto the underlying electrode. Afterward, the applied voltage decreases toward zero, and the RF-MEMS releases as the pull-out voltage is reached ($V_{PO-} \approx -8 \text{ V}$). When the bias crosses the zero axis, the movable plate reaches its rest position, and then starts to move down as the bias increases (positive applied voltage). The RF-MEMS device then collapses onto the underlying surface when the pull-in is reached ($V_{PI+} \approx 15 \text{ V}$). The second half of the measurement registers another two transitions of the MEMS device, namely, the pull-out in the positive range of the applied voltage and the pull-in in the negative range of the applied voltage, being $V_{PO+} \approx 8 \text{ V}$ and $V_{PI-} \approx -15 \text{ V}$, respectively. This measurement is obtained by means of a white-light 3D profiling system based on optical interferometry [30].

The vertical displacement just discussed can be more easily reported versus the applied bias, highlighting the pull-in/pull-out characteristic of a certain MEMS device, as shown in Figure 1.5. The range of continuous tunability, corresponding to a vertical displacement at most equal to $d_0/3$ (see Figure 1.2), is highlighted in the plot.

On the basis of the working principle of the RF-MEMS variable capacitors and switches discussed in the previous pages, several geometries of the suspended MEMS membrane are possible, depending on the requirements, the application, and the expected performance and specifications. For instance, Figure 1.6 reports
Figure 1.5 Pull-in/pull-out characteristic of a MEMS switch. The range of continuous tunability is highlighted in the plot.

Figure 1.6 SEM photograph of an RF-MEMS variable capacitor (or capacitive switch). The suspended capacitor plate is connected to two controlling electrodes and to flexible suspensions.

a SEM photograph of a capacitive switch (shunt capacitance loading the RF line). The suspended plate of the capacitor is the large one in the central part of the device. It is connected to other two rectangular plates that are meant to control the vertical position of the central membrane. Underneath these plates there are two fixed electrodes that, when biased, cause a decrease of the gap between the capacitor plates. Finally, two narrow membranes connect the capacitor and the actuation plates to the surrounding fixed metal, realizing the flexible suspensions for the whole structure. The anchoring part is visible and highlighted on the left of the suspended membrane. The RF-MEMS variable capacitor (or capacitive switch) is framed within a coplanar waveguide (CPW) structure, with two lateral RF ground planes, and a central RF signal line, compatible with on-wafer microprobe measurements. The variable capacitor realized by the suspended MEMS structure loads the RF line in shunt-to-ground configuration. Figure 1.7 shows a close-up of the RF-MEMS variable capacitor concerning a region of the central suspended plate and the left-hand-side actuation electrode. The underlying RF line constituting the fixed capacitor plate is visible, as are the square openings on the suspended MEMS
A typical experimental C–V characteristic (i.e., capacitance versus applied voltage) of an RF-MEMS variable capacitor is reported in Figure 1.8. A sudden large increase in the capacitance with increasing pull-in (actuation) of the microdevice is visible. The capacitance, that is, in the range of about 200 fF when the RF-MEMS device is not actuated, shifts to about 2.5 pF when the suspended membrane collapses onto the underlying electrode.

Other examples concerning the surface micromachining of RF-MEMS variable capacitors are discussed in the literature, such as in the work by Park et al. [31], and Goldsmith et al. [32]. Beside standard implementations of micromachined RF-MEMS variable capacitors, the attention of research has also been focusing on the improvement of performance and characteristics. For instance, Liang et al. [33] discussed a solution to extend the tuning range of RF-MEMS varactors. Recently, Mahameed et al. [34] proposed a new design of a zipper RF-MEMS varactor with multiple sensing and controlling interdigitated electrodes in order to improve device robustness versus charge accumulation within the oxide, on one hand, and to better
control the capacitance tuning, on the other. Among the different topologies of RF-MEMS variable capacitors (and capacitive switches), a rather interesting solution to increase the tuning range is constituted by the so-called toggle-switch geometry. In this case, a push–pull mechanism, operated by means of multiple biasing electrodes, enables one to control the displacement of the suspended capacitor plate both toward the underlying electrode and upward [35]. When the central capacitor plate moves upward, the tuning range is extended to capacitances lower than the capacitance corresponding to the RF-MEMS rest position.

1.3.2 Inductors

MEMS technology also proved to be suitable for the fabrication of high-performance inductors. Spiral coils can be easily electrodeposited above a substrate. For this purpose, the work reported in [36] shows the realization of a metal spiral inductor framed within a CPW structure compatible with the experimental characterization on a probe station. The center of the spiral coil is connected to the output by means of an overpass, that is, a suspended metallization, that makes it possible to cross all the windings and to bring the RF signal to the output. The Q factor of a MEMS inductor can be significantly increased by choosing a low-loss substrate [37] as well as by reducing the coupling of the inductor windings with the substrate by depositing a good insulating layer in between [38]. However, MEMS technology also enables other solutions at manufacturing level that significantly reduce losses of inductors and, in turn, enhance the Q factor. Such solutions consist in having the metal inductor coil suspended above an air layer rather than a silicon one [39]. Cross-sectional schematic views of suspended MEMS inductors are reported in Figure 1.9. In particular, Figure 1.9a shows the cross section of an RF-MEMS inductor kept suspended by means of a sacrificial layer, which is then removed to release the floating structure [40]. This is a typical approach based on surface micromachining fabrication steps, and is similarly used for the release of the suspended RF-MEMS variable capacitors discussed in the previous section. Differently, the other two cross sections show how it is possible to suspend MEMS inductors through a bulk micromachining approach, that is, through the removal of the substrate material (e.g., silicon). In Figure 1.9b, the air cavity underneath the inductor coil is obtained by removing the substrate material from the top side of the wafer [41]. On the other hand, in Figure 1.9c the removal is done from the bottom side of the substrate until a thin membrane is left nonetched in order to mechanically sustain the inductor metallization [42]. An example of a MEMS inductor based on gold and suspended by means of a sacrificial layer (i.e., surface micromachining) is reported in Figure 1.10. The RF signal is brought from the central part of the coil to the output by means of an underpass. This means that a vertical transition brings the electrical signal from the gold level to a conductive buried layer. RF-MEMS-based inductors can also be easily integrated within more complex networks, for example, also comprising microswitches, variable capacitors, and so on. The microphotograph reported in Figure 1.11 shows a close-up of a complex
1.3 RF-MEMS Lumped Components

RF-MEMS network for the conditioning of RF signals that highlights the presence of suspended MEMS inductors. The reconfigurability typical of MEMS technology has also been investigated concerning lumped inductors, and there are various techniques enabling such a tuning capability. One of the most straightforward techniques employs the use of RF-MEMS switches to vary the length of the metal line realizing the inductor [43, 44]. Moreover, self-assembly techniques are also used in order to realize high-Q-factor inductors that can be tuned by thermally stressing the device [45]. Another solution consists in deploying a suspended movable metal plate on top of a spiral planar inductor. The metal plate is electrostatically actuated, and when it approaches the underlying coil, the interaction of the plate with its magnetic field changes the inductance [46].

More exotic approaches to reconfigure the inductance of RF-MEMS metal coils are also discussed in the literature. For instance, in [47] the inductance is modified by using a micropump that injects a fluid between the spirals, shortening the length of the electrical path and, in turn, reducing the inductance.
1.3.3 Ohmic and Capacitive Switches

The commonest and most well known class of RF-MEMS devices is represented by the microswitches (ohmic and capacitive). The literature reports a large amount of valuable realizations of switches based on MEMS technology for RF applications, as they represent the key components capable, on one hand, of enabling the reconfigurability of the network/platform comprising them, and also presenting, on the other hand, high performance and good characteristics compared with common implementations of relays in standard semiconductor technology. Concerning the mechanical working principle of RF-MEMS microswitches, two main classes can be identified, namely, the clamped–clamped and the cantilever switches. A SEM image of a clamped–clamped switch is reported in Figure 1.12.