Edited by **Stepan Lucyszyn**

Advanced RF MEMS

THE CAMBRIDGE RF AND MICROWAVE ENGINEERING SERIES

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Imperial College London

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Advanced RF MEMS

An up-to-date guide to the theory and applications of ratio frequency microelectromechanical systems (RF MEMS). With detailed information about RF MEMS technology, as well as its reliability and applications, this is a comprehensive resource for professionals, researchers and students alike.

- Reviews RF MEMS technologies
- Illustrates new techniques that solve long-standing problems associated with reliability and packaging
- Provides the information needed to incorporate RF MEMS into commercial products
- Describes current and future trends in RF MEMS, providing perspective on industry growth
- Ideal for those studying or working in RF and microwave circuits, systems, microfabrication and manufacturing, production management and metrology, and performance evaluation

Stepan Lucyszyn is currently an Associate Professor within the Optical and Semiconductor Devices group at Imperial College London (UK). He has published extensively on RF MEMS. As an IEEE Distinguished Microwave Lecturer (2010–2012), he gives presentations on RF MEMS at many international events. An experienced editor, he co-edited *RFIC and MMIC Design and Technology* (IET, 2001) and served for four years as a Member of the Editorial Board for the *IEEE/ASME Journal of Microelectromechanical Systems*. He is a Fellow of the IET, Institute of Physics and Electromagnetics Academy. In August 2010, Dr Lucyszyn was awarded the DSc degree of Imperial College in the field of Millimetre-wave and Terahertz Electronics.

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This book is dedicated to Petro Lucyszyn and Anna Lucyszyn (née Kusznier)

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Preface

Radio frequency microelectromechanical systems (RF MEMS) have just entered a new and exciting era, with this previously elusive technology finally appearing on the open market. In 2008, in the United States and Japan, the first real devices were released and made commercially available to all. Today, there is intense research and development (R&D) activity, and at all levels from concept to manufacture, within North America, Europe and Asia.

The first book to be dedicated to RF MEMS was published in 2002, and two others soon followed in 2003. Within these books, the most recent references to be cited were papers published back in January 2003. Therefore, the motivation for another book on the subject is clear. At this point, I would like to pay homage to the groundbreaking book entitled *RF MEMS: Theory, Design and Technology*, by Gabriel M. Rebeiz. Indeed, all these books collectively represent a major literary milestone in RF MEMS and could be considered as a springboard for the later activities that led to the first commercially available devices.

This book is a by-product of a Network of Excellence, called Advanced MEMS for RF and Millimetre-Wave Communications (AMICOM), funded by the European Union (EU), with all of the contributing authors being (in one way or another) associated with this network. Although the most significant technologies within the United States and Asia are represented, it should be of no surprise that there is a strong European feel to this book. Having said this, the number of institutions within the EU that have ongoing activities in RF MEMS far exceeds those represented by this book.

My first priority as editor was to identify critical areas of RF MEMS that had not already been covered in detail within the previously published books on the subject. Therefore, the intention of this new book is to complement existing books on RF MEMS by avoiding the need for too much overlap. Because of the expanding activities and wealth of new publications, it soon became apparent that the scope of the book should be confined to RF MEMS technologies that conform to their literal definition, i.e. RF components that have some form of reconfigurable actuation. This excludes, for the most part, micromechanical resonators and thin-film bulk acoustic resonator (FBAR) technologies, which deserve their own dedicated books to do them justice. Even with its limited remit, the 9-page list of abbreviations reflects the wide range and diversity of science and technology introduced within the book (e.g. those associated with materials, devices, circuits, subsystems and applications).

Having identified the critical areas to be covered, for an *advanced* book, my second objective was to find contributing authors that already had international recognition for their knowledge, hands-on experience and success in their respective specialist areas. In fact, I did not have to look too far, because Europe is well known for its world-class research institutes that have major ongoing programmes associated with RF MEMS. It is hoped that this book will represent the second major literary milestone in RF MEMS and will be considered as a springboard for future activities leading to volume production and the market exploitation of ubiquitous applications. To this end, this book should appeal to those either studying or working in RF areas relating to systems, circuit and component design, microfabrication and manufacturing, product management, metrology and performance evaluation and future concept development.

This book has three main themes: *Review*, *Reliability* and *Applications*. The first four chapters serve as an updated review of RF MEMS technologies, paying particular attention to RF MEMS switches. The introduction in Chapter 1 gives a basic overview and lays the foundation for the rest of the book by helping to define some of the terminology and concepts. This chapter may be of particular interest to those who have not been exposed to the many facets that this technology has to offer. Chapter 2 explains, in rigorous mathematical detail, important aspects of electrostatic actuation that underpin the majority of RF MEMS devices. This is then followed in Chapter 3 by a review of the more conventional types of RF MEMS switches and their associated fabrication technologies. The most successful design solutions converge on simple architectures that may already be protected by intellectual property rights and patent law. Some may say that this is one of the reasons for the slow progress in RF MEMS commercialisation. For this reason, there will always be a need for innovative designs that can give superior performance for niche applications and avoid patent infringement. A selection of more specialist, *niche*, switches are reviewed in Chapter 4. Here, innovation-led devices are compared with the performance-driven devices that are now commercially available.

The next five chapters tackle the critical issues associated with reliability that have, until recently, hampered the commercial exploitation of RF MEMS technologies. Chapter 5 identifies the general problems associated with reliability, from definition to the need for standardisation. With the growing interest in capacitive membrane switches, the fundamental physics that underlie charging effects are discussed in Chapter 6. With the need for greater operational RF power levels, thermal aspects and material structural stress are reviewed in Chapter 7, and Chapter 8 addresses the related failure mechanisms and design considerations for high-power switches. Modern packaging solutions are covered in detail in Chapter 9. This is because packaging has a dramatic effect on reliability, levels of integration and, ultimately, on cost.

The last four chapters are associated with the applications of RF MEMS, from circuit to systems levels and their adoption into commercial products. Chapter 10 explores reconfigurable impedance-matching networks and filter circuits of growing importance for commercial exploitation. The more traditional areas of phase shifters and delay lines are covered by Chapter 11. A discussion on how RF MEMS can influence the design of subsystems architectures is presented in Chapter 12. Finally, through detailed comparison with competing technologies (existing and emerging), Chapter 13 attempts to look into the future of RF MEMS by creating a unique industry roadmap. It should be stressed that many of the predictions made are based on current trends and forecasts made by industry at around the time of writing. It remains to be seen whether such speculation does indeed turn out to be accurate or just wishful thinking. In terms of commercial activities, every reasonable attempt has been made to avoid introducing errors because of the dynamic and, some may say, volatile nature of the current RF MEMS industry. For example, at the time of your reading, company names may have changed or their selected product lines expanded or contracted.

When I was invited to edit this book, I considered it to be an honour and a privilege to serve the international RF MEMS community in this way. Therefore, I would like to express my sincerest gratitude to the AMICOM partners and, in particular, Professor Roberto Sorrentino (University of Perugia) for his support and guidance throughout this project. I would also like to thank the EU for funding AMICOM (grant number FP6–507352) and the UK Engineering and Physical Sciences Research Council for funding the Platform Support for 3D Electrical MEMS project (grant number EP/E063500/1), among others.

Because only 2 of the 22 contributing authors have English as their first language, this book presented a formidable task for the vast majority. For this reason, I would like to extend my deepest gratitude to all the contributing authors, but especially to those that have had to battle with English. This has been a long and uniquely challenging project for Cambridge University Press, but they have supported it throughout. Therefore, I wish to thank Dr Julie Lancashire and Sarah Matthews, in particular, for their patience, and Sabine Koch for lightening some of my administrative load.

I am indebted to E. M. Yeatman for first introducing me to the topic of RF MEMS, just over a decade ago, R. Maeda for allowing me to work in his MEMS laboratory (Tsukuba, Japan) and C. Papavassiliou for inviting me to join AMICOM at its early preconception phase. Since then, many people have deeply influenced my thinking: I wish to express my immense gratitude to M. Kawamura and T. Nishino (in Japan) and my colleagues A. S. Holmes and I. D. Robertson (in the UK), to name just a few.

Finally, for the time that has been stolen from my work and family, I acknowledge the support of all my PhD students and close working colleagues at Imperial College London and will continue to seek forgiveness from my wife.

Abbreviations

AC	alternating current
ACC	(adaptive or autonomous or) automatic cruise control
ADC	analogue-to-digital converter
ADS	advanced design system
AESA	active electronically scanned array
AFM	atomic force microscopy
AFRL	Air Force Research Laboratory
AIPAA	active integrated phased-array antenna
Al	aluminium
AlCuMgMn	aluminium copper magnesium manganese
ALD	atomic layer deposition
AlGaAs	aluminium gallium arsenide
AlN	aluminium nitride
Al_2O_3	aluminium oxide
AMDF	automated main distribution frames
AMICOM	Advanced MEMS for RF and Millimetre-Wave Communications
ANSYS	analysis system
Ar	argon
ARRRO	Applied Research Roadmap for RF Micro/Nano Systems Opportunities
a-Si	amorphous silicon
ASIC	application-specific integrated circuit
a-SiC	amorphous silicon carbide
ATE	automatic/automated test equipment
atm	atmosphere
Au	gold
$AuNi_5$	gold nickel
AuSn	gold tin
Au-SnPb	gold-tin lead
Au-TiW	gold-titanium tungsten
BAW	bulk acoustic wave
BCB	benzocyclobutene
BGA	ball grid array
BiCMOS	bipolar and complimentary metal oxide semiconductor

BMW	Bavarian Motor Works
BPF	bandpass filter
BSOI	bonded-silicon-on-insulator
BST	barium strontium titanium oxide
C	capacitor
CAD	computer-aided design
CBED	convergent beam electron diffraction
CDMA	code division multiple access
CEA-LETI	Commissariat à l'Énergie Atomique – Laboratoire d'Electronique et de Technologie de l'Information
CMOS	complementary metal oxide semiconductor
CMP	chemical-mechanical polishing
C/N	carrier-to-noise power ratio
CNRS-IEMN	Centre National de la Recherche Scientifique – Institut d'Electronique et de Microelectronique du Nord
CNRS-LAAS	Centre National de la Recherche Scientifique – Laboratoire d'Analyse et d'Architecture des Systèmes
CNT	carbon nanotube
CPW	coplanar waveguide
CR	capacitance ratio
CSEM-LETI	Centre Suisse d'Electronique et de Microtechnique SA – Laboratoire d'Electronique et de Technologie de l'Information
CSP	chip-scale package (or chip-size packaging)
CST	computer simulation technology
CTE	coefficient of thermal expansion
Cu	copper
C-V	capacitance-voltage
CVD	chemical vapour deposition
CW	continuous wave
C2W	chip-to-wafer
DAC	digital-to-analogue converter
dc	direct current
DCT	discharge current transients
DFR	design for reliability
DFT	design for testability
DGS	defected ground structures
DIPIE	displacement iteration pull-in extraction
DLP	digital light processing
DMD	digital micromirror device
DMTL	distributed MEMS transmission line
DoCoMo	Do Communications Over the Mobile Network
DOF	degree of freedom
DPDT	double-pole double-throw
DPST	double-pole single-throw

DRIE	deep reactive ion etching
DUT	device under test
DVB-H	digital video broadcasting-handheld
D2W	die-to-wafer
EADS	European Aeronautic Defence and Space
EBSD	electron backscattered diffraction
EDA	electronic design automation
EM	electromagnetic
EPFL	Ecole Polytechnique Federale de Lausanne
epi-seal	epitaxial polysilicon-seal
ESA	European Space Agency
ESA	electronically scanned array
ESD	electrostatic discharge
EU	European Union
EUMA	European Microwave Association
FBAR	thin-film bulk acoustic resonator
FBK-irst	Fondazione Bruno Kessler – Istituto per la Ricerca Scientifica e Tecnologica
FCC	Federal Communications Commission
FDTD	finite-difference time-domain
FEM	finite-element method
FETs	field-effect transistors
FGCPW	finite-ground coplanar waveguide
FhG-ISiT	Fraunhofer – Institut für Siliziumtechnologie
FM	frequency modulation
FMEA	failure mode and effect analysis
FOI	Totalförsvarets forskningsinstitut (or Swedish Defence Research Agency)
FOM	figure-of-merit
FOV	field of view (or vision)
FP6	6th Framework Programme
GA	giga-ampere
GaAs	gallium arsenide
GaN	gallium nitride
GCPW	grounded coplanar waveguide
GHz	gigahertz
GPa	gigapascal
GPS	global positioning system
GSG	ground-signal-ground
GSM	Groupe Spécial Mobile (or global system for mobile)
G/T	power gain-to-noise temperature ratio
HDMI	high-definition multimedia interface
He	helium
HF	hydrofluoric

HfO_2	hafnium dioxide
HFSS™	high-frequency structure simulator
HMICs	hybrid microwave integrated circuits
HRL	Hughes Research Laboratories
HRS	high-resistivity silicon
HRSi	high-resistivity silicon
HTCC	high-temperature cofired ceramic
Hz	hertz
IBM	International Business Machines
IC	integrated circuit
ICT	Information and Communication Technology
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IEE	Institution of Electrical Engineers
IET	Institution of Engineering and Technology (Formally IEE)
IMD	intermodulation distortion
IMEC	Interuniversity Microelectronics Center
IMST	Institute of Mobile and Satellite Communication Techniques
IMT	Institut de Microtechnique
In	indium
IP_3	third-order intermodulation intercept point
IQ	in-phase quadrature-phase
Ir	iridium
IR	infrared
ISM	industrial-scientific-medical
K-band	IEEE radar band letter designation for 18 to 26.5 GHz
Ka-band	IEEE radar band letter designation for 26.5 to 40 GHz
KAIST	Korea Advanced Institute of Science and Technology
kbps	kilobits per second
kgf	kilogram force
KPFM	Kelvin probe force microscopy
Kr	krypton
Ku-band	IEEE radar band letter designation for 12 to 18 GHz
KULeuven	Katholieke Universiteit Leuven
L	inductor
LAN	local-area network
LC	inductor-capacitor
LCP	liquid crystal polymer
LG	Lucky Goldstar
LIDAR	light detection and ranging
LNA	low-noise amplifier
LPCVD	low-pressure chemical vapour deposition
LRR	long-range radar
LRS	low-resistivity silicon

LTCC	low-temperature cofired ceramic
LTE	long-term evolution
LTO	low-temperature oxide
MAM	metal-air-metal
MATLAB	matrix laboratory
Mbps	megabits per second
MCM	multichip module
MCM-C	ceramic multichip module
MCM-D	deposited thin-film multichip module
MCM-L	laminated multichip module
MDF	main distribution frames
MEMS	microelectromechanical systems
METU	Middle East Technical University
MHz	megahertz
MIL-STD	military-standard
MIM	metal-insulator-metal
MIMO	multiple-input and multiple-output
MIT	Massachusetts Institute of Technology
MMICs	monolithic microwave integrated circuits
MMID	mm-wave identification
mm-wave	millimetre-wave
Mo	molybdenum
MOS	metal oxide semiconductor
MPRWG	metal-pipe rectangular waveguide
MSL	microstrip line
MST	microsystems technology
MTTF	mean time to failure
MWS	Maxwell-Wagner-Sillars
N	nitrogen
N	Newton
Na	sodium
NANO RF	Hybrid Carbon Nanotube – CMOS RF Microsystems
NATALIA	New Automotive Tracking Antenna for Low-Cost Innovative Applications
NB	narrow band
NEMS	nanoelectromechanical systems
Ni	nickel
NiFe	nickel iron
NNSA	National Nuclear Security Administration
NoE	Network of Excellence
NTT	Nippon Telegraph and Telephone
NXP	Next Experience
N_2	nitrogen
O	oxygen

O_2	oxygen
O-H	oxygen-hydrogen
O-ring	circular-shaped ring
PA	power amplifier
PAE	power-added efficiency
PAN	personal area network
PASSI™	passive integration in silicon
PC	personal computer
PCB	printed circuit board
Pd	palladium
PDA	personal digital assistant
PDMS	polydimethyl-siloxane
PE	plasma-enhanced
PECVD	plasma-enhanced chemical vapour deposition
permalloy	nickel-iron magnetic alloy
petaflops	10^{15} floating point operations per second
PF	Poole-Frenkel
pHEMT	pseudomorphic high-electron-mobility transistors
PIFA	planar inverted-F antennas
PIN	*p*-type/intrinsic/*n*-type
Poly-Si	polycrystalline silicon or polysilicon
ppm	parts per million
PRISM	Center for Prediction of Reliability, Integrity and Survivability of Microsystems
Pt	platinum
PZT	lead zirconium titanate
P_{1dB}	1 dB compression point
Q	quality
Q-band	RSGB band letter designation for 33 to 50 GHz
R	resistor
RADAR	radio detection and ranging
RADARAUGE	Phasengesteuertes Radarmodul bei 79 GHz Auf Organischen und Keramischen Substraten
R&D	research and development
RETINA	Reliable, Tuneable and Inexpensive Antennas by Collective Fabrication Processes
RF	radio frequency
RFB	radio function block
RFIC	radio frequency integrated circuits
RFID	radio frequency identification
RFOW	radio frequency on-wafer
Rh	rhodium
RH	relative humidity
RIE	reactive iron etching