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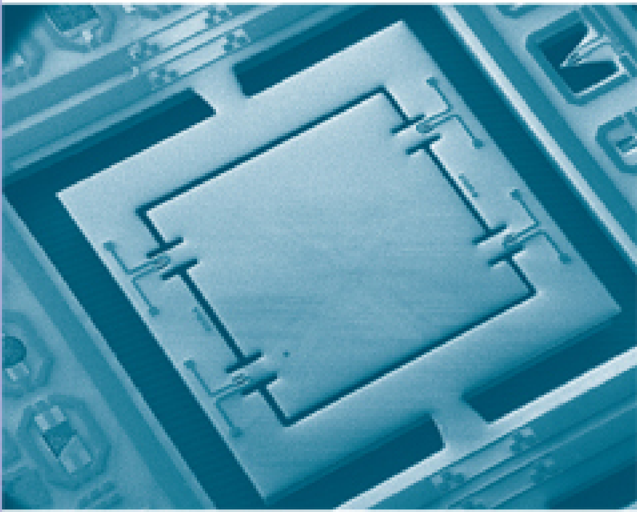
Acoustic Wave and Electromechanical Resonators

CONCEPT TO KEY APPLICATIONS



Humberto Campanella

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Alba del Mar, Aire, Río, Bosque . . .

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Preface

Micro- and nanoresonators have become key components of virtually all modern radio frequency (RF) systems and sensors. As fabrication and packaging technologies have enabled high-production yield and high-performance devices, miniature resonators have left the laboratory to take up industrial applications. However, the complexity and huge variety of acoustic and electromechanical resonator technologies sometimes make it difficult to understand the mechanisms involved in their operation. Efficacy on decision making with regard to choosing the right technology for our application is thus often prevented. Also required is mastery of several disciplines, from applied physics and materials to manufacturing and system level applications.

How can we give an effective answer to these issues so as to benefit design, process, and application engineers? Keeping them in mind, this book provides comprehensive and wide coverage of thin-film bulk acoustic wave resonators (FBAR), microelectromechanical (MEMS), and nanoelectromechanical (NEMS) resonators, at both the technology and application levels. Hence, this work contributes to the field with a thorough and practical resonator description that gathers, for the first time, state-of-the-art design and modeling, fabrication and characterization techniques, integration with standard integrated circuit (IC) technologies, and industrial and laboratory applications. Moreover, practical case studies complement the theoretical and laboratory background.

The book assumes basic undergraduate-level preparation in physics, material science, electronics, chemical, mechanical, or electrical engineering. The intended audience includes the following:

1. Senior undergraduate or beginning graduate students involved in advanced education related to MEMS, RF systems, or sensors;
2. Process and design engineers, related to clean room and micro- and nanofabrication processes and modeling of MEMS devices;
3. MEMS, NEMS, and FBAR device researchers who are already familiar with the fundamentals of both MEMS and circuit design.

The contents of this book stem largely from academic and clean room experience. They follow what is to the author's view the logical sequence of FBAR, MEMS, and NEMS resonator production flow.

Chapter 1 is an introductory chapter to MEMS and NEMS resonator technologies. It covers the context and theoretical background of electromechanical devices. The discussion differentiates between MEMS and NEMS, their transduction mechanisms, and current fabrication technologies.

Chapter 2, on the other hand, specializes in bulk and surface acoustic wave resonators, like thin-film bulk acoustic wave resonator (FBAR), solidly mounted resonator (SMR), and surface acoustic wave resonator (SAW) technologies. As in the previous chapter, physical fundamentals of acoustic wave propagation, piezoelectricity, and applications are discussed.

Chapter 3 addresses the varied universe of resonator models by first defining a design flow and the role of modeling in the production of resonators. Electromechanical transformers, equivalent circuits, analytical models, and finite element models are covered.

Chapter 4 explains the fabrication and technological details of resonator fabrication by illustrating the case of FBAR manufacturing. Materials, processes, and structure characterization are described.

Chapter 5 deals with characterization. The contents provide the reader with concepts and experimental setup of electrical, atomic force microscope, and optical interferometry techniques.

Chapter 6 discusses performance optimization, thus dealing with frequency stability, temperature compensation, and frequency tuning. Detailed coverage of a novel focused-ion-beam-assisted technique for FBAR tuning is provided.

Chapter 7 deals with technological issues of FBAR, MEMS, NEMS resonator, and complementary metal oxide semiconductor (CMOS) technologies integration. As the MEMS-CMOS concept expands in current implementations, the subject is of central concern of process engineers and IC designers.

Chapter 8 reviews state-of-the-art sensor applications of FBAR, MEMS, and NEMS resonators. A balanced discussion of academic research and industrial products is preserved in the chapter.

Chapter 9 reviews classical passive and active RF applications. It revisits them under the light of the latest FBAR and MEMS resonator technologies, enabling the development of new architectures. Special attention is given to high-impact commercial RF microdevices and microsystems.

Chapter 10 closes the book by studying three implementation cases. Practical examples of FBAR fabrication, conceptual design of a temperature-compensated (TC) oscillator, and 434-MHz MEMS resonator read out circuit design are studied.

Acknowledgments

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CHAPTER 1

MEMS and NEMS Resonator Technologies

This introductory chapter addresses the fundamentals of micro- and nanoelectromechanical (MEMS and NEMS) resonators. Throughout this book, we employ the acronym MEMS to designate electron devices based on silicon. In the Section 1.1, MEMS and NEMS are defined and their main attributes described so we can identify their main differences from the beginning. Next, in the Section 1.2, a theoretical background on the physics behind the operating principles of MEMS and NEMS resonators is presented. The fundamental relationships of mechanical harmonic oscillators and transduction mechanisms are reviewed, thus supporting the discussion on the resonance modes and different resonator structures.

Second 1.2 deals with production and technological aspects of MEMS and NEMS resonator design and fabrication. Section 1.3, the production cycle of MEMS and NEMS shows the steps to develop and fabricate a resonator, from concept to application dimensioning. The section also describes the technologies currently employed in MEMS and NEMS fabrication. Two approaches are considered: the common to integrated circuit (IC), which is suitable for MEMS, and the nanofabrication-based techniques, more suitable for NEMS.

1.1 What Is MEMS and What Is NEMS?

Microelectromechanical systems (MEMS) are movable structures and systems with micrometer sizes. The concept also involves the related fabrication technology. Nowadays, it is generally accepted that MEMS have at least one of their dimensions in the range from hundreds of nanometers to hundreds of micrometers. Nanoelectromechanical systems (NEMS) have dimensions below the 100-nm conventional limit. Although some MEMS may also have submicron dimensions, a more determinant aspect differentiating MEMS and NEMS is their base technology. MEMS have been conceived under the integrated circuit (IC) paradigm, in which silicon is the base material for substrate, integration, and device fabrication. MEMS are fabricated according to the same fabrication techniques and processes of ICs, especially from complementary-metal-oxide-semiconductor (CMOS) technologies. Actually, MEMS and CMOS circuits can coexist for integrated applications. CMOS has become the predominant IC technology, whose potential is not only exploited for ICs but also for a variety of MEMS-based applications. Recently integrated microsystems featuring calibration by digital programming, self-testing, and digital interfaces have been implemented on a single chip, demonstrating the strength of CMOS-based MEMS [1].

NEMS devices, on the other hand, are not scaled-down MEMS, but a quite different technological approach. Although it is widely implemented, silicon is no longer the main base technology of NEMS. New materials and structures like carbon nanotubes, nanowires, and organic composites are being investigated and implemented in many NEMS demonstrators [2–5]. Scaling down has been achieved by IC technology reduction, but mainly by introducing new fabrication tools, like electron beam lithography (EBL) [6], atomic force microscope [7], and nano-imprint [8], among others. The dominant physical phenomena are also different at the MEMS and NEMS scales, which imposes new engineering challenges. Due to technological development at both fabrication and material levels, new applications have appeared, many of them relying on NEMS devices. This integrated approach of NEMS technology and applications is known as the nano-bio-info-cognitive (NBIC) convergence. The schema of Figure 1.1 illustrates the different approaches of MEMS and NEMS technologies and the NBIC concept. Three different technologies can be differentiated: microelectronics, MEMS, and NEMS. The baseline material for both microelectronics and MEMS is silicon, and applications can be found in information technologies, neuroscience, biotechnology, cognitive science, and learning, among many others [9].

Materials, base technology, and applications of micro- and nanodevices are diverse and go beyond traditional fields of electronics after the conception of the NBIC convergence. Figure 1.2 shows how, before the NBIC, silicon is almost exclusively the material for fabricating microprocessors, digital signal processors (DSP), microcontrollers, analog devices, silicon MEMS, and integrated circuits in general (at left). After the NBIC, new materials and structures like polymers, organic composites, carbon nanotubes, or nanowires make part of specialized systems on the same chip. The situation has given rise to the bio-MEMS, lab-on-a-chip (LoC), micro total analysis systems (μTAS) and system-on-a-chip concepts (SoC) [10–12].

MEMS and NEMS play a central role on the miniaturization of electronic SoC, LoC, and μTAS. Information and communication technologies (ICT) have bene-

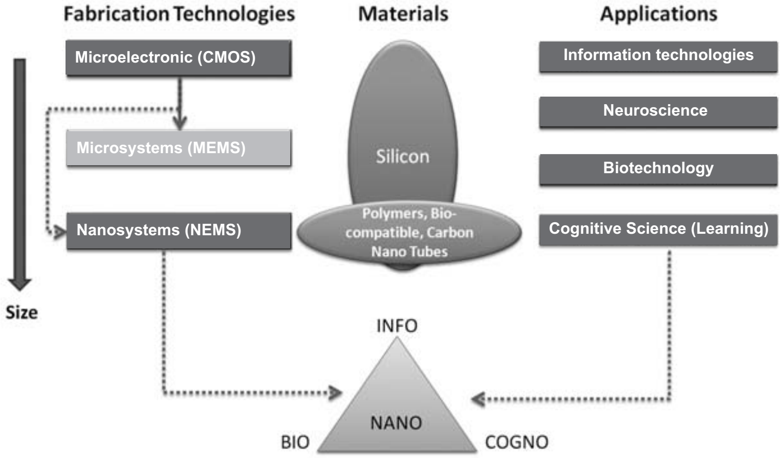

Figure 1.1 The NBIC convergence concept.

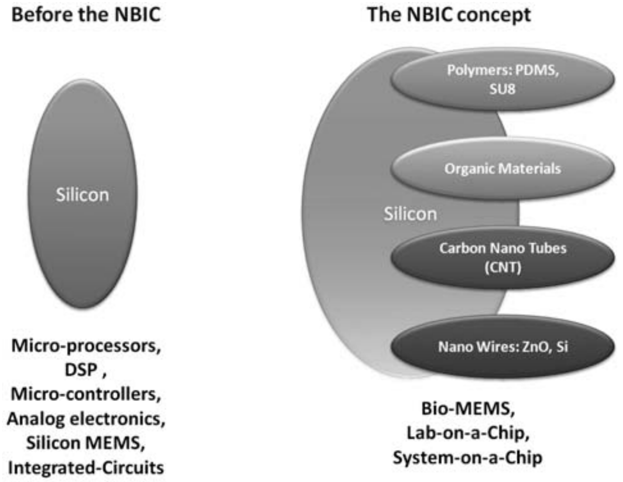

Figure 1.2 Impact of the NBIC on the materials and applications of technology.

fited from the MEMS and NEMS boom as well. Technological advances of micro- and nanoelectronic engineering fields have led to a drastic reduction of size and price in sensors and radio frequency (RF) components. New technologies have also enabled their integration into single microelectronic chips. Ultrahigh sensitivity, faster response times, and power and size efficiency are some of the benefits that have leveraged the implementation of MEMS in integrated sensor systems and modern mobile communication transceivers.

A detailed, comprehensive, and rigorous discussion on MEMS and NEMS history would take a complete book. If one has to elect the first MEMS device produced in history, it is the gold resonating MOS gate transistor invented by H. C. Nathanson at the Westinghouse Laboratories in 1967, which implemented the surface micromachining technique [13]. Thus, we see how the technological breakthroughs of microelectronics and micromachining techniques have allowed the evolution of MEMS and NEMS. Therefore, one can say that the MEMS era began with the pressure microsensor in the 1970s. It was followed by the actuator, microlenses and accelerometers in the 1980s; the RF devices, chemical sensors, micromirrors, antennas, and gears in the 1990s; and the medical applications, the LoC, μTAS, bio-MEMS, and NEMS devices developed in the following decade. This list shows a representative group of the major advancements of electronics, MEMS, and NEMS history [14]:

- 1947: Germanium transistor invention (Bell Labs: W. Shockley, J. Bardeen, W. Brattain);
- 1958: Silicon-made force sensor commercialization;
- 1958: First integrated circuit (Texas Instruments: J. Kilby);
- 1961: First silicon sensor (Kulite, *bare silicon strain gages*);
- 1967: Surface micromachining invention (Westinghouse: J. Nathanson, *resonant gate transistor*);
- 1967: Anisotropic silicon etching (R. M. Finne and D. L. Klein);