

Preface

This book is meant to introduce piezoelectric microelectromechanical system (MEMS) resonators to a broad audience of engineers, graduate students, and researchers with the scope of offering a review of the field as well as generating excitement for future research work and stimulating entrepreneurial activities in this area.

The progress enabled by MEMS manufacturing methods has transformed the field of acoustic resonators. Piezoelectric materials have historically been the workhorse of practically any mechanical resonator on the market. The use of quartz crystals and ceramic resonators is widespread and can be found in electronic oscillators, filters, physical and gravimetric sensors, microphones, and ultrasonic transducers just to mention a few examples. These devices have been going through constant improvements and miniaturization since their first implementation approximately 100 years ago. Nonetheless, these piezoelectric acoustic resonant devices rely on bulk materials; hence they are hard to integrate with advanced manufacturing processes used in integrated circuits (IC). The use of micromachining techniques to manufacture micromechanical resonators offers the potential to build billions of these acoustic devices on silicon wafers, making them an extremely low-cost technology that could dramatically change the existing market dynamics. MEMS resonators have indeed received significant industrial attention and some of them are commercially available. Silicon-based resonators developed by several start-up companies are now sold in the millions for timing products. Piezoelectric-based resonators, namely bulk acoustic wave (BAW) resonators (covered in Chapters 8 and 16 of this book), are sold in billions for filtering applications.

Historically, the adoption of thin films of piezoelectric materials for manufacturing MEMS devices followed a relatively bumpy path. Many of the engineers working in the IC industry used to label piezoelectric materials as exotic. To add to this perception, many of the materials initially used for piezoelectric MEMS, such as zinc oxide and lead zirconate titanate (PZT), were indeed not compatible with semiconductor-focused manufacturing facility. The advent of new materials, such as aluminum nitride (see Chapter 1 of the book), has transformed the space and generated a growing interest in the use of piezoelectric materials for the making of

MEMS. At international MEMS conferences, it is quite impressive to witness the growing number of publications that rely on piezoelectric materials for the making of MEMS devices. Many foundries have also accepted the use of piezoelectric materials in their manufacturing line and products using PZT and AlN are commercially available. Similarly, in the field of acoustic resonators, MEMS researchers have developed new classes of piezoelectric miniaturized resonant devices that are deemed to transform the fields of radio frequency (RF) communication and sensing. Clear examples of this ongoing innovation are the thin-film bulk acoustic resonators (FBARs) that we can find in practically any modern phone as well as miniaturized contour-mode resonators, microphones, and ultrasonic transducers that several start-up companies are commercializing.

We believe we are at an inversion point of a trend that will see the explosion in the development of piezoelectric MEMS resonators. Commercial opportunities to replace existing products with smaller, lower cost, and higher performance piezoelectric MEMS resonators will continue to present themselves. Furthermore, the ability to manufacture these devices on large substrates and interconnect them in large systems will mark the development of integrated mechanical circuits that can transform existing paradigms of communication and sensing. For example, very low power RF sensor nodes that monitor the crowded electromagnetic spectrum as well as frequency-agile RF front ends that enhance the data capacity of our networks can be envisioned thanks to the continuous progress that researchers are making in the area of piezoelectric MEMS resonators.

This book captures some of the most exciting developments in the area of materials and devices for the making of piezoelectric MEMS resonators and offers direct examples of the technical challenges that need to be overcome in order to commercialize these types of devices. Part I reports on some of the most widely used piezoelectric materials that the research community has adopted for the making of MEMS resonators. This part focuses on well-established materials such as AlN (Chapter 1 by Murali) and PZT (Chapter 2 by Polcawich and Pulskamp), but also discusses emerging interest in materials such as gallium nitride (GaN in Chapter 3 by Rais-Zadeh and Weinstein) and lithium niobate (LN in Chapter 4 by Gong). These two materials are representative of different emerging trends that aim at bringing “exotic” materials on silicon. GaN is an established electronic material. The ability to co-fabricate mechanical resonators in the same thin film on large silicon substrates will offer new opportunities to develop tightly integrated microsystems for RF and sensing applications. Thin films of LN on silicon are presented as representatives of emerging activities to exploit the unique properties of bulk materials and transfer them onto silicon substrates, hence enabling new capabilities not possible with films deposited by physical vapor deposition processes. A similar fabrication approach is described in Chapter 9 (by Chang) in regard to the use of thin films of quartz to make shear-mode MEMS resonators. Part II focuses primarily on the description of different kinds of resonators classified based on their mode of vibration. The main parameters that determine resonator performance, namely the quality factor (Q) and electromechanical coupling, are first introduced in Chapter 5 by Abdolvand. Flexural resonators used for low frequency

applications such as in ultrasonic transducers are described in Chapter 6 by Horsley. The focus is then switched to higher frequency resonators with a detailed description of contour-mode resonators (Chapter 7 by Rinaldi), thickness mode resonators (Chapter 8 by Hashimoto), and shear-mode resonators (Chapter 9 by Chang). Each subchapter describes the constitutive equations of motion of these resonators and guides the readers through the derivation of their electrical equivalent models. Examples of practical implementations of these classes of devices are described to showcase the level of performance that can be accomplished by these resonators. Chapters 10 and 11 deal with more advanced design concepts of piezoelectric MEMS resonators. In Chapter 10 Pan describes methods to temperature-compensate piezoelectric resonators so that they can operate over industrial temperature ranges. In Chapter 11 Kamon describes finite element methods for modeling the response of piezoelectric resonators with a focus on open challenges related to the modeling of Q and nonlinearity. Part III deals with more practical aspects associated with the fabrication (Chapter 12 by Tabrizian), test, and evaluation of piezoelectric MEMS resonators. Industry and academic perspectives are presented and details rarely found in the literature are provided on the requirement for test and evaluation of MEMS resonators (see Chapter 13 by Gubser on reliability and quality assessment and Chapter 14 by Pai on large volume testing and calibration). Finally, Part IV reports on two examples of commercialization paths for piezoelectric MEMS resonators. Chapter 15 by Kuypers reports on the initial efforts and lessons learned in commercializing piezoelectric MEMS resonators for the timing market. Chapter 16 by Aigner is focused on BAW resonators and their successful insertion into the filter and duplexer market. We believe that these two subchapters should serve as a source of inspiration and advice for future entrepreneurs in the space.

The editors would like to thank all the authors who have contributed to this book. There are no words to describe their sense of dedication to the topics covered in this book. It is through the commitment and excitement shown by the authors of this book that a community of researchers and engineers working on piezoelectric MEMS resonators could be built. Through this book, we hope to continue to educate new generations of graduate students, young engineers, and researchers and instill them with the same passion for piezoelectric MEMS resonators.

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