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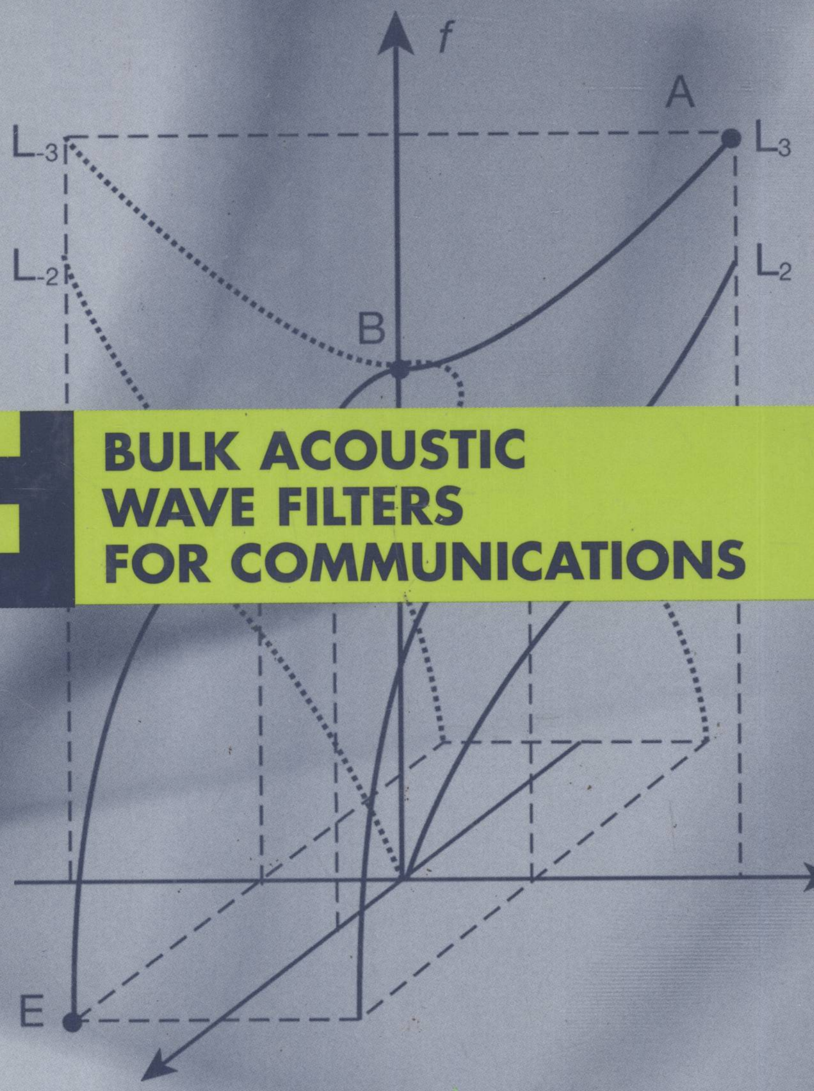
editor



RF BULK ACOUSTIC WAVE FILTERS FOR COMMUNICATIONS

RF Bulk Acoustic Wave Filters for Communications

Ken-ya Hashimoto

Editor

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Preface

Nowadays, electromechanical (EM) resonators are widely used in most sophisticated electronic equipment. For example, bulk acoustic wave (BAW) resonators using crystal quartz are indispensable for frequency or time generation owing to their outstanding performances.

The mobile communication market has grown explosively in last two decades. From a technological point of view, this growth is significantly indebted to the rapid evolution of silicon technologies, and most of all, functionalities are now realized by the use of silicon integrated circuits (Si-IC). However, highly precise frequency generation and excellent radio-frequency (RF) filtering are exceptional. They were only realizable by the use of quartz resonators and surface acoustic wave (SAW) devices, respectively.

RF-BAW devices employing a piezoelectric thin membrane were proposed in 1980. Although their excellent performance was well recognized, the majority of engineers believed that their applicability was very limited due to extremely tight requirements given to the device fabrication.

However, the tremendous efforts of a few believers moved mountains. RF-BAW devices progressed surprisingly in the last decade and are now mass produced. Furthermore, they are attempting to take over the current RF-SAW filter market.

The devices also receive much attention from Si-IC industries for their use as a core element in sophisticated RF front-end and/or one-chip radio modules based on the system-on-chip (SoC) or system-in-package (SiP) integration with active circuitry.

This book deals with key technologies and hidden know-hows necessary for the realization of high-performance RF-BAW resonators and filters. All the authors are prominent professionals in this field, and they did their best to transfer their knowledge to the younger generation. This book is invaluable not only for young engineers and students who wish to acquire this exotic technology, but also for experts who wish to further extend their knowledge. It is extremely hard for any person to prepare such a monograph solely, and only fruitful collaboration of these authors could make this difficult task possible.

By the way, the term *film bulk acoustic wave resonator* (FBAR) might be more familiar to a majority of readers. However, its use is often limited to the category of a free-standing membrane fabricated by the surface or bulk micromachining technology. Namely, the *solidly mounted BAW resonator* (SMR) employing the multilayered reflector(s) is excluded from this category. From this reason, we follow this categorization, and the RF-BAW resonator is used as the whole set of these two categories throughout this book.

In Chapter 1, Dr. Keneth Lakin, a pioneer of the RF-BAW devices and a technical leader in this field, reviews the background and history of the RF-BAW resonators and takes readers on a virtual tour of extensive efforts that brought the technology to its current success.

In Chapter 2, Dr. Lakin gives detailed explanations on resonator and filter topologies that frequently appear in current RF-BAW technologies.

Electrical characteristics of RF-BAW device are simulated quite well by computer simulation and its use is vital in current device design. In Chapter 3, Dr. Jyrki Kaitila describes the BAW device basics, explaining the one-dimensional modeling, detailing various second effects inherent for the precise simulation, and then discussing numerical techniques and underlying physics.

In Chapter 4, Dr. Robert Aigner and Dr. Lueder Elbrecht discuss RF-BAW devices based on the solidly mounted resonator technology. First, they consider their design and then discuss their fabrication for mass production in a semiconductor fabrication environment.

In Chapter 5, Dr. Richard Ruby, the father of FBAR, reviews free-standing bulk acoustic resonators (FBARs). Dr. Ruby begins this chapter with a short history about the high obstacles that he and his group encountered, how he struggled, and how he achieved a great triumph at the last minute.

In Chapter 6, Dr. Masanori Ueda compares the RF-BAW device with the RF-SAW device from various points of view. Dr. Ueda has been involved in the research and development of both of these devices, and can evaluate them without bias.

As described before, BAW device performances can be simulated numerically fairly well. However, achievable performances are critically dependent on employed manufacturing process, especially the quality of deposited piezoelectric thin films. In Chapter 7, Dr. Sergey Mishin and Yuri Oshmiansky describe one of the most important technologies for the fabrication of RF-BAW devices, namely, deposition of high-quality thin films mandatory for realization of high-performance BAW devices.

In Chapter 8, Dr. Gernot Fattinger and Dr. Stephan Marksteiner discuss one more important factor for the realization of high-performance RF-BAW devices: namely, characterization of RF-BAW materials and devices. They also discuss the major technologies of laser probing and electrical properties.

Integration of RF-BAW devices with semiconductor circuitry is one of the most important concerns for the future in this community. In Chapter 9, Dr. Marc-Alexandre Dubois, a principal researcher of the famous MARTINA European Consortium, details monolithic integration of RF-BAW devices on Si.

In Chapter 10, Dr. A. Bart Smolders, Dr. Jan-Willem Lobeek, and Dr. Nicolaus J. Pulsford discuss the RF integration from another aspect—system-in-package (SiP) integration. They explain various technologies used in the SiP integration, demonstrate its effectiveness, and then show how the BAW technologies fit well with RF-SiP, which will be the mainstream for further RF integration.

Ken-ya Hashimoto
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CHAPTER 1

Background and History

Ken Lakin

1.1 BAW Technology Background

The purpose of this chapter is to give a brief history of the development of BAW technology which is covered in technical detail in later chapters of this book. First it is necessary to define what the BAW technology is and then put the history in that context. For the purposes of this book, BAW history is interesting not so much as who did what when (that will be apparent from numerous references) but how other technologies were drawn upon to make the development of the modern thin film BAW technology possible. Microelectronics has played a key role over the years by providing materials-processing techniques previously unavailable. Review papers give an overview of thin film resonator technology [1–5].

1.1.1 Basic Definitions

The term bulk acoustic wave (BAW) refers to primary acoustic waves that propagation in the bulk of a material whose dimensions are infinite and wherein the wave occupies all of that volume. There are three possible propagation modes called the normal modes of the material. Those modes are well understood for a large number of materials whose elastic properties are known. In more practical terms, a wave in a finite three- dimensional region can only approximate the propagation characteristics of an infinite region. The first approximation required to support a BAW is that the lateral extent of the medium is much larger than the wavelength and cross-section of the wave. The practical definition of BAW is imprecise and depends on what artifacts crop up due to the finiteness of the beam. For example, a beam starting out as being of comparable dimensions to the wavelength would appear as a point source and spread widely, due to diffraction, but could be described as some complex linear combination of the normal modes. The second approximation is that the lateral extent of the wave, and therefore of the medium, is such that the wave is primarily one-dimensional but with some residual effects due to lateral finiteness. In the direction of propagation the material extent may be very finite, such as a half-wavelength thick for a resonator. Yet in such a case, dimensions will appear large in the direction of propagation because the wave bounces within the resonator between parallel surfaces maintaining its characteristics as if propagating over considerable distance. Typical average lateral dimensions might be approximately 100 times the wavelength for resonators in filters designed for 50-ohm source and load impedances.

Whereas finiteness is a distortion imposed on BAW, other modes of propagation are uniquely tied to the finiteness of a structure. For example, waves can propagate along and be guided by a surface or at an interface. The most notable being the solid to air interface that supports surface acoustic waves (SAWs). A feature of waves is that they tend to be guided by regions of slower velocity and lower energy density. If there is a lateral deformation at or very near a surface, the material can expand perpendicular to the force (Poisson effect) out into the air region. That added degree of freedom makes the surface appear mechanically softer and as a result the SAW is confined to the surface. In the case of SAWs the material region must be just a half space with the relevant approximation that the material is sufficiently thick that the wave does not exist at any other surfaces.

If the material region is formed as a plate with two parallel surfaces, but large in lateral extent, then another set of waves, plate waves (PW), can propagate along the parallel boundaries of the plate. These waves are most pronounced when the thickness of the plate is comparable to the propagation wavelength. It turns out that such a geometrical constraint is met by a typical BAW resonator. Further, plate waves can be generated in BAW resonators and can plague high-performance BAW resonators with parasitic resonances.

Other modes of propagation are possible in the typical BAW structural approximation but PW are the most pronounced.

Since a resonator can be though of as a confinement structure for a wave bouncing between reflecting surfaces, it is only a manner of properly generating and confining a wave to make a useful resonator. Two issues then emerge. First, how to generate the wave, and second how to confine the wave so that most of the energy is stored with a minimum amount of energy loss except on a controlled basis.

1.1.2 Role of Piezoelectric Materials

The most straight forward method of generating an acoustic wave is to use a piezoelectric material. The piezoelectric direct and inverse effects are described in general by the equations,

$$T = cS - eE \tag{1.1}$$

$$D = eS + \varepsilon E \tag{1.2}$$

Here (1.1) is Hook's law of elasticity, T is stress (force per unit area), S is strain, e is the piezoelectric coefficient, c is mechanical stiffness, ε is permittivity, and E is the electric field. The second equation shows the contribution of mechanical strain to electric charge generation and displacement current. Accordingly, mechanical deformations and electric properties are piezoelectrically coupled.

As will be shown in subsequent chapters, the strength of the piezoelectric coupling determines the bandwidth of filters and the mechanical losses in the material will determine resonator Q and accordingly filter insertion loss.