ANNUAL JOURNAL OF ELECTRONICS, 2015, ISSN 1314-0078

Acoustic Dispersion Analysis of the Resonant Modes in FBAR

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Abstract – **A procedure to build a two dimensional finite element model (FEM) of thin film bulk acoustic wave resonator (FBAR) and obtain the dispersion curves of its resonant modes is described in this article. A classic parallel plate device is analyzed and the dispersion curves of its main spurious harmonics are given.**

Keywords – **FBAR, acoustic waves, resonant modes, dispersion**

I. INTRODUCTION

Film Bulk Acoustic Wave Resonators (FBAR) are piezoelectric devices essential for the modern wireless telecommunication systems. Due to their high power handling capabilities, high quality factors and good temperature stability they are widely used for realizing stable bandpass filters with good selectivity in the modern RF front-ends [1], [2].

The FBAR devices consist of thin layer of piezoelectric material placed between two metal electrodes. When alternating electrical signal is applied at the electrodes, an acoustic wave is exited due to the reverse piezoelectric effect. The piezoelectric materials have anisotropic properties in the different directions of their crystallographic lattice and the acoustic waves travel at different speed depending on their direction and on the geometry of the piezoelectric layer [3]. This effect causes dispersion of the acoustic waves. To determine the resonant frequencies and to be able to design an FBAR device, the effects of wave dispersion have to be studied in detail.

The dispersion of the main resonant modes of field bulk acoustic wave resonator is analyzed in this article. A classical aluminum nitride (AlN) parallel plate resonator is studied using finite-element modeling (FEM) tools. The primary objective is to obtain the dependence of the acoustic velocity on the wavenumber for all major modes that are excited by parallel plate electrodes. This relation is essential in the FBAR design process. For the sake of simplicity, the electrodes are assumed to be infinitely thin in all calculations and simulations in the article.

II. FBAR STRUCTURE

In its simplest and most widely used configuration the FBAR devices consist of a piezoelectric material placed between the plates of a parallel capacitor as shown in Fig.1. When an electric field is applied between the plates, an acoustic wave travelling in parallel to the electric field is excited. The device resonates only for the frequencies that satisfy the relation:

$$f = \frac{V_{WAVE}}{\lambda}, \tag{1}$$

where V_{wave} is the speed of propagation of the acoustic wave and λ is the wavelength [3]. Typically aluminum nitride (AlN) is used as piezoelectric material, although other materials, such as zinc oxide (ZnO) and cadmium sulfide (CdS) have been used in the past. All those materials are crystals with anisotropic properties in the different directions of their crystallographic lattices. This, of course, applies to the V_{wave} as well. The finite dimensions and anisotropic properties constitute the wave dispersion that is observed in those devices for certain modes.

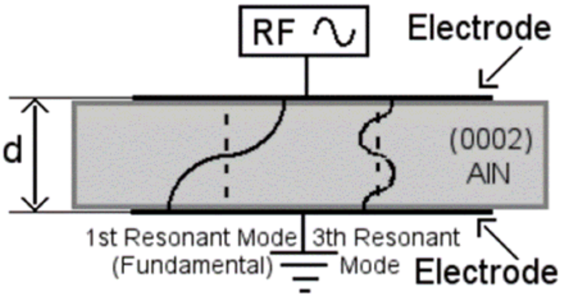

Fig. 1. Structure of an FBAR device [3].

A standing wave will form for acoustic waves with wavelengths that satisfy:

$$\lambda = \frac{2d}{n}, \tag{2}$$

where n=1,3,5... represents the different longitudinal modes (harmonics), and d is the spacing between the electrodes. The first and third modes, excited by the parallel plate electrodes, are marked in Fig. 1. Due to the finite dimensions of the resonator and the anisotropy of the active material, acoustic energy is reflected in other directions and the device will also resonate at other “more complex” modes: transverse (shear), Lamb and other [3]. Most often the resonators are designed to operate at the primary longitudinal harmonic (n=1), while all other modes are considered parasitic and measures should be taken in the design phase to suppress them.

III. ACOUSTIC DISPERSION AND RESONANT MODES.

Dispersion is a physical phenomenon in which the phase velocity of a wave is dependent on its frequency. The dispersion is usually caused by [4]:

- geometric boundary conditions, i.e. reflections by the walls of a waveguide,

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- specific material properties of the transmission medium, i.e. crystals with anisotropic properties.

The bulk acoustic wave piezoelectric resonators are usually designed to work with the longitudinal modes. There the wave travels in parallel to one of the crystal axes and is reflected by the perpendicular plates of the electrodes and no dispersion should occur. However, due to the finite dimensions of the devices, a portion of the acoustic energy is reflected in other directions, which excites other modes that are dispersive: transverse waves with horizontal polarization (Fig. 2) [5], Lamb waves (Fig. 3) [3].

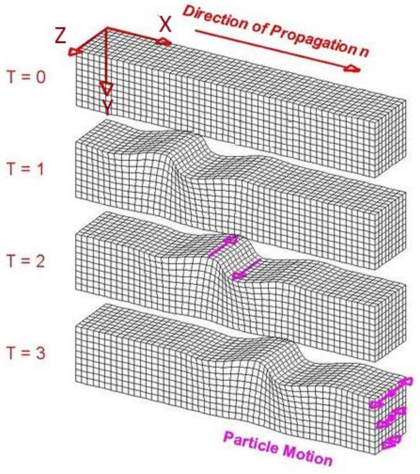

Fig. 2. Shear waves with horizontal polarization (SH) [6].

The SH waves exhibit lateral particle motion, that causes transverse wave propagation. The Lamb waves have elliptical particle motion and depending on its direction are categorized as symmetric or antisymmetric. The symmetric modes are denoted as S_i, and the antisymmetric as A_i, where i is the mode order.

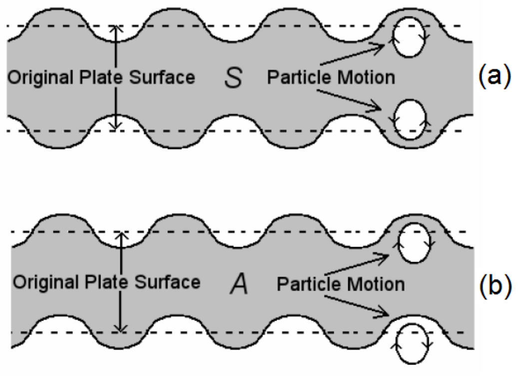

Fig. 3. Lamb acoustic waves: (a) symmetric and (b) antisymmetric [3].

IV. TWO-DIMENSIONAL FEM ANALYSIS OF FBAR

The dispersion of the resonance modes of a classic FBAR structure with parallel plate electrodes is studied. FEM software is used for the analysis. A two dimensional model of the structure is built (Fig. 4). Using 2D model significantly reduces the number of vibration modes, compared to a three dimensional model. This allows to easily isolate the primary shear and Lamb resonance modes excited by the parallel plates and requires much less computational resources. For the same reason, it is assumed that the electrodes have infinitesimal thickness and weight, which eliminates the mass loading effect. Aluminum nitride is used as piezoelectric material in the model. It has thickness of 10 µm and the C-orientation axis of the crystal is perpendicular to the electrode plates. Its *length* is variable. To examine the dispersion, Floquet periodicity is applied to the sidewalls of the AlN resonator. The wave number $ka=\pi n/length$, *where* $n=1,2,\ldots$, is swept from 0 to $\pi/5\mu\text{m}$ to obtain the dispersion as a function of ka. This is roughly equivalent to running a parametric analysis along the device *length,* with values ranging from infinitely long device down to device with length of 5 µm.

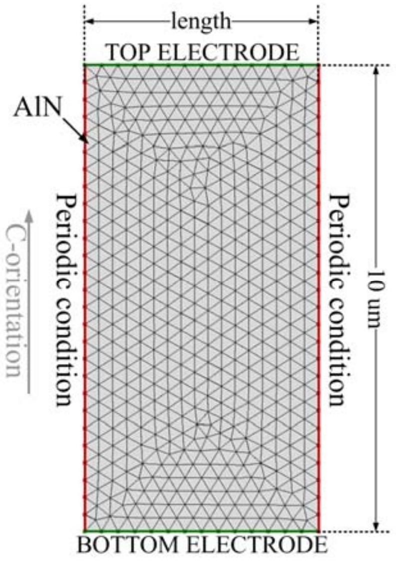

Fig. 4. Two dimensional finite element model of a FBAR device, used to determine its resonance modes and their acoustic dispersion as function of the wavenumber ka.

The purpose of this dispersion analysis is to determine the properties of the spurious modes that have similar resonance frequencies to the main resonance and design the device geometry accordingly to reduce their influence.

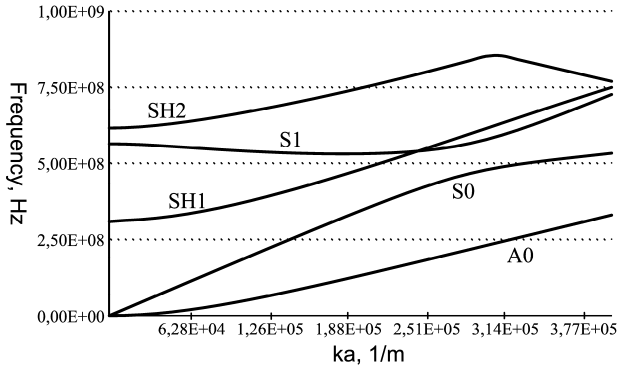

Fig. 5. Acoustic dispersion of the main Lamb and shear modes in the analyzed FBAR.

The dispersion curves of the spurious modes with frequencies close to the designed resonator frequency are shown in Fig. 5. Among them are three Lamb harmonics –

A0, S0 and S1, and two SH harmonics – SH1 and SH2. The resonance frequency of the first longitudinal harmonic can be calculated using formulas (1) and (2). Since the device is 10 μm thick and the longitudinal acoustic speed in C-oriented AlN is around 11000 m/s, in the given example the main resonant frequency is around 550 MHz. Depending on the values of *ka*, modes S1, S0 and SH1 may match the main resonant frequency. SH2 is close to it for small values of the wavenumber. The dispersion curve of mode S1 is very close to the main resonant mode for device lengths down to around 12.5 μm (*ka*=2.51e-5) or larger lengths multiples of this number. This means that S1 will interfere with the main resonant mode almost regardless of the device length. In those cases the S1 mode has to be suppressed using other measures. Most commonly they include designing specific shape of the terminals or specific shape of the device itself (apodization) to ensure the unwanted mode is suppressed. To properly design an apodized device a 3D FEM analysis has to be used to verify that all the unwanted modes are suppressed.

V. CONCLUSION

The main resonance modes of a classic parallel plate FBAR device are reviewed and a procedure to build a two dimensional finite element model is described. The proposed FEM model is used to simulate the behavior of the device and obtain the dispersion curves of the main spurious resonant modes. They are either shear (SH1, SH2) or Lamb modes (A0, S0, S1). All those harmonics show relative strong acoustic dispersion.

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