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9.5-12 GHz Solidly Mounted Bulk Acoustic Wave Resonators Utilizing TE Overtone Mode

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1. Introduction

Acoustic wave filters are expected to cover a high-frequency range of 5-10.25 GHz for vehicle-to-everything, WiFi, LAN, ICT, and UWB.[1, 2] For such applications, various devices such as plate acoustic wave (PAW), grooved surface acoustic wave (SAW), and bulk acoustic wave (BAW) devices are being researched.[3-7] PAW and BAW devices are suitable for high-frequency applications, but self-supported piezoelectric plates thinner than 500 nm are fragile and difficult to withstand high-power signals.

In comparison to the self-supported devices, a solidly-mounted BAW resonator (SM-BAWR) is more robust. Nevertheless, the use of an ultra-thin piezoelectric plate for high-frequency applications leaves other challenges. Firstly, electrode resistance increases, if the thickness of the electrodes is shrunk in proportion to that of the piezoelectric plate. Contrarily, relatively thick electrodes lead to a frequency drop due to mass loading as well as the decrease of an electromechanical coupling factor. Secondly, the fabrication of an ultra-thin piezoelectric plate with a uniform thickness is challenging for $LiNbO_3$ (LN) and $LiTaO_3$ (LT).

Theoretically, thickness extension (TE) and shear (TS) modes of BAW have higher overtones (3rd, 5th etc.). However, the impedance (Z) ratio of the overtone response is generally much lower than that of the fundamental mode. This research aims to selectively enhance the overtone response of SM-BAWRs and improve their overall performance by optimizing the thickness of acoustic layers in a Bragg reflector. To achieve a wideband and high-frequency response, TE mode in LN is considered, as the velocity of the TE mode is higher than that of the TS mode, and LN has a higher electromechanical coupling factor than LT, AlN, and ScAlN.

2. Simulation

Overtone responses generally exhibit a smaller coupling factor and a lower Z ratio compared to the fundamental mode, which makes it challenging to preferentially excite the overtones. In this study, we propose a novel approach of optimizing the acoustic layer thickness of the Bragg reflector for 3rd overtone excitation. For the fundamental mode, the theoretical optimum thickness of each acoustic layer is $\lambda/4$, where λ is the wavelength of the fundamental mode and twice the piezoelectric plate thickness. The optimal thickness for exciting the 3rd overtone was searched in a region much smaller than $\lambda/4$ by finite element method (FEM) simulation.

The SM-BAWRs composed of an upper Al electrode, a 1 μm thick 36ºY LN plate, a lower Al electrode, and 3 sets of SiO_2 and W films on a Si substrate were considered in the simulation. Fig. 1 shows the simulated frequency characteristics for (a) $\lambda/4$ and (b) $\lambda/20$ as at the thicknesses of each acoustic layer. When the acoustic layer is $\lambda/4$ thick, the fundamental mode is predominantly excited. When it is $\lambda/20$ thick, on the other hand, the 3rd overtone is strongly excited compared to the fundamental mode.[10)]

3. Fabrication and Frequency Characteristics

3.1 Single 36ºY LN plate

We fabricated the SM-BAWRs with the following structure: From the top, two Al electrodes, 36ºY LN of 1 μm thickness, Al electrode of 100 nm thickness, 4 sets of SiO_2/Ta with an average thickness of 0.06λ, SiO_2 for bonding, and Si substrate. Fig. 2 shows the measured frequency characteristics. Despite the 1 μm thickness of LN, the excitation of the fundamental mode at around 3 GHz is minimal, while the 3rd overtone mode at 9.5 GHz with an Z ratio of 31 dB is more strongly excited.

3.2 Polarization-flipped 36ºY LN double layer

Using a polarization-flipped, double-layered piezoelectric ceramic plate, the 2nd mode of the TE mode can be excited, resulting in trapped energy regardless of the effective Poisson's ratio.[11)] In this study, we considered combining the opposite polarities of 36ºY LN on the thin Blagg reflector to excite the 3rd overtone of the 2nd mode. The fabricated device has the following structure: From the top, two Al electrodes, 216ºY LN of 1 μm thickness, 36ºY LN of 0.9 μm thickness, Al electrode of 100 nm thickness, 4 sets of SiO_2/Ta with an average thickness of 0.06λ, where λ is the average of two LN plate thicknesses (0.95 μm), SiO_2, and Si substrate. The difference of the LN thicknesses is due to an error in polishing.

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Fig. 3 shows the measured frequency characteristic. Two 3rd overtones are strongly excited, one at 9.5 GHz with an *Z* ratio of 29 dB and the other at 12 GHz with an *Z* ratio of 32 dB. The difference in thickness between the two stacked LN plates resulted in the excitation of 9.5 GHz by 1 μm thick LN and 12 GHz by 0.9 μm thick LN. It is expected that using the same thickness of two LN plates will lead to a higher *Z* ratio. This is potentially possible by dry etching of LN.

4. Conclusion

We simulated and fabricated two types of SM-BAWRs using a single thin 36°Y LN plate and stacked plates of 216°Y LN and 36°Y LN with the opposite polarities. To preferentially excite the 3rd overtone of TE mode, a Bragg reflector with extraordinarily thin layers was used for both devices. The 36°Y LN plate of 1 μm thickness was supported with a Blagg reflector with an average acoustic layer thickness of 0.06λ. As a result, the 3rd overtone of TE mode was excited at 9.5 GHz with an *Z* ratio of 31 dB. The polarization-flipped, stacked LN plates of 1 and 0.9 μm thicknesses were supported with a similar Bragg reflector. The overtones of TE mode at 9.5 GHz with an *Z* ratio of 29 dB and 12 GHz with an *Z* ratio of 32 dB were excited. This research demonstrated a new method to preferentially excite the overtone mode using SM-BAWR, and further optimizations will lead to enhanced performance in high-frequency applications.

Acknowledgment

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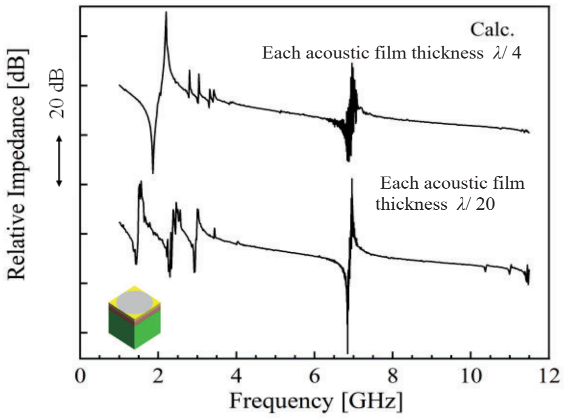

Fig. 1 Simulated frequency characteristics of TE mode SM-BAWRs with acoustic laver thickness of $\lambda/4$ and $\lambda/20$.

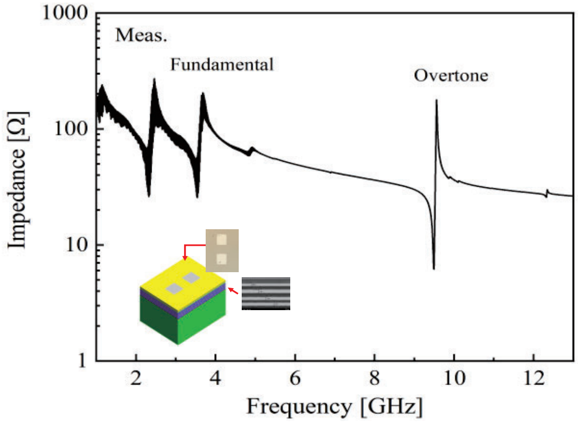

Fig. 2 Measured frequency characteristic of SM-BAWR using 36°Y LN and Bragg reflector with average layer thickness of 0.06λ.

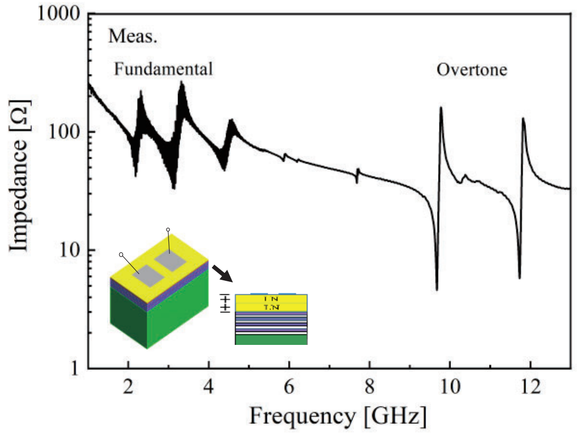

Fig. 3 Measured frequency characteristic of SM-BAWR using 216°Y LN/ 36°Y LN and Bragg reflector with average layer thickness of 0.06λ.