1PL-1

Improvement of high-frequency BAW resonators using polarization inverted structures and high-overtone mode resonance

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1. Introduction

AlN film bulk acoustic wave (BAW) resonators are widely used as frequency filters in mobile communication devices [1] because of their high frequency operation, high quality factor (Q), and relatively good temperature stability. The operating frequency of BAW resonators and filters needs to be increased for applications in next-generation communication systems such as beyond 5G and 6G. However, to operate at frequencies higher than 5 GHz, the thickness and volume of the AlN film BAW resonator must be substantially reduced, which will result in degradation of the Q factor, bandwidth, and power handling capability.

Although standard single-layer film BAW resonators (**Fig. 1(a)**) resonate in a fundamental mode, n-layer polarization-inverted film BAW resonators (**Fig. 1(b)**) can resonate strongly in n-th overtone-mode. The n-th overtone mode BAW resonators can operate at n-times higher frequency than a standard single-layer BAW resonator with the same device thickness and volume. This characteristic of the high-overtone mode polarization-inverted film BAW resonator is expected to suppress the degradation of the Q values and power handling capability in the high-frequency film BAW resonators. In addition, the polarization inverted film BAW resonators, which can have a large piezoelectric film thickness while maintaining a high resonance frequency, can suppress the reduction of the resonance frequency due to the mass loading effect of electrodes. Therefore, multilayer polarization inverted piezoelectric films will play an important role in high frequency BAW filters for next-generation mobile communications. Various polarization inverted film BAW resonators with $LiNbO_3$ [2], BST [3], PZT/$PbTiO_3$ [4], PMN-PT/PZT [5], $PbTiO_3$ [6], ZnO [7], and ScAlN [8] films have been reported previously. Recently, more than 10 GHz high overtone mode BAW resonators with polarization inverted structure are being considered for ultrahigh frequency filter applications [9-11].

In this study, we analyzed the frequency characteristics and BAW behavior in the polarization inverted film solidly mounted resonators (SMRs) by FEM analysis to demonstrate the advantage of the polarization inverted structures for high frequency BAW resonators. We fabricated the multilayer polarization inverted AlN-based (SiAlN/AlN, GeAlN/AlN) film SMRs operating in high-overtone mode resonances. The frequency and resonance characteristics of the SMRs were investigated.

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2. Analysis of polarization inverted film SMRs

The effective electromechanical coupling factors k_{eff}^2 and Q values of AlN film SMRs are generally lower than those of AlN FBARs because of the leakage BAW energy into the acoustic Bragg mirror layer and substrate. Recently, we have demonstrated experimentally and theoretically that the elastic constant c_{33} of n-layer polarization-inverted AlN films in BAW resonators is pseudo-n^2-times higher than that of a single-layer AlN film [12]. Thus, the acoustic impedance of the n-layer polarization-inverted AlN films is pseudo-n-times higher than that of the single-layer AlN film. The use of multilayer polarization-inverted AlN films in SMRs could improve the BAW isolation between the AlN film and acoustic Bragg mirror. As a result, in the polarization-inverted AlN film SMRs, BAW energy is expected to be strongly trapped in the AlN film, leading to an improvement in k_{eff}^2.

Fig. 2 shows the admittance frequency characteristics of the single-layer AlN FBAR, the single-, two-, four-, and eight-layer polarization-inverted AlN film SMRs operating at 10 GHz, which were analyzed by FEM. The bandwidth ($\sim k_{eff}^2/2$) of the polarization-inverted AlN film SMRs increased with increasing the number of the polarization-inverted layers and was close to that of the single-layer AlN FBAR.

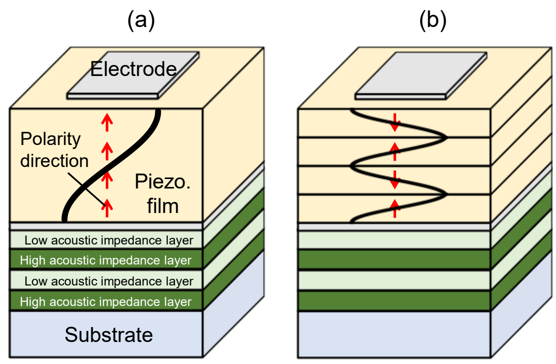

Fig. 1 (a) single-layer film and (b) polarization inverted film BAW resonators (SMR structure)

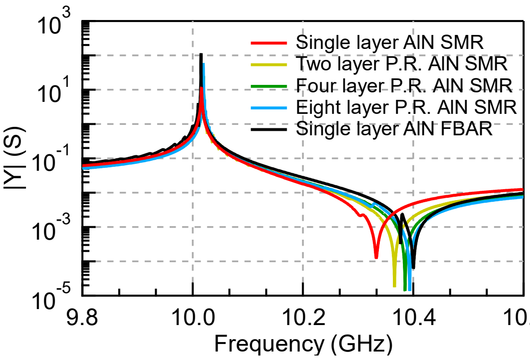

Fig. 2 Admittance frequency characteristics of polarization inverted AlN film SMRs analyzed by FEM.

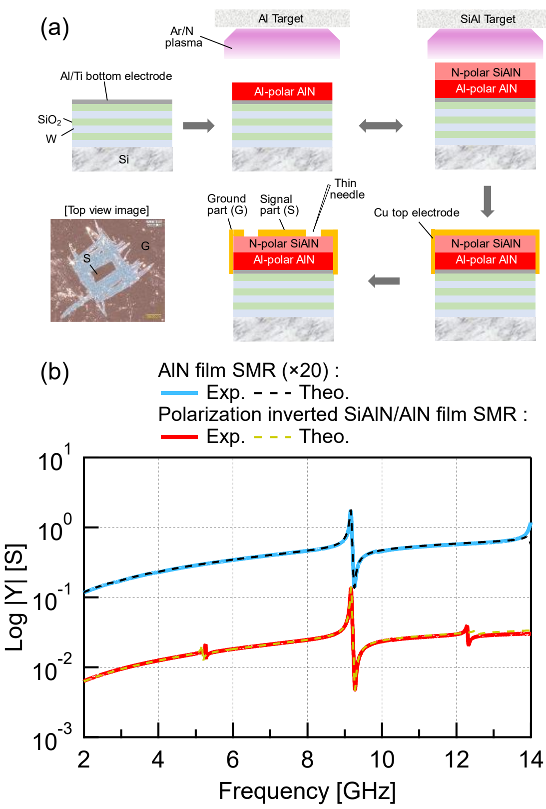

Fig. 3 (a) Fabrication process and (b) admittance frequency characteristics for the single layer AlN film and two-layer polarization-inverted SiAlN/AlN film SMRs.

From the BAW particle displacements at the resonance frequency in the SMRs analyzed by FEM, we also confirmed that the increasing the number of polarization inverted AlN layers induced an increase in the BAW energy trapped in the AlN film, leading to the improvements of the bandwidth in the polarization inverted film SMRs.

3. Fabrication and performance of polarization inverted AlN-based film SMRs

We have demonstrated that Si or Ge doping above ~3 at% causes the polarization inversion from Al-polarity to N-polarity in c-axis oriented AlN films and that multilayer polarization inverted film can be grown by alternately depositing the Al-polar pure AlN layer and the N-polar Si or Gr doped AlN layer [12.13)]. By the fabrication process shown in **Fig. 3(a)**, we have successfully fabricated high-overtone mode polarization inverted GeAlN/AlN film SMRs operating at ~2.5 GHz [14)] and SiAlN/AlN film SMRs operating at ~5 GHz [15)]. **Fig. 3(b)** shows the frequency characteristics of the two-layer polarization inverted SiAlN/AlN film SMRs operating at ~9 GHz measured by network analyzer. Although the film thickness of the two-layer SiAlN/AlN film (~940 nm) was more than twice that of the single-layer AlN film (~350 nm), the second-overtone mode resonance in the SiAlN/AlN film SMRs was observed at the same frequency as the fundamental mode resonance in the AlN film SMR. Moreover, as in the case of the 2.5 GHz and 5 GHz operating SMRs [14,15)], Q values of the polarization inverted film SMR were improved from those of the single-layer film SMR. These results experimentally demonstrate that the high-overtone mode polarization-inverted film SMRs can have larger thickness, larger device volume, and higher Q value than the standard single-layer film SMRs, while maintaining the high resonance frequency.

4. Conclusion

We theoretically found that the BAW energy trapping in the piezoelectric films and the bandwidth in the SMRs improved with increasing the number of polarization-inverted layers. We fabricated the high-overtone mode SMRs with polarization-inverted film by alternately growing AlN and Si doped AlN layers. The SMRs operated at almost the same frequency as the standard single-layer AlN film SMR. The Q values of the polarization-inverted film SMRs improved with increasing the number of polarization-inverted layers. These results show that the polarization-inverted film SMRs are a leading candidate for use in next-generation high-frequency BAW resonators.

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