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Fabrication and evaluation of high-order mode solid mounted resonators with polarity inverted GeAlN/AlN multilayered films

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1. Introduction

Film bulk acoustic wave (BAW) resonators consisting of top electrode / piezoelectric film / bottom electrode are used as mobile communication frequency filters. 5G and beyond 5G BAW resonators will be required to operate at further high frequencies. For high frequency operation, piezoelectric film thicknesses of the BAW resonators are very thin. For example, less than 0.55 μm of AlN film is needed at 10 GHz operation. The thin piezoelectric film thickness causes degradation of resonance characteristics, such as low Q values and low electromechanical coupling factors[1]. Moreover, the thin piezoelectric film thickness also causes low power handling capability. Thin electrode films are demanded to maintain high operation frequency in BAW resonators. However, the electrode conductivity becomes low. Therefore, decrease of Q values and electromechanical coupling factors may be occurred in the BAW resonators with very thin electrode films. A polarity inverted (PI) AlN film structure can be fabricated by alternately growing an Al-polar AlN film and an N-polar AlN film. The *n*-layer PI film BAW resonators resonate in *n*-th mode. Therefore, PI film BAW resonators have larger piezoelectric film thickness than that of standard BAW resonators. PI structures may solve degradation of resonance characteristics and the low power handling capability of BAW resonators.

AlN films are used as piezoelectric films of BAW resonators, because of their high BAW velocity V_L and low propagation loss. Methods for control of the polarity direction in AlN films have been reported, such as insertion of a buffer layer, Si or Ge doping to AlN films, and ion beam irradiation during film growth. In our previous study, we fabricated an eight-layer SiAlN/AlN film high overtone bulk acoustic wave resonator operating in 8th mode resonance[2].

In this study, first, we theoretically investigated the resonance characteristics of the PI film solid mounted resonators (SMRs) by Mason's equivalent circuit models. Then, mono- to four-layer PI GeAlN/AlN film SMR was fabricated by growing GeAlN/AlN films on acoustic Bragg mirror substrates consisting of Al electrode film / 3 pairs of (SiO_2 / W) / Si substrate. Crystal orientations of the PI films were evaluated by XRD analysis. The frequency characteristics of admittance in the mono- to four-layer PI film SMRs were evaluated.

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2. Theoretical analysis of characteristics in the polarity inverted AlN film SMRs.

To investigate the advantages of PI film SMRs, we simulated the frequency characteristics of the admittance in PI film SMRs by Mason's equivalent circuit models. The structures of SMRs were consisted of top Al electrode / PI AlN films / bottom Al electrode / 3 pairs of (SiO_2 / W) / Si. The longitudinal wave velocity V_L and coupling factor k_t^2 of the AlN films in the models were set to 11,000 m/s and 6%, respectively.

A) The effect of the electrode film thickness on resonance frequencies in PI film SMRs

Piezoelectric film thicknesses of the SMRs were determined via the equation $d=V_L/2f_r$ (V_L: BAW velocity, f_r: resonance frequency). The AlN film thickness of the monolayer AlN film SMR was 0.55 μm at 10 GHz operation. The AlN thicknesses of each layer in PI films was also 0.55 μm. We evaluated the f_r of PI AlN film SMR with Al top and bottom electrode films from 0 to 240 nm. **Figure 1** shows the f_r of mono-, two-, four-, six-, and eight-layer PI film SMRs as a function of Al top and bottom electrode thickness. f_r decreased dramatically in monolayer AlN film SMR. The decrease was inhibited as the number of PI layers increased. The PI film SMRs enable high frequency operation even with thick electrode films. Therefore, the decrease of conductivity by thinning the electrode film, which degrades the resonance

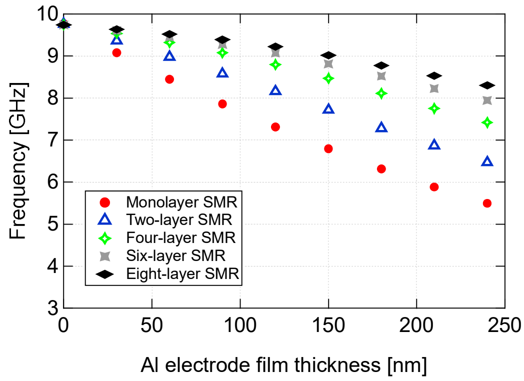

Fig. 1 Resonance frequencies f_r of 10 GHz polarity inverted AlN film SMRs with 0.55 μm of AlN layers.

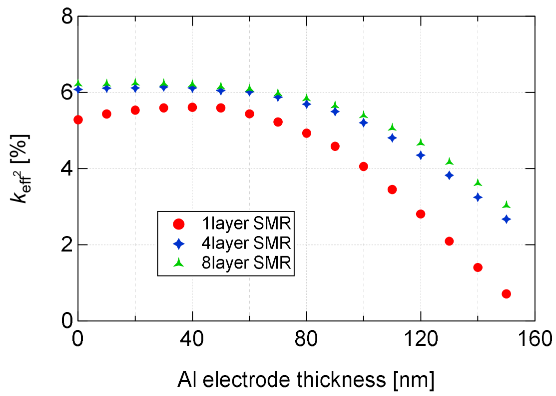

Fig. 2 k_{eff}^2 of mono-, four-, and eight-layer polarity inverted film SMRs at 10 GHz operation.

performance, may be overcome using PI AlN film SMRs.

B) Effective electromechanical coupling coefficient of 10-GHz PI film SMRs

Ultrathin AlN films may cause the degradation of effective electromechanical coupling factor k_{eff}^2 of the SMRs, because the ratio of the electrode film to the piezoelectric film increases. We evaluated the k_{eff}^2 of mono- to eight-layer PI AlN film SMRs operating at 10 GHz. As the Al electrode film thickness was varied from 0 to 150 nm, the piezoelectric AlN film thicknesses of the mono-, four-, and eight-layer film SMRs were adjusted to resonate at 10 GHz. **Figure 2** shows the k_{eff}^2 of the mono-, four-, and eight-layer PI AlN film SMRs operating at 10 GHz. Four- and eight-layer PI AlN film SMRs have better k_{eff}^2 than the monolayer film SMR of all range of Al thickness. Moreover, the k_{eff}^2 of the monolayer AlN film SMR decreased more dramatically with increasing Al thickness than that of four- and eight-layer film SMRs.

3. Polarity inverted GeAlN/AlN film SMRs

To fabricate mono- to four-layer PI film SMRs, we grew Al-polar AlN films for odd layers and N-polar $Ge_{0.05}Al_{0.95}N$ films for even layers by a magnetron sputtering deposition on Al electrode / 3 pairs of (SiO_2 / W) / Si substrate. The layer thickness of SiO_2 (596.8 nm) and W (541 nm) were adjusted to reflect longitudinal BAW around 2.5 GHz. **Figure 3** shows the 2θ-θ XRD patterns. (0002) AlN peak appeared around 36° in each layer. From these results, we confirmed that c-axis oriented AlN films were grown on the Bragg mirror substrate. **Figure 4** shows the admittance of mono- to four- layer PI GeAlN / AlN film SMRs. Resonance frequencies shifted to higher frequency with increasing the number of the PI layers. The AlN thicknesses of 1st to 4th layers were 1st layer=1.64 μm, 2nd layer=1.7 μm, 3rd layer=1.43 μm, and 4th layer=1.64 μm, respectively. Although

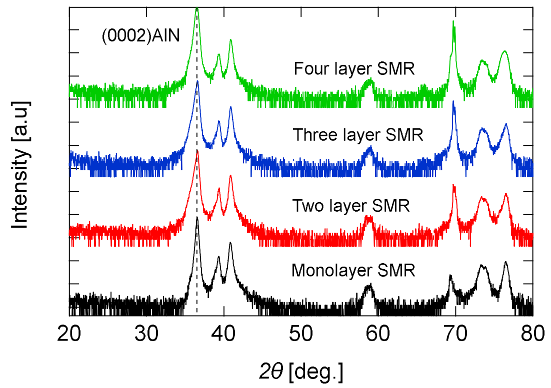

Fig. 3 2θ-θ XRD patterns of mono- to four-layer GeAlN/AlN film SMR.

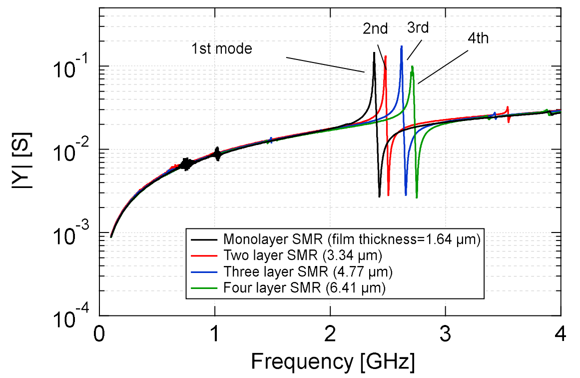

Fig. 4 Admittance of mono- to four-layer polarity inverted GeAlN/AlN film SMRs.

two- to four- layer AlN/GeAlN film SMRs have two- to four-times thicker piezoelectric film than that of the monolayer film SMR, they resonated at approximately the same frequency. From these results, we confirmed that mono- to four-layered film SMR resonated in the 1st–4th order mode.

4. Conclusion

Our theoretical results revealed that the decrease of the resonance frequency and k_{eff}^2 were suppressed by using PI films. We fabricated mono- to four-layer PI $Ge_{0.05}Al_{0.95}N$/AlN film SMRs. The AlN film thicknesses of the PI film SMRs operating around 2.5 GHz are two- to four-times thicker than that of the monolayer film SMR. Moreover, these SMRs resonated in 1st to 4th mode resonance.

Acknowledgement

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References

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