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Polarity inverted SiAlN/AlN film solid mounted resonators operating in high-overtone mode resonance

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1. Introduction

Multilayer polarity inverted film bulk acoustic wave (BAW) resonators operate in the high-overtone mode resonance. As a result, they can operate at higher frequencies and have larger device volumes, providing high power handling capability, than standard monolayer film BAW resonators. We have reported the fabrication of multilayer polarity inverted SiAlN or GeAlN/AlN film BAW resonators [1-3]. Furthermore, the elastic constant c_{33} of n-layer polarity inverted AlN films in BAW resonators was found to be pseudo-n^2 times higher than that of monolayer AlN films [1]. This pseudo-high elasticity, which leads to the high acoustic impedance, in polarity inverted AlN films may enable the improvement of the effective electromechanical coupling k_{eff}^2 and Q values in AlN film solid mounted resonators (SMRs) with acoustic Bragg mirrors.

In this study, the characteristics of multilayer polarity inverted AlN film SMRs were analyzed by finite element method (FEM) analysis. We fabricated and evaluated the polarity inverted multilayered SiAlN/AlN film SMRs operating around 5 GHz.

2. FEM analysis

We examined the influences of the polarity-inverted structures on the BAW particle displacements and the k_{eff}^2 in the polarity inverted AlN film SMRs by FEM analysis (Femtet, Murata Software). **Fig. 1(a)** shows the two-dimensional FEM model of the polarity-inverted AlN film SMRs. We set the electrode film thicknesses to 0 nm to neglect the effect of the films on the SMR characteristics. The thicknesses of (0° 0° 0°) AlN and (0° 180° 0°) AlN layers, SiO_2 layers, and W layers were set to 535, 150, and 135 nm, respectively, to resonate at 10 GHz. The material quality factor (Q_m) of all layers was not considered.

Fig. 1(b) shows the u_3-direction BAW particle displacements in the eight-layer polarity-inverted AlN film SMR at the anti-resonance frequency. The four-wavelength resonance were found in the eight-layer polarity-inverted AlN film SMR. The ratio of the BAW particle displacements in the AlN film ($Trap_{\mathrm{AlN}}$) to the total BAW particle displacement in monolayer to ten-layer polarity inverted AlN film SMRs was calculated using $Trap_{AlN} = d_{AlN}/(d_{AlN} + d_{SiO2} + d_W + d_{Si})$. d_{AlN}, d_{SiO2}, d_{W}, and d_{Si} are the total u_3-direction displacements in the AlN film, SiO_2 layer, W layer, and Si substrate, respectively. As shown in **Fig. 1 (c)**, increasing the number of polarity inverted AlN layers from one to ten induced an increase in the $Trap_{\mathrm{AlN}}$ values. Furthermore, the k_{eff}^2 values, obtained from resonance and anti-resonance frequency, exhibited a similar behavior to that of the $Trap_{\mathrm{AlN}}$ values. These results show that the BAW energy is more trapped in AlN films using the polarity inverted structure, which improves the k_{eff}^2 in AlN film SMRs.

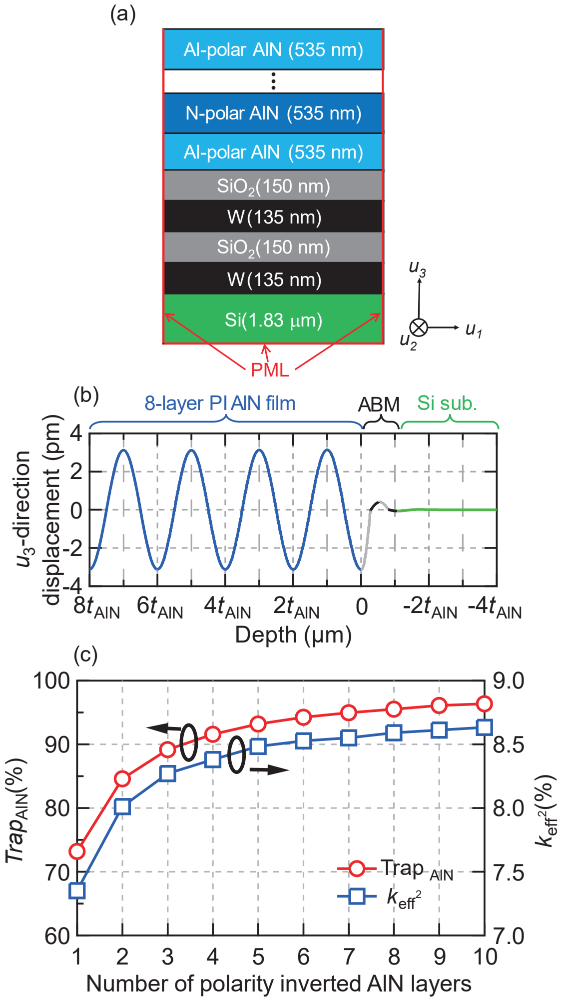

Fig. 1 (a) FEM model of a polarity-inverted (PI) AlN film SMR. (b) u_3-direction BAW particle displacements in the eight-layer PI AlN SMR. (t_{AlN}:AlN layer thickness of 535 nm, ABM: Acoustic Bragg Mirror) (c) $Trap_{\mathrm{AlN}}$ and k_{eff}^2 of monolayer to ten-layer PI AlN film SMRs.

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3. Fabrication of SiAlN/AlN film SMRs

A monolayer AlN film and two- and four-layer polarity-inverted SiAlN/AlN films, shown in **Fig. 2(a)**, were fabricated on acoustic mirror substrates with Al electrode (100 nm)/three pairs of SiO$_2$ (300 nm)/W (270 nm) films/Si substrate (0.5 mm). The Al-polar AlN films were grown as the 1st and 3rd layers, and the N-polar SiAlN films1) were grown as the 2nd and 4th layers by RF magnetron sputtering. An Al-Si alloy target with a Si concentration of 7.5wt% was used to grow the SiAlN layers. The Si concentration in the SiAlN layers, as measured by EPMA, was approximately 4at%. Cu top electrode films (~200 nm) were deposited onto the SiAlN/AlN films by vacuum evaporation to fabricate the SMRs.

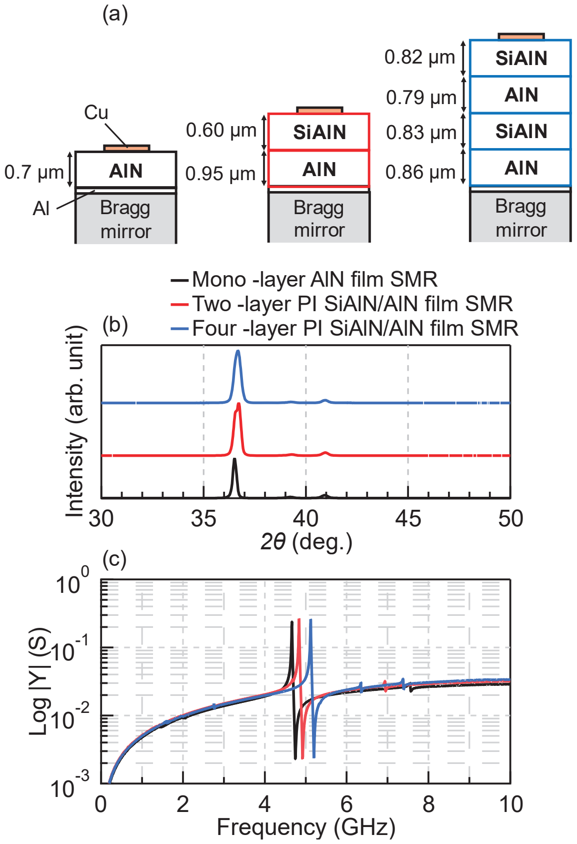

Fig. 2 (a) Configurations, (b) θ-2θ XRD patterns, and (c) admittance frequency characteristics for the monolayer AlN film SMR and the two- and four-layer polarity-inverted (PI) SiAlN/AlN film SMRs.

Table I Q and k_{eff}^2 values of the polarity inverted (PI) SiAlN/AlN film SMRs

SMR Structure	Q_r	Q_a	k_{eff}^2 **(%)**
monolayer	330	260	4.2
two-layer PI	350	260	4.3
four-layer PI	400	330	3.7

4. Evaluation of SiAlN/AlN film SMRs

We estimated the crystalline orientation of the SiAlN/AlN films by θ-2θ X-ray diffraction (XRD) analysis. As shown in **Fig. 2(b)**, the (0002) AlN peaks were observed at $2\theta \approx 36°$ in the patterns of all the films. The rocking curve full-width at half-maximum of the (0002) AlN peaks in the monolayer AlN film and the two- and four-layer SiAlN/AlN films were 2.8°, 2.6°, and 2.6°, respectively.

We measured the admittance frequency characteristics of the SMRs using a network analyzer. As shown in **Fig. 2(c)**, the resonance peaks were observed at ~5 GHz in all SMRs. As shown in **Fig. 2(a)**, the total SiAlN/AlN film thicknesses in the two- and four-layer polarity-inverted film SMRs were approximately two and four times larger, respectively, than that in the monolayer AlN film SMR. Thus, the two and four layer polarity-inverted SiAlN/AlN film SMRs operated in the second and fourth overtone mode resonances, respectively. In addition, large peaks of other overtone mode resonances did not appear over a wide frequency range from 0 to 10 GHz. As shown in **Table I**, the increase in the number of layers in the polarity-inverted SiAlN/AlN film led to the increase in the resonance Q_r and anti-resonance Q_a of the SMRs. We speculate that the enhancements of the BAW energy trapping to the SiAlN/AlN film due to the polarity-inverted structure could lead to this increase in Q values. On the other hand, the improvement of the k_{eff}^2 in polarity inverted film SMRs was not observed experimentally. A low k_t^2 in SiAlN film1) may cause the non-improvement of k_{eff}^2.

5. Conclusion

We theoretically investigated the characteristics of the multilayer polarity-inverted AlN film SMRs by FEM. The enhancement of the BAW energy trapping in the AlN films by polarity-inverted structures caused the improvement of the k_{eff}^2 of the AlN film SMRs. The two-layer and four-layer polarity-inverted SiAlN/AlN film SMRs were fabricated. They could operate in second- and fourth-overtone mode resonance at ~5 GHz and had higher Q values than those of the monolayer AlN film SMR.

Acknowledgment

This work was supported by JSPS KAKENHI (22K14288) and Asahi Glass Foundation.

References

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