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Piezoelectric characteristics of c-axis oriented GeAlN films and applications to polarity inverted film HBARs

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1. Introduction

Film bulk acoustic wave (BAW) resonators consisting of top electrode films / piezoelectric films / bottom electrode films are widely used as frequency filters in mobile communications. The resonance frequency f_r of the BAW resonator was roughly determined from $f_r=v/2d$ (v: BAW velocity, d: thickness of piezoelectric film). c-Axis oriented AlN films, which have the high longitudinal BAW velocity of approximately 11,000 m/s and low mechanical loss, were selected as the piezoelectric layers for high frequency BAW resonators. The thin AlN piezoelectric layer thickness of ~1 μm is required to operate at high frequency of more than 5 GHz. Moreover, the ultra-thin top and bottom electrode films are also required, which contribute to the low conductivity in the electrodes. These significant thinning of the piezoelectric film and electrode films may cause the low power handling capability and the degradation of Q factors and electromechanical coupling factors in AlN film BAW resonators.

n-layered polarity inverted (PI) film BAW resonators can operate in *n*th mode resonance. Therefore, when the total thickness of *n*-layered PI film is equal to that of monolayer film, the resonance frequency of the PI film BAW resonator is *n*-time higher than that of the monolayer film BAW resonator. When *n*-layered PI film BAW resonator is operated at the same frequency as the monolayer film BAW resonator, the thickness of *n*-layered PI film is *n*-times larger than that of monolayer film. Thus, we believe that the PI film will solves the problems in film BAW resonators operating at high frequency. It has been reported that the polarity of c-axis oriented AlN films can be controlled by insertion of buffer layer [1)], ion beam irradiation during film growth [2)], and Ge or Si doping [3,4)]. In USE 2021, we demonstrated that the multilayered PI structure can be obtained by alternately growing the Al-polar AlN film and N-polar SiAlN film [4)].

In this study, we investigated the effect of Ge doing to AlN films on the crystalline orientation, polarity direction, piezoelectric and elastic properties. In addition, the PI GeAlN/AlN film was fabricated, and the characteristics of the PI film BAW resonator was estimated.

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2. GeAlN film growth

Ge doped AlN (GeAlN) films were grown by an RF magnetron sputtering deposition. Ge ingots (99.99%, Kojundo chemical laboratory Co. Ltd) were put on the 2-inch Al target (99.999%, Furuuchi Chemical). They were simultaneously sputtered, and GeAlN films were deposited on the highly (0001) oriented Ti films (200 nm) / silica glass substrates (0.5 mm). Ge concentrations in the GeAlN films, which were evaluated by EPMA (JEOL, JXA-8200), were varied from 0 % to approximately 12 % by changing the total amount of Ge ingots from 0 g to 0.31 g. The RF power to cathode with the target was set to be 125 W. The film growth gas pressure was adjusted to be 0.75 Pa. The gas ration of N_2:Ar was 1:2. The substrate was not heated during the film growth. The film thicknesses of the GeAlN films were 2.5 - 4.6 μm.

3. Characteristics of GeAlN films

We evaluated the crystalline orientation of GeAlN films by a 2θ-θ XRD analysis. (0002) AlN peaks around 2θ = 36º, indicating that c-axis is normal to the substrate surface, were observed in GeAlN films with Ge concentration of 0-8%. However, the peak intensity decreased with increasing Ge concentration in the films, and the (0002) AlN peak disappeared in GeAlN films with Ge concentration of 11.9 %.

The polarity direction of the GeAlN films were determined by a press test shown in **Fig. 1**. When the compressive stresses were applied to the films, negative amplitudes, indicating Al-polarity, were observed in Ge concentration of 0.0%-2.4%. On the other hand, positive amplitudes, indicating N-polarity, were seen in Ge concentration of more than 6%. The polarity in Ge concentration of 3.2-4.8% could not be determined, because the sigh of the amplitudes varied by the samples.

Next, HBARs with Au electrode films / GeAlN films / Ti electrode films / silica glass substrate were fabricated. The thickness-extensional mode electromechanical coupling factor k_t^2 and longitudinal BAW velocity V_L of the GeAlN films were estimated by comparing the experimental conversion losses of the HBARs and the theoretical curves, calculated by a Mason's equivalent circuit model.

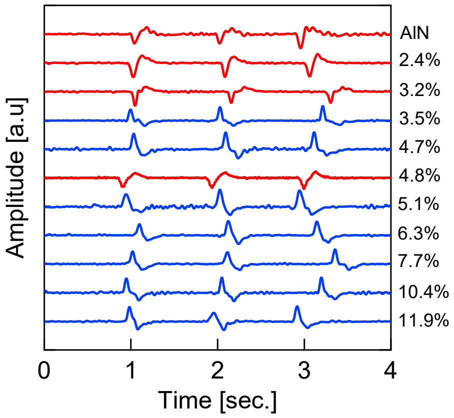

Fig. 1 Press test for $Ge_xAl_{1-x}N$ films (x=0-0.119).

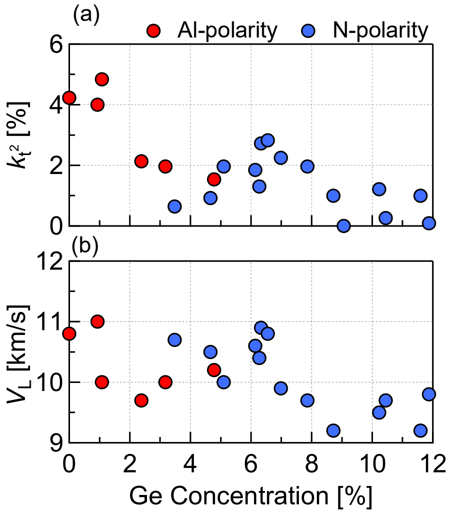

Fig. 2 Thickness-extensional mode electromechanical coupling factor k_t^2 and longitudinal wave velocity V_L for c-axis oriented GeAlN films.

As shown in **Figs. 2 (a) and 2(b)**, the k_t^2 and V_L of the GeAlN films were decreased with increasing Ge concentration. The decrease of k_t^2 may be due to the degradation of crystalline orientation by Ge doping.

4. Polarity inverted GeAlN/AlN film resonators

We fabricated eight-layered GeAlN/AlN film by growing Al-polar pure AlN films in 1st, 3rd, 5th, and 7th layer and N-polar GeAlN films in 2nd, 4th, 6th, and 8th layer. Ge concentrations of the GeAlN layers were adjusted to be approximately 6%. The thicknesses of each layer were 1.3-1.6 μm. To investigate whether the polarity inverted structure was fabricated, the frequency characteristics of longitudinal wave conversion loss in the eight-layered GeAlN/AlN film HBAR were measured by a network analyzer. As shown in **Fig. 3**, the conversion loss reached minimum of 2.1 dB in 8th mode resonance around 3.4 GHz. The values of conversion losses in other mode resonances were large. Thus, the eight-layered GeAlN/AlN film HBAR operated at 8th mode resonance.

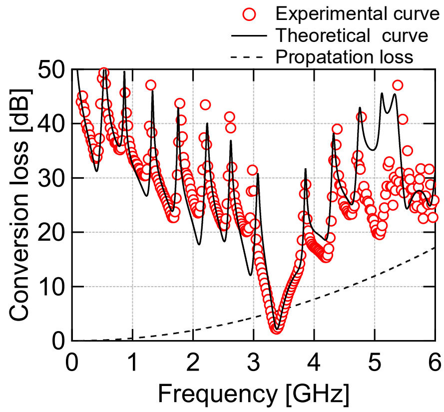

Fig. 3 Frequency characteristics of longitudinal wave conversion loss of the eight-layered polarity inverted GeAlN/AlN film HBAR.

In addition, the experimental conversion loss curve was good agreement with the theoretical curve, calculated by the modified Mason's model considering eight-layered PI structure. These results indicated that the PI structure could be fabricated by alternately growing AlN layers and GeAlN layers. The k_t^2 of 1st, 2nd, 3rd, 4th, 5th, 6th, 7th, and 8th layers were approximately 3.2%, 1.2%, 1.7%, 1.2%, 1.7%, 0.8%, 1.7%, and 0.6%, respectively. The degradation of the crystalline orientation in AlN and GeAlN films by stacking the layers may causes this decrease of k_t^2.

5. Conclusion

Ge doping of more than 6% led to the polarity inversion from Al polarity to N-polarity in c-axis oriented AlN film. The k_t^2 and V_L of GeAlN films decreased with increasing Ge concentration. The eight-layered PI film was obtained by combining AlN layer and GeAlN layer. The eight-layered PI GeAlN/AlN film HBAR operated in 8th mode resonance.

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