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# Growth of c-axis parallel oriented ScAlN films by ion-beam assisted sputtering and their application in pure shear mode resonators

IBAD 法による c 軸平行配向 ScAlN 薄膜の形成とすべりモード共振子への応用

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## 1. Introduction

Increment of the piezoelectric constant $d_{33}$ in c-axis oriented AlN film by doping Sc has been reported. In the case of Sc concentration of 43%, the $d_{33}$ reaches 27 pC/N[1)] and is almost 500% higher than that of pure AlN film. Thereafter, many studies measured and calculated material constants of ScAlN film (e.g., dielectric constant, piezoelectric constant, elastic constant, density)[3,4)]. It is also important to know the electromechanical coupling coefficient. We have reproted that thickness extentional mode $k_t$ of c-axis oriented $Sc_{0.41}Al_{0.59}N$ film reached 0.35[4)]. Considering that the $k_t$ of pure AlN single crystal is 0.30, high $k_t$ was obtained by doping Sc. On the other hand, the piezoelectric constant $e_{15}$ calculated by density functional theory (DFT) does not change even if Sc was doped with AlN film[3)]. However, there is no experimental report of shear mode $k_{15}$ in ScAlN film.

In previous study, we have demonstrated c-axis parallel oriented pure AlN film growth by an ion-beam assited RF magnetron sputtering and have evaluated $k_{15}$ of the film samples[5)]. c-Axis parallel oriented AlN film excites shear wave and is suitable for viscosity sensors of liquid, beacause shear wave does not leak energy so much in liquid. In this study, we evaluate $k_{15}$ of c-axis parallel oriented ScAlN film prepared by an ion-beam assitsed RF magnetron sputtering.

## 2. Experimental details

Four AlN or ScAlN film samples were fabricated by an grazing ion-beam assisted RF magnetron sputtering, as shown in **Fig. 1**. A metallic Al disk on which metallic Sc grains were put was used for sputtering target. The Sc concentration of samples was controlled by changing weight of Sc grains. Before the ScAlN film growth, the Al electrode film was deposited on each silica glass substrate. The substrte was irradiated with ion-beam generated by electron cyclotron resonance (ECR) ion source (MB00-J009, ULVAC) during the ScAlN film growth. The incident angle of the ion beam was set at 20º to the substrate surface. The sputtering source was perpendicular to the ion-beam. The substrate was set at 55 mm and 90 mm from sputtering source and ion-beam source, respectively. The deposition conditions were optimized to the based pressure of under $3.0\times10^{-4}$ Pa, process pressure of 0.2 Pa, gas ratio of $Ar/N_2 = 1/3$, RF power of 150 W, process time of 7 hours, and ion-beam accelerating voltage of 3 kV.

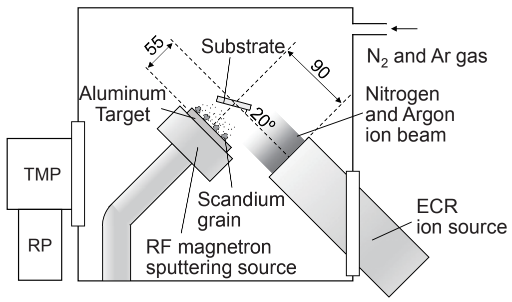


Fig. 1 Ion-beam assisted RF magnetron sputtering system.

## 3. Results and Discussion

*A. Sc concentration and Crystalline orientation*

Film thicknesses of all the samples were 1.4 -1.8 $\mu$m. Sc concentration and surface condition of the samples were measured by an energy dispersive X-ray spectrometry (EDS) and a scanning electron microscope (SEM, JSM-7500F, JEOL), respectively. Sc concentration of the four samples were 0, 8, 13, and 18%. **Figure 2** shows surface SEM-image of $Sc_{0.08}Al_{0.92}N$ film. The crystal grain orients parallel to substrate. The direction of c-axis corresponded to the direction of ion-beam.

Crystalline orientation was evaluated by an X-ray diffraction (XRD, X'Pert Pro MRD, Philips). The observed diffraction peak in the $2\theta$-$\omega$ scan corresponded to wurtzite AlN $(10\bar{1}0)$ shown at 33.2º, but the intensity of the peak was very small. The (0002) pole figure of $Sc_{0.08}Al_{0.92}N$ film was shown in **Fig. 3**. Two highly concentrated {0002} poles were found near $\psi$ = 87º, $\phi$ = 358º and $\psi$ = 88º, $\phi$ = 178º diffracted $(10\bar{1}0)$ oriented grain. The c-axis was both

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oriented parallel to the substrate plane and aligned unidirectionally in the substrate plane. The c-axis direction also corresponds to the direction of ion-beam irradiation direction. Considering that the pole figure shows highly peak but the XRD patterns shows weak peak, the out-of-plane orientation is random.

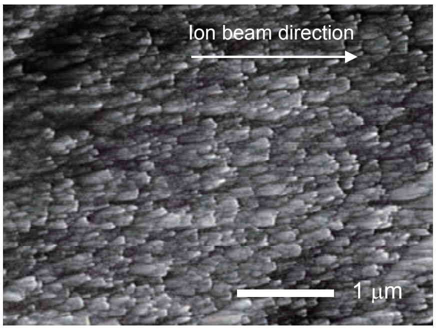


Fig. 2 Surface SEM-image of $Sc_{0.08}Al_{0.92}N$ film.

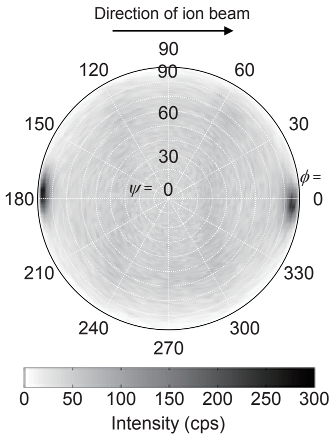


Fig. 3 (0002) pole figure of $Sc_{0.08}Al_{0.92}N$ film.

*B. Piezoelectric properties*

High overtone bulk acoustic wave resonators (HBARs) were fabricated by depositing top Cu electrode on the samples to measure piezoelectric property. Time responses of acoustic waves propagating in the samples were measured by a network analyzer (E5071C, Agilent Technologies). Shear waves were observed in all the samples. Then, the conversion losses were also measured. The results of AlN and $Sc_{0.13}Al_{0.87}N$ films are shown in **Fig. 4**. The theoretical curves were also calculated by a one dimensional mechanical transmission line model. The theoretical curves at $k_{15}$ = 0.009, 0.040, 0.044, and 0.015 were in good agreement with the experimental plots of Sc concentration of 0, 8, 13, and 18%, respectively. The $k_{15}$ of $Sc_{0.13}Al_{0.87}N$ film is four times larger than that of AlN film. However, $k_{15}$ of AlN film was much smaller than that in previous study (0.057). Furthermore, the $k_{15}$ of $Sc_{0.18}Al_{0.82}N$ film decreased by 0.015. Because the phase transition from a piezoelectric wurtzite to a non-piezoelectric cubic was occurred at Sc concentration of near 43%[1,2,4], this decrease cannot be related to the phase transition. The probable reason is degradation of the crystallization caused by impurities in Sc grains. Therefore, further experiment is required including growth method of AlN film.

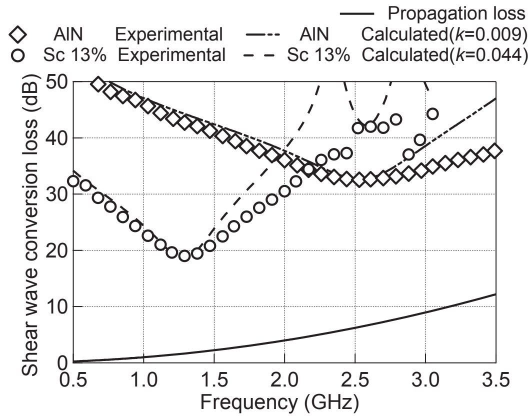


Fig. 4 Experimental and calculated conversion losses of AlN and $Sc_{0.13}Al_{0.87}N$ films.

## 4. Conclusion

c-Axis parallel oriented ScAlN film was fabricated by grazing an ion-beam assisted RF magnetron sputtering. c-Axis was oriented parallel to substrate and the direction corresponded to the direction of ion-beam. All the samples excited only shear wave, and $k_{15}$ increased by doping Sc with AlN. However, the $k_{15}$ of all the samples were smaller than that in previous study. Further experimental studies are needed in order to understand the effect of doping Sc on $k_{15}$. The $e_{15}$ might not increase as M. A. Caro *et al*. calculated[3]. On the other hand, in the c-axis parallel oriented ScAlN film/substrate structure, increment of $e_{33}$ contribute to obtain a high electromechanical coupling coefficient $K^2$ of Sezawa mode SAW[6]. Experimental analyses of SAW devices consisting of c-axis parallel oriented ScAlN film are also expected.

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