2PL

ScAlN, ZnO, and $PbTiO_3$ polarization inverted thin multilayers for BAW and SAW applications

ScAlN, ZnO, $PbTiO_3$分極反転薄膜の BAW および SAW デバイス応用

Takahiko Yanagitani [1, 2, 3†] ([1]Waseda University; [2]ZAIKEN; [3]JST-CREST)
柳谷隆彦 [1, 2, 3†] ([1]早大院 先進理工, [2]各務材料技術研究所, [3]JST-CREST)

1. Introduction

Polarization-inverted multi-layer structure is attractive for thin film BAW resonator, SAW device, ultrasonic microscope, and non-linear optics applications. We here introduce the growth method of the structure for ScAlN, ZnO, and epitaxial $PbTiO_3$ films. We also demonstrate the performance of the overtone mode resonators consisting of the polarization-inverted multi-layer.

2. Polarization inverted thin multilayers for BAW and SAW applicatoins

Single piezoelectric layer resonator excites fundamental (1st) mode resonance. In contrast, *n*th polarization inverted multilayer film resonator excites *n*th high overtone mode resonance. Therefore, the resonant frequency in *n*th polarization inverted film resonator is *n* times higher than that of single piezoelectric layer resonator when both films have equal thickness. On the other hand, in the same operating frequency, polarization inverted multilayer make it possible to increase their film thickness. This contributes to the rigidity of the device and the high power handling capability.

It is well known that the energy trapping mode cannot occur when ratio of longitudinal wave and shear wave velocities $(c_{33}^D/c_{44}^E)^{1/2}$ in the piezoelectric plate is smaller than 2 [1]. Thickness extensional mode (TE) in ZnO film have energy trapping mode because the ratio $(c_{33}^D/c_{44}^E)^{1/2} = 2.33$ exceeds 2. In contrast, TE energy trapping mode cannot be used in the AlN and $Sc_{0.41}Al_{0.59}N$ films in standard electrode configuration because the ratio of AlN and $Sc_{0.41}Al_{0.59}N$ are 1.75 and 1.51, respectively[2]. On the other hand, Kittaka et al. proved that 2nd overtone TE mode in polarization inverted $PbTiO_3$ structure have energy trapping mode although the ratio in $PbTiO_3$ is 1.91 [3]. It is expected that overtone TE mode in polarization inverted AlN and ScAlN multilayer also have energy trapping mode.

Nakamura et al. reported 60 MHz 2nd overtone TE mode resonator in domain inverted $LiNbO_3$ plate [4]. Larson et al. reported 2nd overtone TE mode FBAR consisting of polarization inverted c-axis oriented AlN films [5].

For SAW applications, high K^2 values were expected in the polarization-inverted two-layer, especially in the second mode Sezawa-SAW propagating at the boundary of the two-layer, compared with usual Rayleigh-SAW in the single layer.

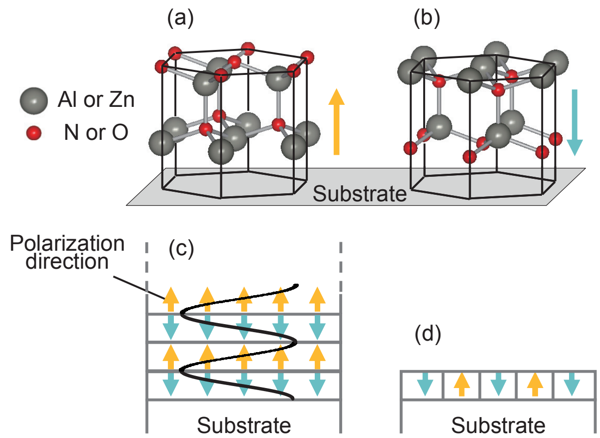

Fig. 1. (a) N-polar (000-1) AlN film or O-polar (000-1) ZnO film, (b) Al-polar (0001) AlN film or Zn-polar (0001) ZnO film, (c) polarization inverted multilayered structure, and (d) periodically polaization inverted structure.

3. Polarization inverted thin film growth

3.1. Ion beam irradiation induced polarization inverted thin film growth

c-axis oriented AlN or ZnO film can be classified as either an (000-1) N- or O-polarity shown in **Fig. 1 (a)** or an (0001) Al- or Zn-polarity shown in **Fig. 1 (b)**. The insertion of a buffer layer is one of the approaches to control polarization direction in the wurtzite film growth [5]. However, the multilayer polarization-inverted structure, such as that shown in **Fig. 1 (c)** cannot be obtained by these polarization inversion techniques using buffer layer surface because the polarity of the second and subsequent layers cannot be controlled.

We previously investigated the development

yanagitani@waseda.jp

of unusual a-axis (c-axis parallel) oriented wurtzite films by ion beam irradiation during film growth. This should be caused by the ion beam tolerant (or sputtering yield) anisotropy of wurtzite crystal. Similarly, we can assume that the polarization inversion of wurtzite films is induced by ion beam tolerant anisotropy between (0001) and (000-1) planes. On the basis of this assumption, the effect of ion beam irradiation on the polarization of c-axis oriented wurtzite ScAlN films was investigated.

3.2 Determination of sign of polarization

The polarity of the piezoelectric films can be determined by a press test [8]. Compressive stress was applied to the top electrode by an oscilloscope probe to measure the piezoelectric response of the films using an oscilloscope. The polarity of the films can be determined from the sign of the piezoelectric response. We can use c-plane ZnO single crystal (Tokyo Denpa Co., Ltd., 10×10×0.5 mm^3, >1010 Ω·m) as a reference sample for the press test. When the compressive stress was applied, a negative or a positive amplitude response appeared in the Zn-polar or O-polar ZnO single crystal, respectively, as shown in **Figs. 2 (a)**.

3.3 Polarization inverted AlN and ScAlN films

As shown in **Fig. 2 (b)**, when the compressive stress was applied, a negative response, indicating Al-polarity, were observed in the film grown using the condition which is close to the commonly-used AlN film growth condition (RF substrate bias =0.00W). In contrast, a positive response, indicating N-polarity, were observed in the film grown with an RF bias of 0.50 W. These results demonstrate that the polarity of the AlN film is inverted from Al-polarity to N-polarity by enhancing ion beam irradiation during the film growth. As previously assumed, the polarization inversion by ion beam irradiation may result from ion beam tolerant anisotropy between N-polar (000-1) and Al-polar (0001) crystal planes. We deduced that Al-polar (0001) oriented crystal growth is inhibited by ion beam irradiation, and relatively damage tolerant N-polar (000-1) oriented crystals develop preferentially. Detailed results of the various substrate bias wattage were described in the literature [9].

3.4 Polarization inverted ZnO films

We can control the polarization of the ZnO films by ion beam irradiation [10]. **Fig. 3** shows frequency response of the conversion loss of the four layered ZnO high overtone mode bulk acoustic resonator (HBAR). 4th mode resonance excitation with suppression of the 1st, 2nd, and 3rd resonance modes, indicating complete polarization inversion in each layer, were clearly observed.

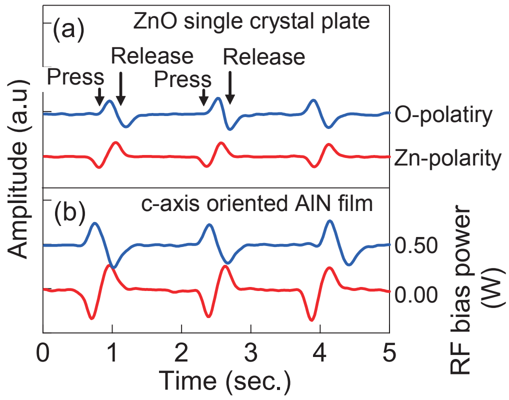

Fig. 2. Piezoelectric responses of (a) ZnO single crystal plate as a reference and (b) the response of AlN films grown with and without an substrate RF bias. Al-polarity and N-polarity are indicated as red lines and blue lines, respectively.

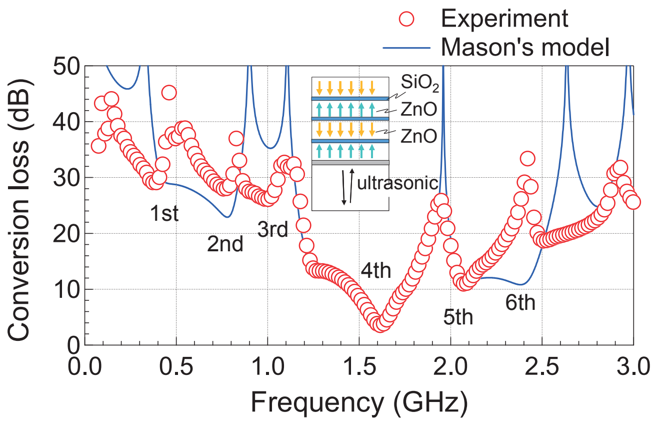

Fig. 3. Frequency response of the conversion loss of the four layered ZnO HBAR, (0001) ZnO / SiO_2 /(000-1)ZnO/ SiO_2 / (0001)ZnO / SiO_2 / (000-1) ZnO / (0001) Ti / silica glass substrate.

Acknowledgment

The author are grateful for a research collaboration with Dr. Shinji Takayanagi of Doshisha University, and Dr. Masashi Suzuki of University of Yamanashi.

References

1. H. Tanaka, H. Shimizu, and K. Yamada, IEICE Trans. Fundamentals (Japanese Edition), **62-A**, (1979) 477.
2. T. Yanagitani, H. Ichihashi, M. Suzuki, S. Takayanagi, M. Matsukawa, EEE Ultrason. Symp., *Abstract* 6G-4, (2015) 326.
3. T. Kittaka, A. Ando, T. Okada, and Y. Sakabe, IEICE Tech. Report, **87**, (1987) 1 (in Japanese)
4. K. Nakamura, H. Ando, and H. Shimizu, Proc. IEEE Ultrason. Symp., (1986) 719.
5. J. D. Larson III, S. Mishin, and S. Bader, Proc. IEEE Ultrason. Symp., (2010) 1054.
6. T. Yanagitani and M. Kiuchi, J. Appl. Phys., **102**, (2007) 044115.
7. S. Takayanagi, T. Yanagitani, and M. Matsukawa, Appl. Phys. Lett., **101**, (2012) 232902.
8. J. F. Rosenbaum, Bulk Acoustic Wave Theory and Devices (Artech House, Boston, 1988).
9. M. Suzuki, T. Yanagitani, and H. Odagawa, Appl. Phys. Lett., **104**, (2014) 172905.
10. R. Hashimoto, T. Yanagitani, R. Ikoma, S. Takayanagi, M. Suzuki, H. Odagawa, and M. Matsukawa, presented in IEEE Ultrason. Symp., *Abstract book* IUS3-H-6, (2013).