High-quality AlN/sapphire-based Surface Acoustic Wave Filter With 5.75 dB Insertion Loss

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Keywords: surface acoustic wave filter, AlN films, RF sputtering, device parameters

Abstract

High-quality c-axis AlN films with a full width at half maximum (FWHM) of 84.93 arcsec on sapphire have been fabricated by RF reactive magnetron sputtering. The insertion loss of two-port type AlN-based SAW filter can be improved to 5.75 dB, which is the minimum result so far. The impact of device parameters (acoustic wavelength, acoustic aperture and two structural designs within the same area) on the performance of AlN-based SAW filter was studied experimentally. The results showed that the SAW filter with wavelength (λ) of 8 µm exhibits lower insertion loss of 9.09 dB than that with λ of 12 µm and 16 µm. The insertion loss and out-of-rejection of SAW filter along a-direction [11-20] exhibit 5.53 dB and 5.43 dB improvement compared with that along m-direction [1-100] of AlN films. The SAW filter with acoustic aperture of 30λ shows the minimum insertion loss of 5.75 dB compared with acoustic aperture of 15λ and 60λ. With the same device size, filters with larger acoustic finger pairs (N=200) and smaller acoustic aperture (W=15λ) exhibits 12.9% improvement of insertion loss compared with the filter with N=100 and W=30λ.

INTRODUCTION

Traditional $LiNbO_3$ and $LiTaO_3$ based surface acoustic wave (SAW) filter in front-end radio frequency modules have been widely used for mobile communications. However, the working frequency of traditional SAW filters is below 3 GHz due to the low acoustic velocity of piezoelectric substrate, which cannot meet the increasing demand for very high frequency applications. The working frequency of SAW devices can be effectively increased by increasing the acoustic velocity of piezoelectric materials. As a result, Aluminum nitride (AlN) based SAW devices have attracted much attention for high frequency applications due to high acoustic velocity of AlN. Our previous experimental results indicate that the resonant frequency of AlN/Sapphire based SAW resonators is 60% higher than that of $LiNbO_3$ based SAW resonators[1].

A large variety of deposition methods have been reported to fabricate high-quality AlN films on sapphire, such as pulsed laser deposition (PLD)[2], metal organic chemical vapor deposition (MOCVD)[3] and RF reactive magnetron sputtering[4]. Among these, magnetron sputtering has been recognized as a dominant technology for the fabrication of AlN films for MEMS devices including film bulk acoustic wave filter (FBAR), SAW devices and so on, due to the characteristics of low cost, high uniformity, and low growth temperature. The performance of AlN-based SAW devices is closely related to the crystal quality of films [5]. However, the FWHM value of XRD rocking curve of AlN (002) plane of most published sputtered AlN film on sapphire is ranging between 300 arcsec and 2° [6-8], which cannot meet the requirement for the fabrication of AlN based SAW filter with high performance. In this work, high-quality c-axis AlN films on sapphire with a FWHM value of 84.93 arcsec were grown by RF reactive magnetron sputtering. A minimum insertion loss (IL) of 5.75 dB of SAW filter has been obtained based on our AlN films, which is much better than the IL (25.58 dB) of our previous reported SAW filter based on AlN films with a FWHM value of 720 arcsec [9]. Moreover, the impact of device parameters on the performance of AlN-based two-port type SAW filter was studied systematically.

EXPERIMENTS AND RESULTS

Highly oriented c-axis AlN (0002) thin film with a thickness of 900 nm was deposited by RF reactive magnetron sputtering on 2-inch (0002) sapphire wafers with a thickness of 430 µm. A two-port type Rayleigh wave AlN-based SAW filter with Ti/Al electrodes (10 nm/400 nm) was fabricated.

Fig. 1 shows the X-ray Diffraction (XRD) 2θ-ω scan pattern of sputtered AlN films on sapphire. The diffraction peak at 2θ=36.03° corresponds to AlN (0002) plane. The inset of Fig. 1 exhibits the XRD rocking curve of AlN films, indicating that the full width at half maximum (FWHM) value of AlN films is as low as 89.01 arcsec.

The surface morphology of these AlN films was characterized using Atomic Force Microscopy (AFM). As shown in Fig. 2, 3D AFM image of sputtered AlN films reveals a relatively flat and uniform surface with a root mean square (rms) roughness of 1.57 nm in a range of 10×10 μm.

Fig. 3(a) demonstrates the frequency response (S_{21}) of SAW filter with different acoustic wavelength. Insertion loss of the sample is defined as the S_{21} amplitude at center frequency f_c, and out-of-band rejection is extracted by the gap between insertion loss and average S_{21} amplitude within a relatively flat frequency range from 690 MHz to 700 MHz. As λ increases from 8 μm to 16 μm, the corresponding center frequency shows a decrease from 709.28 MHz to 355.56 MHz. The typical frequency response of Rayleigh-mode vibration obviously attenuates with the increase of λ. Fig. 3(b) describes the dependence of insertion loss and out-of-band rejection on normalized AlN thickness h/λ. The best performance with insertion loss of 9.09 dB and out-of-band rejection of 14.61 dB is achieved for SAW devices with λ of 8 μm, corresponding to the h/λ of 0.1125. This indicates that more energy can penetrate the sapphire substrate with the increase of λ from 8 μm to 16 μm, which will degrade the device performance.

Fig. 4 depicts the performance of SAW filter with different acoustic propagation angle. Propagation angle of 0°, 60° and 30°, 90° show the same frequency response, corresponding to a-direction [11-20] and m-direction [1-100] of AlN films respectively. The center frequency of SAW filter along a-direction shows 2.05% higher than that along m-direction due to larger Young's modulus. The insertion loss and out-of-rejection of the filter along a-direction [11-20] exhibit 5.53 dB and 5.43 dB improvement compared with that along m-direction [1-100] due to the suppression of beam steering effect.

Fig. 5 shows the frequency responses (S_{21}) of the SAW devices with different acoustic aperture. When the acoustic aperture increases from 15λ to 60λ, out-of-band rejection degrades sharply, while the insertion loss decreases at first from 7.85 dB to 5.75 dB and then increase to 7.51 dB. The lowest insertion loss is 5.75 dB for acoustic aperture of 30λ.

Fig. 6 shows the frequency responses of two different designs with the same device size. Device with acoustic aperture W of 15λ and finger pairs N of 200 shows smaller insertion loss than the device with W of 30λ, and N of 100. This may be attributed to the larger electrode resistivity for longer acoustic aperture.

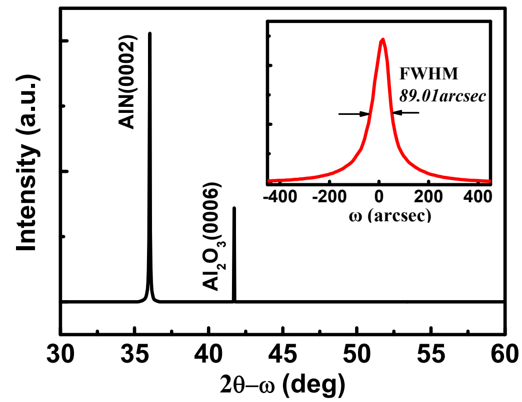


Fig. 1. The 2θ-ω XRD scan pattern of AlN thin films, and the inset shows the XRD rocking curve of AlN films.

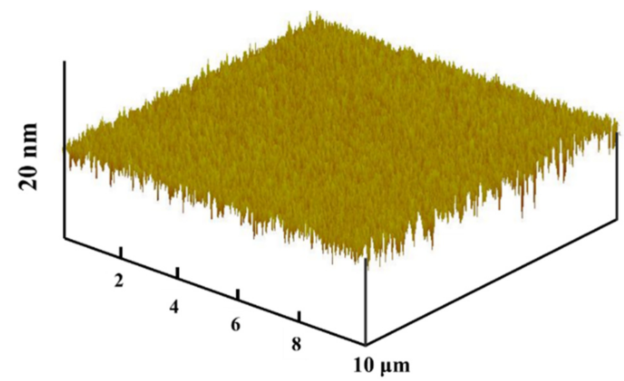
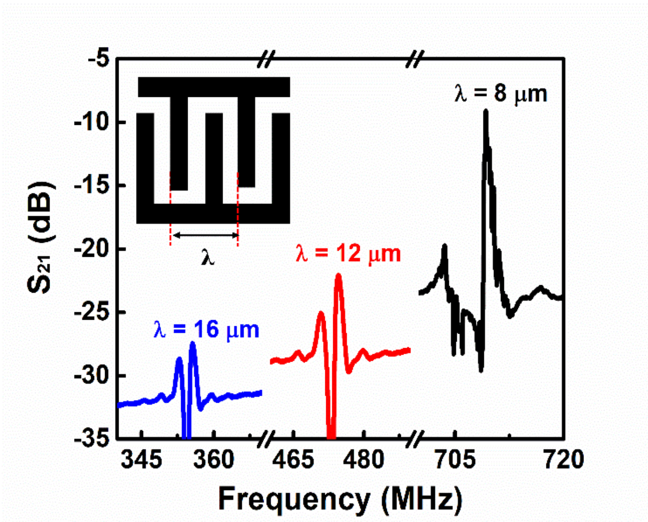
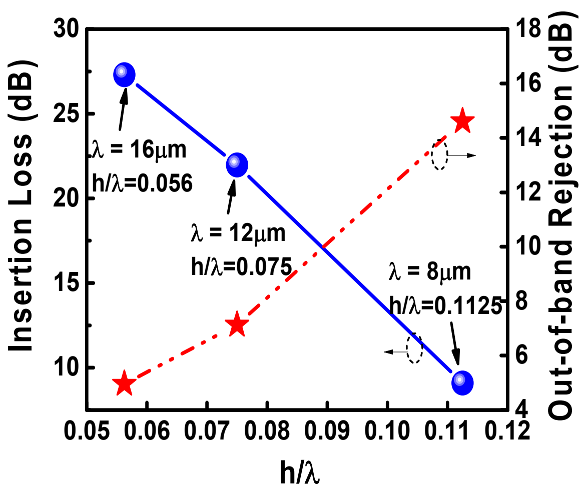


Fig. 2. 3D AFM image of AlN films in a range of 10×10 μm.



(a)



(b)

Fig. 3. (a) Frequency response (S_{21}) of SAW resonators with different acoustic wavelength. (b) Dependence of insertion loss and out-of-band rejection on normalized AlN thickness h/λ.

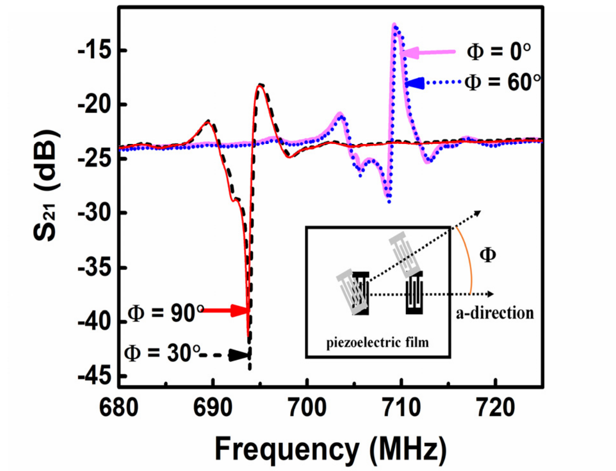


Fig. 4. Frequency response (S_{21}) of AlN based SAW filter with different propagation angle.

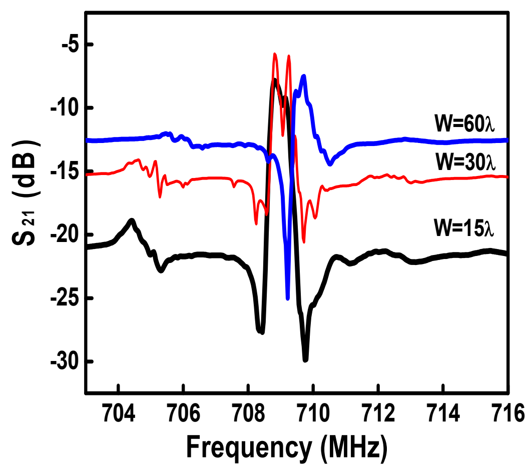


Fig. 5. Frequency response (S_{21}) of AlN based SAW filter with different acoustic aperture.

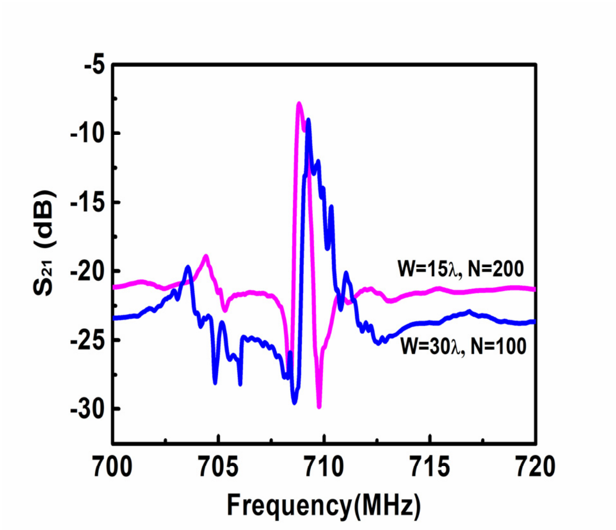


Fig. 6. Frequency response (S_{21}) of AlN based SAW filter with two designs within the same device size.

Conclusions

In summary, high-quality AlN films were obtained with FWHM of 84.93 arcsec on sapphire by RF sputtering to fabricate high-performance SAW devices. Our experimental results showed that filter with λ of 8 μm exhibits better performance than that with λ of 12 μm and 16 μm. Both insertion loss and out-of-rejection of SAW filter along a-direction [11-20] are improved compared with m-direction [1-100] of AlN films due to the suppressed beam steering effect. Insertion loss has a minimum at acoustic aperture of 30λ, displaying a value of 5.75 dB. With the same device size, filter with more finger pairs and smaller acoustic aperture may enable lower insertion loss for high frequency SAW devices.

Acknowledgements

This work was supported by the National Key R&D Program of China (Nos.2017YFB0402900), the National Natural Sciences Foundation of China (Grant Nos. F040704, 61376090 and 61674143), and the One Hundred Person project of the Chinese Academy of Science.

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Acronyms

SAW: Surface Acoustic Wave

AlN/Sapphire: AlN films on Sapphire substrate

XRD: X-ray diffraction

AFM: Atomic force microscopy

FWHM: Full Width at Half Maximum