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Synthesis and microstructural characterisation of reactive RF magnetron sputtering AlN films for surface acoustic wave filters

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Abstract

Wurtzite aluminium nitride (AlN) thin films were deposited by RF reactive magnetron sputtering technique on (1 0 0) silicon substrates at low temperature (400 °C). The microstructural properties of sputtered AlN films were investigated using X-ray diffraction (XRD), scanning electron microscopy, transmission electron microscopy and atomic force microscopy (AFM), to aim improvement of piezoelectric coupling for surface acoustic wave (SAW) devices. It was found that the AlN films deposited in the optimum experimental conditions, as revealed by XRD and selected area electron diffraction, exhibit a high (0 0 2) preferred orientation, where columnar crystals are grown in a non-epitaxial pattern and aligned almost perpendicular to silicon substrate. The ω rocking curve, shows that the standard deviation of columns of thin AlN films is less than 1°, which exhibit a high quality of these films. Furthermore, the AFM found a very low surface roughness less than 7 Å, which is very crucial to decrease a loss propagation in AlN films. The films synthesised with optimum conditions were used to perform SAW devices by developing inter-digital transducer on AlN/Si structure. Frequency characteristics show that the realised SAW devices exhibit good filtering performances and a good compromise between phase velocity, electromechanical coupling coefficient and temperature coefficient of frequency.

Keywords: Aluminium nitride; Surface acoustic wave devices; Sputtering; Microstructure

1. Introduction

Aluminium nitride (AlN) is of great technological interest due to its exceptional mechanical, thermal and optical properties. Furthermore, AlN is a promising and potential candidate for surface acoustic wave (SAW) devices because of its high sound velocity (up to 6000 m/s) [1,2] in comparison with conventional SAW materials as quartz or $LiNbO_3$.

High-quality crystalline AlN thin films are typically grown by molecular beam epitaxy, reactive evaporation [3], chemical vapour deposition (CVD) [4] and sputtering methods [5,6]. However, the substrate temperature adopted in the conventional CVD method was very high, so a smooth surface morphology of the AlN films could not be obtained by this method due to its high grain growth rate.

Since large surface roughness may lead to increase scattering and hence increase propagation loss especially when high frequency is reached [7]. For these reasons, reactive RF magnetron sputtering method was adopted here for AlN films deposition [8].

In this work, we report on the deposition of AlN thin films on Si(1 0 0) by RF reactive magnetron sputtering. We report their structural, microstructural and morphological characterisation by X-ray diffraction (XRD), selected area diffraction pattern, transmission electron microscopy (TEM) and atomic force microscopy (AFM). Furthermore, we studied the AlN/Si layered structure SAW filter performances in term of frequency response, electromechanical coupling coefficient and the stability of temperature by determining the temperature coefficient of frequency (TCF).

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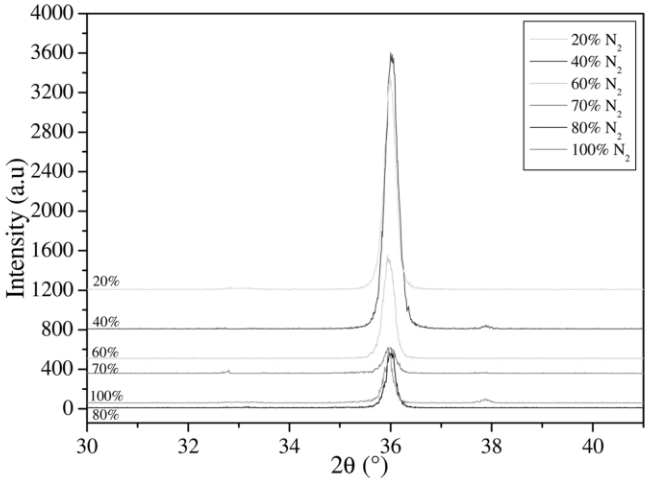

Fig. 1. XRD pattern of AlN thin films elaborated in different nitrogen concentration.

2. AlN deposition

The AlN thin film was prepared by reactive RF magnetron sputtering on silicon Si(1 0 0) substrates. The system employed a simple chamber with a water-cooled 99.999% pure aluminium target disk of 4 inch (107 mm) in diameter and 6.35 mm thick. The distance between the cathode and the substrate holder was fixed to 80 mm. A turbomolecular pump was used to evacuate the sputtering chamber to 2×10^{-7} mbar prior to the film deposition. Pre-sputtering for 15 min using 99.999% pure argon was performed before nitrogen was admitted gradually to reach the desired gas composition. After obtaining the equilibrium condition, the shutter was opened and the deposition of the film was started. The gas discharge pressure was kept constant to 4.7×10^{-3} mbar, the RF power was fixed to 170 W, the substrate holder temperature was heated at 400 °C and the nitrogen concentration in Ar/N_2 gas mixture was varied from 0 to 100% N_2. In order to perform the better comparison between different samples, the deposition time of AlN films was adjusted to obtain 2 μm thick of various N_2 partial pressures. The thickness of deposited films was measured by scanning electron microscopy from the cross section of structure.

3. Microstructural and morphological characterisations

The crystallographic analyses of the AlN thin films realised by XRD as a function of the nitrogen fraction in the Ar/N_2 gas mixture, for the constant thickness samples, demonstrate a strong dependence on AlN crystalline films quality. All deposited films were shown to be hexagonal wurtzite AlN by θ/2θ incidence XRD scanning. The evolution of preferred orientation (0 0 2) was recorded by θ/2θ XRD results in Fig. 1. We can observe that the optimum for AlN preferred orientation is obtained for the 40% N_2 concentration. Therefore, the AlN thin film is strongly textured with *c*-axis normal to the surface. The ω rocking curve for (0 0 2) reflection for AlN film elaborated in optimal conditions is presented in Fig. 2. Fitted Gaussian peaks give the full-width half maximum corresponding to the standard deviation (S.D.) of 0.9° for this film. This indicates that the *c*-axis of various crystallites is spread symmetrically at approximately 0.9°. This value is lower than those generally obtained by other group [9–11], and testify the very good crystalline quality of our deposited films. AlN thin films growth in optimal experimental conditions was then studied more closely under TEM in order to investigate the transition between randomly oriented crystals and columnar growth. No apparent microstructure discontinuities can be discerned from images shown in Fig. 3a for the interface between silicon substrate and AlN film. From Fig. 3b, which presents only an AlN film columns, we can deduce that the columns width was approximately 30 nm. This information about grain columns size is very important to predict the surface roughness of AlN films. In fact, the grain size is linked to surface roughness, which is very critical for SAW applications. The measurements of surface roughness were accomplished using AFM (Fig. 4) for the maximum thickness variation (Z_{max}) and root mean square (rms) thickness variation within an area of 30×30 μm^2. AFM analysis reveals a value of rms surface roughness of 6.79 Å and a maximum thickness variation of 5.20 Å. These values of surface roughness are very low for the AlN thin films elaborated by sputtering. These results can be put in relation with a very low

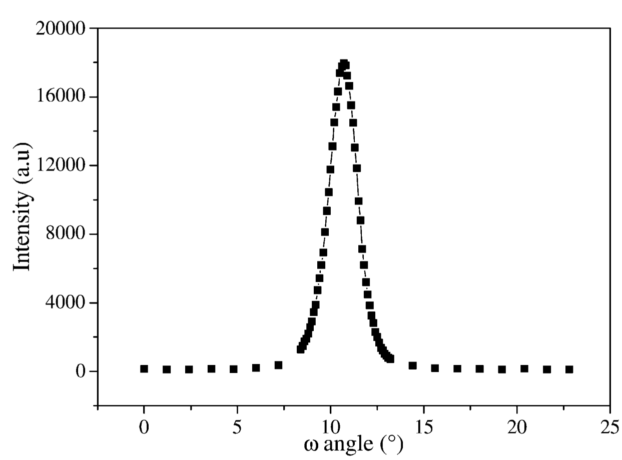

Fig. 2. ω Rocking curve of AlN film growth in 40% N_2 nitrogen concentration.

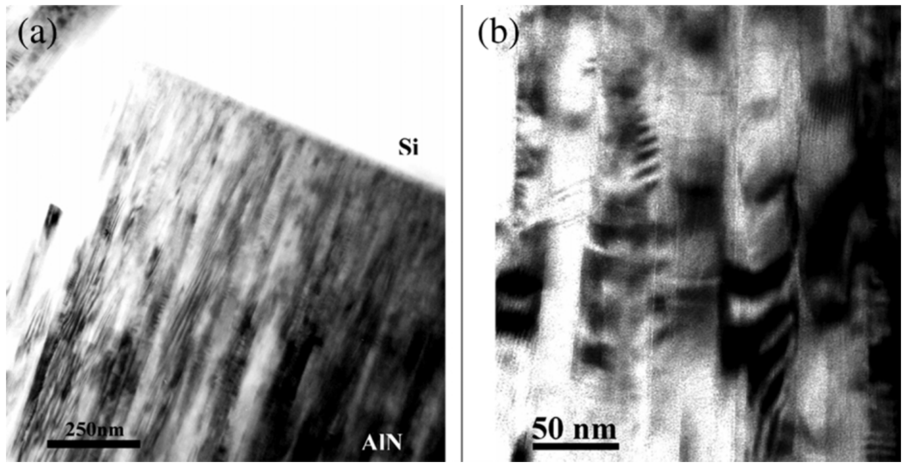

Fig. 3. (a) Cross-sectional TEM image of AlN film growth at 40% N_2. (b) (0 0 2) AlN film columns.

acoustic loss in the AlN films and consequently high performances of SAW devices are expected [12].

The selected area electron diffraction (SAED) taken from AlN/Si interface for AlN film synthesised in optimal growth experimental conditions is presented in Fig. 5. We can observe as indexed in figure, diffraction spots from the AlN layer, which indicates the (0 0 2) preferred orientation and confirms the XRD results.

4. Achievement and characterisation of SAW filter

Performances of SAW devices are determined by measuring the frequency responses of S parameters (S_{11}, S_{12}, S_{21} and S_{22}). Owing to the symmetry of devices, only two of them are relevant ($S_{11}=S_{22}$ and $S_{12}=S_{21}$). S_{11} correspond to reflection mode and will be used to determine the electromechanical coupling coefficient (K^2) from Smith chart using the method described in Refs. [13,14]. K^2 indicates the efficiency with which electromagnetic energy is converted to mechanical. It is a direct function of structural properties of the piezoelectric film. S_{12} corresponds to transmission mode (Fig. 6). From this response, one can deduce the centre frequency attenuation and stop band rejection of device, as well as the phase velocity and the TCF of AlN/Si structure.

After the deposition of the piezoelectric (0 0 2) oriented AlN layer, a thin 150-nm aluminium layer was deposited onto the AlN/Si sample by sputtering. Thus, inter-digital transducers (IDTs) with a spatial period (λ)

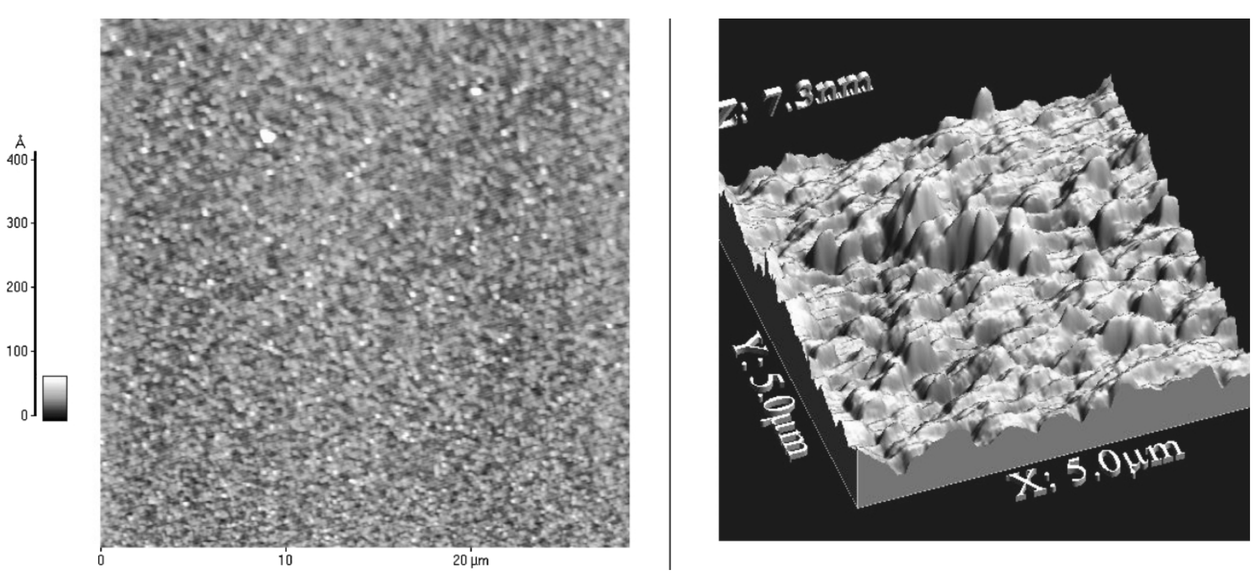

Fig. 4. AFM surface morphology of AlN thin films. (a) 2D image; (b) 3D image.

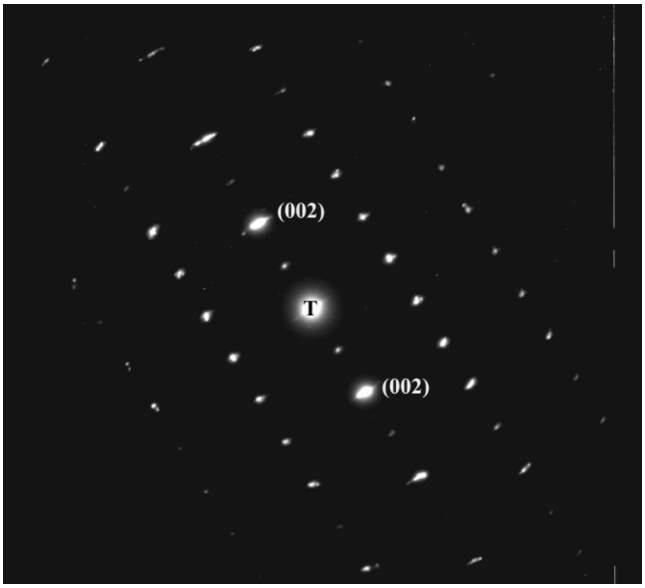

Fig. 5. SAED of AlN film growth on silicon substrate.

of 16 were prepared by a conventional photolithography and aluminium wet etching. The IDTs are uniform and single type with metalisation ration of 50%.

The frequency response (S_{21}) of a two-port IDT/AlN/Si SAW filter is shown in Fig. 6. One can observe the practical filter performance of realised device: an insertion loss (<-31.5 dB) at the centre frequency ($f_0=316$ MHz) and 15 dB of band rejection level. Note that no particular design of IDT was performed to optimise the frequency response. The relatively high value of insertion loss is due to the semiconducting properties of silicon substrate. With insulated substrate as sapphire [15] or diamond [14], insertion loss will be strongly reduced. Taking into account the wavelength ($\lambda=16$ μm) and the centre frequency value, the calculated acoustic phase velocity is $V_\varphi=f_0\lambda=5054$ m/s.

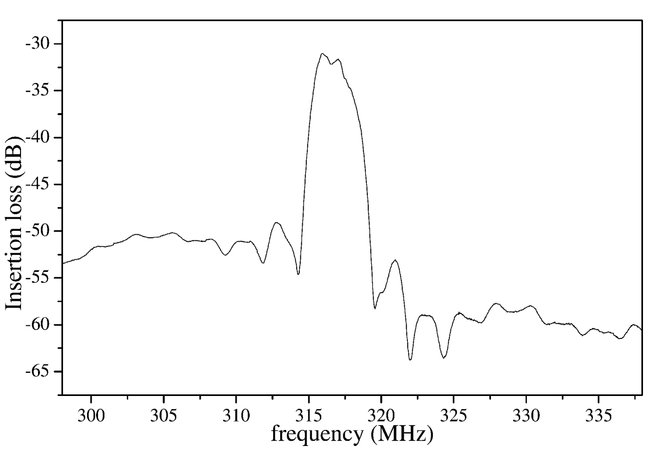

Fig. 6. Frequency response of AlN/Si layered structure SAW filter.

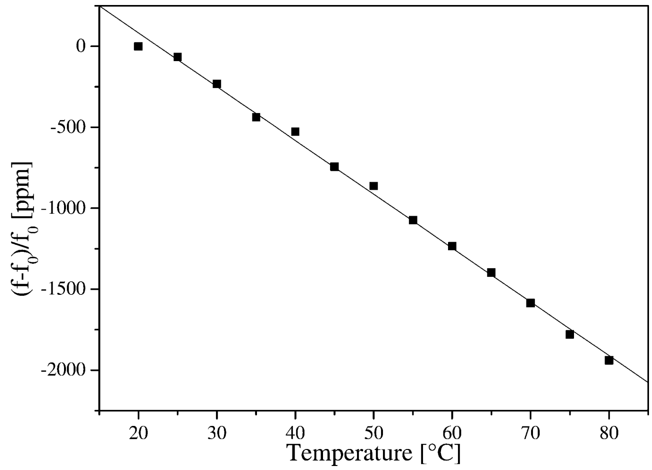

Fig. 7. Temperature dependence of the fractional of the frequency for the AlN/Si layered structure.

Electromechanical coupling coefficient (K^2) was also measured and the obtained value is $K^2=1.7\%$.

Temperature stability of frequency filters is a critical issue for SAW devices in communication and sensor applications. SAW structures with low TCF are then the purpose. In this sense, the centre frequency of the SAW filters was investigated as a function of temperature. Fig. 7 shows the temperature dependence of the centre frequency. One can observe that the centre frequency decreases linearly when the temperature increases in the range of 20–80 °C. The value of TCF deduced from this curve is -28 ppm/°C. The realised structure shows a good compromise between phase velocity, K^2 and TCF. As comparison, quartz and $LiNbO_3$ show the following characteristics [16]: ST-cut quartz: SAW velocity=3158 m/s, $K^2=0.14\%$ and TCF=0; $LiNbO_3$: SAW velocity=3990 m/s, $K^2=5.5\%$ and TCF=74 ppm/°C.

5. Conclusion

We successfully deposited highly *c*-axis oriented AlN films on the (1 0 0) Si substrates by RF reactive magnetron sputtering. It was found that optimum for AlN (0 0 2) preferred orientation is obtained for the 40% N_2 concentration in Ar–N_2 gas mixture at 400 °C substrate temperature. Low S.D. (0.9°) of AlN film columns was measured testifying the good crystalline quality of AlN films. The AFM analysis exhibits a very low surface roughness less than 7 Å, which is strongly lower than the surface roughness obtained generally for AlN thin films using sputtering deposition method. The surface roughness is very crucial for a good functioning and a high performance of SAW devices based on AlN thin films. Consequently, we have formed an AlN/Si layered structure SAW filter with a practical filtering characteristics. The performed structure IDT/AlN/Si exhibits a good compromise between phase velocity, electromechanical coupling coefficient and temperature stability.

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