LOW TEMEPARTURE AlN THIN FILMS GROWTH FOR LAYERED STRUCTURE SAW and BAW DEVICES

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Abstract – In this work, c-axis oriented aluminium nitride thin films on silicon substrates were deposited by reactive RF magnetron sputtering method at various substrate temperature (without heating – 400°C) with the same thickness (1.4µm). The structural, morphological and optical properties of AlN films were investigated by X-ray diffraction, field emission scanning electron microscope, atomic force microscopy and Fourier transform infrared absorbance spectroscopy. It was found that the AlN films showed the same highly (002) preferred orientation with low full with of half maximum of rocking curve, which is about 2° for all the films elaborated in various temperatures. The optical properties of these films analysed by FTIR exhibit an absorption bands attributed to vibrational modes of Al-N bonds, in particular E1(TO) at 678cm^{-1} and A1(TO) at 613cm^{-1}. The surface roughness of films determined by AFM is less than 0.5nm for the film grown at low temperature, which is very suitable SAW devices achievement. Elastic properties of deposited AlN films were evaluated by realisation and characterisation of AlN/silicon SAW device. Experimental results show that realised structure exhibits a good frequency response and practical values of electromechanical coupling coefficient and temperature coefficient of frequency.

I. INTRODUCTION

Aluminium nitride (AlN) has been considered as an attractive thin film piezoelectric material for integrated circuit (IC) compatible surface acoustic wave (SAW) devices. This compatibility requires a deposition process in relatively low temperature. Many techniques, such as sputtering [1, 2, 3], chemical vapour deposition [1, 4, 5] and molecular beam epitaxy [1, 6] have been used to fabricate AlN films on various substrates. Using silicon as the substrate is highly attractive for device applications due to potential integration with well-developed silicon technologies. In most cases mentioned previously, the deposition temperatures are quite high. High temperature deposition has the drawback of degradation of the substrate and AlN film during growth due to thermal damage. Then, elaboration of AlN films at low temperatures has become very important and valuable [7, 8]. Sputtering technique was adopted here for AlN films deposition.

The choice of AlN as a piezoelectric thin film for SAW and BAW applications, is due to its high acoustic velocity to allow the achievement of high frequency. In fact, the increase of the operation frequencies of SAW devices can be accomplished using high resolution lithography techniques (e-beam), or high acoustic wave velocity materials. The first solution is highly demanding in terms of fabrication costs, the second one is easier if high quality fast materials can be grown by standard thin films deposition techniques such as sputtering [7]. In this work, the high crystalline quality, high acoustic velocity and high piezoelectrical coupling AlN thin films deposited at low temperature, are presented, to permit the achievement of high frequency SAW devices based on non-piezoelectric and no high acoustic velocity substrates, such as silicon.

In our previous work [9-11], we already studied the growth of AlN thin films on silicon substrates using RF and DC reactive magnetron sputtering method, which are interesting of their microstructural, electrical and physico-chemical properties. In this study, we present our latest results concerning AlN thin films deposited at low temperature on Si(100) substrates, after the optimisation of growth process. We pointed out the correlation between surface roughness of AlN films and the frequency response of SAW devices based on these films. We have investigated the crystalline structure by XRD, the optical properties of AlN films by Fourier transform infrared absorbance spectroscopy (FTIR), and the microstructure by field emission scanning electron microscopy (FESEM) and transmission electron microscopy (TEM). SAW devices are realised based on low deposition temperature AlN films, and we have pointed out the high crystalline quality and piezoelectrical properties of these films.

II. EXPERIMENTAL

AlN thin films were deposited by a RF planar magnetron sputtering system on silicon Si(100) substrates. The Aluminium target (purity 99.99%) diameter was 107 mm and 6.35 mm thick. The distance between the cathode and the substrate holder was 80 mm. The deposition chamber was pumped down to a base pressure of 1.10^{-7} mbar by a turbomolecular pump prior to the introduction of the argon-nitrogen gas mixture for AlN thin film production. The gas discharge mixture was Ar/N_2 and the total pressure was kept constant at 5.10^{-3} mbar. The nitrogen percentage in the Ar/N_2 gas mixture was 60 %. The RF power delivered by the RF generator was 170W. The substrate and the chamber wall were grounded. The substrate holder was maintained without heating and after heated to obtain different deposition temperatures until 400°C. In order to perform a better comparison between the different samples, the deposition time of AlN films was adjusted to obtain 1.4µm tick films for various deposition temperatures. The thickness of deposited films was measured by FESEM from the cross section of structure.

XRD using Cu-kα cathode has been employed to determine the crystalline properties of the AlN thin films. The diffracted intensities were collected in θ-2θ scan and ω rocking curve scan modes. The optical properties of AlN films were evaluated by FTIR. The FTIR spectra were measured over the 400-4000cm^{-1} range with a spectral resolution of 4cm^{-1}. The microstructure were studied by FESEM and TEM in order to determine the dependence of grain size with the film thickness, and the evolution of AlN thin films microstructure in various phases of growth. Eventually, atomic force microscopy measurements, operating in contact mode, were taken to determine the evolution of surface roughness and the surface morphology of AlN films with temperature deposition.

III. RESULTS AND DISCUTIONS

The preferred orientation of AlN thin films elaborated in different deposition temperature was investigated by XRD. Figure 1 shows the XRD patterns of these films deposited on Si(100) substrates. All the peaks were indexed on the basis of the hexagonal wurtzite type structure. We can observe that the preferred orientation of all the films is the (002) orientation corresponding to the c-axis perpendicular to the surface. The XRD peaks intensities are the same for all the films, which indicate that the film synthesised without heating presents the same degree of (002) preferred orientation. However, from the ω rocking curve scan mode, we have founded that the FWHM of rocking curve of all the films is varies from 1.56° to 2.8°, with the minimum value obtained for the film deposited without heating (WH) (1.56°), as shows figure 2. This result attest that the AlN (WH) thin film presents the best (002) preferred crystalline orientation with the lower FWHM rocking curve. This evolution of crystalline orientation quality can be explain by the possibility of formation of defects in the films at high temperature by promoting the diffusion of impurities into the films introducing structural disorder [12].

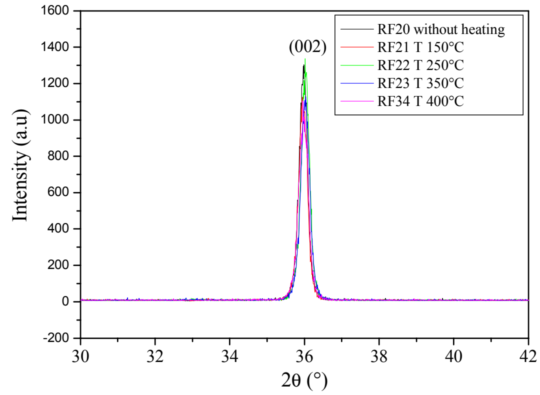


***Fig. 1** : XRD pattern of AlN films deposited at various temperatures*

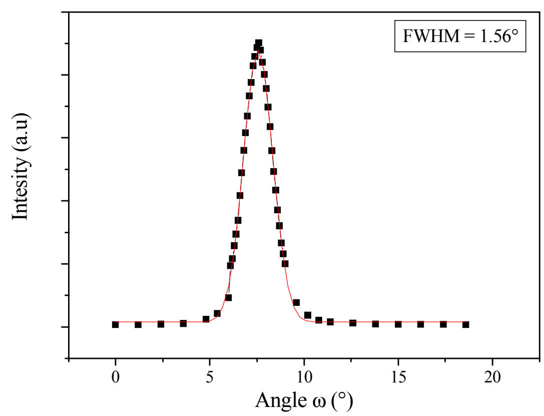


***Fig. 2** : Rocking curve of AlN film elaborated without heating*

Optical characterisation of AlN thin films was carried out to evaluate the phonon modes in the films and a presence of oxygen contamination. As is know, FTIR spectroscopy is valuable tool to study materials structural characteristic and physical properties as the characteristic phonon frequency. Figure 3 shows FTIR reflectance spectra taken from AlN samples. The spectral range shown corresponds to transverse and longitudinal optical phonon energy range. A strong FTIR reflectance peak around 678cm^{-1} was observed in these AlN films, and a very little peak was observed around 613cm^{-1}. The two peaks were attributed to E1(TO) and A1(TO) phonon modes in the films. The E1(TO) mode indicates that the AlN film is oriented c-axis perpendicular to the surface, (002) preferred orientation. This result corroborates the high preferred (002) crystalline orientation of all AlN films. Furthermore, the FTIR analysis allow to deduce that the residual stress in our AlN film is constant for all deposition temperature and it is estimated from the FTIR peak position to –1.5GPa.

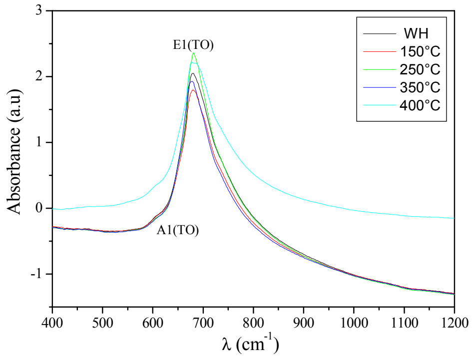


Fig. 3 *: FTIR spectra of AlN films*

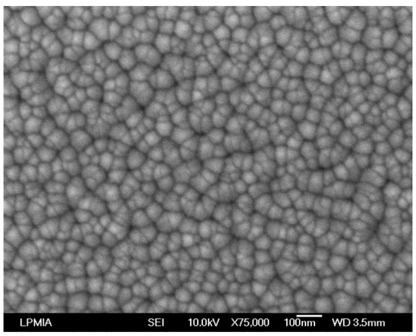
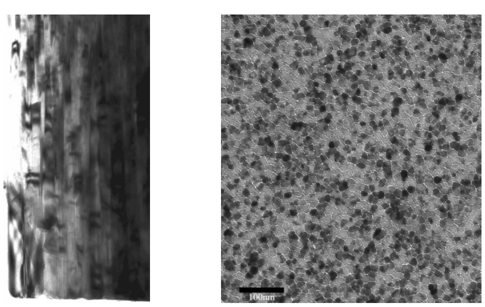


Fig. 4 *: FESEM image of AlN film synthesised (WH)*

FESEM and TEM characterisations were made to analyse AlN film microstructure. As show figure4, we can see, the grain and boundaries of AlN film grown without heating. The average grain size from this image was estimated about 30nm. TEM analysis was done to investigate the cross section of this film. Figure 5-a shows the image of columnar structure of AlN film (WH), and exhibits dense and crack free film. To analyse the microstructure of the first growth phases of AlN film (WH), we have realised a film with very low thickness about 100nm. As show figures 5-b, TEM image presents the plane view of this film and we can distinguish the grain and boundaries and the grain size was evaluated about 20nm. From all these results, we can conclude that the grain size of AlN film increases with thickness. The formation of columnar structure of AlN films was established since the first growth phases.



5-a **5-b**

Fig. 5 *: a. Cross section TEM image, b. Plane view TEM*

AFM measurements enable us to characterise the film morphology evolution with growth experimental conditions. We can use this technique to measure the roughness of AlN thin films. In figure6, we show the surface morphology of films elaborated in various deposition temperatures. As show AFM images, a granular morphology is observed. All images are exhibited in the quasi-same vertical scale to have a clearly observation. From these images, the rms roughness of film synthesised without heating presents the lower roughness measured at 4.54Å than the other films. This evolution can be explained by the fact that the high deposition temperature favourite the swelling of grain columns and consequently the increasing of surface roughness.

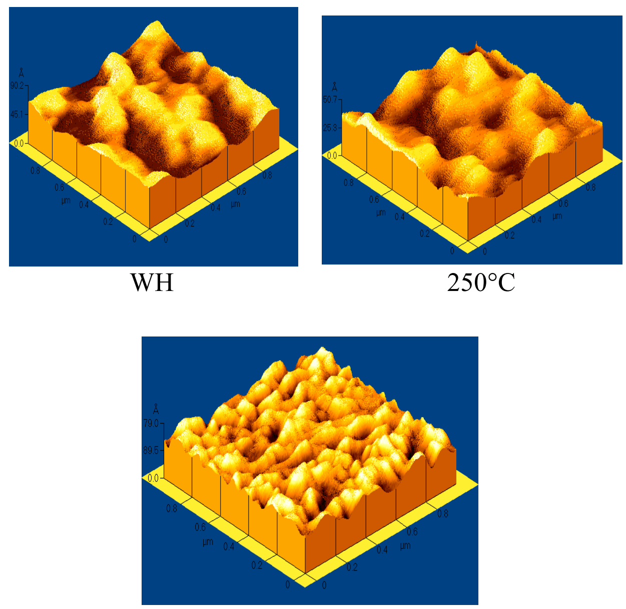


Fig. 6 *: Three-dimensional (1µm*1µm) AFM images of various AlN thin films*

The SAW transducers were fabricated on the AlN film surface by forming an array of aluminium interdigitated electrodes (IDTs). The thickness of the aluminium layer was 150nm. It was deposited, patterned and etched using UV lithography technique and wet etching. The individual finger widths were 8µm and spacings were 4µm to facilitate harmonic generation [13, 14]. The IDTs were developed on AlN/Si layered structure based on AlN films elaborated without heating and at 400°C The wavelength of generated SAW is then 24 µm. Figure 7 shows the frequency responses of the both AlN/Si structure SAW devices realised using these AlN films. The represented responses exhibit the fundamental harmonic of AlN/Si SAW devices, which have a resonance frequency around 211MHz. This frequency corresponds, taking into account the wavelength value of 24µm, to SAW velocity of 5064m/s. This result involves, the good crystalline quality of the both AlN thin films elaborated at without heating and at 400°C. Concerning the characteristics of the frequency responses in term on insertion loss and rejection, we can observe that the SAW device based on AlN(WH) presents a better response characteristics than the SAW device based on AlN film deposited at 400°C.

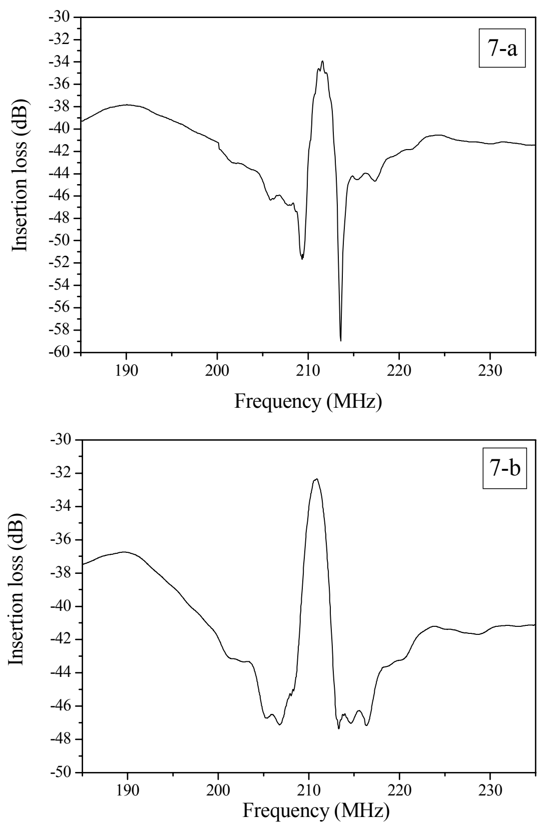


Fig. 7: Frequency responses of AlN/Si structure SAW devices : a)- AlN (400°C). b)- AlN (WH)

The rejection and insertion loss of the AlN (WH) are 14dB and –33.35dB respectively, while those of AlN(400°C) are 10dB and –34dB. These results are in concordance with the results obtained using AFM measurements presented above In fact, the structure realise with AlN film (WH) exhibits a lower roughness which enable to reduce the propagation losses and consequently the improvement of the rejection and the insertion loss of frequency response. This correlation between morphological properties of AlN thin film and the frequency response characteristics is very interesting to predict the SAW devices performances.

To complete this study, we have measured the electromechanical coupling coefficient (K^2) of the two structures AlN/Si based on the films elaborated at 400°C and without heating. The results obtained show a better K^2 value for SAW structure based on AlN (WH) measured of 0.54%, while the coefficient of the structure base on film synthesised at 400°C was measured of 0.34%. These results corroborate the structural analysis, which were showed that the AlN film deposited without heating presents a better (002) preferred orientation than the others films. The theoretical value of K^2 of this structure, taking into account the film thickness is 0.13%. This difference between the experimental and theoretical values remains difficult to explain. The measurement of TCF was also carried out and show a quasi-similar values for the two structures: –26.13ppm/°C and –29ppm/°C for the structures base on films elaborated at 400°C and without heating respectively.

IV. CONCLUSION

AlN films were grown by RF reactive magnetron sputtering on Si(100) substrate at different deposition temperature. We have pointed out the effect of the deposition temperature on structural, morphological and acoustical properties of AlN films. We have showed that we can obtain a high oriented (002) AlN films with a low FWHM rocking curve for the films elaborated without heating. The low surface roughness AlN film can also obtained without heating and allow to have very low acoustic losses which involve the achievement of high SAW devices performances. These results offer the great possibility for integrated circuit (IC) compatible SAW devices. These physical characterisations were corroborated by forming AlN/Si SAW devices based on AlN film synthesised without heating, which exhibited a practical frequency characteristics better than those obtained for the AlN film deposited at high temperature.

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