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Growth and characterization of *c*-axis inclined AlN films for shear wave devices

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Abstract
This paper reports on the growth and the characterization of *c*-axis inclined AlN thin films synthesized at low temperature. These films are of significant interest for shear wave generation in the shear mode resonators that operate as a liquid sensor. AlN films were deposited on 3 inch (1 0 0) silicon wafers using an RF-magnetron sputtering planar system. A SiO_2 buffer layer was used to promote the *c*-axis inclination. This *c*-axis inclination of AlN thin films was investigated using scanning electronic microscopy and x-ray diffraction in $\theta/2\theta$, χ and rocking curve scan modes. These analyses showed up to 10° of *c*-axis inclination in our planar charging system at low temperature. An AlN film thickness variation of about ±5% was recorded. In this study, we only presented the effect of the pressure on the *c*-axis inclination of AlN films. A discussion about the effect of this parameter and the role of the SiO_2 buffer layer is reported. A shear mode acoustic wave device based on the deposited *c*-axis inclined AlN film was constructed and showed a phase velocity of 5832 m s^{-1}. This value of shear velocity is discussed.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Piezoelectric AlN thin films are of continued interest for exciting the acoustic waves for surface acoustic wave (SAW) and bulk acoustic wave (BAW) devices [1–3]. Many growth methods, such as MO-CVD [4] and magnetron sputtering [5–8], have been used for the deposition of these films in order to generate specific modes of surface or bulk waves. Most of these techniques induce films exhibiting a strong tendency to grow with their *c*-axis perpendicular to the film plane. The purpose of this study was to obtain AlN thin films with the inclined *c*-axis suitable for shear wave excitation by using a planar deposition system. Reactive sputtering is commonly used for the deposition of thin films since it is compatible with the planar technology in addition to being a low temperature technique that provides a relatively good thickness uniformity [9]. The low temperature deposition of inclined *c*-axis AlN films is very important in regard to device processing. *c*-axis inclined AlN films allow the realization of surface acoustic wave resonators and film bulk acoustic resonators (FBAR) based on shear excitation for liquid sensor applications. Indeed, according to the transversal polarization of shear modes, they are more sensitive in liquid media than those which are longitudinal. Shear acoustic waves do not produce any compressional motion in the liquid and, hence, no energy leakage [10]. To generate shear waves, the *c*-axis inclination must be between 5° and 30° [11]. In this paper, we report the growth and characterization of *c*-axis inclined AlN films on silicon substrates using a SiO_2 buffer layer, deposited in a planar sputtering system with no additional hardware modifications and without tilting the substrate. The advantage of this system is that we may achieve, for the same principal experimental parameters affecting the rate (power, distance target substrate), a better growth rate than with other methods. However, these other methods, based on adding hardware modifications to the system or deposition on tilted

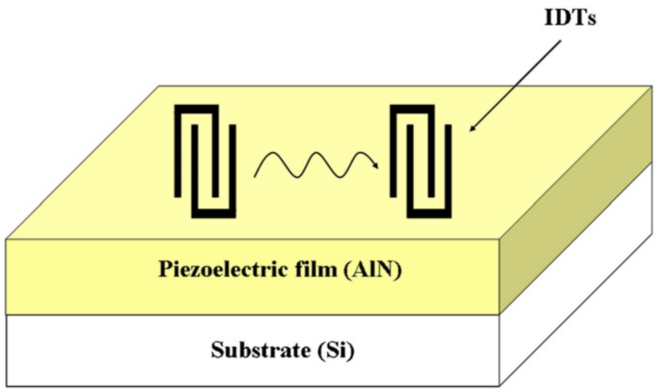


Figure 1. Diagram of a layered structure SAW device.

substrates, may achieve a higher AlN column inclination. In the case of hardware modifications to the deposition system, if we have a selective blind between the target and the substrate to block certain vertically impinging particles, we can assume that the growth rate will be decreased. In our case, the thickness uniformity will be determined on the 3 inch substrate, which will determine the limitation of our growth process. The effect of the SiO_2 buffer layer and of the sputtering pressure on the AlN *c*-axis inclination is presented and discussed. The particularity of this study is that, because of using AlN films for shear mode SAW devices, a metallic film such as platinum or aluminium cannot be used to promote the crystalline quality, which can be done with BAW devices [11–13]. Placing a metallic layer under the AlN layer increases its resistivity, and consequently, we can generate a leakage current between the two neighbouring fingers of the interdigital transducers (IDTs) (figure 1). On the other hand, using the SiO_2 amorphous buffer layer decreases the crystalline quality of our films, but this layer is necessary in our process to enhance the *c*-axis inclination.

2. Experimental procedure

AlN thin films were reactively deposited on a silicon wafer from a 99.99% pure aluminium 4 inch target and a 99.999% pure nitrogen and argon gas mixture with a conventional RF-magnetron sputtering method. The aluminium and silicon targets were positioned in parallel and in front of the wafers. The base pressure in the chamber and its diameter were respectively 2×10^{-7} mbar and 45 cm. The heater temperature was kept at 200 °C, the nitrogen concentration in Ar/N_2 gas mixture was 70% and the pressure was fixed to 4×10^{-3} mbar, 6×10^{-3} mbar, 8×10^{-3} mbar, 1×10^{-2} mbar and 2×10^{-2} mbar. The RF power applied to the cathode was fixed at 200 W and the deposition time was 1 h. The distance between the target and the substrate was 8 cm. The AlN films were deposited on an amorphous SiO_2 layer, which was already deposited on the (1 0 0) silicon substrate. The SiO_2 layer was synthesized using a sputtering technique. The experimental parameters for the SiO_2 deposition, which we had optimized, were kept at 100 W of RF power, 6×10^{-3} mbar of pressure and $Ar{:}O_2/1{:}1$. The growth was done without heating. The SiO_2 thickness obtained in all the samples was fixed at 100 nm. The role of this amorphous layer was to induce a random orientation on the surface of the substrate. In this case, the flux anisotropy primarily determined the inclination of the columnar AlN films. In contrast, in our first experiments without the SiO_2 buffer layer, no significant *c*-axis inclination was observed.

In our deposition system, the sputtering of AlN films was performed with a 4 inch target on a 3 inch wafer. The determination of the thickness uniformity on the 3 inch substrate was carried out by the thickness measurement using SEM observations. Actually, after the AlN film deposition, the wafer split into different pieces (1.5×1.5 cm^2), and the film thickness was measured by cross-sectional analysis.

X-ray diffraction using Cu Kα radiation was used to determine the crystalline properties of the AlN thin films in terms of preferred orientation and *c*-axis inclination. We used $\theta/2\theta$, χ and rocking curve (RC) scan measurements for this purpose. To avoid any ambiguity, for the RC measurements, the radial direction of the wafer was set parallel to the diffraction plane, and for the χ measurements, the radial direction of the wafer was set perpendicular to the diffraction plane. The position of the peak in the RC curve gives information about the orientation distribution of this plane. It indicates how much the measured plane is off the surface normal.

Finally, to investigate the shear mode generation in the resulting deposited films, a shear mode device based on SAW technology was employed, using conventional optical lithography. The principle of a SAW device is based on the launching and detection of elastic waves on piezoelectric materials using IDTs. The operating frequency of this device is $f = V/\lambda$, where V is the phase velocity and λ is the wavelength which is equal to the period of the IDTs (figure 1). The purpose of using this device is to generate shear waves in the AlN films obtained. The coupling coefficient of the shear mode increases with the *c*-axis inclination up to about 40°, as reported by Martin *et al* [11].

3. Results and discussion

3.1. AlN growth

The growth rate of our AlN films was about 550 nm h^{-1} in the centre of the wafer (part 1) and 520 nm h^{-1} on its edge (part 2) (figure 2, inset). The control of the film thickness made using SEM has shown a non-uniformity of ±5%. The area of part 1 was estimated to have a diameter of about 2 cm and part 2 was the rest of the wafer.

The obtained growth rate was lower than the rate obtained by Bjuström *et al* [14]. They reported a growth rate of 2.5 μm h^{-1}, but for a 900 W power discharge, 6 inch target diameter and a distance target substrate of 5.5 cm. Concerning other growth rates obtained for film deposition on a tilted substrate or with a blind for the AlN layer, Link *et al* [15] obtained a growth rate of 245 nm h^{-1} for *c*-axis inclined ZnO films.

Concerning the AlN growth mechanism, in regard to the distance of 8 cm between the target and the substrate, the angle

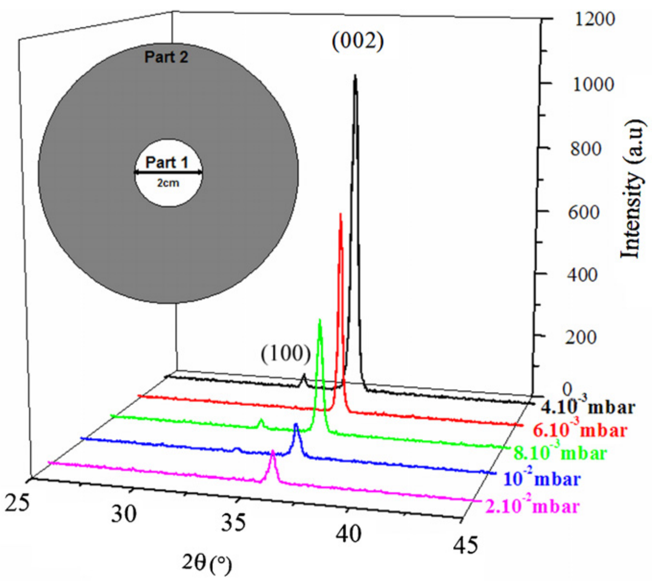


Figure 2. ($\theta/2\theta$) spectra of AlN thin films deposited at different pressures (part 2). The inset exhibits thickness mapping of the wafer.

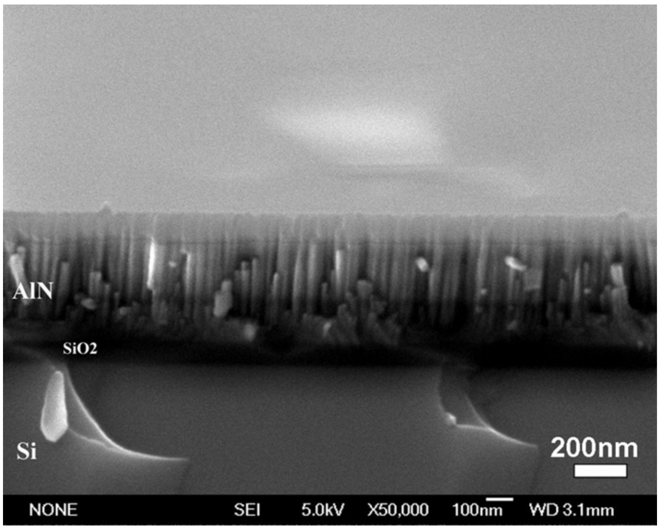


Figure 3. Cross-section SEM image of the centre part of the wafer in which no inclination is observed.

between the normal to the surface and the incidence to the edge of the wafer is about 25.46°. Then, we can expect that in the centre of the wafer we can have vertical columns and at the edge, they are inclined. In fact, as shown in figure 3, we have obtained vertical columns in part 1 of the wafer. Concerning the rest of the wafer (part 2), inclined columns were obtained, as we will demonstrate in the next section. On the other hand, one can observe that the change in the orientation of the AlN columns on the wafer corresponds to the change in the AlN growth rate. In the next section, the results presented will concern only part 2 of the wafer.

3.2. Results and discussion

The morphological characterizations of AlN films synthesized at different sputtering pressures were done using SEM analysis. Figure 4 shows four cross-section SEM images for samples synthesized at 4×10^{-3} mbar, 6×10^{-3} mbar, 8×10^{-3} mbar and 10^{-2} mbar. AlN columns inclined from the normal to the surface were clearly observed. The average column width is estimated at about 20 nm. The estimated columns' inclination from SEM images varies from 8° for the sample synthesized at a pressure of 4×10^{-3} mbar, to 12.5° for the sample synthesized at a pressure of 8×10^{-3} mbar. The evolution of columns' inclination follows the inclination of *c*-axis. The effect of the deposition pressure on columns' inclination is due to the shadowing effect which is predominant at high pressure. In fact, the shadowing effect is due to the high pressure deposition conditions that lead the angular spreading of the incident depositing particles.

X-ray diffraction in the $\theta/2\theta$ scan mode was carried out on synthesized AlN samples at various sputtering pressures. The morphological and structural analyses were done on the entire wafer. In figure 2, XRD patterns show the [0 0 2] preferred orientations of the deposited AlN thin films of part 2 deposited at different sputtering pressures. Peaks corresponding to the [1 0 0] orientation are observed. To be clearer, we analysed absolutely all the pieces with a size of 1.5×1.5 cm^2 of the wafer using XRD measurements. In part 1, we obtain a pure [0 0 2] preferred orientation (not shown here). Concerning the rest of the wafer, part 2, as shown in figure 2, a significant increase in (0 0 2) peak intensity is recorded as the sputtering pressure decreases. This observation can be interpreted by an increase in the energy of the plasma species due to an increase in the mean free path at low pressure. Consequently, the particles bombard the surface of the layer, inducing an increase of adatom mobility, thus obtaining the (0 0 2) orientation with the *c*-axis perpendicular to the surface. On the other hand, for the AlN sample deposited at lower pressure, a slight shift down towards 2θ in the XRD spectrum is observed. This shift of 0.26° can be attributed to the higher compressive stress in this film than in the others synthesized at higher pressures. This stress is due to the particles bombarding the surface of the film [16].

From these characterizations found using XRD ($\theta/2\theta$) and SEM, we can deduce the inclination of columns from SEM and the inclination of the *c*-axis from XRD. Actually, the inclination of the *c*-axis of AlN films is different from the inclination of the columns [5, 12]. Löbl *et al* [12] proposed a growth mechanism to explain the difference between the column inclination and the *c*-axis inclination. They report that, in the case of inclined columns, the (0 0 2) planes are not perpendicular to them. In fact, there are two cases. The first one is that of the small angle of the flowing direction of the impinging source material. In this case, the (0 0 2) planes are almost always perpendicular to the normal to the surface, and the column inclination is due to the shadowing effect. The second is the case of the large angle of the flowing direction of the impinging source material. Here, the (0 0 2) planes are slightly out of the surface plane with an angle very inferior to the angle of tilted columns. Chen *et al* [5] suggest a second growth mechanism, which mentions that the (0 0 2) planes always grow in a direction perpendicular to the substrate in order to minimize the surface energy, and that the inclined columns are a result of the shadowing effect.

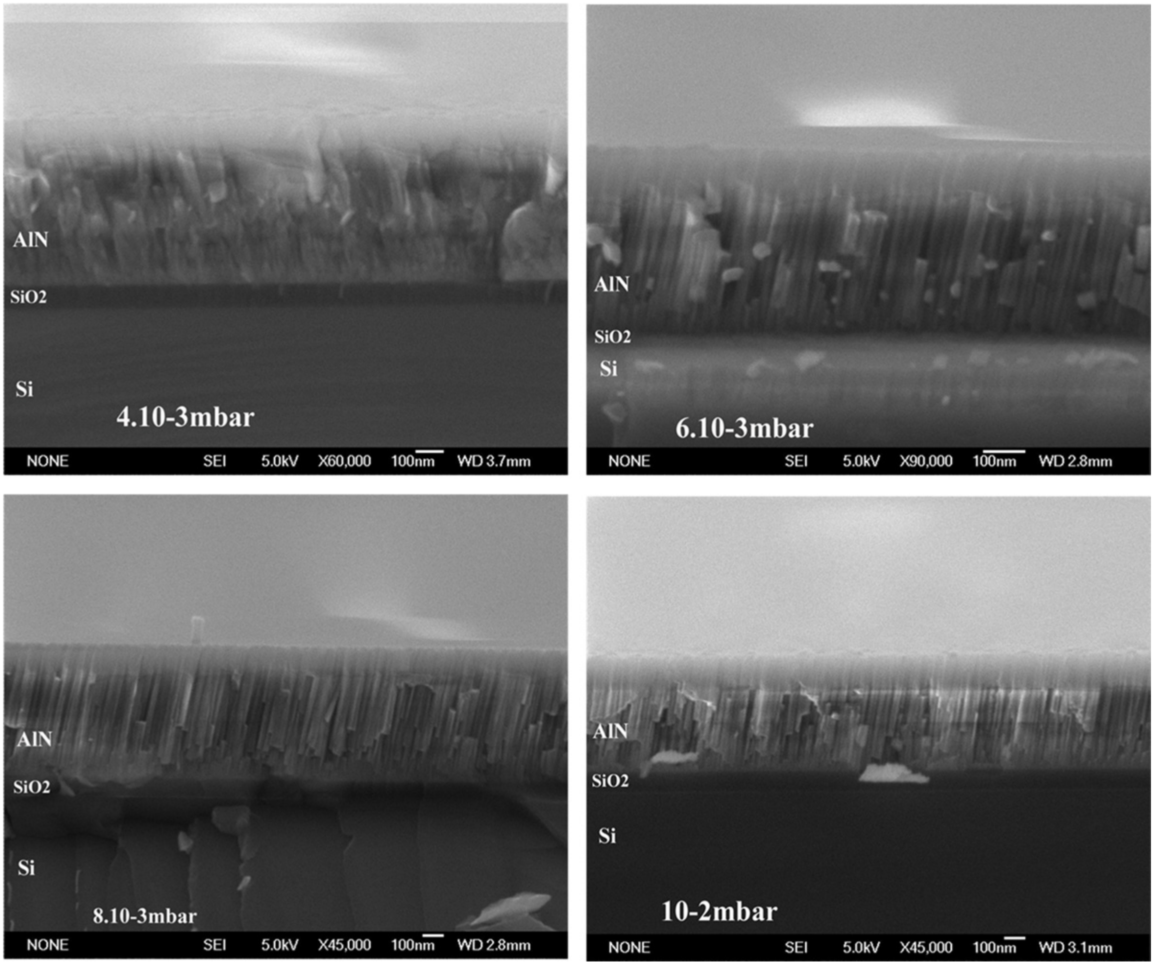


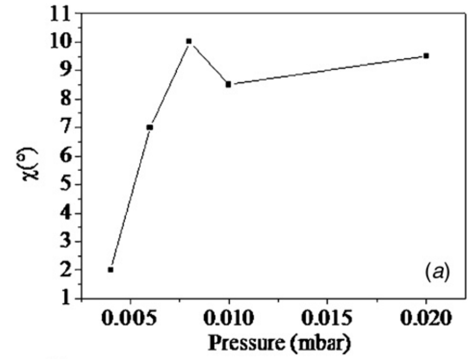
Figure 4. Cross-sectional SEM images of the AlN films synthesized at different pressures (part 2).

Therefore, with our AlN films, we proceeded on to XRD measurements in the χ scan mode in order to determine the *c*-axis inclination and then to estimate the shear coupling coefficient of our AlN thin films.

Figure 5(*a*) exhibits the evolution of the measured inclination as a function of sputtering pressure and figure 5(*b*) shows a typical χ scan achieved on an AlN film synthesized at 8×10^{-3} mbar. An increase in the *c*-axis inclination with pressure is observed. Actually, at a low pressure, the deposited films show grains staying quasi-vertical to the film (inclination of 0° to 2°). This observation confirms the fact that the $\theta/2\theta$ XRD spectrum of the AlN film synthesized at 4×10^{-3} mbar exhibits a high [0 0 2] orientation as shown in figure 2. The transformation from quasi-vertical to tilted growth (inclination up to 10° of *c*-axis) could be induced by decreasing adatom mobility due to the moderate temperature (200 °C in our case) and by the shadowing effect due to higher pressure [15, 17]. The low adatom mobility prevents the adatom jumping at the surface inducing atomic rearrangement which gives a *c*-axis perpendicular to the surface. On the other hand, obtaining a *c*-axis inclination only in part 2 of the wafer is due to the oblique incidence of the impinging flux of the particles. In fact, oblique incidence is due to the cosine distribution of the sputtered particles, which also explains the fact that no *c*-axis inclination was obtained in the centre of the wafer. So, the atoms arriving at the substrate with oblique incidence are more apt to induce tilted columns. This effect is promoted by the surface roughness of the SiO_2 buffer layer leading to different orientations with some oriented towards the inclined flux of the particles. This means that the columns aligned with the inclined net flux direction grow faster than the others (competitive growth regime). The induction of the *c*-axis inclination is facilitated by the SiO_2 buffer layer. Then the impinging particles are deposited on the micro-tilted surface due to the amorphous nature of the SiO_2 layer.

In this study, we have pointed out the effects of two parameters: the first one is pressure. This parameter influences the angle of impinging particles and their kinetic energy which affects the [0 0 2] orientation of the films. The second parameter is the oblique incidence of the impinging flux of the particles, which affects the morphology of AlN films due to the shadowing effect, giving column inclination. The *c*-axis inclination of our films is facilitated by the SiO_2 buffer layer which has an important role in the growth mechanism.

The uniformity of the *c*-axis AlN film in part 2 of the wafer was investigated. We observed a transition region (corona) in part 2 evaluated at a width of 0.5 cm. This transition region presents a non-uniform *c*-axis inclination. Figure 6 graphs the evolution of the *c*-axis inclination of the AlN sample synthesized at 8×10^{-3} mbar as a function of the distance



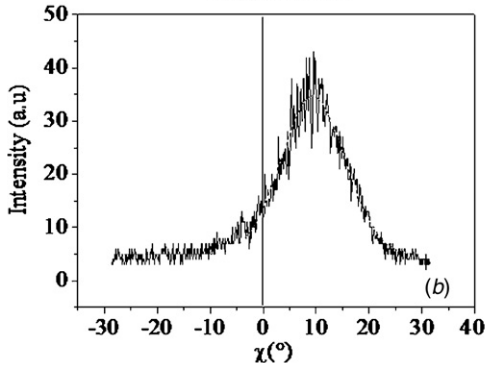


Figure 5. (*a*) The evolution of the *c*-axis inclination with the pressure. (*b*) Typical χ scan mode measurement showing an inclination of about 10° of the *c*-axis.

from the centre of the wafer up to the edge. This transitional region presents an inclination varying between 2° and 7° ± 1°. That is why we consider, in this study, that only 74% of the wafer demonstrates a uniform *c*-axis inclination of up to 10° ± 1°.

To investigate the angular spread of the *c*-axis, a RC measurement was done. Figure 7 shows the measurements resulting from the AlN film produced at 8×10^{-3} mbar, exhibiting a 10° *c*-axis inclination. The fitted Gaussian peak gives the FWHM of 5.5° of the RC. The RC indicates that the *c*-axes of various crystallites are not perfectly parallel, but instead spread symmetrically around 5.5°. One can also observe that the peak intensity corresponds to the ω angle of 28.4°, which means that the *c*-axis is inclined by about 10°. This result confirms the *c*-axis inclination value obtained using χ scan.

The maximum *c*-axis inclination which we obtained is 10°. Consequently, the shear coupling coefficient is estimated, taking into account the results of Martin *et al* [11], to be about $K^2_{\text{eff}} = 0.8\%$.

To clearly demonstrate the generation of shear waves in the obtained *c*-axis AlN film, we implemented a SAW device based on the 10° inclined AlN/SiO_2/Si. The IDTs were constructed by a conventional lithography technique. The period of IDTs was made in aluminium, which corresponds to the wavelength being equal to 12 μm. Figure 8 shows the frequency response obtained, which clearly exhibits shear mode generation. Actually, the identification of shear mode is related to its velocity. The obtained frequency was about 486 MHz. Taking into account the value of the wavelength, the phase velocity is 5832 m s^{-1} which is inferior to the velocity of shear mode in AlN film (6319 m s^{-1}) obtained for the AlN/sapphire layered structure by Xu *et al* [18]. The difference between these two is that, for our structure, the SiO_2 buffer layer and the silicon substrate had a lower phase velocity than the sapphire substrate. So, the obtained velocity reproduces this effect. To point out clearly the generation of shear waves in our structure, we have made another device

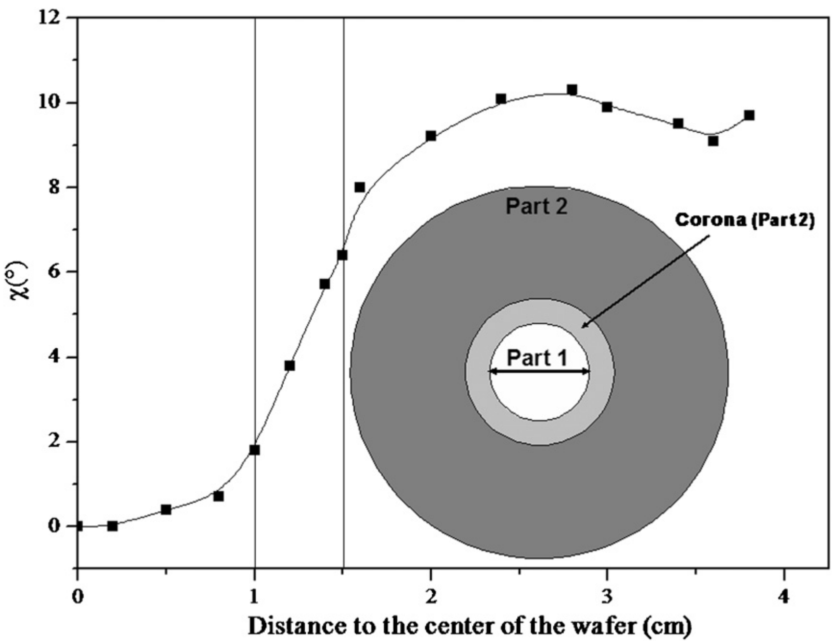


Figure 6. The evolution of the *c*-axis inclination as a function of the distance from the centre of the wafer up to the edge for the sample deposited at 8×10^{-3} mbar. The inset shows the *c*-axis inclination mapping of the wafer.

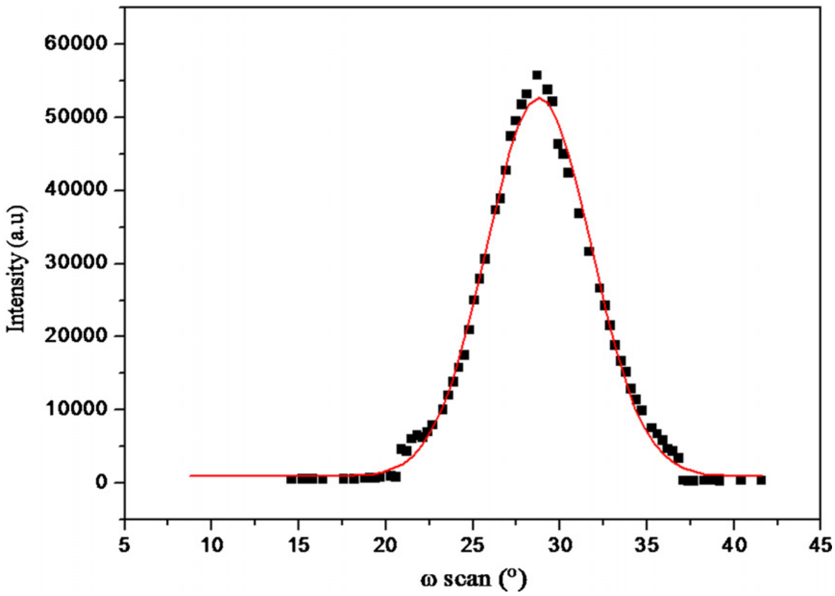


Figure 7. Rocking curve on the [0 0 2] orientation of the *c*-axis inclined AlN thin film deposited at 8×10^{-3} mbar and located in part 2 of the wafer.

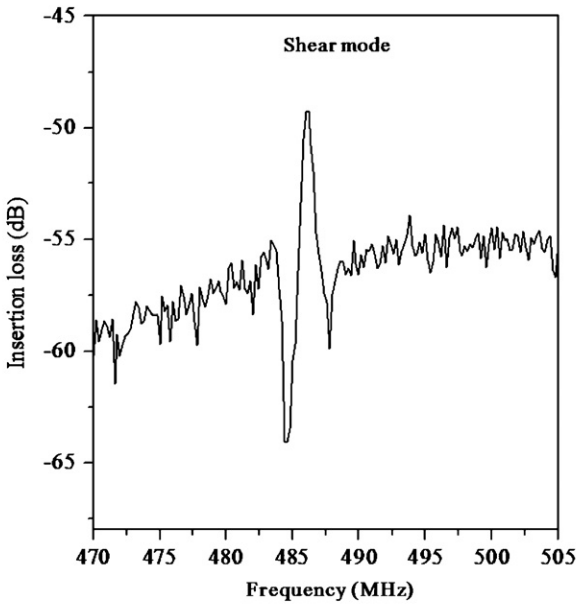


Figure 8. Frequency response of the shear mode SAW device realized on 10° inclined *c*-axis $AlN/SiO_2/Si$.

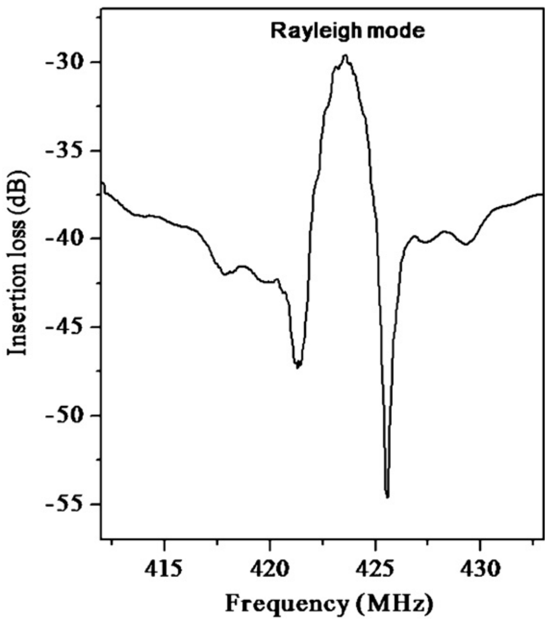


Figure 9. Frequency response of the SAW device based on the AlN film (0° inclination) from part 1 of the wafer.

based on an AlN film from part 1 of the wafer. Figure 9 shows the frequency response of the SAW device based on the perpendicular AlN *c*-axis. The frequency response exhibits an operating frequency of 423.56 MHz. This frequency corresponds, taking into account that the wavelength is equal to 12 μm, to the Rayleigh wave velocity of 5082.72 m s^{-1}, which is slower than the shear wave velocity launched in the AlN film from part 2 of the wafer.

The electrical characteristics, in terms of rejection and insertion loss of the obtained frequency response, can be improved by increasing the *c*-axis inclination and by optimizing the design of the IDTs.

4. Conclusion

The aim of this study was to carry out the deposition of *c*-axis inclined AlN thin films by magnetron sputtering at low temperature in a planar system with no hardware modification and with no inclination of the substrate. We have shown that we can obtain a *c*-axis inclined AlN thin film on about 74% of the wafer. The *c*-axis inclination was found to be constant ±1° and maximal, with an inclination of up to 10° for the given deposition conditions. The structural and morphological characterizations indicated the columnar aspect of the deposited AlN films and the *c*-axis inclination was revealed by XRD measurements. We have shown that the formation of *c*-axis inclined films depends on the sputtering pressure and the oblique incidence of particle flux. The growth mechanism was discussed. We have also presented the excitation of shear mode in the inclined *c*-axis of the deposited AlN film by making a shear mode device. Further optimization is needed to increase the *c*-axis inclination so as to increase the shear mode coupling.

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