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Influence of seed layer on crystallinity and orientation of pulsed – DC sputtered AlN thin-films for piezoelectric actuators

A. T. Tran* [a], H. Schellevis [a], H. T. M. Pham [a], C. Shen [a], P. M. Sarro [a]

[a] *Laboratory of Electronic Components, Technology & Materials (ECTM), DIMES, Delft University of Technology, Delft, The Netherlands*

Abstract

Aluminum Nitride thin films with the desired properties for piezoelectric actuators are grown by pulsed DC sputtering on Si (100) substrates coated with different seed layers (Al/1%Si, Mo, Ti). The influence of sputtering parameters and the seed layers on crystallinity and orientation of the AlN films is investigated. Raman spectroscopy measurements are performed and the results are analyzed to identify the optimal deposition conditions. The high-c axis orientation of AlN thin films obtained with Ti as a seed layer was confirmed by X ray diffraction. It appears that seed layers of 200nm Ti are a valid alternative to Molybdenum or Platinum for IC compatible piezoelectric actuators fabrication.

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Keywords: AlN, (002) orientation; bottom electrode; Raman spectroscopy

1. Introduction

Recently, Aluminum Nitride (AlN) has attracted considerable attention because of its specific physical properties like good chemical stability, large thermal conductivity, and high hardness. In addition, due to its compatibility with IC technology, AlN piezoelectric thin-films are a promising material for the fabrication of actuator [1], sensors [2], microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS) [1, 3].

To build piezoactuators such as the one schematically shown in Fig.1, a thin film of AlN is deposited on a metal electrode that acts as seed layer. Generally, molybdenum or platinum is used as a seed layer. However, to maintain compatibility with IC processing, as often required, an alternative metal as seed layer is needed. This layer should of course preserve the piezoelectricity of the AlN, i.e. do not negatively effect the (002) crystal orientation. In this paper we introduce titanium as a promising material for the bottom electrode of AlN piezoelectric actuators.

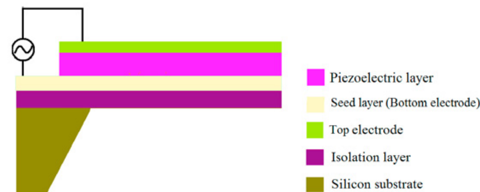

Fig. 1. Schematic cross-section of a piezoelectric actuator based on piezoelectric thin films.

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Raman spectroscopy is used to investigate the crystallinity and orientation of the AlN films deposited by sputtering on different seed layers. Finally, SEM and XRD were used to confirm the optimal sputtering conditions.

2. Experimental Procedures

Thin films (500 nm) of AlN were deposited by pulsed DC sputtering technique (Aviza Sigma 204 DC magnetron PVD system). High-purity Ar and N_2 gases with flow rates of 15 sccm and 41 sccm respectively were let in the sputtering chamber to form a sputtering pressure of 2.3 mm Torr. A sputtering power with frequency of 250 kHz and the duration pulse of 1616ns was tuned from 1kW to 2.5 kW. Various types of substrates were used. Silicon wafers with (100) orientation were used as starting material. A 300-nm low-stress SiN_x dielectric layer was deposited by Low Pressure Chemical Vapor deposition (LPCVD) as dielectric followed by a 200 nm metal layer (including Al (1%Si), Ti, Mo and Ti) as a seed layer. The metal layers were prepared by sputtering as well, using Ar gas at low temperature (around 50 ^oC). To determine the optimal sputtering conditions for AlN films with the required properties, deposition on bare (100) silicon substrates was initially done. The sputtering power (in the range of 1-2.5 kW) and the substrate temperatures (50 ^oC, 300 ^oC and 400 ^oC) were varied until the good crystallity and (002) preferred orientation was observed. Then, several seed layers around 200 nm in thickness were tested.

Table 1. Process parameters for the AlN thin film deposition.

Target	Pure Al
Substrate	Si (100)
Dielectric layer	Low-stress SiN_x
Seed layer	Al (Si 1%), Mo, Ti
Substrate Temperature	50 ^oC, 300, 400 ^oC
Pulsed DC Power	1-2.5 kW
Nitrogen Fraction	73 %
Sputtering Pressure	2.3 mmTorr

To detect the crystal structure and orientation of the AlN films, Raman spectroscopy was performed using a Renisshaw Raman microscope with Argon 514.5 nm laser excitation. Furthermore, X-Ray diffraction measurement (Philips X'Pert SR5056 with Cu-Kα radiation) was used to confirm the high-c axis orientation of the AlN thin films.

3. Results and discussions

Figure 2 and figure 3 exhibit the Raman spectroscopy of AlN films prepared by tuning sputtering power, substrate temperature and employing different seed layers. All samples display the major peak around 655 cm^{-1} and a minor peak at approximately 610 cm^{-1} corresponding to the E_2 (high) mode and the A_1 (TO) mode, respectively. Generally, Lorentzian functions (green line in all graphs) were used to fit the data for determination of the peak

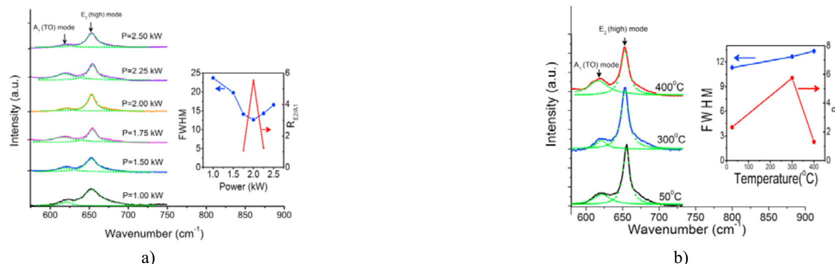

Fig. 2. Raman spectra of AlN thin-films deposited on bare (100) Si (a) at various sputtering powers and (b) with different substrate temperature

Fig. 3. Raman spectra of AlN thin-films deposited (a) on different seed layers and (b) on Ti at room temperature and 300 °C.

positions, FWHM and ratio of integrated area of the E_2 (high) peak and the A_1 (TO) peak ($R_{E2/A1}$) as shown in the insets of Figs. 2 and 3.

It is well known that the crystallinity of AlN films can be detected by the FWHM of the rocking curve of the E_2 (high) mode that is related to interfaces, small grains, point defects [4]. Kuball et al. reported a value of 3 cm^{-1} for extremely high quality AlN bulk crystals [5] and a value of 50cm^{-1} was reported by Perlin et al. [6] for fully deteriorated crystals. In addition, the existence and intensity of Raman modes relate to the direction of light propagation in materials. For AlN crystals, the electric field of light can be separated in two components, parallel and perpendicular to the c-axis, which excite the E_2 (high) and the A_1 (TO) mode, respectively [7]. As a result, the reduction of the A_1 (TO) mode peak indicates that films with higher c-axis orientation are obtained. Conversely, the increasing of the A_1 (TO) mode in the films indicates that other orientations are present in the grains. Consequently, the higher value of integrated area of the E_2 (high) peak and the A_1 (TO) peak ratio ($R_{E2/A1}$) is relative to the higher (002) orientation of the AlN and vice-versa [7].

Fig. 2a shows Raman spectroscopy of AlN deposited at six power steps from 1kW to 2.5 kW while the substrate temperature was kept at 300 °C. Obviously, increasing sputtering power from 1kW to 2kW leads to reduction of the FWHM value of the E_2 high mode from 23.7 to 12.6 meaning that a higher AlN thin films crystallinity was gained by using higher power. However, further increase of the power (over 2kW to 2.5kW) causes a rising of FWHM value indicating a poorer crystalline quality. In general, sputtering gas strongly attacks the substrate at high sputtering power resulting in deterioration of the film crystals [8]. Furthermore, integrated area of the E_2 (high) peak and the A_1 (TO) peak ratio ($R_{E2/A1}$) of AlN with power around 2kW were calculated and plotted in Fig. 2 (in the small graph). The results indicate that 2kW sputtering power is the best value to obtain good crystallinity and high (002) orientation.

The dependence of AlN thin film quality on substrate temperature was afterward investigated keeping the sputtering power at 2kW. Raman measurement of AlN films grown on bare Si (100) at three substrate temperatures (50 °C, 300 °C, and 400 °C) are shown in Fig. 2b. These results examined by FWHM and $R_{E2/A1}$ presented that AlN films deposited at 300 °C gain better c-axis orientation in comparison with AlN films prepared at 50 °C and 400 °C. On the other hand, the crystallinity of films was slightly improved by lowering the growth temperature.

Finally, several metals were selected to investigate the effect of seed layer on the AlN quality. Mo that has been

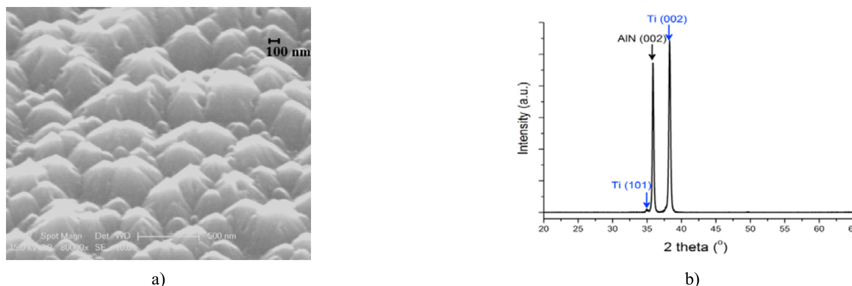

Fig. 4. SEM picture (a) of AlN surface exposed by short etching in MF–322 developer and XRD pattern (b) of AlN thin film prepared at 300 °C on Ti.

widely employed as a bottom electrode of AlN devices due to its lattice match and low resistivity is used as "reference" while Al and Ti were chosen to evaluate their potential as an IC compatible alternative to Mo. Fig. 3a shows the Raman spectra of AlN thin films deposited at low temperature (50 ^oC) using 2 kW sputtering power on different seed layers. It can be seen that deposition on both Mo and Ti resulted in good crystalline structure. On the other hand, AlN thin films prepared on Al seed layers have less crystal quality but they have good c-axis orientation. Bare (100) Si substrate exhibited an intermediate value in comparison with the metal layers.

In another experiment, AlN thin films were deposited at 300 ^oC with 2 kW sputtering power on Ti seed layer. The stacks containing Al layers are not suitable for this kind of investigation due to cracks and hillock formation in the Al layer at high temperature, previously observed [8, 9]. Fig. 3b indicates that the c-axis orientation is remarkably enhanced and the quality of the film crystallinity is stable. Further evidence of the high quality of the AlN thin films on Ti seed layer was provided by scanning electron microscopy (SEM) (Fig. 4a) and XRD pattern measurement (Fig. 4b). The SEM image shows the AlN surface after a short etching in MF–322 developer. The very large grains, good cristallinity and strong c-axis orientation are observed by the SEM image and the XRD pattern in which only (002) peak of AlN diffraction beside two peaks of Ti appear. Additionally, the FWHM of (002) peak of the XRD pattern is extremely narrow with a value of 0.2, again an indication of high crystalline AlN thin-films.

4. Conclusions

From this study it is clear that the crystallinity of AlN layers deposited by pulsed DC sputtering can be controlled by tuning the sputtering power, while the temperature deposition and the type of seed layer have a strong effect on the orientation of the films. Although Mo was confirmed to be a good seed layer for the (002) preferred orientation of AlN thin films, we obtained comparable results when using Ti as seed layer. As this material is much more frequently used in conventional IC processes, it offers a valid alternative to Mo, and favour the integration of piezoelectric actuators devices in CMOS processes and thus their applicability in microsystems.

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