AC reactive sputtering of highly c-axis oriented AlN films for electro-acoustic devices

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Biography

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Abstract

An ac reactive sputtering process by a dual cathode S-Gun magnetron was developed to produce highly c-axis oriented AlN piezoelectric films for electro acoustic devices on silicon wafers and on wafers covered with metal under-layers. XRD measurements have shown that FWHM of AlN (002) diffraction peak has a direct correlation with FWHM of Mo under-layer (110) diffraction peak. AlN films having FWHM < 2° may be obtained only on well-textured Mo electrodes with FWHM below 3°. A dc sputtering process by S-Gun deposition, in combination with pre-deposition rf plasma etch and thin Ti or AlN seed layer deposition, enabled formation of these well-textured Mo electrodes. AlN film orientation is shown to improve with increasing film thickness, due to development of more thorough columnar structure in the thicker films. FWHM improved from 2.5° to 0.9° for 100 nm and 3000 nm thick films, respectively. Technological aspects of stress control in AlN and Mo films are discussed in the paper as well.

Data

I. Introduction

Reactive sputtering technology of aluminum nitride (AlN) films having hexagonal structure with a strong (002) crystal orientation has a significant potential for practical use in different electronic applications, such as transducers and filters in surface acoustic wave (SAW) devices, in microwave bulk acoustic wave (BAW) and film bulk acoustic (FBAR) resonators [1], and in other AlN-based micro-electromechanical systems (MEMS).

In this paper, ac reactive sputtering processes for AlN piezoelectric films and dc sputtering processes for Mo electrode films are described in detail; technology advantages in regard to film crystal orientation and stress control are also presented and discussed.

II. S-Gun magnetron

Currently, one prevalent structure for electro-acoustic devices consists of a piezoelectric film sandwiched between two metal electrodes, fabricated either as a Solidly Mounted Resonator, or as a membrane resonator.

In this research, AlN piezoelectric films and Mo electrodes were deposited in the Endeavor-AT PVD cluster tool (Tegal Corporation, USA) equipped with S-Gun magnetrons [2]. The S-Gun has two independently controlled conical targets mounted concentrically, with a bias-able central anode. The three internal shields-electrodes may also serve as passive anodes for better control of the plasma configuration in the magnetron. In the dc powered S-Gun, power re-distribution between inner and outer targets enables deposition of highly uniform metal films onto stationary substrates. Due to its dual target arrangement, the ac powered S-Gun is uniquely able to realize reactive sputtering processes free of parasitic arcing and disappearing anode effects. Operating in bipolar mode, the two targets act alternatively as anode and cathode of the magnetron discharge and no separate dedicated anode is needed (Fig. 1).

In the experiments reported here, the AlN and Mo films were deposited at ambient temperature without external heating. Typical AlN ac reactive sputtering processes achieved deposition rate of 60 nm/min at a cathode power of 5.5 kW, and typical Mo dc sputtering processes had deposition rate of 400 nm/min at a cathode power of 6 kW.

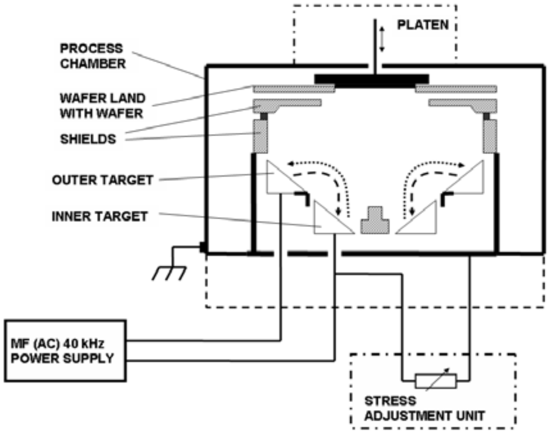


Figure 1. Schematic diagram of the process module with S-Gun magnetron for ac reactive sputtering.

III. AlN crystal orientation

One of the most important requirements for piezoelectric AlN films in electro-acoustic devices is a strong c-axis crystal orientation. Achieving this orientation result depends on the sputter apparatus design, deposition process parameters, and on substrate properties such as surface roughness and, especially, crystal orientation.

AlN films deposited on polished Si (100) wafers in the S-Gun sputtering module demonstrate strong orientation in a wide range of the film thickness (Fig. 2).

Full-width at half-maximum (FWHM) of AlN (002) diffraction peak diminished from 2.5° to 0.9° when film thickness increased from 100 nm to 3000 nm due to development of more thorough columnar texture in the AlN film (Fig. 3).

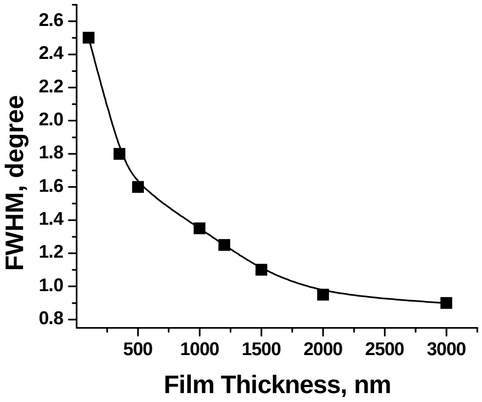


Figure 2. Full-width at half-maximum (FWHM) of the AlN (002) diffraction peak vs. film thickness.

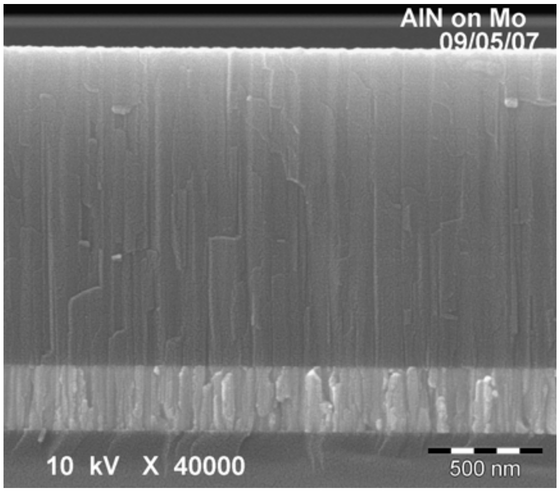


Figure 3. Cross-sectional SEM image of well c-axis oriented AlN film on Mo electrode deposited onto thermal oxidized Si wafer with AlN seed layer. Film thickness: AlN seed layer 15 nm; Mo 300 nm, AlN 1390 nm.

When an AlN film is deposited on a Mo electrode, strong (110) in-plane orientation is required in Mo to get the same well-oriented AlN as grown on Si substrate. Our research has shown that FWHM of the AlN film directly correlates with FWHM of the Mo under-layer (Fig. 4). Highly c-axis oriented AlN films with FWHM < 2° may be obtained on Mo electrodes if FWHM of the Mo is below 3°. SEM cross-sectional micrograph shown in Fig. 3 allows conjecturing an epitaxial growth of the columnar grains of the AlN film on the top of the columnar Mo grains. This 1390 nm thick AlN film demonstrated FWHM = 1.32° on 300 nm thick Mo electrode with FWHM = 2.08° (Fig. 5).

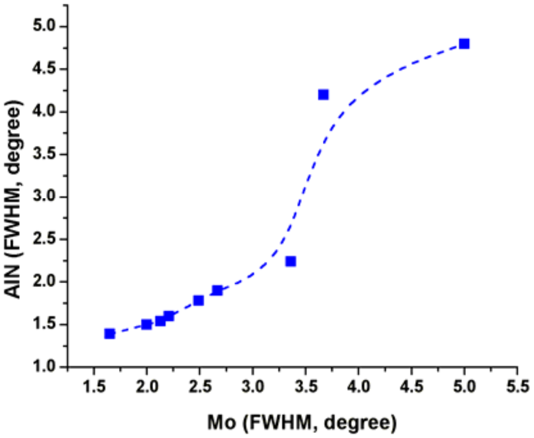


Figure 4. Crystal orientation (FWHM) of 1300 nm thick AlN films vs. crystal orientation (FWHM) of 300 nm thick Mo films.

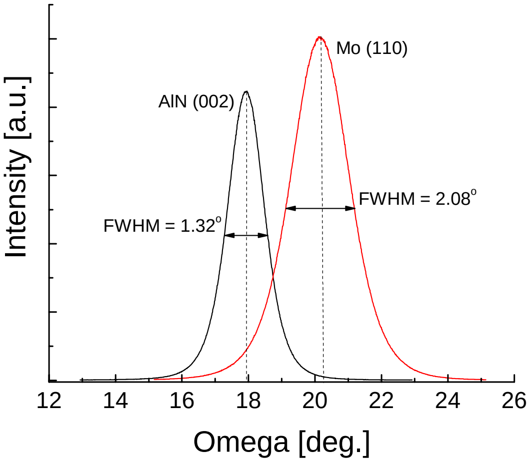


Figure 5. X-ray rocking curves of 1390 nm thick AlN film and 300 nm thick Mo under-layer deposited onto thermal oxidized Si wafer.

IV. Mo film texture

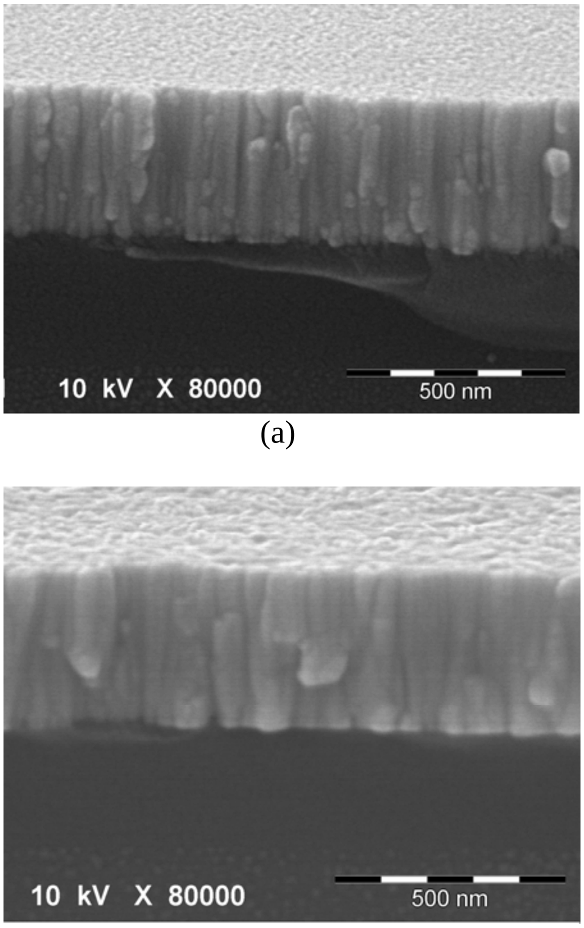
According to data reported by Lee, Lee and Yoon [3], the degree of c-axis texturing of AlN films reactively sputtered at low temperature is closely related to the surface roughness of the under-laying Mo film. Our results confirmed that nucleation surface conditions control grain orientation, but they indicated also that a strong texture in the under-layer is especially important for growing highly-textured AlN films.

We found that FWHM of Mo films depends significantly on substrate properties. It is relatively easy to get textured Mo with strong (110) orientation on crystalline Si wafers, but it is more complicated to get the same result on amorphous SiO_2 surfaces. Since many electro-acoustic devices have silicon dioxide or diamond-like layers under the bottom metal electrode, successful sputter technology should also enable deposition of well-textured metal electrodes on such substrates.

One of the most effective approaches to create well-oriented metal electrode for electro-acoustic devices is based on the application of so-called “seed layers” [4]. Very thin (10 – 30 nm) films such as Ti or AlN can modify the surface morphology of the substrate, thus stimulating oriented Mo grain growth starting from the beginning of the deposition process.

We deposited 300 nm thick Mo films on thermal oxidized silicon wafers with and without 150 nm thick AlN seed layer using exactly the same sputter recipe in these experiments. Both films had columnar structure (Fig. 6) and close values of surface roughness (Rms was 0.6 nm without seed layer and 0.5 nm with seed layer), but essentially different crystal orientations. The Mo film deposited with a seed layer showed FWHM = 2°, while the rocking curve from the second film (no seed layer) indicated no orientation at all. 1300 nm thick AlN films deposited onto those two samples had considerably different crystal orientations with FWHM = 1.3° and 10°, respectively.

We have found that the introduction of a seed layer worked significantly better if the wafer was etched in an Ar plasma rf discharge right before seed layer deposition.



(a)

(b)

Figure 6. Cross-sectional SEM micrographs of 300 nm thick Mo films on thermal oxidized silicon wafers: (a) film with strong (110) crystal orientation (FWHM = 2.2°) deposited over 15 nm thick AlN seed layer; (b) non-oriented film deposited without seed layer.

In order to achieve better device performance (for example, higher Q- factor), it is necessary to provide in-situ plasma etch of the bottom Mo electrode after its patterning, right before the piezoelectric layer deposition. It is also useful to etch the AlN piezoelectric layer to improve its surface smoothness before deposition of the top electrode.

V. Stress control in AlN and Mo films

Low intrinsic stress is another important requirement for the thin film stacks employed in electro-acoustic devices, especially devices having the membrane type of architecture. Stress in reactively sputtered AlN films is well-controlled by varying Ar gas pressure during AlN deposition. Fig. 7 shows that compressive stress is reduced, and may even be converted to tensile stress, with increasing Ar pressure in the S-Gun from 1E-3 to 5E-3 Torr. The disadvantage of this stress control method is due to the fact that the AlN deposition rate and film thickness uniformity depend on gas pressure too. This is why the S-Gun for AlN reactive sputtering is equipped with a special stress adjustment unit (Fig. 1) ensuring relatively independent stress control by means of re-distribution of discharge current from the inner target between the outer target and the passive anodes of the magnetron.

Tensile stress in Mo films may be effectively reduced by ion bombardment, i.e. deposition with bias. In the S-Gun, negative potential on the substrate is induced by applying rf power, 30 – 300 W, onto the wafer land. Unfortunately, further experiments demonstrated that the higher the rf bias (and thus lower stress in the Mo film), the worse the crystal orientation of the film (Fig. 8).

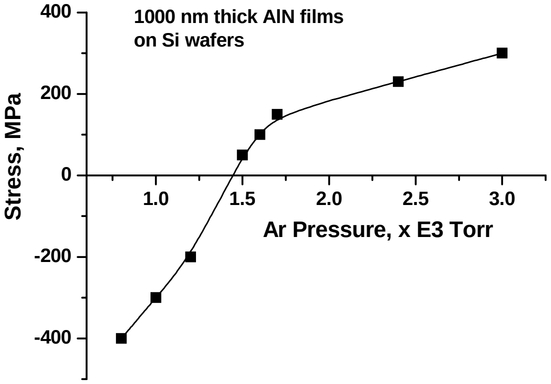


Figure 7. Stress in reactively sputtered 1000 nm thick AlN films vs. Ar gas pressure in the S-Gun.

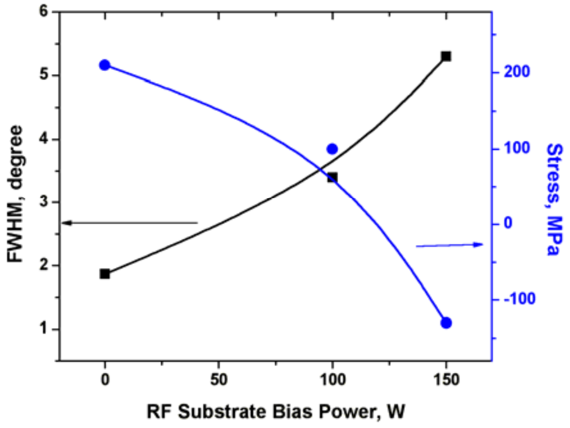
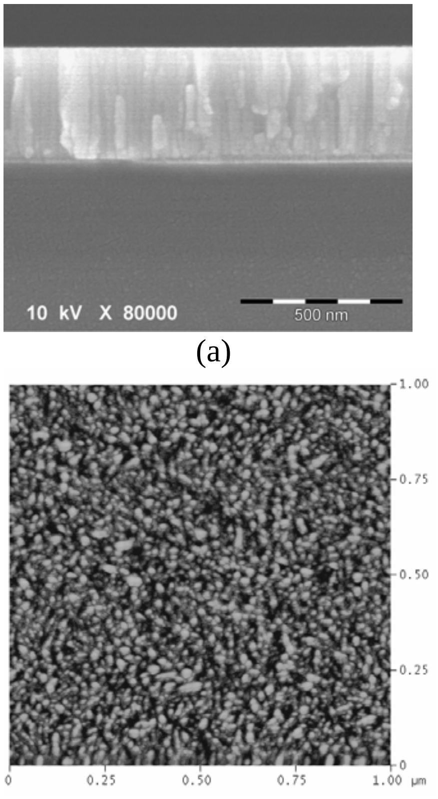


Figure 8. Crystal orientation (FWHM) and intrinsic stress in 300 nm thick Mo films deposited by dc powered S-Gun with substrate rf bias onto thermal oxidized Si wafers pre-covered with Ti seed layer.

To avoid this problem, we have developed a two-step Mo deposition process ensuring formation of superior crystal orientation as well as near zero or, if required, compressive stress in the Mo film. The Mo electrode deposited by this technology exhibits strong (110) texture with FWHM < 2° and has a columnar grain structure and pebble-like surface morphology with roughness Rms = 0.5 nm (Fig. 9).



(a)

(b)

Figure 9. SEM (a) and AFM (b) micrographs of 300 nm thick Mo films deposited on thermal oxidized silicon wafer by two-step process (with 15 nm thick AlN seed layer).

Conclusion

In this project, an ac reactive sputtering process by a dual cathode S-Gun magnetron was developed to produce highly c-axis oriented 100 – 3000 nm thick AlN piezoelectric films for electro-acoustic devices on thermal oxidized silicon wafers, and on wafers covered with metal under-layers. The following results were obtained:

- XRD measurements have shown that FWHM of AlN (002) diffraction peak has direct correlation with FWHM of Mo under-layer (110) diffraction peak. AlN films having FWHM < 2° may be obtained only on well-textured Mo electrodes with FWHM below 3°.
- It was established that dc sputtering processes by the S-Gun module, in combination with a pre-deposition rf plasma etch and thin Ti or AlN seed layer deposition, enabled formation of these well-textured Mo electrodes.
- Orientation of AlN films is enhanced with increasing film thickness due to development of more thorough columnar structure in the thicker films. FWHM improved from 2.5° to 0.9° for 100 nm and 3000 nm thick films, respectively.
- Results obtained on rf plasma etches of the substrate and Mo electrode before AlN deposition confirmed data published elsewhere that low surface roughness of the under-laying material is an important factor ensuring better AlN texturing.
- Tensile stress in Mo films may be effectively reduced by deposition with rf substrate bias, but it was found that rf biasing leads to worse crystal orientation in the Mo film. A two-step Mo deposition process was developed to overcome this issue.

References

[1] M. Ueda, T. Nishihara, J. Tsutsumi, S. Taniguchi, T. Yokoyama, S. Inoue, T. Miyashita, and Y. Satoh, IEEE MTT-S International Microwave Symposium, TU3D-1 (2005).
[2] V. Felmetsger, P. Laptev, Vacuum, 78; 403 – 408 (2004).
[3] S.H. Lee, J.K. Lee, and K.H. Yoon, J. Vac. Sci. Technol., A21 (1), 1 – 5 (2003).
[4] H.C. Lee, J.Y. Park, K.H. Lee, and J.U. Bu, J. Vac. Sci. Technol., B22 (3), 1127 – 1133 (2004).

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