Magnetron Deposition of AlN and ScAlN for Mass-production for BAW Devices and MEMS

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Abstract— Bulk acoustic wave (usually referred to as BAW, FBAR and SMR) filter devices used in cell phones have used piezoelectric AlN for almost two decades.

In the last few years new MEMS devices such as piezoelectric MEMS oscillators (also known as pMEMS), sensors and microphones started using AlN in high volume products.

While it is no longer a great challenge to make limited numbers of wafers employing reactively sputtered piezoelectric AlN films suitable for BAW applications, there are several barriers to making them in a high volume.

Tight control of crystallinity, thickness and thickness uniformity, deposition rate, coupling coefficient and stress through target lifetimes and across wafer are major barriers to high volume production. Independent control of AlN thickness and stress uniformity across wafer is critical for FBAR devices that require high coupling coefficient with tight distribution.

Novel tool innovations have been successfully implemented to address these issues. Data from production tests show that *in-situ* laser interferometry thickness monitoring significantly reduces wafer-to-wafer thickness variations due target rate roll-off.

Use of a unique local enhancement of the magnetron magnetic field and substrate rotation mechanism to compensate for non-radial uniformity profiles eliminates changes induced by variations in target material as well as system asymmetry.

In-situ ion beam milling dramatically improves thickness uniformity.

ScAlN deposition is used in applications requiring much higher coupling coefficient than AlN can produce. Although, similar to AlN deposition, ScAlN process requires much more care to produce uniform films with good surface roughness and no surface defects sometimes called "crystallites". Significant modifications to magnetic fields and ion mill trimming are used to create high concentration ScAlN films usable in filter and MEMS applications.

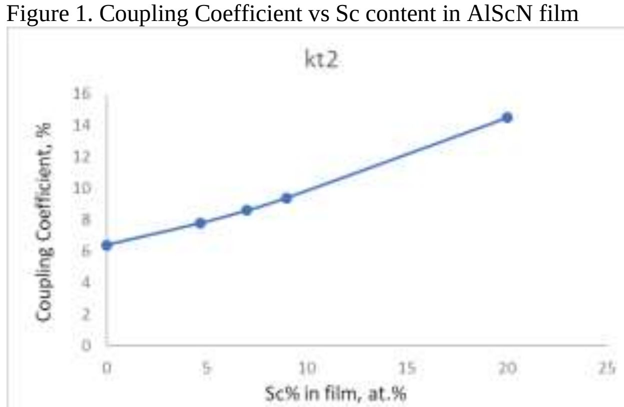
Keywords—Scandium; Aluminum Scandium Nitride; AlN; aluminum nitride; crystallinity; stress

I. INTRODUCTION

In the past, either AC dual magnetron, (pulsed) DC or RF single magnetron sputtering were used to deposit AlN films with acceptable piezoelectric response. The addition of Sc to form AlScN increases coupling coefficient as shown in Figure 1 below.

The effect of sputter gas composition and substrate temperature is widely published [1,2,3]. The distance between cathodes and substrate during deposition was also reported to be important to the quality of the AlScN [4].

Figure 1. Coupling Coefficient vs Sc content in AlScN film

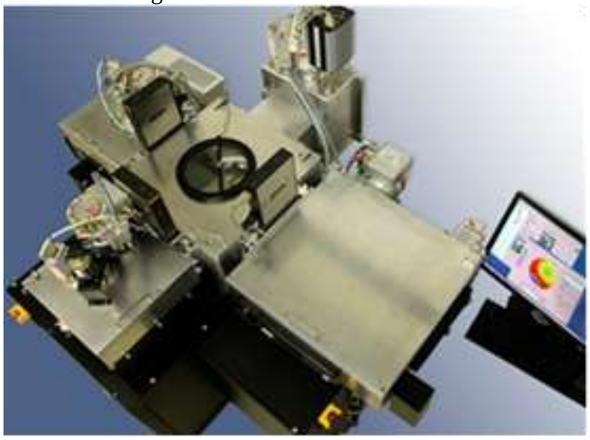


We have found that using AC plasma with two magnetrons, we only need to control Sc composition on each target and the angle of the sputtering surface vs. substrate to get the best quality films. Even though many different configurations can produce acceptable films on a few wafers, it is very difficult to produce films with uniform Sc concentration, coupling coefficient and stress across wafer over the entire target life. With increasing Sc concentration, these problems get worse. Crystallite formation, non-uniform XRD across wafer, Surface roughness, large Sc concentration variation across wafer and over the target life, stress variation across wafer and thickness variation across wafer and over the target life are the most common problems.

II. EQUIPMENT

In this work, we used Advanced Modular Systems cluster tool with AlN, AlScN and Mo deposition chambers, and ion beam trimming module (shown in Figure 2). Both AlN and AlScN depositions use a dual magnetron with AC power applied between targets. Frequency of AC power is 40 kHz and power may vary from 3 to 7 kW. High purity 99.9999% argon and nitrogen process gasses we used for all depositions. The gas flow mixture had between 0% and 40% of argon. No wafer heating was used in this system.

Figure 2. AMS Cluster tool with AlN, AlScN deposition and Ion Beam Trimming Modules



We used two targets made out of aluminum bases and Sc pieces to adjust film composition.

The trimming module uses DC focused ion source with argon process gas to improve thickness/uniformity of either AlN or AlScN films. Film thickness trimming/tuning is processing based on ion beam scanning across a wafer with power variation based on film thickness map. Use of the trimming process opens up a much wider process window for stress and Sc concentration control because it allows avoiding of spending too much effort on controlling thickness uniformity during deposition.

Simple resonators with three layer's Bragg reflector were manufactured during investigation for piezoelectric coupling coefficient measurements.

III. COMPOSITION CONTROL

Above mentioned configuration provides good crystallinity, stress and thickness across a substrate thru whole target life, see figures 3 and 4 below.

Figure 3. XRD data: Omega across a substrate and 2Theta at the beginning and end of target life

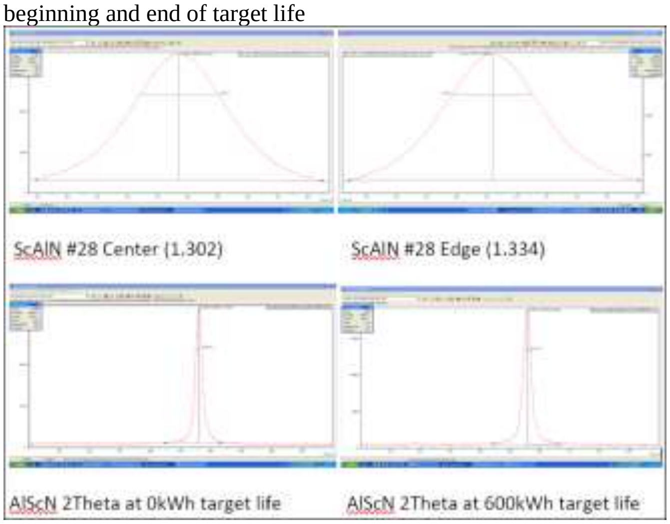
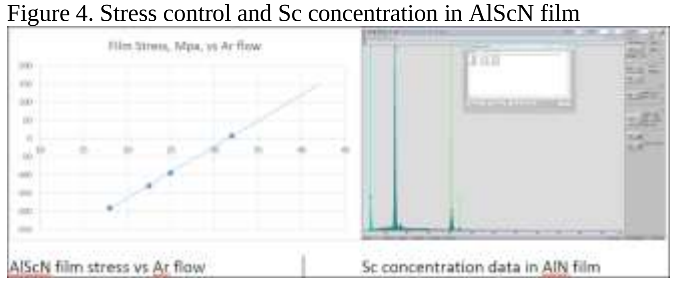


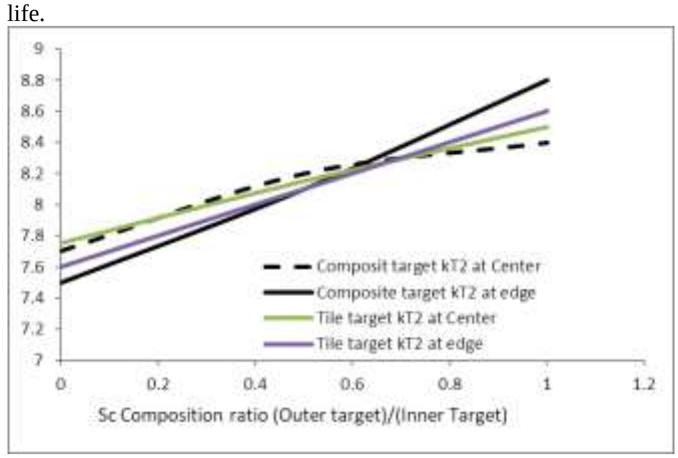
Figure 4. Stress control and Sc concentration in AlScN film



Since coupling coefficient is very sensitive to Sc composition in AlN film, in this work we focus on Sc concentration in AlN film across a substrate and thru target life.

For dual target configuration, concentration of Sc across wafer can be easy controlled by adjusting concentration of Sc on the inner and outer targets, since most material from inner target is deposited on the wafer center and most material from outer target is deposited on the edge of a wafer, until the concentration across a wafer is uniform [5]. Multi-piece targets produced results that are very similar to the composite targets with the same concentration of Sc. Figure 5 shows a comparison of kt^2 between composite targets and multipiece targets.

Figure 5. Coupling coefficient across wafer as a function of scandium concentration in two targets in the beginning of the target life.



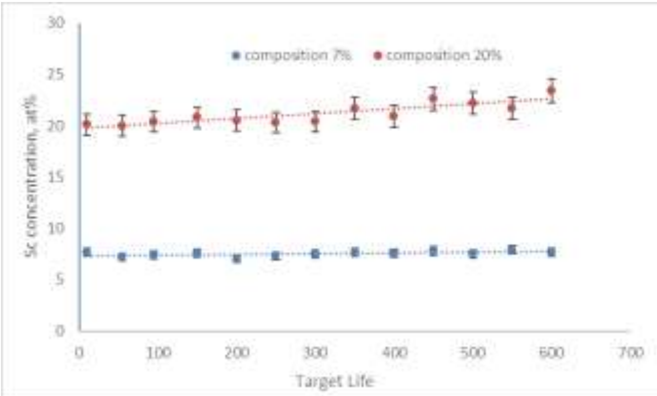
Rotating wafer during deposition assures the same Sc concentration at the same distance from the center of the wafer.

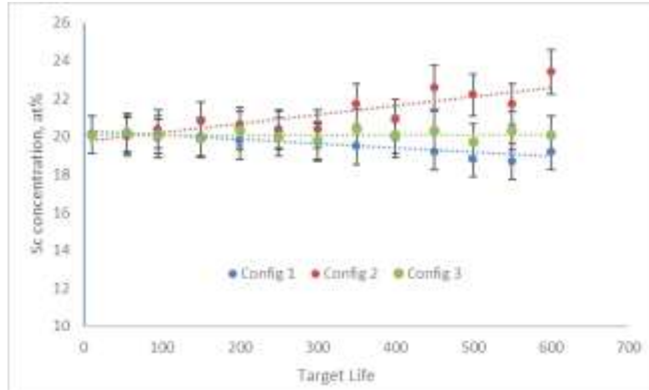
But in order to have production worthy system, it must deliver the same Sc concentration over the entire target life.

Unfortunately, the same design that gives the best AlN deposition is not adequate for the AlScN deposition.

One of the problem is accuracy and repeatability of measurement tools. We picked composition of the inner and outer targets to give us uniform Sc concentration across wafer. We ran 7% and 20% Sc depositions for the entire target life. Results are shown in the Figure 6 below.

Figure 6. Sc concentration in film for 7% and 20% configuration during target life in standard AlN configuration





As can be seen, at lower Sc concentration, because of the noise in the concentration measurement, which can be as high as 10% of measurement value, it is not obvious that the concentration increases over the target life, but at 20%Sc it is clear that concentration rises over the target life.

Second problem is scattering of ad-atoms during sputtering process. Al and Sc ad-atoms have different scattering angles under identical electric and magnetic fields due to difference in mass. Depending on the angle of the target surface vs. substrate surface, different amount of Sc and aluminum will arrive at different locations on a wafer.

Over the target life, erosion pattern of target, called “racetrack”, produces different angles from which material is sputtered. By adjusting magnetic field, we were able to keep the angle of material coming from the target and the area of the racetrack balanced in such a way as to keep Sc concentration uniform and consistent over the target life. The maximum concentration of Sc on the wafer comes from the surface that is parallel to the wafer. The minimum amount comes from the area that is almost perpendicular to the wafer. Figure 7 below demonstrates different concentrations of scandium over the target life from different magnetic field configurations. By adjustment of magnetic field and target profile we were able to control the same Sc concentration during target life.

Figure 7 Impact of magnetic field and target racetrack for Sc concentration over target life.

IV. SUMMARY

We demonstrated production worthy AlScN deposition system. Thickness and thickness uniformity over the target life are maintained using in-situ laser interferometer, wafer rotation and thickness trimming using ion beam module.

Average stress and stress distribution across a substrate are controlled by process gas flow and secondary magnetic field.

Sc concentration across wafer over the entire target life is maintained by using two independent magnetrons with multi-pieces (pure Al and pure Sc) targets and magnetic fields oriented in such a way as to compensate with the slope of the target material and magnetic field keeping area of the “racetrack” in balance to get stable Sc concentration.

REFERENCES

[1] Morito Akiyama, “Influence of temperature and scandium concentration on piezoelectic response of scandium aluminum nitride alloy thin films”, Applied Physics Letters, Oct. 2009, Vol.95, Iss. 16, pp. 2107- 2107-3

[2] Pau Muralt, et. al., “Electromechanical properties of AlScN thin films evaluated at 2.5 GJz film bulk acoustic resonators”, Applied Physics Letters 99, 2011

[3] Keiichi Umeda1, et. al., “PIEZOELECTRIC PROPERTIES OF ScAlN THIN FILMS FOR PIEZO-MEMS DEVICES”, MEMS 2013, Taipei, Taiwan, January 20 – 24, 2013

[4] Simon Fichtner, et. al., “Identifying and overcoming the interface originating c-axis instability in highly Sc enhanced AlN for piezoelectric microelectromechanical systems”, J. Appl. Phys. 122, 035301 (2017)

[5] Sergey Mishin, et. al., “Production worthy system for piezoelectric multimaterial depositions”, 2014 IEEE Frequency Control Symposium

[6] Sergey Mishin, “Improving Manufacturability of Bulk Acoustic Wave and Surface Acoustic Wave Devices”, IEEE SPAWDA