Optimizing high concentration Scandium Aluminum Nitride films

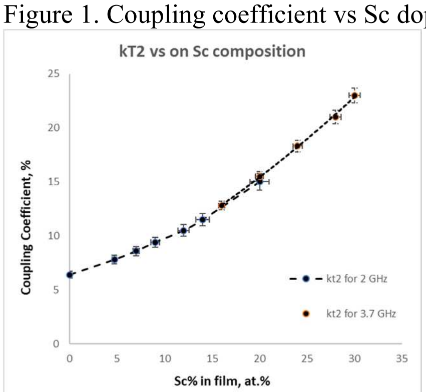
Sergey Mishin
Advanced Modular Systems, Inc.
Goleta, CA USA
smishin@amssb.com

Yury Oshmyansky
Advanced Modular Systems, Inc.
Goleta, CA USA
yoshmyansky@amssb.com

I. Introduction

Adding Scandium (Sc) to the aluminum nitride (AlN) is widely used to significantly increase coupling coefficient in Piezo-MEMS devices [1], [2], [3] and [4]. Figure 1 shows relationship between Coupling coefficient and Sc content in AlN film.

Figure 1. Coupling coefficient vs Sc dopant in AlN film



Optimizing process to keep coupling coefficient high and uniform across wafer without having sporadic “crystallites” is a major challenge, see Figure 2 the AlScN surface with “crystallites”.

Figure 2. SEM of AlSc(30)N film with “crystallite” formation.

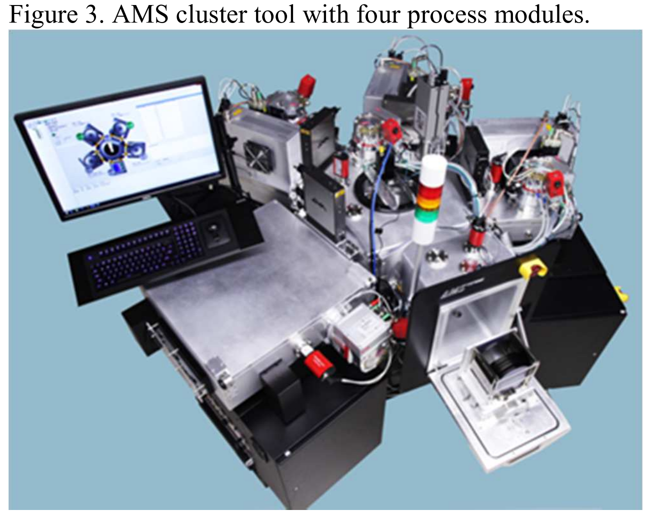
We have identified critical parameters that make manufacturing of greater than 30%Sc films possible.

II. Methods/Results

In this investigation we used Advanced Modular Systems cluster tool with AlN, Mo and AlScN deposition chambers and ion beam trimming module, see Figure 3.

The deposition chambers use standard dual conical magnetron with AC/DC configuration for piezoelectric deposition and DC/DC configuration for Mo deposition, as well as high-density plasma configuration for all processes. Frequency of AC power is 40 kHz and power may vary from 3 to 9 kW. Wafer rotation was used to compensate edge to edge non-uniformity. Additional DC power supply was using for center to edge thickness uniformity improvement. Al target bases with inserted Sc pieces were used to adjust AlScN film composition.

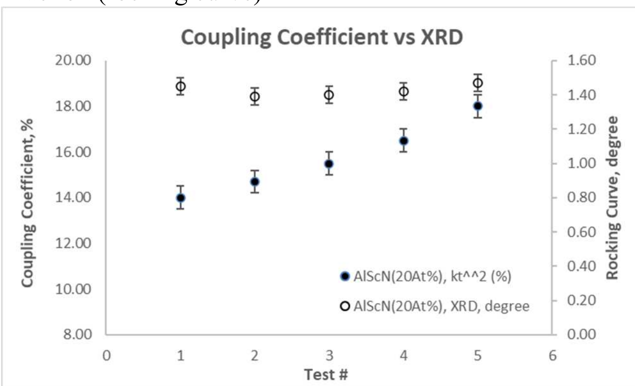
Figure 3. AMS cluster tool with four process modules.



The trimming module uses DC focused ion source with up to 5kV acceleration voltage. This module was used for substrate surface clean up before deposition, as well as for improvement of surface roughness of the AlN barrier layer deposited before AlScN deposition.

We investigated thickness and stress AlN barrier impact on the AlSc(30%)N deposition, as well as some deposition parameters for AlScN deposition itself

Figure 4. Variations of Coupling Coefficient and XR Diffraction (rocking curve)



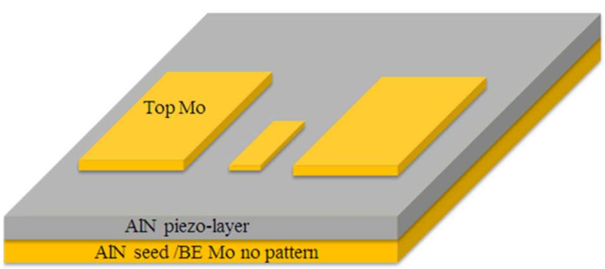
Since rocking curve doesn't always follow the coupling coefficient, see figure 4, and in order to investigate most important process parameters, simple HBAR devices were manufactured to measure kT2.

HBAR devices for 3,200 MHz frequency, with 1700A of electrode thickness and 6000A of AlSc(30%)N piezo thickness were manufactured.

We use two ground pads and one signal pad. The ground pads are 430um x 430um. The signal pad is 98um x 167um and the pitch for the structure is 43um. We use 350um pitch probes though. The manufactured HBAR is shown on Figure 5.

Actual data for HBARs and FBAR resonators were confirmed.

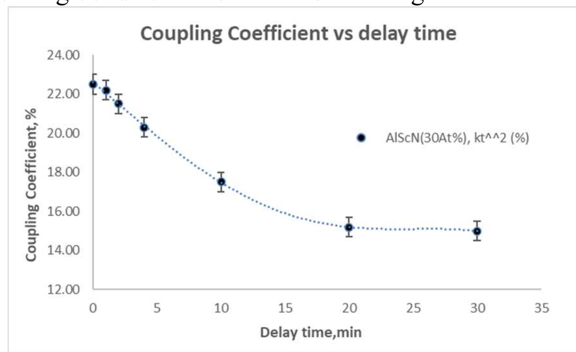
Figure 5. HBAR structure.



Measurements were done on Agilent Network Analyzed E5071B with Cascade RF probe station.

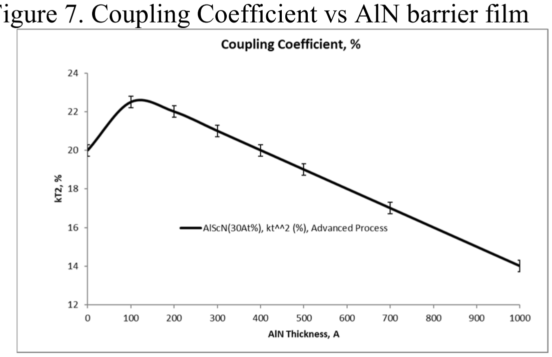
The first parameter is surface cleaning/bond-activation with high energy Ion bombardment and delay time between cleaning and AlN barrier deposition. It is important to have ion beam treatment done right before AlN barrier layer deposition. Figure 6 shows correlation between coupling coefficient and the time wafer sits in the load-lock at 1E-6 Torr vacuum. During delay time between ion beam treatment and AlN deposition, surface covered by monolayer of oxygen and water vapor, which dramatically reduce coupling coefficient of devices.

Figure 6. Coupling coefficient vs delay time of surface cleaning/bond activation with Ion Milling



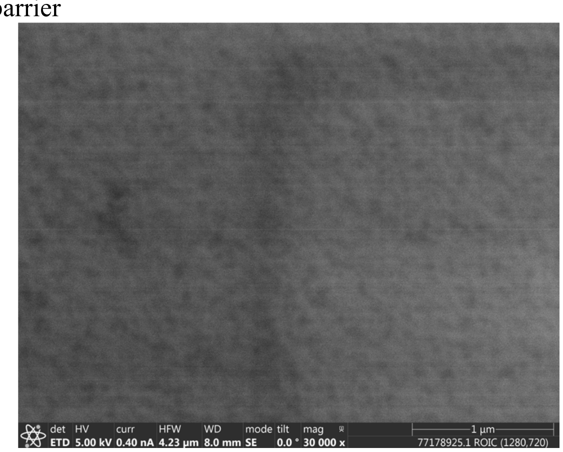
Barrier layer itself is another critical part of getting high quality AlScN film. As can be seen from the Figure 7 below, deposition, that uses no barrier layer, has lower coupling coefficient. Very thin barrier layer improves coupling coefficient. But, as this layer gets thicker, coupling coefficient drops. This happens due to thicker AlN film has stronger crystal orientation, but, the higher Sc content in AlN film, the bigger lattice constant mismatch with pure AlN film. This mechanism can promote growth of un-desired "crystallites".

Figure 7. Coupling Coefficient vs AlN barrier film



We further investigated the impact of stress in the barrier layer on the formation of the "crystallites".

Figure 8. SEM of AlSc(30)N film for compressive AlN barrier



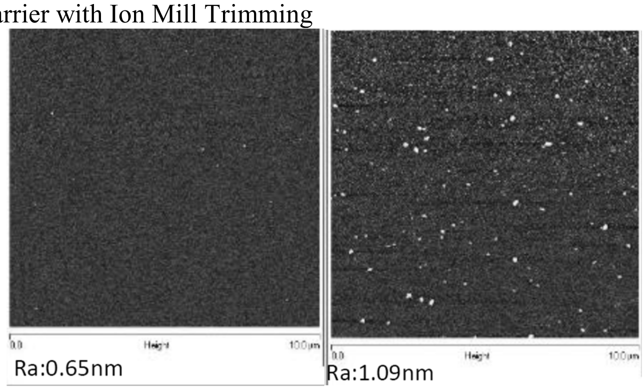
As can be seen in Figure 8, compressive stress in the AlN barrier film leads to a reduction in the "crystallite" formation in the AlScN films.

At the same time, tensile stress of AlN barrier leads to "crystallites" formation, see Figure 2.

We also tried depositing thicker barrier layers and trimming them with Ion Mill down to 100A thickness. Barrier layers that had highly compressive stress and were trimmed shown improvement in both surface roughness of the AlScN films and number of the "crystallites".

Neutral or tensile stress barrier films actually performed worse after trimming, having rougher AlScN surface, more crystallites and worse crystal orientation. Figure 9, shows AFM data of AlScN film, including surface roughness, for compressive and tensile AlN barrier with Ion mill trimming.

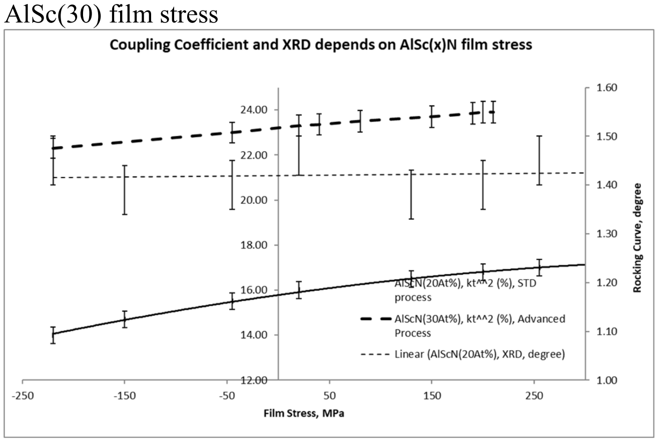
Figure 9. AFM of AlSc(30) film and Surface Roughness (Ra) for processes with Compressive (Left) and Tensile (Right) AlN barrier with Ion Mill Trimming



Regarding AlSc(30)N deposition process itself, parameters, such as AC deposition power and stress have dramatic impact on device coupling coefficient.

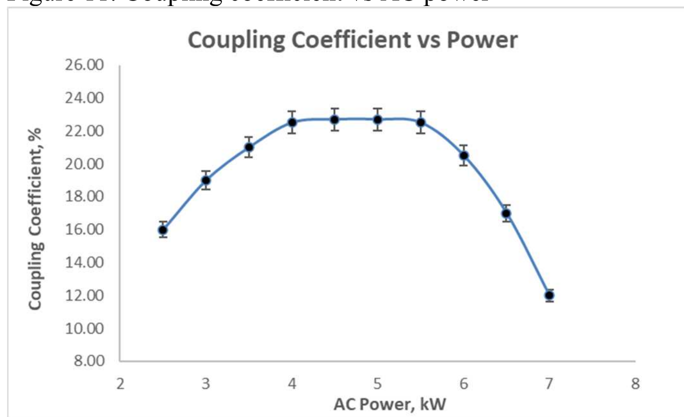
As previously was discussed in [5] AlScN film with more tensile stress provides higher coupling coefficient, see Figure 10, even if rocking curves show about the same values for films with different stress.

Figure 10. Coupling Coefficient and Rocking curve vs AlSc(30) film stress



Deposition power has also impact on kT2 of highly dopped AlN film. As can be seen on Figure 11, there is a range of deposition power between 4 to 5.5 kW, where maximum coupling coefficient can be reached. This is different compared to pure AlN film, since it can be stable and well oriented with AC power up to 12 kW. This result shows some weakness of crystals of 30% Sc dopped AlN film

Figure 11. Coupling coefficient vs AC power



III. Conclusions

Using high voltage bombardment of the electrode material in conjunction optimized barrier layer before the AlScN deposition improves coupling coefficient and reduces "crystallite" formation in high concentration AlScN films. Using highly compressive barrier film in conjunction with ion mill trimming, further improves the quality of the high %Sc films.

Further optimization of deposition of AlSc(30)N film leads to stable and repeatable process with high Coupling coefficient.

Keywords—Scandium, aluminum nitride, coupling coefficient, film stress

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