Stress control for highly doped Aluminum Scandium Nitride films

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Abstract—Recently, highly Sc doped aluminum nitride films have been used for variety of applications ranging from microphones to PMUT sensors. Deposition on different substrate surfaces such as Pt, Mo, W, Si, SiO2 and SiN (both patterned and un-patterned) lead to requirement to be able to control stress over 1GPa range. In order to obtain zero stress on different surfaces, equivalent process condition on Si wafers requires large stress offset. Stress is typically controlled by adjusting deposition pressure and/or substrate bias. For concentrations above 20%atomic Sc, stress control using substrate bias results in non-uniform stress across wafer. Stress control using adjustment in deposition pressure can produce good stress control across a wafer but can only produce stress adjustment with good thickness uniformity control over a limited stress range. Furthermore, at Sc concentrations above 30%, sporadic crystal growth is observed on more tensile depositions. In this presentation, we demonstrated stress control over 1 GPa range, by using a secondary magnetic field that is easily adjusted from outside of the magnetron and vacuum environment. We were able to obtain stress variation across 200mm wafer below 100MPa. No sporadic crystal growth was observed between 20% Sc and 32% Sc range.

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

I. INTRODUCTION

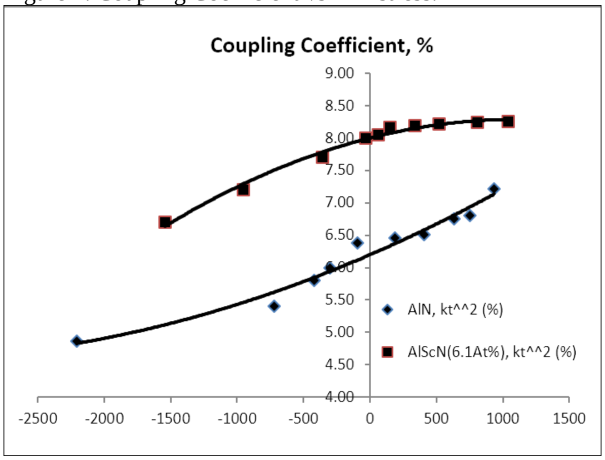
In this investigation we used multiple piece targets to produce highly piezoelectric AlScN films.

When standard magnetic fields, that are used for AlN deposition, are used for AlScN deposition, stress variation from center to edge is more than 500MPa. Because piezoelectric response is highly dependent on stress, see figure 1, this results in unacceptable variation across wafer.

When RF substrate bias is used to adjust stress, average stress becomes more compressive at higher substrate bias. Unfortunately, substrate bias has almost no impact on stress uniformity across wafer.

When pressure or gas flow is used to control stress. There is a large impact on average stress and thickness uniformity across wafer, but the impact on stress uniformity is typically less than 200MPa at the most.

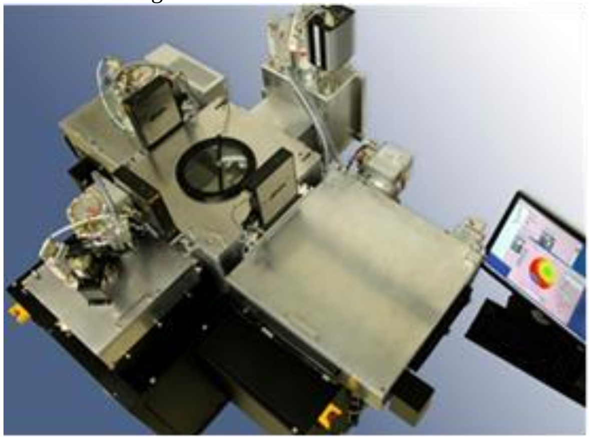
Figure 1. Coupling Coefficient vs film stress.



II. EQUIPMENT

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

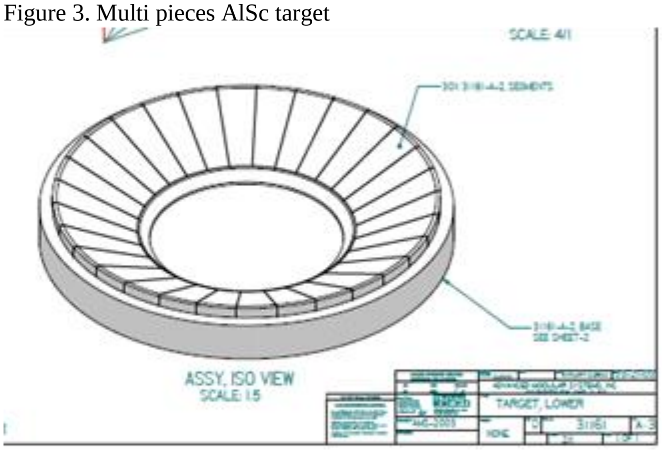
Figure 2. AMS Cluster tool with AlN, AlScN deposition and Ion Beam Trimming Modules



Both depositions use a dual magnetron system with positive plasma column and with AC power applied between targets. Frequency of AC power is 40 kHz and power may vary from 3 to 10 kW. It is a reactive deposition process in deep poison mode.

Main difference between AlN and AlScN chambers is that AlScN deposition is using targets composed of Al and Sc pieces compared to AlN process that uses pure Al targets. Based on simple geometry of target's surface, deposited film composition is proportional to the surface of specific pieces of target material. As sputtering area of Sc increases, composition of Sc in deposited film also becomes higher.

Figure 3. Multi pieces AlSc target



Magnetic field is optimized for each chamber to produce uniform stress across wafer.

Substrate rotation is used to compensate for the variation of scattering for different materials and composition non-uniformity across the substrate.

The trimming module uses DC focused ion source with argon process gas to improve thickness/uniformity of deposited 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 composition control, because it allows avoiding of spending too much effort on controlling thickness uniformity during deposition.

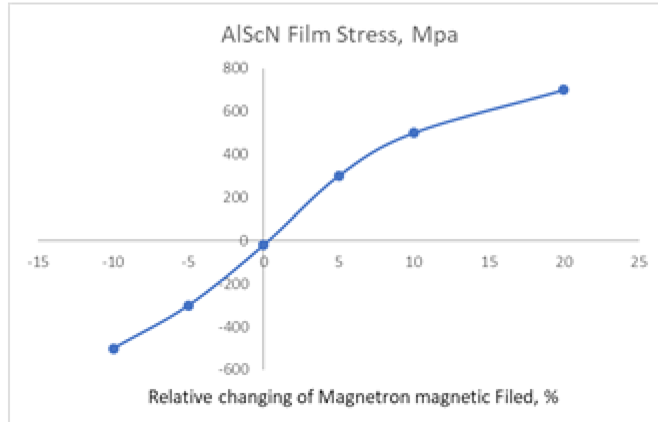
III. FILM STRESS CONTROL

The system uses standard dual conical magnetron with AC deposition source. Since material from inner target is mostly deposited on the center of the substrate and material from outer target is mostly deposited on the edge of the substrate, independent adjustment and control of target's properties and magnetron parameters (including magnetic fields) allows an independent control of film stress on the center of the substrate relative to the edge of the substrate.

For example, targets have a sloped surface. This shape allows us to control angle and energy of the material that is coming off the targets.

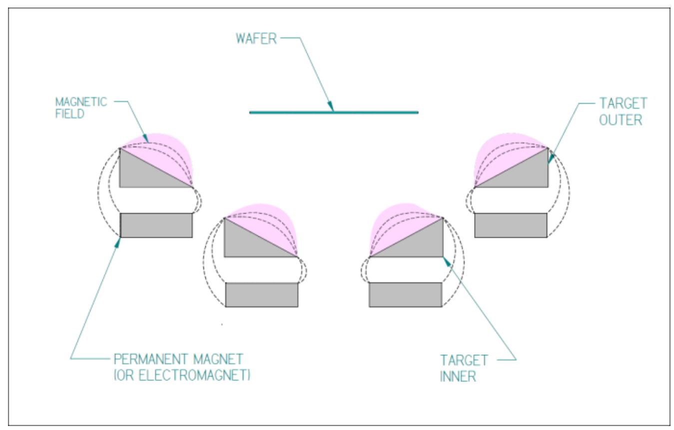
Since magnetron magnetic field also has significant impact on the film stress, see figure 4, independent adjusting horizontal and vertical magnets on inner and outer magnetron allows us to dial in stress variation on a wafer.

Figure 4. AlScN film stress vs secondary magnetic field strength.



Adding magnets underneath the horizontal surface of the magnetron allows us to make stress across the wafer more tensile or compressive in the center of the wafer depending on the desired stress profile. Figure 5 shows magnetic field configuration that allows stress control across wafers.

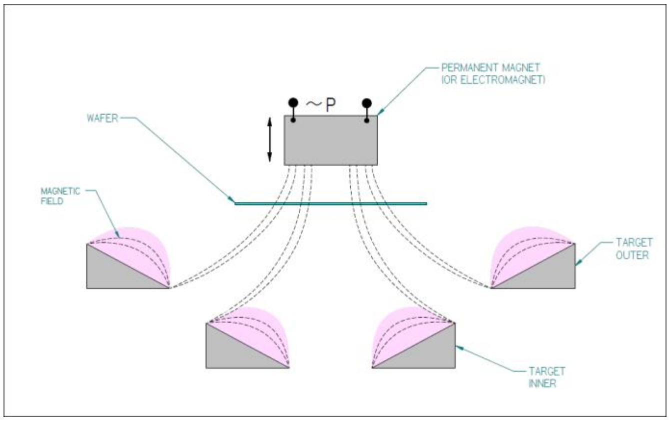
Figure 5. Magnetic field configuration with outside magnets below magnetrons



Applying magnetic field with specific polarity on the bottom of the lower magnetron can increase or decrease stress in the center of the wafer.

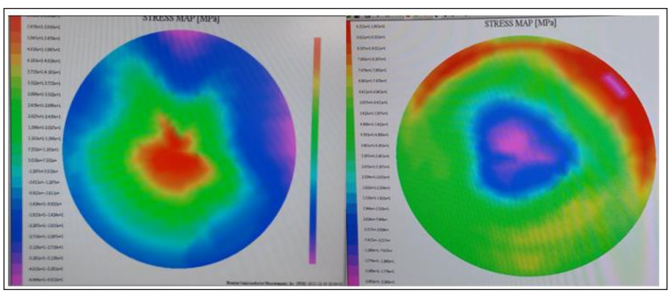
Another option to control film stress uniformity across a wafer is disbalancing magnetron magnetic field either on inner target or outer target, by putting magnets behind a substrate. This created additional electron traps and, as result, ion clouds either in the center of the substrate or on the edge of the substrate. Excessive of ions cause higher bombardment of growth film and, as result, more compressive film stress in that area of the substrate, see figure 6.

Figure 6. Magnetic field configuration with magnets behind the substrate



When stress is made more tensile in the center, it also makes average stress more tensile. In order to compensate tensile stress, we can use RF to make average stress more compressive on the wafer and increase in pressure/gas flow to make average stress more tensile to meet the desired average stress on a wafer target.
Figure 7 shows stress control from more tensile in the center to more compressive in the center.

Figure 7. Stress control from more tensile (red) in the center (left) to more compressive (blue) in the center (right).



Total stress variation across a wafer can be achieved as low as 100MPa in the wide average stress range, see figure 8 and 9.

Figure 8. Stress variation across two wafers for low average stress

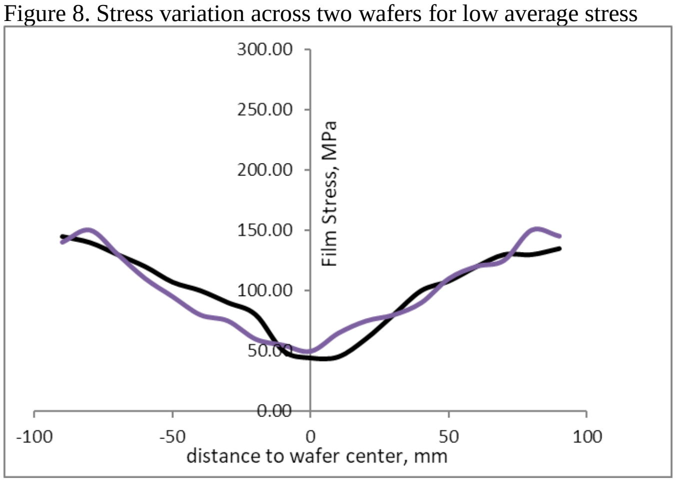
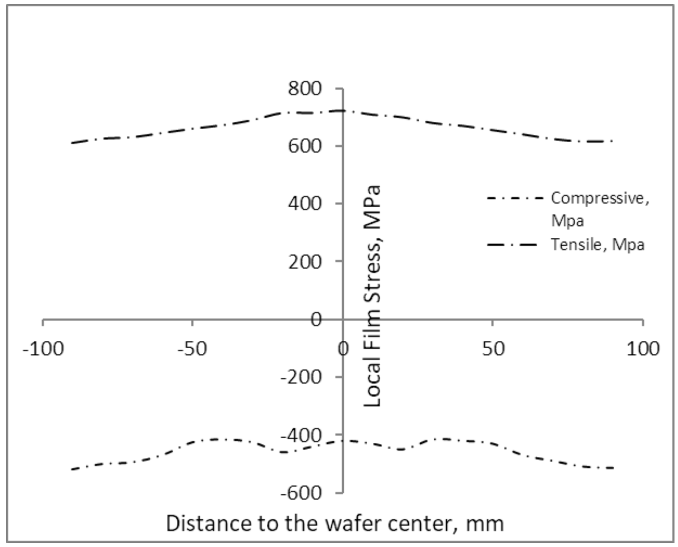
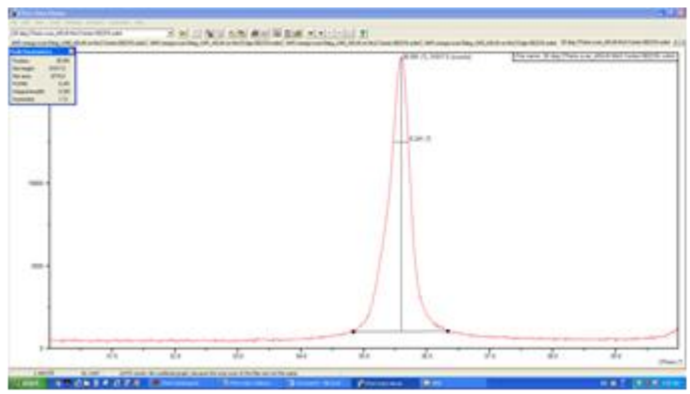


Figure 9. Stress variation across wafers for high compressive and high tensile average stress



Even with high average film stress, AlScN films show high crystallinity and no sporadic nucleation in film, see figure 10.

Figure 10. 2Theta X-Ray diffraction of AlScN film without any abnormal peaks



Sometimes is very difficult to obtain desired average film stress, film stress uniformity across wafer and thickness uniformity across wafer at the same time. For this reason, we use trimming process to correct thickness uniformity and focus on film stress uniformity with the magnetic fields control.

IV. SUMMARY

Using magnetic field adjustment in combination with substrate bias, pressure/gas flow control, we were able to demonstrate excellent stress control from highly tensile to highly compressive average stress. Thickness uniformity was controlled with trimming. Having a large number of independently controlled parameters allows a very precise control of stress and thickness uniformity in AlScN deposition process

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