Improving Manufacturability of AlN Deposition Used in Making Bulk Acoustic Wave Devices

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***Abstract* — Bulk acoustic wave (usually referred to as BAW or FBAR) signal filter devices are currently used in more than 50 million CDMA phones produced in the last three years. 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. Control of uniformity, deposition rate, and stress through target lifetimes and from target-to-target variations in are major barriers to high volume production. Novel tool innovations have been successfully implemented to address these issues. Data from production tests show that *in-situ* laser interferometric thickness monitoring significantly reduces wafer-to-wafer thickness variations due target rate roll-off. Uniform, consistent sputtering target metallurgy is shown to be a critical factor. Use of a unique local enhancement of the magnetron magnetic field to compensate for non-radial uniformity profiles eliminates changes induced by variations in target material as well as system asymmetry. Adjustment of stress is achieved though process gas flow control.**

***Index Terms* — BAW, FBAR, AlN, sputtering.**

I. Introduction

Bulk acoustic wave (usually referred to as BAW or FBAR) filters are currently used in more than 50 million CDMA phones produced in the last three years. It is no longer a great challenge to make small volume AlN suitable for BAW applications. On the other hand there are several barriers to making them in a high volume. Target-to-target variations in uniformity, deposition rate, and stress are a major issue. Changes in the above parameters throughout the target life are the second major problem.

For high-volume filters, stringent control of both the material parameters — dielectric, mechanical and piezoelectric — and the thickness of the layers are critical. Following is a list of the sputtering system requirements for AlN films that most people have as they start developing BAW filter technology:

- Intrinsic electro-acoustic coupling k_t^2 must be above 6.4%.
- Uniformity of film thickness across the wafer and repeatability of thickness wafer-to-wafer must be controllable <0.5% 1σ.
- Stress must be tightly controlled
- Deposition rate must be above 700A/min.

Even though it is not a trivial matter, many companies have demonstrated the above mentioned parameters on a relatively small number of wafers. It is only after running tens thousands of wafers and using many targets from different target vendors, our customers came to us with somewhat different set of high volume production related issues:

- Wafer-to-wafer repeatability is impacted by the first wafer warm-up effect and deposition rate changes throughout the target life.
- Cross-wafer thickness uniformity changes throughout the target life.
- Stress changes throughout target life.
- Target-to-target variations in uniformity, stress, and deposition rate.

Using in-situ thickness monitor dramatically reduces problems with changing deposition rate. Using secondary magnetic field to compensate for non-radial uniformity problems takes care of changes induced by both system asymmetry as well as variations in target material

II. Wafer-to-wafer thickness control with In-situ laser interferometry

. When wafer volumes were low, operators run a test wafer and used the results to adjust deposition parameters before each batch of wafers. This wafer also serves as a warm-up wafer. After system sits idle for more than an hour, deposition rate on the first wafer is about 1% lower than on the next wafer. Deposition rate on the following wafers stabilizes quickly and if only a handful of wafers are run, the user can compensate for this by running a test before each batch and selecting appropriate parameters to have repeatable deposition.

In high volume production twenty-five wafers are run together in one cassette/batch. Most targets experience deposition rate roll-off throughout the target life. This can be as much as 20% from beginning of the target to the end of the target. With thick AlN films, in one cassette the deposition rate can drop as much as 3% from first to the last wafer. Most systems address this problem by increasing deposition time or power by a computer-controlled routine based on the historical data collected on the system to compensate for deposition rate decrease. This technique works well for the processes that can tolerate 1% 1-σ thickness control. However, BAW filter production requires better control.

Wafer-to-wafer repeatability below 0.2% can only be accomplished by in situ film thickness monitoring using laser interferometer incorporated into the sputtering chamber design, Figure 1. .

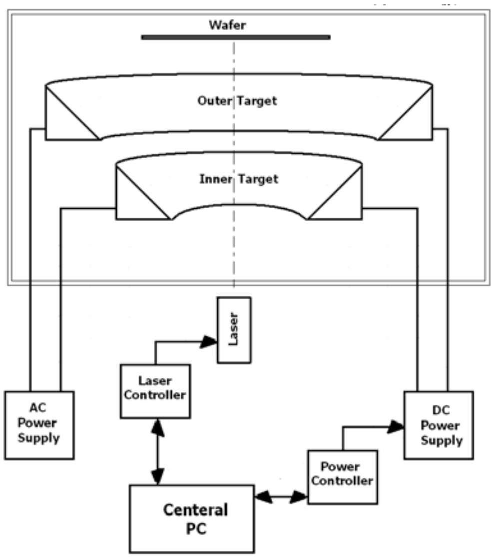

Figure 1. Schematic of in situ laser interferometer.

The laser is aimed at the wafer through a window located in the base of the magnetron. The incident light beam is reflected by the growing AlN surface. Both reflections are routed through to a beam splitter and into a photo detector. During the AlN film deposition, the interference between the two reflected light components causes the output current of the photo detector (vs. time) to exhibit a periodic pattern of maxima and minima, Figure 2. These can be related to the film thickness, index of refraction, and laser free-space wavelength by standard interferometry equations. With laser light at 635 nm and an index of refraction in AlN of 2.075, the change in AlN thickness to move from a maximum to minimum (or minimum to maximum) in the interference pattern corresponds to 76.5 nm of AlN. With suitable interpolation, the measurement is made accurately to less than ±0.2%, for an AlN film thickness in the range of 1 to 3 µm.

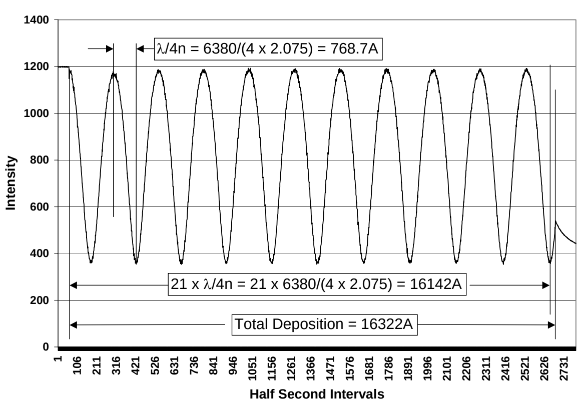

Figure 2. Interference intensity used to calculate film thickness.

This approach is not novel in itself. Maydan et.al (1) describes a similar deposition system concept; however, the main problem with the technique is measuring thickness on patterned wafers. In their approach, a stepper motor is employed to drive the laser spot to the scribe line to make repeatable measurements. This is a cumbersome and not very reliable method. The development introduced here utilizes a software algorithm to separate signals from different surfaces on a patterned wafer and to automatically determine appropriate thicknesses whether blanket and patterned films alike. Figure 3 shows wafer-to-wafer repeatability with the in situ laser interferometer of less than 25A for the two conditions. In comparison, data from a repeatability study without the laser shows wafer-to-wafer control to be greater than 50A.

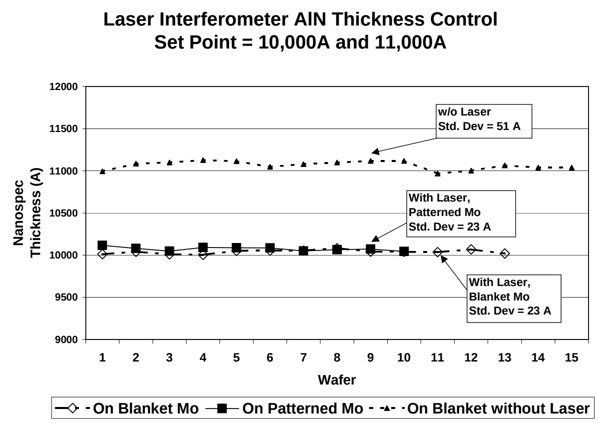

Figure 3. Wafer-to-wafer repeatability improvement to better than 25A with in situ laser interferometer.

III. UNIFORMITY CORRECTIONS DUE TO SPUTTERING TARGET NON-CONSISTENCY

The sputtering target material typically used in the reactive deposition of AlN is high purity (99.9995%) Al. As there is no solute to promote grain refinement in this material, it is difficult to obtain targets with consistent fine grain microstructures. Generally, the inconsistency leads to film thickness profiles that are not radially concentric. This non-concentricity varies from target to target. To alleviate this problem an adjustable local enhancement of the magnet field has been designed enabling one to increase the field over an adjustable arc (ϕ) positioned at a user-selected angle (θ),

Figure 4. Figures 5a and 5b illustrate the adjustment effect on improving radial concentricity.

Once concentric, power adjustment to the dual ring magnetron enables on to reduce radial non-uniformity. Protocols are being developed to make these adjustments automatically by connecting the output from thickness measuring tool such as a 49-point map from a interferometer to the central controlled of the sputtering tool and allowing the computer to determine ϕ and θ and then adjusting the DC power for radial uniformity.

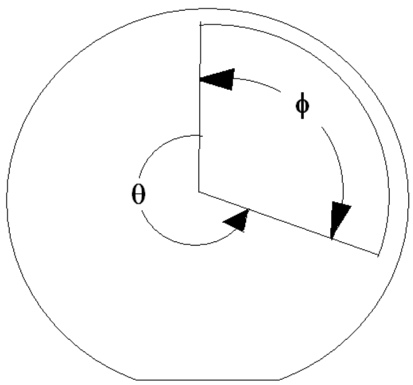

Figure 4. Schematic of range of adjustment of the localized magnetic field enhancement

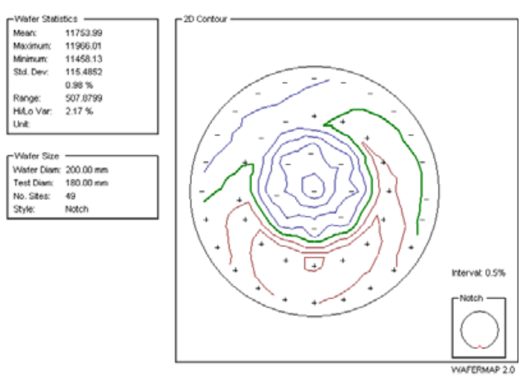

Figure 5a

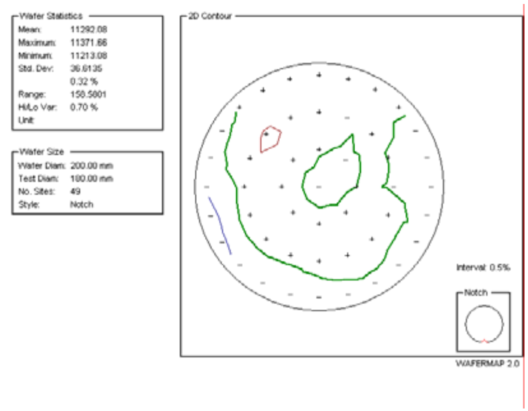

Figure 5b

Figure 5a and 5b. Reduction of uniformity non-concentricity using the localized magnetic field enhancement.

IV. STRESS ADJUSTMENT

A key to easily and automatically controlling stress is to design a cathode for an AlN process in which a magnetic field strength is identified that yields a "0" stress level and provides a reasonably good deposition rate, Figure 6. Once this is achieved, one can adjust the film stress simply with the adjustment of gas flow rate. In an piezoelectric AlN process, a N2 rich gas mixture with Ar is utilized. Small adjustments in either gas can drive stress from tensile to compressive as illustrated in Figure 7.

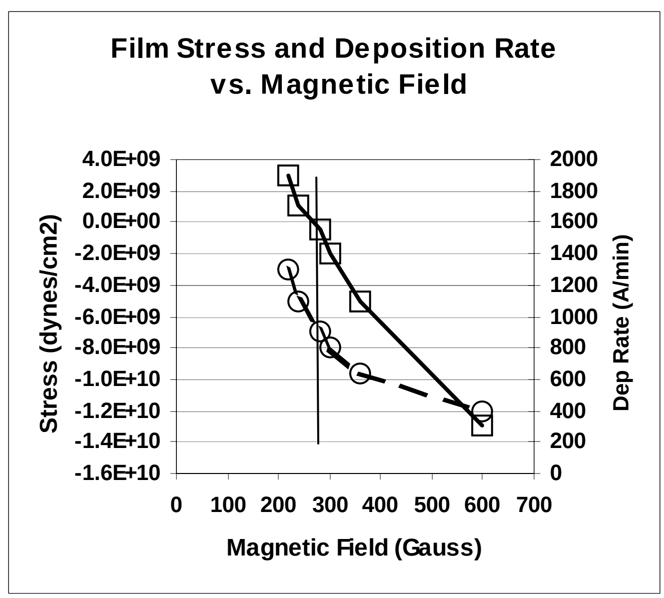

Figure 6. Plot of film stress and deposition rate as a function of the magnetic field strength of the magnetron.

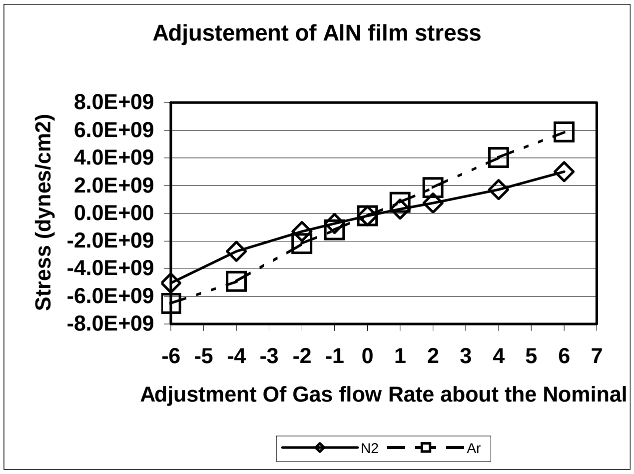

Figure 7. Plot of film stress as a function of the gas flow rate.

Protocols are being developed to make these adjustments automatically by connecting the output from stress measuring tool to the central control of the sputtering tool and allowing calculation of the gas adjustments at the same time it determines ϕ, θ and DC power for radial uniformity.

V. DISCUSSION

Most people find that stress control, uniformity, and deposition rate change throughout target life. Most methods to control cross-wafer uniformity and stress also impact deposition rate. Stress can be controlled by controlling deposition gas flow rate or substrate bias. Both of these will have impact on cross-wafer uniformity and deposition rate.

Typical round flat planar magnetrons suffer from the fact that once the erosion profile is developed early in target life, there is limited ability to vary the film thickness profile. Often the equipment solution is to vary the target to substrate distance. Using distance between wafer and target to control uniformity impacts deposition rate and stress. Thus, trying to come up with automated control of all of these parameters to maintain stress, uniformity, and film thickness throughout the target life is almost impossible. But if wafer thickness is taken out of the equation by using laser interferometer to control thickness, this task becomes doable. Inputting uniformity data into the tool control software enables the computer system to determine the optimum position of the magnet enhancement.

VI. CONCLUSION

Two major improvements have been successfully implemented into AlN deposition system: laser interferometer for thickness control and the local enhancement of the magnetic field for uniformity control throughout the target life. In-situ thickness control is an indispensable feature of a production worthy AlN deposition machine. It allows user to automate other things such as stress and cross-wafer uniformity control through target life and target-to-target. The position-able and adjustable magnetic field enhancement is critical to compensate for asymmetrical uniformity problems that vary target-to-target and throughout the target life.

References:

1. Maydan et.al patent 4,618,262 “Laser interferometer system and method for monitoring and controlling IC processing”
2. Mishin, us11/085,362