Sputtering Processes for Bulk Acoustic Wave Filters

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INTRODUCTION

Bulk Acoustic Wave (BAW) filters, which are synthesized from Film Bulk Acoustic Resonators (FBAR), have been called "a technology of the future and likely to always stay that way", for the last thirty years. Much R&D has been done on FBARs over this period, in both university and industrial settings [1-6]. Even though several companies were able to produce reasonable quality BAW filters for military applications, the cost barrier has kept such filters from becoming a high-volume consumer commodity item. In contrast, Surface Acoustic Wave Filters (SAW) [7] were able to be manufactured in high volumes and hence became the filter technology of choice for miniaturization. Agilent Technologies has recently shifted this paradigm by shipping production quantities of cellular phone duplexers during the second half of 2002. Duplexers contain two FBAR filters that must meet the most stringent specifications of any handset filter application.

FBAR filter technology is based on thin films of piezoelectrically active materials, such as aluminum nitride (AlN) or zinc oxide (ZnO), and of suitable electrode materials, such as aluminum or molybdenum. For successful, high-volume manufacture of RF and microwave filters, stringent control of both the material parameters – dielectric, mechanical, & piezoelectric - and the thickness of the layers is very important. One of the keys to the success was a custom sputtering system from Advanced Modular Sputtering Inc. (AMS), Goleta, CA (Figure 1). In resonator applications, frequency control is very important to yielding good product. The FBAR resonator frequencies are set by the thickness of the piezoelectric & electrode films, which must be accurate to ~ 0.2%, an astonishing level in the thin-film industry! Satisfying this requirement was a major impetus to develop a custom tool. Capable of depositing metal & piezoelectric films of sufficiently well controlled material properties and thickness, the AMS deposition system enables wafer level yields at the 50% level.

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Figure 1 – AMS Custom Cluster Tool for Sputter Deposition.

DEVICE DESCRIPTION

FBAR filters [8] are realized in a ladder topology, as a series of electrically connected, air suspended membrane-type resonators, made of piezoelectric aluminum nitride sandwiched between two molybdenum metal electrodes. Figure 2 provides a sketch of the structure and the resulting RF filter characteristics. There are two critical aspects to making FBAR filters: 1) performance and 2) the cost of the filter.

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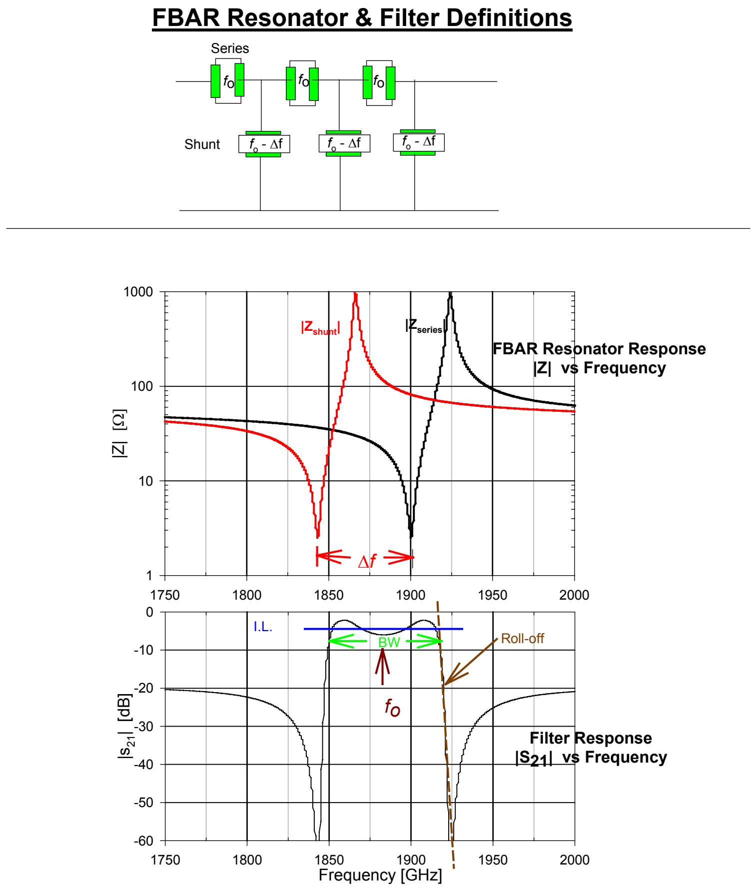

Figure 2 – Illustrating the FBAR resonator ladder filter topology (top panel). The series and shunt resonators exhibit impedance vs. frequency characteristics (middle panel), which produce the filter pass-band response for an RF filter (bottom panel).

Filter performance has three main components: 1) in-band insertion loss and bandwidth, 2) roll-off rate from in-band to out-of-band states, & 3) out of-band rejection (see lower panel of Figure 2). The electro-acoustic coupling coefficient k_t^2, and the quality factor or "Q" of AlN, are the key material parameters in determining the filter response. The coupling constant k_t^2 determines the insertion loss and bandwidth of the filter, while Q controls the roll-off of the filter (roll-off is defined by the maximum insertion loss in-band and the minimum rejection allowed at the out-of-band corner).

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Figures 3 and 4 illustrate the typical low insertion loss and good out-of-band performance for FBAR filters made from films deposited with the AMS sputtering system.

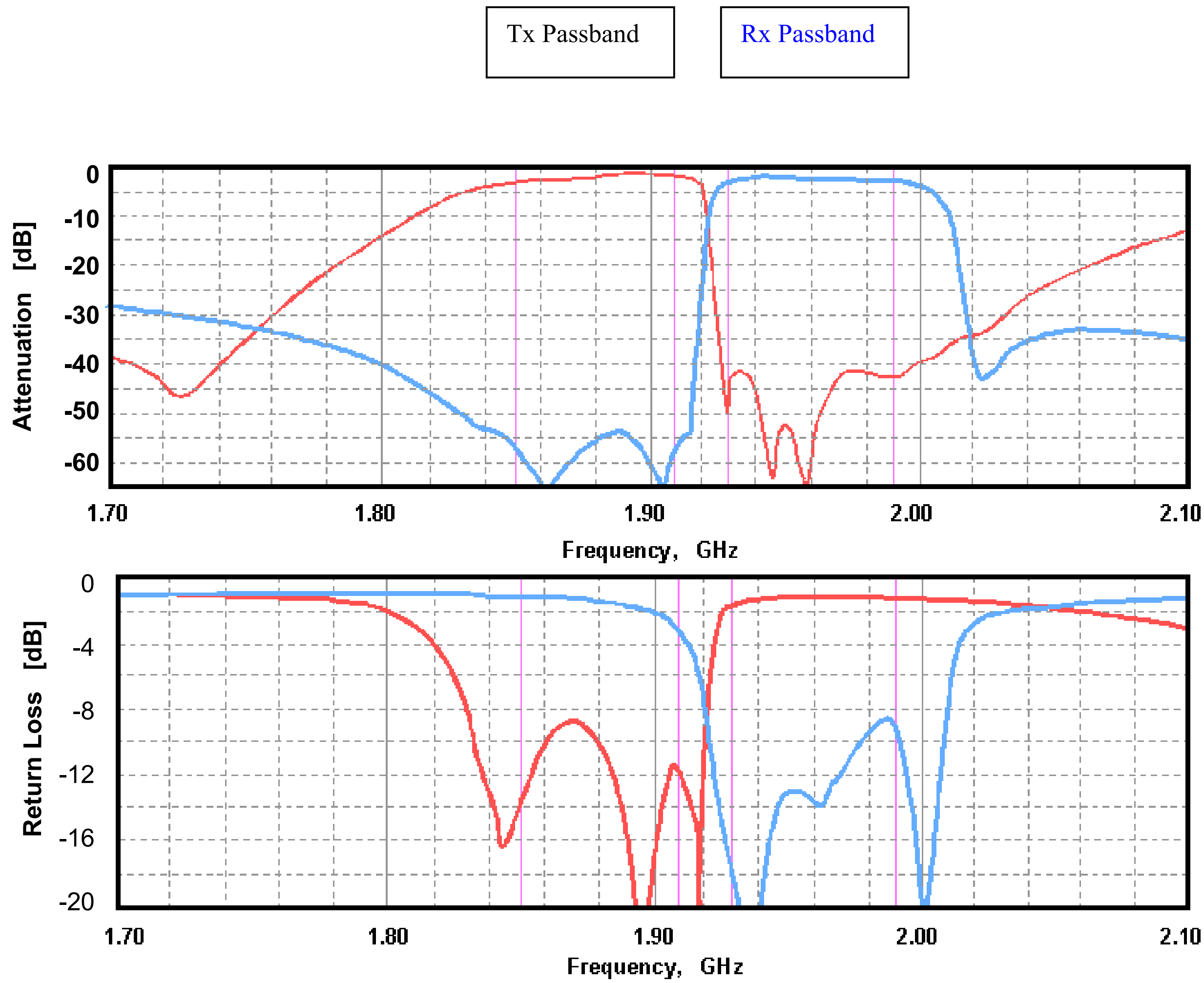

Figure 3 and 4 - Measured performance of an Agilent HPM7903 FBAR duplexer, circa August 2000. Both Attenuation (Insertion Loss) and Return Loss $|S_{11}|$ at the Rx and Tx ports are shown.

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The first key innovation is the use of molybdenum for the electrodes [9,10]. Molybdenum is used to minimize the acoustic attenuation and provide good electrical conductivity, both of which improve Q and boost k_t^2. The second is the ability to sputter AlN films with independent control of residual stress and k_t^2, at high deposition rates.

In wireless and microwave applications, different filter characteristics are needed. For example, in filters intended for transmit (Tx) chain usage, very rapid roll-off from in-band to out-of-band regions & low insertion loss in-band are important. Producing FBAR material with high effective k_t^2 and Q helps achieve the desired response.

In order to compare FBAR filter performance with respect to competing technologies and design methodologies, it is useful to use the k_t^2 *Q product as a figure of merit. FBARs exhibit both a series and a parallel resonance (see the middle panel of Figure 2), with a Q factor defined for each. Typically, the parallel quality factor Q_p is lower than the often-quoted series quality factor, Q_s. However, for filter applications, the parallel Q_p is much more critical and is the one we quote here. There are many published papers claiming high coupling coefficient and Q for FBARs [11,12], k_t^2 *Q_p products ~ 5 to 20 are typical numbers, but these are not adequate for good PCS duplexer performance. For producing commercially competitive parts, the k_t^2 *Q_p product needs to be above 50, a typical result produced by the AMS sputtering system.

An FBAR resonator may be constructed either as a freestanding membrane technology, or as a solidly mounted resonator (SMR) [4]. In the SMR, a series of acoustical mismatching layers are used to prevent the sound wave from penetrating into the substrate material where Q lowering dissipation would occur. The choice of a "free" standing membrane gives the best Q due to the air/resonator interface, and lack of additional layers in which the sound wave may be attenuated. Also a freestanding membrane eliminates the need to deposit multiple layers, the deposition and control of which would create a barrier for high-volume manufacturing throughput.

A freestanding membrane may be fabricated by providing a hole in the silicon with a sacrificial support structure on the silicon substrate that is etched out after the processing is done. This leaves the membrane supported at the edges over a shallow hole (~2 – 4 microns deep) in the silicon wafer. A potential problem with a freestanding membrane is that it may buckle inwards toward the bottom of the hole and actually come in contact with the substrate, a process which can also lower the Q. Avoiding this problem requires that stress in the films be negligible or slightly compressive, user selectable, in order to force the membrane to stay flat or bow up away from the bottom of the hole. An alternative choice is to etch the silicon wafer away from the back [12]. While this approach eliminates the possibility of the membrane touching the substrate, it mechanically weakens the wafer and hence is considered unsuited for production.

Turning again to the dual questions of quality & competitive pricing, several companies have recently demonstrated adequate quality Tx and Rx SAW filters in the 900 MHz cellular phone bands, and Rx filters in the 1900 MHz PCS bands. On the other hand, power-handling problems [13] have limited SAW filters in Tx applications at 1900 MHz. Although FBAR filters

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have demonstrated much better power-handling characteristics [14], they still have to compete in the market with SAW filters that are manufactured for 5 – 10 cents each (in quantities of millions) for RF cellular phone applications. Thus, cost of manufacturing FBAR filters is an even more important consideration than pure performance of the parts.

Fast and reproducible deposition of high-quality AlN films is paramount for low-cost manufacturing of FBARs. Several techniques [15,16] such as CVD, metallic Al deposition in nitrogen, and RF sputtering of Al in nitrogen, have been demonstrated for growing single crystal or polycrystalline AlN with a well-oriented crystallographic c-axis. This is the main prerequisite to obtaining acceptable piezoelectric properties. However, for FBAR production, reactive sputtering at moderate temperatures has proven to be the most practical technique.

ALUMINUM NITRIDE DEPOSITION

In over a decade of developing aluminum nitride deposition techniques for FBARs, we have evaluated four different "cluster-tool" sputtering systems and one batch system, all from renowned thin-film companies. None of these systems have satisfied all of the requirements for production quantities of FBARs, especially the control of the electro-acoustic coupling constant at a high and consistent value, and adequate throughput leading to competitive production costs. Following is a list of the sputtering system requirements for producing micron thickness, highly piezoelectric aluminum nitride films or high-quality molybdenum films in a production environment:

- System must have very low levels of oxygen and water during deposition,
- Aluminum nitride must be sputtered at as high a power as possible to increase adatom mobility, leading to high film quality,
- Substrate must be at as high a temperature as possible to improve adatom mobility, with the chamber walls and shields at low temperature to prevent outgassing of undesirable gases,
- Intrinsic electro-acoustic coupling k_t^2, wafer-to-wafer and across-wafer, must be reproducible and repeatable throughout the target life.
- Uniformity of film thickness across the wafer and repeatability of thickness wafer-to-wafer must be controllable throughout the target life. It must be better than 0.2% one sigma for the filter yield to be 50%.
- AlN deposition rates of 700 to 1000A/minute are necessary to produce filter products at a low enough cost to be competitive with other filters on the market.

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After several years of trying to modify standard systems, it was decided that a custom-built system designed specifically for aluminum nitride was necessary. Advanced Modular Sputtering (AMS), Inc., Goleta, CA built a unique, AC-magnetron-based, three-chamber cluster tool to provide the required film characteristics, as well as high throughput. In addition to the unique hardware features, a completely new software package had to be developed to allow control of the deposition process as well as running the three chambers simultaneously without compromising throughput. A major result of this work is to realize that systems designed for sputtering conducting thin films, will not work well in producing dielectric films.

For depositing thin films of conducting materials (typically metallic aluminum, or titanium nitride), most sputtering systems on the market have an optimized DC magnetron source. In such a system, small changes in magnetic field do not produce significant changes to the film properties. The material deposited on the shields around the magnetron is conducting, therefore does not change the plasma characteristics throughout the life of the target, so the film properties and deposition rates are not altered significantly. Likewise, the residual stress does not vary greatly from run to run.

On the other hand the film properties and deposition rates of dielectric materials, like aluminum nitride, are significantly affected by small changes in the magnetic field. The build-up of dielectrics on the shields causes changes in the uniformity and deposition rate of the film, run to run, throughout the life of the target. Most systems use “bipolar” DC magnetrons or a standard dual magnetron with AC power supplies [17,18], either type of which can cause significant changes in stress, film uniformity, deposition rate, and film quality throughout the target life. The typical compensation for film stress and uniformity involves adjustment of gas pressure or substrate bias. The goal is to provide independent control of all sputtering parameters to achieve the desired AlN material attributes. Since there aren’t enough independent process parameters available to control all the AlN thin film parameters to the desired specifications, throughout the target life, certain sputtering machine parameters were added to the list of possible control elements.

In this development, magnetic field was optimized to produce a high deposition rate of the aluminum nitride film, while maintaining the highest coupling coefficient and a slightly compressive stress. The following three figures show the impact of total magnetic field at the target rings in the AMS system, on coupling coefficient, deposition rate and stress.

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Figure 5 is a graph showing the dependence of k_t^2 of aluminum nitride on the strength of the magnetic field. Note that the coupling reaches a broad maximum near 290 Gauss, where it is insensitive to changes in the field at the targets.

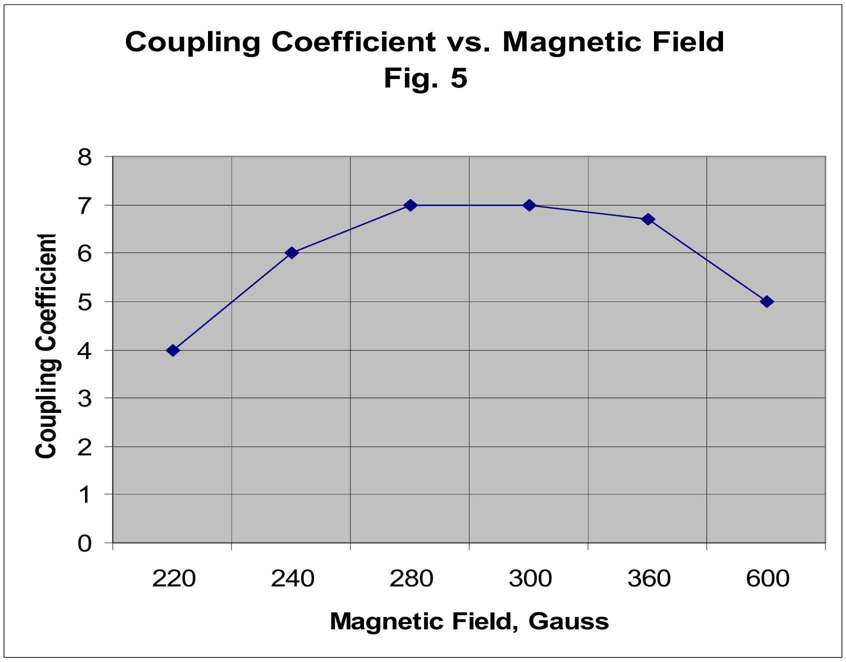

Figure 5 - Film coupling coefficient dependence as a function of the magnetic field strength. Note: for optimum coupling constant k_t^2, magnetic field ~ 290 Gauss is required.

Magnetic field also acts to decrease the sputter rate. Figure 6 illustrates that at a field of 290 Gauss, which gives optimum k_t^2 coupling coefficient, the deposition rate drops nearly 2:1 from that experienced at 200 Gauss. This is a major price to be paid, for relative insensitivity to magnetic field induced changes in k_t^2.

Residual stress in the films, which is controlled partly by gas pressure, and partly by magnetic field, must be controlled to obtain membranes that bow upwards and which do not become disconnected from their perimeter support or develop cracks in the interior. By design, the stress can be made to be almost zero to slightly compressive, at a magnetic field of ~ 280 Gauss. Figure 7 illustrates the dependence of residual stress on magnetic field.

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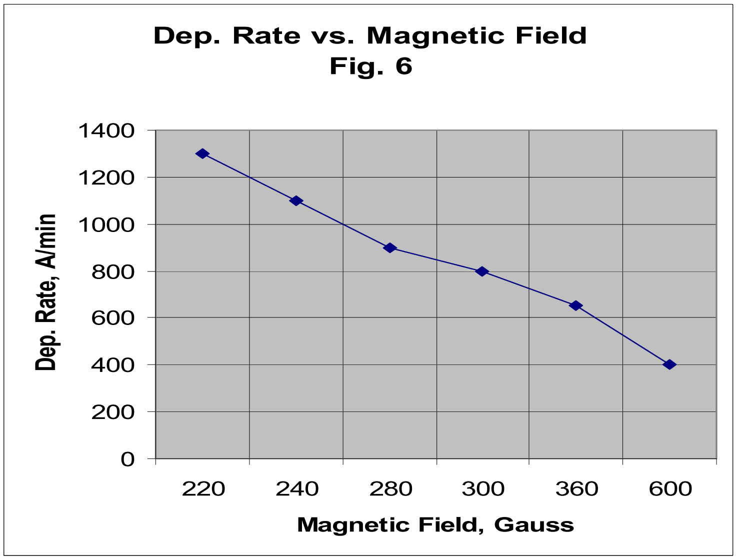

Figure 6 - Deposition rate as function of the magnetic field at the target ring location

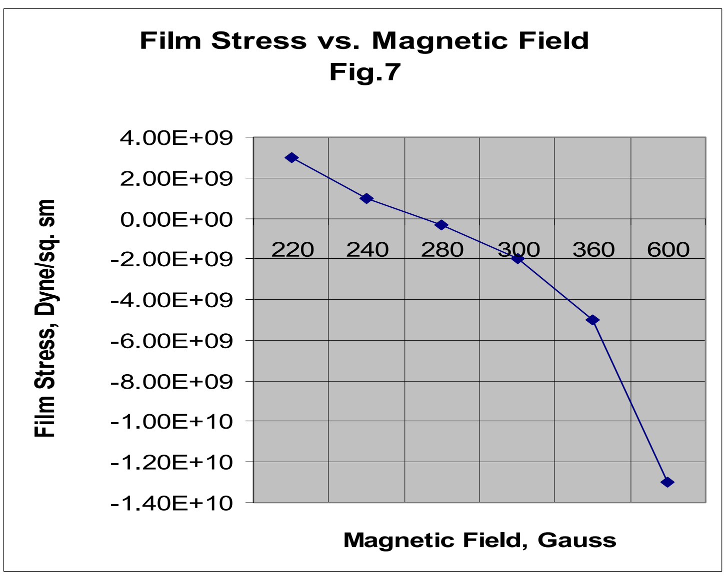

Figure 7 – Film stress as function of the magnetic field strength. The minimum stress occurs at 280 Gauss where it changes from tensile to compressive.

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Uniformity of the film thickness over the entire wafer has a big impact on FBAR wafer yield. Uniformity is especially sensitive to target profile changes from run to run. Magnetron sputtering targets erode non-uniformly due to the magnetic field design. As a result, the contour of the target ring is altered, and changes in the deposition parameters occur. Those more quickly eroding target areas are commonly referred to as “race-track”. As the “race-track” gets deeper during target life, the uniformity and rate of deposition changes. In conventional systems with a single target ring, gas pressure is used to adjust uniformity. Unfortunately, gas pressure also has a huge impact on the stress in the aluminum nitride films, so is not useful for correcting the run-to-run changes in uniformity.

The AMS system uses two magnetron target rings. It was found that using a standard DC power supply connected between the two magnetron rings allows excellent uniformity control throughout the target life. Uniformity is thus achieved without altering gas pressure and without any other significant impact on film properties. Since the DC supply can be controlled from the process recipe, adjustments are easily automated through the system computer. The results of varying the DC bias power between the two rings, is summarized in Figure 8.

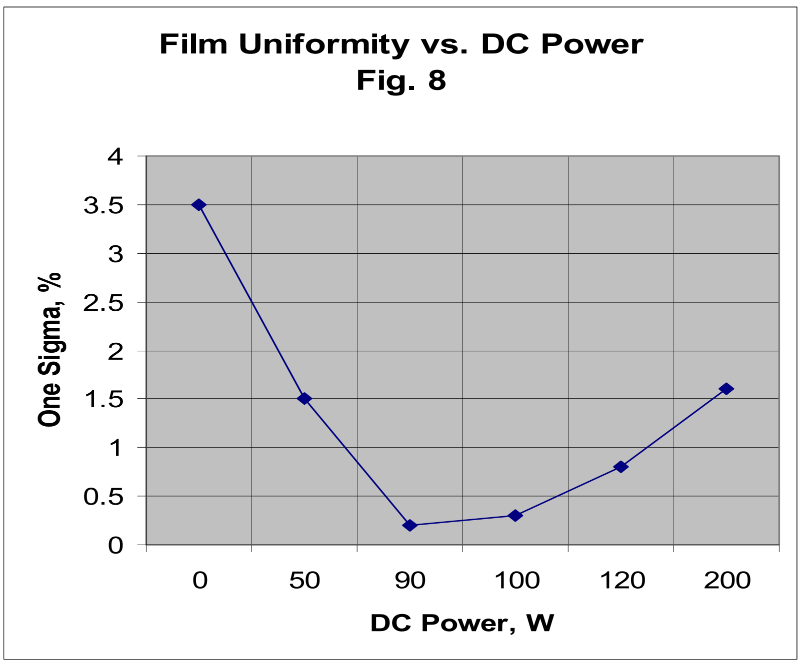

Figure 8– Uniformity of the deposited film for different amounts of power from the secondary DC power supply.

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Further refinements resulted from running thousands of wafers through the system. Since the AMS system was specifically designed for an aluminum nitride process, we eliminated the anode, ground and floating potential between the two magnetrons and inside the inner magnetron. Eliminating most surfaces on which insulating aluminum nitride is unintentionally deposited improved plasma stability throughout the target life. The magnetic field was further optimized by adjusting the position of the "race-track" on each target to fine-tune stress and film uniformity.

Throughout the target life as the “race-track” gets deeper and the deposition rate decreases, the deposition time is increased by a computer-controlled routine based on the historical data collected on the system. This technique works well for the processes that can tolerate 1% one-sigma thickness control. However FBAR filters require better control.

Wafer-to-wafer repeatability below 0.2% can only be accomplished by in-situ film thickness monitoring. After a significant amount of experimentation, we found that an in-situ laser interferometer meets this need. The laser is aimed at the wafer through a window located in the middle of the magnetron. The incident light beam is reflected by the growing AlN surface as well as the molybdenum electrode. Both reflections are routed through to a beamsplitter 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. 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 expected to be made accurately to ~ +/-0.1%, for an AlN film thickness in the range of one micron.

To summarize the results on AlN deposition, it was found that a magnetic field of 280 to 290 Gauss was the best compromise in this investigation. AlN films were deposited with deposition rates close to 900 A/min, better than 0.5% uniformity and better than 0.2% run-to-run repeatability. The films had run-to-run stable coupling coefficient of about 7%, and slightly compressive stress.

CONCLUSION

After years of development, AMS has successfully demonstrated a deposition system with the ability to manufacture FBARs in high volume and at low cost. It is found that the magnetic field applied to the targets has a profound affect on film uniformity, deposition rate, and electro-acoustic coupling coefficient. To meet the stringent requirements for high quality FBAR filters, the AMS deposition system utilizes a combination of an improved reactive sputtering system with optimization of the magnetic field applied to the targets. The resulting film stacks exhibit

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uniformity of 0.5% across the wafer, better than 0.2% run-to-run repeatability, and high electro-acoustic coupling may be achieved at deposition rates of 700 to 1000 Angstroms per minute.

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