Thickness Control by Ion Beam Milling in Acoustic Resonator Devices

Sergey Mishin
AMSystems, Inc.
Goleta, CA, USA
s.mishin.ams@cox.net

Yury Oshmyansky and Frank Bi
Avago Technologies
Fort Collins, CO,USA

Abstract—In this paper, practical aspects of production worthy methods for film uniformity adjustment (trimming) used in manufacturing of Film Bulk Acoustic Resonator (FBAR) filters [1], [2] have been presented. Two-step trimming in conjunction with thickness "smoothing" technique control total thickness range to within less than 8A on product wafers with variable surface film etch rates even with difficult to measure film thickness. Trimming processes were used to allow using one wafer from a batch to provide compensation feedback in the FBAR devices. Combining ion mill with deposition in the same tool produces <0.1% uniformity in the deposited films.

I. INTRODUCTION

As performance FBAR filters have continued to improve, it became desirable to be able to control thicknesses of the films used in these technologies to well below 0.1% uniformity. A number of different deposition systems are used in making filter in commercially viable environment. Majority of these machines provide film uniformities that are an order of magnitude worse than acceptable. It is impractical to improve film thickness uniformity as deposited below 0.5%, but relatively easy to improve the thickness uniformity after the deposition. The range of use of FBAR technology has been extended greatly by developing production worthy trimming methodology. In the last decade a new technique using ion beam based machines to improve uniformity of the films was adapted in making BAW (bulk acoustic wave) devices [3]. Ion beam milling techniques that have been used effectively to improve uniformity in making of optics and tuning of the quartz crystals were successfully adapted to the FBAR, BAW and SAW (surface acoustic wave) devices to meet frequency control requirements. Use of trimming for these technologies presented a new set of issues that have to be addressed:

(i) Ion source has to be optimized: beam size of the ion source must be small enough to allow uniformity correction of films that have large thickness gradient, but large enough to provide high wafer throughput. Due to the small beam size, re-deposition of the removed film on the wafers surface can result in degraded electrical performance of the FBAR filters. Etch rate cross-wafer uniformity and repeatability over time can result in 30A to 50A variation in thickness from the lowest to the highest thickness in a batch of wafers. For the acoustic resonator application <20A variation of film thickness is desired.

(ii) Uniformity maps are not always smooth and continuous. Sometimes because either deposition equipment limitations or measurement equipment accuracy, thickness profiles have large anomalies that cause problems for trimming.

(iii) FBAR product wafers are usually exposed to photo-resist or chemical and plasma treatments in the course of processing. This frequently leads to the significantly different etch rates of the surface layer compared to the bulk material as well as erroneous thickness measurements that lead to significantly different device performance at final test.

(iv) Film characteristics change over time due to the changes in the deposition tool conditions. This also leads to variation of device performance at the final test.

In this paper, an extremely practical approach to trimming is described. A standard production tool was used to trim variety of materials. Different techniques are described for production and development needs of thickness trimming technology.

II. EQUIPMENT

In this investigation we used Advanced Modular Systems cluster tool with three modules: two aluminum nitride PVD deposition modules and ion beam trimming module shown in Figure1.

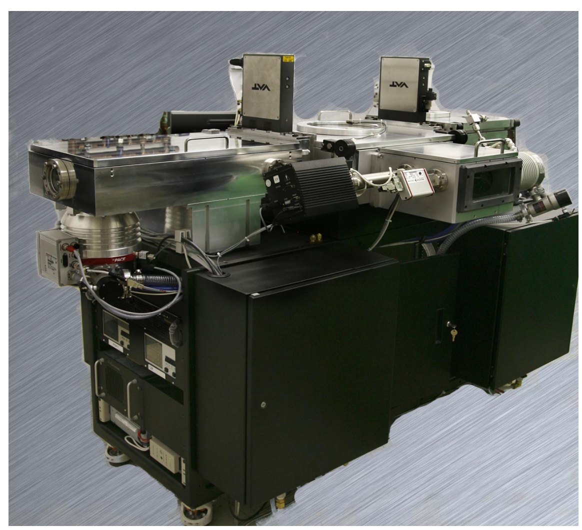

Figure 1: AMSystems cluster tool

PVD deposition uses a dual conical magnetron with AC power supply. It is a reactive deposition using aluminum target and argon and nitrogen process gasses. Trimming module uses DC source with argon processing gas. Wafer is moved by linear drive above the source at constant speed. The source is moved in the direction perpendicular to the wafer motion by another linear drive. Power of the source is adjusted by the system software based on the wafer thickness uniformity map. Ion source has a beam size of about 10mm FWHM. Figure 2 shows etch pattern from the single scan of the ion source used in this investigation.

III. Wafer Processing

The basic trimming process involves optimizing trimming module process parameters and getting a good thickness uniformity map. Several key techniques that produce excellent results will be discussed in this section.

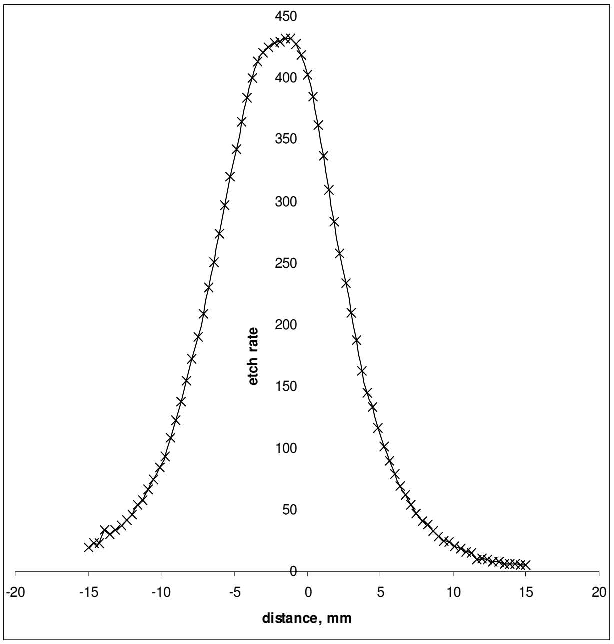

Figure 2: Shape of the ion beam

A. *Trimming module optimization*

The ion source used in the trimming process can have beam size between sub mm to 20 mm diameter. The smaller size provides ability to improve uniformity on wafers with large gradient of thickness. The larger beam diameter increases average etch rate. In this investigation we found that for 150mm wafers with between 10,000 and 70,000 dice, the beam diameter between 5 and 10mm is most productive.

Because of the re-deposition of the trimmed material on the ion source, it is important to re-calibrate the source periodically. We found that performing one calibration per cassette of wafers is more than sufficient. The calibration takes care of both changing source condition as well as other changes to the system over period of time. Re-deposition on a wafer is a common issue in the small beam trimming equipment. We found that our Rp (parallel resistance) degrades as much as 20% after ion standard trimming. The re-deposited material can be cleaned up with a short sputter clean in another machine or the trimming process can be adjusted to minimize re-deposition problem. First, we split trimming into two passes under the ion source, reducing re-deposition in half. Second, we perform first trim to about 80 to 90% of the total required removal. Second trimming step removes the remaining material, further, reducing re-deposition by a factor of 5 to 10. Thus, total re-deposition is reduced by factor of 10 to 20. This technique completely eliminates Rp degradation problem related to the trimming process. Using two pass process also improves uniformity of trimming rate across wafer. When ion source warms up, etch rate increases slightly. In order to keep constant trimming rate, it is necessary to warm-up source to a steady state temperature. But even without warm-up two-step trimming produces only 2-3% variation of etch rate across wafer.

In this investigation, milling was accomplished using constant speed of wafer and source movement and variable power. The advantage of varying power over varying speed of wafer movement comes in play when the gradient of the thickness changes very sharply. It is much faster to adjust power than to mechanically adjust speed of wafer motion [4]. It is even possible to remove close to zero amount of material at zero power. It is extremely difficult to adjust wafer speed to accomplish the same result.

B. *Wafer map processing*

Basic trimming requires a thickness uniformity map. Minimum of 25 points are required for a 6” wafer. Using as many points as practical improves accuracy of trimming. Trimming tool converts data into a 10,000 point grid that extrapolates thicknesses between points. Thickness uniformity maps can used to improve film uniformity by more than twenty times. This performance is easily achieved on fresh and clean test wafers for both film uniformity and film target thickness.

Unfortunately, on patterned wafers uniformity maps sometimes tend to have a lot of thickness discontinuities. Using a software program such as Matlab™ , data can be “smoothed” into a profile that can be easily trimmed.. An example of raw and “smoothed” data from the same wafer is shown in the Figure 3.

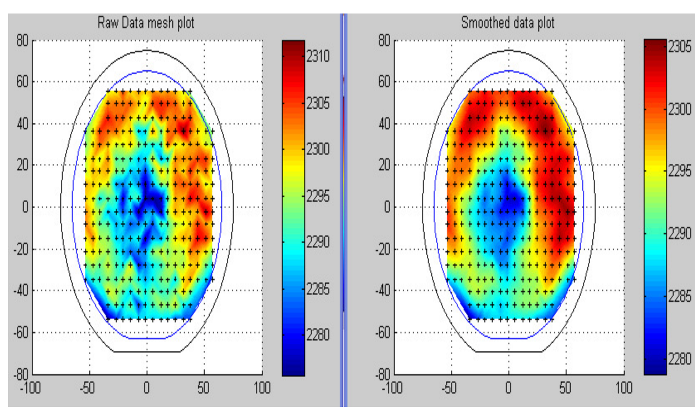

Figure 3: Raw and “smoothed” data

IV. TWO-STEP TRIMMING

Two-step trimming is beneficial not only in reduction of the re-deposition but also to the accuracy of the trimming. By trimming 80 to 90% of the desired thickness in the first step and the remainder the second step, it is fairly easy to compensate for most of the systematic errors associated with trimming hardware. An example of repeatability and accuracy of trimming is shown in Figure 4.

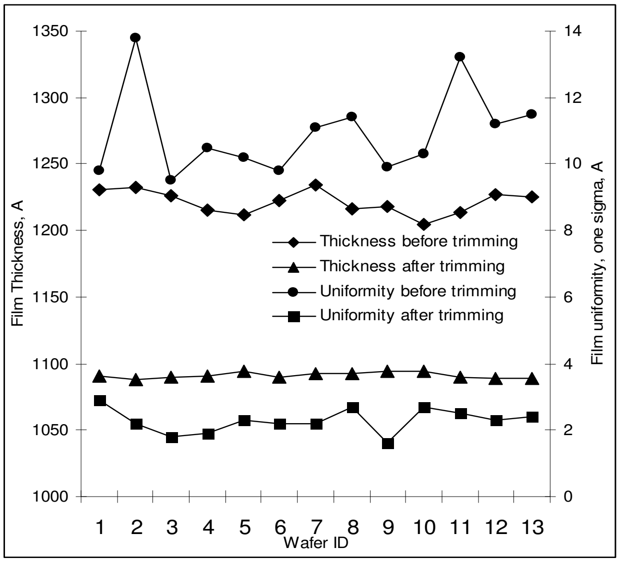

Figure 4: Silicon dioxide repeatability test with two-step trimming.

Two-step trimming is also effective in compensating for the problems with surface condition and measurement issues. One of the best illustrations of the benefit from two-step trimming is Aluminum trimming for SAW filters. Aluminum forms a surface oxide that can vary from 5A to 15A, depending on the deposition technique and the amount of time wafers sit before trimming [3]. Aluminum oxide etches between 2 to 4 times slower than the bulk aluminum. Etch rates of different materials trimmed in the AMSystems trimming tool are listed in the Table 1.

Material	Rate (Ang/min.)
Ag	17500
Al	6125
Ni	5250
NiFe	3500
Au	15750
AlN	1995
Mo	10725
SiO2	4400-5200
W	6825
Cr	3518
Pt	7875
Al2O3	1365-3000
CoNiFe	5278
Cu	8750
Ru	5300-7800
Fe	4375
FeO	6125
SiC	2650-13650
Si	3500
Si3N4	3000

Note: This table uses ~40mA Ion Beam Current

Table 1: Etch rates of materials on the AMSystems trimming tool

Target removal for aluminum is typically 200A. When targeting 200A removal based on the bulk aluminum etch rate, we typically remove 160A to 180A during the first trimming. The second trimming is done within a couple hours targeting 20A to 50A and assuming less than 5A aluminum oxide on the surface. Typical results are within 5A to 10A of the desired target. This is significantly better than 50A after one trim process.

When product wafers go through patterning process, small amounts of photo-resist can be trapped on the surface. Reflectometers can measure these areas incorrectly, see figure 5.

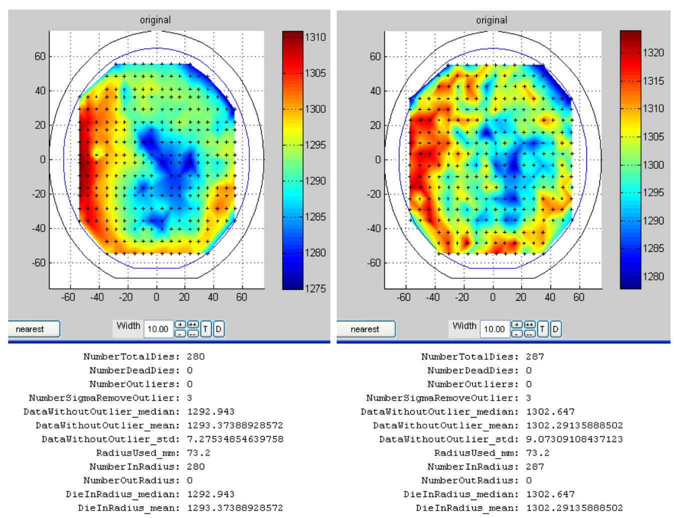

Figure 5: The same wafer, film thickness measurement before and after photolithography process.

Splitting trimming into two steps, 1st trimming 40A less than the final target thickness, 2nd trimming 0A to 40A produces the best results. Because the amount of surface contamination is variable both wafer-to-wafer and across wafer, the one trim process can produce variable improvement in the thickness uniformity. Two-step trimming removes the surface that distorts reflectometers results and gets thickness close to the desired target. Second trimming makes fine adjustment on a cleaned surface. In order to perform second trimming, ion beam has to remove between 0A and 100A. Setting power to zero at the thinnest location on the wafer produces precise second trimming [4] with minimum loss of material.

V. ONE TOOL DEPOSITION/TRIMMING

In a standard FBAR processing, deposition and trimming are performed in two different systems. When the deposition tool and trimming tool are combined into a single cluster tool, it is much more cost effective and saves processing time since in a cluster tool wafers can be processed simultaneously in both deposition and trimming modules.

For example, in the FBAR aluminum nitride deposition, taking a map of the first wafer and using it in a trimming tool for all of the product wafers improves uniformity by factor of 3 to 5 times. Total processing time for 25 wafer cassette is 12 hours for deposition only and 12.5 hours for deposition and trimming.

Because wafer uniformity is not identical over the life of the target, second trim is important for the precise thickness control. Measuring wafers after deposition/trim and performing second trim produces less than 5A standard deviation uniformity required for tight frequency control of the FBAR devices. Figure 6 demonstrates typical results obtained in the AMSystems cluster tool containing aluminum nitride deposition and trimming module on 10,000A films.

VI. SEND AHEAD WAFER PROCESSING

Deposited films sometimes have different film characteristics due to the changes in deposition machine conditions. It is only at the final test that these differences can be detected. It is fairly easy to process one wafer from the batch from the deposition step all the way to the final test. Then adjust deposition based on the data from this "send ahead wafer" and finish the rest of the batch. One such application is silicon dioxide layer used in the bulk acoustic resonator technology. This film is used to adjust TCF (temperature coefficient of frequency) of the device. The amount of temperature compensation per angstrom of SiO_2 during a particular deposition is usually consistent within a deposition batch but can vary batch to batch. All wafers in a batch (usually 25 wafers) have SiO_2 deposition at the same time. One wafer is sent-ahead and is finished in couple of days. Based on the measurements collected on this wafer, SiO_2 is trimmed by 0A to 50A to obtain correct TCF on the entire batch.

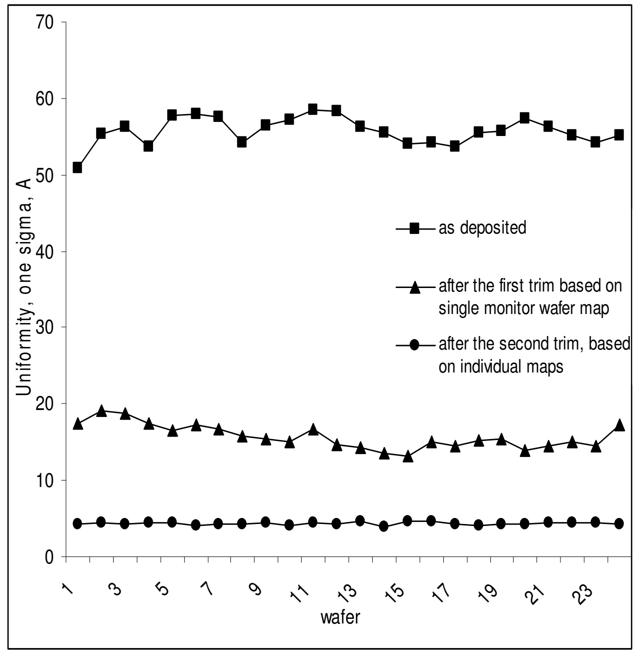

Figure 6: Deposition and trimming in the same tool

VII. SUMMARY

A practical approach to addressing production issues of thickness trimming was demonstrated through data "smoothing", two-step trimming, send-ahead wafer, and deposition/trimming cluster tool. Thickness control necessary in SAW/FBAR/BAW technology was demonstrated.

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