Practical issues with ion beam milling in acoustic wave resonator technologies

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ABSTRACT

Innovative techniques were proven effective in resolving common issues with thickness adjustment by ion beam milling (also known as trimming) [1]. Two-step ion milling offers a highly effective technique for overcoming issues associated with surface oxide in Al, Co, Ni, Fe alloy, Ru and other film's trimming. Films with slow etching oxides were trimmed to within less than 5A from desired thickness and less than 10A total range across the substrate. Uniformity of aluminum nitride (AlN) and silicon dioxide (SiO2) films were improved to less than 8A (total range) using two-step milling. Trimming processes were used to allow using one wafer from a batch to provide compensation feedback in the Bulk Acoustic Wave (BAW) devices [2,3]. Combining ion mill with deposition in the same tool has been proven practical in production and R&D environments. In a standard aluminum nitride deposition with in-situ trimming, thickness uniformity of less than 0.1% was demonstrated.

Keywords: trimming, BAW, milling, thickness, uniformity

1 INTRODUCTION

In the recent years, the size of the cellular phone was reduced dramatically in part due to the propagation of extremely small and high performance filters. These filters are frequently using either BAW or SAW (Surface Acoustic Wave) technologies. As the performance of these filters has continued to improve, it became desirable to be able to control thicknesses of the films used in these technologies to 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. In the last decade several companies used ion beam based machines to improve uniformity of the films. Beam sizes varied from sub-millimeter to tens of millimeters. Eventually, most commercial machines chose the beam size between 5 and 10mm. Much smaller size tended to reduce the speed of processing, larger size reduced the accuracy of the trimming. 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 BAW and SAW to meet frequency control requirements. After the trimming tools became commercially available, other industries started adapting trimming equipment to control thickness in the applications like disc drive magnetic heads.

Initial results enabled commercial use of trimming machines, but as the requirements got tighter and the trimming started being used for different applications the following issues became critical:

(i) Patterned product wafers don't always behave as well as test wafers. Periodically, product wafers can sit around before ion mill trimming for anywhere between few minutes to several days. They are also sometimes 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.

(ii) Another manufacturing issue is that deposited materials can have variable surface properties (such as index of refraction, for example) that thickness measurement tools don't catch, leading to significantly different device performance at final test.

(iii) Most ion beam trimming systems have an etch rate uniformity and repeatability limitations. Etch rate uniformity, for the ion mill trimming tool used in this investigation, is about 1-3% across wafer. Wafer-to-wafer repeatability is about 1-3%. Over the life of the chamber clean cycle etch rate can change as much as 10%. Because, typical trimming is between 100A and 500A, unless frequent etch rate tests are performed, it would not be uncommon to have 30A to 50A variation in final 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.

(iv) 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. Most common problem is a large thickness gradient across small portions of the substrate. Other times, measuring equipment algorithms have problems with specific films or film thicknesses.

(v) Some film characteristics change over time and the final product has electrical characteristics that can't be fixed at the point the devices are measured.

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 use of thickness trimming technology.

2 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 [4], shown in Figure 1. 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 [4]. 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. Beam shape of the source used in this investigation is shown in Figure 2. The size of the beam is about 10mm FWHM.

Figure 1: AMSystems cluster tool

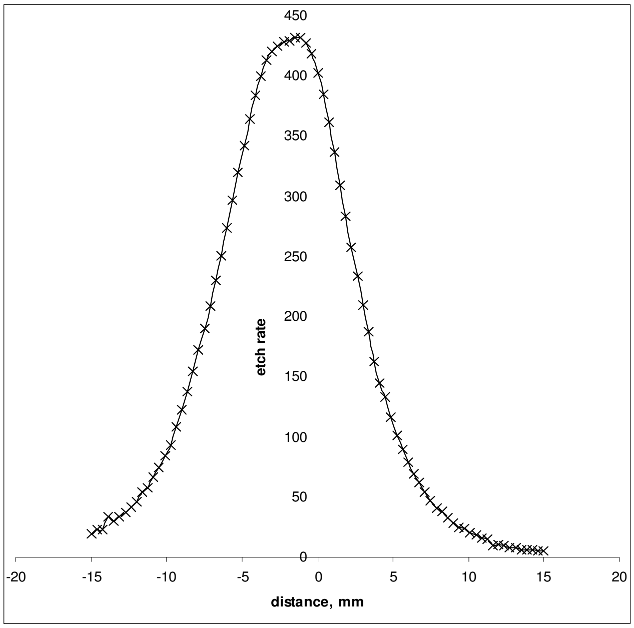

Figure 2: Etch profile of AMSystems ion mill beam

Electrical characteristics of the trimming source are shown in the Figure 3.

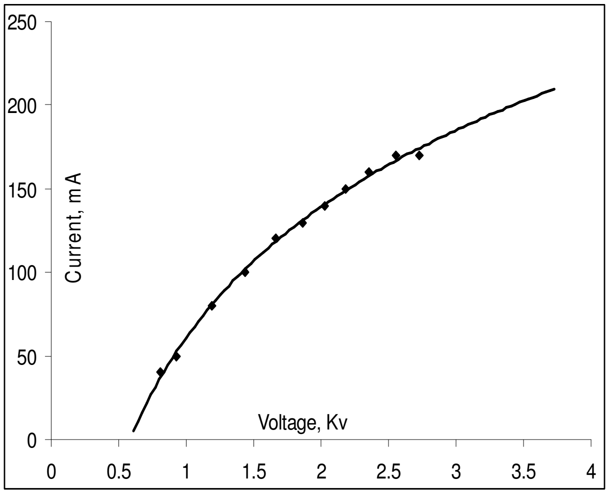

Figure 3: V-I characteristics of the DC trimming source

3 DATA PROCESSING

Thickness uniformity maps are 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. It is also important to be able not only to improve cross wafer uniformity but also to hit the desired target. When thickness is measured on a clean un-patterned monitor wafer it is very easy to get smooth, continuous uniformity thickness map using a single pass trimming. Unfortunately, on patterned product wafers uniformity maps sometimes tend to have a lot of thickness discontinuities. Using a software program such as Matlab™, data can be "smoothed or filtered" into a profile that can be easily used for trimming. An example of raw and "smoothed" data from the same wafer is shown in Figure 4.

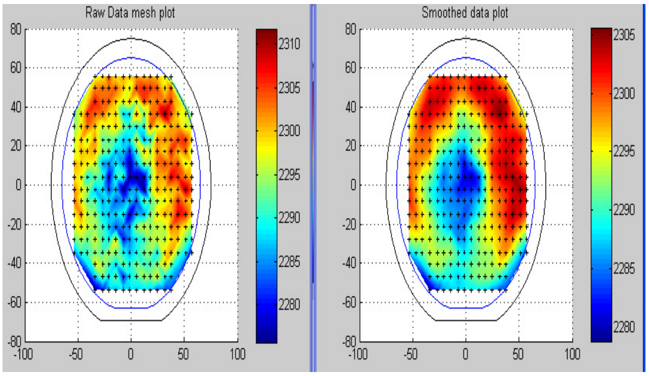

Figure 4: Raw and "smoothed" data

4 TWO-STEP TRIMMING

Another way to improve the final distribution of thickness is to trim about 80 to 90% of the total thickness during the first trim, measure the thickness or another thickness dependant parameter again and then finish the remaining material in the second trim. First trimming is designed to improve uniformity by factor of 4 to 8 and get all dice within 50 to 100A of the final target. The second trimming is done after frequency or thickness is re-measured and gets all dice within <10A of the desired thickness target. One of the best illustrations of the benefit from two-step trimming is Aluminum trimming for Surface Acoustic Wave (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 [1]. Aluminum oxide etches between 2 to 4 times slower than the bulk aluminum. Target removal for aluminum is typically 200A. When targeting 200A removal based on the bulk aluminum etch rate, we remove about 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. Etch rates of different materials trimmed in the AMSystems trimming tool are listed in the Table 1.

In the case of SiO2 films, the final thickness uniformity and wafer-to-wafer repeatability is mostly limited by the accuracy of the thickness measurement. Because second trim removes between 0 and 100A, the final thickness variation is <10A. Reflectometers are commonly used to measure thickness of dielectric films. These machines are fast and can measure up to 100 points per minute. The drawback is that they don't measure index of refraction of the material. Reflectometers work well on the clean test/monitor wafers. When product wafers go through patterning process, small amounts of photo-resist can be trapped on the surface. Reflectometers can measure these areas incorrectly. We split trimming into two steps, 1st trimming 40A less than the final target thickness, 2nd trimming 0A to 40A. 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 reflectometer 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. Trimming was accomplished by moving wafer and source at constant speed and adjusting the power. Setting power to zero at the thinnest location on the wafer produces precise second trimming [4].

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 ion beam trimming tool

Another common problem encountered in trimming is a large thickness gradient or simply a large change of thickness over a small distance. Figure 5 shows improvement in uniformity and wafer-to-wafer repeatability on two-step trimming of SiO2 wafers with a large initial gradient. It can be seen that both wafer to wafer uniformity as well as within wafer uniformity are significantly improved.

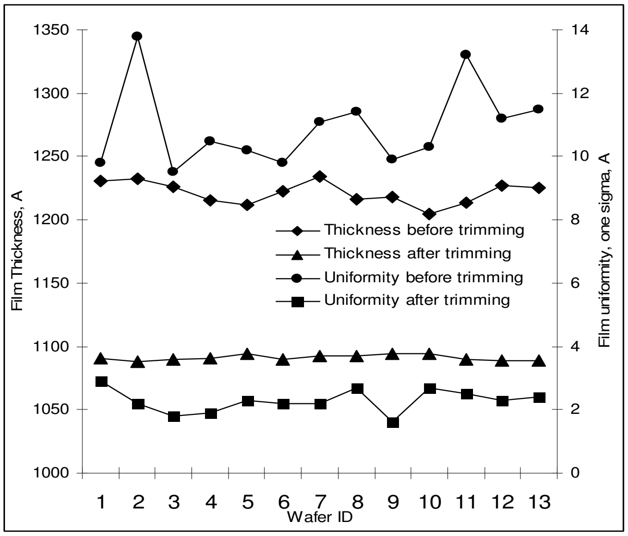

Figure 5: Silicon dioxide repeatability test

5 ONE TOOL DEPOSITION/TRIMMING

In a standard BAW or SAW processes, deposition and trimming are performed in two different systems. When the deposition system and trimming system 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 a BAW process aluminum nitride deposition can be continuously adjusted through the target life. 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. 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 BAW devices. Figure 6 demonstrates typical results obtained in the AMSystems cluster tool containing aluminum nitride deposition and trimming module.

6 SEND-AHEAD PROCESSING

Sometimes, due to the variations in the critical depositions, final product wafers have different characteristics than desired. It is possible to process one wafer from a batch at the critical step process, finish it, measure it; adjust the rest of the wafers based on the final results from the send-ahead wafer. One such application is silicon dioxide layer used in the bulk acoustic resonator technology. This film is used to adjust temperature coefficient of frequency of the device. The amount of temperature compensation per angstrom of SiO2 during a particular deposition is usually consistent within a deposition batch but can vary over period of time. All wafers in a batch (usually 25 wafers) have SiO2 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, SiO2 is trimmed by 0A to 50A. It is important to trim all layers, including electrodes and piezoelectric film, for the best results. If all layers on all wafers have maximum of <20A thickness variation from each other, this technique is very effective. If wafers have a lot of variations from the send-ahead wafer, this technique is much less effective.

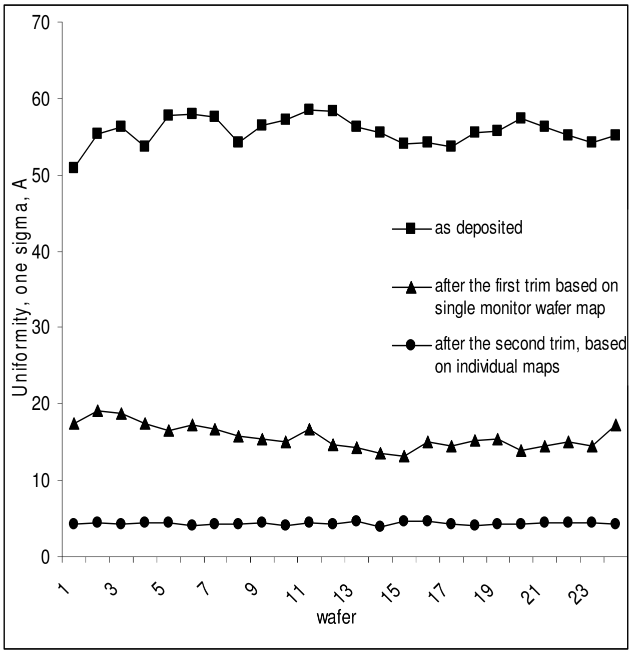

Figure 6: Deposition and trimming in the same tool

7 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/BAW technology was demonstrated.

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