

## Effective Manufacturing Utilizing Mass Metrology

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### Abstract

**In modern manufacturing, measurement decisions are critical to successfully identifying and eliminating sources of process variability. The increasing complexity of today's technology often leads to the implementation of very complex and advanced analytical metrology techniques into the volume production environment. These can be slow and expensive. In this paper it will be shown how mass metrology effectively meets the challenges in quantifying manufacturing variability. Mass change is a measure of process performance, capturing information that a single parameter measurement, such as thickness will not.**

### INTRODUCTION

In deploying metrology for process monitoring the decision as to which metrology technique is used has traditionally centered on the key single parameter that needs to be measured. Film deposition will lead to the adoption of a thickness measurement; in etch, critical dimension (cd) measurement will lead to the adoption of some form of microscopy technique and so on. The disadvantage of single parameter metrology is that there are often many other parameters that can vary and which might be missed, thus impacting fab yield. This results in the adoption of complex and often slow metrology forcing production engineers into a compromise between the need to make a measurement and the number of measurements that can economically be made. Compromises on the number of measurements on a wafer, or the number of wafers to be measured increases the chance of undetected problems and exposes the fab to more yield risk.

Mass metrology offers an alternative to single parameter metrology. As a process monitor mass, is able to measure sequential change in a process uncovering the true mean of the process, rapidly and reliably alerting production engineers to changes in that mean. When mass change indicates that the process is performing within specification, wafers can continue to the next process step without the need for further metrology. When mass change indicates a process has changed beyond specification, process engineering decisions can immediately be made. Perhaps the

wafers need to be pulled from the production line altogether, or the wafers can be routed to the appropriate analytical metrology tool to identify the change and initiate the appropriate response. Mass measurement is acting as a gatekeeper for critical parametric measurements. The result is immediate and measurements are performed on the product wafers, providing information on the exact process carried out.

### MASS METROLOGY

Mass metrology is a sophisticated weight measurement where weight variability of the measured wafer is determined and then compensated for, in the measurement. Process change is accurately determined by mass measurement before and after the process step. With a resolution of 10 $\mu$ g and repeatability of less than 80 $\mu$ g, mass metrology is capable of measuring process variations that are typically equivalent to film thickness or etch depth variations in the Ångström region. Wafer contact is backside only, and a wafer measurement will typically take less than 1 minute, making this ideal for fast measurement of product wafers.

### PRODUCTION IMPLEMENTATION

While there are many proven production applications for mass metrology<sup>[1,2,3]</sup> this paper will concentrate on how mass metrology has been effectively implemented in a Bulk Acoustic Wave (BAW) filter manufacturing process. A BAW filter generates acoustic waves piezoelectrically by transforming electromagnetic waves in the frequency range of 1 to 5GHz. The actual frequency of the filter is defined by the layer thicknesses in the device - the device comprises thin film layers that make up the piezoelectric resonator, the electrodes, and in the case of solidly mounted resonators, the Bragg reflector – and the acoustic delay and impedance of the active layers in the device.

A BAW production line is metrology intensive, the engineer is faced with many measurement choices and the need for measurement is driven by the very strong relationship between the individual layers of the device and the final frequency of the device. Variations in layer

properties will cause variations in the actual frequency compared with the design or target frequency, negatively impacting yield.

BAW DEVICE MODELING

The frequency of a BAW resonator is determined by how long an acoustic wave takes to travel through a layer, the “acoustic” thickness, and how an acoustic wave is reflected and transmitted at an interface, the “acoustic” reflectivity (fig. 1). In modeling a resonator density and thickness are critical

$$\omega \cdot \frac{d}{v_L} = \text{frequency} \cdot \text{acoustic delay}$$



$$Z_L = \rho \cdot v_L = \text{density} \cdot \text{acoustic velocity}$$

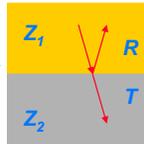


Figure 1 Acoustic Delay and Acoustic Velocity

components. For density, theoretical values are typically used but in the manufacturing process both density and thickness will vary, presenting the need to measure and correct for this variance. To correct for variations, an accurate model with layer thickness (Rudolph Metapulse200) and mass change (Metryx Mentor OC23) information is used to adjust for film density (fig 2). Actual material densities are characterized and fed back to the device designers.

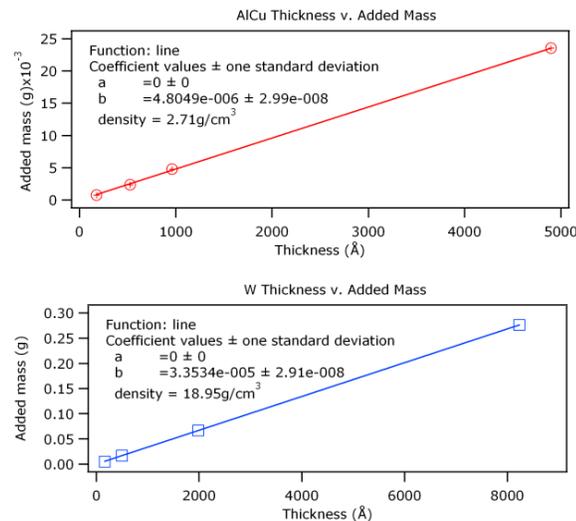


Figure 2 Deposited film density for Al and W

FILM DENSITY

Film density can provide a quick and clean method to characterize the changes in film properties, for example, density measurement is used in determining the dielectric constant variation of SiOC low k films using the Clausius-Mosotti relationship<sup>[4]</sup>, and with low k films critical for advanced technology nodes such as 32nm and beyond, this is an important application for density measurement.

The importance of density in the production of the BAW resonator is shown in fig. 3, where the sensitivity of the resonator frequency (fs) and coupling coefficient (K2e) to the density of the W electrode is shown. It can be seen from this data that a 2% error in W density leads to an 8Mhz shift in resonator frequency and a 0.4% shift in coupling coefficient. Referring back to fig. 2, the measured film density for W is 18.95g/cm3. The theoretical value for W

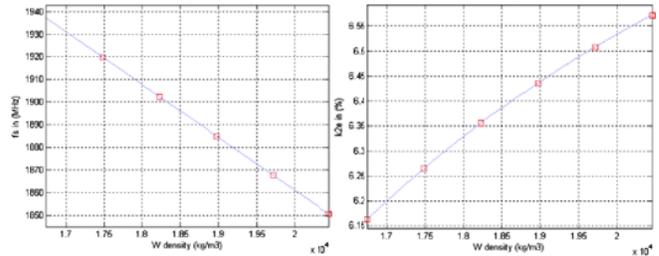


Figure 3 Frequency (left) and coupling sensitivity (right) to density

Density is 19.3g/cm3. Therefore, without the correction between the theoretical density of W used in design and the actual film density produced in the BAW line it can be seen that the difference between the two would be close to 2% presenting the risk of a significant shift in resonator frequency from the designed target frequency.

MATERIAL AND PROCESS SELECTION

Density can be an important indicator of a films suitability for a given purpose. Consider, for example, the need for a SiN passivation layer in the BAW process. This film is typically deposited at a high temperature to get the desired film properties. But the high temperature process can cause integration issues, such as the formation of hillocks in a temperature sensitive underlying layer. Lower temperature SiN films are possible but this also leads to lower density films. Typically, optical metrology such as ellipsometry is used to measure the SiN film thickness and refractive index (RI). However film density does not correlate with RI as shown in fig. 4 and so density changes cannot be tracked with this method. In this case mass metrology is needed to monitor the density variations in the deposited SiN film.

The selection of process materials is always a challenge for process integration and provides another driver for

metrology. For example, in selecting the chemicals used in a wet etch process not only does the chemical need to have the capability to etch the desired material; it also has to be highly selective to other materials in the device. To investigate the required chemical for a post dry etch residue clean, mass

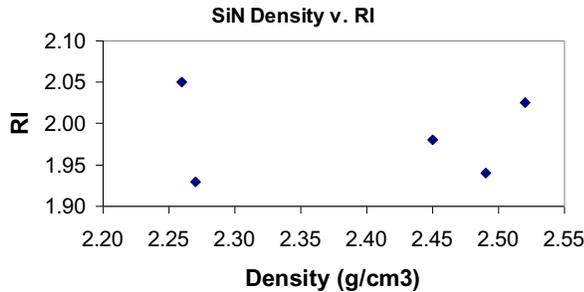


Figure 4 Density vs refractive index

metrology is used to accurately determine the removal rate of the materials exposed to the etchant. Fig. 5 shows the results of such a test for the chemical EKC265. The mass removed has been converted into a thickness value and it can be clearly seen that 20Å of W has been removed. Adoption of this chemical would therefore require a 20Å loading of W in the deposition process to maintain the appropriate target thickness, which as has already been shown (fig. 3), is critical to resonator frequency.

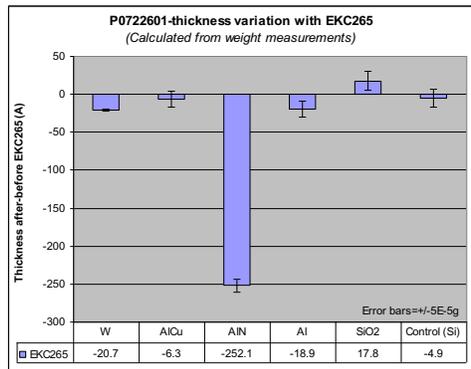


Figure 5. Wet etch tests with mass metrology

### METROLOGY CHOICES

As we have stated in the introduction, most metrology choices are driven by the need or desire to measure a single parameter. But there are many cases where there are physical, technical or commercial limitations in this choice. For example, in metal deposition processes the choice of metrology is often limited and governed by the thickness of the metal, and also by the nature of the underlying metal.

In the case where thin film metrology is complex due to the multi-layers involved the metrology cycle time can be long. In the BAW line mass metrology is used to determine a “true mean” value while thin film metrology is used on a

sample of a few wafers to maintain the fidelity of the within wafer information. A good example is the physical vapor deposition of a multilayer film. When the number of layers is high (>3) or if the same material repeats within the stack it can be challenging to get an accurate total film thickness. Thermo-acoustic metrology methods, for example, can determine layers such as this but the modeling time increases with the complexity of the stack. Therefore a few wafers are sampled from within the production lot for thin film metrology to get individual layer thickness and within wafer uniformity data. Since the uniformity profile does not significantly change within the lot, the sample size need not be a large percentage of total number of wafers. To get information on all of the wafers, mass metrology is used to get a mass calculated “true mean” thickness. The uniformity profiles can be scaled to each wafer based on the data from the sampled wafers if this is necessary for any feed-forward applications. The mass calculated thickness “true mean” value can be used as SPC data without the time delay of using thin film metrology for each wafer. This combination of metrology draws on the strengths of each technique to reduce the cycle time without sacrificing data loss.

One example from the BAW resonator line is the measurement of a deposited layer of aluminium on top of a patterned layer of the same material. Here, the influence of the underlying layer causes erratic results in the measurement of the deposited top layer (fig 6a) suggesting at best an average overshoot of 100Å from the target deposition thickness of 1200Å and at worst a number of wafers with a large excursion that may need to be taken from the production line.

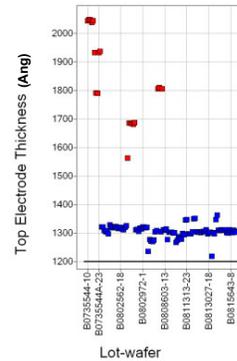


Figure 6a Al Thickness Measurement

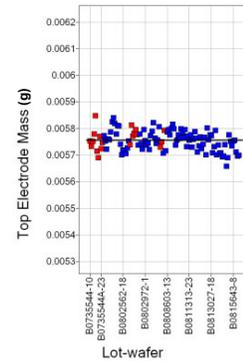


Figure 6b Al Mass change

However, mass metrology of the same wafers (fig 6b) shows that the wafers are, in fact, very close to the target thickness. The average mass change is calculated to be equivalent to a thickness of 1206Å, with a range of 40Å. Because of the similarity of the films, acoustic thickness measurement was unable to recognize the film interface. Both layers are contributing to the measurement hence the erratic results. In this case mass metrology has replaced the thickness measurement and is used as a production monitor and SPC

data source for this layer with the added benefit that mass measurement is not only sensitive to thickness changes but also to density and step coverage changes.

Metrology choice is often driven by the need to deliver control in a process or sequence of processes. For example, in the formation of buried capacitors in DRAM production mass metrology has been successfully used as an etch process monitor, feeding forward the mass change data in an APC loop to control the final volume of a trench capacitor<sup>[5]</sup>. Similarly, in BAW production, mass is used in a number of measurement points in the wafer grinding process. BAW filters are commonly used in cell phones where each device is competing for increasingly finite real estate within the phone. While BAW devices are considerably smaller than the SAW filters they replace, there is still the need to deliver a compact and thin package. To control package height finished BAW wafers are typically thinned to around 150µm. The process involves a number of key measurements.

Firstly, due to significant variability in the incoming material, the thickness of the carrier and the wafer itself needs to be known so that the correct wafer grinding process can be run. Prior to the adoption of mass metrology for these measurements, carrier thickness was determined with drop measurement by micrometer (a manual process that was time consuming, prone to error and wafer breakage), and BAW wafer thickness was measured by acoustic reflection probing (a time consuming and relatively complex technique). Mass measurement can be used to determine wafer thickness rapidly and has been shown to correlate well to the two techniques it has replaced (fig. 7).

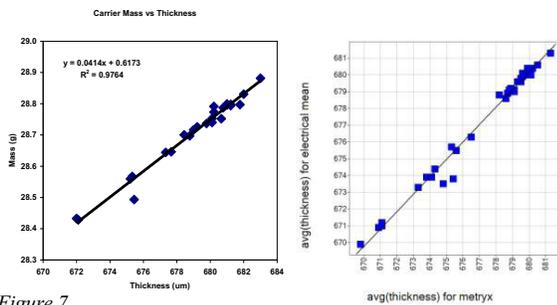


Figure 7  
 Left: Carrier mass and drop height micrometer thickness correlation  
 Right: BAW wafer mass and acoustic reflection thickness correlation

Secondly, the grinding process is fairly coarse and puts some strain onto the thinned wafer. A post grind dry etch process is used to remove damage and to relieve stress, reducing wafer bow. As this etch process is also used to achieve the final target thickness of the finished wafer, the post grind thickness needs to be known so that the correct etch recipe can be selected. The mass change resulting from the grind process is used to calculate the finished post grind wafer thickness. This information is then fed forward to the dry

etch process such that the finished wafers all have the same final thickness (fig. 8).



Figure 8 Upper plot: Thickness delta from target.  
 Lower plot: product wafer thickness determined by mass metrology

## CONCLUSIONS

Mass metrology has been effectively adopted across the BAW production line. The ability to provide data quickly and easily directly on product wafers allows for the introduction of SPC methodology resulting in a tight control on process mean, leading to improved yields. Process risk is lowered from obtaining a better understanding of material characteristics as well as increasing the metrology coverage of production wafers. Finally rapid measurements allows for process engineering teams to react quickly to process drift and excursion, reducing the potential yield hit of these events.

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