Full Metrology Solutions for Advanced RF with Picosecond Ultrasonic Metrology

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ABSTRACT

Picosecond Ultrasonics (PULSE™ Technology) [1] has been widely used in thin metal film metrology because of its unique advantages, such as being a rapid, non-contact, non-destructive technology and its capabilities for simultaneous multiple layer measurement. Measuring velocity and thickness simultaneously for transparent and semi-transparent films offers a lot of potential for not only monitoring process but offers insight into the device performance. In this paper, we show Picosecond Ultrasonics provides a complete metrology solution in advanced radio frequency (RF) applications. This includes measurement of various thin metal films for wide thickness ranges with extremely excellent repeatability which could meet stringent process control requirements, simultaneous multilayer measurement capability, and simultaneous measurement of sound velocity and thickness for piezoelectric films which play a key role in the performance of RF devices.

INTRODUCTION

All signal processing requires filters that evaluate signals and remove undesirable frequencies while preserving desirable frequencies. Modern smartphones are required to filter, transmit, and receive paths for 2G, 3G, and 4G in up to 15 bands, as well as support Bluetooth, Wi-Fi, and other wireless communications. Phones such as these could require up to 40+ filters. The revolution of communication technology is driving a dramatic increase in the number of RF bands that smartphones and other mobile devices must support which significantly increases the number of RF filters. Not surprisingly, with the move to higher frequencies and 5G, the complexity of the devices is expected to increase as well as the performance requirements. At these higher frequencies, surface acoustic wave (SAW) filters require smaller width and pitch of the interdigital transducers, which limits their performance. Bulk acoustic wave (BAW) filters is the primary technology employed above 2.5GHz [2]

METROLOGY REQUIREMENTS AND CHALLENGES

Such advances in filter technologies will place stringent demands on manufacturing which in turn will require very accurate metrology techniques.

The thickness for the full stack can shift the center frequency and affect the device performance, and piezoelectric layer thickness control is key for SAW and BAW devices. The frequency accuracy (3σ) of 0.1% requires film thickness control within the same accuracy or better. Thin film deposition systems with wafer uniformity of (3σ <2%) cannot meet these standards. To overcome this limitation, semiconductor equipment manufacturers have developed a trimming process. Monitor wafer thickness measurements are helpful for characterizing deposition chambers and process qualification but do not help with device-level process control. RF filter manufacturers require the ability to not only measure the thickness but would like to be able to adjust the thickness via a trimming process as thickness is directly correlated to the filter characteristics. It becomes important to accurately measure thickness on multiple sites on production wafers. Typically, the measured thickness is forwarded to a trimming tool to adjust the thickness profile across the wafer and improve the thickness uniformity to enhance device performance and yield. Another parameter that is also helpful for process control is the ability to monitor the acoustic velocity. Velocity variations can also shift center frequency and affect RF device performance.

We have previously demonstrated the application of Picosecond Ultrasonic Technology for characterizing the inter-digital transducer (IDT) thickness and sound velocity of SiO_2 [3]. IDT thickness needs to be controlled at Angstrom level to achieve the desired filter frequency in the final product. The excellent repeatability (3 sigma < 0.15Å) and accuracy of the technique enabled measurements on device wafers and met the tight process control requirements.

In this paper, we discuss other use cases of PULSE Technology for RF filter process monitoring and control.

PICOSECOND ULTRASONIC TECHNOLOGY: BASICS ABOUT PICOSECOND ULTRASONIC AND APPLICATIONS

Picosecond Ultrasonic Technology is a non-contact, non-destructive pump-probe laser acoustic technique for film thickness, sound velocity, Young's Modulus, density, and roughness measurement. It has been widely adopted as the tool-of-record for metal film thickness metrology in semiconductor fabs around the world. An acoustic wave is launched in a film by a 100fs laser pulse (pump) focused onto the film surface. The acoustic wave travels away from the surface through the film at the speed of sound in the film. At the interface with another material, a portion of the acoustic wave is reflected and comes back to the surface while the rest is transmitted. The probe pulse detects this reflected acoustic wave as it reaches the wafer surface. One can detect the change of optical reflectivity that is caused by the strain of acoustic wave. Using standard sound velocity in the material, thickness can be readily extracted using first principles technique. In addition to thickness, depending on applications and the stack up of films, film density, sound velocity, Young's Modulus, and surface roughness can also be measured.

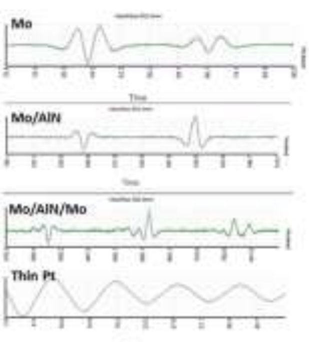
Picosecond Ultrasonic Technology provides excellent repeatability and stability for single layer and full stack thickness measurements. The small beam spot and rapid measurement time can enable direct measurement on actual device structures and allows measurement of multiple die. The capability of measuring both thickness and sound velocity at the same time gives the Picosecond Ultrasonic technique unique technological advantages.

ADVANTAGES OF PICOSECOND ULTRASONICS FOR ADVANCED RF APPLICATIONS

The following sections are some of the recent advanced applications in RF filter process control.

1.1. Typical filmstack and tight control for film thickness

Figure 1 and table 1 show typical measurement signal (left) and performance (right) of Mo, Mo/AlN, Mo/AlN/Mo, and Pt of Picosecond Ultrasonics used for a BAW RF device. As we can see the piezoelectric layer has the repeatability of 0.03% for 3 sigma while the repeatability for both top electrode and bottom electrode metal layers are better than 0.04%.



Stack	Layer	3 sigma
Mo	Mo	0.03%
Mo/AlN	Mo	0.03%
	AlN	0.03%
Mo/AlN/Mo	Mo	0.04%
	AlN	0.03%
	Mo	0.03%
Thin Pt	Pt	0.06%

Figure 1. Typical measurement raw signal from RF stacks, and Table 1. Typical repeatability performance for different stacks of common RF applications

1.2. Device level process control for RF devices

More and higher frequency bands require tighter process control to improve device performance. 3σ frequency accuracy must be < 0.1%. To meet this target, the uniformity of the deposited thin films must be roughly < 0.1% as well. But the best thin film deposition system achieves 3σ uniformity across the wafers of no better than 2%. To overcome this limitation, equipment vendors have developed a trimming process. Picosecond Ultrasonic Technology has been adopted to monitor the pre- and post- trimming process because of its accuracy and robustness.

The following two figures show measurement of SiO_2 thickness at pre- and post- trimming. The thickness is scaled to protect customer confidentiality. The piezoelectric layer film thickness was measured by Picosecond Ultrasonics before trimming and after trimming. For both wafers, as shown in left and right, you can see that thickness varies in a wide range and is well controlled as designed using trimming process for all measured sites.

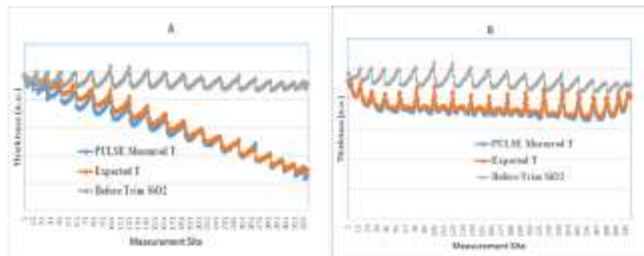


Figure 2. Pre- and post-trimming process monitored by Picosecond Ultrasonics

1.3. Wide thickness range

With Picosecond Ultrasonic Technology, depending on tool configuration, we can measure a film thickness range from 50Å to ~20µm depending on material parameters. Figure 3 shows typical repeatability performance for Mo, W, AlCu, and TiW films ranging from 100Å to 15000Å. We can see excellent repeatability for all thickness range. Because of its first principle and standard-less nature of Picosecond Ultrasonics, we can use one single recipe to cover the whole thickness range from tens of Angstroms to tens of microns with excellent repeatability. We can see that 3 σ of dynamic repeatability is below 0.20% for these films.

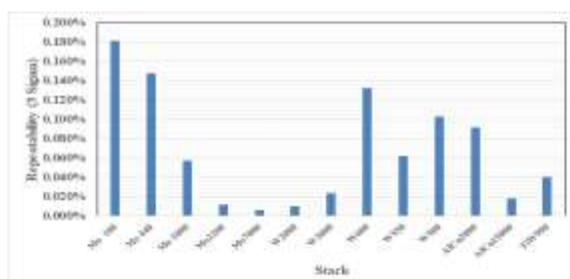
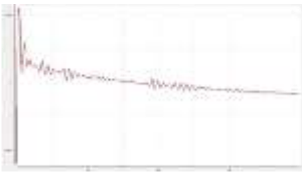


Figure 3. 3σ repeatability for typical filmstack used in RF

1.4. Multilayer measurement capability and accuracy

Tight control of frequency for RF filters relies on even tighter thickness control for every layer in the stack although the piezoelectric layer plays the most critical role. Figure 4 shows a typical measurement signal from a BAW device using Picosecond Ultrasonics. From the measurement, we report the thickness of six layers in the stack. The thickness and repeatability are shown in table 2.

We rescaled the thickness to protect customer confidentiality. The accuracy has been confirmed with TEM with R^2 linear correlation higher than 0.97 for all layers. For the piezoelectric layer, the linear correlation R^2 between Picosecond Ultrasonics and TEM cross section is about 0.998% with the slope about 1.0.



	Average Thickness		
Layer	Element	Thickness [a.u.]	3 Sigma
1	Top Metal	136.6	0.046%
2	Top Electrode	106.2	0.017%
3	Piezoelectric Layer	1753.1	0.095%
4	Bottom Electrode	153.1	0.020%
5	Bottom Metal	98.6	0.156%
6	Bottom Layer	126.4	0.253%

Figure 4. Picosecond Ultrasonic measurement signal of a multilayer stack and Table 2. Thickness (arbitrary unit) and dynamic repeatability (3σ) for each layer

1.5. Simultaneous measurement of thickness and sound velocity

Piezoelectric layer thickness and sound velocity variation and uniformity is critical for center frequency control in RF devices. For piezoelectric films, such as oxide or AlN films on silicon or other metal transducers, the opaque substrate absorbs energy from the pump pulse, launching a sound wave that travels up through the transparent film at the speed of sound. The strain causes a local change in the index of refraction of the film. The partial reflection of the probe beam from the moving sound wave, combined with the partial reflection from the film surface, leads to destructive and constructive interference at the detector [4]. As a result of this time dependent interference, the measured signal oscillates with a period, τ, from which the sound velocity (V) in the material can be determined by

$$V = \frac{\lambda}{2n\tau cos\varphi}$$

where n is the index of refraction, λ is the wavelength, and φ is the angle of refraction. We can also report Young's Modulus calculated from measured sound velocity. Figure 5a and 5b show the typical performance for thickness and sound velocity measurement on oxide films. We can see that 3σ of repeatability at site level for both thickness and sound velocity is below 0.06%. For wafer average of nine site measurements, 3σ of the repeatability is below 0.02%. The excellent repeatability makes it possible for tighter control of the piezoelectric layer and then adjust the center frequency of filters.

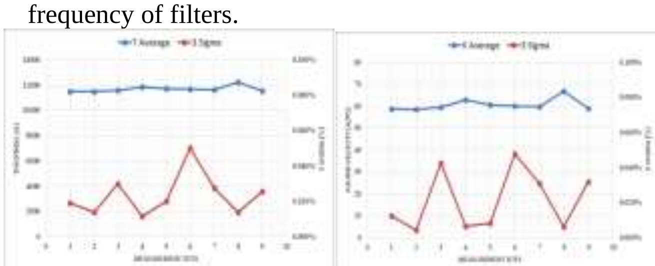


Figure 5a). Example of SiO_2 *thickness and repeatability by Picosecond Ultrasonic. 5b). Example of* SiO_2 *sound velocity and repeatability by Picosecond Ultrasonic.*

1.6. Long term stability and tool matching

Long term stability of the tool and tool-to-tool matching are extremely critical for process control in a high volume manufacturing environment. First principle nature of Picosecond Ultrasonics and its intrinsic standard enables its long-term stability without standard calibration as most metrology tools require. Its long-term stability is better than 1.0% for 3σ and tool-to-tool matching is better than 0.5% at site-level. Typical performance for within wafer average is ~ 3σ < 0.3% for both long-term stability and tool-to-tool matching for wafer average thickness. Figure 6 shows dynamic repeatability and tool-to-tool matching for three layers, top layer Mo, piezoelectric layer AlN, and bottom Mo of six wafers. We can see that dynamic repeatability is well below 0.05% for all three layers of the six wafers, and tool-to-tool matching is well below 0.25%.

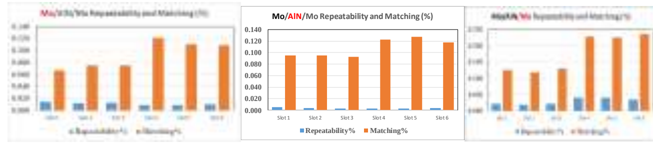


Figure 6. Mo, AlN and Mo dynamic repeatability and tool to tool matching for the tri-layer stack Mo/AlN/Mo.

1.7. Concentration measurement

Doping into piezoelectric layer can increase piezoelectric coefficients, soften the material, increase permittivity, and boost electromechanical coupling K^2 significantly. The PULSE technique has also shown sensitivity to detect concentration changes by monitoring the changes in velocity. Figure 7 shows sound velocity of AlN has a clear correlation with element X doping level with $R^2 = 0.97$.

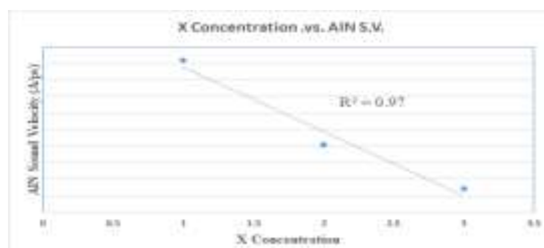


Figure 7. Correlation of element X concentration and AlN sound velocity

RF filter process control requires stringent metrology due to tight process tolerances. PULSE technology can measure thickness, sound velocity, Young's Modulus and these are critical to the RF filter process that has very tight process control limits. The PULSE technique can also simultaneously measure full stacks for multilayer metal stack measurements with excellent repeatability and long-term stability. In RF filter applications, temperature compensation top SiO_2 for SAW and sacrificial top metal layer for BAW are monitored to adjust center frequency. PULSE technology is widely used to monitor the device level trimming process to enhance yield and reduce cost. With the implementation of Discover® data analytics software, information turnaround time for process control and monitoring is enhanced.

REFERENCES

[1] C. Thomsen, H. T. Grahn, H. J. Maris, J. Tauc, Phys. Rev. B, vol. 34, 1986, pp. 4129-4138

[2] R. Aigner, 2008 IEEE Ultrasonics Symposium, 2008.
[3] J. Dai, R. Mair, K. Park, X. Zeng, P.Mukundhan, C. Kim, and T. Kryman, March 18-19, 2019 CSTIC, Shanghai, China
[4] J. L. Arlein, S. E. M. Palaich, B. C. Daly, P. Subramonium, and G. A. Antonelli, J. of Appl. Physics, vol 104, 2008, pp 033508 1-6