Advantages of Picosecond Ultrasonic Technology for Advanced RF Metrology

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ABSTRACT

Picosecond Ultrasonics (PULSE™ Technology) has been widely adopted as the tool-of-record for metal film thickness metrology in semiconductor fabs around the world. It provides unique advantages, such as being a rapid, non-contact, non-destructive technology, and has capabilities for simultaneous multiple layer measurement. In this paper, we describe the unique advantages of Picosecond Ultrasonics for advanced radio frequency (RF) applications. RF filter process control requires stringent metrology due to tight process tolerances. The first principles-based PULSE technology does not require external calibration standards and provides robust measurement capability for multi-layer thickness measurements. For advanced RF applications, the capability of PULSE technology to measure both velocity and thickness simultaneously for transparent and semi-transparent films offers a lot of potential for not only monitoring processes but offers insight into the device performance. The PULSE technique can also simultaneously measure full stack for multilayer metal stack measurements with excellent repeatability and long-term stability which makes process control more efficient and reliable. Fast throughput makes it possible for a high sampling rate for RF applications which is the key for device level process control and yield improvement.

INTRODUCTION

ADVANCES IN RF TECHNOLOGY AND METROLOGY CHALLENGES

The global RF semiconductor market size is growing rapidly at a CAGR of 8.5% in the next five years from 17.4 billion in 2020 to 26.2 billion USD in 2025 [1]. The rollout of 5G technology and its enabled Internet of Things (IoT) are the main driving force for this growth. Each 5G device requires up to 100 filters to make sure each band is isolated to avoid interference that will drain battery life, reduce data speeds, and cause dropped calls. RF filters are becoming more and more critical for all signal process applications. 5G devices require Bulk Acoustic Wave (BAW) filters which can work better at higher frequencies [2]. With more and more filters to fit into a device, the size of filters is also shrinking dramatically in three dimensions. These advances in filter technology place stringent demands on manufacturing which in turn requires accurate and precise metrology techniques. Both thickness and acoustic properties of the piezoelectric layer determine the frequency response of filters. Thickness accuracy and uniformity requirements for the films are beyond what process tools can offer at deposition and there are several options available to achieve such tight controls post-deposition. Metrology techniques employed for characterizing these properties must meet the sensitivity, accuracy, and stringent repeatability requirements. The thickness of the full stack and especially the thickness and sound velocity of the piezoelectric layer are key to realizing the extremely tight process control of frequency accuracy (3σ) of 0.1% or better [4]. A high sampling rate on a hundred-micron level device is needed to make sure all devices across the wafer can meet the requirements which require fast throughput with a small measurement probe.

PICOSECOND ULTRASONIC TECHNOLOGY: BASICS AND APPLICATIONS

Picosecond Ultrasonic Technology (PULSE™) 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 measurements 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 [3].

ADVANTAGES OF PICOSECOND ULTRASONICS FOR ADVANCED RF APPLICATIONS

PULSE technology as implemented in the MetaPULSE® metrology system is a non-contact, non-destructive first principle technique. It provides the capability for measuring metal films from 50Å to 12µm with the option to extend to 35 µm. The laser beam is focused to a tight spot (7x10µm) on the wafer, enabling measurements on devices (15µm). Measurements take a few seconds per site and the high throughput allows mapping of the whole wafer in minutes.

Measurements are used to feed forward to the trimming process to adjust the center frequency and improve across wafer and wafer to wafer variability. Also, when combined with frequency measurements through Onto Innovation's Discover® software, value added statistical processing control (SPC) is provided to improve yield.

In this paper, we demonstrate how Picosecond Ultrasonics can provide a unique and efficient metrology solution in advanced radio frequency (RF) applications because of the advantages described previously. Additionally, in high volume manufacturing one of the critical requirements is the ability to have robust capability to cover process variations in addition to excellent repeatability, long term stability, and tool-to-tool matching. The ability to measure multi-layer stacks eliminates the need to measure on monitor wafers and provides direct feedback for process monitoring and control.

3.1 First Principle Techniques

One of the unique value propositions of the Picosecond Ultrasonic technology is that it offers first-principle approach to modeling the measured data. Thickness measurement relies on locating the echoes, transit time of the acoustic pulse through the films, for thickness calculation. Using known speed of sound from the literature, thickness can be readily calculated without the need for additional calibration. Competing technologies like X-ray metrology require daily or weekly standards and cannot measure repeating layers in a multi-layer stack. Also, depending on how the filmstacks were developed, operator-induced errors or impact to accuracy is common. Time-to-solution (TTS) is another important parameter in developing recipes and with the PULSE system, models are developed in a few hours and don't need to be constantly adjusted to account for variations.

3.2 Wide thickness range and excellent repeatability

With Picosecond Ultrasonic Technology, depending on tool configuration, we can measure a film thickness range from 50Å to ~35µm depending on material parameters. Figure 1 shows typical dynamic repeatability performance for AlCu, Cu, TiN, W, Mo, AlN, Cr, Ru, and Ti films ranging from 300Å to 9000Å. We can see excellent repeatability for all thickness ranges, mostly less than 0.10% for 3 sigma of 9 point wafer average thickness. Because of the 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.

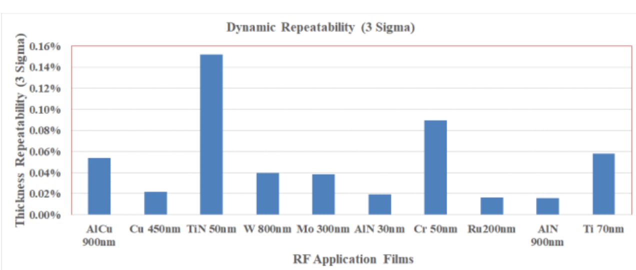


Figure 1. Typical repeatability performance for different stacks of common RF applications

3.3 Multilayer measurement capability and accuracy

The accurate control of thickness for the full stack is the key for frequency control for RF filters, and the center frequency relies on tighter thickness control for every layer in the stack although the piezoelectric layer plays the most critical role. One of key advantages for Picosecond Ultrasonic technology is its simultaneous measurement capability for multilayers stack. We have demonstrated measurements of up to eight layers in a multi-layer stack with excellent repeatability for each layer. Figure 2 shows typical measurement performance from a BAW device using Picosecond Ultrasonics. From the measurement, we can report the thickness of five layers in the stack of metal A/metal B/AlN/metal B/metal C simultaneously. Metal A, metal B, and metal C are different metal films. We can see that 3-sigma of thickness for all five layers is less than 0.1%. Another advantage of Picosecond Ultrasonic technology is that it can measure multiple layer thickness in the stack with the same material, in this case Ru that is impossible for some metrology techniques used in the RF field.

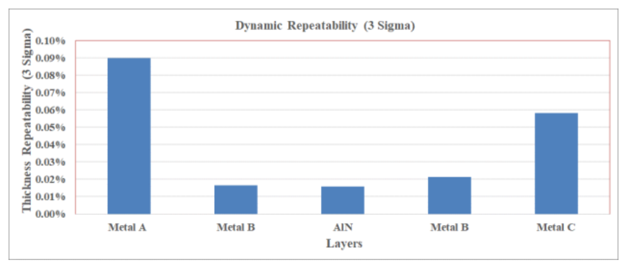


Figure 2. Thickness dynamic repeatability (3σ) for each layer of a five-layer stack metal A/metal B/AlN/metal B/metal C.

3.4 Simultaneous measurement of thickness and sound velocity

Both thickness and sound velocity of the piezoelectric layer play critical roles for center frequency control in RF devices. One of the very key advantages of Picosecond Ultrasonic technology is its capability to measure both thickness and sound velocity simultaneously for the piezoelectric layer. 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 [5]. 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 3a and 3b show the typical performance for thickness and sound velocity measurement on aluminum nitride. We can see that 3σ of repeatability at site level for both thickness and sound velocity is below 0.050%. The excellent repeatability makes it possible for tighter control of the piezoelectric layer and then adjust the center frequency of filters.

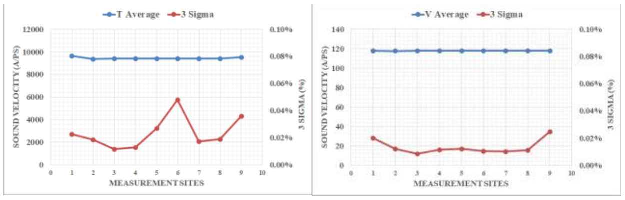


Figure 3a). Example of AlN *thickness and repeatability by Picosecond Ultrasonic. 3b). Example of* AlN *sound velocity and repeatability by Picosecond Ultrasonic.*

3.5 Long term stability and tool matching

Because of tight process control requirements for RF filters, comprehensive measurement over a lot of sampling sites per wafer are necessary to provide more accurate monitoring for more devices per wafer. This will need a lot of metrology tools in the production line, and excellent matching is a must to make sure every tool delivers the same performance. Long term stability of the tool and tool-to-tool matching are extremely critical for process control in a high-volume manufacturing environment.

As discussed previously, because of the first principle nature of the technique its intrinsic long-term stability is excellent and tool-to-tool matching is better than 0.5% at site-level. Typical performance for within wafer average is 3σ < ~0.3% for long-term stability. Figure 4 shows site-level tool-to-tool matching for three layers, a). bottom electrode layer Mo, b). piezoelectric layer AlN, and c). top electrode Mo. We can see that measurements from different tools show the exact same trend, and tool-to-tool matching for wafer average is well below 0.10%.

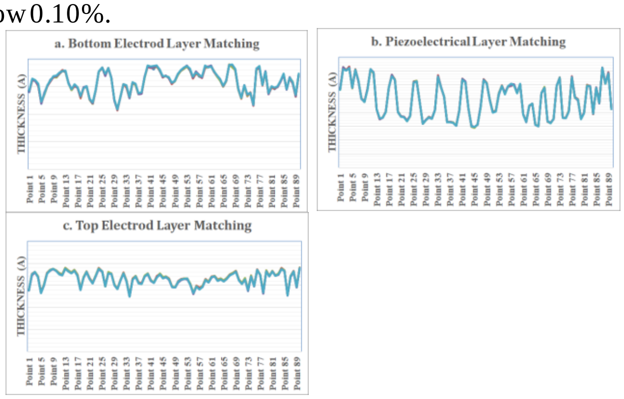
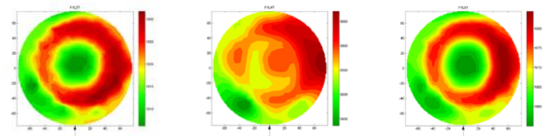


Figure 4. Site level of a). bottom electrode Mo, b). AlN and c). top electrode Mo tool to tool matching for the tri-layer stack Mo/AlN/Mo.

3.6 Production use-case

Picosecond Ultrasonic technology has been widely adopted by advanced RF filter manufacturers for monitoring the pre-and post- trimming process not only because of its accuracy and robustness, but also because the rapid measurements coupled with the small spot size make device level process control possible. More and higher frequency bands require 3σ frequency accuracy < 0.1%. To meet this target, the uniformity of the deposited thin films must be roughly < 0.1% as well. Currently, thin film deposition systems cannot meet this tight requirement and 3σ uniformity across the wafers is no better than 2%. To overcome this limitation, a trimming process has been developed and Picosecond Ultrasonic technology has been widely used to monitor device level thickness variations for advanced RF applications. A very high sampling rate has become possible for device level process control across the wafer because its fast throughput and small spot size. Figure 5 shows ~ 400 point measurement for three layers of a BAW device, a). bottom electrode layer, b). piezoelectric layer, and c). top electrode layer respectively.



a b c

Figure 5. Nearly 400 measurement site maps for a). bottom electrode Mo, b). AlN and c). top electrode Mo for the tri-layer stack Mo/AlN/Mo.

CONCLUSIONS

RF filter process control requires stringent metrology due to tight process tolerances. PULSE technology has been proven to be the only metrology technology to meet the challenges demanded from the tight process control limits for advanced RF applications. With its unique technical advantages, PULSE technology delivers excellent repeatability for tight process control, and it can measure both thickness and sound velocity for the piezoelectric layer, such as SiO_2, AlN, with GR&R capability. It can simultaneously measure full stack for multilayer metal stack measurements with excellent repeatability and long-term stability which makes process control more efficient and reliable. Fast throughput makes a high sampling rate possible for RF applications which is the key for device level process control and yield improvement.

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