Monitoring Critical Process Steps in 3D NAND and Advanced RF using Picosecond Ultrasonic Metrology

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ABSTRACT

Picosecond Ultrasonics (PULSE™) is a rapid, non-contact, non-destructive first principles acoustic metrology technique for in-line metal film thickness measurements. We demonstrate measurement capability for transparent and semi-transparent films, by analyzing the oscillatory component of the signal described as Brillouin oscillations. Longitudinal sound velocity, thus calculated, is used in determining film thickness. In this paper, we discuss the application of the technology in 3D NAND and advanced RF filters. The additional parameter not only helps characterize the material and improve the accuracy of the reported thickness but is also correlated to critical process parameters; etch rate in 3D NAND and resonant frequencies in RF filter.

INTRODUCTION

Picosecond ultrasonic technology (PULSE™), as implemented in MetaPULSE® G system, is a pump-probe laser acoustic technique for the measurement of metal film thickness. A 0.1ps laser pulse (pump) is focused to a small (~ $5\times7\mu m^2$) spot onto a wafer surface to create a sharp acoustic wave. The acoustic wave travels away from the surface through the film at the speed of sound. At the interface with another material, a portion of the acoustic wave gets 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 or alternatively detect the deflection of reflected probe beam that is caused by the deformation of surface due to the acoustic wave using a position sensitive detector (PSD). Both of these modes, reflectivity and PSD are used in characterizing metal films (Figure 1). Knowing the speed of sound in the material, and the arrival time of the echoes, thickness is readily extracted using first principles technique. Information on film density and surface roughness, depending on the application, can also be obtained by fitting the damping rate of the echoes and the width of the echoes, respectively.

In the case of transparent or semi-transparent 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. This effect can also been described as a Brillouin oscillation given that it is an interaction of photons and acoustic phonons [1]. 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 (1)

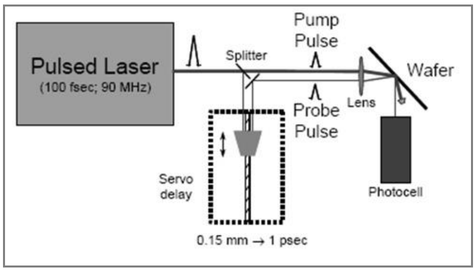
$$V=\frac{\lambda}{2n\tau\cos\varphi} \qquad (1)$$

where n is the refractive index and φ is the angle of optical probe beam within the film.

Applications in 3D NAND

3D NAND, driven by data intensive applications, changes the paradigm for manufacturing by providing an opportunity for vertical scaling using a highly repetitive and precise deposition and etch process. Hardmasks are used for etching deep, high aspect ratio features that conventional photoresists cannot withstand. Amorphous carbon (a-C)-based hard masks provide superior etch selectivity, chemical inertness and mechanically strong [2]. Monitoring a-C thickness is critical to the 3D NAND process as it goes through an iterative etch process. Film thickness and repeatability affects the active area of cell and consistency of the litho/etch performance. This is especially relevant as the films get thicker in advanced NAND stacks where high aspect ratio structures (64X) are critical and the a-C films are ~2µm thick. The films are opaque and optical metrology solutions are not robust for process monitoring

Shown in Figure 2 is the raw data of change in reflectivity versus delay time from PULSE measurements. Oscillations seen at earlier times (<100ps) are used in determining the longitudinal sound velocity. As the sound wave travels through the film and reflects at the interface



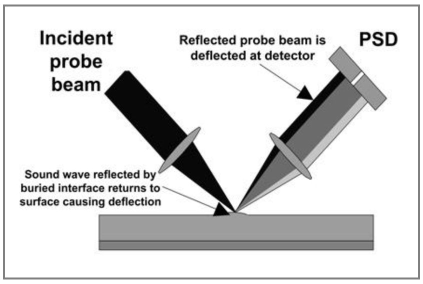


Figure1 (a): Schematic representation of picosecond ultrasonic technology. (b) In position sensitive detection (PSD), reflected sound wave causes a displacement of the wafer surface and thus the deflection of the reflected probe beam on the detector.

between film and underlying layer, it generates acoustic echoes (~700ps). Thickness of the film is calculated using the velocity determined from the early signal and the echo arrival position. The variation in the echo position from ~620ps to ~770ps represent real variation in thickness. Velocity values provided by the technique served a two-fold purpose. First, when used in the calculation of the thickness, it provided a more accurate representation of wafer level variation and second, the velocity values have helped provide feedback to the etch process optimization.

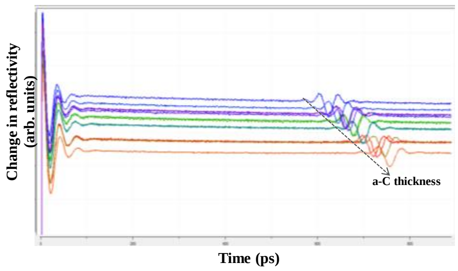


Figure 2: PULSE signal from a-C hardmask. Oscillations seen at earlier time is used for calculating the velocity and echoes at ~700ps for calculating thickness.

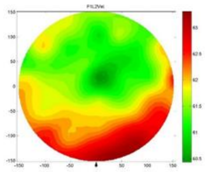


Figure 3(a) : Within wafer uniformity profile of velocity

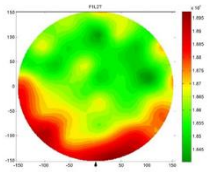


Figure 3(b): Within wafer uniformity profile of thickness

The small spot technique allows for measurements very close to wafer edge. Within wafer uniformity profiles of velocity and thickness, Figure 3, as well as high resolution line scans (0.5mm EE) are useful during process development and optimization (Figure 4). 3σ repeatability performance for thickness and velocity are < 0.5%.

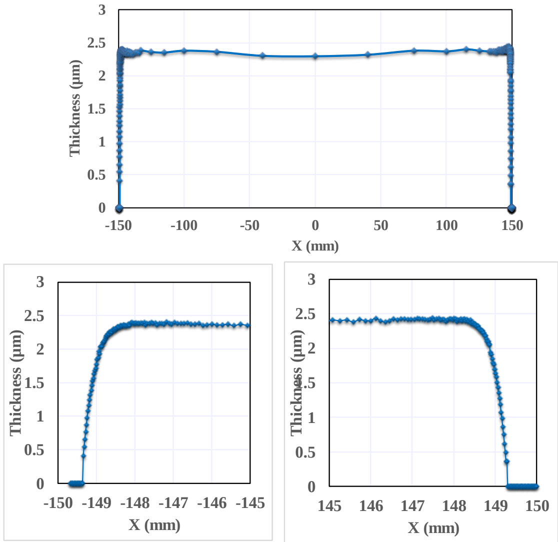


Figure 4: High resolution line scans across the wafer. Zoomed-in view of left and right edge profiles

Applications in SAW and BAW

Surface acoustic wave (SAW) devices are used in telecommunications, and other areas where precise filtering is need. As smartphones integrate more SAW filters and duplexers for multiple band on a single chip, requirements for process control are tighter. The drawback for SAW filters is their thermal stability. A SAW filter's response may shift downward by as much as 4 MHz as temperature increases. Most devices make use of silicon dioxide's (SiO_2), positive temperature coefficients of elasticity (TCE) to compensate other materials' negative TCE and CTE (coefficient of thermal expansion). Typical within wafer uniformity of frequency is < 2MHz for such samples and the thickness uniformity is ~ 0.25%. At > 2.5GHz SAW filter performance is limited and bulk acoustic wave (BAW) filters is the primary technology that is employed. Film bulk acoustic wave resonators (FBAR) are the dominant BAW filter and performance is determined by the thickness and acoustic property of the piezoelectric aluminum nitride (AlN) layer either with or without metal electrodes, such as Molybdenum (Mo) [3]. Accurate measurement of the film thickness and sound velocity is critical to the design of high performance RF filters as the resonant frequencies are directly related to these values.

PULSE measurements are made in-line and on patterned structures. In Figure 5, raw data from the temperature compensation (TC) oxide layer is shown. Raw data is characterized by high signal to noise ratios (SNR) from which both velocity and thickness values can be reliably extracted using signal processing techniques. The high SNR contributes to the excellent repeatability for both velocity (Vel.) and thickness (T), 3 sigma <0.05% (Table 1). We were able to verify that the reported sound velocity correlates to filter performance (Figure 6), thus eliminating the need for send ahead wafers and/or monitor wafer measurements.

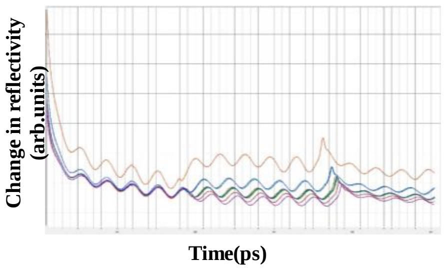


Figure 5: Raw data of TC oxide layer

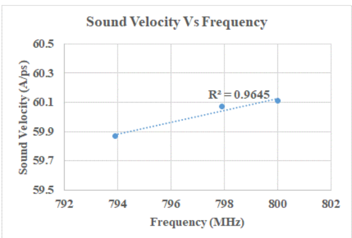


Figure 6: Correlation between sound velocity and RF filter frequency.

Similarly, during BAW process development, radial line scan profiles for both velocity and thickness are used in process development and optimization. Shown in Figure 7 is an example from a 5G development process. Piezoelectric aluminum nitride film is characterized in a Mo/AlN/substrate stack. In this example, AlN thickness varies between 1.7-2.5% in the radial scan depending on the quadrant. Sensitivity of the method to track process changes have been validated by designing a two dimensional skew of wafers of varying AlN (5000Å-1.5µm) and Mo thickness (100-140Å). The technique had excellent accuracy as verified by using cross-sectional scanning electron microscopy (SEM) with correlation coefficient R^2> 0.95. Optical constants used in the calculation of thickness was obtained using the S2000™ focused beam ellipsometer system.

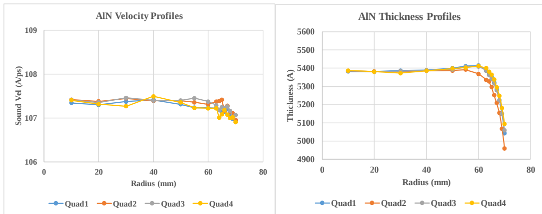


Figure 7: Longitudinal velocity and thickness profiles in different quadrants of the AlN wafer.

Table 1: Summary of velocity and thickness repeatability on oxide samples

#	Vel. (Å/ps)	Vel. 3σ (%)	T (Å)	T 3σ (%)
1	59.87	0.015	11712.9	0.015
2	60.07	0.012	11945.1	0.009
3	60.11	0.012	11799.0	0.015

CONCLUSIONS

In summary, we have successfully demonstrated the measurement of longitudinal sound velocity and thickness of critical films in both 3D NAND and RF filter processes. Measurements are highly repeatable and exceed the stringent requirements needed for process monitoring and control. Additionally, the non-destructive nature of the technology enables in-line measurements on product wafers thus providing direct feedback for process control and eliminating the need for test or send ahead wafers.

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