Monitoring Critical Process Steps in 3D NAND using Picosecond Ultrasonic Metrology with both Thickness and Sound Velocity Capabilities

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ABSTRACT

Amorphous carbon (a-C) based hard masks provide superior etch selectivity, chemical inertness, are mechanically strong, and have been used for etching deep, high aspect ratio features that conventional photoresists cannot withstand. Picosecond Ultrasonic Technology (PULSE™ Technology) 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 [1]. Simultaneous measurement of velocity and thickness for transparent and semi-transparent films offers a lot of potential for not only monitoring the process but offers insight into the device performance. In this paper, we show successful applications of Picosecond Ultrasonics in 3D NAND. This includes measurement of various thin metal films and simultaneous measurement of sound velocity and thickness for amorphous carbon films which has been widely used as hard mask materials.

INTRODUCTION

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. Currently, commercially available 3D NAND products have 64-layer and 96-layer tier stacks in high volume manufacturing and a 128-layer stack is in pilot production. To make 3D NAND, the most difficult and critical process is the high-aspect ratio (HAR) etching step. In this process, an etch tool drills tiny circular holes from the device top to the bottom substrate. A device may have up to 2.5 million tiny channels in one chip. Hard masks 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 are 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 sound velocity (mechanical property) and repeatability affect the active area of a cell and consistency of the deposition/etch performance. Picosecond Ultrasonic Technology (PULSE™ Technology), implemented in the MetaPULSE® G system, is a non-contact, non-destructive pump-probe laser acoustic technique for the measurement of metal film thickness. It is a proven workhorse in semiconductor fabs around the world. A 0.1ps laser pulse (pump) is focused to a small (~ $10\times15\mu m^2$) 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 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 or alternatively detect the deflection of reflected probe beam that is caused by the deformation of the 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. Knowing the speed of sound in the material, and the arrival time of the echoes, thickness is readily extracted using the 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. The latest system improvement included some additional modifications to the experimental setup to enhance the signal to noise (SNR). A detailed description of the modification and the resulting benefits will be discussed in the paper. Semi-transparent films such as a-C films can absorb energy from the pump pulse, launching a sound wave that travels down through the semi-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 [3]. 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.

Using the PULSE technique, we have performed high resolution line scans (0.5mm EE) on different types of amorphous carbon films and demonstrated 3σ repeatability performance for thickness and velocity of < 0.5%. Accuracy of the technique has been correlated to cross-section scanning electron microscopy (SEM) with R^2> 0.95. 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 were found to have a correlation to the etch process enabling a direct monitor of this process.

APPLICATION IN 3D NAND

1. Metal film thickness measurement using PULSE Technology

PULSE Technology has been widely adopted as the process of record tool for metal thickness measurement. In 3D NAND, it has been used for the measurement of AlCu, W, Cu, Cu Seed, Ta, TaN, Ti, TiN, WSi, and etc. Figure 1a shows the typical measurement of a 350Å Ta films and its modeling example. Figure 1b shows the thickness profiles of 13 points across the wafer. PULSE Technology can be used to measure films down to 50Å and ~20µm depending on the material's property. It can also be used to measure up to eight layers of the stack simultaneously with excellent repeatability.

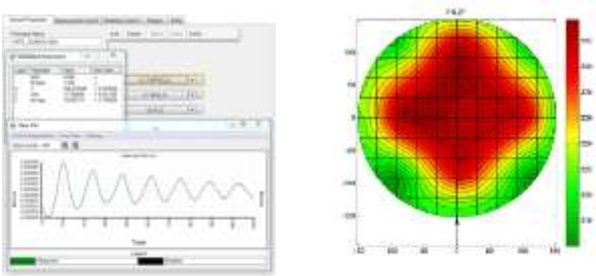

Figure 1a. Typical measurement of a 350Å Ta films and its modeling example. Figure 1b. Thickness profiles of 13 points across the wafer.

2. Repeatability of thickness measurement by PULSE Technology

PULSE Technology has been widely used for the measurement of AlCu, W, Cu, Cu Seed, Ta, TaN, Ti, TiN, WSi, and etc. Table 1 shows the typical dynamic thickness repeatability (3σ) performance for a 13 point measurement.

Film	Thickness	Repeatability (3 sigma)
ACL	10k~17k	<0.3%
AlCu	4k~8k	<0.3%
Thin W	250	<0.6%
Thick W	400~3000	<0.3%
Cu Seed	200~500	<0.3%
Cu	500~6000	<0.3%
Ta, TaN,TiN & Ti	50~200	<0.6%
	200~1000	<0.3%
WSi	600~1000	<0.3%

Table 1. Typical dynamic repeatability performance for PULSE measurement for commonly used metal films in 3D NAND

3. Simultaneous sound velocity and thickness measurement by PULSE Technology

The following figure shows a standard a-C measurement and modeling example using PULSE Technology. The top red curve shows the raw signal, and the following bottom two graphs show sound velocity and thickness reported from the measurement.

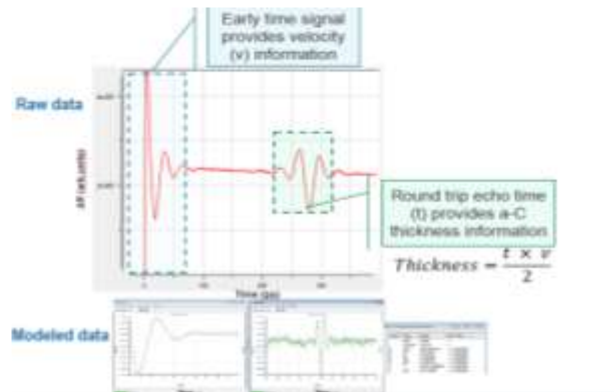

Figure 2. Raw signal and modeling example of measurement on a-C films using PULSE Technology

4. 49-point measurement for thickness and sound velocity

Through measurement and modeling algorithm improvement, we have significantly improved the repeatability for both thickness and velocity while maintaining high throughput. Table 2 shows the typical dynamic repeatability (3σ) for sound velocity and thickness based on the average for 49 points per wafer.

	49 points	
	Sound Velocity (3σ)	Thickness (3σ)
Wafer 1	0.40%	0.18%
Wafer 2	0.37%	0.17%

Table 2. Dynamic repeatability for sound velocity and thickness measurement based on 49 points

5. 49-point profile across the wafer for thickness and sound velocity

Figure 3 shows a typical 49-point profile for thickness and velocity. We can see that thickness and sound velocity have different profiles. Because both thickness and sound velocity play important roles in HAR etching. Monitoring thickness and sound velocity are very critical for the HAR etching process.

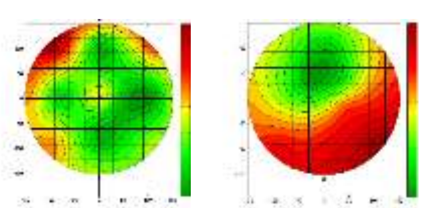

Figure 3. 49 point profiles for thickness (left) and

sound velocity (right)

6. PULSE thickness measurement correlation with SEM

Figure 4 shows the SEM correlation of PULSE thickness measurement with input from simultaneous sound velocity measurement. We can see a correlation with R^2=0.95 that indicates very strong correlation of the PULSE measurement with the SEM measurement. In order to protect the confidentiality of the data, we have not shown the actual thickness values but suffice it to say that the excellent correlation was validated across the process window.

The technique has also been proven on next generation a-C materials, including metal-doped hard masks.

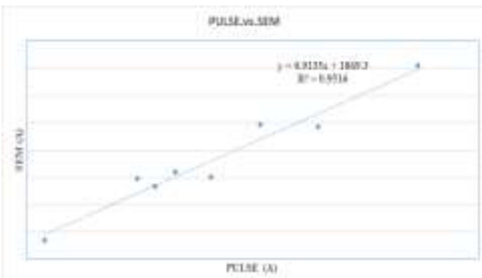

Figure 4. Correlation of PULSE thickness measurement with SEM thickness measurement

CONCLUSIONS

In summary, PULSE Technology has been successfully used for thickness measurement of both metal and amorphous carbon. Excellent repeatability of this technique can meet the stringent demands for process control. Besides film thickness, it can also measure velocity of semi-transparent and transparent films simultaneously, and a-C films for etching process control. We have demonstrated both thickness and velocity measurement capability for amorphous carbon based hard masks, and sound velocity has been found to be very well correlated to etch characteristics.

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