3D Stress Measurements Using KLA-Tencor Profilers

D. Smith

Introduction

As devices continue to shrink in size, bowing of the substrate can present problems with tolerances that are critical to proper device functionality. In semiconductors, film stress is a direct cause of film delamination and has negative influences on the performance and reliability. Stress is also a critical parameter that should be monitored for the Photovoltaic and Hard Disk Drive industries.

Monitoring stress due to film deposition is of utmost importance during device manufacturing. At the film level, two main failure mechanisms occur due to film stress. The first is film adhesion, which causes the creation of crystalline defects and surface deformations that limit the growth of thicker films. Second, large stresses in strongly adhered films can cause film peeling[1], rendering the film useless. At the device level, stress formation rarely ever causes instant yield loss; instead it reduces the product lifetime. This is a major problem costing logic, memory, and solar cell manufacturers millions of dollars annually in product service and warranties.

By combining well established theories and models of stress calculation and the accuracy of the KLA-Tencor P-16+ stylus based profiler, 3D Stress can be used to provide accurate thin film stress measurements independent of the substrate or film material and surface characteristics. This is in contrast to optical based stress measurement systems, whose capabilities are limited to specific material types.

Background

The first stress measurement tool calculated stress based on one center point and one side point. As processes evolved and became more complex, Flexus developed a scanning tool that measured points across the entire substrate. Current device evolution dictates that film layers will get thinner. As this happens, a single 2D cross-section does not yield information representative of the entire surface, and 3D metrology is needed. The 3D Stress option available on the newest generation KLA-Tencor Profilers allows for high resolution analysis of stress over the entire substrate.

Stress is an indirect measurement; it occurs as a result of thermal expansion differences between the film and substrate[2]. This causes the substrate to bow, thus changing its original shape. The substrate's Radius of Curvature can be obtained by measuring the bow and deflection of the substrate. By comparing the change in the Radius of Curvature, before and after film deposition, it is possible to calculate the stress using the cantilever beam technique developed by G. Gerald Stoney for the measurement of thin film stress , where

$$\sigma = \frac{1}{6R}\frac{E}{(1-\upsilon)}\frac{t_s^2}{t_f}$$

$$= \frac{1}{6}\frac{E}{(1-\upsilon)}\frac{t_s^2}{t_f}\left[\frac{1}{R_F} - \frac{1}{R_s}\right]$$

where

$$\frac{E}{(1-\upsilon)} = \text{wafer elastic constant}$$

and $\sigma = \text{stress}$

$t_s = \text{wafer thickness}$

$t_f = \text{film thickness}$

$R = \text{Radius of Curvature (RoC)}$

$R_s = \text{RoC of Substrate}$

$R_f = \text{RoC of Substrate with Film}$

$E = \text{Young's Modulus of substrate)}$

$\upsilon = \text{Poisson's Ratio}$

Stoney developed this technique in 1909, and the equation has proven a reliable measure of stress for most film applications.

3D Stress Measurement Technique

All stress measurements should be performed in a 3-point chuck, to remove the influence of the stage itself. Prior to the first scan, the P-16+ performs an automated stage level, to remove any unnecessary leveling error. Then the system takes a series of radial scans across the substrate diameter, rotating by a user defined increment between each scan. The total number of scans taken is equal to 180/N, where N is the Radial Interval in degrees. The length of the diameter scans are automatically computed as 80% of the inputted substrate diameter in the Stress Recipe. Additionally, the Radial Interval is variable, so that the user can optimize lateral resolution and throughput. To address fast paced technology development, the Stress Recipe offers the user the ability to add new Wafer Elastic Constants into the Substrate Database.

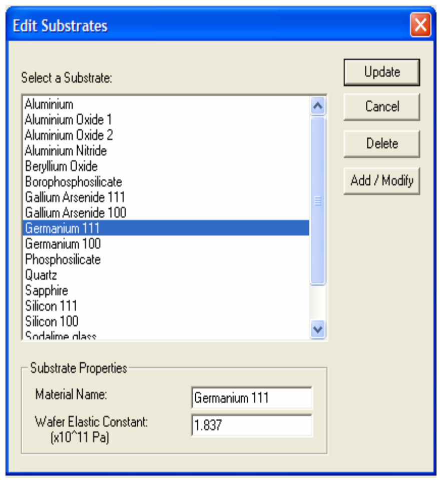

Figure 1: Substrate Database, allowing the use to enter new substrates and their properties.

Once the pre-deposition and post-deposition scans have been obtained, the pre-deposition data is subtracted from the post-deposition data and a difference curve is obtained. This curve is then fit using a fifth order polynomial, leveled using the center one-third of the curve, and the resulting Radius of Curvature is determined. Using the Radius of Curvature value the Stress is then computed.

3D Stress Data Analysis

From the user's viewpoint, the stress is calculated in an intuitive and easy to use method. Simply select the two data sets for comparison and enter the film thickness.

The data analysis portion is performed by Apex Advanced Analysis Software. Within the Apex report, the user can examine the Average, Center, and Maximum stresses and radii. For increased flexibility, localized stresses can also be examined through user-defined cursors. Data rendering includes the Stress Map, Difference Map, and Curvature Map.

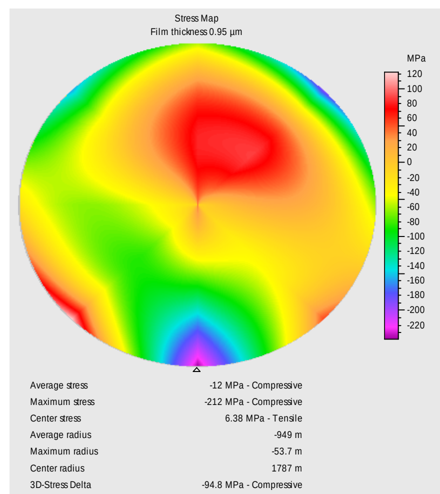

Figure 2: The Stress Map as rendered by Apex, based on a 1µm thick Silicon film on a Germanium substrate.

Stress Measurement Resolution

Stress resolution is dependent on three parameters: the vertical range of the profiler, the elastic properties of the substrate, and the thickness of the substrate and film. For the P-16+, the vertical range depends on the head used, with a range of 6.5-1048µm.

The minimum resolution is based on the optical flatness used (λ/3), which translates to a minimum bow of 500Å. The elastic properties of the substrate differ depending on the substrate used. Typically these vary between 1 x 10^{11} Pa and 5 x 10^{11} Pa. Finally, film and substrate thickness are important for determining stress resolution. Typical values for substrate thickness are on the order of hundreds of microns, while film thickness may vary between 50 Å and 2μm. Using these parameters, we can now determine the stress resolution, shown in Table 1.

	Aluminum σ_{min}-σ_{max} (MPa)	Silicon (100) σ_{min}-σ_{max} (MPa)	Silicon Carbide σ_{min}-σ_{max} (MPa)
P-16+	17–1763	30 – 3090	79 – 8160

Table 1. Stress Resolution for a range of substrates assuming substrate thickness to be 500 microns and over a 100mm section.

Conclusions

The P-16+ has the capability to analyze 3D stress through a fully automated method. The system incorporates a fifth order polynomial fit to accurately calculate radius and advanced algorithms to calculate stress. The flexibility of the Stress Recipes makes the P-16+ ideal for an R&D environment and the automation makes 3D stress production-worthy. Since the P-16+ is a stylus based metrology system, the measurements are not influenced by material transparency. With its intuitive operation and its flexible analysis routines, the P-16+ offers users the ability to analyze global or localized stresses, which can not be done using simple 2D Stress routines.

References

1. Campbell, Stephen A. (1996). *The Science and Engineering of Microelectronic Fabrication*. New York: Oxford University Press.

2. Wolf, S. and Tauber, R. N. (1986). *Silicon Processing for the VLSI Era, Volume 1*. Sunset Beach: Lattice Press.