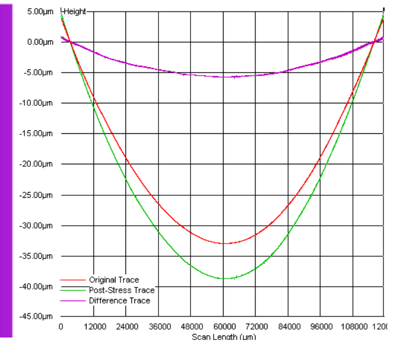
KLA INSTRUMENTS

Thin Film Stress Measurements using KLA Stylus-Based Profilers

HRP®-Series and Tencor™ P-Series Profilers



Introduction

As devices continue to shrink in size, the bowing of the surface may present problems with tolerances that are critical for proper device performance. In semiconductors, film stress has a direct influence over electronic properties such as semiconductor bandgap shifts, superconductor transition temperatures and magnetic anisotropy.[1]

Monitoring stress due to film deposition is of foremost importance during device manufacturing. At the film level, stresses typically affect film adhesion and create crystalline defects and surface deformations that limit the growth of thicker films. At the device level, stress formation rarely ever causes instant yield loss; instead, it reduces the product lifetime. Lifetime reduction is a major problem costing 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 stylus-based profilers, these profilers can be used to provide accurate thin film stress measurements, regardless of the material and surface characteristics.

Background

Stress cannot be measured directly; it occurs as a result of film deposition. Film deposition will cause the substrate to bend and change 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 radius of curvature before and after film deposition, it is then possible to estimate the stress using the cantilever beam technique developed by G. Gerald Stoney for thin film stress measurements[2]:

$$\sigma = \frac{1}{6R}\frac{E}{(1-\upsilon)}\frac{t_s^2}{t_f} = \frac{1}{6}\frac{E}{(1-\upsilon)}\frac{t_s^2}{t_f}\left[\frac{1}{Rf} - \frac{1}{Rs}\right]$$

where

$E/(1-\upsilon)$ = wafer elastic constant

t_s = wafer thickness

t_f = film thickness

R = radius of curvature

R_s = radius of curvature of the bare substrate

R_f = radius of curvature of substrate with film

E = Young's modulus for the wafer (substrate)

υ = Poisson's ratio

Stress Measurement Technique

The HRP® and Tencor™ P-series profilers are used to take measure the full diameter of the substrate without the need to stitch, providing a profile of the substrate's bow and deflection. A pre-deposition scan and a post-deposition scan is collected, and the change in the substrate's radius of curvature due to film deposition is then calculated and the stress computed.

The HRP-series and Tencor P-series models provide the user with two algorithms for calculating stress: n^{th} order polynomial and 13 point least squares fit. Older generation models provided only one method: 13 point least squares fit. The polynomial fitting procedure allows the user to specify a 5^{th}, 6^{th}, or 7^{th} order polynomial for the radius of curvature calculation. For an n^{th} order polynomial, n+1 coefficients exist:

$$y = c_0 + c_1x + c_2x^2 + \ldots + c_nx^n$$

In order to determine the coefficients, an example using a 3^{rd} order polynomial is considered:

$$y = c_0 + c_1x + c_2x^2 + c_3x^3$$

To evaluate the coefficients, four equations are required. These equations are produced by simply multiplying the above equation by x^3, x^2, x, and 1 (the coefficients of the unknowns). The resulting four equations are:

$$x^3y = c_0x^3 + c_1x^4 + c_2x^5 + c_3x^6$$

$$x^2y = c_0x^2 + c_1x^3 + c_2x^4 + c_3x^5$$

$$xy = c_0x + c_1x^2 + c_2x^3 + c_3x^4$$

$$y = c_0 + c_1x + c_2x^2 + c_3x^3$$

Using Crout's method for solving simultaneous equations, the four coefficients are then found, and a polynomial is obtained that represents the height as a function of position. The second derivative of this polynomial is used to determine the curvature[3].

The 13 Point Least Squares Fit method consists of fitting local data to arcs and calculating the mean curvature based on the local curvature of these arcs. Since this method incorporates the same data points multiple times, it is more susceptible to noise variation and is therefore less robust.

The Least Squares Fit algorithm does not incorporate the first and last 5% of the data collected. The remaining data is divided into three segments of length 0.3L, where L is the scan length. The local radius of curvature is determined for each segment by calculating the local radius for points 1-13 followed by points 2-14 until data point N-12 (where N is the total number of data points in the segment). The average radius of each segment is the mean of the local radii.

The method for calculating the local curvature requires a 2nd order polynomial (where, again, the second derivative is used to calculate the curvature). The general equation for the polynomial is:

$$y = a_0 + a_1x + a_2x^2$$

The predicted value for this equation is:

$$\hat{y} = a_0 + a_1x + a_2x^2$$

The sum of the squares of the residuals (y_i- $\hat{y}_i$) are minimized by the following equations:

$$\partial(\sum_n^{n+12}(y_i - (a_0 + a_1x_i + a_2{x_i}^2)]^2)/\,\partial a_0$$

$$\partial(\sum_n^{n+12}(y_i - (a_0 + a_1x_i + a_2{x_i}^2)]^2)/\,\partial a_1$$

$$\partial(\sum_n^{n+12}(y_i - (a_0 + a_1x_i + a_2{x_i}^2)]^2)/\,\partial a_2,$$

where n is the first data point. The equations are further simplified to:

$$13a_0 + a_1\sum_n^{n+12}x_i + a_2\sum_n^{n+12}{x_i}^2 = \sum_n^{n+12}y_i\, a_0\sum_n^{n+12}x_i + a_1\sum_n^{n+12}{x_i}^2 + a_2\sum_n^{n+12}{x_i}^3 = \sum_n^{n+12}x_iy_i$$

$$a_0\sum_n^{n+12}{x_i}^2 + a_1\sum_n^{n+12}{x_i}^3 + a_2\sum_n^{n+12}{x_i}^4 = \sum_n^{n+12}{x_i}^2y_i$$

We can then solve these equations for the coefficients using a matrix determinant or simple substitution and calculate the curvature.

Collecting Stress Data

For accurate stress measurements, it is important to use either a universal chuck configured for stress or a stress chuck. A stress chuck has three posts to support the sample and two or three pins to properly align the sample (two pins for a sample with a notch and three pins for a sample with a flat). *Note that the position of the support posts and locating pins will need to be adjusted based on sample size.* The support posts hold the sample in a neutral position so prevent influence on the wafer shape by (a) the shape of the chuck, and (b) gravitational influence, by evenly distributing the sample weight. The locating pins ensure the sample is placed in a repeatable position for improved accuracy, repeatability, and safety. Figure 1 shows a stress locator plate for use with 8-inch (200mm) wafers.

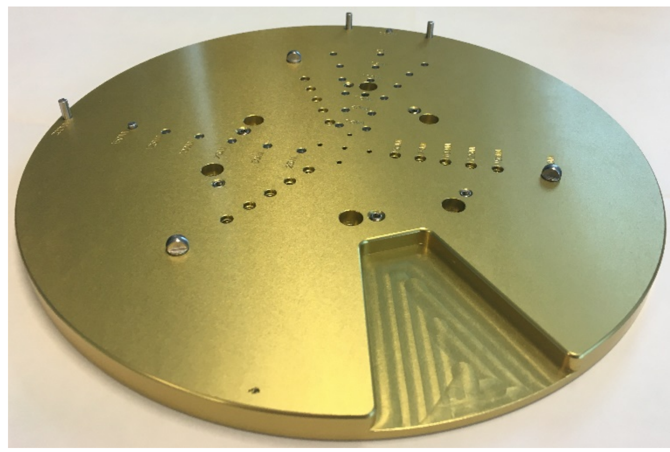


Figure 1. The universal chuck configured for stress measurement, with three locator pins (outer edge) and three support posts (mid-radius). Pin and post positions are adjustable to accommodate different wafer sizes.

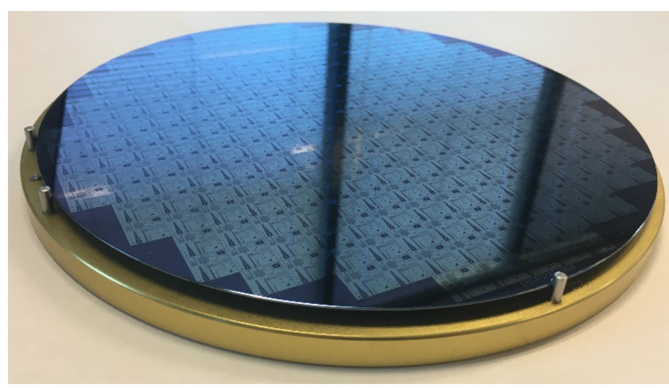


Figure 2. A 200mm patterned wafer on a universal chuck configured for stress measurement. The three locator pins are visible along the outer edge, and the wafer is sitting on top of the three support posts (not visible).

The profiler collects data using a diamond stylus in contact with the surface, with the same recipe used for both pre- and post-deposition data collection to guarantee that the collected data exhibits the same material properties and data resolution. The direct measurement technique of the stylus profiler can measure any sample without influence from the sample properties, which can be an issue for some optical profiling techniques. The stress recipe is created to optimize data collection, and the key parameters include scan length, applied stylus force, scan rate, sampling rate and vertical range. The stress recipe also allows the user to choose which algorithm the tool uses to calculate the stress. The polynomial fit algorithm provides the best measurement repeatability, but a 13-point least squares fit is also available to enhance matching to older stress measurement techniques.

Recommended measurement parameters include:

- Stylus tip radius ≥ 2µm;
- Length should be 80% of the total wafer diameter and measured through the wafer center;
- Applied force of 2mg;
- Scan rate of 1-5mm/s;
- Sampling rate of 200hz;
- Vertical range depends upon the known bow of the wafer. For unknown bow, start with the highest available range in order to accommodate the most bow. If the bow is known to span a smaller vertical range, then use the smaller range.

Ensuring Stress Measurement Accuracy

The Tencor and HRP stylus profilers incorporate an optical flat to ensure that the stage is moving flat in the horizontal plane. A known radius mirror is also measured to ensure accurate motion for a curved surface, as shown in Figure 3. Table 1 lists the flatness specifications as a function of scan length, as well as bow and stress repeatability.

Table 1. Scan flatness and repeatability specifications.

	Specifications	Reference
Scan Flatness*	40nm over 30mm scan	1/20λ, 150mm optical flat
	75nm over 60mm scan	
	170nm over 130mm scan	
Bow Repeatability*	0.1%	20m radius mirror
Stress Repeatability	2.5%	Polynomial fit calculation

**Scan flatness and bow repeatability based on 15 repeats, 2mm/s scan speed, 2mg force, 200Hz, maximum vertical range, 80mm scan for a 100mm mirror, 120mm scans for a 150mm wafer.*

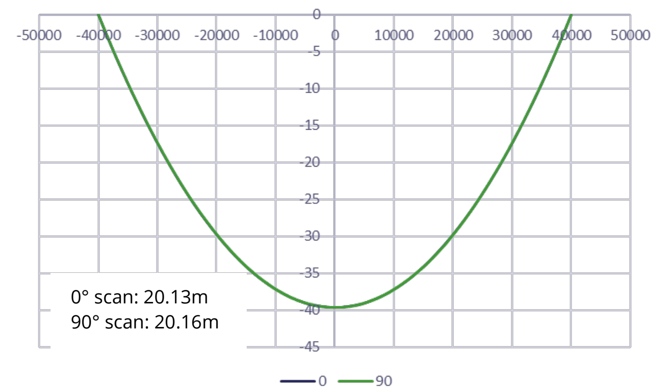


Figure 3. Measurements of a mirror with a certified radius of 20.13 ± 0.5m.

Stress Measurement Resolution

Stress resolution is dependent on three parameters: the vertical range of the profilers, the elastic properties of the substrate, and the thickness of the substrate and the film. For the Tencor P-series, the vertical range depends on the head used, with a range of 6.5µm-1000µm. The HRP, on the other hand, can vary between 3.25µm and 327µm in vertical travel. The vertical resolution is sub-Å for all ranges. The bi-axial elastic moduli 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 the stress resolution. Typical values for substrate thickness are on the order of hundreds of microns, while film thickness will typically vary between 100Å and 2µm, and there may be applications for thicker films. Table 2 lists example stress values that can be obtained.

Table 2. Measured stress for a range of substrates.

GaAs	Si (100)	Silicon Carbide
8MPa 8-inch wafer 2µm film 5µm bow	132MPa 8-inch wafer 500nm film 25µm bow	13.4GPa 6-inch wafer 200nm film 250µm bow

Conclusions

The HRP-series and Tencor P-series profilers provide an effective means to monitor and measure stress in thin films. Monitoring these stresses is critical since high stresses may cause failure in semiconductor devices. The profilers collect data using a stylus tip in constant contact with the surface, using long scans without the need for stitching, in order to ensure data accuracy and repeatability. This direct measurement is independent of material and optical properties of the sample, generating results with sub-Å vertical resolution. Two different algorithms, indicated in the stress recipe, may be used to analyze the data: 13 least squares fit and a higher-order polynomial fit. Based on the change in radius of curvature before and after film deposition, Stoney's equation is then used to deliver accurate, repeatable measurements of film stress.

References

1. "Material Science of Thin Films", Chapter 12, p 711-712, Milton Ohring, 2nd Ed., 2002.
2. "Tencor P-11 Long Scan Profiler Operations", KLA, 1996, section 11.
3. Wafer Stress Application Option, Ch. 14.

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