Thin Film Stress Measurements using KLA-Tencor Stylus Based Profilers

HRP-Series and P-Series Profilers

Introduction

As devices continue to shrink in size, the slightest bowing of the surface may present problems with tolerances that are critical to proper device performance. In semiconductors, film stress have a direct influence over electronic properties such 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. This 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-Tencor stylus based profilers, these can be use 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] , 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

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

and σ = stress

t_s = wafer thickness

t_f = film thickness

R = Radius of Curvature

R_s = Radius of Cusrvature of 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 P-series Profilers are used to take long scans across the substrate's diameter providing a profile of the substrate's bow and deflection. A pre-deposition scan and a post-deposition scan is collected, the change in the substrate's Radius of Curvature due to film deposition is calculated and the Stress computed.

The KLA-Tencor HRP-series and P-series models provide the user with two algorithms for calculating stress, nth-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 5th, 6th, or 7th order polynomial for the radius of curvature calculation. For an nth 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 3rd 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 which represents the height as a function of position. The second derivative of this polynomial is used to determine the curvature.[4]

The 13 Point Least Squares Fit method is a more complicated method, which 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:

$$\partial\left(\sum_{n}^{n+12} (y_i-(a_0+a_1x_i+a_2x_i^2))]^2\right)/\partial a_0$$

$$\partial\left(\sum_{n}^{n+12} (y_i-(a_0+a_1x_i+a_2x_i^2))]^2\right)/\partial a_1$$

$$\partial\left(\sum_{n}^{n+12} (y_i-(a_0+a_1x_i+a_2x_i^2))]^2\right)/\partial a_2\,,$$

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.[4,5]

Collecting Stress Data

When collecting film stress data, the user should follow the next 3 steps.

1. Use a stress locator plate.
2. Create a recipe and use it for both: Pre-Deposition and Post Deposition measurements.
3. Collected data should be clean from sudden abnormalities.

Film stress measurements are very sensitive to proper instrument set up. It is important to use a stress locator plate that helps to load the substrate and, in combination with the recipe, guarantees the scans are collected over the same surface area. Figure X shows a stress locator plate for use with 6-inch (150mm) wafers. By using the same recipe for Pre-Deposition and Post-Deposition scans it guarantees the data collected exhibits the same material properties and data resolution.

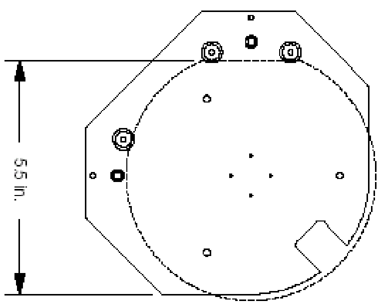

Figure X. 6-inch (150mm) flat or square substrate locator for Stress measurements.

When collecting stress data the stress locator should be positioned inside the system and on top of the standard 8-inch (200mm) sample stage chuck.[X]

Next, a recipe must be created with the required analysis for the given substrate same recipe shall be used

Monitoring Profiler Stress Accuracy

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 P-series, the vertical range depends on the head used, with a range of 6.5μ-1027μ. The HRP, on the other hand, can vary between 3.25μ and 131μ in vertical travel. The minimum resolution is based on the optical flatness used (λ/3), which translates to a minimum flatness specification of 500Å. The elastic properties of the substrate differ depending on the substrate used. Typically these vary between 1×10^{11} Pa and 5×10^{11} Pa. Finally, film and substrate thickness is important for determining stress resolution. Typical values for substrate thickness are on the order of hundreds of microns, while film thickness may vary between 100 Å and 2μ. Using these parameters, we can now determine the stress resolution (Table 1).[6]

	Aluminum σ_{min}-σ_{max} (in MPa)	Silicon (100) σ_{min}-σ_{max} (in MPa)	Silicon Carbide σ_{min}-σ_{max} (in MPa)
P-series	17– 1763	30 – 3090	79 – 8160
HRP	17 - 225	30 –394	79 – 1041

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

Conclusions

References

1. *"Material Science of Thin Films"*, Chapter 12, p 711-712, Milton Ohring, 2nd Ed., 2002.

FLX application note #1, 6, and 7. KLA-Tencor

2. "*Tencor P-11 Long Scan Profiler Operations*", KLA-Tencor, 1996, section 11.

4. Wafer Stress Application Option, Ch. 14.

5. Statistics book

6.Profiler Application Note #1, 1988. Tencor.

X. Profiler Manual, Locators section