Thin Film Stress Measurement Using Dektak Stylus Profilers

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Introduction

Film deposition and planarization processes employed in the manufacture of semiconductors, MEMS, thin film filters and other devices, generate stress in both the substrate and the deposited film. Excessive film stresses can lead to deformation, cracking, delamination, shorts and other failures that can render a device unusable. Accurate assessment of the deformation caused by film stress is critical for developing controllable processes and producing high quality devices.

Veeco's Stress Measurement Analysis, an optional software package for Dektak® stylus profilers, calculates tensile and compressive stresses and displays the results. This application note discusses stress measurement methodology, the algorithms behind the Dektak Stress Measurement Analysis, and important considerations for achieving accurate stress calculations.

Measurement Theory

The standard stress measurement technique is straightforward: one measures the curvature of the substrate prior to deposition, then measures the substrate along the same trace after a film is applied. The Stress Measurement analysis uses the bending plate method[1,2] to calculate stress in a deposited thin film layer, based upon the change in curvature and material properties of the film and substrate.

The key parameters needed to make the stress calculation are the substrate's radius of curvature before and after deposition. If the height of the substrate is expressed as a continuous function of distance along the substrate, $y = f(x)$, then the radius of curvature at any point may be calculated as:

$$R(x) = \frac{(1 + y'^2)^{\frac{3}{2}}}{y''} \qquad (1)$$

where $y' = dy/dx$, and $y'' = d^2y/dx^2$

Assuming an initially flat substrate, the stress in the film can then be calculated as:

$$\sigma = \frac{1}{6}\left(\frac{1}{R_{post}} - \frac{1}{R_{pre}}\right)\frac{E}{(1-\upsilon)}\frac{t_s^2}{t_f} \qquad (2)$$

where

σ = stress in the film, after deposition

R_{pre} = substrate radius of curvature, before deposition

R_{post} = substrate radius of curvature, after deposition

$\mathbf{E}$ = Young's modulus

υ = Poisson's ratio

t_s = substrate thickness

t_f = film thickness.

Each scan is fit with a 5th order polynomial by the method of least squares. The fit to each scan is then differentiated to produce the function $y'(x)$ and again to produce $y''(x)$.

These functions are substituted into equation 1 to calculate the radius of curvature as a function of scan position before and after deposition. The two radii are substituted into equation 2 to calculate pre-deposition and post-deposition stress. The difference between these values is the film induced stress. Negative values of stress are compressive (convex surface); positive values are tensile (concave surface). The units of stress are dynes/cm^2 (1 dyne = 10^{-5} Newton).

Equipment List

Accurate stress measurement requires scans across a significant portion of the center of the substrate (typically 70% or greater), and the pre- and post-deposition scans must represent the same portion of the substrate. While stress can be measured using any Dektak profiler with the Stress Measurement Analysis installed, the Dektak 8 Advanced Development Profiler is the recommended instrument, due to its long scanning capability (up to 50 mm standard, 100 mm optional), 3-point suspension stage, and optional programmable theta positioning.

A larger diameter stylus (e.g., 12.5 μm radius) is recommended to allow for high speed scanning without scratching.

[1] In some texts, R is approximated as $r^2/2\delta$, where r is the radius of the substrate and δ is the deflection of the substrate at its center due to film stress. This is a good approximation for average stress on shallow parabolas, such as wafers with uniform film deposition, but is not generally true for all cases, and does not calculate variations in stress across the substrate surface.

Making a Stress Measurement

1. Position the substrate on the stage's three alignment ball bearings (the steel balls are included in the Stress Measurement Analysis package). It may be necessary to raise the stage's position pins slightly to accommodate the height of the ball bearings.

▶ **TIP:** Alternatively, you can place the substrate on the bare stage, but do not apply vacuum, as this may distort the substrate. The three-ball suspension used with the Dektak 8 is more repeatable and is therefore the recommended method.

2. Verify that the stage is level to within 1% of the measurement range. Auto-leveling, a feature with the programmable stage option, simplifies the leveling process.

Now set up the system to measure pre-deposition curvature.

3. Choose **File>New** to create a new recipe file. Select Standard rather than 3D mode.
4. Click the Scan Routines icon, or choose **Window>Scan Routines** to view the current parameters. Click in the Scan Parameters area to open the Scan Parameters dialog box (Figure 1).
5. Set the Scan Length to approximately 80% of the substrate diameter, to exclude edge effects in the outer 10%. The scan Duration will automatically be set to provide the fastest scan.
6. Set the scan range to the highest available value, to achieve sufficient resolution while also allowing for significant stress-induced curvature.

▶ **TIP:** The 1 mm option for the Dektak 8 is recommended for stress measurements as it accommodates a larger degree of substrate curvature.

7. Choose a medium value for Stylus Force. For softer film materials, reduce the force to avoid scratching at high scan speeds.
8. Under Profile choose Hills & Valleys, then click OK to close the window.
9. Click the Sample Positioning icon.
10. Move the scanner to the left edge of the wafer (i.e., drive the stage until the X value is at a minimum), then move in approximately 1/2" from the left edge to the start location. Choose **Edit>Enter Scan Location** to store it.

You are now ready to measure the curvature of the substrate before deposition.

11. Click the Scan button to measure the bare substrate.

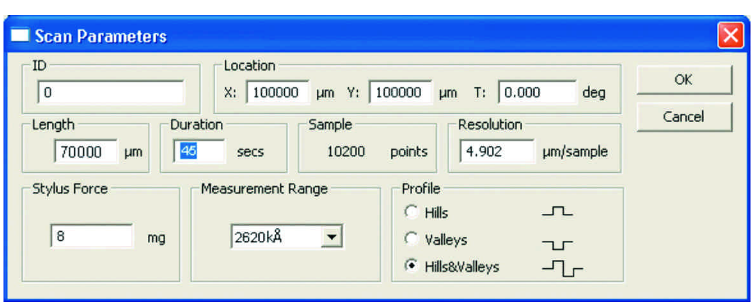

Figure 1. Scan Parameters dialog box.

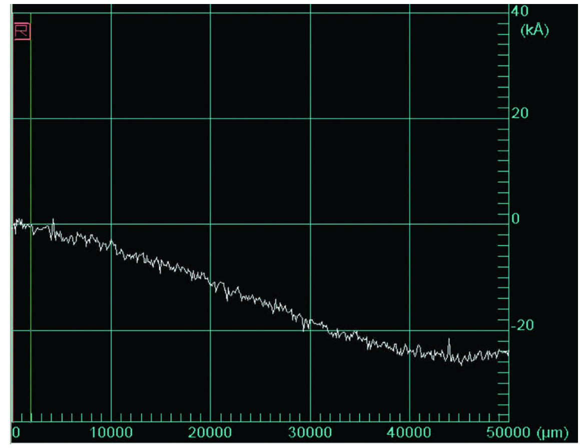

Figure 2. Pre-deposition wafer scan after software leveling.

12. The Dektak software's data leveling algorithm improves measurement accuracy. To invoke it, click and drag the R (Reference) and M (Measurement) cursors to approximately 500 µm from either end of the scan. Choose **Edit>Enter Software Leveling**. Click the Level the Trace icon. The results will appear similar to Figure 2.
13. Choose **File>Save** to store the pre-deposition data.

▶ **TIP:** It is a good idea to save your measurement automation at this point as well. Open the Automation Program screen, then choose **File>Save As**. With the data stored you will be able to complete the stress measurement, even if the system is disturbed in some way during the deposition step.

14. Choose Sample Positioning, then click the Unload Stage button to remove the wafer for film deposition. The stylus tower will automatically be raised.
15. Following deposition, reposition the coated substrate on the stage, paying careful attention to notch/flat alignment.

16. Click the Scan button to scan the coated substrate. The stylus tower will automatically be lowered and the scan will begin.
17. Choose **File>Save** to store your post-deposition scan data.

You now have all the data you need to run the Stress Measurement Analysis.

18. With the post-deposition scan data on screen, choose **Analysis>Compute Stress**. This will open the Stress Parameters Dialog Box (Figure 3).
19. To the right of the Elasticity box, click Select. You will be presented with a list of standard substrate materials (Figure 4). Choose the substrate material to obtain its elasticity constant, then click OK. If the actual value for your substrate is different than that given value, you can change it in the Elasticity field.

▶ **NOTE:** The measured values of Young's Modulus and Poisson's Ratio vary considerably from source to source depending on measurement method. For Silicon in the <100> and <111> orientations, Dektak stress calculation software uses the values measured by Brantley[3].

20. Enter the substrate and film thicknesses in microns.
21. At the bottom of the dialog, click Select to locate the pre-deposition scan data. Click OK to calculate the film stress and display the results (Figure 5). The results can be printed as well. The results are also displayed as a plot (Figure 6). Downward curvature in the plot indicates compressive stress; upward curvature indicates tensile stress.

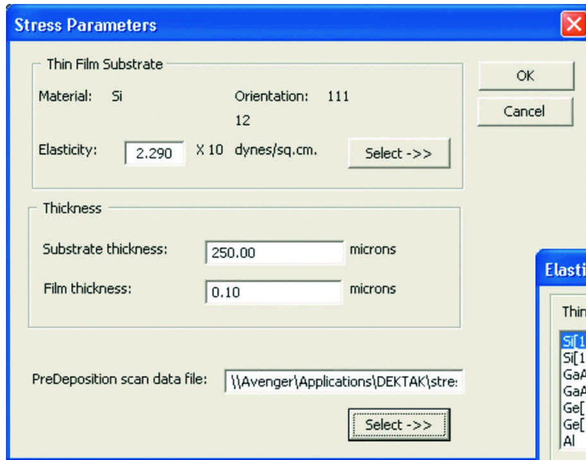

Figure 3. Scan Parameters dialog box.

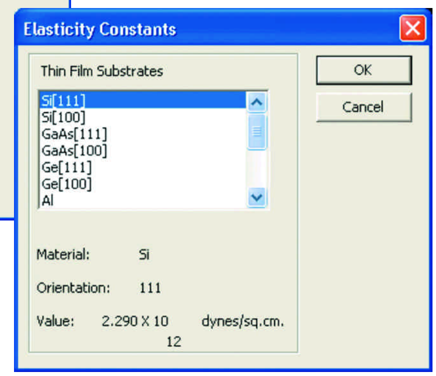

Figure 4. Choose the substrate material to obtain its elasticity constant.

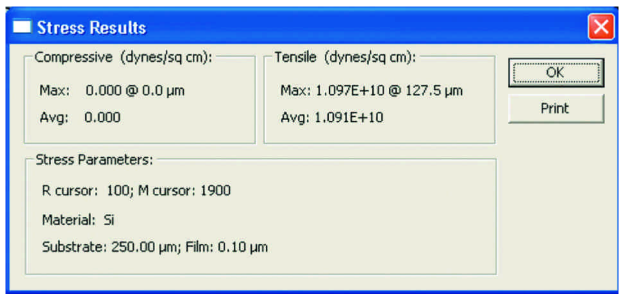

Figure 5. Stress Results Summary Window.

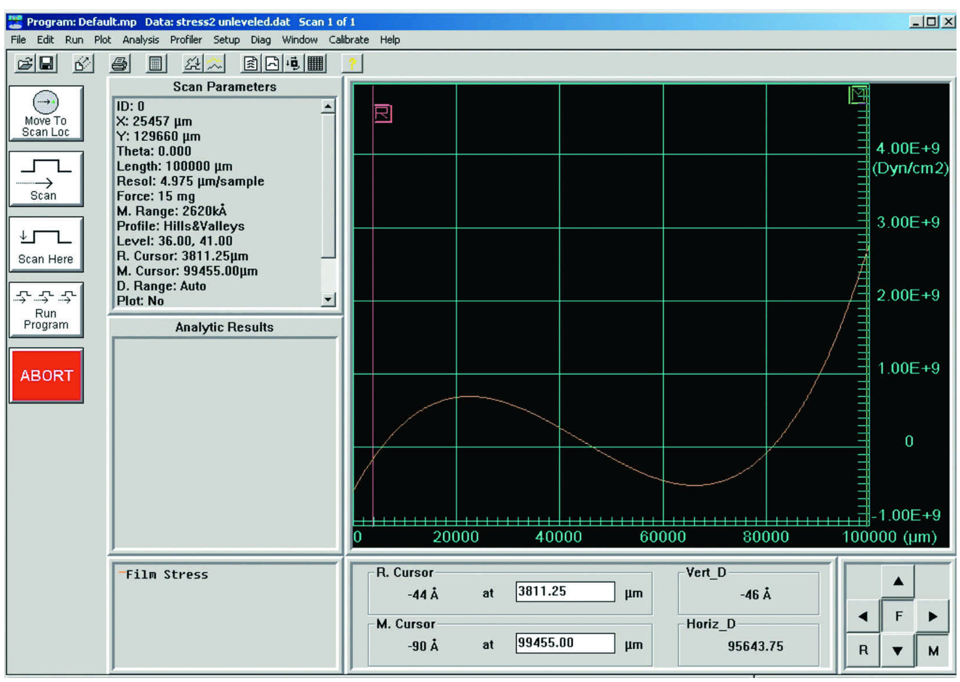

Figure 6. Stress Measurement results. The orange trace indicates that both tensile and compressive stresses are present following deposition.

Measurement Tips

1. The Stress Measurement analysis is designed to characterize unpatterned wafers. Surface features will skew the curve fits and may lead to inaccurate stress measurement.
2. Use appropriate fixtures to ensure that the pre-deposition and post-deposition scans overlap precisely. Bear in mind that stress is calculated from the change in substrate curvature, not from the absolute curvature; therefore, slight offsets in substrate position can produce large errors in the stress results.
3. Perform two stress measurements at 90 degree angles to achieve a more complete image of the substrate distortion.
4. If the substrate has been heated or cooled prior to stress measurement, let it reach thermal equilibrium before scanning.
5. Near the edges of a scan, the first and second derivatives of the curve fits will deviate because they are unconstrained by actual scan data. Place the R and M cursors at least 10% of the scan length away from each edge to exclude the ends of the scan. The stress calculation will still be plotted to the edges, but the summary data in the Stress Results window will reflect only the area between the cursors.
6. It is important to make a pre-deposition scan on the actual substrate, rather than substituting a measurement of a generic, flat surface such as an optical flat or straight line. Unless the actual substrate is exceptionally flat, such a substitution will lead to an inaccurate assessment of the film stress.
7. Both pre- and post-deposition scans must have the same number of data points. Do not abort either scan before completion.
8. Based on user experience with production silicon wafers[4], stress resolution down to the order of 1×10^8 dyne/cm^2 is practical. Very low film-induced curvature may lead to stress calculations which are below the practical resolution of the profiler.

Conclusion

Accurate stress measurement helps process developers avoid non-planarity effects to ensure uniform deposition and high part performance. for samples up to 200 mm in diameter. The Stress Measurement Analysis option for Dektak stylus profilers gives you the flexibility to accurately characterize film stress, as well as roughness and steps, for comprehensive film analysis on a single platform.

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References

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