Surface Profilometry as a tool to Measure Thin Film Stress, A Practical Approach.

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Abstract-- As the film decreases in thickness the requirements of more accurate increases and more film properties are needed in order to fully characterize them. Thickness and Stress are only a couple of film properties needed to utilize these films and know about the process.

Stress is very important when it comes to thin films; due to the nature of the film delaminating and failure of the device can result. For some films conventional reflectometry and interferometric techniques are not useful since the films are not transparent. For these opaque (not transparent) films Stylus Profilometry is the technique recommended because it can easily measure thickness parameters as well as stress and surface roughness.

***Index Terms*—Profilometry, Surface Metrology, Stress Measurement.**

I. Introduction

STYLUS Profilometry is one of the common tools to measure surface film characteristics. In this paper the basics of profilometry is discussed including the measurement hardware as well as how a stress measuring can be obtained using one example of Thermal Oxide on a 4 inch silicon wafer. The tool referred thought this paper is the Tencor P2 Profilometer.

II. Principles of operation

The stylus profilometry tool is based on contact measurement of the sample. A stylus is moved across the feature to measure and the vertical displacement of the stylus is converted to a height value in Z equivalent to the step height in the feature studied. This process involves some mechanical and electronic devices in order to perform the conversion. The principle can be described as the one used in early phonograph players. The sample is located in an X, Y, θ stage, the resolution of the stage is very important in determining the resolution of the actual measurement. The component of the system will be discussed later in detail.

Topography is the main measurement the tool is capable of. By dragging the stylus over a certain line across the wafer, the surface topography can be determine from the output of the displacement sensor correlated to the travel of the sample in X,Y giving a topography reading across the line of scan. Multiple scans one next to the other can give 3D information and provide a three-dimensional map of the surface.

A. Wafer Stage

In typical Profilometer tools the stage is an X, Y, θ stage in which the movements are controlled by stepper motors or servo motors. The motors are connected using a set of reduction gears to a "worm" screw. The stage is mounted in a rail and contacting the screw using a nut. The pace of the screw determines the resolution in conjunction with the reduction gear set.

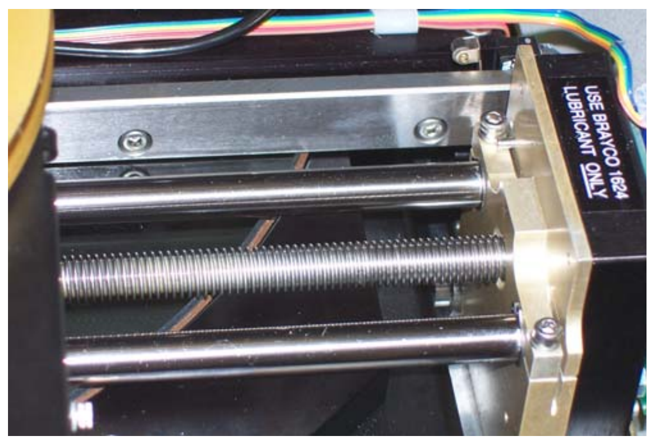

Figure 1. X Displacement mechanism for the wafer stage in the Tencor P2. The worm screw can be apreciated as well as the scew encoder in the black box at right.

For registration an optical encoder is connected to the worm screw in order to measure the rotation of the screw and determine the position of the stage. The resolution of the encoder can vary from 360 pulses per revolution to 36000 pulses per revolution, giving 1 degree to 0.01 degree respectively. The resolutions of the screw to the movement stage ratio is determine by the pacing of the screw and varies from tool to tool, even from revisions in the same tool maintaining the same resolution and travel because the parameters can be adjusted one to the other by the controlling software.

The motors used can be stepper motors which move by a series of pulses in a configuration of 2 or 4 electrical winding. These motors have very good resolution a repetition rates. With 300 steps per revolution a result of 1.2 degrees per step is achieved. Current control algorithms enable the motors to do half steps (0.6 degrees per revolution) or even micro-

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stepping in which the steps are divided into 16 or 32 micro steps giving up to 0.01875 degrees per step. The mechanical translation system (worm screw / reduction gears) can convert this accuracy to translational resolutions of 0.5 microns or 0.1 microns.

Other kind of motors used are the DC-Servos, these rely on complex current control algorithms and encoder feedback circuit to control the position of the shaft of the motor very precisely. Servos have faster reacting times but require complex electronics and control systems to give the accuracy and power of the stepper motors.

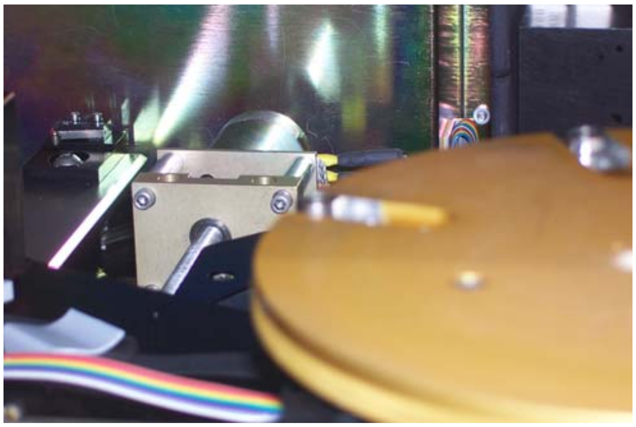


Figure 2. Y Stage driving mechanism. The servo motor can be seen at the back together with the reduction gears and the worm screw.

Some high-end Profilometry tools use Servo Driven Stages and interferometric feedback to correctly position the stage. The Tencor P2 uses servo driven stage and optical encoding in the shaft of the worm screw to provide the feedback, the system uses multiple feedback, one in the motor shaft and other in the worm screw. This scheme is also true for the θ, or rotation axis of the stage. The P2 is capable of stage resolutions in the order of a 0.01 microns and 0.001 degrees in the θ rotation axis. The maximum Scan length is 210 mm or 8.2 inches. This is not the actual stage limits but since is only capable of recording 5000 points in horizontal resolution and the fastest speed this yield to the maximum travel distance.

III. Z Axis – Stylus displacement measurement

The height or Z axis measuring is done by a stylus in contract with the surface being measured. The Stylus is located at the end of a cantilever arm. The opposite end of the cantilever is counter-balanced by a weight that is mounted in a screw system actuated by a motor; the motor can move the counter-weight closer or farther from the pivoting center of the cantilever regulating the pressure of the tip. In the P2 this force can be programmed to be from 1 to 100 milligrams. The Stylus used in the P2 has a tip radius from 1.5 to 2.5 microns and has a tip Shank angle of 45 degrees.

By dragging the stylus over the surface the cantilever will move in Z direction (up/down) and the force that the stylus impinges over the sample is controlled by the counter-weight system. The linear Z displacement has to be converted to an electric signal in order to be measured, but this has to be a non-contact technique for position measurement.

Depending of the resolution different methods for converting this position into an electrical signal are used.

A. Capacitive

In a capacitive sensing system the sensing element is a parallel plate capacitor. This measurement technique is based on the equation of the parallel plate capacitor.

$$C = K\varepsilon_o \frac{A}{d} \quad [1]$$

Where:
K: Dielectric Constant
εo: Permittivity (8.85pF/m)
A: Plate common Area
d: Plate separation

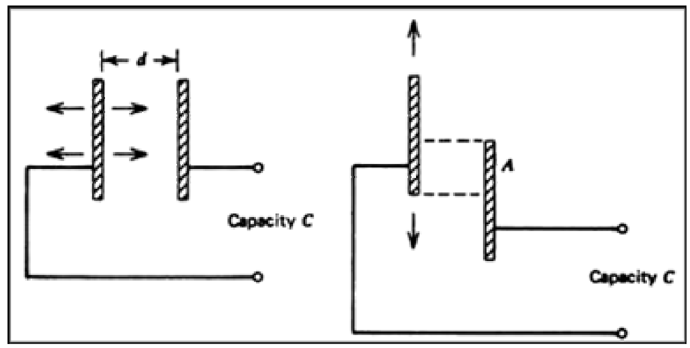
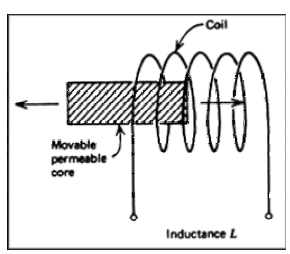


Figure 3. Capacitive Sensor [1]

The sensor can operate by multiple ways. First the plates can be mounted one on the cantilever and the other in a fixed position with respect to the cantilever. By changing the plate common area, this is the common shared area between either plates or the plate separation the capacitance change. By using this capacitor in an oscillator circuit as the timing device the frequency of the oscillator becomes dependant of the capacitance and then of the area or distance between the plates that is coming from the actual displacement of the cantilever.

B. Inductance



In this method a movable permeable core is moved in and out of a coil. The inductance of the coil is changed by the actual core being inserted in the coil magnetic field. Used in a similar way of the capacitor the frequency output is a function of the position of the core in the coil.

Figure 4. Inductive Displacement measurement [1]

C. Variable Reluctance

The variable reluctance sensor is an inductive sensor but it differs from the inductive in that a moving core is used to vary a magnetic flux coupling between two or more coils rather than changing the actual inductance of the coil. This kind of sensor is sensitive to changes in both linear and angular displacement. The common configuration of this Variable Reluctance sensor is called a Linear Variable Differential Transformer (LVDT).

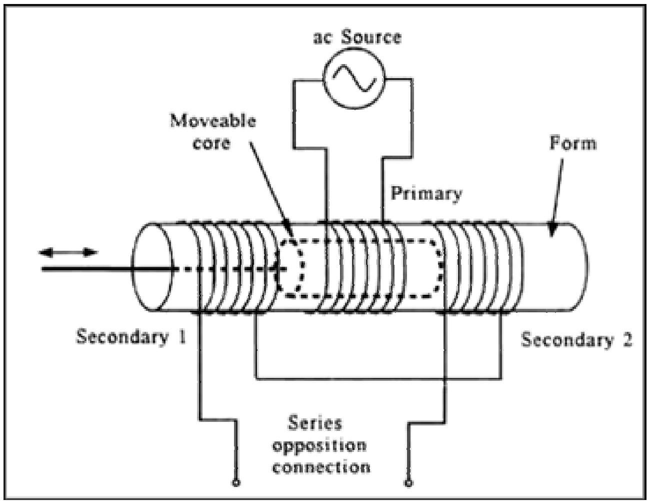


Figure 5. Basic configuration of a LVDT Sensor [1]

The LVDT is a primary coil in which an A.C. signal is introduced. Then two coils are wound in series opposite next to the primary. The voltage amplitude is a function of the position of the core. When the core is in the middle, just in the center of the primary coil the flux is the same for the other 2 coils, since they are in subtraction configuration (opposite series) the output will be minimal or null. When the core moves the differential amplitude of the signal increases when the core is moved from one coil to the other coil and since there is a phase change when the coil goes trough the central primary coil the direction can be determined. That is by measuring the amplitude voltage and phase from the resulting differential coil the displacement can be calculated.

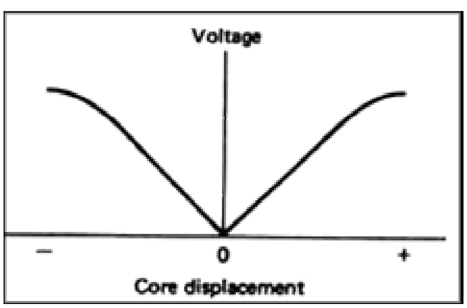


Figure 6. LVDT Signal response due to core displacement [1].

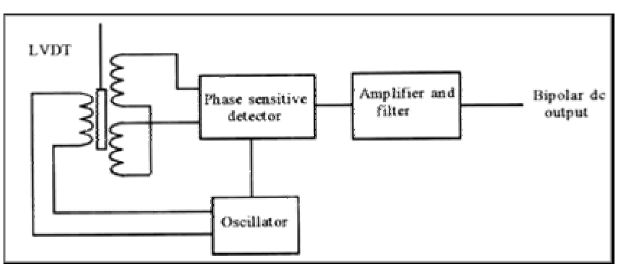


Figure 7. LVDT Signal Processing block Diagram [1]

This is the more commonly used sensor system for stylus Profilometer applications. By changing the position of the measuring point in the cantilever arm the resolution can be increased to 1 to 10 angstroms range in the stylus tip. The P2 stylus range is 20 microns up from the level position to 280 microns down range. The Tencor P2 has resolutions in the Z direction of 1A at 13 micron of total travel distance.

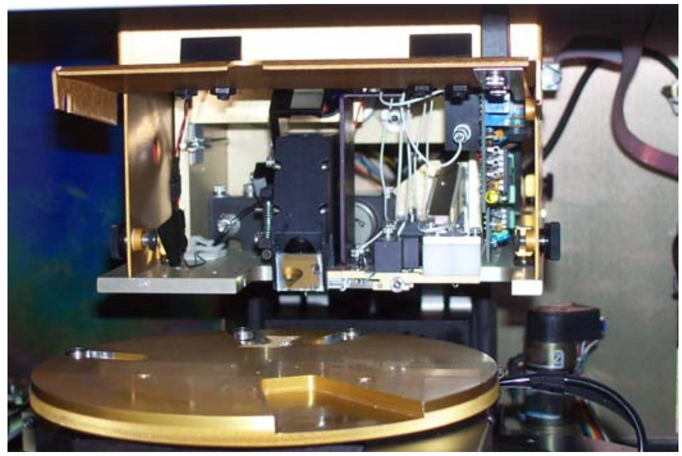


Figure 8. Measurement head of the Tencor P2. The stylus tip can be observed under the square mirror over the center of the stage**.**

The Tencor P2 Profilometer uses a LVDT system, the LDVT linear displacement element is housed inside the black box in figure 8. Inside this box is the imaging optics in charge of presenting the stylus tip image during measurement.

D. Piezoelectric Transducers

The piezo effect is when a crystal material is subjected to pressure or stress and generates a small current or voltage depending of the configuration. The inverse is also used to generate small movements due to the crystal reaction to an electric current is a deformation in volume. Many piezo elements are stacked together to produce movement and are used as motors in micro-movement stages for SEM and in stage vibration control due to their fast response times.

As a sensing element Piezoelectric transducers are commonly used for vibration measurements due that the output response is greater at changes in volume or elongation than a linear proportional change. In stylus profilometry they find application in the surface roughness measurements.

IV. Film Stress Measurement Basics

It's important to monitor thin film stress because is one characteristic that can be used to monitor film quality and deposition process variations.

Stress can be measured in a Profilometer as the deflection or curvature that the film induces to the substrate. This is a differential measurement. This is the sample has to be measured before the stress inducing process and after the process to find the change in curvature due to the stress. For this purpose a relative long scan of the sample has to be taken before the process and then after the process. After these measurements are taken then a mathematical algorithm calculates the stress based on the following formulas:

$$\sigma = \frac{1}{6R}\frac{E}{1-\upsilon}\frac{ts^2}{tf} \qquad (1)$$

Where:

$\frac{E}{1-\upsilon}$:Substrate Elastic Constant (E is Young's Modulus and v is Poisson Ratio)
ts: Substrate Thickness
tf: Film Thickness
R: Radius of Curvature

The Radius of curvature can be calculated using the following equation:

$$R = \frac{L^2}{8B} \quad \text{if L >>B} \qquad (2)$$

Where:
B: Bow (maximum between trace and its chord)
L: Chord Length (scan length)

NOTE: All geometric dimensions are in the same units.

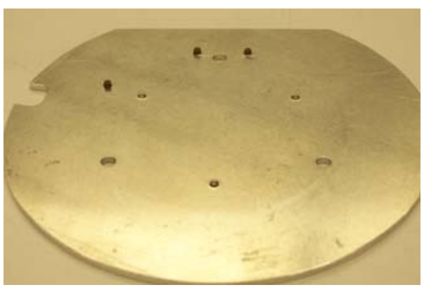


Figure 9. 4 inch wafer holder for stress measurement, 3 tips can the observed in the center as well as 3 darker tips that provide the limits for the wafer position.

These equations are the ones used by the Tencor P2 Profilometer to calculate stress on a thin film. The tool requires a special sample holder which only supports the sample in 3 points without vacuum, since applying a vacuum under the sample can severely affect the measurement due to the deformation of the substrate.

The P2 calculates 3 different stress values across the wafer: [4]

- Average Stress from the least square fit of the entire profile
- Maximum Stress based on the maximum of 13 overlapping sections of one-third of the length and offsets across the total profile
- Center Stress computed at the center third of the profile.

The Stress measurement can be done in two ways in the P2, one is the differential method, and this is one measurement before the process and other after the process. And the second is the post-stress measurement. In this case only a post measurement is done and the software computes the stress relying on the assumption that the initial substrate is perfectly flat.

V. Practical Application, Stress measurement using the Tencor P2

For this practical application a 4 inch wafer was used. The initial wafer thickness used in both the calculations is 450 microns. The wafer was oxidized by a wet oxidation method at 1000 degrees C. a total of 1.09 microns was grown on both sides of the wafer.

All measurements were done in the Tencor P2 Profilometer using the factory standard "STRESS_4_IN" Recipe for 4 inch wafers having a scan length of 75 mm. The wafer should be mounted in the special test fixture showed in figure 9. Both flats (fixture and wafer) should be oriented towards the back side of the stage and the vacuum should only be applied to the stress fixture.

A Good measuring practice is to take note of the X, Y and θ positions of the stage in order to find the same place of the scan for each of the two measurements. The system defaults to the center of the wafer, but since is a long scan (75 mm for 4 inch wafers) the stylus should be positioned by ¼ of an inch of the border. An important consideration is that the scan can not be aborted in the process in order to have all the data points. If the scan is aborted then the second measurement will not correlate to all the points in the previous plot.

Figure 10. Tencor P2 Long Scan Profilometer. (Left)

An initial measurement of the oxide was performed and was saved. Then the oxide from the back side was removed by masking the top side with photo resist. The oxide etch was performed in buffered Hydrofluoric acid for 20 minutes (etch rate ~ 560A/min). The wafer was measured again giving the results on figure 11 and then the complete oxide was then removed before doing the last measure, figure 12**.**

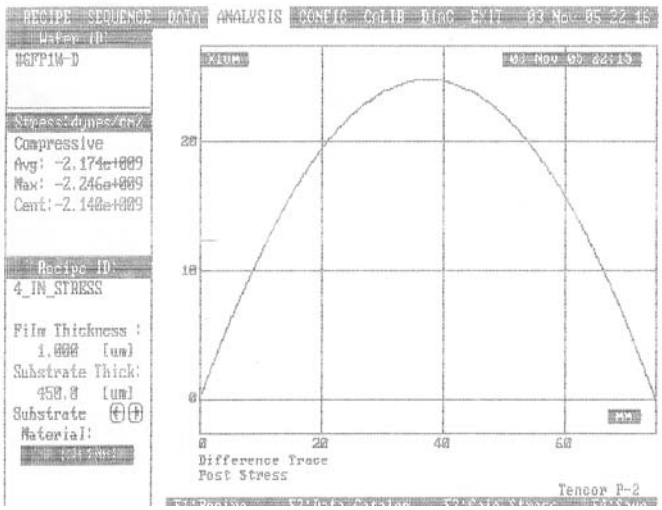


Figure 11. Plot of stress analysis from the wafer with only oxide in the front side (back side oxide removed).

The initial wafer measurement is for calibration purposes, the Tencor P2 calculates the stress via a differential measurement from the calibration and the 2nd reading.

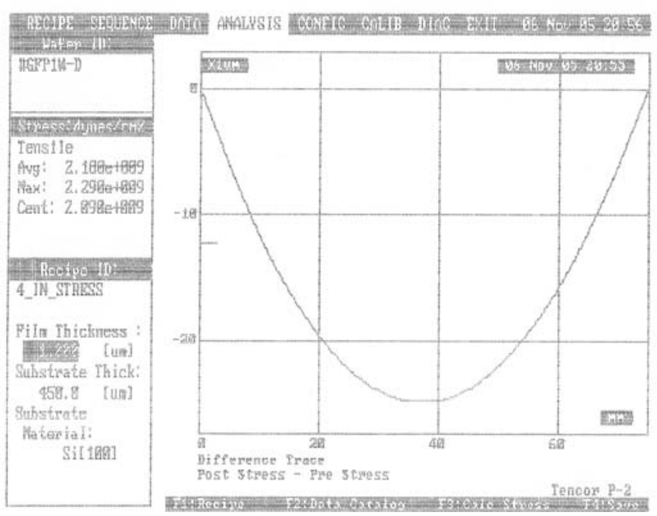


Figure 12. Plot of the stress measurement with the remaining oxide removed from the wafer (front side).

From figure 12 it can be said that the oxide on the top layer presents a tensile stress that is measured as a compressive stress related to the substrate. The stress value is -2.174E9 dines/cm2, that is 217 MPa.

After the removal of the oxide completely from the wafer the residual stress on the silicon became 2.188E9 dines/cm2 or 218 MPa, as measured is tensile, but can be addressed as compressive because the residual top oxide surface has been removed.

The literature [3] suggests a residual stress on the silicon of -275 to -225 MPa, the negative meaning compressive and this numbers refer to grown wet at 950 degrees C. Knowing from the oxidation process of the wafer, the process used was wet oxide at 1000 degrees C. Higher temperatures mean lower stress due to the growth kinetics. The obtained values are very close (only 3% difference from the lower limit).

Using equations (1) and (2) the Tencor P2 analyzes the data and finds a fit of the data to the equation (2) using the least squares method. Then with the values of radius of curvature and the film and substrates characteristics the (1) is fitted and solved for the stress value. The solving of equation (1) is done using a least square fit method to include all the data points in the profile.

Given the extension of the scanned profile (75 mm) and the amount of data points (as it can be seen in the appendix) the manipulation of that data and the computation to relate it to the equations (1), (2) shown are not discussed in this paper.

VI. Conclusion

For the Stress measurement it can be observed that is 100% surface related. Any surface topology and affect the measurement as well as the status of the tool. Included here the quality of the wafer holders and the 3 indentations that lift the wafer from the chuck, by using the differential technique the errors due to the tool can be cancelled due to the differential nature. But errors not consistent between runs can affect the measurement.

Acknowledgment

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