3D Profiler Measurement Parameters

P-Series and
HRP-Series Profilers

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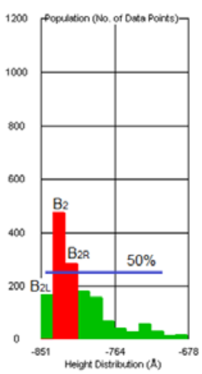

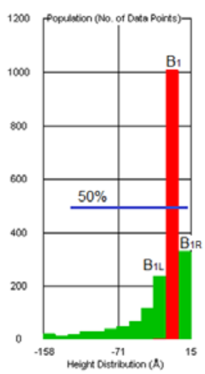

Introduction

When using the P-Series or HRP-Series profilers, the user sets up recipes that may include a variety of 3D measurement parameters. Although these parameters are discussed briefly within the Profiler Reference Manual, this Applications Note serves to provide greater mathematical detail regarding the equations used to generate the parameter values. Also included in this discussion are manual post-scan measurements based on 3D scan data.

Background

3D measurements are based on the unfiltered 3D scan data; these measurements do not include the applied Noise or Waviness Filters that the user defines within the Scan Recipe. The Noise and Waviness filters apply to 2D data only. The 3D data includes only the 3D Median Filter and any leveling that has been applied via 3D Line Leveling, 3D Planar (triangle) Leveling, and Histogram-based Leveling. 3D measurements may be calculated for the entire scan (Full Scale) and/or for a smaller user-defined sub-region (Boxed) within the original large scan. Note that any measurements calculated for a Boxed region use the Full Scale leveling plane as the baseline reference. The user may prefer to level the scan with respect to the boxed region of interest.

Definitions

The following pages list the 3D measurement parameters according to measurement category:

- General Parameters
- Roughness Parameters
- Bearing Ratio and Cutting Depth Parameters
- Manual 3D Measurements Parameters
- Histogram Depth Parameters
- Chemical-Mechanical Polishing (CMP) Analysis Parameters

A basic definition is provided along with the equation(s) used to generate the parameter values. In a calculation, x has M data points and y has N data points, and zi,j refers to the specific height value z at the location (xi,yj). The number of data points M and N used in the calculation depends upon the lateral dimensions of the region of interest and the recipe parameters selected.

The height value z depends on the step height calibration for the vertical range used for the measurement. Therefore, all parameters are based on the step height calibration unless noted. In the following calculations, the leveled z plane is defined as the reference plane, with height of 0, unless otherwise noted.

3D General Parameters

Within the General Parameters category, the 3D measurements include Total Indicator Runout [TIR3D], SlopeX, and SlopeY, 3D Peak (Sp) and 3D Valley (Sv). These measurements can be based on the full scan area and/or a partial boxed region.

Total Indicator Runout is defined as the difference between the highest and lowest points in the region, in units of length:

$$TIR3D = z_{max} - z_{min} \qquad (1)$$

SlopeX is defined as the root-mean-square value of the surface slope in the x direction, in units of degrees:

$$SlopeX = \tan^{-1}\sqrt{\frac{1}{(M-1)(N-1)}\sum_{i=2}^{M}\sum_{j=1}^{N}\left(\frac{z_{i,j}-z_{i-1,j}}{\Delta x}\right)^2} \qquad (2)$$

where Δx is the sampling step in x direction.

SlopeY is similarly defined as the root-mean-square value of the surface slope in the y direction, in units of degrees:

$$SlopeY = \tan^{-1}\sqrt{\frac{1}{(M-1)(N-1)}\sum_{i=1}^{M}\sum_{j=2}^{N}\left(\frac{z_{i,j}-z_{i,j-1}}{\Delta y}\right)^2} \qquad (3)$$

where Δy is the sampling step in y direction.

3D Peak (Sp) is defined as the height difference of the highest peak from the reference z plane.

$$S_p = z_{max} \qquad (4)$$

3D Valley (Sv) is the height difference between the lowest valley and the reference z plane.

$$S_v = z_{min} \qquad (5)$$

3D Roughness Parameters

Within the Roughness Parameters category, the 3D measurements include:

- RMS Deviation [Sq]
- Arithmetic Mean Deviation [Sa]
- Skewness of surface height distribution [Ssk]
- Kurtosis of surface height distribution [Sku]
- RMS Slope [Sdeltaq]
- Ten Point Height [Sz]
- Density of Summits [Sds]
- Developed Interfacial Area Ratio [Sdr]

RMS Deviation of a Surface is defined as the root-mean-square value of the departures relative to a reference plane, the leveled z plane, in units of length:

$$Sq = \sqrt{\frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N} z_{i,j}^{2}} \qquad (6)$$

This parameter is insensitive to sampling interval but is sensitive to the sampling area and is indicative of surface roughness.

Arithmetic Mean Deviation is defined as the arithmetic mean of the absolute values of the surface departures above and below the leveled z plane, in units of length:

$$Sa = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}\left|z_{i,j}\right| \qquad (7)$$

Skewness is defined as a measure of asymmetry of surface deviation about the mean Z plane, based on the RMS deviation. Skewness is a dimensionless quantity:

$$Ssk = \frac{1}{MN(Sq)^3}\sum_{i=1}^{M}\sum_{j=1}^{N} z_{i,j}^{3} \qquad (8)$$

A symmetric surface height distribution about the mean will yield Ssk ≈ 0. If the data is weighted more heavily above or below the mean, Ssk will be positive or negative, respectively, as shown in Figure 1.

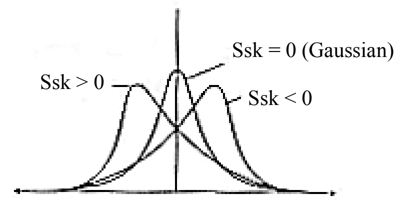

Figure 1 Skewness of Surfaces

Kurtosis is a measure of the peakedness or sharpness of the surface height distribution, in dimensionless units. It is a measure of the spread of the data. A Gaussian distribution has a kurtosis value of 3, a peak sharper than the Gaussian has a kurtosis value greater than 3, and a peak flatter than the Gaussian has a kurtosis value less than 3, as shown in Figure 2:

$$Sku = \frac{1}{MN(Sq)^4}\sum_{i=1}^{M}\sum_{j=1}^{N} z_{i,j}^{4} \qquad (9)$$

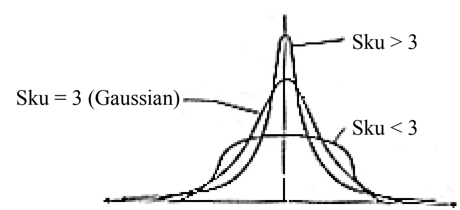

Figure 2 Kurtosis of Surfaces

RMS Slope is defined as the root-mean-square value of the surface slope. The surface slope at any point is described as:

$$\rho_{i,j} = \left[\left(\frac{z_{i,j} - z_{i-1,j}}{\Delta x} \right)^2 + \left(\frac{z_{i,j} - z_{i,j-1}}{\Delta y} \right)^2 \right]^{1/2} \quad (10)$$

then the root-mean-square slope over the entire sampling area is (dimensionless):

$$Sdeltaq = \sqrt{\frac{1}{(M-1)(N-1)} \sum_{i=2}^{M} \sum_{j=2}^{M} \rho_{ij}^2} \quad (11)$$

Ten Point Height is defined as the average value of the absolute heights of the five highest peaks and the depths of the five deepest valleys, where the determination of a peak or valley is based on an eight nearest-neighbor comparison. Ten-Point Height has units of length:

$$S_z = \frac{1}{5} \left[\sum_{i=1}^{5} |z_{pi}| + \sum_{i=1}^{5} |z_{vi}| \right] \quad (12)$$

Density of Summits is defined as the number of summits (local height maximums) per unit sampling area, based on an eight nearest-neighbor comparison, in units of $Area^{-1}$.

$$Sds = \frac{\text{Number of Summits}}{(M-1)(N-1)(\Delta x)(\Delta y)} \quad (13)$$

This parameter is greatly influenced by the sampling interval.

Interfacial Area Ratio is defined as the percent increase of the interfacial (actual) surface area over the projected surface area. The interfacial surface area is calculated by summing the average area of each of the smallest sampling quadrilaterals, where the average area of a quadrilateral is defined as:

$$A_{ij} = \frac{1}{4} \begin{pmatrix} \left[\Delta y^2 + (z_{i,j} - z_{i,j+1})^2 \right]^{1/2} + \\ \left[\Delta y^2 + (z_{i+1,j+1} - z_{i+1,j})^2 \right]^{1/2} \end{pmatrix} \times \begin{pmatrix} \left[\Delta x^2 + (z_{i,j} - z_{i+1,j})^2 \right]^{1/2} + \\ \left[\Delta x^2 + (z_{i,j+1} - z_{i+1,j+1})^2 \right]^{1/2} \end{pmatrix} \quad (14)$$

The projected surface area is simply the scan area (M-1)(N-1)(Δx)(Δy). Therefore, the increase in surface area is the interfacial area minus the projected area, and the interfacial area ratio is then expressed as:

$$Sdr = \left(\frac{\sum_{i=1}^{M-1} \sum_{j=1}^{N-1} A_{i,j}}{(M-1)(N-1) \cdot \Delta x \cdot \Delta y} - 1 \right) \bullet 100\% \quad (15)$$

3D Bearing Ratio and Material Volume Parameters

Within the Bearing Ratio and Material Volume category, the 3D measurements include Surface Bearing Ratio [Sbi] and Material Volume [Vm]. Both of these parameters require the operator to specify from one to three reference Z values (zones).

Surface Bearing Ratio is defined as the ratio of the number of the data points that lie at or above the specified cutting depth, which is measured from the peak point of the scan:

$$Sbi = \frac{S_n}{M \cdot N} \quad (16)$$

Where Sn is the total number of data point whose z height value is bigger or equal than the specified cutting depth.

Material Volume is defined as the material portion enclosed between two reference planes. The first reference plane is parallel to the mean (leveling) plane at a height Z = Zmax. The second reference plane is also parallel to the mean (leveling) plane, at a height specified by the user (Z is equal to the "Depth" value):

$$Vm = \frac{\Delta x \Delta y}{(M-1)(N-1)} \sum_{j=1}^{N} \sum_{i=1}^{M} z_{i,j} \quad (17)$$

The accuracy of the material volume calculation is dependent on recipe parameters such as scan rate, scan frequency, and Y-axis spacing.

Manual 3D Measurements

Specific locations of the surface can be measured using cursor boxes specified by the operator. These can be entered into the 3D scan recipe or after the 3D scan is completed, the operator may choose to manually perform measurements based on the 3D data. These measurements include Average Height and Step Height, and require the user to click and drag the cursor box(es) to define the region(s) of interest.

Average Height is the mean Z height within the measurement box, defined with respect to the leveling plane, in units of length:

$$\text{Average Height} = \frac{1}{MN} \sum_{j=1}^{N} \sum_{i=1}^{M} z_{i,j} \quad (18)$$

Step Height is the difference between the mean Z heights of the two operator-defined measurement boxes, in units of length:

$$\text{StepHeight} = \left[\frac{1}{M_1 N_1}\sum_{j=1}^{N_1}\sum_{i=1}^{M_1} z_{i,j}\right] - \left[\frac{1}{M_2 N_2}\sum_{j=1}^{N_2}\sum_{i=1}^{M_2} z_{i,j}\right] \qquad (19)$$

Histogram Depth Parameters

2D histogram depth analysis enables automatic measurement of step height(s) based on the use of a histogram to identify significant populations of data (modes). Histogram depth analysis can be separated into three functions:

- Data Selection Definition
- Bin Definition
- Depth Definition

Data Selection Definition allows the user to define regions of the scan to be included or excluded, using the cursors. The user can choose:

- All Data
- Data Within Measurement Cursors
- Data Outside Measurement Cursors

Figure 3 shows a copper CMP dishing, erosion, and recess scan. This scan is divided into two regions represented by the white and light gray areas, with the gray area representing the location of the cursors. This enables analysis of the dishing, gray area, by using *Data Within Measurement Cursors*. Analysis of the erosion and recess, white area, can be done using *Data Outside Measurement Cursors.*

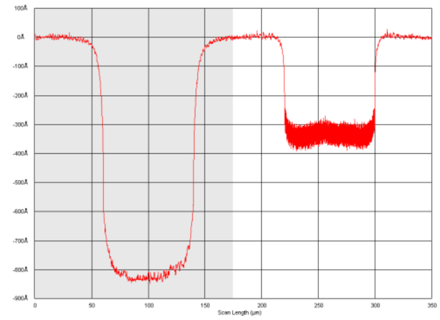

Figure 3 Copper CMP scan showing the use of the data exclusion cursors to be able to analyze the dishing separate from the erosion and recess.

Bin Definition allows the user to define the properties of significant populations of data. A histogram operates by placing each data point in the scan into a bin that represents the z-height range of that data point. The bins are then analyzed to find significant populations of data (modes). The parameters for bin definition include:

- Number of Bins
- Bin Z-Range Data Inclusion
- % for Qualifying Neighboring Bins
- Minimum Mode Population
- Minimum Depth

Number of bins is used to define the width (z-range) of each bin:

$$w_{bin} = \frac{(z_{max} - z_{min})}{n} \qquad (20)$$

where n is the number of bins, z_{max} and z_{min} are the maximum and minimum z-heights of the data included in the histogram. Figure 4 shows the change to the dishing histogram when the number of bins is increased from 30 to 60.

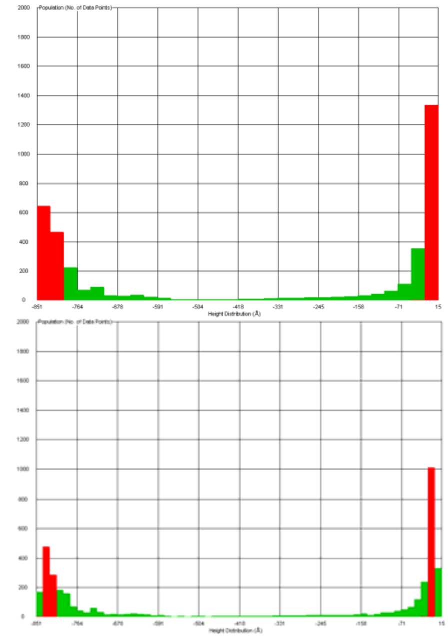

Figure 4 Dishing histogram where the number of bins have been increased from 30 (top) to 60 (bottom).

Bin Z-Range Data Inclusion has two parameters, *Lower Bound Percentile* and *Upper Bound Percentile*. This allows the user to exclude data from the bin width calculation in Equation 46. For example, if the scan contains a spike, it will distort the width of each bin since the z_{max} value will increase. The user can use the *Upper Bound Percentile* to exclude a portion of the data, such as the data from 99 to 100% of the total z-height. Similarly the user can use the *Lower Bound Percentile* to exclude data at low end, such as the data from 0 to 1%.

The next step is to define the modes, which are significant populations of data. In Figure 3 there are two modes, the top surface and the bottom of the dishing region, with the modes displayed as red bins in Figure 4. The algorithm will find a maximum of three modes, using the following recipe inputs and equations 21, 22, and 23:

- $B_{\%}$ = % Qualifying for Neighboring Bins
- $M_{\%}$ = Minimum Mode Population
- M_D = Minimum Depth

$$M_1 > M_{\%} \cdot \sum_{i=1}^{n} B_i \qquad (21)$$

where B_i is number of the data points in each bin and M_1 is the first mode. The bin(s) considered for inclusion in M_1 is the bin with the most data points, B_1, and the neighboring bins to the left and right, B_{1L} and B_{1R}:

$$M_1 = (B_1 + B_{1L} + B_{1R}) \qquad (22)$$

where B_{1L} and B_{1L} are included only if they are greater than the product ($B_{\%}$ * B_1).

This process is repeated to find the second and third modes, M_2 and M_3, with the additional criteria to be considered a mode that:

$$(M_1 - M_2) > M_D$$
$$\text{and } (M_2 - M_3) > M_D \qquad (23)$$

Figure 5 shows how this algorithm is applied to the dishing portion of the scan in Figure 3, using $B_{\%}$ = 50% and M_D = 500 Å.

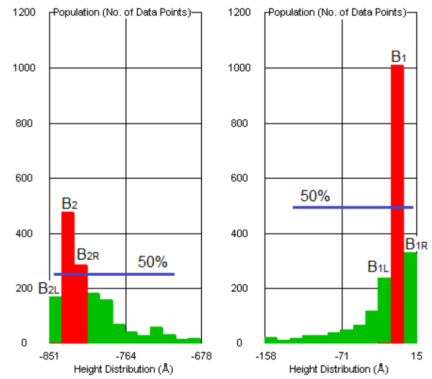

Figure 5 The left and right histograms (zoomed in from Figure 4) show the application of B% criteria to determine the modes. M1 = top surface of the dishing structure, with the data from B1 only. M2 = bottom surface of the dishing structure, with the data from B2 and B2R. Since M1 – M2 are separated by > 500 Å, MD criteria, M2 is a valid mode.

Depth Definition defines how to calculate a maximum of two steps heights using the modes found. The user can calculate the *Mean* of a mode:

$$z_{mean} = \frac{1}{n} \sum_{i=1}^{n} z_i \qquad (24)$$

where n = total number of data points in the bin(s) that are contained in the mode. Or the user can calculate the *Percentile* of a mode:

$$n_{\%} = \frac{p}{100} * N + \frac{1}{2} \qquad (25)$$

where p = percentile and N = total number of data points in the bin(s) contained in the mode. The $z_{\%}$ is the height which results from the ordered rank of the z-height values within the mode that is closest to the $n_{\%}$ value.

The modes are also differentiated either by the z-height, such as *Highest Plane* or *Lowest Plane*, or by the number of points in the mode, such as *Most Populous Plane*. The user then defines one of the modes as a reference and the step heights *Depth 1 and Depth 2* are calculated relative to the reference or relative to each other.

To calculate the dishing in Figure 3, the user would select the *Highest Plane* as the *Reference Mode* and the *Depth 1* as the difference between the *Lowest Mode and Reference*. To calculate the erosion and recess in Figure 3, white area, the user would first change to *Data Outside Measurement Cursors* and use similar bin definition values used in the dishing example. The erosion is calculated by selecting the *Highest Plane* as the *Reference Mode* and the *Depth 1* as the difference between the *Lowest Mode and Reference*. The recess is calculated by selecting Depth 2 as the difference between the *Depth 2 Mode and Depth 1 Mode*, which results in measuring from the Lowest Plane to the Next Lowest Plane.

CMP Analysis Parameters

Chemical Mechanical Planarization (CMP) is commonly used in a copper process to remove excess plated copper through chemical and mechanical polishing of the wafer surface. Within CMP analysis, the 2D measurements include:

- Dishing
- Erosion
- Recess
- Edge-over-Erosion

The CMP algorithm includes the same *Data Selection Definition* option described earlier in the *Histogram Analysis* section.

In the *Feature Definition* section, the user can define the *Minimum Width* of the dishing or erosion pad and a *Noise Filter*, both improve the accuracy and stability of finding the CMP features. The *Minimum Width* should be set to about 75% of the actual pad width. The *Noise Filter* smoothes the profile such that features are easily identified from roughness and noise. Similar to *Feature Detection*, the *Noise Filter* is only used as an aid to find the features, but does not impact the calculation of the CMP parameters.

Dishing is defined as the height difference between the field dielectric and the metal pad. The metal pad surface height is the mean height calculation as shown in Figure 6.

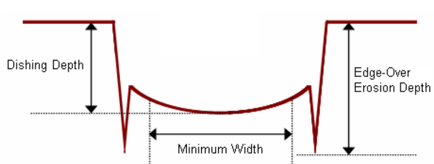

Figure 6 Example of CMP Dishing Pad with Edge-over-Erosion.

Edge-over-Erosion is defined as the height difference between the field dielectric and the trenches at the edges of the dishing or erosion pads. The trench height is the mean height calculation of the trenches, or a single trench if only one is detected as shown in Figure 6.

Erosion is defined as the height difference between the field dielectric and the erosion pad dielectric. The erosion depth is the height difference between the reference surface and the average of local maxima in the middle 50% range of the CMP feature as shown in Figure 7.

$$z_e = z_{ref} - \frac{1}{n}\sum_{i=1}^{n} z_{\max,i} \qquad (26)$$

where z_{max} is the local maxima in the measurement region and z_{ref} is the field dielectric surface.

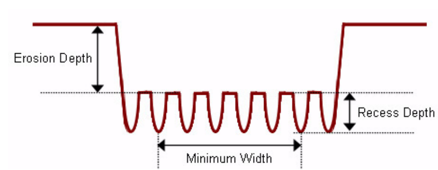

Figure 7 Example of Erosion Pad with Recess.

Recess is defined as the height difference between the erosion pad dielectric and the recess metal. The recess height is the height difference of the average of local maxima and minima in the middle 50% range of the CMP feature, as shown in Figure 7.

$$z_r = \frac{1}{n}\left(\sum_{i=1}^{n} z_{\max,i} - \sum_{i=1}^{n} z_{\min,i}\right) \qquad (27)$$

where z_{max} is the local maxima and z_{min} is the local minima in the measurement region.

Conclusion

This applications note has described the 3D measurement parameters available in the P-series profilers: P-7 and P-17 and HRP-series profilers: HRP-250 and HRP-350. Additional applications notes are available to describe the 2D measurement parameters as well as the 2D and 3D parameters available in Apex Advanced Analysis software.