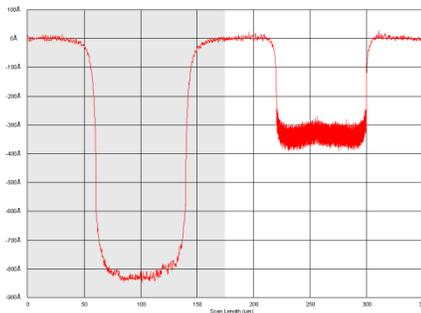# 2D Measurement Parameters

P and HRP Series Profilers

Weiqiang Mu

Introduction

When using the P-series and HRP-series profilers, the user sets up scan recipes which include calculations of various 2D measurement parameters. Although these parameters are discussed briefly within the Profiler User Manual, this Applications Note serves to provide greater mathematical detail regarding the equations used to generate the parameter values. The Apex software installed on the tools has a larger number of 2D parameters, which will not be discussed in this applications note.

Background

The 2D scan output may be displayed as the "Normal," "Roughness," and/or "Waviness" traces. Each 2D measurement parameter calculation is generated from one of these three traces. The Normal data includes the short-wavelength cutoff filter or low (frequency) pass filter, if defined in the scan recipe (either as "Default" or as a specific wavelength). The low pass filter makes the data smoother by removing the high frequency signals. Normal 2D data will also include any leveling that has been applied via the leveling cursors.

In addition to the low-pass noise filter, the user may also choose to specify a waviness filter. The waviness filter defines a spatial frequency cutoff at which the longer and shorter wavelength components of the 2D Normal trace are separated. The shorter wavelengths comprise the Roughness trace, and the longer wavelengths comprise the Waviness trace. The shape of the Gaussian filter cutoff is selected in the Scan Recipe. RC filter is also available for matching to results from older profiler software that does not support Gaussian filtering. Note that the waviness filter is not applied to 3D scan data as a whole, but will be applied to any individual 2D profiles taken from the 3D scan. For additional information regarding cutoff filters, please refer to the Profiler User Manual.

2D Parameters

The measured value in height 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.

The 2D measurements may be based on Normal, Roughness, or Waviness traces of the individual 2D profiles, and are organized into the following seven categories:

- General Parameters
- Roughness Parameters
- Waviness Parameters
- Bearing Ratio and Cutting Depth Parameters

- High Spot Count and Peak Count Parameters
- Histogram Depth Parameters
- Chemical-Mechanical Polishing (CMP) Analysis Parameters

Unless otherwise indicated, these parameter calculations are based on the position and width of the left and right measurement cursors, where the X position of each cursor is taken to be the horizontal midpoint, and the Z value at this location is the average Z value within the band defined by the cursor width:

$$x_{L,R} = \frac{1}{2}[x_1 + x_2]_{L,R}$$
(1)

$$z_{L,R} = \left[\frac{1}{M}\sum_{i=x_1}^{x_2} z_i\right]_{L,R}$$
(2)

where M is the number of data points comprising the cursor width.

Data points are numbered such that the first X data point is located at x = 0. The spacing between data points will hereafter be referred to as Δx.

If the position of either measurement cursor is changed, the user must perform the "Calc" command in order for the Statistics window to reflect the updated measurement values. The user can also use "edit recipe" and reprocess the raw data to apply these new cursor positions to all sites of the sequence data. Since the data stores the raw data, the user can also use the "edit recipe" function to modify filtering, leveling, enable and disable parameters.

2D General Parameters

Within the General Parameters category, the 2D measurements include:

- Step Height [StpHt]
- Total Indicator Runout [TIR]
- Average Height [Avg]
- Slope
- Radius [Rad]
- Area of Peaks [Area+]
- Area of Valleys [Area-]
- Total Area [Area]
- Peak [Pp]
- Valley [Pv]
- Profile Length [ProfL]
- Distance to Edge [Edge]
- Step Width [StpWt]
- Bump Height [BumpHt]

These parameters are referenced to the Normal trace and will reflect any leveling applied to the profile.

Step Height is defined as the difference between the average Z value of the left measurement cursor and the average Z value of the right measurement cursor:

$$StpHt = z_R - z_L$$
(3)

where z_R and z_L are given by eq. (2).

Total Indicator Runout is defined as the difference between the highest and lowest points in the profile, measured between the left and right measurement cursors. This is the same as the maximum peak-to-valley Z deviation:

$$TIR = z_{max} - z_{min}$$
(4)

Average Height is defined as the arithmetic mean of the Z data between the left and right measurement cursors:

$$Avg = \frac{1}{M}\sum_{i=1}^{M} z_i$$
(5)

Slope is based on the ratio of the difference in vertical positions to the difference in horizontal positions of the measurement cursors. The slope is reported in degrees, with respect to the horizontal:

$$Slope = \tan^{-1}\left[\frac{z_R - z_L}{x_R - x_L}\right]$$
(6)

Radius is defined with respect to a least-square circle fit to the data between the measurement cursors, where the measurement cursors define two points of a circular arc. It is based on the radius of curvature calibration instead of the height calibration. Note that the trace should not be leveled unless definite level reference points exist.

(Formula: See Appendix)

Area of Peaks is defined as the total area bounded by the leveled baseline and the profile where it rises above the baseline. This calculation is based on positive-valued data between the left and right measurements cursors, inclusive, and the endpoint values are both divided by 2:

$$\text{Area+} = \Delta x \cdot \left[\sum_{i=2}^{M-1} z_i + \left(\frac{z_1 + z_M}{2} \right) \right] \quad (7)$$

where $z = 0$ if negative-valued.

Area of Valleys is defined as the total area bounded by the leveled baseline and the profile where it sinks below the baseline. This calculation is based on negative-valued data between the left and right measurements cursors, inclusive, and the endpoint values are both divided by 2:

$$\text{Area} - = \Delta x \cdot \left[\sum_{i=2}^{M-1} |z_i| + \left(\frac{|z_1| + |z_M|}{2} \right) \right] \quad (8)$$

where $z = 0$ if positive-valued.

Total Area is defined as the sum of Area+ and Area-:

$$\text{Area} = (\text{Area}+) + (\text{Area}-) \quad (9)$$

Peak is defined as the maximum Z value relative to the leveled reference line, between the left and right measurement cursors.

$$\text{Pp} = \max\{z_i \mid z_L \leq z_i \leq z_R\} \quad (10)$$

Valley is defined as minimum Z value relative to the leveled reference line, between the left and right measurement cursors.

$$\text{Pv} = \min\{z_i \mid z_L \leq z_i \leq z_R\} \quad (11)$$

Profile Length is defined as the arc length of the entire 2D scan. Note that this measurement is independent of the measurement cursor positions:

$$\text{ProfL} = \sum_{i=1}^{M-1} \sqrt{[z_{i+1} - z_i]^2 + [\Delta x]^2} \quad (12)$$

Distance to Edge is defined as the horizontal distance from X = 0 to the X location of the edge feature specified in the Scan Recipe (Up and Down Edge, Up and Down Base, Convex, Concave, Bump, and Model). If no edge has been specified, the software will return the value 0. This parameter is independent of the measurement cursor positions:

$$\text{Edge} = x_{edge} \quad (13)$$

Step Width is defined as the width of the edge feature specified in the scan recipe, based on up-edge/down-edge or down-base/up-base pairs. For example, if an up edge (down base) has been specified, the software finds the position of the first down edge (up base) that follows it. If no edge has been specified, the software will return the value 0. This parameter does not work with convex or concave arc, bump and model feature detection, and it is independent of the measurement cursor positions:

$$\text{StpWt} = x_{downedge} - x_{upedge}, \text{ or}$$

$$\text{StpWt} = x_{upbase} - x_{downbase} \quad (14)$$

Bump Height is defined as the difference between the arithmetic mean of the highest 10 data points of a bump and the reference line:

$$\text{BumpHt} = \frac{1}{10} \sum_{i=1}^{10} z_{max,i} - Z_{ref} \quad (15)$$

where $z_{max,i}$ is the 10 highest data points of the bump, and Z_{ref} is the reference line height.

The reference line is the average height of the lowest mode (plane) of the left and right halves of the scan:

$$Z_{ref} = (Z_{left} + Z_{right}) / 2 \quad (16)$$

The lowest mode for each half is determined after excluding the highest 10% of the data and lowest 5% of the data, from each half. See the histogram analysis description for more details on how a mode is determined.

Please note that the bump height analysis assumes that the bump is in the center of the scan.

2D Roughness Parameters

Within the Roughness Parameters category, the 2D measurements include:

- Average [Ra]
- Maximum Ra [MaxRa]
- RMS [Rq]
- Peak [Rp]
- Valley [Rv]
- Peak/Valley [Rt]
- Height 10pt [R5z]
- Height 6pt [R3z]
- Mean Ht Sampling Length [Rz]
- Max Ht Sampling Length [Rmax]
- Roughness Height [Rh]
- Mean Peak Height [Rpm]
- RMS Slope [Dq]
- RMS Wavelength [Lq]
- Std. Dev. Height [SD]

These parameters are referenced to the Roughness trace and will include any leveling applied to the profile. Note that when a waviness filter has been specified, the roughness and waviness Z data will differ from the normal Z data. In calculating these parameters, the cursors refer to *the left edges of the*

measurement cursors, except Max Ht Sampling Length (Rmax) and Roughness Height (Rh).

Average (roughness) is defined as the arithmetic average Z deviation from the reference line. For Ra, MaxRa, and Rq, the reference line is defined by the leveled, mean-shifted data between the measurement cursors. First, the data between the two measurement cursors are leveled based on the positions of the left and right *measurement* cursors. The data between the cursors are then divided into two halves, split at the midpoint, as shown in Figure 1.
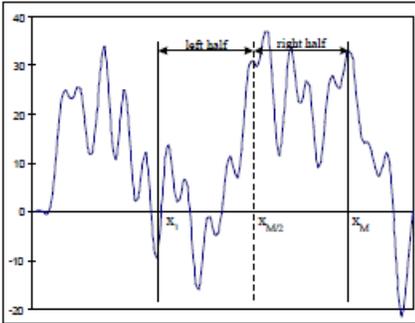
Figure 1: The data between the left edges of the measurement cursors is leveled using the mean Z values of the left and right regions.
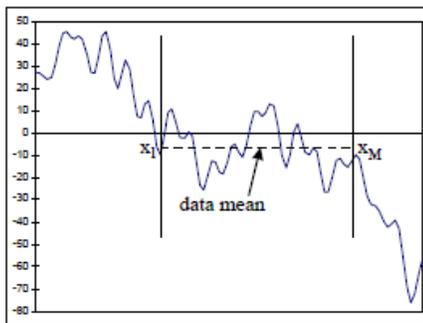
Figure 2: The Ra, MaxRa, and Rq values are calculated relative to the mean of the leveled data.

The mean Z values of both halves are calculated, and the data between the measurement cursors are leveled by subtracting a 1st-order fit:

$$z_i' = z_i - (x_i - x_1)\left(\frac{\bar{z}_{right} - \bar{z}_{left}}{x_{3M/4} - x_{M/4}}\right) \quad (17)$$

The Ra value is then calculated with respect to the mean of this leveled data, where the leveled data are shown in Figure 2:

$$R_a = \frac{1}{M}\sum_{i=1}^{M}\left|z_i' - \bar{z}_i'\right| \quad (18)$$

Maximum Average (roughness) is defined as the maximum Ra value calculated from each of 19 (local) overlapping sections, where each section is 10% of the sampling length. Reference lines are defined for each section as for the Ra calculation:

MaxRa = max [Ra$_1$, ...Ra$_{19}$], or max [Ra$_1$,...Ra$_{(M/5)-1}$] if M<100, where Ra is defined in eq. (18).

RMS (roughness) is defined as the root-mean-square Z deviation from the reference line, where the reference line is defined as for Ra, using eq. (17):

$$Rq = \sqrt{\frac{1}{M}\sum_{i=1}^{M}(z_i' - \bar{z}_i')^2} \quad (19)$$

Peak (Roughness) is defined as the maximum Z deviation above the mean, corresponding to the highest point between the measurement cursors (note that this value is referenced to the mean of the data, not the leveling line):

$$Rp = z_{max} - z_{avg} \quad (20)$$

Valley (Roughness) is defined as the maximum Z deviation below the mean, corresponding to the lowest point between the measurement cursors (note that this value is referenced to the mean of the data, not the leveling line):

$$Rv = z_{min} - z_{avg} \quad (21)$$

Peak/Valley (Roughness) is defined as the difference between the highest and lowest points in the profile, measured between the left and right measurement cursors. This is analogous to the TIR measurement on the Normal trace:

$$Rt = z_{max} - z_{min} \quad (22)$$

Height 10pt is defined as the height difference between the average of the five highest peaks and the average of the five deepest valleys, calculated relative to the reference line between the left and right measurement cursors. The peak and valley determinations are based on a two-nearest-neighbor comparison, not including the endpoints of the measurement region:

$$R5z = \frac{1}{5}\left[\left|\sum_{i=1}^{5}z_{pi}\right| + \left|\sum_{i=1}^{5}z_{vi}\right|\right] \quad (23)$$

Height 6pt is defined as the height difference between the average of the three highest peaks and the average of the three deepest valleys, calculated relative to the reference line between the left and right measurement cursors. The peak

and valley determinations are based on a two-nearest-neighbor comparison, not including the endpoints of the measurement region:

$$R3z = \frac{1}{3}\left[\left|\sum_{i=1}^{3} z_{pi}\right| + \left|\sum_{i=1}^{3} z_{vi}\right|\right] \quad (24)$$

Mean Ht Sampling Length also known as *Mean Roughness Depth,* is defined as arithmetic mean value of the single total indicator runout (TIR) of consecutive sampling length. The total sampling length L, which is between the measurement cursors, is divided into n consecutive parts. For each part, the TIR is defined as eq. (4). Then the Mean Ht Sampling Length is:

$$R_z = \frac{1}{n}\sum_{i=1}^{n} TIR_i \quad (25)$$

Max Ht Sampling Length also known as *Maximum Roughness Depth*, is defined as the largest single total indicator runout (TIR) within the evaluation length. The total sampling length L is divided into n consecutive parts. For each part, the TIR is defined as eq. (4). Then the Max Ht Sampling Length is:

$$R_{zmax} = max[TIR_1, TIR_2, \ldots TIR_n] \quad (26)$$

Roughness Height is defined as the difference between the mean Z value of the left measurement cursor and the mean Z value of the right measurement cursor on the Roughness trace. This is analogous to the Step Height measurement on the Normal trace:

$$Rh = z_R - z_L \quad (27)$$

Mean Peak Height is defined as the average of five peak heights. These five peak heights are the local maxima of five equal-length, adjacent segments of the data between the measurement cursors:

$$Rpm = \frac{1}{5}\begin{bmatrix} Rp_{i=1}^{i=0.2M} + Rp_{i=0.2M+1}^{i=0.4M} \\ + Rp_{i=0.4M+1}^{i=0.6M} + Rp_{i=0.6M+1}^{i=0.8M} \\ + Rp_{i=0.8M1}^{i=M} \end{bmatrix} \quad (28)$$

RMS Slope is defined as the RMS deviation of the slope from the average slope, in dimensionless units of length divided by length:

$$Dq = \sqrt{\frac{\sum_{i=1}^{M}(z_{i+1} - z_i - Da \cdot \Delta x)^2}{(x_R - x_L) \cdot \Delta x}} \quad (29)$$

where the average slope:

$$Da = \frac{z_R - z_L}{x_R - x_L} \quad (30)$$

RMS Wavelength is defined as the dominant spatial wavelength that comprises the surface, weight by the amplitude of the various spatial components.

$$Lq = (2\pi) \cdot (Rq/Dq) \quad (31)$$

where Rq and Dq are defined as in equation (19) and equation (29), respectively.

Std. Dev. Height is defined as the standard deviation from the mean of the roughness data between the measurement cursors:

$$SD = \sqrt{\frac{1}{M}\sum_{i=1}^{M}\left(z_i - z_{avg}\right)^2} \quad (32)$$

2D Waviness Parameters

Within the Waviness Parameters category, the 2D measurements include:

- Average [Wa]
- RMS [Wq]
- Peak [Wp]
- Valley [Wv]
- Peak/Valley [Wt]
- Waviness Height [Wh]

Except Waviness Height (Wh), the measurement cursors for these parameters refer to the left edges of the cursors. These parameters use the data between the two measurement cursors on the Waviness trace and will include any leveling applied to the profile.

Average (waviness) is defined as the arithmetic average Z deviation from the reference line. For Wa and Wq, the reference line is defined by the leveled, mean-shifted data between the two measurement cursors. The data is first leveled based on the cursors. The data between the cursors is divided into two halves, split at the midpoint, as shown in Figure 1. The mean z values of both halves are calculated, and the data between the measurement cursors is leveled by subtracting a 1st-order fit:

$$z_i' = z_i - (x_i - x_1)\left(\frac{\bar{z}_R - \bar{z}_L}{x_{3M/4} - x_{M/4}}\right) \quad (33)$$

The Wa value is then calculated with respect to the mean of this leveled data, where the leveled data is shown in Figure 2:

$$Wa = \frac{1}{M} \sum_{i=1}^{M} \left| z_i^{'} - \overline{z}_i^{'} \right| \qquad (34)$$

RMS (waviness) is defined as the root-mean-square Z deviation from the reference line, where the reference line is defined as for Wa:

$$Wq = \sqrt{\frac{1}{M} \sum_{i=1}^{M} (z_i^{'} - \overline{z}_i^{'})^2} \qquad (35)$$

Peak (Waviness) is defined as the maximum Z deviation above the mean, corresponding to the highest point between the measurement cursors. Note that this value is referenced to the mean of the data, not the leveling line:

$$Wp = z_{max} - z_{avg} \qquad (36)$$

Valley (Waviness) is defined as the maximum Z deviation below the mean, corresponding to the lowest point between the measurement cursors. Note that this value is referenced to the mean of the data, not the leveling line:

$$Wv = z_{min} - z_{avg} \qquad (37)$$

Peak/Valley (Waviness) is defined as the difference between the highest and lowest points in the profile, measured between the left and right measurement cursors. This is analogous to the TIR measurement on the Normal trace:

$$Wt = z_{max} - z_{min} \qquad (38)$$

Waviness Height is defined as the difference between the average Z value of the left measurement cursor and the average Z value of the right measurement cursor. This is analogous to the Step Height measurement on the Normal trace:

$$Wh = z_R - z_L \qquad (39)$$

2D Bearing Ratio and Cutting Depth Parameters

Within the Bearing Ratio and Cutting Depth Parameters category, the 2D measurements include:

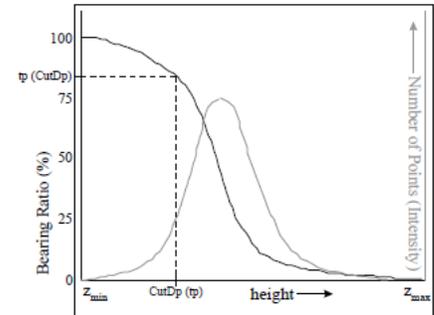- Bearing Ratio [tp]
- Cutting Depth [CutDp]

These parameters are referenced to the Normal trace and will include any leveling applied to the profile. The user may specify up to three cutting depths in order to obtain up to three corresponding bearing ratios.

Likewise, the user may specify up to three bearing ratios in order to obtain up to three corresponding cutting depths.

2D Bearing Ratio is defined as the percentage of data points that lie at or above an absolute Z value (cutting depth), which is specified by the user. The bearing ratio is based on data between the left and right measurement cursors, inclusive:

$$tp(CutDp) = \frac{n}{M} \times 100\% \qquad (40)$$

where n is the number of data points for z ≥ cutting depth.

Figure 3: The height histogram (gray) and the bearing ratio (black).

2D Cutting Depth is defined as the absolute Z value at or above which the ratio fraction of data points lie. The user specifies a ratio value from 0.0 to 1.0, and the measurement is based on data between the left and right measurement cursors, inclusive:

$$CutDp(ratio) \leq z_i \leq z_{max} \qquad (41)$$

where $1 \leq I \leq (M \times ratio)$.

The data is first binned and then the CutDp value is determined by linear interpolation of the bearing ratio. This is derived from the amplitude histogram of the binned data. Figure 3 shows an amplitude histogram and its corresponding bearing ratio.

2D High Spot Count and Peak Count Parameters

Within the High Spot Count and Peak Count Parameters category, the 2D measurements include:

- High Spot Count [HSC]
- Mean Spacing Sm [1/HSC]
- Peak Count [PC]
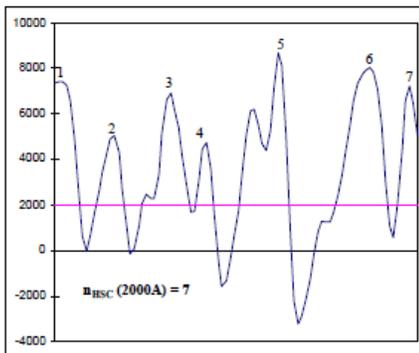- Mean Spacing Sm [1/PC]

These parameters are referenced to the Normal trace, between the left and right measurement cursors, and will include any

leveling applied to the profile. The user may specify up to three input values per parameter in order to obtain up to three corresponding measurements.

High Spot Count is defined as the number of peaks per millimeter of scan length that project above the input height value. For the profile above the specified height, all the connected sections of the profile are considered as one peak, as shown in Figure 4:

$$HSC(h) = \frac{n_{HSC}}{L(mm)} \qquad (42)$$

where nHSC is the number of peaks, L is the distance between measurement cursors, with h < z_{max}.

Figure 4: The data shows seven maxima projecting above h =2000Å. HSC(h) = n/L.

Mean Spacing HSC is defined as the mean length between adjacent peaks that project above the input height value. This value is the inverse of HSC(band), in micron or angstrom:

$$SmHSC(h)=[HSC(h)]^{-1} \qquad (43)$$

Peak Count is defined as the number of peaks and valleys per millimeter of scan length that project beyond the input band.

The band is centered about z = 0 and occupies a width of ±(b/2). For this measurement, peaks and valleys are defined as the maximum excursions outside of the band, as shown in Figure 5:

$$HSC(h) = \frac{n_{PC}}{L(mm)} \qquad (44)$$

where n_{PC} is the number of peaks and valleys, with $|z_{max,min}| > b/2$.
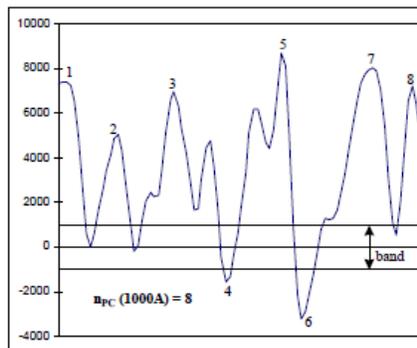
Figure 5: The data shows eight max/min projections beyond b/2 = ±1000Å. PC(b) = n/L.

Mean Spacing PC is defined as the mean length between adjacent peaks and valleys that project beyond the input band. This value is the inverse of PC (band), in micron or angstrom:

$$SmPC(band)=[PC(band)]^{-1} \qquad (45)$$

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 6 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*.
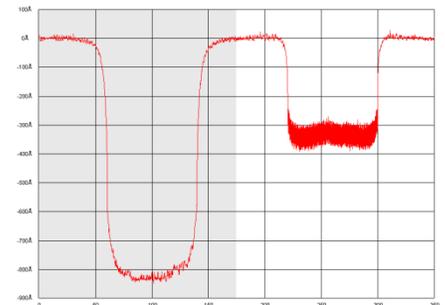
Figure 6: Copper CMP scan showing the use of the data exclusion cursors to be able to analyze the dishing separate from the erosion and recess.

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:

$$w_{bin} = \frac{(z_{max} - z_{min})}{n} \qquad (46)$$

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 7 shows the change to the dishing histogram when the number of bins is increased from 30 to 60.
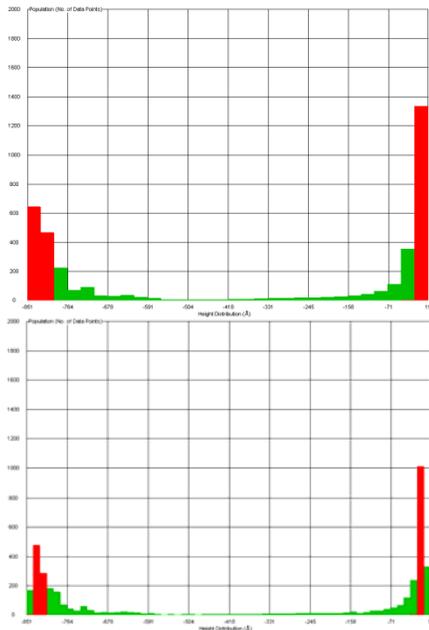
Figure 7: Dishing histogram where the number of bins have been increased from 30 (top) to 60 (bottom).

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 6 there are two modes, the top surface and the bottom of the dishing region, with the modes displayed as red bins in Figure 7. The algorithm will find a maximum of three modes, using the following recipe inputs and equations 47, 48, and 49:

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

$$M_1 > M_\% \cdot \sum_{i=1}^{n} B_i \qquad (47)$$

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}:
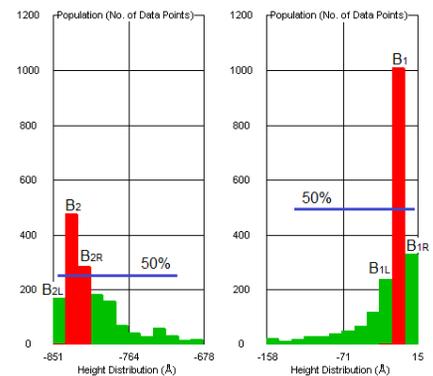
$$M_1 = (B_1 + B_{1L} + B_{1R}) \qquad (48)$$

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:

$$(M_1 - M_2) > M_D$$
$$\text{and } (M_2 - M_3) > M_D \qquad (49)$$

Figure 8 shows how this algorithm is applied to the dishing portion of the scan in Figure 6, using $B_\%$ = 50% and M_D = 500 Å.

Figure 8: The left and right histograms (zoomed in from Figure 7) show the application of $B_\%$ criteria to determine the modes. M_1 = top surface of the dishing structure, with the data from B_1 only. M_2 = bottom surface of the dishing structure, with the data from B_2 and B_{2R}. Since M_1 − M_2 are separated by > 500 Å, M_D criteria, M_2 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:

$$z_{mean} = \frac{1}{n} \sum_{i=1}^{n} z_i \qquad (50)$$

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:

$$n_{\%} = \frac{p}{100} * N + \frac{1}{2} \qquad (51)$$

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 6, 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 6, 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:
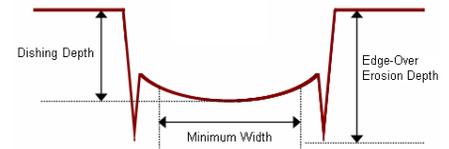
- Dishing
- Erosion
- Recess
- Edge-over-Erosion

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 9.

Figure 9: 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 9.

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 10.

$$z_e = z_{ref} - \frac{1}{n}\sum_{i=1}^{n} z_{\max j} \qquad (52)$$

where $z_{\max}$ is the local maxima in the measurement region and z_{ref} is the field dielectric surface.
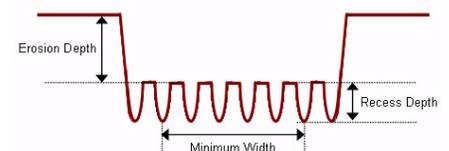
Figure 10: Example of Erosion Pad with Recess.

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 10.

$$z_r = \frac{1}{n}(\sum_{i=1}^{n} z_{\max j} - \sum_{i=1}^{n} z_{\min j}) \quad (53)$$

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 2D 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 3D measurement parameters as well as the 2D and 3D parameters available in Apex Advanced Analysis software.

Appendix

The mathematical equation to calculate the center of a circle with least square fitting:

Define:

$$u_i = x_i - \bar{x};$$
$$v_i = y_i - \bar{y}$$
$$S_u = \sum_i u_i$$
$$S_{uu} = \sum_i u_i^2$$
$$S_{uuu} = \sum_i u_i^3$$
$$S_v = \sum_i v_i$$
$$S_{vv} = \sum_i v_i^2$$
$$S_{vvv} = \sum_i v_i^3$$
$$S_{uv} = \sum_i u_i v_i$$
$$S_{uuv} == \sum_i u_i^2 v_i$$
$$S_{uvv} = \sum_i u_i v_i^2$$

Then center of the circle is:

$$x_c = \bar{x} + \frac{1}{2} \cdot \frac{(S_{uuu} + S_{uvv}) \cdot S_{vv} - (S_{vvv} + S_{uuv}) \cdot S_{uv}}{S_{uu} S_{vv} - S_{uv}^2}$$

$$y_c = \bar{y} + \frac{1}{2} \cdot \frac{(S_{vvv} + S_{uuv}) \cdot S_{uu} - (S_{uuu} + S_{uvv}) \cdot S_{uv}}{S_{uu} S_{vv} - S_{uv}^2}$$

And the radius of the circle is:

$$r = \left\{ (x_c - \bar{x})^2 + (y_c - \bar{y})^2 + \frac{S_{uu} + S_{vv}}{N} \right\}^{1/2}$$