Background Statement for SEMI Draft Document 3335D
NEW STANDARD: GUIDE FOR DETERMINING NANOTOPOGRAPHY
OF UNPATTERNED SILICON WAFERS FOR THE 130 nm TO 22 nm
GENERATIONS IN HIGH VOLUME MANUFACTURING

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The draft is based on a former draft document 3335C.

During SEMICON® Japan 2008 the AWGTF discussed how to restart the Standard development for NT.

Working Group Members to carry out this work were:
- M. Yoshise - KLA
- J. Sinha - KLA
- F. Riedel - Siltronic
- F. Passek - Siltronic
- J. Valley - Raytex

The document went into yellow ballot in July 2009.

The document was rejected during SEMICON Europe in October 2009. A new draft was presented during SEMICON Japan 2009. It was agreed to change the test method to a guide, extend its applicability to design rules down to 22 nm, and issue the revised draft for ballot in Cycle 1 of 2010.

The preliminary results of this ballot will be reviewed by the International AWG task force during its meeting in conjunction with the North American spring meeting in San Jose the week of March 29th, 2010. The ballot will be reviewed and adjudicated during SEMICON West in July 2010.
NEW STANDARD: GUIDE FOR DETERMINING NANOTOPOGRAPHY OF UNPATTERNED SILICON WAFERS FOR THE 130 nm to 22 nm GENERATIONS IN HIGH VOLUME MANUFACTURING

1 Purpose
1.1 Front-surface wafer height variations over specified distances need to be properly controlled to assure that wafers are acceptable for selected process steps. Nanotopography parameters are included in the International Technology Roadmap for Semiconductors (ITRS) since 2003. Nanotopography on a wafer surface prior to chemical-mechanical planarization (CMP) processes can result in variations of post-CMP film thickness with potential negative consequences for circuit performance, process cost and yield. Nanotopography features are characterized by their height variation within an area, and are discriminated from other features of similar height by their spatial wavelength range. Back-surface nanotopography may also impact wafer suitability for selected process steps. This guide may be applicable to either front- or back-surface measurements of nanotopography.
1.2 This guide provides procedures and a decision tree (Figure1) for selecting the different possible options in generating Nanotopography data. The key options used in the calculation are specified to define the data reported. This guide is intended for use in the exchange of silicon wafers and is not intended for process development where a wider range of options and data reporting formats may be appropriate.

NOTE 1: SEMI M43, guide for reporting wafer nanotopography provides a framework for reporting nanotopography surface features on silicon wafers but does not offer specific guidance on important topics such as filtering. The present guide gives such guidance and also addresses industry standard practices applied to wafers for advanced technology nodes. Not all nanotopography reported by SEMI M43 complies with the requirements of this guide.

2 Scope
2.1 This guide covers the determination and reporting of the nanotopography of unpatterned silicon wafer surfaces for device generations from 130 nm to 22 nm. Typical examples include dips, bumps or waves on the wafer surface that have dominant spatial wavelengths less than 20 mm and vary in peak-to-valley (P-V) height from a few nanometers to several hundred nanometers.
2.2 This guide specifies the technique for collecting and analyzing nanotopography data.
2.3 Use of the peak-to-valley (P-V) metric is specified for nanotopography quantification. An alternative deviation metric is described in Related Information 1.
2.4 Spatial representations of the defective areas on a wafer surface are outside the scope of this guide.

NOTICE: This standard does not purport to address safety issues, if any, associated with its use. It is the responsibility of the users of this standard to establish appropriate safety and health practices and determine the applicability of regulatory or other limitations prior to use.

3 Limitations
3.1 Use of this guide is intended to reduce measurement-system-specific effects. However, this guide is not intended to fully describe the signal processing algorithms applied to determine the nanotopography. The reported nanotopography is influenced by limitations and parameters of the measurement system. These limitations include:
3.1.1 The finite spatial bandwidth of the measurement system and the applied filtering results in surface variations outside the bandwidth of operation not being measured accurately. Also, the finite out-of-band rejection of filtering may produce artifacts in regions where the power in the rejected bands is high.
3.1.2 Measurement results may differ between systems of different design because different measurement systems employ different measurement methodologies and operate over different spatial bandwidths. Some measurement systems measure the surface height directly, while others determine it indirectly through measurement of the local surface slope or local curvature. Use of these different methods also may result in differences of the reported nanotopography.
3.1.3 All measurement systems have a noise floor; features with height variations near this noise floor may be reported improperly.

3.1.4 The reported shape of some features may also depend on the spatial sampling methodology employed by the measurement systems.

3.1.5 Both the spatial extent of a surface height sample and the spatial sampling interval may affect the bandwidth limits as well as the measured magnitude of surface height features.

3.1.6 The overall response of a spatial-domain high pass filter will depend on the spatial–filter digital implementation used to produce the specified double Gaussian high-pass filtering.

3.1.7 The measurement system itself may have impact on the reported height data, i.e., wafer handling or holding, the measurement principle and the design of the system may result in non-wafer related contributions or artifacts in the reported height values.

3.2 Reported nanotopography also varies with interactions between wafer and measurement system. These limitations include:

3.2.1 Measurements within or near regions of extreme topography, such as the edge region of wafers with strong edge roll-off, may cause incorrect height measurement within the FQA.

3.2.1.1 These regions tend to accentuate mechanical differences between measurement systems

3.2.1.2 These regions tend to accentuate differences in the implementation of the measurement system filtering and analysis.

3.2.2 Closely spaced features may be counted as a single feature, or as no feature, if the spatial extent of the surface height sample is larger than the feature, or is larger than the spacing between features.

3.2.3 Reported features may result from the combination of the actual surface features, the manner in which the wafer is supported, or be caused by particles trapped between the wafer and the support.

3.2.4 High-pass (spatial frequency) filtering is used with these measurements to remove the (long-spatial wavelength) effects of wafer shape (such as bow, warp and sori). This filtering along with the wafer shape and wafer edge roll-off may affect the reported results.

3.2.5 At some spatial locations anomalous or extreme surface height variations of the wafer may exceed the ability of the measurement system to properly acquire the original height data in those locations.

3.3 Nanotopography characterization does not include microroughness, which applies to a shorter spatial wavelength range

3.4 Use of either the constant or shrinking filter requires a different data treatment in the near edge region compared to the inner area of the wafer.

3.5 The choice of constant or shrinking filter in the near edge region will produce different results.

3.5.1 A shrinking length (without extrapolation) results in lower reported nanotopography in the affected region.

3.5.2 A constant filter (requiring extrapolation) can result in either higher or lower reported nanotopography.

3.6 P-V measurements for analysis areas that extend beyond the FQA boundary (partial analysis areas) are based on fewer data points than analysis areas completely within the FQA boundary. Statistically this tends to reduce the reported P-V for these partial analysis areas.

4 Referenced Standards

4.1 SEMI Standards

SEMI M1 — Specifications for Polished Single Crystal Silicon Wafers
SEMI M20 — Practice for Establishing a Wafer Coordinate System
SEMI M43 — Guide for Reporting Wafer Nanotopography
SEMI M49 — Guide for Specifying Geometry Measurement Equipment for Silicon Wafers for the 130 nm to 22 nm Technology Generations
SEMI M59 — Terminology for Silicon Technology

NOTICE: Unless otherwise indicated, all documents cited shall be the latest published versions.

5 Terminology

5.1 Definitions of general terms for silicon technology are found in SEMI M59.

5.2 Other applicable terms are defined as follows:
5.2.1 **analysis area** — an area on the height map of a wafer inside of which height variations are used to calculate nanotopography.

5.2.2 **partial analysis area** — an analysis area whose area is partly outside FQA while its center is still inside FQA.

5.2.3 **analysis map** — a map where the value at any coordinate represents the metric-determined nanotopography for an analysis area centered on that coordinate in the height map.

5.2.4 **height map** — a representation of surface height as a function of position on a wafer surface \((z(x, y))\).

5.2.5 **nanotopography metric** — the parametric technique applied to data within each analysis area of filtered height map to quantify nanotopography, for example the P-V metric or deviation metric.

5.2.6 **support area of filter** — for a spatial-domain filter, the area of the height map, centered on a surface height sample, which affects the filtered output at that height sample.

5.2.7 **surface height sample** — the measured or derived out-of-plane height value of the wafer surface at a known spatial coordinate.

**NOTE 2:** Both extrapolated and filtered data are derived surface heights. All derived surface heights are subject to limitations, even at the limit of perfect height measurement. Derived data must never be assumed to correspond to physical features on the wafer. However, prudent use of derived data is a required aspect of this guide.

6 Procedure

6.1 **Data Acquisition** — Measure the height map of the wafer front surface or back surface within the FQA. Support the wafer during measurement in such a way as to minimize support-induced height artifacts in the wavelength range of interest. The minimum height map sample density is two points per mm in both \(x\)- and \(y\)-directions.

**NOTE 3:** The data density determines the high spatial-frequency of the height data unless a low-pass smoothing filter is applied.

6.2 **Calculation of the high-pass filtered wafer height map**

6.2.1 **Near Edge Treatment** — Select between applying a shrinking filter or constant filter for near edge data treatment. Constant and shrinking refer to the spatial-domain filter’s support area. For the case of constant filtering data extrapolation beyond the FQA boundary is typically required. An appropriate data extrapolation method, agreed upon between the supplier and customer, is implemented to derive the height map outside the FQA before filtering is performed.

**NOTE 4:** Different extrapolation methods, e.g., Zernike functions or Chebishev polynomials, are feasible. The extrapolation algorithm is provided by the measurement system. Extrapolated height data must be physically reasonable compared to the adjacent measured data. Ideally the extrapolation enables the high pass filter to result in reported nanotopography which is not impacted by the closeness to the FQA boundary.

6.3 **High-pass Filtering**

6.3.1 Implement a spatial-domain high-pass filter such that its overall response approximates that of a frequency-domain double Gaussian filter with a cut-off wavelength (50% response) of 20 mm (see Appendix 1).

**NOTE 5:** Previous industry practice for nanotopography measurement used a proprietary data acquisition and filter method to generate SQM (Surface Quality Monitor) data. Both SQM and later emulation of SQM, e.g., SQMM, exhibit strong non-isotropic response in the filtered height maps. The double Gaussian filter required in this guide avoids this strong non-isotropic response.

6.3.1.1 In the case when the shrinking filter is selected for the near edge region the spatial domain filter is scaled so that the filter support area just reaches the edge of the FQA. Therefore the shrinking filter only requires using height data from within the FQA to determine the filtered height map. Shrinking the filter in this way has the effect of gradually reducing the amplitude of high spatial frequency nanotopography in the radial band near the FQA boundary.

6.3.1.2 In the case when the constant filter is selected for the near edge region, the implemented spatial-domain filter remains constant within the complete FQA. Height data outside the FQA must be generated in order to keep the filter cut-off wavelength constant while producing the NT data in the near edge region. The measured height data inside the FQA is used to generate physically reasonable height data beyond FQA boundary. This extrapolation area extends from the measured data boundary outward far enough so that the constant filter’s support area contains height data for all points within the FQA.

6.3.1.3 After high-pass spatial filtering the resulting height map is defined only within the FQA.

**NOTE 6:** High-pass filtering removes long spatial wavelength (low spatial frequency) wafer shape and topography effects. This filtering process effectively generates a slowly varying global reference surface and presents filtered height with zero mean. This...
filtering process is not to be confused with the nanotopography analysis process. It must occur prior to the nanotopography analysis process.

6.4 **Nanotopography Analysis Process** — Analysis of the nanotopography map is performed using two analysis areas. Wafer level nanotopography values for these two analysis areas are calculated using the following procedure:

6.4.1 Select circular (Figure 2) or square (Figure 3) analysis areas for peak-to-valley (P-V) data analysis

**NOTE 7:** The shape of the analysis area may have significant impact on the result. A square analysis area tends to accentuate nanotopography along its diagonal directions, which are ~1.4 times longer than axial directions within each analysis area. A circular analysis area results in nearly isotropic analysis, limited only by sample density.

6.4.1.1 Use analysis areas of diameters 2 mm and 10 mm in case of circular analysis area.

6.4.1.2 Use analysis areas of $2 \times 2$ mm² and $10 \times 10$ mm² size in case of square analysis area.

6.4.2 For all surface height samples within the FQA, calculate and store the P-V value for both the 2 mm and 10 mm analysis areas centered on that height sample. Analysis includes data from all analysis areas whose centers lie wholly within or on the FQA boundary (includes partial analysis areas). However, only filtered height data within the FQA is used in the calculation of the P-V metric.

**NOTE 8:** For a height map with $N$ height samples within the FQA there are $N$ P-V values reported for both the 2 mm and 10 mm analysis areas, respectively. Typically these values are stored either as a linear array or as a two-dimensional map.

6.4.3 Statistical analysis of the P-V metric data produces the threshold curve, $T$, for each of the two sets of nanotopography P-V values:

$$T(t) = 1 - \text{CDF}(t)$$

where CDF($t$) is the cumulative distribution function (%) as a function of the value of the nanotopography metric $t = \text{P-V}$, in nanometers.

6.4.4 For each threshold curve, determine the P-V value $t$, in nanometers, at which $T(t) = x$. Where $x$ is a value agreed between wafer supplier and its customer. Record these threshold P-V values as $t_1$ and $t_2$, as the wafer nanotopography at the threshold $x$ for the 2-mm and 10-mm analysis areas, respectively.

**NOTE 9:** As default value $x=0.05$ is recommended because this value is widely used in industry.

**NOTE 10:** For a nanotopography map with $N = 100,000$ height samples the 0.05% threshold reports the P-V value which is ranked 50 below the maximum P-V value. This statistic is far more stable than the maximum P-V while clearly reporting a value that scales with the worst nanotopography across the entire FQA.

6.5 **Analysis Report** — Report the following elements for each set of calculations:

6.5.1 Surface height sample density,

6.5.2 Diameter of the FQA used in the determination of the reported nanotopography metrics,

6.5.3 SEMI M20 based coordinates of exclusion zone perimeters, if any,

6.5.4 The type of high pass filter chosen for the near edge region, either constant or shrinking,

6.5.5 The shape of the area chosen for the P-V analysis of the nanotopography, either circular or square,

6.5.6 The P-V values, $t_1$ and $t_2$, at the 0.05% threshold for both the 2 mm and 10 mm analysis areas, respectively.
Figure 1
Decision tree for selecting different key options in generating Nanotopography data.

Figure 2
Circular Analysis Area of Diameter $D_i$, Displaying Center and Included Data Samples at which the Surface Height is taken into Account.
Figure 3
Square Analysis Area of Size $D_i$, Displaying Center and Included Data Samples at which the Surface Height is taken into Account.
APPENDIX 1
FILTER CONSIDERATIONS

NOTICE: The material in this appendix is an official part of SEMI Mxx and was approved by full letter ballot procedures on [date].

A1-1 Double Gaussian High-pass Filter Definition
A1-1.1 A high-pass filter is applied to the acquired height data array to reduce low-spatial frequency components in the data. The filter is defined by its transmission \( G(\lambda, \lambda_c) \), a function of spatial wavelength \( \lambda \). \( G \) is defined to have a value of 0.5 at \( \lambda_c \), the cutoff wavelength.

A1-1.1.1 A Double Gaussian high-pass filter is used for nanotopography. The filter is typically implemented by low-pass filtering the height data array and subtracting it from the original height data array. It is defined as follows:

\[
G_{DLP} = 1 - G_{DLP}
\]

where \( G_{DLP} \) is the Double Gaussian low pass filter response, given by:

\[
G_{DLP}(\lambda, \lambda_c) = G_{LP}(\lambda, 1.331\lambda_c) \cdot (2 - G_{LP}(\lambda, 1.331\lambda_c))
\]

where \( G_{LP} \) is the Gaussian low pass filter response, given by:

\[
G_{LP}(\lambda, \lambda_c) = \exp\left[-\left(\frac{\lambda_c}{\lambda}\right)^2 \cdot \ln 2\right]
\]

A1-1.2 Combining Eqs. (A1-1), (A1-2), and (A1-3),

\[
G_{DHP} = 1 - 2\exp\left[-1.228\left(\frac{\lambda_c}{\lambda}\right)^2\right] + \exp\left[-2.456\left(\frac{\lambda_c}{\lambda}\right)^2\right]
\]

A1-1.3 Figure A1-1 shows the Double Gaussian high pass filter response. Note that the transmission decreases with increasing normalized wavelength \( \lambda/\lambda_c \) (decreasing frequency).

A1-2 Low-pass Filter Implementation
A1-2.1 When applied to a sampled (pixel) data array, the low-pass filter is implemented in the spatial domain as a weighted average of height data array pixel values within the filter support area. The pixels at the center have the highest weights. This filter process is a convolution of the filter kernel with the height data array.

A1-3 Extension to Two Dimensions
A1-3.1 The one-dimensional Gaussian filter defined above can be extended to two-dimensions for the image processing by replacing the wavelength \( \lambda \) using the following formula

\[
\lambda = \sqrt{\lambda_x^2 + \lambda_y^2}
\]

Where \( \lambda_x \) and \( \lambda_y \) are the wavelengths in the x and y directions, respectively.
Figure A1-1

Response Function of a Double Gaussian High-pass Filter.
RELATED INFORMATION 1

DEVIATION METRIC

NOTICE: The material in this related information is not an official part of SEMI Mxx and was approved by full letter ballot procedures on [date].

R1-1 Introduction

R1-1.1 The deviation metric is not used in high volume manufacturing. However, for some specific applications this metric may be helpful. The wafer surface coordinate assigned with a deviation value is identical with the wafer position related to this deviation while in the P-V metric the exact peak and valley positions are only related within the size range of the analysis area to the coordinate assigned with the reported P-V value.

R1-1.2 The deviation metric determines the largest height deviation of all points within an analysis area of the filtered height map relative to the height of the center point of this analysis area.

R1-1.3 To probe deviations on a length scale comparable to P-V metric analysis, the size of the analysis area has to be doubled, i.e., instead of 2 mm and 10 mm a 4 mm and 20 mm analysis area will be used.

R1-2 Generating Nanotopography Data Based on the Deviation Metric

R1-2.1 The procedure to generate NT data based on deviation metric of a wafer is corresponding to P-V metric:

R1-2.2 For all 4 mm and 20 mm analysis areas, centered at each individual point on the filtered height map, and lying at least with its center within the FQA, calculate the maximum height deviation of this area and assign this value to the coordinate of the center of the analysis area.

R1-2.3 For partial analysis areas the number of height values taken into account in the NT calculation is reduced because only data of the filtered height map within FQA is used.

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