SEMI M40-1109
GUIDE FOR MEASUREMENT OF ROUGHNESS OF PLANAR SURFACES ON SILICON WAFERS

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1 Purpose

1.1 This guide provides procedures for specifying the measurements to be used in characterizing and reporting roughness of the planar surfaces of silicon wafers. It may also be applicable to other types of planar wafer materials. It should be noted that the roughness of polished surfaces of silicons, such as those specified in SEMI M1 is generally in the microroughness range.

1.2 This guide provides nomenclature and procedures for roughness determination that employ three key methodologies:

1.2.1 Standardized scan site patterns,

1.2.2 Roughness abbreviations, and

1.2.3 Reference test methodologies with respect to identifying specific roughness measurements.

2 Scope

2.1 This guide incorporates the following methodologies:

2.1.1 Standardized scan patterns for both local and full-area surface characterization,

2.1.2 A set of roughness abbreviations that describe measurement conditions in a short-hand code, and

2.1.3 Reference test methodologies for three generic types of roughness measuring instruments. These general categories may include, but are not limited to:

- Profilometers — AFM and other scanning probe microscopes; optical profilometers; high-resolution mechanical stylus systems,
- Interferometers — interference microscopes, and
- Scatterometers — Total integrating scatterometers (TIS), angle-resolved light scatterometers (ARLS), scanning surface inspection systems (SSIS).

2.2 Procedures to obtain a representative value of roughness for a surface are specified.

2.3 Roughness nomenclature is intended to remove ambiguities with respect to identifying the roughness measurements used and the results achieved.

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 This guide does not apply to measurements in the edge region of wafers.

3.2 This guide does not apply to spatial wavelengths ≤10 nm.

3.3 This guide is not intended to define specific roughness parameters; these can be found in other standards.

3.4 The bandwidth of the measurement tool and the bandwidth used can severely influence the result of roughness measurements.

3.4.1 Differences in either long or short bandwidths used between two instruments can produce significantly different results.

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3.4.2 The codes listed in Table 1 of this guide do not identify instrument transfer functions.

3.5 The presence of films may affect light scattering measurements.

4 Discussion

4.1 Roughness of silicon wafer surfaces is becoming frequently specified for bare silicon wafers.[1] These specifications refer to the roughness of both the final polished front and the back surfaces of a wafer. Various techniques are currently used to measure the surface roughness of silicon wafers. These techniques include AFM scanning probes, mechanical and optical profiling, interferometric microscopes, and light (electromagnetic radiation) scattering. Mechanical profiling techniques are widely used in other industries and are well standardized. Profiling techniques are generally limited to line scans and therefore provide information of only a very small part of a surface. Interferometric techniques for roughness measurements are similarly limited, whereas light scattering techniques can scan the entire wafer surface.

4.2 Historically a variety of roughness parameters for profiling techniques have evolved and have been standardized, including rms roughness (R_q) and average roughness (R_a). Profiling instruments measure the surface topography and derive roughness statistics, such as R_q, from a series of height data. Light scattering techniques measure R_q from the angular dependence of scattering; some light scattering systems derive other parameters through interpretation and estimation.

4.3 A roughness value representative of an entire wafer surface, or a large portion of the surface, cannot be based on data obtained at a single point. Yet, specifications often describe a single value for a wafer. Therefore, this guideline suggests and defines standardized patterns of scan sites that can be described and used unambiguously. A model describing the relationship between several types of roughness variation, scan patterns, and reported results is included in the attached Related Information to assist users in specifying and interpreting these variables.

4.4 A common feature of all roughness measurements is their dependence on the bandwidth and transfer function of the tool used. In addition, high or low spatial frequency software filters are common and affect reported results. Widely different numbers can be reported for the same surface by two measurement instruments. This guideline includes suggestions on specifying and reporting the instrument bandwidth and transfer function.

5 Referenced Standards and Documents

5.1 *SEMI Standards*

SEMI E89 — Guide for Measurement System Analysis (MSA)

SEMI M1 — Specifications for Polished Single Crystal Silicon Wafers

SEMI M20 — Practice for Establishing a Wafer Coordinate System

SEMI M50 — Test Method for Determining Capture Rate and False Count Rate for Surface Scanning Inspection Systems by the Overlay Method

SEMI M52 — Guide for Specifying Scanning Surface Inspection Systems for Silicon Wafers for the 130 nm, 90 nm, 65 nm, and 45 nm Technology Generations

SEMI M53 — Practice for Calibrating Scanning Surface Inspection Systems Using Certified Depositions of Monodisperse Reference Spheres on Unpatterned Semiconductor Wafer Surfaces

SEMI M58 — Test Method for Evaluating DMA Based Particle Deposition Systems and Processes

SEMI M59 — Terminology for Silicon Technology

SEMI ME1392 — Guide for Angle Resolved Optical Scatter Measurements on Specular or Diffuse Surfaces

SEMI MF1048 — Test Method for Measuring the Effective Surface Roughness of Optical Components by Total Integrated Scattering

SEMI MF1811 — Guide for Estimating the Power Spectral Density Function and Related Finish Parameters from Surface Profile Data

1 In the SIA International Technology Roadmap for Semiconductors, available from the homepage of International SEMATECH; http://www.sematech.org

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5.2 *ASME Standard*[2]

ASME B46.1 — Surface Texture (Surface Roughness, Waviness, and Lay)

5.3 *DIN Standards*[3]

DIN 4760 — Form Deviation, Waviness, Surface Roughness; System of Order, Terms and Definitions

DIN 4768 — Determination of Values of Surface Roughness Parameters Ra, Rz, Rmax by Means of Electrical Contact (Stylus) Instruments; Terminology, Measuring Conditions

DIN 4777 — Metrology of Surfaces; Profile Filters for Electrical Contact Stylus Instruments; Phase-Corrected Filters

5.4 *ISO Standards*[4]

ISO 468 — Surface Roughness – Parameters, Their Values and General Rules for Specifying Requirements

ISO 1879 — Instrument for the Measurement of Surface Roughness by the Profile Method – Vocabulary

ISO 1880 — Instruments for the Measurement of Surface Roughness by the Profile Method – Contact (Stylus) Instruments of Progressive Profile Transformation – Profile Recording Instruments

ISO 3274 — Instruments for the Measurement of Surface Roughness by the Profile Method – Contact (Stylus) Instrument of Consecutive Profile Transformation – Contact Profile Meters, System M

ISO 4287/1 — Surface roughness – Terminology – Part 1: surface and its parameters

ISO 4288 — Rules and Procedures for the Measurement of Surface Roughness Using Stylus Instruments

5.5 *JIS Standards*[5]

JIS B 0601 — Surface Roughness – Definitions and Designation

JIS B 0652 — Instruments for the Measurement of Surface Roughness by the Interferometric Method

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

6 Terminology

6.1 Acronyms, terminology, and symbols used in silicon technology may be found in SEMI M59.

6.2 Additional terminology related to angle resolved scattering measurements is discussed in SEMI ME1392.

6.3 Additional terminology related to the instrument transfer function, the power spectral density function, and related finish parameters is discussed in SEMI MF1811.

6.4 Other terminology related to the measurement of surface roughness may be found in ASME B46.1; DIN 4760; ISO 468, 1829, and 4287/1; and JIS B 0601.

7 Instruments and Capabilities

7.1 *Profilometers*

7.1.1 The high spatial frequency limit of AFM, mechanical and optical profilers can be approximated by the radius of the mechanical tip or by the diameter and intensity profile of the laser spot, respectively. Their response functions are complicated, and in some cases are a combined effect of the probe and the measured surface. The high spatial frequency limit of such tools has to be set or selected reasonably removed from that limit in order to achieve

2 American Society of Mechanical Engineers, Three Park Avenue, New York, NY 10016-5990, USA. Telephone: 800.843.2763 (U.S./Canada), 95.800.843.2763 (Mexico), 973.882.1167 (outside North America); http://:www.asme.org

3 Deutsches Institut für Normung e.V., Available from Beuth Verlag GmbH, Burggrafenstrasse 4-10, D-10787 Berlin, Germany; http://www.din.de

4 International Organization for Standardization, ISO Central Secretariat, 1 rue de Varembé, Case postale 56, CH-1211 Geneva 20, Switzerland. Telephone: 41.22.749.01.11; Fax: 41.22.733.34.30; http://www.iso.ch

5 Japanese Industrial Standards, Available through the Japanese Standards Association, 1-24, Akasaka 4-Chome, Minato-ku, Tokyo 107-8440, Japan. Telephone: 81.3.3583.8005; Fax: 81.3.3586.2014; http://www.jsa.or.jp

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reasonable, comparable, and repeatable measurements. Properties of stylus instruments are described in DIN 4768 and DIN 4777, and in ISO 1880, ISO 3274, and ISO 4288.

7.2 *Interference Microscope*

7.2.1 The high spatial frequency limit of these instruments is defined by the focusing optics or in some cases by the pixel spacing of the detector array. The high spatial frequency limit of such tools has to be set or selected reasonably removed from that limit in order to achieve reasonable, comparable, and repeatable measurements. See JIS B 0652 for descriptions of this type of instrument.

7.3 *Scattering Instruments*

7.3.1 A straightforward relation between scattered light intensity and roughness exists only for sufficiently smooth surfaces. The Rayleigh smooth-surface criterion, given below, is frequently used for estimating the smooth-surface limit.[6]

$$\frac{1}{2}\left(\frac{4\pi a\cos\theta_i}{\lambda}\right)^2 << 1 \tag{1}$$

$$m << 1 \tag{2}$$

where:

m = profile slope,

λ = wavelength of incident light,

a = amplitude of sample profile (half of the peak-to-valley height), and

θ_i = incidence angle of the light beam.

7.3.2 Corresponding amplitude examples assuming a limit of 0.1 result in $a \leq 23$ nm for $\lambda = 633$ nm, $\theta_i = 0°$ and $a \leq 51$ nm for $\lambda = 488$ nm, $\theta_i = 70°$.

7.3.3 The equivalent rms-roughness values for a sinusoidal profile and for a limit of 0.1 are $R_q \leq 16$ nm for $\lambda = 633$ nm, $\theta_i = 0°$ and $R_q \leq 36$ nm for $\lambda = 488$ nm, $\theta_i = 70°$.

7.3.4 Light scattering tools can be applied to rougher surfaces than those surfaces identified in equations 1 and 2, but then other mathematical approaches as compared to PSD curves have to be applied to calculate roughness or slope values. Also, the slope of the PSD curve can be important in certain situations (Stover).

7.3.5 There is a basic high spatial frequency (short spatial wavelength) limit for light scattering tools which cannot be exceeded. This limit is twice the inverse wavelength, $(2/\lambda)$, of the light used in case of grazing incidence ($\theta_i = 90°$), and one inverse wavelength, $(1/\lambda)$, in the case of normal incidence ($\theta_i = 0°$). These conditions follow directly from the one-dimensional grating equation:

$$f_x = \frac{\sin\theta_s \cos\phi_s - \cos\theta_i}{\lambda} \tag{3}$$

where:

θ_s = scattering angle in the incident plane, and

ϕ_s = scattering angle out of the plane-of-incidence.

NOTE 1: f_x becomes −1 when the light is scattered back in the direction of the incoming light in the incident plane ($\phi_s = 180°$).

7.4 *Total Integrating Scatterometers (TIS)*

7.4.1 These instruments most often use an incidence angle close to zero. The low and high frequency limits of the accessible spatial bandwidth are defined by the design of the optical system. An appropriately designed system may be able to access a spatial bandwidth from about 0.8 µm to about 40 µm. These systems may also be designed so

6 Stover, J. C, "*Optical Scattering, Measurement and Analysis*," Second Edition, SPIE Optical Engineering Press, Bellingham, WA (1995): p. 79.

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that the scattered signal can be broken into low spatial frequency (near specular) and high spatial frequency (large scatter angle) bands. See SEMI MF1048 for information on the use of this type of instrument.

7.5 *Angle-resolved Light Scatterometers (ARLS)*

7.5.1 The high spatial frequency limit of this technique is defined by incident and scattering angles and the illumination wavelength used.

7.5.2 The low spatial frequency limit is given by:

- the above equations (for incidence angle),
- the diameter of the incident illumination spot at the wafer surface,
- the solid collection angle of the optical system, and
- the smallest angular distance allowed by the instrument between specular reflected light and the detector.

7.5.3 The roughness may be measured by using a fixed incidence angle and by recording the intensity of scattered light at various scattering angles in the plane of incidence. The two-dimensional PSD curve of the surface can then be calculated from the angular spectrum of the scattered light (BRDF). The rms (micro)roughness, R_q, as well as the rms slope, m_q, may be calculated from a one-dimensional or isotropic power spectral density (PSD) curve for a given spatial bandwidth as long as the above mentioned limits are accommodated.

7.5.4 Such tools may be able to access a spatial bandwidth range of about one-half the wavelength of the illuminating light up to several hundred µm.

7.6 *Scanning Surface Inspection Systems (SSIS)*

7.6.1 SSIS measurements are integrated scatter measurements similar to those made by TIS systems, in that they gather light over large solid angles; however, there are some significant differences. In general, most SSIS avoid light collection within five to ten degrees of the specular beam, because in this region the scatter tends to be dominated by surface roughness scatter (which becomes background noise) competing with the signal from laser light scattering events. The early (older) scanners generally had one detector measuring light from a very large solid angle collector. Later systems tend to use several smaller collection angles, each with their own detector. Whatever the arrangement, each collection angle can be defined in terms of its spatial frequency band pass region, and each detector will have some background haze component (or threshold) that is caused by surface roughness. Thus, in the absence of laser light scattering events, measured haze may be converted to an rms roughness for the defined spatial frequencies. This conversion assumes that the surface meets the necessary (smooth, clean, front surface reflective) conditions required for roughness calculations, and that other noise sources, such as background electronic noise and Rayleigh air scatter, are not issues. See SEMI M50, SEMI M52, SEMI M53, and SEMI M58 for information on calibration and use of SSISs.

8 Roughness Measurements

8.1 *Parameters*

8.1.1 The parameters rms roughness, R_q, and average roughness, R_a, are generally used for silicon wafer surfaces. Other roughness measurement parameters, such as the peak to valley (the arithmetic difference between the highest and lowest points on the surface profile), R_t, and ten point roughness height (average value of the absolute values of the heights of the five highest profile peaks and the depths of the five lowest profile valleys on the surface profile taken within the evaluation length), R_z, may also prove useful. This guideline does not suggest which parameters to use, rather it suggests how to incorporate any parameter into a standardized measurement specification.

8.1.1.1 SEMI MF1811 gives detailed information on the extraction of the roughness parameters from linear scans of a surface. In particular, the function R_q is related to a one-dimensional measurement of the surface profile as follows:

$$R_q = \left[\frac{1}{L} \int_0^L Z(x)^2 \, \mathrm{d}x \right]^{1/2} \tag{4}$$

8.1.1.2 The digital approximation of R_q for a profile consisting of N equally spaced points is:

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$$R_q = \left[\frac{1}{N} \sum_{i=1}^{N} Z_i^2 \right]^{1/2} \tag{5}$$

8.1.1.3 Experimentally, the profile is always limited by the spatial bandwidth of the measurement. For a profile of length L, consisting of N equally spaced points, the lower spatial frequency limit f_1 can never be less than $1/L$ and the upper spatial frequency limit f_2 can never be greater than the Nyquist limit, $N/2L$. In practical cases, $f_1 \approx 2/L$; the achievable value of f_2 depends on instrumental parameters.

8.1.1.4 R_q can also be estimated by integrating the one-dimensional power spectral density (PSD) function, $PSD(f)$, over the spatial frequency range between two spatial frequencies, f_1 and f_2, that lie within the bandwidth of the measurement:

$$R_q = \left[\int_{f_1}^{f_2} PSD(f)\,\mathrm{d}f \right]^{1/2} \tag{6}$$

8.1.1.5 In all cases, R_q must be reported together with the lower and upper limits, f_1 and f_2, respectively, of the spatial frequency bandwidth over which it has been determined. Alternatively, the spatial bandwidth may be expressed in terms of the upper and lower spatial wavelengths, λ_2 (= $1/f_2$) and λ_1 (= $1/f_1$), respectively.

8.1.2 R_a and R_t are discussed in ASME B46.1.

8.1.3 R_z is discussed in ISO 4287/1.

8.2 *Measurement Sites*

8.2.1 Roughness can vary considerably across a wafer surface. It may also have a preferential direction or anisotropy, often called lay. Many measurement techniques are limited to a very small measurement area and to one or two scan directions. Therefore specific measurement patterns must be defined to obtain representative and reproducible results. These patterns should correspond to effects observed on wafers in different manufacturing steps. These processing steps can generate features on a wafer surface with rotational symmetries ranging from mirror to infinite. The wafer slicing process may produce low symmetry, while single-wafer polishing can produce high symmetry.

8.2.2 In cases where only a small number of spots is measured, the spot pattern and the scan orientation have to be identified. See Figure 1 for some patterns and orientations; others may be agreed upon between interested parties.

8.3 *Site Patterns*

8.3.1 *One-point* — This can be useful for rapidly reviewing results of a quantity of wafers. This is often at the wafer centerpoint.

8.3.2 In applications where only a small number of locations are to be measured, the pattern and orientation of the local scans have to be identified. Measurements are performed at locations as outlined in Figure 1. The coordinates of each of the locations in the scan patterns are given in Table 1. In this table, r is the nominal wafer diameter. For each local scan, a representative roughness is calculated. The wafer's representative roughness is then a function of the n individual representative scan values. The roughness variation can be calculated by the average, the standard deviation, the maximum or the range (Max-Min) of the individual scan values. Other statistical approaches may be employed.

8.3.3 Standard patterns include:

- 1-point wafer center,
- 5-point wafer center plus four point at $2r/3$ from the wafer center (where r is the nominal radius of the wafer), and
- 9-point wafer center plus four points at $2r/5$ and four at $4r/5$ from the wafer center.

NOTE 2: These patterns have been shown to be useful with a range of symmetries and values. See Related Information 1, which describes various experiments and models relating to surface roughness of silicon wafers.

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8.3.4 Standard measurement orientation patterns include:

- *Type A* — linear scans parallel and perpendicular to the fiducial bisector, and
- *Type B* — linear scans at 45° relative to the fiducial bisector.

NOTE 3: Type A is generally used for all surfaces. Type B has been reported to be useful for some surface conditions on (111) wafers.

Table 1 Scan Pattern Locations

Location		*X, Y Coordinates (per SEMI M20)*	*Scan Direction (for line and area tools), parallel to:*
Center Point		0, 0	*Y*-axis
Point #	Location		
		5-point Pattern	
1	Center	0, 0	*Y*-axis
2	$2r/3$	0, $2r/3$	*Y*-axis
3	$2r/3$	$-2r/3$, 0	*X* -axis
4	$2r/3$	0, $-2r/3$	*Y*-axis
5	$2r/3$	$2r/3$, 0	*X*-axis
9-point Pattern			
1	Center	0, 0	*Y*-axis
2	$4r/5$	0, $4r/5$	*Y*-axis
3	$4r/5$	$-4r/5$, 0	*X*-axis
4	$4r/5$	0, $-4r/5$	*Y*-axis
5	$4r/5$	$4r/5$, 0	*X*-axis
6	$(r\sqrt{2})/5$	$(r\sqrt{2})/5$, $(r\sqrt{2})/5$	*Y*-axis
7	$(r\sqrt{2})/5$	$-(r\sqrt{2})/5$, $(r\sqrt{2})/5$	*X*-axis
8	$(r\sqrt{2})/5$	$-(r\sqrt{2})/5$, $-(r\sqrt{2})/5$	*Y*-axis
9	$(r\sqrt{2})/5$	$(r\sqrt{2})/5$, $-(r\sqrt{2})/5$	*X*-axis
Full FQA Scan			
Full FQA		Raster Scan	*X*-axis
Full FQA		Concentric Circles or Spiral	*R* – Theta

8.4 *Bandwidth*

8.4.1 Two issues affect the bandwidth of the roughness results. The first is the bandwidth of the roughness measuring tool, which is discussed in § 7. The second bandwidth effect is from the analysis software, which is user selected to emphasize certain spatial frequencies. Both long and short spatial wavelength (or frequency) limits must be defined in µm (or μm^{-1}). When entering this information into a measurement, specification wavelength units shall be used. Profiling instruments should have scan length and bandwidth adjusted according to DIN 4768 and DIN 4777 or ASME B46.1.

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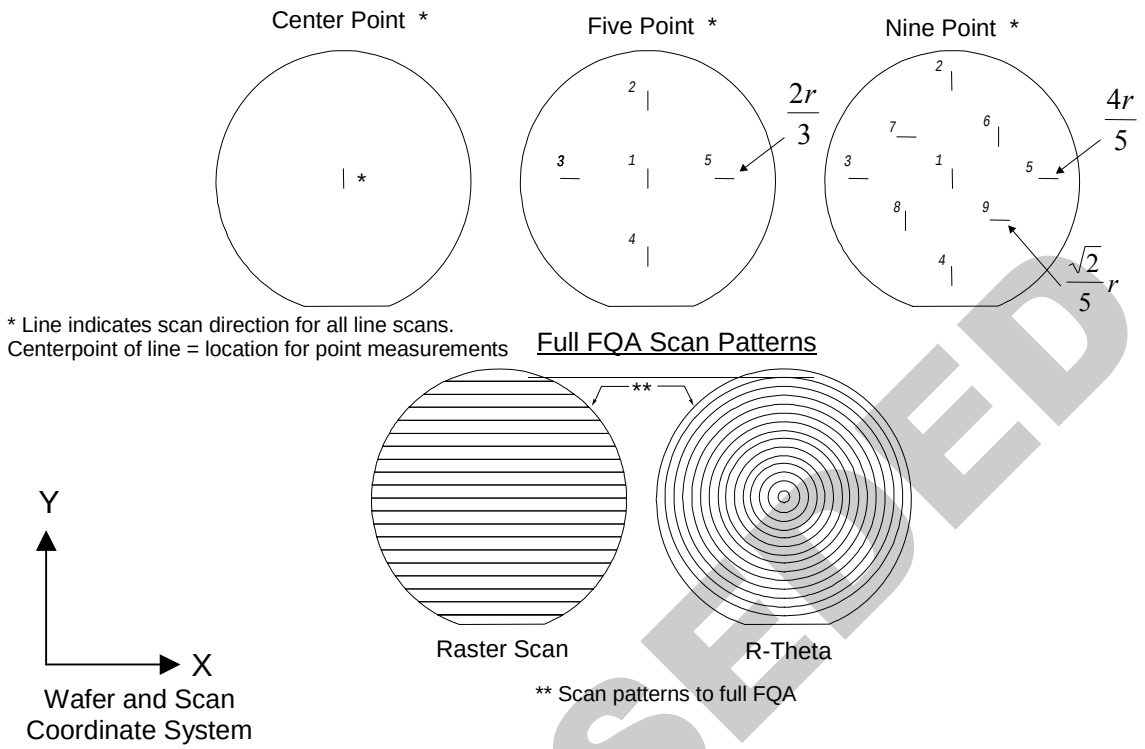
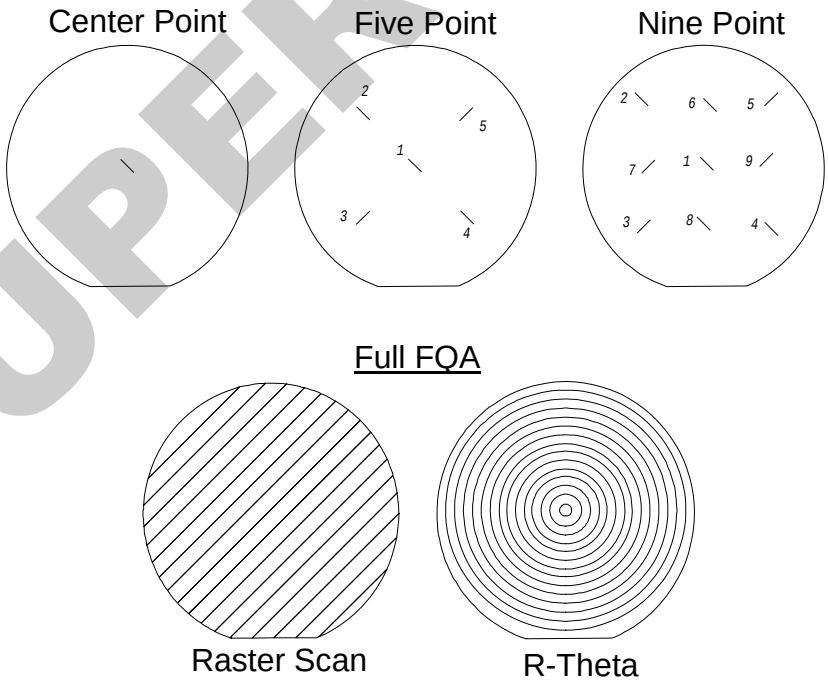
Type A Local Scan Patterns



Type B Local Scan Patterns



NOTE: R-Theta scan may be implemented in either a circular or a spiral pattern.)

Figure 1
Patterns of Locations on a Silicon Wafer Surface for Measuring

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