

SEMI PV46-0613 (Reapproved 0419) TEST METHOD FOR IN-LINE MEASUREMENT OF LATERAL DIMENSIONAL CHARACTERISTICS OF SQUARE AND PSEUDO- SQUARE PHOTOVOLTAIC SILICON WAFERS

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1 Purpose

- 1.1 The geometrical dimensions of photovoltaic (PV) silicon (Si) wafers are key specification parameters (see SEMI PV22).
- 1.2 Parameters such as edge length and diagonal of a wafer appear to be obvious, if the wafers are perfectly square or pseudo-square.
- 1.3 However, SEMI PV22 allows deviations of the side lengths and corner angles of the nominally square wafers within a specified range, potentially resulting in nonsquare wafers.
- 1.4 In addition, the edges of real wafers usually cannot be represented by straight lines. They are curved to some extent.
- 1.5 This creates an ambiguity in measuring the edge lengths and other geometrical dimensions of wafers.
- 1.6 This Test Method defines selected terms and a test method for measuring corresponding parameters.

2 Scope

- 2.1 The test method covers square and pseudo-square Si wafers for PV applications, with a nominal edge length ≥ 125 mm and a nominal thickness ≥ 100 μm .
- 2.2 This Test Method measures lateral geometrical dimensions of crystalline PV Si wafers.
- 2.3 This method employs an in-line, noncontacting and nondestructive method for characterizing clean, dry PV Si wafers supported by a mechanism that move the test specimen through the measurement equipment.
- 2.4 The surface condition of the wafers may be as cut, etched or passivated.
- 2.5 The test method is intended for in-line high throughput measurements. Therefore it is mandatory to operate the measurement system under statistical process control (SPC), for example ISO 11462, in order to obtain reliable, repeatable and reproducible measurement data.
- 2.6 The test method is based on recording and evaluating images of the wafer surface obtained by a digital camera under diffuse white light illumination.
- 2.7 The test method does not include the measurement of wafer thickness or thickness variation. For this measurement see SEMI PV41.
- 2.8 Other measurement techniques may also provide similar information, but they are not the subject of this Test Method.

NOTICE: SEMI Standards and Safety Guidelines do not purport to address all safety issues associated with their use. It is the responsibility of the users of the Documents to establish appropriate safety and health practices, and determine the applicability of regulatory or other limitations prior to use.

3 Limitations

- 3.1 Excessive tilt and warp of the wafer on the transport belts may result in distorted wafer image and may impact the measurement result.
- 3.2 Large edge chips or v-grooves on the wafer edges also may result in erroneous measurement results.

4 Referenced Standards and Documents

4.1 SEMI Standards and Safety Guidelines

SEMI E89 — Guide for Measurement System Analysis (MSA)

SEMI MF1569 — Guide for Generation of Consensus Reference Materials for Semiconductor Technology

SEMI PV22 — Specification for Silicon Wafers for Use in Photovoltaic Solar Cells

SEMI PV32 — Specification for Marking of PV Silicon Brick Face and PV Wafer Edge

SEMI PV41 — Test Method for In-Line, Noncontact Measurement of Thickness and Thickness Variation of Silicon Wafers for PV Applications Using Capacitive Probes

4.2 ISO Standards¹

ISO 11462-1 — Guidelines for Implementation of Statistical Process Control (SPC) – Part 1: Elements of SPC

ISO 11462-2 — Guidelines for Implementation of Statistical Process Control (SPC) – Part 2: Catalogue of Tools and Techniques

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

5 Terminology

5.1 Abbreviations and Acronyms

5.1.1 *MSA* — measurement system analysis

5.1.2 *SPC* — statistical process control

5.2 Definitions

5.2.1 *cathetus, of a nominally square or pseudo-square Si wafer* — a line segment between a wafer corner and an adjacent chamfer corner.

5.2.2 *cathetus length* — the shortest distance between a wafer corner and an adjacent chamfer corner point.

NOTE 1: The cathetus length of a nominally square or pseudo-square wafer is denoted by 'F' in SEMI PV22.

5.2.3 *chamfer line, of a nominally square or pseudo-square Si wafer* — second order polynomial line fit to the corner chamfer of a wafer.

5.2.4 *chamfer length, of a nominally square or pseudo-square Si wafer* — the shortest distance between adjacent intersections of the chamfer line and the adjacent edge lines.

5.2.5 *corner, of nominally square or pseudo square Si wafer* — the intersection of adjacent edge lines.

5.2.6 *corner angle, of a nominally square or pseudo-square Si wafer* — the included angle between adjacent edge lines.

5.2.7 *diagonal length, of a nominally square Si wafer* — the shortest distance between opposite corners of a wafer.

5.2.8 *diagonal line, of a nominally square Si wafer* — a straight line through opposite wafer corners.

NOTE 2: The diagonal length of a nominally square wafer is denoted by 'G' in SEMI PV22.

5.2.9 *edge length, of a nominally square or pseudo-square Si wafer* — the shortest distance between adjacent corners.

NOTE 3: The edge length of a nominally square or pseudo-square wafer is denoted by 'A' in SEMI PV22.

5.2.10 *edge line, of a nominally square or pseudo-square Si wafer* — first or second order polynomial line fit to the wafer edges, excluding chamfers at wafer corners.

5.2.11 *fit line* — a line fit to a set of x-y-coordinates.

¹ International Organization for Standardization, ISO Central Secretariat, BIBC II, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland; Telephone: +41.22.749.01.11, <http://www.iso.org>

5.2.12 *reference points, of a nominally square or pseudo-square Si wafer* — points on the wafer perimeter/edges used for assigning metrics to the wafer.

5.2.13 *short diagonal length, of a nominally square Si wafer* — the shortest distance along a diagonal line between an intersections of a chamfer line and a diagonal line.

NOTE 4: The short diagonal length of a nominally square wafer is denoted by ‘E’ in SEMI PV22.

5.2.14 *short edge length, of a nominally square or pseudo-square Si wafer* — the shortest distance between adjacent chamfer corner points along one wafer edge.

NOTE 5: The short edge length of a nominally square wafer is denoted by ‘C’ in SEMI PV22.

6 Summary of Test Method

6.1 The wafer resting on the transport mechanism is moved in the *x*-direction, the direction of travel, past a diffuse white light source and a digital camera (see Figure 1).

6.2 A gray scale picture of the wafer is recorded by the digital camera and processed according to § 12.

6.3 Edge lengths, corner angles, diagonals and chamfer lengths are reported according to § 13.

7 Apparatus (see Figure 1)

7.1 *Light Source* — Illuminates the wafer homogeneously with diffuse white light. Light shields prevent light from entering the camera directly.

7.2 *Camera* — A digital camera with a resolution of at least 2048 pixels, positioned above the wafer surface. The line of sight of the camera is nominally perpendicular to the wafer surface and the camera-wafer surface distance is ≥ 3 times wafer diagonal. The exposure time of the camera has to be set so that the image does move less than 3 pixels during exposure. The noise level (3σ) of the camera shall be $\leq 1\%$ of the peak signal and the dynamic range shall be ≥ 255 gray levels.

7.3 *Computer* — For controlling the measurement system and with software for recording and processing the camera images according to § 13.

7.3.1 *Wafer Transport* — Consisting of a mechanism that transports the wafer continuously through the measurement apparatus without obstructing the line of sight of the camera and the illumination. The mechanism shall not leave traces or residue on the wafer surface.

8 Safety Precautions

8.1 The entire equipment must be placed in a closed housing and secured with a safety lock that switches the tool off, and stops the transport mechanism when the housing is opened.

9 Test Specimens

9.1 Clean, dry Si surface.

10 Preparation of Apparatus

10.1 The suitability of the equipment is determined by performing a statistically based measurement system analysis (MSA) to ascertain that the equipment is operating within the manufacture’s stated specification, for example, according to SEMI E89.

10.2 Verify that the camera, illumination and wafer are aligned and adjusted according to the manufacturer’s specifications.

10.3 Determine the SPC control limits for the measurement equipment using a set of selected wafers.

NOTE 6: As this Test Method is intended for a high throughput, high volume measurement the equipment cannot be calibrated for measuring each individual wafer. Therefore careful SPC has to be performed.

11 Calibration and Standardization

- 11.1 Verify that the camera, illumination and wafer are aligned and adjusted according to the manufacturer's specifications.
- 11.2 Calibrate the equipment using reference material with known dimensions.
- 11.3 Measure the reference material according to § 12.
- 11.4 Compare the measured side lengths with the known dimensions of the reference material and determine correction factors cf_x and cf_y for the x - and y -axes, respectively.

12 Procedure

- 12.1 Adjust the equipment and calibrate it according to the supplier's instructions.
- 12.2 Verify the equipment is within SPC limits.
- 12.3 Measure the wafer.
 - 12.3.1 Place a wafer on the transport mechanism so that its surface normal is tilted $\leq 3^\circ$ with respect to the line of sight of the camera.
 - 12.3.2 Align the wafer so that its leading edge is perpendicular to the transport direction.
 - 12.3.3 Move the wafer through the measurement station.
 - 12.3.4 Capture a raw image RI and process it according to § 13.
 - 12.3.5 Report the side lengths, diagonals, corner angles, chamfer lengths and chamfer radius, if applicable, according to § 15.
- 12.4 Repeat with the next wafer.

13 Image Processing

- 13.1 Assign a coordinate system to the image so that the x -axis is parallel to the wafer transport direction and the y -direction perpendicular to it. The origin of the coordinate system is at the lower left corner of the wafer (corner K_1).
- 13.2 Process the raw wafer image RI according to the two main steps (see Figure 2):
 - 13.3 *Step 1: Wafer Edge Detection*
 - 13.3.1 Exclude, for fitting, any segments of the wafer edge where intentional marks such as notches (see SEMI PV32) are applied.
 - 13.3.2 Apply an appropriate filter to the raw image RI for detecting the wafer edges and define the x - y -coordinates representing the wafer edges by a subpixeling procedure. Report the type of filter used.
 - 13.4 *Step 2: Line Fitting (see Figures 3 and 5)*
 - 13.4.1 Fit a straight line to the x - y -coordinates representing the wafer edges excluding the chamfers resulting in four edge lines a_i with $i = 1$ to 4.

NOTE 7: If a higher order polynomial fit line is used report it.
 - 13.4.2 The intersections of the edge lines of adjacent edges define four imaginary reference points, the corner points $K_i(x,y)$ with $i = 1$ to 4.
 - 13.4.3 For nominally square wafers, fit a first order polynomial to the x - y -coordinates in the chamfer regions, resulting in four chamfer fit lines h_i with $i = 1$ to 4.
 - 13.4.4 For nominally pseudo-square wafers, fit a second order polynomial to the x - y -coordinates in the chamfer regions, resulting in four chamfer fit lines h_i with $i = 1$ to 4.
 - 13.4.5 Identify four pairs of reference points, where the chamfer corner points $B_{i,j}(x,y)$ —with $i = 1$ to 4 denoting the wafer corner and $j = 1$ to 4 denoting the wafer sides that are intersected by the chamfer line—by the intersections of the chamfer fit lines h_i with the adjacent edge fit lines a_i .

13.4.6 Draw straight diagonal lines $g_{1,3}$ and $g_{2,4}$ through opposite corners K_1 , K_3 and K_2 , K_4 , respectively. The intersection of $g_{1,3}$ and $g_{2,4}$ defines the wafer center M .

13.4.7 Identify additional auxiliary reference points on each edge line $X_{j,k}(x,y)$ with j denoting the edge line and $k = 1, 2$ or 3 as follows:

13.4.7.1 $X_{i,2}$ at the center between the adjacent corners

13.4.7.2 $X_{i,1}$ and $X_{i,3}$ at a distance V from the adjacent corners.

13.4.8 For square wafers only: Identify the intersections of $g_{1,2}$ and $g_{2,4}$ with h_i by $B_{i,g}$ with $m = 1$ to 4 .

14 Calculations (see Figure 2)

14.1 Multiply any x -coordinate with cf_x and any y -coordinate with cf_y .

NOTE 8: The labeling of the lines, lengths and points follows SEMI PV22 where possible. Lines are labeled by lower case letters, lengths and points by capital letters.

14.2 For square and pseudo-square wafers (see Figures 4 and 6):

14.2.1 Calculate and report the four side lengths A_i of the wafer as the shortest distances between adjacent corners points K_i .

14.2.2 Calculate and report the four short side lengths C_i of the wafer as the shortest distance between adjacent chamfer corners points $B_{m,n}$.

14.2.3 Calculate and report the wafer widths $W_{p,q,r}$ with $p,q = 1,3$ or $2,4$ and $r = 1, 2$ or 3 as follows:

14.2.3.1 The widths $W_{1,3,2}$ and $W_{2,4,2}$ as the distances between $X_{1,2}$ and $X_{3,2}$ and between $X_{2,2}$ and $X_{4,2}$, respectively.

14.2.3.2 The widths $W_{1,3,1}$ and $W_{1,3,3}$ as the distances between $X_{1,1}$ and $X_{3,1}$ and between $X_{1,3}$ and $X_{3,3}$.

14.2.3.3 The widths $W_{2,4,1}$ and $W_{2,4,3}$ as the distances between $X_{2,1}$ and $X_{4,1}$ and between $X_{2,3}$ and $X_{4,3}$.

14.2.4 Calculate the four corner angles ω_i , $i = 1$ to 4 , as the inner angles between adjacent fit lines at the four corners. Report the corner angles ω_i .

14.2.5 Calculate for each pair of chamfer corner points the four chamfer lengths H_i as the shortest distances between adjacent chamfer corner points $B_{i,j}$. Report the chamfer lengths H_i .

NOTE 9: The chamfer lengths are not the lengths of 2nd order polynomials between the corresponding intersections.

14.3 Calculate and report the cathetus lengths $F_{i,j}$ as the distances between the wafer corners points K_i and the adjacent chamfer corner points $B_{i,j}$.

14.4 For square wafers only:

14.4.1 Calculate and report the diagonal lengths $G_{1,3}$ and $G_{2,4}$ as the shortest distances between:

14.4.1.1 The corner points K_1 and K_3 , and

14.4.1.2 The corner points K_2 and K_4 .

14.4.2 Calculate and report the diagonal lengths $E_{1,3}$ and $E_{2,4}$ as the shortest distances between:

14.4.2.1 The intersections of the chamfer lines h_1 and h_3 and the diagonal lines g_1 , and

14.4.2.2 The intersections of the chamfer lines h_2 and h_4 and the diagonal line g_2 .

14.4.3 Calculate and report the chamfer angles $\alpha_{i,j}$ (see Figure 7). They are determined either by the chamfer lengths H_i and the adjacent cathetus lengths $F_{i,j}$ or by the corner angles ω_i and the adjacent cathetus lengths $F_{i,j}$ according to the laws of planar trigonometry using:

$$\cos \alpha_{i,j} = \frac{(H_i^2 F_{i,j}^2 - F_{i,j}^2)}{2 H_i F_{i,j}} \quad (1)$$

or any equivalent relation.

14.5 For pseudo-square wafers only:

14.5.1 Calculate and report the diameters $D_{1,3}$ and $D_{2,4}$ as the shortest distance between opposing rounded chamfers through the center of the wafer.

15 Report

15.1 Report the following elements.

15.1.1 *General Information*

15.1.1.1 Date and time of test.

15.1.1.2 Identification of operator.

15.1.1.3 Identification number of measurement equipment.

15.1.1.4 Software revision.

15.1.1.5 Calibration and SPC status of measurement equipment.

15.1.1.6 Ambient temperature.

15.1.1.7 Lot identification.

15.1.1.8 Each wafer's ID.

15.1.2 *Image Processing Parameters*

15.1.2.1 The order of the polynomial used for fitting the wafer edges, if applicable.

15.1.2.2 The type of filter for used for finding the wafer edges.

15.1.3 *Dimensional Parameters*

NOTE 10: The order in which the results for the four wafer edges, corners and angles are reported may depend on the orientation of the wafer during measurement.

15.1.3.1 Four side lengths A_i .

15.1.3.2 Four short side lengths C_i .

15.1.3.3 Four chamfer lengths H_i .

15.1.3.4 Eight cathetus lengths F_{ij} .

15.1.3.5 Distance V .

15.1.3.6 Six wafer widths $X_{p,q,r}$.

15.1.3.7 Four corner angles $\omega_1, \omega_2, \omega_3, \omega_4$.

15.1.3.8 Four chamfer angles a_i .

15.1.3.9 For square wafers only:

15.1.3.9.1 Two diagonal lengths $G_{1,3}$ and $G_{2,4}$.

15.1.3.10 Two short diagonal lengths $E_{1,3}$ and $E_{2,4}$. For pseudo-square wafers only:

15.1.3.10.1 Two diameters $D_{1,3}$ and $D_{2,4}$.

16 Precision and Bias

16.1 The precision of the method has been determined experimentally by performing an MSA. Summary results regarding repeatability and reproducibility are reported in Tables 1 through 3. Details of the MSA are reported in Related Information 1.

16.2 Establishing bias requires certified reference materials which are currently unavailable.

16.3 Provisional reference materials may be qualified by using equipment capable measuring certified reference materials and as silicon wafers (see SEMI MF1569).

16.4 In the absence of interlaboratory test data to establish its reproducibility this Test Method should be used only after the parties to the test have established reproducibility and correlation satisfactory to each party involved.

16.5 For calculating the precision over tolerance ratios (P/T) the tolerances T as follows were used:

16.5.1 Side length, diagonal or diameter: $T = 2000 \mu\text{m}$, according to SEMI PV22.

NOTE 11: In SEMI PV22 this tolerance is reported in millimeter units as 2 mm, not in micrometer units.

16.5.2 Chamfer length of square wafers: $T = 1500 \mu\text{m}$, according to SEMI PV22.

NOTE 12: In SEMI PV22 this tolerance is reported in millimeter units as 1.5 mm, not in micrometer units.

16.5.3 Chamfer length of pseudo-square wafers: $T = 4800 \mu\text{m}$. This tolerance is not specified in SEMI PV22, it is derived from the tolerances in 16.5.1 by planimetry, see Related Information 3.

16.5.4 Cathetus length: $T = 3400 \mu\text{m}$ or $T = 1000 \mu\text{m}$ for pseudo-square or square wafers, respectively. These tolerances are not specified in SEMI PV22, they are derived from the tolerances in ¶ 16.5.1 by planimetry, see Related Information 3.

16.5.5 Angles: 1° . Again, this tolerance is not specified in SEMI PV22, it is assumed to be a reasonable choice.

16.6 Precision was defined as $6\sigma_r$ with σ_r as the total standard deviation, combined for repeatability and reproducibility.

16.7 σ_r was pooled for single crystalline and multicrystalline wafers for side lengths and corner angles, but was determined separately for the remaining metrics.

Table 1 MSA Results for Side Lengths and Corner Angles

<i>Crystal</i>	<i>Mono and Multi</i>					
<i>Metric</i>	$\sigma_r/\mu\text{m}$	P/T		<i>Metric</i>	σ_r/deg	P/T
W_{241}	7.8	3.1%		ω_1	0.24	3.1%
W_{133}	7.3	2.7%		ω_2	0.24	4.6%
W_{243}	9.0	4.0%		ω_3	0.25	3.4%
W_{131}	9.5	4.5%		ω_4	0.25	3.1%
W_{132}	7.3	2.6%				
W_{242}	8.6	3.7%				

Table 2 MSA results for Chamfer Lengths, Cathetus Lengths and Diameters/Diagonals

<i>Crystal</i>	<i>Mono</i>			<i>Multi</i>	
<i>Metric</i>	$\sigma_r/\mu\text{m}$	P/T		$\sigma_r/\mu\text{m}$	P/T
H_1	6.9	2.3%		6.9	3.1%
H_2	8.3	2.5%		8.3	4.6%
H_3	7.1	2.1%		7.1	3.4%
H_4	6.8	3.3%		6.8	3.1%
F_{11}	5.8	1.1%		5.8	3.3%
F_{14}	5.8	1.1%		5.8	3.3%
F_{21}	6.6	1.3%		6.6	4.3%
F_{22}	7.0	1.1%		7.0	4.9%
F_{43}	5.8	1.5%		5.8	3.3%