SEMI PV42-0314 (Reapproved 0320)
TEST METHOD FOR IN-LINE MEASUREMENT OF WAVINESS OF PHOTOVOLTAIC (PV) SILICON WAFERS BY A LIGHT SECTIONING TECHNIQUE USING MULTIPLE LINE SEGMENTS

This Standard was technically approved by the Photovoltaic – Materials Global Technical Committee. This edition was approved for publication by the global Audits and Reviews Subcommittee on December 12, 2010. Available at www.semiviews.org and www.semi.org in March 2020; originally published January 2013; previously published March 2014.

1 Purpose

1.1 Silicon (Si) wafers for photovoltaic (PV) applications cut from a Si ingot or Si brick by multiple wire sawing contain surface undulations/ripples characteristic for this cutting process, so called waviness.

1.2 This waviness is a surface feature where the peaks and valleys of the waves are parallel to the wires of the saw and the direction of the wave is perpendicular to those wires.

1.3 Waviness may significantly impact the quality of solar wafers.

1.4 Waviness is frequently specified for Si wafers for solar cells as a maximum peak-to valley range.

1.5 Therefore process and quality control during manufacturing of wafers requires continuous monitoring of saw marks and waviness with a method that provides reproducible values.

1.6 Process and quality control during manufacturing of wafers requires continuous monitoring of waviness with a noncontact method that supports high throughput.

2 Scope

2.1 This Test Method determines the maximum peak-to-valley of waviness of multi or single crystal Si wafers that typically runs across the entire wafer surface and along the wire direction.

2.2 This Test Method employs an in-line, noncontacting and nondestructive method for measuring the waviness of clean, dry as-cut silicon wafers supported by two belts that move the test specimen through the measurement equipment.

2.3 This Test Method covers square and pseudo-square PV Si wafers, with a nominal edge length ≥125 mm and a nominal thickness ≥100 µm. It applies to both single-crystalline and multi-crystalline Si wafers.

2.4 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) (e.g., ISO 11462) in order to obtain reliable, repeatable and reproducible measurement data.

2.5 The Test Method is based on a light sectioning technique (see Related Information 1) where patterns of line segments or spots of light are projected onto a wafer surface and saw marks as well as the waviness peaks and valleys are oriented perpendicular to the direction of wafer transport.

2.6 Other measurement techniques may also provide similar information about the waviness of a wafer as compared to this Test Method, 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 Loading of wafers onto the measurement system must ensure that the waviness crests/valleys are transverse, not parallel, to the direction of travel through the measurement system. Measurements made on wafers loaded with waviness parallel to the direction of travel will not be suitable for characterizing the wafers' surface topography.

3.2 Wafer surface height vibration caused by transport during measurement may adversely impact measurements.

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3.3 The transverse locations where the measurements are taken on the wafer surface are critical. When comparing measurement results obtained by different equipment or by subsequent measurements on the same equipment it should be verified that the measurements are taken at the same transverse locations on the wafer surface.

3.4 Measurement of waviness height variations depends on the physical setup of the measurement equipment, its optoelectronic noise level, and the calibration of measured signal to height.

3.5 Variations of the projected light line image due to optical imperfections, including those of the wafer surface (such as grain boundaries or stains), may affect the measurement result.

3.6 Wafer saw marks may impact the waviness measurement results.

4 Referenced Standards and Documents

4.1 *SEMI Standards and Safety Guidelines*

SEMI E89 — Guide for Measurement System Analysis (MSA)

SEMI M59 — Terminology for Silicon Technology

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

4.2 *ISO Standards*[1]

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

NOTE 1: Refer to SEMI's Compilation of Terms (COTs) for a list of the most current terms and their definitions.

5.1 Terms and acronyms relating to silicon and other semiconductor technology are defined in SEMI M59.

5.2 *Other Abbreviations and Acronyms*

5.2.1 *AOI* — angle of incidence

5.2.2 *COB* — center of brightness

5.3 *Other Terms Used in this Standard*

5.3.1 *angle of incidence, of projected light line* — the angle between the line of sight of the projector and the surface normal (of the wafer).

5.3.2 *center line (CL)* — an imaginary straight line bisecting a square or pseudo-square wafer surface. It is equidistant from opposing edges of the wafer surface.

5.3.3 *center of brightness (COB) line* — a line fitted through a multiple pixel image representing the weighted average of the pixel values transverse to the projected line direction.

5.3.4 *pixel width and height, effective* — the distances on the wafer surface imaged by one picture element, or pixel, of the image sensor in perpendicular directions.

5.3.5 *saw mark* — a topographic step or groove along the sawing wire direction on the surface of a wafer, generated by the wire of the multiple wire saw.

5.3.6 *scan line* — an imaginary line parallel to a wafer edge and parallel to the wafer transport direction along which measurements are performed.

5.3.7 *waviness* — the more widely spaced component of surface texture. [SEMI M59]

[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

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6 Summary of Test Method

6.1 Four patterns of light line segments are projected on the wafer surface at an AOI α as the wafer, resting on belts, is moved along in the x-direction, the direction of belt travel. These segments provide illumination for image acquisition along four scan lines.

6.1.1 The four scan lines are front-left (FL), back-left (BL), front-right (FR) and back-right (BR).

6.1.2 Each of these four projected light patterns are used identically to sample wafer topography at discrete transverse locations y, the direction perpendicular to the x-direction, ultimately producing N times four surface height variation profiles: $H(x, y_{FL})$, $H(x, y_{BL})$, $H(x, y_{FR})$ and $H(x, y_{BR})$, where N is the number of line segments in a pattern.

6.2 When loaded onto the conveyor belt system the wafer is oriented such that:

6.2.1 The wafer's waviness crests/valleys are perpendicular to the direction of belt travel.

6.2.2 Each projected light pattern illuminates the wafer surface at a distance Δ from the nearest wafer edge.

6.3 Each projected pattern's scattered light from the wafer surface is imaged by a camera system viewing the wafer surface at normal incidence. Alternatively the positions of projector and camera may be interchanged.

6.4 Overlapping images of the projected light pattern scattered from the wafer surface are acquired during wafer transit.

6.5 Height deviations from planar, along each scan line of the wafer surface, due to steps, grooves or waviness result in small transverse translations of the projected light pattern on the wafer surface that are recorded by the image of the projected light line segment (see Related Information 1).

6.6 The images are processed and evaluated by an algorithm according to § 14.

6.6.1 A calibration factor for each of the four projected light patterns image acquisition systems is determined using reference material with known step heights.

6.6.1.1 Small variations in the optical systems, such as the AOI of the projection and the actual viewing angle of the camera being slightly off-normal, make a purely geometrical calculation based on AOI less precise than is possible through calibration.

6.6.1.2 Calibration factors therefore are used to more precisely quantify surface height variation and reduce system-to-system measurement variation.

7 Interferences

7.1 Vibrations of the test specimen relative to the probe-measuring axis may produce errors. Internal system monitoring may also be used to detect non-repetitive and repetitive system mechanical translations.

7.2 Substantial variations in wafer surface properties may negatively impact the measurement result or possibly prevent measurement of some wafers.

7.2.1 Wafer surface roughness variation, along a scan line within a single wafer or between wafers, may impose signal to noise constraints on the optical system when imaging the light scatter from a nominally diffuse scattering surface.

7.3 Variation of pixel height and width within a camera system may not be corrected through the calibration.

7.4 Mechanical variations in equipment adjustment may introduce errors.

7.5 Temperature gradients across the measurement set-up may affect the measurement performance.

7.6 Large surface defects, such as pits or chips, or contamination, such as slurry residue or particles, also may impact the measurement result.

8 Apparatus (see Figure 1)

8.1 *Wafer Transport Device* — Consisting of two belts, which transport the wafer continuously through the measurement apparatus without obstructing the projected light line or the line of sight of the cameras. The material of the belts shall not leave traces or residue on the wafer surface.

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8.2 *Projector* — Projecting one of the following patterns at an AOI α onto the wafer surface at a distance Δ from the wafer edge during transport.

8.2.1 *Pattern A* — N closely adjacent and equidistant parallel line segments that are oriented nominally parallel to the direction of belt travel. Typically $N = 1$ or $N = 2$, but more are possible. The distance between two adjacent line segments is denoted as δ.

8.2.2 *Pattern B* — N adjacent light spots (to be understood as limit of short line segments). Typically $N = 1$ or $N = 2$, but more are possible. The distance between two adjacent spots is denoted as δ.

8.2.3 The distance Δ is measured from the wafer edges to the outmost part of the pattern.

8.3 In total four projectors are used, two above the wafer and two below the wafer.

8.4 *Sensor* — An imaging digital camera system with an effective pixel width s_w and an effective pixel height s_h. It is set-up with its line of sight normal to the wafer surface, recording images of the projected light pattern on the wafer surface while in transit. In total four cameras are used, two above the wafer and two below the wafer.

8.5 *Computer* — For controlling the measurement system and equipped with software for synchronously acquiring and processing the camera images according to § 14.

8.6 The positions of projectors and corresponding cameras may be interchanged, meaning that the projector AOI is normal and the camera views the wafer surface at an oblique angle.

9 Test Specimen

9.1 Clean, dry Si wafers with an as-cut surface condition.

10 Safety Precautions

10.1 The entire equipment has to be placed in a closed housing and has to be secured with a safety lock that stops the belts and safely switches the tool off when the housing is opened.

10.2 If required by local, national or international safety requirements, eye protection goggles have to be used by operators and maintenance personnel.

11 Preparation of Apparatus

11.1 The suitability of the equipment is determined by performing statistically based instrument repeatability and reproducibility study to ascertain whether the equipment is operating within the manufacture's stated specification, for example, according to SEMI E89.

11.2 Align line pattern projectors and digital cameras with respect to the wafers to be measured according to the manual of the supplier of the equipment.

11.3 Adjust the sensitivity of the camera and the light intensity of projected light pattern so that the intensity profile of the image of the light pattern in the camera extends over at least three digital intensity levels above the noise level of the camera while avoiding saturation and image bloom.

11.4 Define the control limits for SPC for the measurement equipment with a set of selected wafers.

NOTE 2: 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.

12 Calibration and Standardization

12.1 Each projection and camera imaging system is calibrated by using one or more reference wafers.

12.2 The reference wafers shall contain topographic surface features with known step height.

12.2.1 Care has to be taken selecting a tool for establishing the surface feature heights or depths of the reference wafers. This tool has to be calibrated with traceable reference materials and be nondestructive, typically noncontact.

12.3 Measure the reference wafer(s) according to the procedure given in § 13, but omitting steps ¶¶ 14.4 and 14.5.

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