

SEMI PV51-0214 (Reapproved 0320) TEST METHOD FOR IN-LINE CHARACTERIZATION OF PHOTOVOLTAIC SILICON WAFERS BY USING PHOTOLUMINESCENCE

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, 2019. Available at www.semiviews.org and www.semi.org in March 2020; originally published February 2014.

1 Purpose

- 1.1 Multicrystalline silicon (mc-Si) wafers produced by casting and controlled solidification usually contain regions containing high grown-in defect density in addition to the grain boundaries.
- 1.2 These defects may consist of impurity elements as well as structural defects within grains such as dislocations and dislocation networks, which may impact the solar cell efficiency negatively.
- 1.3 The defective areas are frequently close to the sidewalls and bottom of the ingot from which the wafers are cut.
- 1.4 Wafers containing highly defective areas impact the yield of a manufacturing line and should be excluded from solar cell manufacturing.
- 1.5 Therefore methods are required that allow a fast in-line characterization and sorting of wafers.
- 1.6 This method uses photoluminescence for detecting defective areas in wafers.

2 Scope

- 2.1 This Test Method identifies defective areas in crystalline silicon (Si) wafers.
- 2.2 It employs an in-line, noncontacting and nondestructive method for characterizing clean, dry, as-cut Si wafers supported by a mechanism that moves the test specimen through the measurement equipment.
- 2.3 The method covers square and pseudo-square Si wafers for photovoltaic (PV) applications, with a nominal edge length ≥ 125 mm and a nominal thickness ≥ 100 μm . It applies to both single-crystalline as well as multicrystalline Si wafers.
- 2.4 The 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 method is based on recording and evaluating near-infrared photoluminescence (PL) radiation emitted from the wafer after excitation with monochromatic light.
- 2.6 Other measurement techniques may also provide similar information about the defective areas of a wafer as compared to this Test Method, but they are not the subject of this Test Method.
- 2.7 The test may also be used for off-line, stationary characterization of Si wafers provided the requirements of the test method are met.

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 Substantial variations of doping concentration across a wafer or between successive wafers may impact the measurement result.
- 3.2 Substantial variations of surface texture across a wafer or between successive wafers may also impact the measurement result.
- 3.3 The temperature of the wafers must be $23 \pm 5^\circ\text{C}$ when measured.

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

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 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 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 *MSA* — measurement system analysis

5.2.3 *PL* — photoluminescence

5.3 Definitions

5.3.1 *bright grain boundaries, on a Si wafer* — grain boundaries that appear as bright lines on a dark background in a PL image. They usually occur close to the wafer edges in edge impurity areas or in wafers from the bottom or the top of an ingot.

5.3.2 *dark line defect, on a Si wafer* — an area on a Si wafer with a high density of defects, mainly grain boundaries, appearing as dark lines in a PL image.

5.3.3 *defect cluster, on a Si wafer* — an area on a Si wafer with a high density of dislocations and other defects.

5.3.4 *edge impurity area, of a Si wafer* — an area along the edge(s) of a Si wafer with a high concentration of impurities, characterized by a high recombination of excess charge carriers resulting in dark PL images. It occurs most frequently along the edge(s) of wafers or in wafers from the bottom or the top of an ingot.

6 Summary of Test Method

6.1 The wafer resting on a transport mechanism is moved past an infrared laser light source and a digital line camera.

6.2 A narrow strip of infrared light with wavelength λ_e is projected on the wafer parallel to the leading edge of the wafer moving along the transport direction (see Figure 1).

6.3 The light projected on the wafer generates electron-hole pairs in the bulk of the wafer that emit light with a wavelength $\lambda_{pl} > \lambda_e$ when they recombine, creating the PL light or radiation.

6.4 The PL light emitted from the illuminated strip is imaged by a line array of sensors (digital line camera) through a filter that blocks light with wavelength λ_e and transmits light with wavelength λ_{pl} .

6.5 Successive images of the illuminated strip on the wafer are recorded by the digital line camera as the wafer is advanced, creating a full-wafer scan.

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>

6.6 The full-wafer image is processed and evaluated by appropriate algorithms and size and location of defective areas are reported.

6.7 At regular time intervals, a reference material is measured and used for normalizing the PL picture of the sample under test.

7 Apparatus (see Figure 1)

7.1 *Projector* — One or more light sources that project sections of a narrow strip of full width at half maximum (FWHM) width w of continuous infrared light under an angle of incidence (AOI) α on the wafer surface, so that an uninterrupted light strip is generated across the entire wafer. The distance of the projector to the wafer surface is greater-than or equal to wafer diagonal. The infrared light wavelength λ_e is selected so that it is $\leq 1 \mu\text{m}$ and its penetration depth in Si is $\geq 10 \mu\text{m}$. The projector may consist of more than one light source.

7.2 *Camera* — Digital camera with a line array of sensors (≥ 1024 pixels) and set up with its line of sight perpendicular to the wafer surface, recording the PL radiation emitted by the wafer. The distance of the sensor to the wafer surface is the same as for the projector. The noise level (3σ) of the camera shall be $\leq 1\%$ of the peak signal and the dynamic range shall be ≥ 255 gray levels. The sensor array is selected for the light wavelength λ_{pl} .

7.3 *Camera Filter* — An optical filter that transmits only light with a wavelength $\geq \lambda_{pl}$.

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

7.5 *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 stops the belts and switches off the tool when the housing is opened.

8.2 The infrared light used is invisible to humans. Special provisions shall be taken to protect the eyes of operators during maintenance activities.

8.3 Protecting goggles shall be used by operators and maintenance personnel if required by local, national or international safety requirements.

8.4 Avoid illuminating the wafer when it is not moving through the equipment. This might result in heating the wafer locally and deforming/breaking it.

9 Test Specimens

9.1 Clean, dry Si wafers with as-cut surfaces.

10 Preparation of Apparatus

10.1 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.

10.2 Align the projector and the camera according to the supplier's instructions.

10.3 Adjust the sensitivity of the camera and the light intensity of projected line segment so that the intensity profile of the image of the light line segment in the camera extends over at least three digital intensity levels above the noise level of the camera.

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

NOTE 1: 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 Record a PL image of a single crystalline wafer—the calibration wafer—with the same size and surface condition as the samples under test and with known homogeneous excess charge carrier lifetime and doping concentration.

11.2 Average the gray values of this PL image along the x -direction, so that an intensity profile $I_{cal}(y)$ is obtained.

11.3 Store this profile for future use.

11.4 Calculate the average gray value $I_{cal,m}$ of the calibration wafer and store it, too.

11.5 Immediately afterwards generate and store an intensity profile $I_{ref,cal}(y)$ of the reference material strip.

11.6 Repeat and store the calibration in regular time intervals, after any maintenance activity involving the light source and if the light source is changed.

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.

12.4 Place a wafer on the transport belts.

12.4.1 Align the wafer so that its leading edge is parallel to the projected light strip.

12.4.2 Move the wafer through the measurement station.

12.4.3 Scan the entire length of the wafer.

12.4.4 Record the successive digital PL images of the projected light strip during the scan.

12.4.5 Combine the successive strip images to a digital gray scale raw image RI of the entire wafer.

12.4.6 Process RI according to § 13.

12.4.7 Report all required parameters according to § 15.

12.4.8 Repeat with the next wafer.

12.5 Use a strip of monocrystalline Si as long as the sample under test as reference material and measure it in regular time intervals:

12.5.1 Orient the Si strip so that its long axis is perpendicular to the belt travel direction.

12.5.2 Record its PL image.

12.5.3 Average its intensity along the x -direction to obtain an average intensity profile $I_{ref}(y)$ and use it for temporal and spatial flat-field correction for subsequent test samples according to ¶ 14.7.

13 Image Processing Operations

13.1 Several standard operations are used for processing the digital image RI . They are shortly outlined here. For more detailed information the reader is referred to literature.

13.2 *Threshold Operation*² — All pixels with a gray value below a threshold value are marked 1, all other pixels with 0, or vice versa.

13.3 *Dynamic Threshold Operation* — Each pixel is compared to a threshold calculated by a function based on the values of the pixels in an area surrounding the pixel under evaluation.

² See [http://en.wikipedia.org/wiki/Thresholding_\(image_processing\)](http://en.wikipedia.org/wiki/Thresholding_(image_processing))