Crystalline Silicon Terrestrial Photovoltaic Cells –

Supply Chain Procurement Specification Guideline

Prepared by

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Photovoltaic Reliability Laboratory

Solar America Board for Codes and Standards

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Executive Summary

This study report documents the need for a supply chain procurement specification and standard that applies to photovoltaic (PV) cells. Many PV module manufacturers depend on third party solar cell manufacturers for their supply of silicon cells. Each individual module manufacturer currently develops and uses their own cell procurement specification. No common, baseline procurement specification exists for use by the entire industry.

This study report presents a proposed standard with thorough explanations and justifications for each section of the standard. This proposed standard, entitled "Crystalline Silicon Terrestrial Photovoltaic Cells – Supply Chain Procurement Specification Guideline" follows the format of the ASTM but can be easily adapted to formats of other standard making bodies such as SEMI, IEEE and IEC.

This study report recommends that the content of the proposed standard serve as the starting point for a thorough discussion of this topic by appropriate standards making bodies. Comments from stakeholders, especially the cell and module manufacturers who will most benefit from this work, are particularly invited. The report closes with recommendations for additional supply-chain specification standards related to PV module manufacture including encapsulant, backsheet, junction box, cables, glass superstrate, and framing materials.

Author Biography

Dr. Govindasamy (Mani) TamizhMani is the president of TUV Rheinland PTL (Photovoltaic Testing Laboratory) and a professor in the Department of Electronic Systems at Arizona State University. Dr. Mani has been involved in R&D activities related to photovoltaics and fuel cells for over 25 years and photovoltaic module testing and certification activities for over 10 years. He has been involved in test standards' development activities since 1996. He has served or has been serving as a member of various standards committees including Canadian Standards Council, IEEE, IEC and ASTM. He has taught graduate level courses related to photovoltaics, fuel cells, electrolysis and batteries, has published more than 50 journal and conference papers, and has served as a reviewer of numerous conference and journal publications including IEEE Photovoltaic Specialists Conference, *Progress in Photovoltaics and Journal of the Electrochemical Society.*

Solar America Board for Codes and Standards

The Solar America Board for Codes and Standards (Solar ABCs) is a collaborative effort among experts to formally gather and prioritize input from the broad spectrum of solar photovoltaic stakeholders including policy makers, manufacturers, installers, and consumers resulting in coordinated recommendations to codes and standards making bodies for existing and new solar technologies. The U.S. Department of Energy funds Solar ABCs as part of its commitment to facilitate wide-spread adoption of safe, reliable, and cost-effective solar technologies.

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Introduction

Background and Issue

A large number of photovoltaic (PV) standards have been developed for modules and systems by the technical committees of various standards organizations, including ASTM (E44-09), IEEE (SCC21) and IEC (TC82). Only very few industry standards, however, have been developed for issues related to individual solar cells. Cell-level standards, developed thus far have been limited to those that deal only with performance-measurements issues. They exclude issues faced by the module manufacturers during the stages of procurement of cells from the cell manufacturers and production of modules based on the procured cells.

Almost all the modules that are sold in any part of the world have to meet the design qualification requirements of the module standards [IEC 61215: Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval; IEC 61646: Thin-film terrestrial photovoltaic (PV) modules - Design qualification and type approval]. In order to qualify the entry of these modules in the marketplace, these module standards call for severe environmental, electrical, and mechanical stress tests. In addition, practically every module manufacturer provides a warranty exceeding 20 years, which makes it imperative for them to ensure that their modules work for decades to come. The cells are the heart of every PV module. If the cells fail, the entire module fails. Recent failure-rate analysis conducted by Arizona State University (ASU) Photovoltaic Testing Laboratory indicates that a large portion of the accelerated module qualification failures are related to the failure of the cell itself [IEEE Photovoltaic Specialists Conference, San Diego, May 2008]. Based on field failures as a percentage of the total number of failures observed from 1994 through 2005 at BP Solar and Solarex, BP Solar reported about 86% of the field failures are corrosion or breakage of cell or cell-related components [SPIE Solar Energy Conference, San Diego, August 2008]. In this Solar ABCs study, effort has been made to initiate developing a cell prequalification specification standard for the benefits of module as well as cell manufacturers.

Purpose of each section of the proposed standard:

The proposed potential standard, entitled “Crystalline Silicon Terrestrial Photovoltaic Cells –Supply Chain Prequalification Specification,” is presented in part two of this document. The general format of ASTM standards has been used as the basis for the proposed standard. It would be a simple editorial process to convert this format to another format of other standards, such as IEEE and IEC. The content presented in this proposed standard is based on industry’s need for the development of procurement specification for solar cells. The content presented in each section of this standard intends to meet the expectation of the module manufacturers so they can use this standard to develop their own procurement specifications. In the following paragraphs, the purpose of each section is explained so that the reader is informed of the necessity of each section.

Purpose of section 1: Scope

Because a large number of module manufacturers depend on the cell manufacturers for their cell supply, the individual manufacturers use their own procurement specifications. The proposed standard aims to develop a standardized specification so that the entire industry could benefit from using a common, baseline procurement specification. This section, scope, provides the scope and limitation of the proposed standard.

Purpose of section 2: Packing, marking, and storage

Because wafer-based PV cells are fragile and sensitive to storage conditions, this section provides requirements for meeting the baseline packing, labeling, and storage requirements. These requirements are very similar to the requirements used by the electronic industry.

Purpose of section 3: Process and wafer characteristics

Reliability of the modules and the system depend on the core element: the solar cell itself. The failure modes and mechanisms of the solar cells heavily depend on the materials and processes involved in making the solar cells. The wafer properties and cell processing methods including the adhesion of the metallic layers and solder connection heavily influence the final characteristics of the PV cells. As reported by the electronic industry, such as Jet Propulsion Laboratory in 1980s, reliability workshops in 1990s, and other technical and scientific literature, solder compositions and soldering conditions—including solder temperature, solder time and soldering pressure—heavily influence the reliability of the PV cells (and hence the modules and the system) in field conditions. This section identifies the required process and wafer characteristics to meet the intent of this standard.

Purpose of section 4: Cell characteristics

This section is composed of two sub-sections: non-performance characteristics and performance characteristics. Non-performance characteristics include visual, dimensional, physical, chemical, electrical, and mechanical parameters. Performance characteristics include various performance parameters, such as short-circuit current, open-circuit voltage, maximum power, temperature coefficients, measurement tolerance and production tolerance at the standard test conditions. This section also includes the required performance parameters at a low light level because they are required in the module qualification standards such as IEC 61215.

Purpose of section 5: Declaration letter for modification

The entire PV industry has successfully followed the module-retest guideline for over 11 years. Any change in the cell characteristics, module design, materials, components, or processing of the module may require a repetition of some or all of the qualification tests to maintain type approval per IEC 61215. Specifically, the module-retest guideline calls for an extensive retest if any significant cell modifications are declared by the module manufacturers. For the module retesting, the module manufacturers are required to submit a "Similarity Declaration Form" so that the test laboratories can determine which additional tests are required to maintain the type approval certificate per IEC 61215. In the proposed standard, a similar approach is recommended for the specification modification of the PV cells. This document proposes to require a declaration from the cell manufacturers, before each shipment, to identify the significant modifications to the cell so that the module manufacturers could make an appropriate procurement decision.

Purpose of section 6: Documentation

The documentation is a certified compilation of all the datasheets and process sheets generated as per all other sections of this document. It is proposed to include the requirement of a certificate of conformity confirming full compliance with the specifications of this standard.

Conclusions

- In this study, a proposed content for a potential standard entitled "Crystalline Silicon Terrestrial Photovoltaic Cells –Supply Chain Procurement Specification Guideline" has been developed and presented. The purpose of each section in the proposed standard is explained.
- For the dimensional and other key characterizations of a solar cell, due to the absence of dedicated cell characterization standards, the proposed standard relies on and refers to several silicon wafer standards (SEMI standards developed for the electronic industry). There is a need to develop dedicated standards specific to solar cells and solar cell wafers so that both cell and module manufacturers can use them for the development / procurement of solar cells. All the referenced electronic industry specific SEMI standards may need to be replaced with the to-be-developed solar cell specific standards.

Recommendations

- To make the proposed content/standard a consensus standard, a thorough discussion on the format and content of the proposed content/standard will need to be carried out by a standards committee from IEEE, ASTM, SEMI or IEC.
- To improve the proposed/content of the standard, comments from the stakeholders, especially the supply/procurement specifications used by the cell/module manufacturers, are requested.
- The development of additional supply-chain procurement specification standards for other module components, such as encapsulant, backsheet, junction box, glass superstrate, frame material and cables, are recommended.

PROPOSED STANDARD

IEEE/IEC/ASTM/SEMI Designation: XXXXXX-08

Crystalline Silicon Terrestrial Photovoltaic Cells – Supply-Chain Procurement Specification

1. Scope

1.1 This standard provides the minimum required information to prequalify the photovoltaic (PV) cells that would assist the module manufacturers in identifying suitable alternative sources for establishing the supply chain.

1.2 This standard applies only to wafer-based crystalline silicon solar cells. A separate standard for thin-film cells will be established in the future.

1.3 This standard does not apply to cells used with concentrated sunlight (higher than 3X).

The intent of this standard is to identify the minimum cell procurement specifications that could be used by the module manufacturers to design and construct modules capable of passing the qualification of photovoltaic modules as defined in IEC 61215 and IEC 61730-2 and of withstanding prolonged exposure in typical climates. The actual lifetime expectancy of modules containing the cells procured using this standard will depend on the cell characteristics, design/packaging characteristics, their environment, and the conditions under which they are operated.

1.4 The minimum procurement information of PV cells includes sampling, packing, marking and storage procedures; process and wafer characteristics; cell characteristics (dimensional, visual, electrical, physical and mechanical); module package-ability, a declaration letter to inform the module manufacturers regarding cell process, material or structure modifications, if any; and a documentation including a full report with all the characteristics identified in this standard.

1.5 The module manufacturer may call for additional information to investigate the suitability of the supplied cells in their specified module construction package.

1.7 This standard is not intended to waive or replace any tests or requirements of the qualification standards (such as IEC 61215 and IEC 61730-2) or their retest guidelines.

2. Packing, marking, and storage

The cells shall be accompanied by documentation detailing packing, marking, and storage procedures. Each smallest packing unit shall carry the following clear and indelible markings:

- name, monogram, or symbol of manufacturer;
- cell type (monocrystalline or polycrystalline silicon) and its designation;
- lot number;
- quantity in each pack;
- date and place of manufacture (marked on the package or be traceable from the lot number);
- indication of electrode polarities;
- stacking ability for storage;
- ambient conditions for storage;
- maximum recommended time for storage.

Cells should be packed in such a manner to ensure minimal damage to the product during transportation. As a guideline, the following apply:

- cells should be packed with a specified maximum unit number per pack;
- cells in each pack shall have originated from the wafers of no more than two different ingots;
- packs shall be contained in compartmented, cushioned boxes suitable for shipping and handling;
- outermost container shall bear clearly legible labels stating, for example, “Fragile; Handle with Care”

3. Process characteristics, wafer characteristics and module package-ability

The cells should have been manufactured from specified materials and components in accordance with the relevant drawings and process sheets and subjected to the manufacturer’s normal inspection, quality control, and production-acceptance procedures. All the relevant datasheets and/or product specifications shall be included in the documentation of this supply chain specification. The documentation may contain certified material test report, certificate of conformance, certified electrical measuring record, certificate to quality management, etc.

3.1 Process characteristics

3.1.1 Adhesion strength

The material and composition of all the surface layers for soldering shall be provided along with supporting documentation. The adhesion strength data of all surface layers able to be soldered shall be reported with the tape testing according to IEC 60326-2, test 13a (for example, with the use of 3M 810 tape). The adhesion force shall be between 2 N/cm and 4 N/cm or acceptable to the module manufacturer.

3.1.2 Solder connection

The “solderability” inspection shall be carried out according to EN 60068-2-44. The adhesion strength of solder connection shall be measured using the test method of EN 61189-2 (2M05) or another suitable method acceptable to the module manufacturer. The minimum peel strength shall be 1 N per mm of solder tab width or acceptable to the module manufacturer. The cell supplier shall provide details for suitable solder compositions and soldering conditions including solder temperature solder time and soldering pressure. Any limitation on the soldering method and soldering conditions shall be clearly identified.

3.2 Wafer characteristics

The surface characteristics of the wafers used for the cell fabrication shall be reported. These surface characteristics include visible surface damage, saw damage marks, and stains. All the key characteristics of the wafers used for the cell fabrication shall be reported according to the applicable SEMI standards listed in Annex, which include the following:

- type of silicon ingot (monocrystalline or polycrystalline) used;
- crystal growth technique;
- nominal crystal orientation, if applicable;
- wafer sawing technique;

- conductivity type and dopant;
- nominal resistivity;
- nominal dimensions (thickness, length, width and diameter if pseudo-square size);
- extent of warping;
- bulk structural defects, if any;
- impurity concentration range (interstitial oxygen and substitutional carbon);
- wafer surface preparation process; and
- average carrier lifetime.

3.3 Module package-ability

The package-ability of the cells, in at least one module package, shall be demonstrated by the cell manufacturers through meeting the pass requirements of IEC 61215 and IEC 61730 (part 2) standards.

4. Cell characteristics

All the relevant datasheets and/or product specifications shall be included in the documentation of this supply chain specification. The documentation may contain certified material test report, certificate of conformance, certified electrical measuring record, certificate to quality management, etc.)

4.1 Non-performance characteristics

The non-performance characteristics include visual, dimensional, physical, chemical, electrical and mechanical parameters. As a minimum, the following non-performance characteristics and information shall be reported:

- visual defects of metallization (broken finger, missing busbar print, etc);
- edge defects, visible chips, indents, and stains;
- cracked/broken cells (no cracked or broken cells are allowed at packing);
- color category;
- metallization materials;
- diagrammatic representation of metallization (including busbars) location and dimensions (thickness, length and width) (see Figures 1A and 1B for a sample technical drawing);
- anti-reflective coating material and thickness and whether it is deposited before the metalization or on top of the metalization;
- type top and bottom semiconductor layer materials and thickness;
- type and concentration of dopants of the cell active layers;
- nominal series resistance and low shunt cut-off resistance of the cell;
- dimensions of the cell including cell thickness, length and width with tolerances;
- total thickness variation;
- shape of cell (square, pseudo-square etc.);
- adhesion strength of all surface layers including antireflective coating and

metallization according to IEC 60326-2, test 13a;

- extent of warping according to SEMI MF1390-04;
- concentricity (the distance between the centre of the circle and centre of the square in pseudo-square cells); and
- cell breaking strength (during soldering and stringing; a method to measure breaking strength needs to be developed/defined at the time of actual standard development).

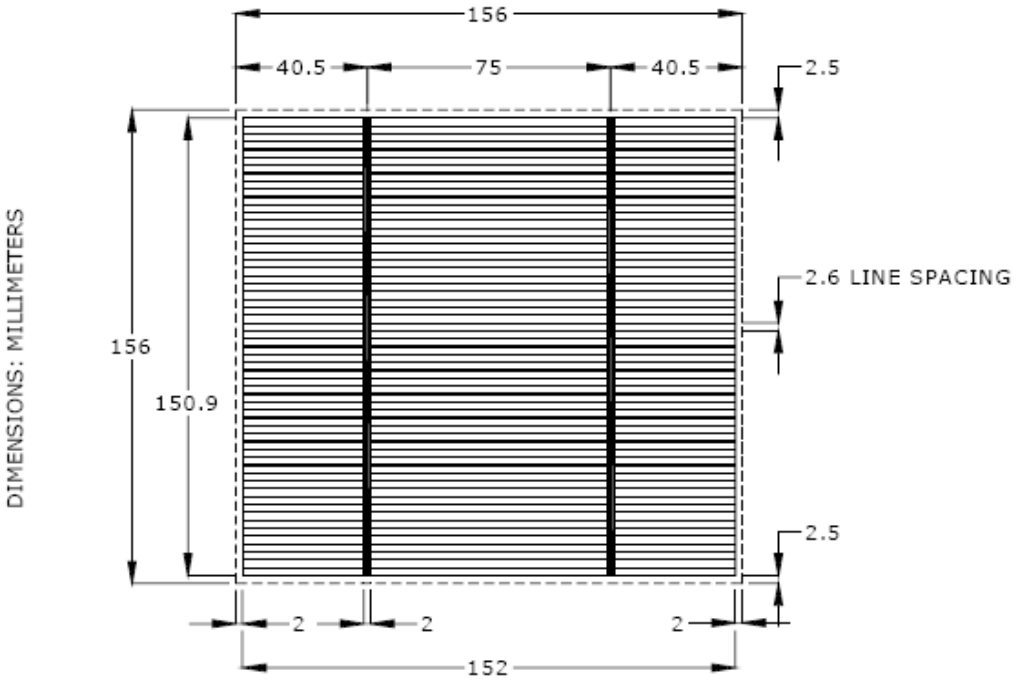

Figure 1 (A): Sample dimensions of the front side metallization of a solar cell [tolerance to be specified]

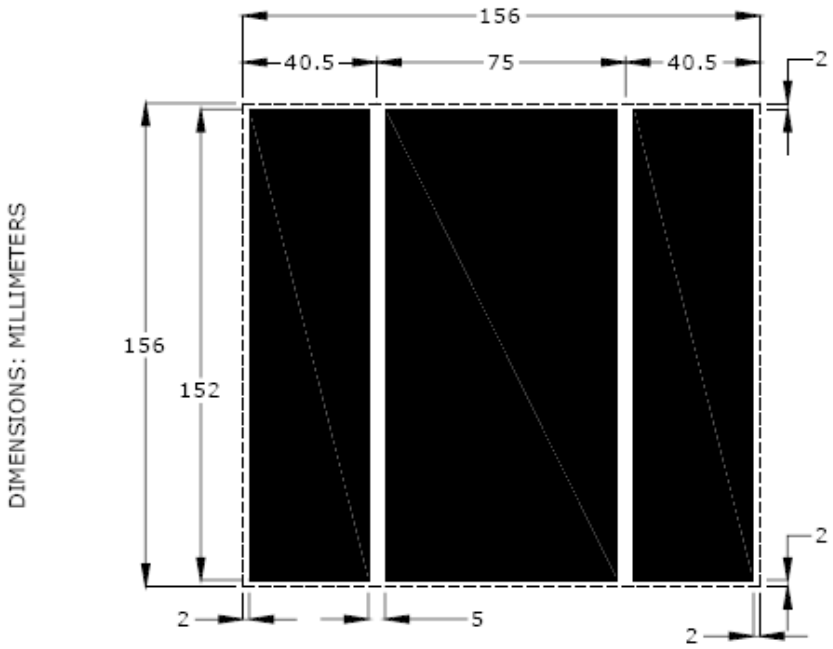

Figure 1 (B): Sample dimensions of the back side metallization of a solar cell [tolerance to be specified]

4.2 Performance characteristics

The performance characteristics at both standard test conditions (STC) and low irradiances shall be reported as shown in **Table 1**. The STC condition refers to 1000 W/m² irradiance, 25°C cell temperature and AM 1.5G spectrum. The parameters are to be obtained and reported as stabilized after at least 5 kWh/m² light conditioning (to address the light induced degradation, if any). For the low irradiances, the parameters are to be obtained and reported for the AM 1.5G spectrum unless otherwise required.

Table 1. Performance Characteristics of the Solar Cell

Performance Parameter	Symbol (Unit)	Value
Short circuit current @ STC	I_{sc} (A)	
Open circuit voltage @ STC	V_{oc} (V)	
Current at maximum power @ STC	I_{mp} (A)	
Voltage at maximum power @ STC	V_{mp} (V)	
Maximum power @ STC	P_{mp} (W)	
Fill factor @ STC	FF (%)	
Cell efficiency @ STC	(%)	
Cell efficiency tolerance @ STC	(%)	
Production Tolerance @ STC	I_{sc} (%)	
	V_{oc} (%)	
	I_{mp} (%)	
	V_{mp} (%)	
	P_{mp} (%)	
Measurement Tolerance @ STC	I_{sc} (%)	
	V_{oc} (%)	
	I_{mp} (%)	
	V_{mp} (%)	
	P_{mp} (%)	
Temperature Coefficients @ STC	α_{Isc} (%/°C)	
	β_{Voc} (%/°C)	
	β_{Vmp} (%/°C)	
	δ_{Pmp} (%/°C)	
	ε_{FF} (%/°C)	
Short circuit current @ 25°C, 200 W/m²	I_{sc} (A)	
Open circuit voltage @ 25°C, 200 W/m²	V_{oc} (V)	
Current at maximum power @ 25°C, 200 W/m²	I_{mp} (A)	
Voltage at maximum power @ 25°C, 200 W/m²	V_{mp} (V)	
Maximum power @ 25°C, 200 W/m²	P_{mp} (W)	
Fill factor @ 25°C, 200 W/m²	FF (%)	
Cell efficiency @ 25°C, 200 W/m²	(%)	
Reverse breakdown voltage	V	

5. Declaration letter for modifications

Changes in material selection, components, and manufacturing process of the cells can impact electrical performance, safety and reliability of the modules. Significant changes in the structure, materials, components, and/or processing of the cell require a supplier declaration, as these changes may warrant retesting of the modules per module design qualification and type approval standard such as IEC 61215. Significant changes to the cell manufacturing process must be declared to the module manufacturers and agreed upon prior to the modifications being made. This declaration shall be made for every shipment to the module manufacturer. These modifications include, but not limited to the following:

- nominal performance parameters, including cell efficiency, Pmax, Isc, Voc and FF at standard test conditions, and low irradiance;
- metallization materials and/or process;
- anti-reflective coating material and thickness and location in cell structure (before or after metallization);
- change in type of diffusion process;
- semiconductor layer materials;
- order of cell process if the change involves the metallization system;
- change of manufacturing site of the solar cells not under the same QA system;
- supply of cells from a different manufacturer;
- reduction in nominal cell thickness by greater than 25%;
- number of recommended cells per string;
- type and concentration of dopants for the active layers of the cell;
- minimum shunt resistance for cell sorting;
- total thickness variation;
- shape of cell (square, pseudo-square etc.);
- adhesion strength of all surface layers including antireflective coating and metallization, if process changed;
- extent of warping, if process changed;
- visible stains and cracks, if process changed;
- concentricity (the distance between the centre of the circle and centre of the square in pseudo-square cells);
- crystal growth method of the wafers; and
- wafer surface etching materials, composition and process.

6. Documentation

All the relevant datasheets and/or product specifications identified in this standard shall be included in the documentation in accordance with the relevant sections of ISO/IEC 17025. The documentation may contain certified material test report, certificate of conformance, certified electrical measuring record, certificate of quality management etc. The documentation shall include at least the following information:

- a title;
- name and address of the supplier;
- name and address of the test laboratory and location where the tests were carried out, if applicable;
- unique identification of the report and of each page;
- description and identification of the cell;
- packing, marking, and storage procedures as identified in this standard;
- process and wafer characteristics as identified in this standard;
- cell characteristics including physical, electrical, mechanical, and dimensional characteristics as identified in this standard;
- a statement of the estimated tolerance for each of the reported parameter, where relevant;
- a letter of commitment to declare the significant cell modifications;
- date(s) of tests, where relevant;
- identification of test method used, where relevant;
- any deviations from, additions to, or exclusions from this standard, and any other information relevant to a specific to the supplied solar cell;
- measurements, examinations, and derived results supported by tables, graphs, sketches, and photographs as appropriate including temperature coefficients of short-circuit current, open-circuit voltage and peak power, power at standard test conditions and low irradiance per IEC 61215 standard, and a description of data acquisition system (including scan time and current-voltage pair collection procedure, if pulse solar simulator used) and classification of the solar simulator used for the performance measurements;
- All the measurements shall be traceable as per ISO 17025 requirements
- a signature and title, or equivalent identification of the person(s) accepting responsibility for the content of the report, and the date of issue;
- certificate of conformity confirming full compliance with the specifications of this standard.

References

The documents provided in this section were used to develop most of the proposed standard. Few standards are available because they are specific to the dimensional and other key characteristics of a PV cell. This standard, therefore, references a large number of SEMI standards that are related to silicon wafers used in the electronic industry rather than the solar industry. These references will need to be changed when the solar industry develops its own standards for PV cells.

IEC Standards:

IEC 61215 (2005): Crystalline silicon terrestrial photovoltaic (PV) modules-Design qualification and type approval

IEC 60904-1: Photovoltaic devices-Part 1: Measurement of photovoltaic current-voltage characteristics

IEC 60068-2-44: Environmental testing-Part 2: Guidance on tests: Soldering

IEC 61189 series: Test methods for electrical materials, printed boards and other interconnection structures and assemblies

IEC 60326-2, Printed boards-Part 2: Test methods

IEC 61730 (part 2): Photovoltaic (PV) module safety qualification: Requirements for testing

IECEE Retesting Guidelines for design modifications per IEC 61215

EN Standards:

EN 50380 (2003): Datasheet and nameplate information for photovoltaic modules

EN 50461 (2006): Solar cells - Datasheet information and product data for crystalline silicon solar cells

SEMI Standards:

SEMI MF523-02: Practice for unaided visual inspection of polished silicon wafer surfaces

SEMI MF42-02: Test methods for conductivity type of extrinsic semiconducting materials

SEMI MF84-02: Test method for measuring resistivity of silicon wafers with an inline four-point probe

SEMI MF1535-04: Test method for carrier recombination lifetime in silicon wafers by non-contact measurement of photoconductivity decay by microwave reflectance

SEMI MF26-05: Test methods for determining the orientation of a semi-conductive single crystal

SEMI MF1530-04: Test method for measuring flatness, thickness, and total thickness variation on silicon wafers by automated non-contact scanning

SEMI MF533-02a: Test method for thickness and thickness variation of silicon wafers

SEMI MF1390-04: Test method for measuring warp on silicon wafers by automated noncontact scanning

SEMI MF657-99: Test method for measuring warp and total thickness variation on silicon wafers by noncontact canning

SEMI MF2074-03: Guide for measuring diameter of silicon and other semiconductor wafers

SEMI MF671-99: Test method for measuring flat length on wafers of silicon and other electronic materials

SEMI MF1188-05: Test method for interstitial oxygen content of silicon by infrared absorption with short baseline

SEMI MF1391-04: Test method for substitutional atomic carbon content of silicon by infrared absorption

SEMI MF1809-04: Guide for selection and use of etching solutions to delineate structural defects in silicon

SEMI MF1810-04: Test method for counting preferentially etched or decorated surface defects in silicon wafers

SEMI MF950-02: Test method for measuring the depth of crystal damage of a mechanically worked silicon slice surface by angle polishing and defect etching

DIN/VDE Standards:

DIN/VDE 0126-18-1 (2007): Solar Wafers–Part 1 "Datasheet information and project data for crystalline silicon solar wafer" (German version)

DIN/VDE 0126-18-2-1 (2007): Solar Wafers–Part 2-1 "Measuring the geometric dimensions of silicon wafers – Wafer thickness" (German version)

DIN/VDE 0126-18-2-2 (2007): Solar Wafers–Part 2-2 "Measuring the geometric dimensions of silicon wafers – Variations in thickness" (German version)

DIN/VDE 0126-18-2-3 (2007): Solar Wafers–Part 2-3 "Measuring the geometric dimensions of silicon wafers – Waviness and warping" (German version)

DIN/VDE 0126-18-2-4 (2007): Solar Wafers–Part 2-4 "Measuring the geometric dimensions of silicon wafers – Saw marks" (German version)

DIN/VDE 0126-18-3 (2007): Solar Wafers–Part 3 "Alkaline corrosion damage of crystalline silicon wafers – Method of determining the corrosion rate of mono and multi crystalline silicon wafers" (German version)

DIN/VDE 0126-18-4-1 (2007): Solar Wafers–Part 4-1 "Process for measuring the electrical characteristics of silicon wafers – Minority carrier lifetime, inline measuring method" (German version)

DIN/VDE 0126-18-4-2 (2007): Solar Wafers–Part 4-2 "Process for measuring the electrical characteristics of silicon wafers – Minority carrier lifetime, laboratory measuring method" (German version)

DIN/VDE 0126-18-5 (2007): Solar Wafers–Part 4 "Process for measuring the electrical resistance of silicon wafers" (German version)

DIN/VDE 0126-18-6 (2007): Solar Wafers–Part 6 "Method for measuring substitutional atomic carbon and interstial oxygen in silicon used for photovoltaics" (German version)

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