

SEMI PV15-0211 (Reapproved 1215) GUIDE FOR DEFINING CONDITIONS FOR ANGLE RESOLVED LIGHT SCATTER MEASUREMENTS TO MONITOR THE SURFACE ROUGHNESS AND TEXTURE OF PHOTOVOLTAIC (PV) MATERIALS

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NOTICE: This Document was reapproved with minor editorial changes.

1 Purpose

1.1 Many surfaces used in the photovoltaic industry are textured in order to optimize light absorption and maximize cell efficiency. The required texture usually is not well defined by a single roughness, gloss, or haze specification because the relative amounts of low and high frequency roughness on the surface can both be important.

1.2 Light scatter measured over a range of collection angles (or several individual angles) provides a fast, economical means to monitor, but not to quantify, texture over a range of roughness frequencies. Such measurements allow several degrees of freedom, such as incidence angle, scatter angle, light wavelength, aperture, spot size, etc., which need to be agreed upon between involved parties in order to be able to obtain comparable measurement results. Therefore means are required to uniquely define the measurement parameters, and to allow them to be easily exchanged.

1.3 This Guide covers the language necessary to define scatter measurement conditions to enable measurements that describe changes in the scatter pattern that are present with differences in surface texture. It is not intended to distinguish good from bad or desirable from undesirable, to set scatter levels, or to determine the measurements to be taken.

2 Scope

2.1 This Guide covers angle resolved light scatter (ARLS) measurements performed on monocrystalline (also known as single crystal) and multicrystalline (also known in some regions as polycrystalline) semiconductor wafer surfaces, transparent substrate surfaces, and coated transparent surfaces that may have been purposely modified (textured) to achieve desired reflective and/or transmissive properties.

2.1.1 Measurement of scatter from both reflective and transparent surfaces is well developed. The basic concepts for angle resolved light scatter (ARLS) measurements are published^{1,2} and the use of bidirectional scatter distribution function (BSDF) units to quantify scattered light has been standardized in SEMI ME1392 and ASTM E2837. Making use of these standard units allows scatter specifications to be written and consistent replication of monitoring systems between different locations. If the scattered light is reflected from the illuminated surface, the term is taken as the bidirectional reflective distribution function (BRDF) and if the scattered light is transmitted through the specimen, the term is taken as bidirectional transmittance distribution function (BTDF).

2.1.2 Many surfaces, textured to increase absorption for use in the photovoltaic industry, are in a roughness range that is too rough to give a strong specular reflection, but too smooth to completely diffuse the reflected light. ARLS measurements take advantage of the fact that the scatter from surfaces of this type depends strongly on texture characteristics. If the texture is changed, the scatter pattern changes.

2.2 This Guide provides a framework for defining the conditions of light scatter measurement conditions, under a variety of measurement geometries, as a means to monitor roughness (or texture) on a variety of surfaces manufactured in the photovoltaic industry so that the surface texture can be kept within independently determined acceptable bounds.

2.3 Using scatter measurements to monitor texture does not depend upon knowledge of the detailed surface profile or roughness statistics.

¹ Stover, J. C. "Optical Scattering: Measurement and Analysis." SPIE Press, 1995.

² Stover, J. C., and Hegstrom, E. L. "Scatter metrology of photovoltaic textured surfaces." SPIE Proceedings, August 2010.

2.4 Angle resolved scatter measurements are known to be more sensitive to texture changes than single value measurements such as haze, RMS roughness, and gloss, which tend to be dominated by low spatial frequency roughness.

NOTE 1: Haze is defined in SEMI M59 descriptively and without numeric values. This term is now also used in another context (for example, solar glass properties) and ‘Haze Instrumentation’ is now sold. Fortunately, the numerical value for ‘Haze’ in this new context is equal to the measured total integrated scatter (TIS), which is the subject of SEMI MF1048. Numerically, the measured reflective TIS (or ‘Reflective Haze’) is:

$$\text{Reflective TIS} = \frac{\text{Scattered Power Integrated over a Specified Portion of the Sample Reflective Hemisphere}}{\text{Total Reflected Power}} \quad (1)$$

A similar definition is used for the measured transmissive TIS (or ‘Transmissive Haze’):

$$\text{Transmissive TIS} = \frac{\text{Scattered Power Integrated over a Specified Portion of the Sample Transmissive Hemisphere}}{\text{Total Transmitted Power}} \quad (2)$$

Measured Haze (or TIS) values change with measurement parameters such as the source wavelength, incident angle, polarization, and scatter collection regions. As a result comparing Haze values found for samples where these parameters were different is meaningless. Thus, source wavelength, polarization, incident angle and the scatter collection regions need to be reported directly, or implied by identifying the measurement system used for the tests.

2.5 The specifications for surfaces regarding roughness or texture are expressed as the BSDF obtained with a defined parameter setting, and its specific subsets BRDF and BTDF for measurements performed in reflective and transmissive configurations, respectively.

2.6 If acceptable and unacceptable surface textures can be determined (e.g., by cell performance or some other parameter), then the related scatter patterns can be measured and scatter specifications can be written in BSDF units by identifying sections of the BSDF that have changed significantly.

2.7 Specific values for BRDF or BTDF as well as the measurement conditions are to be agreed upon between the parties to the test. The resulting specifications are flexible enough to accommodate variations in measurement related to different laboratory and production line geometries and situations.

2.8 Profilometer measurements of the surface texture/roughness are not covered in this Guide.

2.9 This Guide is an extension of SEMI ME1392. Understanding and using this Guide requires the use of SEMI ME1392 or a similar document, such as ASTM E2387.

2.10 This Guide does not address or limit how measurements are obtained.

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 The amount and nature of required texture/roughness differs widely for surfaces of materials and objects used in PV manufacturing. In general these surfaces are not optically smooth—that is, they are not mirrors. Although the measured BSDF can be used to detect changes in surface texture under these conditions, it cannot be used to accurately calculate surface statistics such as rms microroughness (R_q), arithmetic average microroughness (R_a), and peak-to-valley ratio (R_t).

3.2 ARLS measurements may be made over all or a portion of the surface area. Under the latter condition, care has to be taken to select measurement points that are representative of the entire surface. Note that surface nonuniformities affect the results.

3.3 The BSDF of a lambertian surface is independent of scatter direction. If a surface scatters nonuniformly from one position to another then a series of measurements over the sample surface must be averaged to obtain suitable statistical uncertainty. Nonuniformity may be caused by irregularity of the surface microroughness or film, optical property inhomogeneity, or subsurface defects. Thus, the orientation of rough surfaces may result in different results being obtained for different angles. This is particularly true in the case of wafer surfaces that have a pattern of saw marks. Although most PV wafers do not have a fiducial, the 15-point measurement plan for square and pseudo-square silicon wafers in EN 50513 (and also cited in this Guide) is aligned with the wire saw direction.

4 Referenced Standards and Documents

4.1 SEMI Standards and Safety Guidelines

SEMI M59 — Terminology for Silicon Technology

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

SEMI MF1048 — Test Method for Measuring Reflective Total Integrated Scatter

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

4.2 ASTM Standard³

ASTM E2387 — Standard Practice for Goniometric Optical Scatter Measurements

4.3 DIN Standard⁴

DIN EN 50513 — Solar Wafers – Data Sheet and Product Information for Crystalline Wafers for Solar Cell Manufacturing

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

5 Terminology

5.1 Acronyms, terms, and symbols related to silicon technology, including many of those in this Guide, are listed and defined in SEMI M59.

5.2 Additional terminology related to surface finish parameters is discussed in SEMI MF1811.

5.3 Other Acronyms Used in this Guide

NOTE 2: Of these, *BRDF* is included in SEMI M59.

5.3.1 *ARLS* — angular resolved light scatter

5.3.2 *BRDF* — bidirectional reflectance distribution function

5.3.3 *BSDF* — bidirectional scatter distribution function

5.3.4 *BTDF* — bidirectional transmittance distribution function

5.3.5 *CCBRDF* — cosine corrected bidirectional reflectance distribution function

5.3.6 *CCBTDF* — cosine corrected bidirectional transmittance distribution function

5.3.7 *PLIN* — plane of incidence

5.3.8 *PV* — photovoltaic

5.3.9 *RMS* — root mean square

5.3.10 *TIS* — total integrated scatter

5.4 Other Terminology Used in this Guide

NOTE 3: Many of these terms used to specify BSDF are taken or adapted from SEMI ME1392. Figures 1 and 2 adapted from SEMI ME1392 are useful for understanding these terms. BRDF and BTDF are the reflective and transmissive subsets of the more general BSDF. Other than the difference as to which side of the sample the scatter is measured, the definitions are identical. For convenience in these figures, the source direction is inverted when going from BRDF to BSDF.

5.4.1 *angle of incidence, θ_i* — polar angle between the central ray of the incident flux and the Z_B axis, normal to the sample surface.

³ ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA; Telephone: 610.832.9585, Fax: 610.832.9555, <http://www.astm.org>

⁴ Deutsches Institut für Normung e. V., Burggrafenstrasse 6, D-10787 Berlin, Germany. Telephone: 49.30.2601.0; Fax: 49.30.2601.1231; <http://www.din.de>

5.4.2 *beam coordinate system, $X_B Y_B Z_B$* — a Cartesian coordinate system with the origin on the central ray of the incident flux at the sample surface, the X_B axis in the plane of incidence (PLIN) and the Z_B axis normal to the surface. The angle of incidence, scatter angle, and incident and scatter azimuth angles are defined with respect to the beam coordinate system.

5.4.3 *bidirectional scatter distribution function (BSDF)* — a description of the distribution of light scattered by a surface, it is the scattered power per unit projected solid angle divided by the incident power:

$$\text{BSDF} = \frac{P_s}{P_i \Omega \cos \theta_s} [\text{sr}^{-1}] \quad (3)$$

5.4.4 *cosine-corrected BSDF* — the scattered power per unit solid angle divided by the incident power:

$$\text{cosine corrected BSDF} = \frac{P_s / \Omega}{P_i} [\text{sr}^{-1}] \quad (4)$$

5.4.5 *incident azimuth angle, ϕ_i* — the angle from the X_B axis to the projection of the incident direction onto the X_B – Y_B plane. It is convenient to use the beam coordinate system shown in Figure 1, in which $\phi_i = 180^\circ$, since this makes ϕ_s the correct angle to use directly in the familiar form of the grating equation. Conversion to a sample coordinate system is straight forward, provided the sample location and rotation are known.

5.4.6 *incident direction* — the central ray of the incident flux specified by θ_i and ϕ_i in the beam coordinate system.

5.4.7 *incident power, P_i* — the radiant flux incident on the sample under test.

5.4.8 *plane of incidence, PLIN* — the plane containing the sample normal (Z-axis) and the central ray of the incident flux.

5.4.9 *receiver* — a system that generally contains apertures, filters, and focusing optics to gather the scatter signal over a known solid angle and transmit it to the scatter detector.

5.4.10 *receiver solid angle, Ω* — the solid angle subtended by the receiver aperture stop from the sample origin.

5.4.11 *sample coordinate system* — a coordinate system fixed to the sample and used to indicate the position on the sample surface for the measurement which is application and sample specific. The Cartesian coordinate system ($X Y Z$) shown in Figure 2 is recommended for flat samples. The origin is at the geometric center of the sample surface with the Z axis normal to the sample.

5.4.12 *scatter* — the radiant flux that has been redirected over a range of angles by interaction with the sample.

5.4.13 *scatter azimuth angle, ϕ_s* — angle from the X_B axis to the projection of the scatter direction onto the X_B – Y_B plane.