Background Statement for SEMI Draft Document 6769B

NEW STANDARD: TEST METHOD FOR RESIDUAL STRESS OF SILICON CARBIDE WAFERS BY PHOTOELASTIC EFFECT

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Background Statement:

Residual stresses are generated in the silicon carbide substrate during the manufacturing process. Larger residual stress will not only cause wafer warpage or even cracking, but also cause piezoresistive effects and affect electrical performance. Substrate suppliers and customers also need a standard method to check substrate quality.
The ballot results will be reviewed and adjudicated at the meetings indicated in the table below. Check www.semi.org/standards under Calendar of Events for the latest update.

TF/ TC Chapter Meeting Information

	TF Review of responses to the letter Ballot	Letter Ballot Review (including Adjudication) by the TC Chapter
Group:	Silicon Carbide Substrate Task Force	Compound Semiconductor Materials China TC Chapter
Date:	TBD	Apr 27th, 2023
Time &Time zone:	TBD	13:00—17:30
Location:	TBD	TBD, Dongguan
City, State/Country:	China	Dongguan, China
Leader(s):	Min Lu (Perfect Crystal) Hongjun Zheng (Perfect Crystal) Fangliang Yan (Mige Lab.)	Jiangbo Wang (HC-SemiTek) Guoyou Liu (CRRC TIMES)
Standards Staff:	Cassie Li (SEMI China) cassieli@semi.org	Cassie Li (SEMI China) cassieli@semi.org

TF meeting's details are subject to change, and additional review sessions may be scheduled if necessary. Contact the task force leaders or Standards staff for confirmation.

Telephone and web information will be distributed to interested parties as the meeting date approaches. If you will not be able to attend these meetings in person but would like to participate by telephone/web, please contact Standards staff.

If you have any questions, please contact to Silicon Carbide Substrate Task Force
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SEMI Draft Document 6769B
NEW STANDARD: TEST METHOD FOR RESIDUAL STRESS OF SILICON CARBIDE WAFERS BY PHOTOELASTIC EFFECT

1 Purpose

1.1 The purpose of this Standard is to standardize a test method for residual stress of silicon carbide wafers by photoelastic effect.

1.2 Residual stress will affect the wafers shape, and even affect the epitaxy and device manufacturing. The standardization will provide the basis for residual stress detection for silicon carbide substrate and epitaxial wafer manufacturers, and help them understand the distribution of residual stress within the product, so as to reduce the residual stress and improve the product quality by adjusting the production process., limiting this effect will improve the qualities of silicon carbide wafers from polishing substrates to epitaxial wafers, and provide solutions for improving silicon carbide products.

2 Scope

2.1 This Standard specifies the test method for measuring residual stress of in 4H/6H Silicon Carbide wafers on the (0001) plane by the photoelastic effect.

2.2 This Standard is applicable to both on-axis and off-axis polished silicon carbide polished substrates, and as well as off-axis silicon carbide epitaxial wafers.

2.3 This Standard is applicable to N-type and semi-insulating silicon carbide wafers.

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3 Referenced Standards and Documents

3.1 *SEMI Standards and Safety Guidelines*

SEMI M59 — Terminology for Silicon Technology

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

4 Limitation

4.1 Because only [0001] crystal direction of 4H/6H silicon carbide shows exhibits optical isotropy, that is, there is no birefringence effect without residual stress. in the absence of residual stress there is no birefringence effect, sSo this method can only measure the residual stress in 4H/6H silicon carbide (0001) plane. Residual stress in other crystal planes can not be measured by using this method.

4.2 Since the stress is calculated by detecting the light intensity of CCD, it is necessary to adjust the exposure time and gain to make the CCD image unsaturated. the exposure time and gain must be adjusted to make the CCD image unsaturated, that is, t The accuracy of the measurement results can be guaranteed within the linear range of CCD.

4.3 The following requirements for the test sample should be met.

4.3.1 The test wafer thickness normally should be less than 1 mm. If the thickness of the N-type silicon carbide sample is too thick, the transmittance of the test light may be too low, and the CCD response is not accurate. The test wafer uneven thickness (Total thickness variation divided by average thickness) should be less than 1%. Uneven thickness of 1% magnitude will lead to 1% residual stress calculation error.

4.3.2 The silicon and carbon surface roughness *Ra* (arithmetic mean roughness) of the test wafer should be less than 1 nm. On the one hand, the high surface roughness *R*a will affect the transmittance, and at the same time. On the other hand, the scattering enhancement due to high *Ra* will affect the polarization degree of the test light.

4.3.3 The bow should be less than 80 µm for 6-inch test wafers and 100 µm for 8-inch test wafer. If the wafer bow is too large, the test light will not follow the direction [0001] in some areas of the sample, and the measured data will be

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biased due to the intrinsic birefringence. For off-axis test wafers, the difference between the practical and labeled off-axis angle of the test wafer should be less than 0.25 deg, which can limit the measurement error of residual stress within 0.5MPa. (See Appendix 1)

5 Terminology

5.1 Terms, acronyms, and symbols relating to Silicon Carbide are defined in SEMI M59.

5.2 *Abbreviations and Acronyms*

~~5.2.1~~ *CCD* — Charge Coupled Device

5.3 *Definitions*

~~5.3.1~~ *residual stress* — the self-balanced internal stress that remains in the wafer after eliminating the effect of external force or uneven temperature field. For wafers in the plane stress state, the residual stress is the difference of the maximum and minimum stress components of each position point in the wafer plane.

~~5.3.2~~ *polarizer and analyzer* — ~~in this Standard,~~ both are linear polarizers in this Standard. A linear polarizer ~~(polarizer)~~ refers to an optical element that can ~~make~~ change natural light (composite light ~~in which~~ with polarized light ~~exists~~ in all directions) into linearly polarized light (light with specific polarization direction ~~in a specific direction of polarization~~), which shields and transmits incident light. The linear polarizer near the light source is called as the polarizer, and the linear polarizer placed last along the optical path is called the analyzer.

~~5.3.3~~ *plane stress state* — it refers to the stress state in which the stress component along the normal direction of the plane of the specimen is zero at each point inside the specimen, that is, the residual stress in the specimen is only distributed in the wafer plane of the specimen.

~~5.3.4 *principal stress* — the maximum and minimum stress components of each position point in the wafer plane.~~

5.3.4 *phase difference* — a beam of polarized light enters the specimen with stress birefringence and is divided into two beams of linearly polarized light with different propagation speeds. After passing through the specimen with a certain thickness, the electric field vector vibrations of the two beams ~~are~~ is no longer synchronized~~, showing~~ and presents the phase difference.

5.3.5 *stress birefringence* — also known as the photoelastic effect. ~~Under the action of stress, the refraction characteristics of some mediums to light will change, and there will be another refractive index besides the intrinsic refractive index.~~ Under the action of stress, the refractive index of the originally isotropic transparent media will display optical anisotropy. At this time, if one beam of light is incident along the optical axis of the medium, there will be two refracted beams propagating in the medium at different speeds. This kind of birefringence caused by stress is called stress birefringence.~~It transmits light to show optical anisotropy.~~

6 Summary of Test Method

6.1 This Standard uses the principle of photoelasticity to test the residual stress inside the silicon carbide wafers. The optical path is shown in Figure 1.

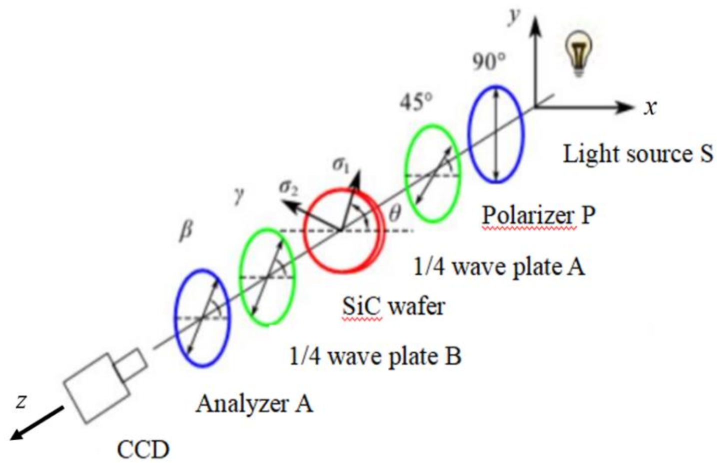

Figure 1

Schematic Diagram of Optical Path Diagram of Photoelastic Method for Measuring Residual Stress of Silicon Carbide Wafers

6.2 The optical setup comprises ~~path includes~~ a light source, a polarizer labeled P and an analyzer labeled A, ~~two~~ a pair of quarter-wave plates, the Silicon Carbide wafer under test ~~to be tested~~, and a CCD camera equipped with an imaging lens for capturing ~~that records~~ images. The imaging lens needs to ensure that the imaging beam is parallel to the optical axis of the optical system.

6.3 It is generally considered that the specimen is in a state of plane stress. In this case, any point (x, y) on the plane has two principal stress components. The first principal stress at any point (x, y) is ~~recorded~~ represented as σ_1, the second principal stress is ~~recorded~~ represented as σ_2, and the direction of the first principal stress is ~~recorded~~ represented as θ. The angles of all optical elements in the above optical path diagram are based on the horizontal direction (x axis), except that the angle of the polarizer P is 90° and the angle of the quarter-wave plate A is 45°, the quarter-wave plate B and the analyzer the angle of A (γ, β) that is variable.

6.4 In the above optical path, the zero off-axis wafer specimen should be parallel to the polarizer to ensure that the light enters the specimen perpendicularly, and the specimen with an off-axis angle should be mechanically rotated to ensure the transmitted optical beam to be parallel to the wafer c axis. Due to the stress birefringence effect, there are two beams of perpendicularly transmitted light with a phase difference (recorded as δ, unit: radians). ~~a~~After passing through the analyzer, the polarization directions of the two beams are the same, ~~and they have~~ which has the conditions ~~to form~~ for forming stable optical interference.

6.5 ~~The fringe field formed by the interference can be denoted as *I*.~~ The interference pattern, denoted as I, is formed by the fringe field. ~~Set~~ By setting the angles (β) of the analyzer and ~~the angle~~ (γ) of the quarter wave plate B to ~~a number of~~ specific values as listed in Table 1 ~~(see Table 1)~~, ~~and~~ the CCD will capture ~~collect~~ six different fringe field images, labeled as I_1, I_2, I_3, I_4, I_5, and I_6.

Table 1 The Specific Angle and Corresponding Light Intensity Expression of Analyzer and Quarter-Wave Plate B

No.	γ	β	*Light intensity equation I*
1	0	π/4	$I_1 = I_b + \frac{I_a}{2}(1 - \cos\delta)$

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2	0	3π/4	$I_2 = I_b + \frac{I_a}{2}(1+\cos\delta)$
3	0	0	$I_3 = I_b + \frac{I_a}{2}(1+\sin\delta\sin 2\theta)$
4	π/4	π/4	$I_4 = I_b + \frac{I_a}{2}(1-\sin\delta\cos 2\theta)$
5	π/2	π/2	$I_5 = I_b + \frac{I_a}{2}(1-\sin\delta\sin 2\theta)$
6	3π/4	3π/4	$I_6 = I_b + \frac{I_a}{2}(1+\sin\delta\cos 2\theta)$

NOTICE: I_a and I_b refer to the light intensity of modulating component, bias component respectively.

7 Apparatus

7.1 Test instrument for mapping ~~detecting~~ the residual stress in ~~mapping of~~ Silicon Carbide wafers:

~~7.1.1~~ The ~~type of testing~~ testing instrument utilized is a collimated polarized light system equipped with a digital image acquisition function;

~~7.1.2~~ The light field must ~~should~~ be uniform with stable intensity ~~and the intensity should be stable~~, devoid of any visible flicker ~~and there should be no visible flicker phenomenon,~~ and the light intensity stability should exceed ~~be better than~~ 1% (calculated as the ~~D~~difference in light intensity divided by the average light intensity) during the test time;

~~7.1.3~~ The light source should be in the visible or near-infrared spectrum ~~is visible or near infrared~~. The half-wave bandwidth of the light source does not exceed ~~greater than~~ 10 nm;

~~7.1.4 Quality requirements for optical components: The center wavelength of the light source must be within the working range of the quarter-wave plate, and the extinction ratio of polarizer P and analyzer A is not less than 100:1 "~~Optical component quality specifications: The central wavelength emitted by the light source must fall within the operational spectrum of the quarter-wave plate. Additionally, the extinction ratio for both the polarizer P and the analyzer A must be at least 100:1;

~~7.1.5 Optomechanical requirements with rotating mechanism: No swing occurs during rotation and the image will not be shifted by a single pixel, the angle error between the orientation of the optical spindle (referring to the polarization axis or the fast axis) and the marking line and the marking error of the rotation angle scale line are less than 1 degree. The optical components are installed on the same flat bottom plate, which is placed vertically in the measurement system to ensure that the entire beam path is vertical~~ Optomechanical specifications for rotating mechanism: The rotation must be smooth without any swing, ensuring that the image remains stable without shifting by even a single pixel. The angular deviation between the optical spindle's orientation (pertaining to the polarization axis or the fast axis) and the marking line, as well as the marking error of the rotation angle scale line, should not exceed 1 degree. All optical components are mounted on a single flat base plate, which is positioned vertically within the measurement system to guarantee that the entire beam path remains perpendicular;

~~7.1.6~~ A digital grayscale camera is utilized ~~used~~, ~~the total number of pixels is not less~~ with a total pixel count of no fewer than 1 million (providing a 150 μm resolution for a 6-inch field of view) , ~~the~~ a pixel depth ~~is~~ of 8 bits, and adjustable ~~the~~ exposure time and gain settings ~~are adjustable~~.

8 Sampling

8.1 This test method is nondestructive and can be applied to either the entire batch of wafers for 100% inspection ~~may be used on either 100% of the wafers in a lot~~ or on a sampling basis.

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8.2 ~~If samples are to be taken, procedures for selecting the sample from each lot of wafers to be tested shall be agreed upon between the parties to the test, as shall the definition of what constitutes a lot.~~ If sampling is required, the procedures for selecting samples from each lot of wafers to be tested must be mutually agreed upon by the parties involved in the testing. Additionally, the definition of what qualifies as a lot should also be established by common consent.

9 Calibration and Standardization

9.1 ~~Calibrate the measuring equipment in accordance with the manufacturer's instructions.~~ Each measuring equipment shall measure a series of ~~wave plates with phase delay values~~ phase retardation standard samples that certified by a third party before use~~. In order~~ to calibrate ~~the accuracy of~~ the measurement system. The phase retardation standard samples also known as wave plates, are usually made of a birefringent wafer of precise thickness, such as quartz, calcite, or mica, with its optical fast axis parallel to the surface of the wafer. They are easily available in the market.

10 Procedure

10.1 Check the test system to ensure that each optical component is placed on the same axis , and confirm that the polarizer P and quarter-wave plate A are correctly oriented ~~in the correct orientation~~ (as referenced in ~~Refer to~~ Figure 1).

10.2 ~~Place~~ Position the specimen on a horizontally mounted adjustable incline hollow ring support stage ~~with adjustable inclination angle~~, ~~and there is~~ ensuring that no additional load is applied to ~~on~~ the specimen (generally, ~~laid~~ it should be placed freely and horizontally on the stage).

10.3 For SiC wafers without off-axis cut, the stress measurement system need to ensure the measurement light beam to be perpendicular to the wafer surface. For off-axis SiC wafers, the stress measurement system need~~s~~ to rotate the wafer to ~~make sure~~ ensure that the measurement light beam passes through the wafer along ~~the~~ its C axis ~~of the wafer~~. ~~The operation can be automatically done by the measurement machine based on the off-axis angle value~~ This rotation can be performed automatically by the measurement apparatus based on the input off-axis angle value provided by the specimen manufacturer.

~~10.3.1 Turn on the light source so that the CCD camera captures a precise image of accurately images the specimen. Adjust the orientation of the analyzer to the vertical position (aligning it with the polarizer that is, the same orientation as the polarizer), continuously and then gradually rotate the quarter-wave plate B. While doing so, observe the image collected by the CCD and make adjustments to adjust the light source as needed during the period. The intensity or the exposure time and gain of the CCD camera ensure that the grayscale value is not saturated when the image is brightest Ensure that the grayscale value does not reach saturation when the image is at its brightest by adjusting the light intensity or by modifying the exposure time and gain settings of the CCD camera.~~

~~10.3.2 According to the order in Table 1, place position the analyzer and the 1/4 wave plate B at a their respective specific angles. take pictures with a CCD camera and store them in sequence, and obtain Utilize the CCD camera to capture and sequentially store images, thereby acquiring six photoelastic fringe field images labeled as~~ I_1, I_2, I_3, I_4, I_5 ~~and~~ I_6~~. Calculate the stress diagram according to Subsequently, calculate the stress diagram in accordance with the procedures detailed in § 11.~~

~~10.3.3 Repeat ¶¶ 10.3.1-10.3.3, until find the inclination angle that corresponds to the minimal residual stress is identified with the least residual stress.~~

~~10.3.4 Moving the wafer along the preset raster path between the light source and the imaging measurement module, and to obtain the residual stress values at of different positions.~~

10.4 ~~Compare the size of the field of view to the size of the specimen to determine if~~ Assess the field of view dimensions relative to the specimen size to ascertain whether a stitched stress map is necessary ~~required~~. ~~If splicing is required, set the splicing grid~~ If stitching is necessary, adjust the stitching grid settings to fit the requirements.

10.5 If stitching is necessary, ~~splicing is required, splice~~ combine multiple stress maps to obtain a comprehensive ~~the~~ stress map of the entire specimen.

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11 Calculations

11.1 For the six digital images obtained in ¶¶ 6.5, the principal stress direction ~~of~~ at each point on the specimen is obtained according to formula (1), ~~and~~ while the phase difference ~~of~~ at each point is obtained according to formula (2):

$$\boldsymbol{\theta = 0.5\, arctan \frac{I_5 - I_3}{I_4 - I_6}, and\, sin\, \delta \neq 0} \tag{1}$$

$$\boldsymbol{\delta = arctan \frac{(I_5 - I_3)\, sin\, 2\theta + (I_4 - I_6)\, cos\, 2\theta}{I_1 - I_2}} \tag{2}$$

11.2 The phase difference δ at the point (x, y) ~~has the following relationship~~ correlates with the difference between the two principal stresses (σ_1-σ_2), i.e., the residual stress, at this point as follows:

$$\boldsymbol{\sigma_1 - \sigma_2 = C\delta\lambda/d} \tag{3}$$

Where:

d — The thickness of the specimen, in millimeters (mm).

λ — The central wavelength of the light source, in millimeters (mm).

C — material constant, the unit is usually N/mm^2, namely MPa.

11.3 In engineering practices, the phase difference δ or the optical path difference (α) of the unit thickness of the specimen is often used to simply represent ~~characterize~~ the value of the residual stress, ~~to avoid~~ thereby avoiding complicated full-field stress calculations. The conversion relationship between phase difference δ and α as follows ~~is~~:

$$\boldsymbol{\alpha = 10^6 \times \delta\, \lambda/(2\pi d)} \tag{4}$$

Where:

α — The optical path difference per unit thickness, in nanometers/millimeter (nm/mm).

δ — Phase difference in radians (rad).

11.4 According to the positive or negative of the numerator and denominator in formula (1), ~~its~~ the range of θ can be broadened to (-π, π) according to formula (5). Even so, the full-field phase difference distribution of the specimen is still limited to 2π.

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$$\theta = \begin{cases} \frac{n}{m} & m > 0, n \geq 0 \\ \frac{n}{m} + \frac{\pi}{2} & m > 0, n \leq 0 \\ \frac{n}{m} + \pi & m < 0, n \leq 0 \\ \frac{n}{m} + \frac{3\pi}{2} & m < 0, n \geq 0 \\ \frac{\pi}{2} & m = 0, n \geq 0 \\ -\frac{\pi}{2} & m = 0, n \leq 0 \end{cases} \quad (5)$$

Where:
$m = I_5 - I_3$.
$n = I_4 - I_6$.

NOTICE: The *m* and *n* have no special significance and only represent the calculation results of numerator and denominator in formula (1), respectively.

11.5 After obtaining the phase difference of the whole field, formula (4) can be used to obtain the stress information expressed by the optical path difference per unit thickness.

11.6 An example of the residual stress mapping of 6-inch silicon carbide substrate is shown in Figure 2.

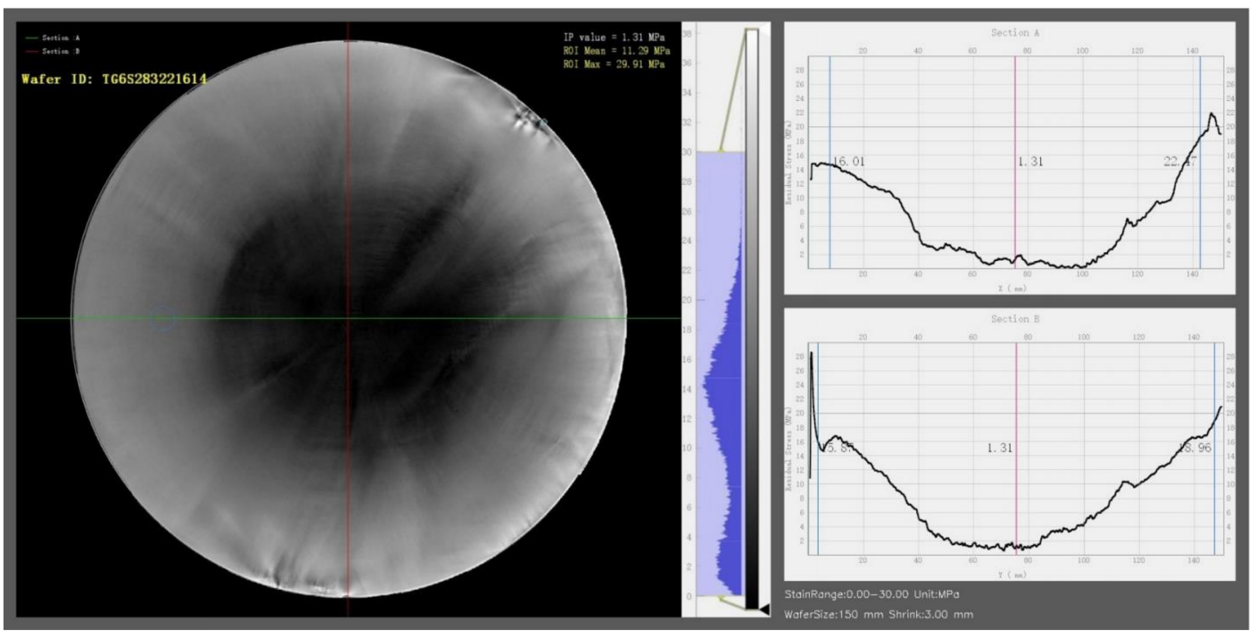


Figure 2

Residual Stress Mapping of 6-Inch Silicon Carbide Substrate

11.7 The shades of color, or the gray scales, indicate the magnitude of the residual stress at different positions. Dark colors indicate smaller stress, and brighter colors indicate larger stress.

12 Report

12.1 The test report should include but not limited to the following:

~~12.1.1~~ The specification and type of the sample;

~~12.1.2~~ The model and test conditions of the instrument used;

~~12.1.3~~ The residual stress distribution map;

~~12.1.4~~ Test date;

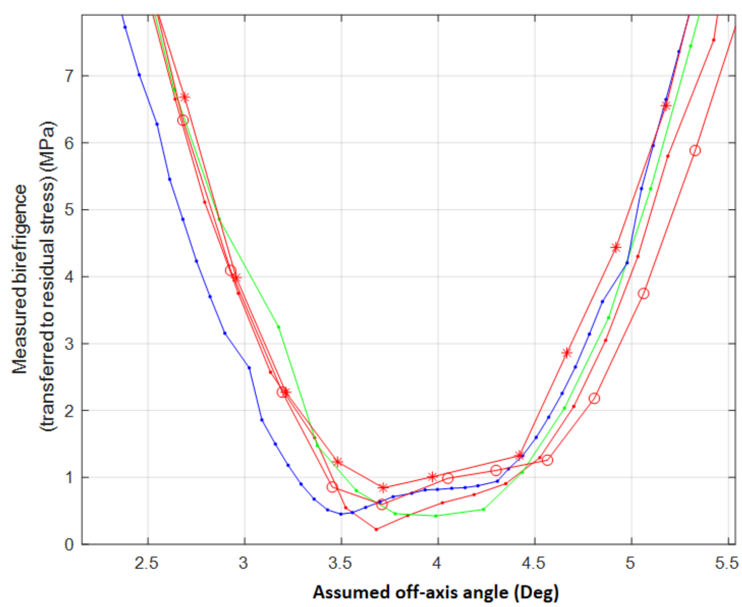
~~12.1.5~~ Number of the standard;

~~12.1.6~~ Tester's signature.

<ins>Appendix 1:</ins>

<ins>THE ANALYSIS OF THE INFLUENCE OF THE SIC WAFER OFF-AXIS AND BOW ON THE RESIDUAL STRESS MEASUREMENT</ins>

<ins>A1-1 In the standard, the off-axis SiC wafers are rotated to align the c axis along the collimated measurement light beam. If the off-axis angle adjustment is not correct, the measured stress will be influenced by the intrinsic birefrigence. The following figure (Figure A1-1) shows the result of residual stress measurement of five 4-degree off-axis SiC wafers measured at different adjustment angle settings, indicating that the incorrect off-axis angle adjustment can induce great intrinsic birefrigence. The results show that +/-0.25degree off-axis error may result in a mean residual stress value variation of less than 0.5MPa, as listed in the Limitation 4.3.</ins>



<ins>Figure A1-1 The mean residual stress measurement results of five SiC wafers (the real off-axis angle: 4 degree) at different wafer rotation angle settings</ins>

A1-2 Wafer bow will cause the wafer crystal plane to bend, and the measurement light beam is thus not parallel to the C axis of the SiC wafer at some locations, causing off-axis angle error similar to A1-1.

Based on the A1-1 tests, the crystal plane bending of +/-0.25 degree is acceptable. Figure A1-2 shows the bow values for 6-inch and 8-inch wafer with 0.25 degree bending angle, respectively. For 6 inch wafer, the bow value of 0.323mm may induce 0.25 deg crystal plane bending. For 8 inch wafer, the bow value of 0.44mm may induce 0.25 deg crystal plane bending. Considering the general manufacturing capability, the standard specifies that the bow should be less than 80 μm for 6-inch test wafers and 100 μm for 8-inch test wafer.

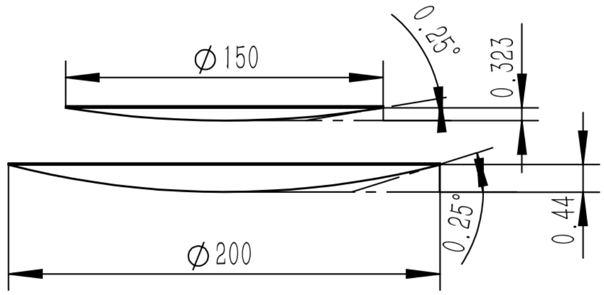


Figure A1-2 The bow values of a 6-inch and 8-inch wafer with 0.25 degree bending angle (Length unit: mm)

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