

SEMI 3D4-0915 (Reapproved 0222) GUIDE FOR METROLOGY FOR MEASURING THICKNESS, TOTAL THICKNESS VARIATION, BOW, WARP/SORI, AND FLATNESS OF BONDED WAFER STACKS

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1 Purpose

1.1 Control of parameters such as bonded wafer stack (BWS) thickness, total thickness variation (TTV), bow, warp/sori, and flatness, is essential to successful implementation of a wafer bonding process. These parameters provide meaningful information about the quality of the wafer thinning process (if used), the uniformity of the bonding process, and the amount of deformation induced to the wafer stack by the bonding process. TTV is also critical in certain bonded wafer manufacturing process steps, since non-planarity can lead to problems in subsequent processing steps, including lithographic overlay and intermittent electrical contact between metal layers in the bonded wafers. This Guide provides a description of tools that can be used to determine these key parameters before, during, and after the process steps involved in wafer bonding.

2 Scope

2.1 This Guide provides examples of the capabilities and limitations of various measurement technologies applicable to BWS as well as their suitability for different applications.

2.2 The Guide describes metrology techniques that are applicable to both temporary and permanently BWSs.

2.3 This Guide is complementary to existing SEMI Test Methods for measuring these parameters on single wafers, in some cases extending existing metrology techniques to a BWS and in other cases describing metrology techniques specific to a BWS.

2.4 The Guide focuses on general measurement techniques including infrared (IR) laser profiling, white light confocal microscopy, visible and IR interferometry, capacitance, back-pressure, and acoustic metrology. Each technology has unique strengths and weaknesses—some rely on front-surface illumination, others on back-surface illumination. Some techniques can measure the thicknesses of individual layers in the BWS, and some are additionally capable of measuring surface nanotopography.

2.5 The metrology examples provided in this Guide originated from industry experts and are believed to be representative of tool performance as of the year 2012. However, as tool and measurement techniques continue to evolve and improve, BWS measurement performance may surpass what is contained in this Guide. The user should investigate metrology suppliers’ current capabilities.

2.6 The measurements described in this Guide are known to be applicable to BWSs with thickness in the range of 750 μm to 1550 μm .

2.7 A wafer stack, as considered in this Guide may include two wafers, where one is a device wafer, and one wafer is a carrier wafer. The wafer stack may include one bonding layer. Bonded wafers may be classified as either temporarily bonded (i.e., a device to a carrier wafer) or permanently bonded. Temporary bonding uses a temporary adhesive that can be reversed using a chemical, optical, and/or mechanical process; permanent bonding could be adhesive, oxide, or metal-metal (e.g., Cu-Cu). Two representative two-wafer stacks are depicted in Figures 1 and 2. The first stack (refer to Figure 1) is a bonded pair of 775 μm thick wafers following TSV formation and the bonding operation. The second stack (refer to Figure 2) is a BWS with a top wafer thinned to ~ 50 μm , and bonded on top of a 775 μm wafer using a temporary adhesive.

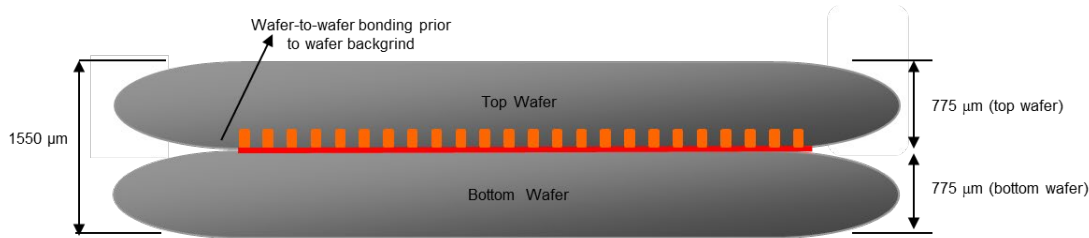


Figure 1
Bonded Wafer Pair Following TSV Formation and Wafer Bonding Operation

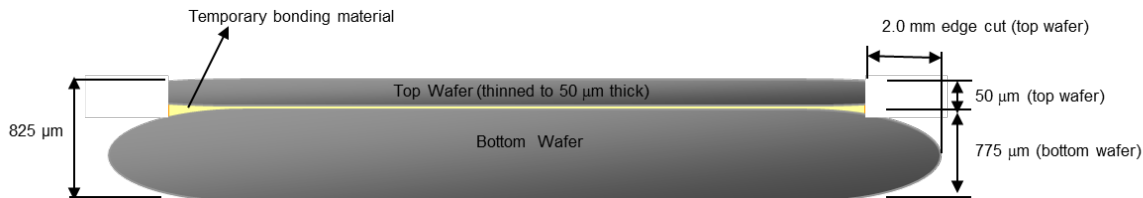


Figure 2
Temporarily Bonded Wafer Pair – Device Wafer is Edge-Trimmed and Thinned

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 While this Guide provides an overview on the use of several available techniques, it does not provide the level of detail typically available in test methods. In addition, all suppliers may not follow SEMI standard measurement methods in their metrology procedures.

3.2 The information in this Guide does not encompass the establishment of specific a methodology for such measurements but is only a guide to the user describing the various types of metrology including their capabilities and limitations.

3.3 This Guide describes metrologies that have been applied to a wafer stack composed of, at most, two wafers. Thus, the user is cautioned that the methods described may be limited when applied to wafer stacks consisting of more than two wafers. In addition, the presence of patterned features such as bumps, TSVs, or pads may adversely affect measurement accuracy and precision, especially of optical techniques.

4 Referenced Standards and Documents

4.1 SEMI Standards and Safety Guidelines

NOTE 1: The SEMI 3DS-IC Global Technical Committee is developing a Guide for Describing Material Properties for a 300 mm 3DS-IC Wafer Stack intended to be used in conjunction with this Standard.

SEMI HB1 — Specification for Sapphire Wafers Intended for Use for Manufacturing High Brightness-Light Emitting Diode Devices

SEMI MF533 — Test Method for Thickness and Thickness Variation of Silicon Wafers

SEMI MF1390 — Test Method for Measuring Bow and Warp on Silicon Wafers by Automated Noncontact Scanning

SEMI MF1451 — Test Method for Measuring Sori on Silicon Wafers by Automated Noncontact Scanning

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

5 Terminology

5.1 Terms and acronyms associated with silicon wafers and silicon technology are listed and defined in SEMI M59. Many of these terms and acronyms can be applied to sapphire and glass wafers and their associated technology. Alternately, the SEMI International Standards: Compilation of Terms (COTs) can be used for a list of the current Abbreviations, Acronyms, Definitions, and Symbols.

5.2 Other Abbreviations and Acronyms

5.2.1 *AM* — acoustic microscopy

5.2.2 *BWS* — bonded wafer stack

5.2.3 *CD* — critical dimension

5.2.4 *CSI* — coherence scanning interferometry

5.2.5 *CWS* — chromatic white light sensor

5.2.6 *IR* — infrared

5.2.7 *TS* — through-silicon via

5.2.8 *TTV* — total thickness variation

5.2.9 *WLI* — white light interferometry

5.3 Other Definitions

5.3.1 *explanation of wafer stack metrology terms*¹ — the parameters primarily measured—wafer bow, warp, and sori—need some explanation as applied to a 2-wafer stack. For the purposes of this Standard, the term ‘wafer stack’ can be equally applied to a single wafer in the definitions below. The definitions for geometric parameters for bonded wafers have been extended from single wafer applications. The schematic diagrams in Figure 3 represent these terms where depictions are of wafer bow with reference planes for each wafer in the stack (A–C), bow with a single reference plane for the stack (D–F), warp with reference planes for each wafer (G–I), warp with a single reference plane for the stack (J–L), and sori (M) for a bonded wafer stack. The dashed lines are the reference planes. Depending on the type of metrology used, either the entire wafer stack or individual wafers in the wafer stack can be measured for thickness, TTV, bow, warp/sori, and flatness. In each scenario, either one or two reference planes are depicted. The reference planes represent the median surface of either the wafer stack taken in its entirety or of each individual wafer in the wafer stack, depending on the type of metrology used and its capability. For example, capacitance metrology or chromatic white light metrology cannot penetrate into the wafer stack; therefore only the reference plane of the wafer stack is applicable.

5.3.2 *back surface* — the exposed surface opposite to that upon which devices have been or will be fabricated.

5.3.2.1 *bow* — the deviation of the center point of the median surface of a free, unclamped wafer from a median surface reference plane established by three points equally spaced on a circle with diameter a specified amount less than the nominal diameter of the wafer; SEMI MF1390 provides a standard test method for measuring the bow of a single wafer. Note that bow is a signed value. The method can be adapted to a bonded wafer stack.

5.3.2.1.1 *bow, back surface, of a wafer stack* — the positive or negative deviation of the center point of the back surface of an unconstrained, horizontally positioned wafer stack from a back-surface reference plane established by three points within the boundary of the fixed quality area.

5.3.2.1.2 *bow, front surface, of a wafer stack* — the positive or negative deviation of the center point of the front surface of an unconstrained, horizontally positioned wafer stack from a front-surface reference plane established by three points within the boundary of the fixed quality area.

5.3.2.2 *chromatic white light sensor (CWS)* — a CWS is based on the principal of confocal optics and relies on chromatic scanning. A lens is used that refracts white light differentially based on its wavelength in order to carry out distance measurements. Resolution depends on the intensity of reflected light.

¹ SEMI M59 — Terminology for Silicon Technology

5.3.2.3 *fixed quality area (FQA)* — the central area of a wafer surface, defined by a nominal edge exclusion, EE, over which the specified values of a parameter apply. Because the nominal edge exclusion relates to the nominal diameter of a wafer, the size of the FQA is independent of wafer diameter and flat length tolerances.

5.3.2.4 *flatness* — the deviation of the front surface of a wafer stack, expressed in TIR or maximum FPD relative to a specified reference plane when the back surface of the wafer stack is ideally flat, as when pulled down by a vacuum onto an ideally flat chuck.

5.3.2.5 *front surface* — the exposed surface upon which devices have been or will be fabricated.

5.3.2.6 *gravity compensation for horizontally-supported wafers* — unlike thickness and TTV measurements which are independent of how the wafer is held, bow and warp measurements are complicated not only by wafer stress but by how the wafer is supported and by gravity. Gravity causes substantial deformation of large diameter or thin wafers, whether they are supported at the edge or in the middle. Unless compensated, gravity will induce a large error in warp measurements. SEMI MF1390 describes three compensation approaches. One approach is to correct for the gravitational effect of warp measurements by inverting the wafer and measuring both the top and bottom surfaces of the wafer. Any differences between two values at the same site are due to the effect of gravity and can be used to correct for single-side measurements. Another approach is to use an analytical expression for gravitational deformation and subtract it from a single-side warp measurement. Measurements obtained on representative wafers can also be performed and the gravity value determined. In addition, the wafer can either rest on a chuck or be supported by three points (SEMI MF1390).

5.3.2.7 *gravity compensation for vertically supported-wafers* — on tools that support the wafer vertically, effects due to gravity are negligible and therefore do not require compensation. Bow is only measured on one side so there is no need to invert the wafer. The manufacturing tolerance for sori is very low, such that a 300 mm diameter silicon wafer must achieve sori in the nanometer range in order to achieve the maximum yields in semiconductor device processing.

5.3.2.8 *interferometry* — a technique that relies on the principal of superposition of multiple beams of light to determine the effect that a material has on the state (phase and amplitude) of the original light beam. It is this introduced phase difference that creates the interference pattern between the initially identical waves. If a single beam has been split along two paths, then the phase difference is diagnostic of anything that changes the phase along the paths. This could be a physical change in the path length itself or a change in the refractive index along the path.

5.3.2.9 *noncontact* — metrology that allows a wafer to be measured without physical contact to the wafer surface, preventing contamination or damage to the wafer substrate.

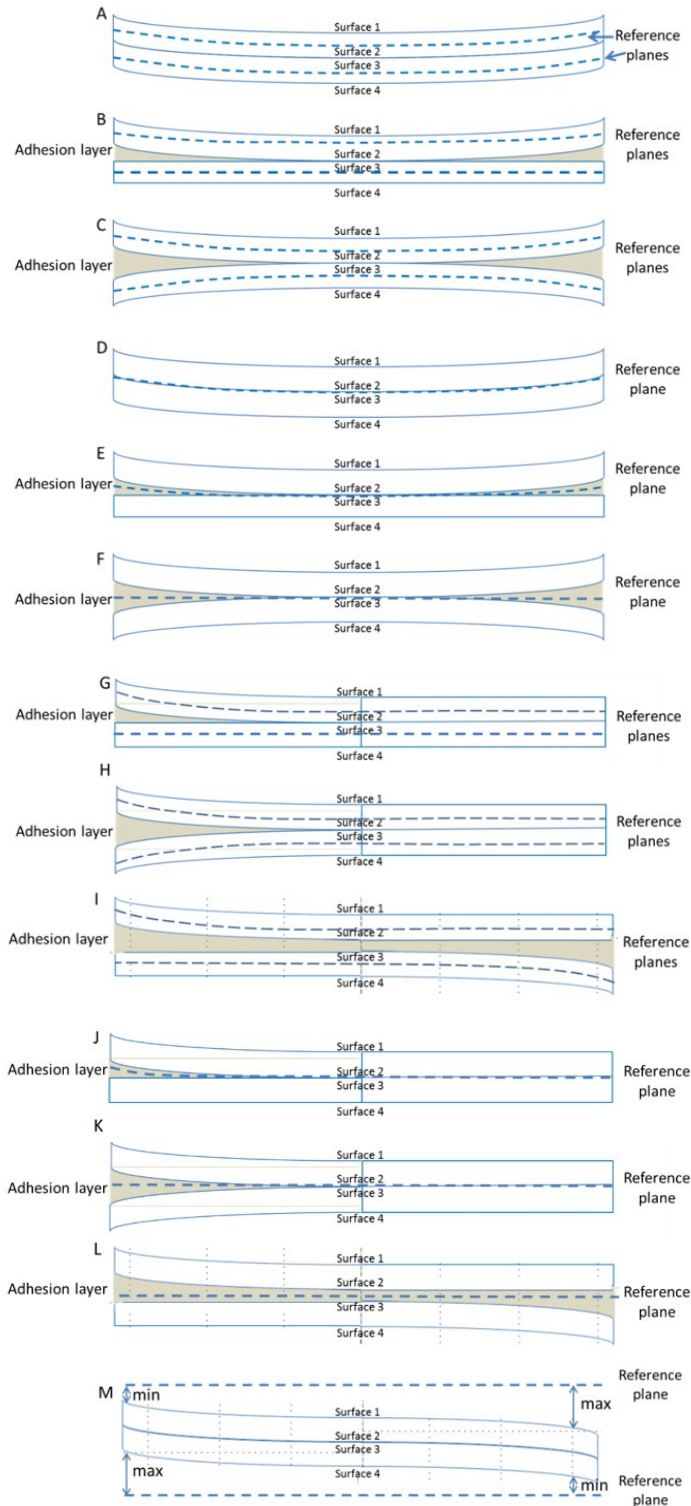
5.3.2.10 *sori* — sori of a bonded wafer stack is the algebraic difference between the most positive and most negative deviations of the front surface of a wafer stack that is not chucked from a reference plane that is a least squares fit to the front surface of a wafer stack within the fixed quality area.

5.3.2.11 *unconstrained condition* — the state of a wafer under test, when the wafer is in a stress-free condition with deformation due only to gravity.

5.3.2.12 *warp* — the difference between the most positive and most negative distances of the median surface of a free, unclamped wafer from a reference plane; SEMI M59 provides a standard test method for measuring the warp of a single wafer. Warp can be zero, even for a wafer with curvature, if the curves are mirror images of each other. SEMI MF1390 measures median surface warp using a three-point back-surface reference plane, resulting in thickness variation being included in the warp value. The use of a median surface reference plane in SEMI MF1390 eliminates this effect. SEMI MF1390 provides a standard test method for measuring the warp of a single wafer. The method can be adapted to the multiple surfaces of a bonded wafer stack.

5.3.2.12.1 *warp, back surface, of a wafer stack* — the algebraic difference between the maximum most positive and minimum most negative deviations of all points of the back surface of an unconstrained, horizontally positioned wafer stack from a back-surface reference plane that is established by three points within the boundary of the fixed quality area.

5.3.2.12.2 *warp, front surface, of a wafer stack* — the algebraic difference between the maximum most positive and minimum most negative deviations of all points of the front surface of an unconstrained, horizontally positioned wafer from a front-surface reference plane that is established by three points within the boundary of the fixed quality area. Hence, the warp must be specified for the back and front surfaces.



#1 The Dashed Lines are the Reference Planes.

Figure 3

Depictions of Bow with Reference Planes for Each Wafer in the Stack (A–C), Bow with a Single Reference Plane for the Stack (D–F), Warp with Reference Planes for Each Wafer (G–I), Warp with a Single Reference Plane for the Stack (J–L), and Sori (M) for a Bonded Wafer Stack

5.4 Measurement Considerations

5.4.1 thickness and total thickness variation (SEMI MF533) — Wafer stacks that are excessively thin may break during processing or have inadequate thermal mass or electrical resistance during certain processing steps. Wafer stacks that are too thick may jam during wafer handling. Excessive thickness variation may generate problems during mechanical handling. Excessive deviation from flatness may cause focus problems in photolithography steps. Thickness is the distance through the wafer stack between corresponding points on the front and back surfaces. Total thickness variation is the difference between the maximum and minimum values of the thickness of a wafer stack within the fixed quality area.

5.4.2 bow (SEMI HBI) — If the median surface of a free, unclamped wafer stack has a curvature that is everywhere the same, bow is a measure of its concave (dished) or convex (mounded) deformation, independent of any thickness variation that may be present.

5.4.3 warp (SEMI MF1390 and HBI) — Warp can adversely affect the yield of semiconductor devices and can affect wafer handling and processing. Warp may be caused by unequal stresses on the two exposed surfaces of a wafer stack. Warp cannot be determined from measurements on a single exposed surface. The median surface may contain regions with upward or downward curvature or both. In some cases, the median surface may be flat. In all cases, warp is a zero or positive quantity.

5.4.4 sori (SEMI MF1451) — Sori solves the ambiguity of warp by measuring the difference between the maximum and minimum distances from the front surface of the wafer stack to a reference plane outside the surface of the wafer stack. SEMI MF1451 provides a standard test method for measuring the sori of a single wafer. A wafer is supported on a small-area chuck with the front surface facing up. Both external surfaces of a wafer are simultaneously measured by an opposed set of probes to obtain a set of values at the same *x*- and *y*-coordinates of the distances between each surface and the nearest probe. The paired distances are used to construct the median surface. Gravity correction can be performed. One half of the thickness at each point is added to the corrected median surface to construct the corrected front surface. A least-squares reference plane is constructed from the corrected front surface. The reference plane deviation (RPD) is calculated at each pair of measurement points. Sori is then reported as the algebraic difference between the most positive RPD and the most negative RPD.

6 Introduction to Bonded Wafer Metrology Techniques

6.1 A list of techniques described in this Guide is shown in Table 1 showing the section number where described, the measurement capabilities, and whether the technique is capable of measuring the individual wafer components and bond layer in the wafer stack. The content is based on supplier information and is subject to change.

Table 1 List of Techniques Described in Guide

<i>Metrology Technique</i>	<i>Section Number</i>	<i>Measurement Capabilities</i>	<i>Capable of Measuring Each Wafer in Bonded Wafer Pair</i>	<i>Capable of Measuring Bond Layer</i>	<i>Metrology Performance Potentially Adversely Affected by Metal Structures Embedded in Wafer Stack</i>
Chromatic White Light Confocal Microscopy	6.1.1	Thickness, TTV, Bow, Warp	N	N	N
Infrared Interferometry	6.1.2	Thickness, TTV, Bow, Warp	Y	Y	Y
Coherence Scanning Interferometry or White	6.1.3	Thickness, TTV, Bow, Warp	N	N	N
Laser Profiling	6.1.4	Thickness, TTV, Bow, Warp	N/Y ^{#1}	N/Y ^{#1}	N/Y ^{#1}
Capacitance Metrology	6.2.1	Thickness, TTV, Bow, Warp	N	N	N
Differential Backpressure Metrology	6.3.2	Thickness, TTV, Bow, Warp	N	N	N

<i>Metrology Technique</i>	<i>Section Number</i>	<i>Measurement Capabilities</i>	<i>Capable of Measuring Each Wafer in Bonded Wafer Pair</i>	<i>Capable of Measuring Bond Layer</i>	<i>Metrology Performance Potentially Adversely Affected by Metal Structures Embedded in Wafer Stack</i>
Acoustic Microscopy	6.4	Thickness, TTV, Bow, Warp	Y	Y	N

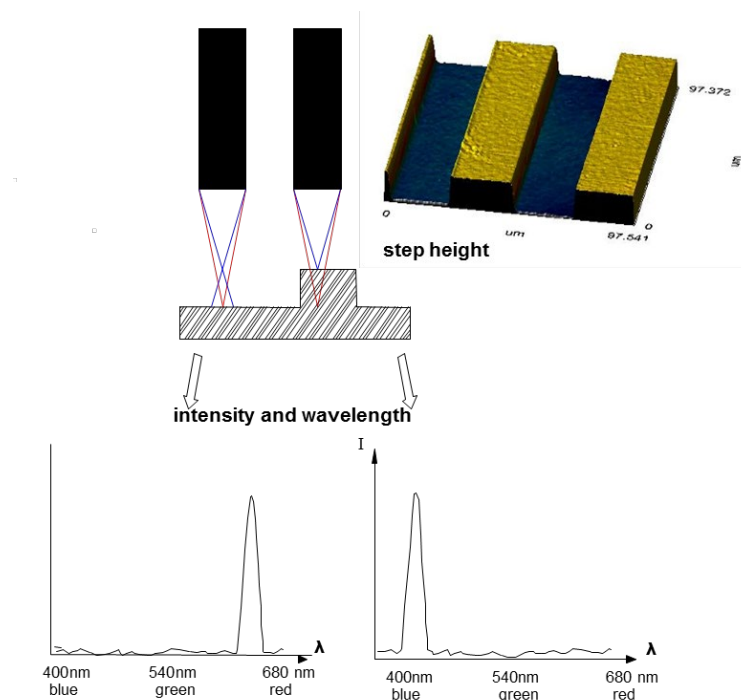
#1 IR wavelength.

6.1.1 Some of the methods shown above have limitations if materials or structures impede penetration of the probe beam. For example, Cu pillars embedded in the temporary bond adhesive or Cu pads in the case of permanent bonded structures would block penetration of an IR beam through the wafer stack. In these cases, to measure the thickness of the individual stacked wafers, a location would need to be chosen that is free of optically-opaque structures. As most methods do not penetrate through the wafer stack, there would be no interference from such structures.

6.2 Optical Techniques

6.2.1 Chromatic White Light Confocal Microscopy

6.2.1.1 Chromatic white light sensor metrology utilizes the principle of wavelength-dependent focal length to determine distance (refer to Figure 4). The spectrum of light reflected from a surface generates an intensity profile as a function of focal length that is used to determine distance to the sample surface. The peak in intensity occurs at the optimal focal point for each wavelength. This technique is useful for determination of 2D profile, 3D topography, planarity, roughness, and wafer contour (bow and warp). Figure 5 shows a typical set of measurement locations used in an analysis. The resulting 2D measurement profiles for thickness, TTV, and warp for an 825 μm thick BWS are shown in Figure 6, and a wafer thickness contour map is shown in Figure 7.



#1 Focal lengths are wavelength dependent, providing distance measurements.

Figure 4
Chromatic White Light Sensor Used for Distance Measurements for Bow, Warp, and Topographical Measurements

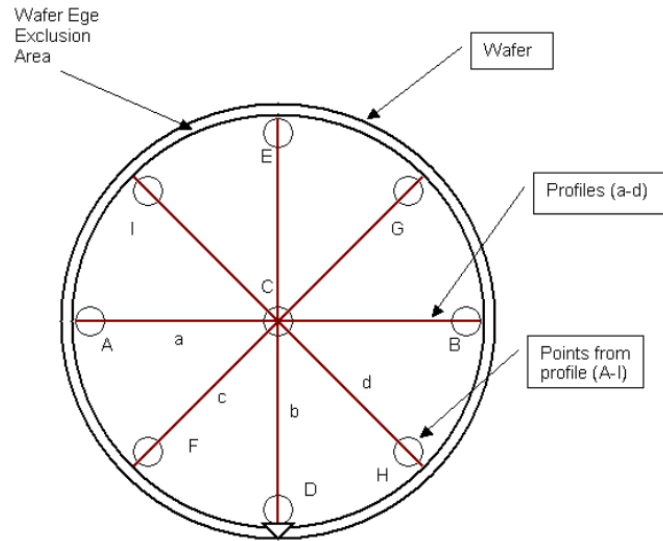
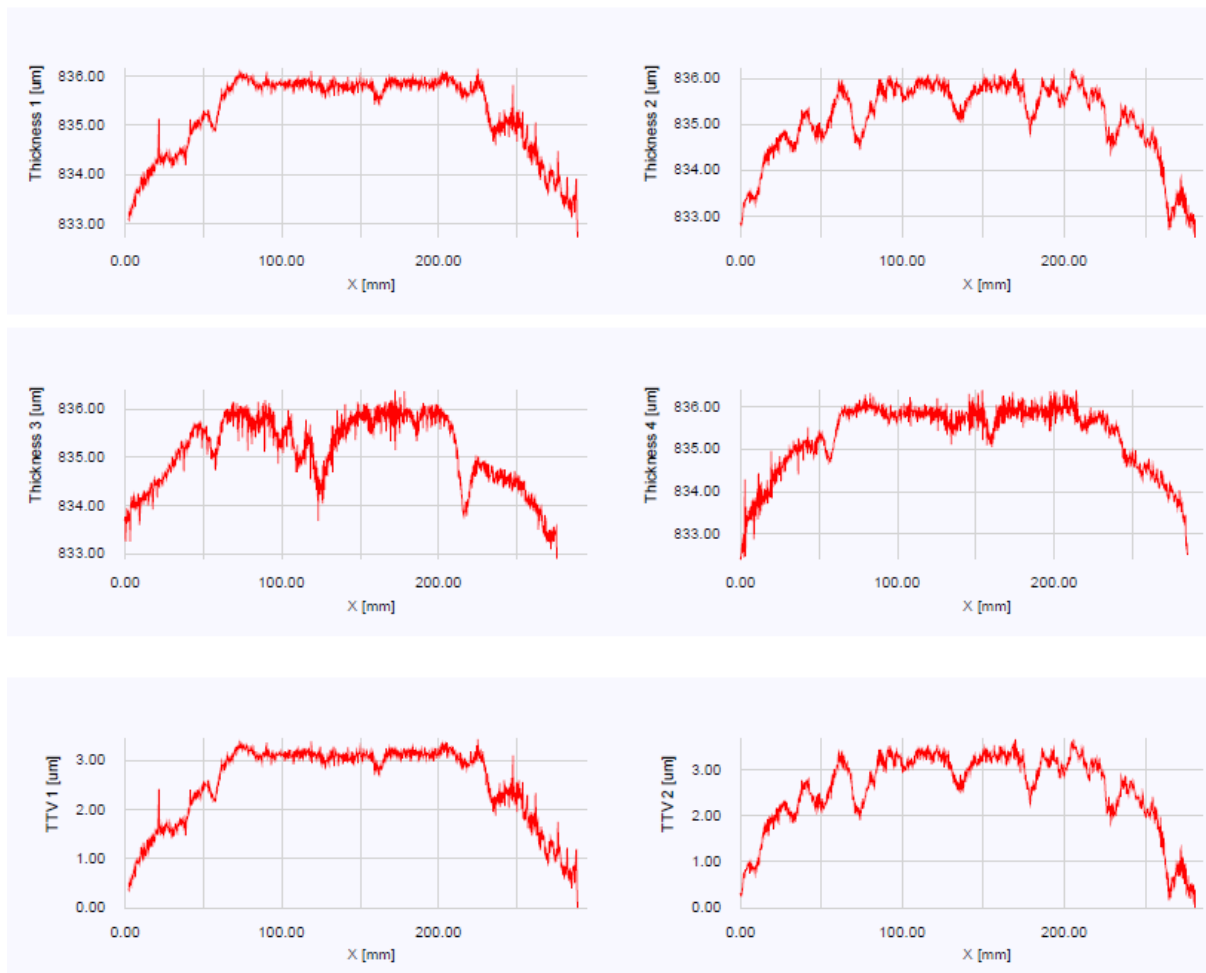


Figure 5
Data Collection Locations Showing Profile (a-d), and Points (A-I)



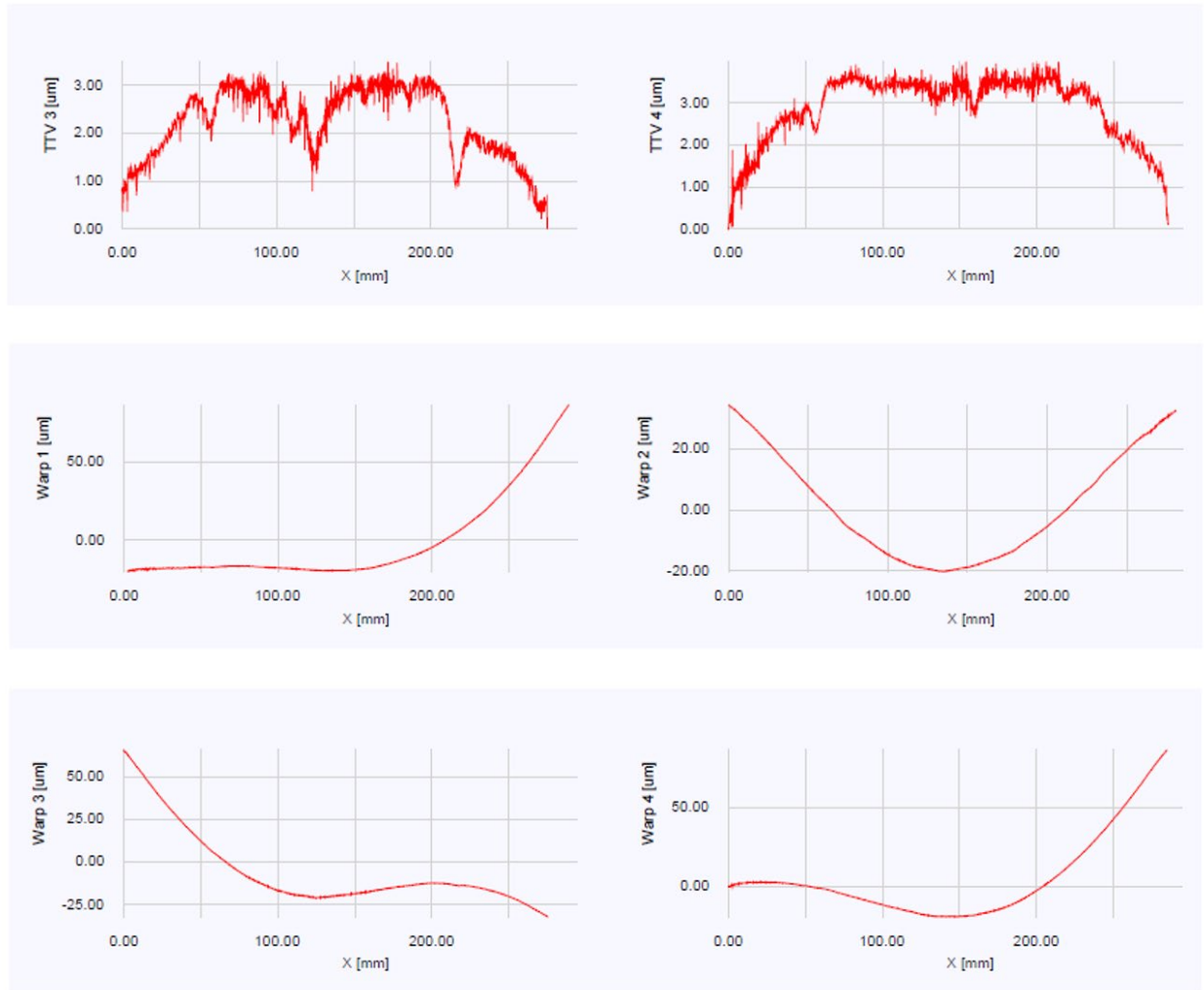


Figure 6
Examples of Line Profile Measurements along Lines a–d from Figure 5
showing Thickness, TTV, and Warp for an 825 μm BWS

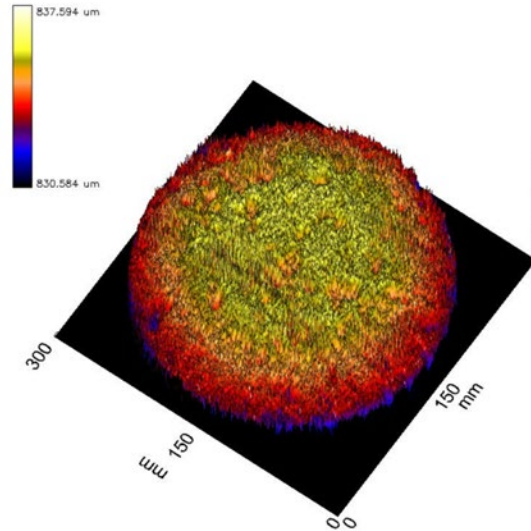


Figure 7
Wafer Map Results for 825 μm Thin Bonded Pair Wafer

6.2.2 Infrared Interferometry

6.2.2.1 Interferometry is a technique in which light waves are superimposed to obtain information on surface profiles or displacements between two surfaces. Infrared interferometry is useful for thickness measurements of substrates that are transparent in near infrared light. Thickness measurements can be performed on single or multilayer films, including adhesion layers in BWS. At each film interface, some incident light is reflected back to a detector.

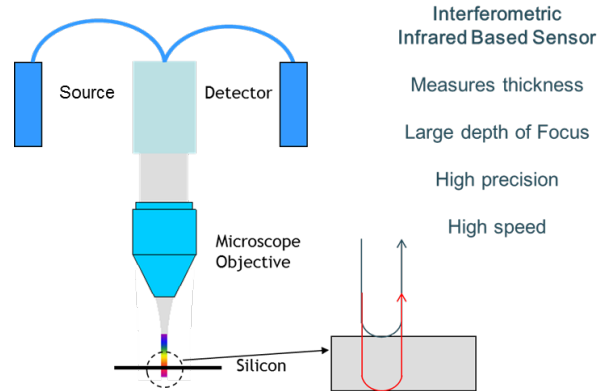
6.2.2.2 When two light waves combine, the resulting pattern is determined by the phase difference between the two waves—waves that are in phase undergo constructive interference while waves that are out-of-phase undergo destructive interference. Typically, a beam of coherent light is split into two beams by a beam splitter. Each beam travels a different path and the two are recombined before arriving at the detector. The path difference, the difference in the distance traveled by each beam, creates a phase difference between them.

6.2.2.3 For a thin transparent medium, the reflection from the top surface interferes with the reflection from the bottom surface. For some wavelengths, the interference is constructive, and for others it is destructive. In general, the reflected intensity follows the Fabry-Perot equation (Equation 1):

$$R = \left| \frac{r_1 + r_2 e^{i2\delta}}{1 + r_1 r_2 e^{i2\delta}} \right|^2 \quad (1)$$

where r_1 is the reflection coefficient at the first surface of the cavity, r_2 is the reflection coefficient at the second surface, and $\delta = 2\pi n l / \lambda$, n is the index of refraction, l is the cavity thickness, and λ is the wavelength. Because of the complex exponential, the reflected intensity is periodic in δ . Since δ is proportional to optical frequency (c / λ), the reflected intensity is periodic in optical frequency with period $c / 2nl$, where n is the index of refraction, l is the layer thickness, and c is the speed of light in a vacuum. Then the basic procedure to measure the thickness is to: 1) measure the reflectance for a spectrum of wavelengths; 2) analyze the measured spectrum for a periodic intensity as a function of optical frequency; 3) calculate thickness from the period and index of refraction.

6.2.2.4 The light source has a wavelength in the neighborhood of 1.3 μm, and is placed facing the back of the wafer. The sensor measures both surfaces of the wafer interferometrically and returns a thickness measurement (refer to Figure 8). The fast (millisecond) and nondestructive measurements based on backside IR illumination allow immediate high volume manufacturing process feedback. The sensor is used for measuring thickness of thick wafers, thinned wafers, and etch depth of TSVs and other features.



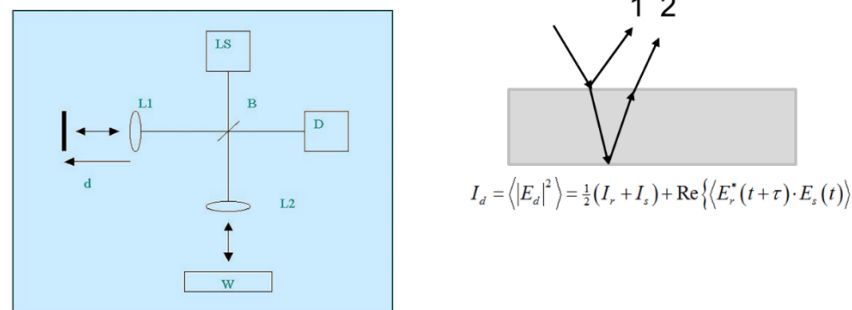
#1 Focal lengths are wavelength-dependent, providing distance measurements.

Figure 8
Infrared Interferometric Sensor Used for Distance Measurements for Bow, Warp, and Topographical Measurements

6.2.2.5 Some tools utilize a dual-sided interferometer to measure wafer geometry parameters such as thickness, shape and flatness. The wafer is held vertically between two sets of optics so that each surface is measured simultaneously. The tool is mainly used by bare silicon wafer suppliers to improve their process for wafer geometry and to qualify wafers before shipment to customers.

6.2.2.6 Wafer geometry data acquired in 3D is capable of providing nanotopography and wafer edge roll-off. Wafer manufacturing issues can affect geometry at the edge of the wafer, causing die defocus and CMP removal non-uniformity.

6.2.2.7 The thickness and warp of the two individual wafers in a bonded pair can be measured using interferometry utilizing the interference between the light reflected from the wafer and the light reflected from a moving mirror. The general scheme of such an interferometer is shown in Figure 9.



#1 Beam 2, which is reflected from the bottom surface of the wafer, is delayed with respect to beam 1 reflected from the top surface. The delay between beam 1 and beam 2 is proportional to the thickness of the wafer. In a real experiment, the incident beam is perpendicular to the surface of the wafer.

Figure 9
Schematic View of an Interferometer System

6.2.2.8 A superluminescent light-emitting diode (SLED) with a broad line width was used and retro-reflecting mirrors were mounted in a nano-motor stage. The dual-probe scheme for total thickness and warp measurement is shown in Figure 10.

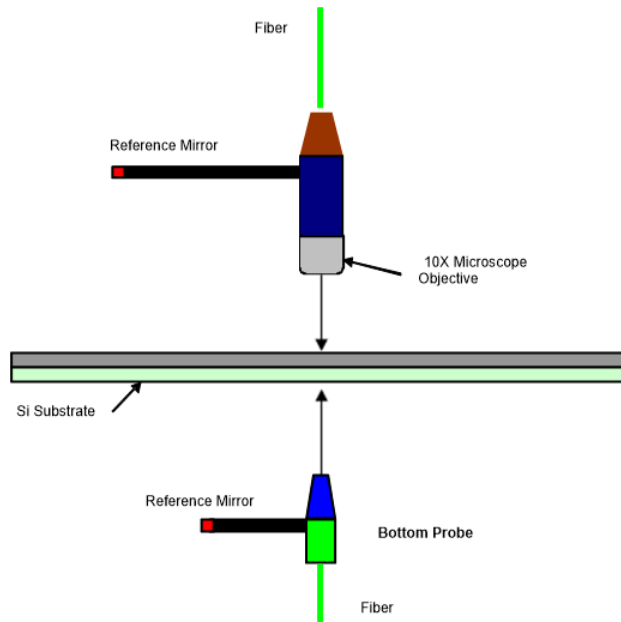


Figure 10
Dual Probe Scheme for the Measurement of the Thickness and Warp

6.2.2.9 In the dual-probe setup, each probe has a reference and a measurement arm. Light from each arm interferes with light from the scanning mirror to generate the first two interference signals in the upper probe. Similarly, light from the reference arm and the back surface of wafer produces the first two interference signals in the lower probe. The distance between the two probes can be determined using the known thickness of a block gauge. This information in conjunction with the two signals from the upper and lower probes makes it possible to measure the total thickness of the wafer. If the wafer surfaces are rough and/or the substrate is opaque to the incident light, the dual probe is a good way to measure its thickness. A typical signal collected by an interferometer system on a bare Si wafer is shown in Figure 11. For warp measurement, the distance between the reference signal and the signal from the front surface of a wafer into the top probe is measured. In a warp measurement, a 300 mm blank wafer is used as the un-warped reference.

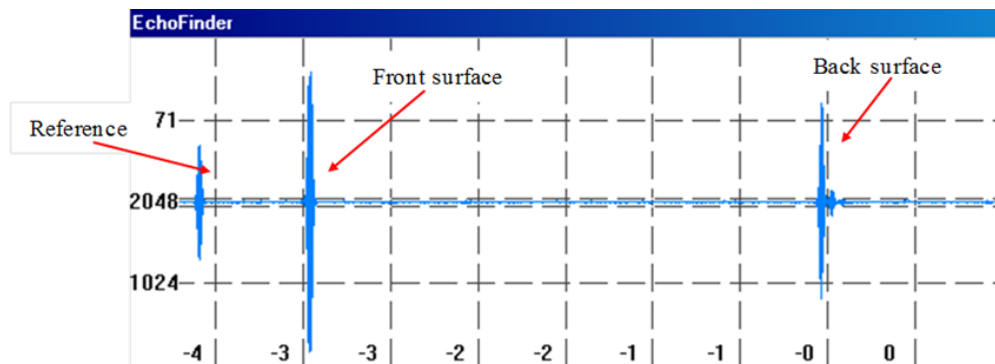


Figure 11
Typical Signal from an Interferometer System

6.2.2.10 In Figure 12, TTV maps are shown with measurement locations (left) as well as 2D TTV (center) and 3D TTV (right) maps for an 825 μm two wafer stack. Typical wafer thickness results are shown in Figures 13 through 15 for a 1550 μm thick two wafer stack.