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AMERICAN SOCIETY FOR TESTING AND MATERIALS
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Standard Test Method for Measuring Warp on Silicon Wafers by Automated Noncontact Scanning [1]

This standard is issued under the fixed designation F 1390; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers a noncontacting, nondestructive procedure to determine the warp of clean, dry semiconductor wafers.

1.2 The test method is applicable to wafers 50 mm or larger in diameter, and 100 µm (0.004 in.) approximately and larger in thickness, independent of thickness variation and surface finish, and of gravitationally-induced wafer distortion.

1.3 This test method is not intended to measure the flatness of either exposed silicon surface. Warp is a measure of the distortion of the median surface of the wafer.

1.4 This test method measures warp of a wafer corrected for all mechanical forces applied during the test. Therefore, the procedure described gives the unconstrained value of warp. This test method includes a means of canceling gravity-induced deflection which could otherwise alter the shape of the wafer. [2] The resulting parameter is described by Warp(2) in Appendix X2 Shape Decision Tree in SEMI Specification M 1. (See Annex A1.)

NOTE 1—Test Method F 657 measures median surface warp using a three-point back-surface reference plane. The back-surface reference results in thickness variation being included in the recorded warp value. The use (in this test method) of a median surface reference plane eliminates this effect. The use (in this test method) of a least-squares fit reference plane reduces the variability introduced in three-point plane calculations by choice of reference point location. The use (in this test method) of special calibration or compensating techniques minimizes the effects of gravity-induced distortion of the wafer.

1.5 The values stated in SI units are to be regarded separately as the standard. The values given in parentheses are for information only.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

F 657 Test Method for Measuring Warp and Total Thickness Variation on Silicon Slices and Wafers by Noncontact Scanning [3]

F 1241 Terminology of Silicon Technology [3]

2.2 *SEMI Standard:*

M 1 Specifications for Polished Monocrystalline Silicon Wafers [4]

3. Terminology

3.1 *Definitions:*

3.1.1 *mechanical signature— of an instrument*, that component of a measurement that is introduced by the instrument and that is systematic, repeatable, and quantifiable.

3.1.2 *median surface—of a semiconductor wafer*, the locus of points equidistant from the front and back surfaces.

3.1.3 *quality area*—that portion of a wafer within the specified parameter is determined.

3.1.4 *reference plane— of a semiconductor wafer*, a plane from which deviations are measured.

3.1.5 *reference plane deviation (RPD)*—the distance from a point on a reference plane to the corresponding point on a wafer surface. A dome-shaped wafer is considered to have positive RPD at its center; a bowl-shaped wafer is considered to have negative RPD at its center.

3.1.6 *thickness—of a semiconductor wafer*, the distance through the wafer between corresponding points on the front and back surfaces.

3.1.7 *wafer—of a semiconductor*, the difference between the maximum and minimum distances of the median surface of a free, unclamped wafer from a reference plane.

3.1.7.1 *Discussion*—Although warp may be caused by unequal stresses on the two exposed surfaces of the wafer, it cannot be determined from measurements on a single exposed surface. The median surface may contain regions with upward or downward curvature or both; under some conditions the median surface may be flat (see figures in Appendix X1).

3.2 Other definitions relative to silicon material technology can be found in Terminology F 1241.

[1] This test method is under the jurisdiction of ASTM Committee F-1 on Electronicsand is the direct responsibility of Subcommittee F01.06 on Silicon Materials and Process Control.

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[2] Poduje, N., "Eliminating Gravitational Effect in Wafer Shape Measurements," NIST/ASTM/SEMI/SEMATECH Technology Conference, Dallas, TX; Technology for Advanced Materials/Process Characterization, February 1, 1990.

[3] Annual Book of ASTM Standards, Vol 10.05.

[4] Available from SEMI, 805 East Middlefield Road, Mt. View, CA 94043.

4. Summary of Test Method

4.1 A calibration procedure is performed. In addition to setting the instrument's scale factor and other constants, this procedure determines the mechanical signature of the instrument and the effect of gravity on the wafer.

4.2 The wafer is supported by a small-area chuck and both external surfaces are simultaneously scanned along a prescribed pattern by both members of an opposed pair of probes.

4.3 The paired displacement values are used to construct a median surface.

4.4 The median surface is mathematically corrected for gravitational effects and for mechanical signature of the instrument.

4.5 A least-squares reference plane is constructed from the corrected median surface.

4.6 The reference plane deviation (RPD) is calculated at each measured point.

4.7 Warp is reported as the algebraic difference between the most positive RPD and the most negative RPD.

5. Significance and Use

5.1 Warp can significantly affect the yield of semiconductor device processing.

5.2 Knowledge of this characteristic can help the producer and consumer determine if the dimensional characteristics of a specimen wafer satisfy given geometrical requirements.

5.3 Changes in wafer warp during processing can adversely affect subsequent handling and processing steps. These changes can also provide an important process monitoring function.

5.4 The test method is suitable for measuring the warp of wafers used in semiconductor device processing in the as-sliced, lapped, etched, polished, epitaxial, or other layer condition and for monitoring thermal and mechanical effects on the warp of wafers during device processing.

5.5 Until the results of a planned interlaboratory evaluation of this test method are established, use of this test method for commercial transactions is not recommended unless the parties to the test establish the degree of correlation that can be obtained.

6. Interferences

6.1 Any relative motion along the probe measuring axis between the probes and the wafer holding device during scanning will produce error in the measurement data. Vibration of the test specimen relative to the probe-measuring axis will introduce error. Such errors are minimized by system signature analysis and correction algorithms. Internal system monitoring may also be used to correct non-repetitive and repetitive system mechanical translations, and failure to provide such corrections may cause errors.

6.2 If a measured wafer differs substantially in diameter, thickness, fiducials or crystal orientation from that used for the gravitational compensation procedure, the results may be incorrect. Approximate errors for differences in diameter and thickness are shown in Appendix X2. If the crystal orientation of the sample to be measured differs from the crystal orientation of the gravity-compensation wafer, then the measured warp value may differ from the actual warp value by up to 15 %. Error tables for fiducial variation have not been generated.

6.3 Different methods for implementing gravitational compensation may give different results. Varying levels of completeness of implementing a method may also give different results.

NOTE 2—The recommended method for gravitational compensation is representative wafer inversion, [5] since it allows the use of a single wafer to establish the compensation that is subsequently applied to sample wafers. The sample wafer inversion method requires that every wafer be measured twice, once in a normal and once in an inverted position, which increases measurement time and subjects the sample to additional handling. Theoretical modeling requires only a single measurement per sample, however it does not address machine signature issues, nor is a rigorous theory presently known to exist.

6.4 Mechanical variations in wafer holding devices between systems may introduce measurement differences. See 7.1.1.

6.5 Most equipment systems capable of this measurement have a definite range of wafer thickness combined with warp (dynamic range) that can be accommodated without readjustment. If the sample moves outside this dynamic range during either calibration or measurement, results may be in error. An overrange signal can be used to alert the operator and measurement data examiners to this event.

6.6 The quantity of data points and their spacing may affect the measurement results. See 7.1.2.

7. Apparatus

7.1 *Warp-Measuring Equipment*, consisting of wafer holding device, multiple-axis transport mechanism, probe assembly with indicator, and system controller/computer, including data processor and suitable software. The system must be equipped with an overrange signal. Instrument data reporting resolution shall be 100 nm or smaller.

7.1.1 *Wafer-Holding Device*, for example a chuck whose face is perpendicular to the measurement axis, and on which the wafer is placed for the measurement scan. The diameter of the wafer holding device shall be 22-mm (0.9-in.) diameter, 33-mm (1.3-in.) diameter, or other value as agreed upon between using parties.

7.1.2 *Multiple-Axis Transport Mechanism*, which provides a means for moving the wafer-holding device, or the probe assembly, perpendicularly to the measurement axis in a controlled fashion in several axes. This motion must permit data gathering over a prescribed scan pattern the entire quality area. Maximum data point spacing to be used shall be 4 mm, or other value as agreed upon between using parties.

7.1.3 *Probe Assembly With Paired Non-Contacting Displacement-Sensing Probes, Probe Supports, and Indicator Unit*—The probes shall be capable of independent measurement of the distance between the probed site on each surface of the sample wafer and the motion plane. The probes shall be mounted above and below the wafer in a manner so that the probed site on one surface of the wafer is opposite the probed site on the other. The common axis of these probes is the

[5] The representative wafer method of gravitational correction is covered by a patent held by ADE Corporation, 77 Rowe Street, Newton, MA 02166. Alternate methods are described in 13.1.2.

measurement axis (see Fig. 1). The probe separation D shall be kept constant during calibration and measurement. Displacement resolution shall be 0.1 µm or better. The probe sensor size shall be 4 by 4 mm, or other value to be agreed upon between using parties. Systems employing either representative wafer inversion of sample wafer inversion methods for gravity compensation must provide precise positioning in both measurement orientations so that measurements are taken at identical locations for each orientation of the sample.

$$z = \frac{D}{2} - a - \frac{t}{2} \tag{1}$$

$$z = -\frac{D}{2} + b + \frac{t}{2} \tag{2}$$

$$z = \frac{b - a}{2} \tag{3}$$

where:

D = the distance from probe b to probe a,
a = the distance from the top surface of the wafer to probe a,
b = the distance from probe b to the bottom surface of the water,
t = wafer thickness, (always a positive number) and
z = the distance between the wafer medium surface and the point halfway between the upper and lower probes.

8. Materials

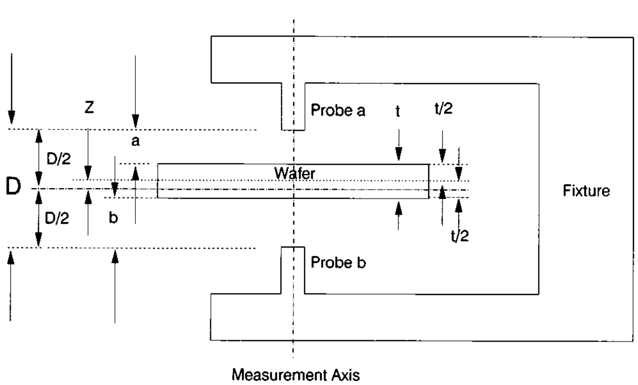
8.1 *Set-up Masters*, suitable to accomplish calibration and standardization as recommended by the equipment manufacturer.

8.2 *Reference Wafer*, the warp value ≤20 µm with a data set that is used to determine the level of agreement between the system under test and the data set (see Annex A1).

8.3 *Representative Wafer*—If using the representative wafer inversion method, a wafer identical in nominal diameter, thickness, fiducials, composition and crystalline orientation to those being measured is required for the calibration procedure. Its warp need not be known.

9. Suitability of Test Equipment

9.1 The suitability of the test equipment shall be determined with the use of a reference wafer and its associated data set in accordance with the procedures of Annex A1, or by performance of a statistically-based instrument repeatability study to ascertain whether the equipment is operating within the manufacturer's stated specification for repeatability.



NOTE 3—For further information on instrument repeatability studies contact Subcommittee F1.95.

9.2 Determination of degree of suitability is currently under investigation.

10. Sampling

10.1 This test method is nondestructive and may be used on either 100 % of the wafers in a lot or on a sampling basis.

10.1.1 If samples are to be taken, procedures for selecting the sample from each lot of wafers to be tested shall be agreed upon by the parties to the test, as shall the definition of what constitutes a lot.

11. Calibration and Standardization

11.1 Calibrate in accordance with the manufacturer's instructions.

12. Procedure

12.1 Prepare the apparatus for measurement of wafers, including selection of diameter, peripheral fiducials, scan area, and data display/output functions.

12.2 Introduce the test specimen into the measurement mechanism and initiate the measurement sequence.

13. Calculation

13.1 The instrument is assumed to be direct reading with all necessary calculations performed internally and automatically as follows:

13.1.1 The displacements (distances) between each probe and the nearest surface of the wafer are determined (in pairs) at intervals along the scan pattern. The distance between Probe *a* and the nearest surface of the wafer is displacement value **a**. The distance between Probe *b* and the nearest surface of the wafer is displacement value **b**. The probes are separated by the distance, *D*, (see Fig. 1). Half the difference of each pair of displacements ($0.5[b - a]$) yields the position z (along the measurement axis) of the median surface of the wafer at each point with respect to a plane halfway between the upper and lower probes.

13.1.2 Gravitational compensation is applied to the median surface by one of the following methods:

13.1.2.1 *Representative Wafer Inversion*— A wafer representative of the lot is measured first in a normal and then in an inverted position. The median surface measurement values are determined at each measurement location in each sample orientation. The results are added to obtain 0.5 ($z_{normal} + z_{inverted}$). This cancels the effect of the representative wafer's shape while retaining the effect of gravity, resulting in a value of each measurement point expressed as $z_{gravity}$. The effect of gravity on subsequent measurements on a sample wafer is cancelled by subtracting $z_{gravity}$ from z_{normal} to produce $z_{compensated}$ at each measurement point.

NOTE 4—The representative wafer inversion technique deals not only with first-order gravitational effects, but also with other effects that may influence the measured value, such as wafer-periphery effects, some machine-specific signature, etc.

13.1.2.2 *Sample Wafer Inversion*—Each sample wafer is measured in a normal position then in an inverted position. The median surface measurement values are determined at each measurement location in each measurement orientation. One half the difference between the normal and inverted measurement values at each point yields the sample wafer's gravity-compensated shape:

$$z_{com} = \frac{z_{nor} - z_{inv}}{2} \quad (4)$$

where:

z_{com} = compensated position at each measurement point,
z_{nor} = normal position at each measurement point, and
z_{inv} = inverted position at each measurement point.

13.1.2.3 *Theoretical Modeling*—Measure each sample wafer and apply gravitational correction that has been developed from a theoretical model. A rigorous model is not known to exist although approximate corrections have been calculated. [6]

13.1.3 A reference plane is constructed that is a least-squares fit to the median surface *z*-position data at all points of the scan pattern. The *z*-value of the reference plane (z_{ref}) is subtracted from the measured *z*-position at each point at all the points of the scan pattern to yield reference plane deviation (RPD) at each point:

$$RPD = z_{com} - z_{ref} \quad (5)$$

13.2 The difference between the largest (most positive) and smallest (most negative) of the reference plane deviations is taken as the warp:

$$warp = RPD_{\max} - RPD_{\min} \quad (6)$$

13.3 Record the calculated warp value.

13.4 For referee or other measurements where the wafer is measured more than once, calculate the maximum, minimum, sample standard deviation, average and range of all measurements on the sample.

[6] Application Note; Gravitational Sag in Silicon Wafers, ADE Corporation, 77 Rowe Street, Newton, MA 02166.

14. Report

14.1 Report the following information:

14.1.1 Date, time and temperature of test,

14.1.2 Identification of operator,

14.1.3 Identification of measuring instruments, including wafer holding device diameter, data point spacing, sensor size, and gravitational correction method,

14.1.4 Lot identification, including nominal diameter and center point thickness,

14.1.5 Description of sampling plan, and

14.1.6 Warp of each wafer measured.

14.2 For referee tests the report shall also include the standard deviation of each set of wafer measurements.

15. Precision and Bias

15.1 Interlaboratory evaluation of this test method is planned to verify its suitability and reliability. Until the results are established, use of this test method for commercial transactions is not recommended unless the parties to the test establish the degree of correlation that can be obtained.

15.2 No standards exist against which the bias of this test method can be evaluated.

NOTE 5—For further information on producing related reference materials to certify the wafer artifacts contact Subcommittee F1.95.

NOTE 6—Since no standard reference material exists for the measurement of warp, the measurement analysis shall include the capability to calibrate warp results to standards agreed upon between the participants in the measurement.

16. Keywords

16.1 noncontact measurement; semiconductor; shape; silicon; wafers; warp

ANNEX

(Mandatory Information)

A1. COMPARING DATA SETS

A1.1 Introduction

A1.1.1 In qualifying a measurement system for operation, it can be useful to compare the values ascribed to an artifact such as a reference standard against those obtained for that artifact on a machine under test. This annex outlines a way in which the multiple measurement data points that generate a single-value quantity of warp can be used to monitor the effects of Interferences more informatively than by using that single-value alone.

A1.1.2 A data set is that set of data used in computation of warp. It is corrected data, that is, all possible after interferences have been removed and the data replanarized in accordance with this test method.

A1.1.3 A referee wafer (artifact) is accompanied by its own data set (referee data set (RDS)), in which each data point is the average of a number of values obtained for that point over a number of "passes" (repeat measurements). The artifact is measured on a machine under test and its RDS is compared against the resultant measured sample data set. Delta-point, delta-warp and other values are computed from the differences. The parameter used to determine agreement between the artifact and the system under test and the acceptable level of this agreement is to be agreed upon between the using parties.

A1.2 Summary of Test Method

A1.2.1 Select a referee wafer of appropriate criteria, for which an RDS has been obtained.

A1.2.2 Measure the referee wafer on the machine under test to obtain a sample data set (SDS).

A1.2.3 Subtract the two to obtain a difference data set (DDS):

$$RDS - SDS = DDS \quad \text{(A1.1)}$$

A1.2.4 The DDS represents the differences between the measurements made on the machine under test and the referee data set. The DDS contains many values. The simplest metric that can be used to determine acceptability is maximum difference, the largest absolute value in the DDS. This represents the worst-case disagreement between the machine under test and the referee data.

A1.2.5 Accept the machine as suitable for measurement if the maximum difference is less than a value that is agreed upon between the parties to the test.

A1.2.6 More complex calculations may also be used, for example, a histogram of the (point-by-point) values of the DDS along with statistical measures (mean, sigma, etc.) may be compared. These measures can be compared to application-specific limits or used to provide insight into the nature and source of the difference, or both.

APPENDIXES

(Nonmandatory Information)

X1. VISUALIZATION OF WARP

X1.1 To calculate warp for a given case, it may be convenient to transform the measurement geometry and to consider the distance between the upper surface of the wafer and a reference plane as d_1, taken to be positive above the plane and negative below, and the distance between the lower surface of the wafer and the reference plane as d_2, taken to be positive below the plane and negative above it, as indicated in the example in Fig. X1.1 .

$$RPD = d_1 - \frac{t}{2} \quad \text{(X1.1)}$$

$$RPD = -d_2 + \frac{t}{2} \quad \text{(X1.2)}$$

$$RPD = \frac{d_1 - d_2}{2} \quad \text{(X1.3)}$$

where:

RPD = reference plane deviation,
d_1 = distance between upper surface of the wafer, and
d_2 = distance between lower surface of the wafer.

X1.2 See Fig. X1.2 for examples of warped wafers with stylized shapes. Sample 4 in Fig. X1.2 represents the example. Calculations for warp of each of these examples is given in Table X1.1 .

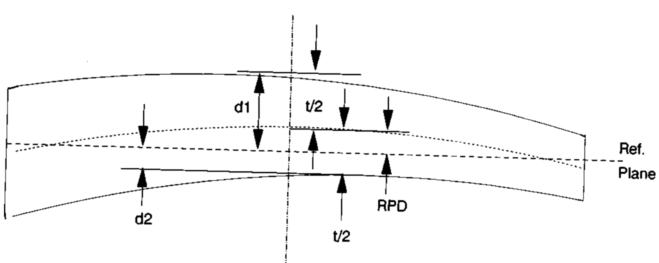
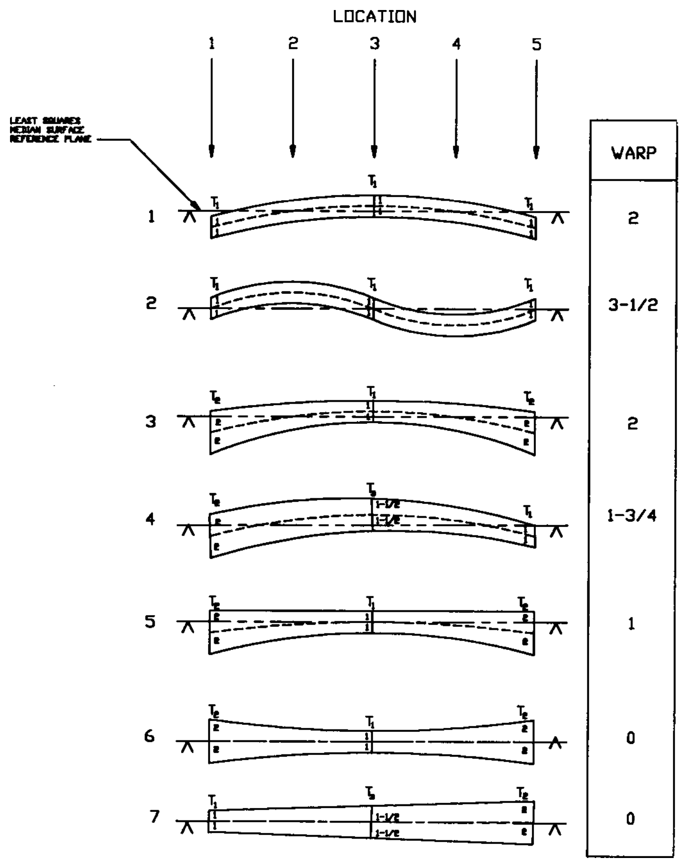


FIG. X1.1 Visualization of Warp



NOTE 1—T_1 is two units, T_2 is four units, and T_3 is three units; the warp values are calculated from Eq 2. The individual measured distances and the calculated differences are shown in Table X1.1.

FIG. X1.2 Visualization of Warp—Stylized Examples

TABLE X1.1 Values for Fig. X1.2

Example	Location	Values			
		d_1	d_2	RPD	Warp
1	1	− ½	2 ½	−1 ½	2
	2	1	1	0	
	3	1 ½	½	½	
	4	1	1	0	
	5	− ½	2 ½	−1 ½	
2	1	1	1	0	3 ½
	2	3	−1	2	
	3	1	1	0	
	4	− ½	2 ½	−1 ½	
	5	1	1	0	
3	1	½	3 ½	−1 ½	2
	2	1 ⅔	1 ⅔	0	
	3	1 ½	½	½	
	4	1 ⅔	1 ⅔	0	
	5	½	3 ½	−1 ½	
4	1	1	3	−1	1 ¾
	2	1 ¾	1 ¾	0	
	3	2 ¼	¾	¾	
	4	1 ¼	1 ¼	0	
	5	0	2	−1	
5	1	1 ½	2 ½	− ½	1
	2	1 ½	1 ¾	− ⅛	
	3	1 ½	½	½	
	4	1 ½	1 ¾	− ⅛	
	5	1 ½	2 ½	− ½	
6	1	2	2	0	0
	2	1 ⅓	1 ⅓	0	
	3	1	1	0	
	4	1 ⅓	1 ⅓	0	
	5	2	2	0	
7	1	1	1	0	0
	2	1 ¼	1 ¼	0	
	3	1 ½	1 ½	0	
	4	1 ¾	1 ¾	0	
	5	2	2	0	

X2. MEASUREMENT ERRORS DUE TO DIFFERENCES IN DIAMETER AND THICKNESS BETWEEN A REPRESENTATIVE WAFER AND A WAFER UNDER TEST

X2.1 For small variations about the calibration values, the relative change of the gravity effect is four times the relative change of the diameter and minus two times the relative change of thickness. The following gives examples of gravity effect errors (in micrometres), that is, deflection at the wafer edge relative to the wafer center point, using a value of 1.60 × 10 12 for Young's modulus with the wafer supported horizontally by a point located at the wafe center point. Standard thickness and diameter tolerances in accordance with SEMI Specification M 1 are used for the calculations, given in Fig. X2.1

X2.2 The deflection induced in a wafer by gravity is modeled as follows:

	Nominal Thickness		725 µm	(SEMI M1.9)	
	Nominal Diameter		200 mm		
			Actual Diameter (mm)		Typical Deflection (µm) for Nominal Thickness/ Nominal Diameter Wafer Supported as Stated
		199.8	200.0	200.2	
Actual	705	0.77	1.37	1.47	
Thickness	725	−0.57	0.00	0.10	24
(µm)	745	−1.80	−1.26	−1.17	

* * * * * * *

	Nominal Thickness		625 µm	(SEMI M1.13)	
	Diameter		150 mm		
			Actual Diameter (mm)		
		149.8	150.0	150.2	
Actual	610	−0.45	0.51	0.56	
Thickness	625	−0.05	0.00	0.05	10
(µm)	640	−0.52	−0.47	−0.42	

* * * * * * *

	Nominal Thickness		675 µm	(SEMI M1.8)	
	Diameter		150 mm		
			Actual Diameter (mm)		
		149.8	150.0	150.2	
Actual	655	0.49	0.54	0.59	
Thickness	675	−0.05	0.00	0.05	9
(µm)	695	−0.54	−0.49	−0.45	

* * * * * * *

	Nominal Thickness		625 µm	(SEMI M1.7)	
	Diameter		125 mm		
			Actual Diameter (mm)		
		124.5	125.0	125.5	
Actual	605	0.25	0.33	0.41	
Thickness	625	−0.08	0.00	0.08	5
(µm)	645	−0.37	−0.30	−0.22	

* * * * * * *

	Nominal Thickness		525 µm	(SEMI M1.5)	
	Diameter		100 mm		
			Actual Diameter (mm)		
		99.5	100.0	100.5	
Actual	505	0.17	0.23	0.29	
Thickness	525	−0.06	0.00	0.06	3
(µm)	545	−0.26	−0.20	−0.15	

NOTE 1—the Deflection induced in a wafer by gravity is modeled as follows:
to get relative (″percentage″) errors:

$$S = \frac{kD^4}{T^2} = gravity\ effect\ (\text{“}sag\text{”})$$

$$\frac{dS}{dD} = 4\frac{kD^3}{T^2}$$

$$\frac{dS}{dD} = -2\frac{kD^4}{T^3}$$

$$\frac{dS}{S} = 4\frac{dD}{D}$$

$$\frac{dS}{S} = -2\frac{dT}{T}$$

FIG. X2.1 Examples of Gravity Effect Errors