Designation: E2244 – 11

Standard Test Method for In-Plane Length Measurements of Thin, Reflecting Films Using an Optical Interferometer[1]

This standard is issued under the fixed designation E2244; 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 procedure for measuring in-plane lengths (including deflections) of patterned thin films. It applies only to films, such as found in microelectromechanical systems (MEMS) materials, which can be imaged using an optical interferometer, also called an interferometric microscope.

1.2 There are other ways to determine in-plane lengths. Using the design dimensions typically provides more precise in-plane length values than using measurements taken with an optical interferometric microscope. (Interferometric measurements are typically more precise than measurements taken with an optical microscope.) This test method is intended for use when interferometric measurements are preferred over using the design dimensions (for example, when measuring in-plane deflections and when measuring lengths in an unproven fabrication process).

1.3 This test method uses a non-contact optical interferometric microscope with the capability of obtaining topographical 3-D data sets. It is performed in the laboratory.

1.4 The maximum in-plane length measured is determined by the maximum field of view of the interferometric microscope at the lowest magnification. The minimum deflection measured is determined by the interferometric microscope's pixel-to-pixel spacing at the highest magnification.

1.5 *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:*[2]

E2245 Test Method for Residual Strain Measurements of Thin, Reflecting Films Using an Optical Interferometer

E2246 Test Method for Strain Gradient Measurements of Thin, Reflecting Films Using an Optical Interferometer

E2444 Terminology Relating to Measurements Taken on Thin, Reflecting Films

E2530 Practice for Calibrating the *Z*-Magnification of an Atomic Force Microscope at Subnanometer Displacement Levels Using Si*(111)* Monatomic Steps

2.2 *SEMI Standard:*[3]

MS2 Test Method for Step Height Measurements of Thin Films

3. Terminology

3.1 *Definitions:*

3.1.1 The following terms can be found in Terminology E2444.

3.1.2 *2-D data trace, n*—a two-dimensional group of points that is extracted from a topographical 3-D data set and that is parallel to the *xz*- or *yz*-plane of the interferometric microscope.

3.1.3 *3-D data set, n*—a three-dimensional group of points with a topographical *z*-value for each (*x*, *y*) pixel location within the interferometric microscope's field of view.

3.1.4 *anchor, n*—in a surface-micromachining process, the portion of the test structure where a structural layer is intentionally attached to its underlying layer.

3.1.5 *anchor lip, n*—in a surface-micromachining process, the freestanding extension of the structural layer of interest around the edges of the anchor to its underlying layer.

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[1] This test method is under the jurisdiction of ASTM Committee E08 on Fatigue and Fracture and is the direct responsibility of Subcommittee E08.05 on Cyclic Deformation and Fatigue Crack Formation.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] For referenced Semiconductor Equipment and Materials International (SEMI) standards, visit the SEMI website, www.semi.org.

3.1.5.1 *Discussion*—In some processes, the width of the anchor lip may be zero.

3.1.6 *bulk micromachining, adj*—a MEMS fabrication process where the substrate is removed at specified locations.

3.1.7 *cantilever, n*—a test structure that consists of a freestanding beam that is fixed at one end.

3.1.8 *fixed-fixed beam, n*—a test structure that consists of a freestanding beam that is fixed at both ends.

3.1.9 *in-plane length (or deflection) measurement, n*—the experimental determination of the straight-line distance between two transitional edges in a MEMS device.

3.1.9.1 *Discussion*—This length (or deflection) measurement is made parallel to the underlying layer (or the *xy*-plane of the interferometric microscope).

3.1.10 *interferometer, n*—a non-contact optical instrument used to obtain topographical 3-D data sets.

3.1.10.1 *Discussion*—The height of the sample is measured along the *z*-axis of the interferometer. The *x*-axis is typically aligned parallel or perpendicular to the transitional edges to be measured.

3.1.11 *MEMS, adj*—microelectromechanical systems.

3.1.12 *microelectromechanical systems, adj*—in general, this term is used to describe micron-scale structures, sensors, actuators, and technologies used for their manufacture (such as, silicon process technologies), or combinations thereof.

3.1.13 *sacrificial layer, n*—a single thickness of material that is intentionally deposited (or added) then removed (in whole or in part) during the micromachining process, to allow freestanding microstructures.

3.1.14 *structural layer, n*—a single thickness of material present in the final MEMS device.

3.1.15 *substrate, n*—the thick, starting material (often single crystal silicon or glass) in a fabrication process that can be used to build MEMS devices.

3.1.16 *support region, n*—in a bulk-micromachining process, the area that marks the end of the suspended structure.

3.1.17 *surface micromachining, adj*—a MEMS fabrication process where micron-scale components are formed on a substrate by the deposition (or addition) and removal (in whole or in part) of structural and sacrificial layers.

3.1.18 *test structure, n*—a component (such as, a fixed-fixed beam or cantilever) that is used to extract information (such as, the residual strain or the strain gradient of a layer) about a fabrication process.

3.1.19 *transitional edge, n*—the side of a MEMS structure that is characterized by a distinctive out-of-plane vertical displacement as seen in an interferometric 2-D data trace.

3.1.20 *underlying layer, n*—the single thickness of material directly beneath the material of interest.

3.1.20.1 *Discussion*—This layer could be the substrate.

3.2 *Symbols:*

3.2.1 *For Calibration:*

σ_{xcal} = the standard deviation in a ruler measurement in the interferometric microscope's *x*-direction for the given combination of lenses

σ_{ycal} = the standard deviation in a ruler measurement in the interferometric microscope's *y*-direction for the given combination of lenses

cal_x = the *x*-calibration factor of the interferometric microscope for the given combination of lenses

cal_y = the *y*-calibration factor of the interferometric microscope for the given combination of lenses

cal_z = the *z*-calibration factor of the interferometric microscope for the given combination of lenses

$cert$ = the certified (that is, calibrated) value of the physical step height standard

$ruler_x$ = the interferometric microscope's maximum field of view in the *x*-direction for the given combination of lenses as measured with a 10-µm grid (or finer grid) ruler

$ruler_y$ = the interferometric microscope's maximum field of view in the *y*-direction for the given combination of lenses as measured with a 10-µm grid (or finer grid) ruler

$scope_x$ = the interferometric microscope's maximum field of view in the *x*-direction for the given combination of lenses

$scope_y$ = the interferometric microscope's maximum field of view in the *y*-direction for the given combination of lenses

$\bar{z}_{ave}$ = the average of the calibration measurements taken along the physical step height standard before and after the data session

3.2.2 *For In-plane Length Measurement:*

α = the misalignment angle

$\sigma_{repeat(samp)'}$ = the in-plane length repeatability standard deviation (for the given combination of lenses for the given interferometric microscope) as obtained from test structures fabricated in a process similar to that used to fabricate the sample and for the same or a similar type of measurement

L = the in-plane length measurement that accounts for misalignment and includes the in-plane length correction term, L_{offset}

L_{align} = the in-plane length, after correcting for misalignment, used to calculate L

L_{meas} = the measured in-plane length used to calculate L_{align}

L_{offset} = the in-plane length correction term for the given type of in-plane length measurement on similar structures, when using similar calculations, and for a given magnification of a given interferometric microscope

$n1_t$ = indicative of the data point uncertainty associated with the chosen value for $x1_{uppert}$, with the subscript "t" referring to the data trace. If it is easy to identify one point that accurately locates the upper corner of Edge 1, the maximum uncertainty associated with the identification of this point is $n1_t x_{res} cal_x$, where $n1_t$=1.

$n2_t$ = indicative of the data point uncertainty associated with the chosen value for $x2_{uppert}$, with the subscript "t" referring to the data trace. If it is easy to identify one point that accurately locates the upper corner of Edge 2, the maximum uncertainty associated with the identification of this point is $n2_t x_{res} cal_x$, where $n2_t$=1.

U_L = the expanded uncertainty of an in-plane length measurement

u_{align} = the component in the combined standard uncertainty calculation for an in-plane length measurement that is due to alignment uncertainty

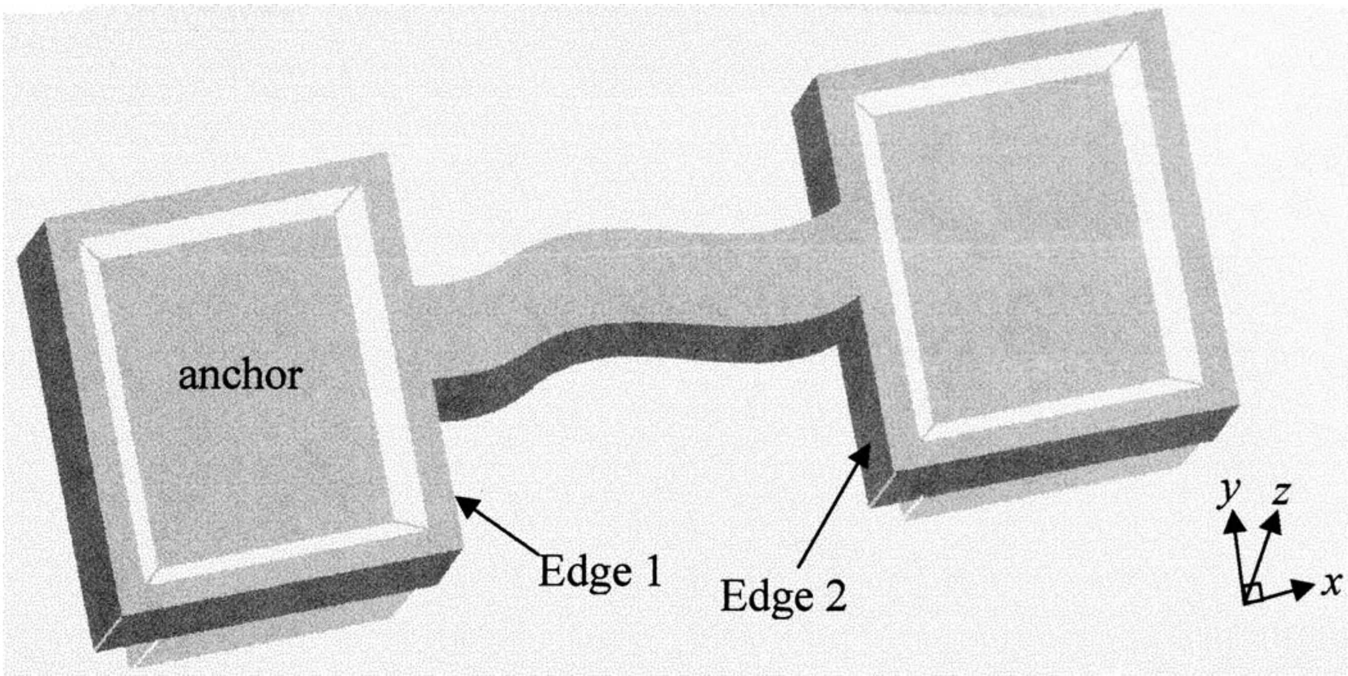


FIG. 1 Three-Dimensional View of Surface-Micromachined Fixed-Fixed Beam

u_{cL} = the combined standard uncertainty for an in-plane length measurement

u_L = the component in the combined standard uncertainty calculation for an in-plane length measurement that is due to the uncertainty in the calculated length

u_{offset} = the component in the combined standard uncertainty calculation for an in-plane length measurement that is due to the uncertainty of the value for L_{offset}

$u_{repeat(L)}$ = the component in the combined standard uncertainty calculation for an in-plane length measurement that is due to the uncertainty of the four measurements taken on the test structure at different locations

$u_{repeat(samp)}$ = the component in the combined standard uncertainty calculation for an in-plane length measurement that is due to the repeatability of measurements taken on test structures processed similarly to the sample, using the same combination of lenses for the given interferometric microscope for the measurement, and for the same or a similar type of measurement

u_{xcal} = the component in the combined standard uncertainty calculation for an in-plane length measurement that is due to the uncertainty of the calibration in the *x*-direction

$x1_{uppert}$ = the uncalibrated *x*-value that most appropriately locates the upper corner associated with Edge 1 using Trace t

$x2_{uppert}$ = the uncalibrated *x*-value that most appropriately locates the upper corner associated with Edge 2 using Trace t

x_{res} = the uncalibrated resolution of the interferometric microscope in the *x*-direction for the given combination of lenses

$y_{a'}$ = the uncalibrated *y*-value associated with Trace a'

$y_{e'}$ = the uncalibrated *y*-value associated with Trace e'

3.2.3 *For Round Robin Measurements:*

ΔL = for the given value of L_{des}, L_{ave} minus L_{des}

ΔL_{ave} = the average value of ΔL over the given range of L_{des} values

L_{ave} = the average in-plane length value for the repeatability or reproducibility measurements that is equal to the sum of the *L* values divided by *n*

L_{des} = the design length

mag = the magnification used for the measurement

n = the number of repeatability or reproducibility measurements

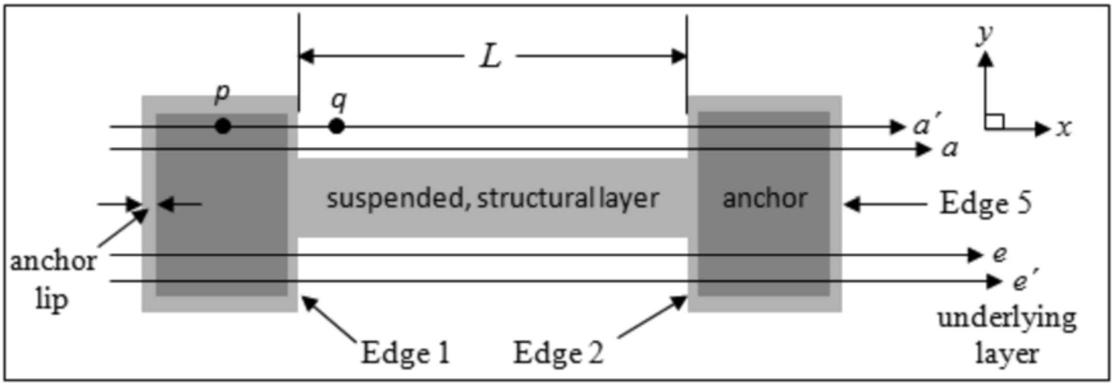
u_{cLave} = the average combined standard uncertainty value for the in-plane length measurements that is equal to the sum of the u_{cL} values divided by *n*

3.2.4 *Discussion*—The symbols above are used throughout this test method. However, the letter "*D*" can replace the letter "*L*" in the symbols above when referring to in-plane deflection measurements, which would imply replacing the word "length" with the word "deflection." Also, when referring to *y* values, the letter "*y*" can replace the first letter in the symbols (or the subscript of the symbols) above that start with the letter "*x*."

4. Summary of Test Method

4.1 Any in-plane length measurement can be made if each end is defined by a transitional edge. Consider the surface-micromachined fixed-fixed beam shown in Figs. 1 and 2. An optical interferometric microscope (such as shown in Fig. 3) is used to obtain a topographical 3-D data set. Four 2-D data traces (one of which is shown in Fig. 4) are extracted from this 3-D data set for the analysis of the transitional edges of interest.

4.2 To obtain the endpoints of the in-plane length measurement for a surface-micromachined structure, four steps are taken: *(1)* select the two transitional edges, *(2)* align the transitional edges in the field of view, *(3)* obtain a 3-D data set,



NOTE 1—The underlying layer is beneath this test structure.
NOTE 2—The structural layer of interest is included in both the light and dark gray areas.
NOTE 3—The light gray area is suspended in air after fabrication.
NOTE 4—The dark gray areas (the anchors) are the designed cuts in the sacrificial layer. This is where the structural layer contacts the underlying layer.
NOTE 5—The 2-D data traces (*a′* and *e′*) are used to determine the misalignment angle, α.
NOTE 6—The 2-D data traces (*a′*, *a*, *e*, and *e′*) are used to determine *L*.

FIG. 2 Top View of Fixed-Fixed Beam in Fig. 1

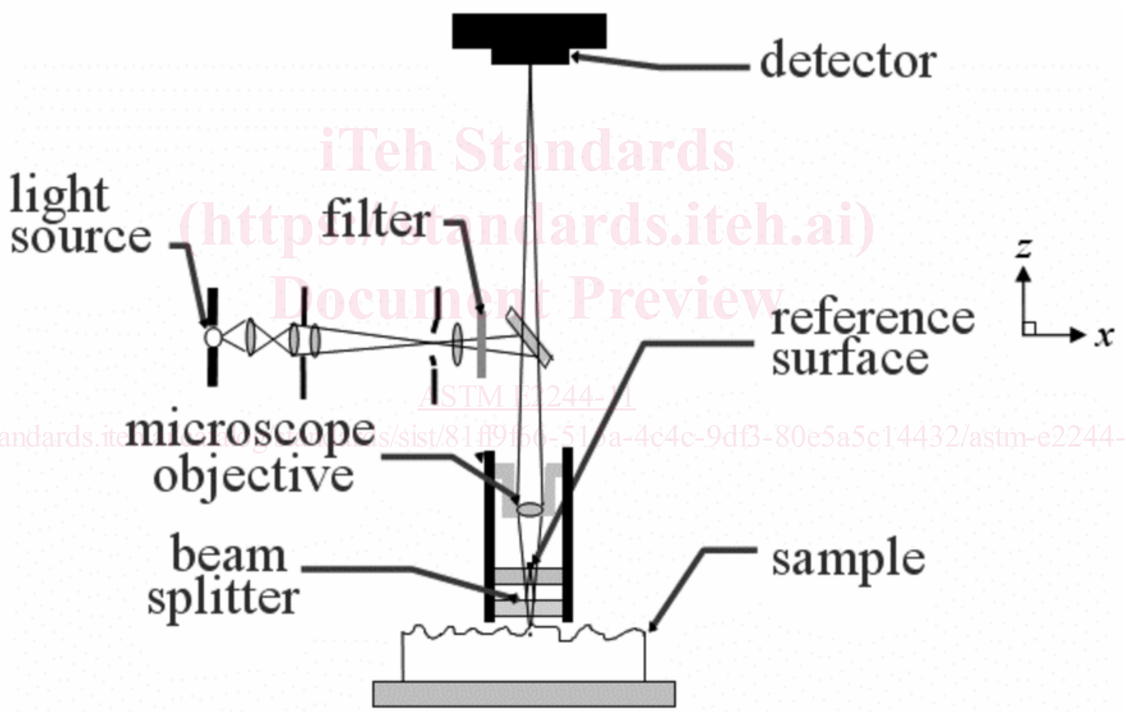


FIG. 3 Schematic of an Optical Interferometric Microscope

and *(4)* obtain the endpoints and associated uncertainties. (This procedure may need to be modified for a bulk-micromachined structure.)

4.3 From each of the four data traces, the *x*-values ($x1_{uppert}$ and $x2_{uppert}$) are obtained at the transitional edges defining *L*, where the subscript *t* is *a*', *a*, *e*, or *e*' to identify Trace *a*', *a*, *e*, or *e*', respectively. The uncertainties ($n1_t$ and $n2_t$) associated with these *x*-values are also obtained. The misalignment angle, α, is calculated from the data obtained from the two outermost data traces (*a*' and *e*') along with the corresponding *y*-values ($y_{a'}$ and $y_{e'}$) associated with these traces. The in-plane length, *L*, is the average of the four calibrated values for ($x2_{uppert} - x1_{uppert}$) times cos(α) plus L_{offset}, the in-plane length correction term.

4.4 Alternatively for a surface-micromachining process, if the transitional edges that define *L* face the same way (for example, two right-hand edges) and have similar slopes and magnitudes, the values for $x1_{lowert}$ and $x2_{lowert}$ can be used instead of $x1_{uppert}$ and $x2_{uppert}$ if the sum of the uncertainties ($n1_t + n2_t$) for the lower values are typically less than the sum of the uncertainties for the upper values. Due to the similarities of the edges involved, the length correction term, L_{offset}, is set equal to zero in the calculation of *L*.

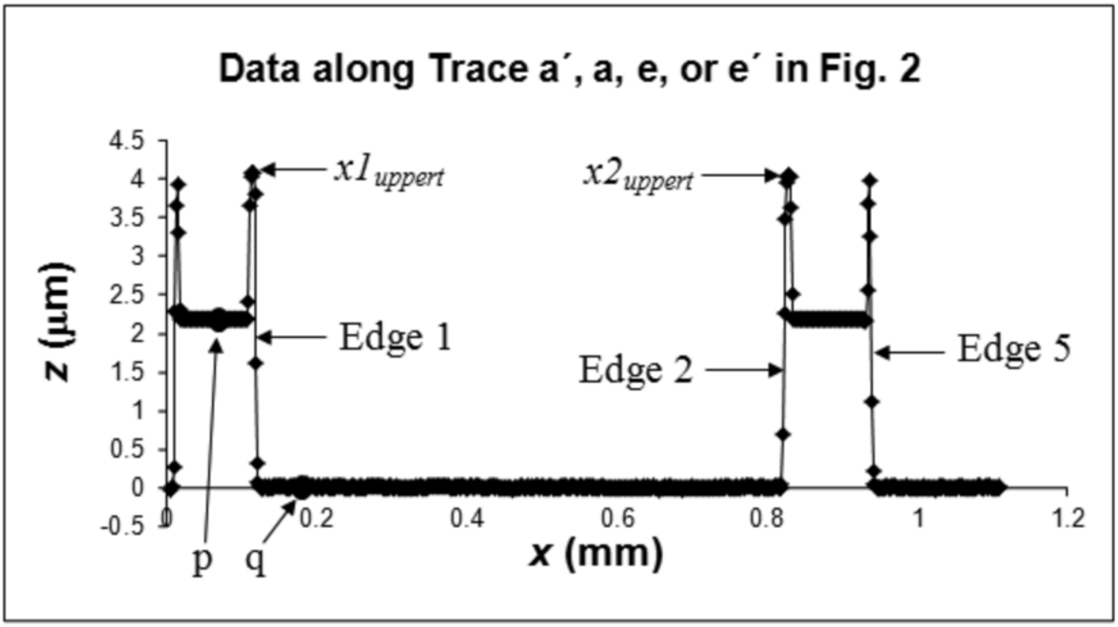


FIG. 4 2-D Data Trace Used to Find $x1_{uppert}$, $x2_{uppert}$, $n1_t$, and $n2_t$

4.5 The equations used to find the combined standard uncertainty are given in Annex A1.

5. Significance and Use

5.1 In-plane length measurements can be used in calculations of parameters, such as residual strain and Young's modulus.

5.2 In-plane deflection measurements are required for specific test structures. Parameters, including residual strain, are calculated given the in-plane deflection measurements.

6. Apparatus[4] (1-3)[5]

6.1 *Non-contact Optical Interferometric Microscope,* capable of obtaining a topographical 3-D data set and exporting a 2-D data trace. Fig. 3 is a schematic of such an interferometric microscope. However, any non-contact optical interferometric microscope that has pixel-to-pixel spacings as specified in Table 1 and that is capable of performing the test procedure with a vertical resolution less than 1 nm is permitted. The interferometric microscope must be capable of measuring step heights to at least 5 µm higher than the physical step height to be measured.

NOTE 1—Table 1 does not include magnifications at or less than 2.5× because the pixel-to-pixel spacings will be too large for this work, or the possible introduction of a second set of interferometric fringes in the data set at these magnifications can adversely affect the data, or both. Therefore, magnifications at or less than 2.5× shall not be used.

NOTE 2—The 1 nm resolution is not mandatory for this test method. In reality, the vertical resolution can be as much as 5 nm. However, the constraint is supplied to alert the user of this instrumental constraint for out-of-plane measurements leading to residual strain, strain gradient, and step height calculations.

TABLE 1 Interferometric Microscope Pixel-to-Pixel Spacing Requirements

Magnification, ×	Pixel-to-Pixel Spacing, µm
5	< 2.00
10	< 1.00
20	< 0.50
40	< 0.40
80	< 0.20

6.2 *10-µm-grid (or finer grid) Ruler,* for calibrating the interferometric microscope in the *xy*-plane. This ruler should be longer than the maximum field of view at the lowest magnification.

6.3 *Double-sided Physical Step Height Standard,* for calibrating the interferometric microscope in the out-of-plane *z*-direction.

6.4 *Thermometer (optional),* to record the temperature during measurement.

6.5 *Humidity Meter (optional),* to record the relative humidity during measurement.

7. Test Units

7.1 The two transitional edges (for example, Edges 1 and 2 in Figs. 1 and 2) defining the in-plane length (or deflection) measurement.

NOTE 3—In a surface-micromachining process, if a transitional edge is on one side of an anchor lip, the anchor lip should be between 4.0 µm and 10.0 µm, inclusive.

8. Calibration[6] (1-3)

8.1 Calibrate the interferometric microscope in the *x*- and *y*-directions using a 10-µm-grid (or finer grid) ruler. Do this for

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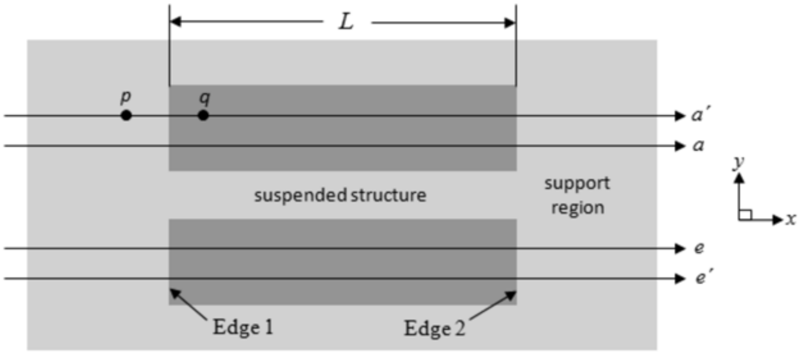
[4] The same apparatus is used (or can be used) in Test Method E2245, Test Method E2246, and SEMI Test Method MS2.

[5] The boldface numbers in parentheses refer to the list of references at the end of this standard.

[6] The same calibration procedure is used as in Test Method E2245 and Test Method E2246. A similar calibration in the z-direction is used in SEMI Test Method MS2.



NOTE 1—The central beam is suspended above a micromachined cavity.

NOTE 2—The dark gray areas are the visible parts of the micromachined cavity.

NOTE 3—The remaining light gray area around the outside of the visible portion of the cavity is suspended in air, attached underneath to the substrate, or both.

NOTE 4—The 2-D data traces (*a′* and *e′*) are used to determine the misalignment angle, α.

NOTE 5—The 2-D data traces (*a′*, *a*, *e*, and *e′*) are used to determine *L*.

FIG. 5 Top View of Bulk-Micromachined Fixed-Fixed Beam

each combination of lenses used for the measurements. Calibrate in the *xy*-plane on a yearly basis.

8.1.1 Orient the ruler in the *x*-direction using crosshairs, if available. Record $ruler_x$ as measured on the interferometric microscope's screen. Determine σ_{xcal}.

8.1.2 Orient the ruler in the *y*-direction using crosshairs, if available. Record $ruler_y$ as measured on the interferometric microscope's screen. Determine σ_{ycal}.

8.1.3 Determine the *x*- and *y*-calibration factors using the following equations:

$$cal_x = \frac{ruler_x}{scope_x} \quad (1)$$

and

$$cal_y = \frac{ruler_y}{scope_y} \quad (2)$$

NOTE 4—Multiply the *x*- and *y*-data values obtained during the data session by the appropriate calibration factor to obtain calibrated *x*- and *y*-data values.

8.2 Calibrate the interferometric microscope in the out-of-plane *z*-direction using the certified value of a physical step height standard. Do this for each combination of lenses used for the measurements.

NOTE 5—Having the physical step height standard calibrated at NIST[7] lowers the total uncertainty in the certified value.

8.2.1 Before the data session, record six measurements of the height of the physical step height standard using six 3-D data sets to accomplish this task. These measurements should be taken spread out evenly along the physical step height standard, being careful to obtain these measurements within the certified range (both along the length and width) of the physical step height standard. If single-sided step height measurements are taken, three measurements should be taken along each side of the physical step height standard.

8.2.2 After the data session, repeat 8.2.1. This step can be skipped if the instrument does not drift significantly during a data session.

8.2.3 Calculate the mean value, $\bar{z}_{ave}$, of the measurements obtained in 8.2.1 and 8.2.2.

8.2.4 Determine the *z*-calibration factor using the following equation:

$$cal_z = \frac{cert}{\bar{z}_{ave}} \quad (3)$$

NOTE 6—Multiply the *z*-data values obtained during the data session by cal_z to obtain calibrated *z*-data values.

9. Procedure (1-3)

9.1 To obtain the endpoints of an in-plane length measurement for a surface-micromachined structure, four steps are taken: *(1)* select the two transitional edges, *(2)* align the transitional edges in the field of view, *(3)* obtain a 3-D data set, and *(4)* obtain the endpoints and associated uncertainties.

NOTE 7—The procedure that follows may need to be modified to obtain the required data. For a bulk-micromachining process, refer to Figs. 5 and 6 instead of Fig. 2 and Fig. 4, respectively, when possible.

9.2 *Select the Two Transitional Edges:*

9.2.1 Select the two transitional edges that define the in-plane length measurement (such as Edges 1 and 2 in Fig. 2). These are the first and second transitional edges.

9.3 *Align the Transitional Edges in the Field of View:*

9.3.1 Align the two transitional edges from 9.2.1 parallel or perpendicular to the *x*- (or *y*-) axis of the interferometric microscope. If the interferometric microscope's pixel-to-pixel spacing is smaller in the *x*-direction than in the *y*-direction, it is preferable to orient the sample such that the in-plane length measurement is taken in the *x*-direction.

NOTE 8—The first transitional edge has *x* (or *y*) values that are less than the *x* (or *y*) values associated with the second transitional edge.

9.4 *Obtain a 3-D Data Set:*

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[7] Physical step height standards are calibrated at NIST as specified in (**4**), Appendix A of (**5**), and Test Method E2530.