



Designation: E2244 – 05

# Standard Test Method for In-Plane Length Measurements of Thin, Reflecting Films Using an Optical Interferometer<sup>1</sup>

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 ( $\epsilon$ ) 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.

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 interferometer. (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 interferometer 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 interferometer at the lowest magnification. The minimum deflection measured is determined by the interferometer'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:<sup>2</sup>

<sup>1</sup> 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.

Current edition approved Nov. 1, 2005. Published December 2005. Originally approved in 2002. Last previous edition approved in 2002 as E2244 – 02. DOI: 10.1520/E2244-05.

<sup>2</sup> 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.

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

## 3. Terminology

### 3.1 Definitions:

3.1.1 *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 interferometer.

3.1.2 *3-D data set, n*—a three-dimensional group of points with a topographical *z*-value for each (*x*, *y*) pixel location within the interferometer's field of view.

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

3.1.4 *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.

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

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

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

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

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

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

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

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

3.1.10 *MEMS, adj*—microelectromechanical system.

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

3.1.12 *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.

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

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

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

3.1.16 *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.

3.1.17 *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.

3.1.18 *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.

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

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

## 3.2 Symbols:

### 3.2.1 For Calibration:

$\sigma_{xcal}$  = the standard deviation in a ruler measurement in the interferometer's  $x$ -direction for the given combination of lenses

$\sigma_{yca}$  = the standard deviation in a ruler measurement in the interferometer's  $y$ -direction for the given combination of lenses

$cal_x$  = the  $x$ -calibration factor of the interferometer for the given combination of lenses

$cal_y$  = the  $y$ -calibration factor of the interferometer for the given combination of lenses

$cal_z$  = the  $z$ -calibration factor of the interferometer for the given combination of lenses

$cert$  = the certified value of the double-sided step height standard

$inter_x$  = the interferometer's maximum field of view in the  $x$ -direction for the given combination of lenses

$inter_y$  = the interferometer's maximum field of view in the  $y$ -direction for the given combination of lenses

$mean$  = the mean value of the step-height measurements (on the double-sided step height standard) used to calculate  $cal_z$

$ruler_x$  = the interferometer's maximum field of view in the  $x$ -direction for the given combination of lenses as measured with a 10- $\mu$ m grid (or finer grid) ruler

$ruler_y$  = the interferometer's maximum field of view in the  $y$ -direction for the given combination of lenses as measured with a 10- $\mu$ m grid (or finer grid) ruler

### 3.2.2 For Alignment:

$xI_{lower}$  = the  $x$ -data value along Edge "1" locating the lower part of the transitional edge

$xI_{upper}$  = the  $x$ -data value along Edge "1" locating the upper part of the transitional edge

$x2_{lower}$  = the  $x$ -data value along Edge "2" locating the lower part of the transitional edge

$x2_{upper}$  = the  $x$ -data value along Edge "2" locating the upper part of the transitional edge

$x_{lower}$  = the  $x$ -data value along the transitional edge of interest locating the lower part of the transition

$x_{upper}$  = the  $x$ -data value along the transitional edge of interest locating the upper part of the transition

### 3.2.3 For In-plane Length Measurement:

$L$  = the in-plane length measurement

$L_{max}$  = the maximum in-plane length measurement

$L_{min}$  = the minimum in-plane length measurement

$sep$  = the average calibrated separation between two interferometric pixels (in either the  $x$ - or  $y$ -direction) as applies to a given measurement or  $sep = (sep_1 + sep_2) / 2$

$sep_1$  = the average calibrated separation between two interferometric pixels at one end of the in-plane length measurement

$sep_2$  = the average calibrated separation between two interferometric pixels at the other end of the in-plane length measurement

$t_{support}$  = in a bulk-micromachining process, the thickness of the support region where it is intersected by the interferometric 2-D data trace of interest

$u_c$  = the combined standard uncertainty value (that is, the estimated standard deviation of the result)

$u_L$  = the component in the combined standard uncertainty calculation that is due to the uncertainty in the calculated length

$u_{xcal}$  = the component in the combined standard uncertainty calculation that is due to the uncertainty of the calibration in the  $x$ -direction

$u_{xres}$  = the component in the combined standard uncertainty calculation that is due to the resolution of the interferometer in the  $x$ -direction

$xI_{max}$  = the smaller of the two  $x$  values ( $xI_{lower}$  or  $xI_{upper}$ ) used to calculate  $L_{max}$

$xI_{min}$  = the larger of the two  $x$  values ( $xI_{lower}$  or  $xI_{upper}$ ) used to calculate  $L_{min}$

$x2_{max}$  = the larger of the two  $x$  values ( $x2_{lower}$  or  $x2_{upper}$ ) used to calculate  $L_{max}$

$x2_{min}$  = the smaller of the two  $x$  values ( $x2_{lower}$  or  $x2_{upper}$ ) used to calculate  $L_{min}$

$x_{res}$  = the resolution of the interferometer in the  $x$ -direction

$z_{upper}$  = the  $z$ -data value associated with  $x_{upper}$

$z_{upper-t}$  = in a bulk-micromachining process, the value for  $z$  when the thickness of the support region,  $t_{support}$ , is subtracted from  $z_{upper}$

### 3.2.4 For Round Robin Measurements:

$\Delta L$  = for the given value of  $L_{des}$ ,  $L_{ave}$  minus  $L_{des}$

$\Delta L_{ave}$  = the average value of  $\Delta L$  over the given range of  $L_{des}$  values

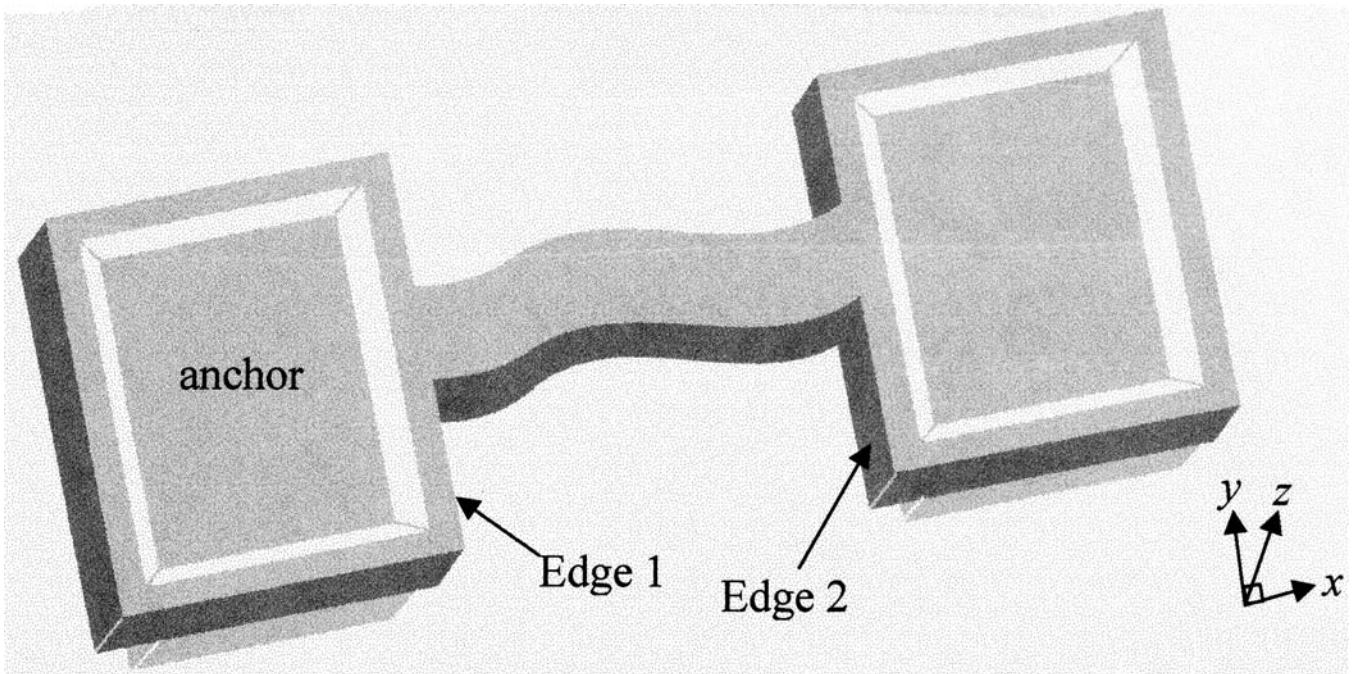


FIG. 1 Three-Dimensional View of Surface-Micromachined Fixed-Fixed Beam



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 ensure alignment.

NOTE 6—A 2-D data trace (“a” or “e”) is used to determine  $L$ .

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

$L_{ave}$  = the average in-plane length value for the reproducibility or repeatability measurements. It 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 reproducibility or repeatability measurements

$u_{cave}$  = the average combined standard uncertainty value for the reproducibility or repeatability measurements. It is equal to the sum of the  $u_c$  values divided by  $n$

3.2.5 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. Also, when referring to  $y$  values, the letter “y” can replace the first letter in 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 interferometer (such as shown in Fig. 3) is used to obtain a topographical 3-D data set. A 2-D data trace (such as

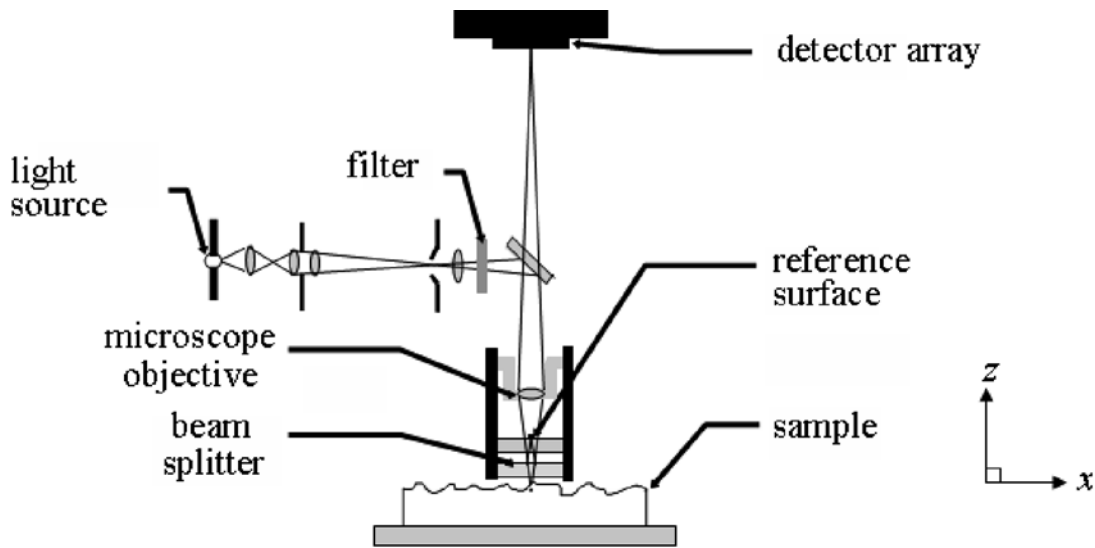


FIG. 3 Schematic of an Optical Interferometer

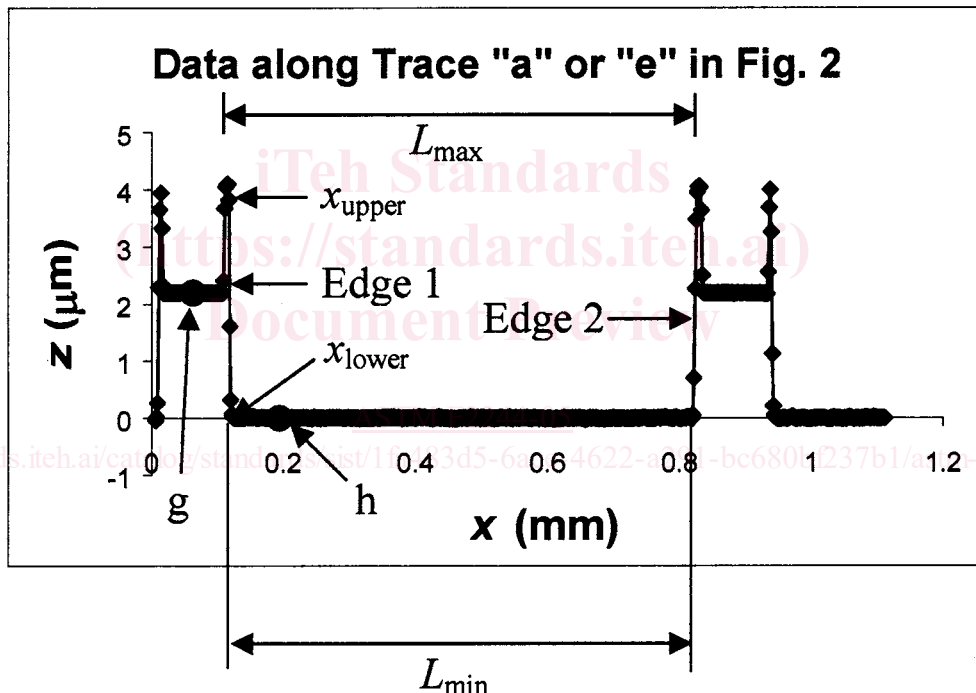


FIG. 4 2-D Data Trace Used to Find  $x1_{min}$ ,  $x1_{max}$ ,  $x2_{min}$ , and  $x2_{max}$

TABLE 1 Interferometer Pixel-to-Pixel Spacing Requirements

Magnification, $\times$	Pixel-to-pixel spacing, $\mu\text{m}$
5	< 1.57
10	< 0.83
20	< 0.39
40	< 0.21
80	< 0.11

shown in Fig. 4) is 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 four transitional edges, (2) obtain a 3-D data

set, (3) ensure alignment, and (4) determine the endpoints. (This procedure is presented in Appendix X1 for a bulk-micromachined structure or a surface-micromachined structure with transitional edges greater than 8  $\mu\text{m}$  in height.)

4.3 At the transitional edges defining  $L$ , the endpoints are  $x1_{min}$ ,  $x1_{max}$ ,  $x2_{min}$ , and  $x2_{max}$ .  $L_{min}$  and  $L_{max}$  are calculated from these values.  $L$  is the average of  $L_{min}$  and  $L_{max}$ .

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, a different approach can be taken. Here,  $L$  is the positive difference between the endpoints  $x1_{lower}$  and  $x2_{lower}$  (or  $x1_{upper}$  and  $x2_{upper}$ ).

## 5. Significance and Use

5.1 In-plane length measurements are 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 these in-plane deflection measurements.

## 6. Apparatus<sup>3</sup>

6.1 *Non-contact Optical Interferometer*, capable of obtaining a topographical 3-D data set and exporting a 2-D data trace. Fig. 3 is a schematic of such an interferometer. However, any non-contact optical interferometer 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 interferometer must be capable of measuring step heights to at least 5 μm higher than the 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 and strain gradient calculations.

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

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

## 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 wide enough to include at least three data points. If the pixel-to-pixel spacing is 1.56 μm, then the anchor lip should be at least 3.2 times greater (or 5.0 μm).

## 8. Calibration<sup>4</sup> (1)<sup>5</sup>

8.1 Calibrate the interferometer in the *x*- and *y*-directions using a 10-μm-grid (or finer grid) ruler. Do this for each combination of lenses used for the measurements. Calibrate in the *xy*-plane on a yearly basis.

### 8.1.1 For Non-reflective Rulers:

8.1.1.1 Orient the ruler in the *x*-direction using crosshairs, if available. Record *ruler<sub>x</sub>* as measured on the interferometer's screen. Determine  $\sigma_{xcal}$ .

8.1.1.2 Orient the ruler in the *y*-direction using crosshairs, if available. Record *ruler<sub>y</sub>* as measured on the interferometer's screen. Determine  $\sigma_{yca}$ .

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

$$cal_x = ruler_x / inter_x \quad (1)$$

and

$$cal_y = ruler_y / inter_y \quad (2)$$

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.

### 8.1.2 For Reflective Rulers:

8.1.2.1 Orient the ruler in the *x*-direction along the bottom edge of the field of view using crosshairs (if available).

8.1.2.2 Select the detector array size that achieves the best lateral resolution.

8.1.2.3 Adjust the intensity with respect to the brightest layer of interest.

8.1.2.4 Eliminate any tilt in the sample by nulling the fringes on the top of the flattest region of the ruler.

8.1.2.5 Recheck the sample alignment.

8.1.2.6 Take an average of at least three measurements to comprise one 3-D data set. Level the 3-D data set, with respect to flat regions of the ruler that are chosen to be symmetrically located with respect to the ruler, if possible.

8.1.2.7 Move the ruler slightly in the *y*-direction and obtain another leveled 3-D data set.

8.1.2.8 Continue until the ruler is out of the field of view.

NOTE 5—Obtain at least five data sets representative of the field of view.

8.1.2.9 For each leveled 3-D data set, extract a 2-D data trace in the *xz*-plane at the same location on the ruler, if possible.

8.1.2.10 Record in tabular form the ruler measurements versus *x* for each *y*.

8.1.2.11 Orient the ruler in the *y*-direction along the left-hand edge of the field of view. Repeat the above steps in a similar manner.

NOTE 6—This step can be skipped if the in-plane measurements are restricted to the *x*-direction due to a smaller pixel-to-pixel spacing in that direction.

8.1.2.12 By interpolating or extrapolating, or both, use the newly created calibrated lookup table(s) to find the calibrated *x* (or *y*, or both) values for pertinent pixels within the field of view. In the vicinity of the measurements to be taken, determine *cal<sub>x</sub>* (or *cal<sub>y</sub>*, or both), as given in Eq 1 (or Eq 2, or both). Also, determine  $\sigma_{xcal}$  (or  $\sigma_{yca}$ , or both).

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

NOTE 7—Calibrating the step height at NIST<sup>6</sup> lowers the total uncertainty in the certified value.

<sup>3</sup> The same apparatus is used as in Test Method E2245 and Test Method E2246.

<sup>4</sup> The same calibration procedure is used as in Test Method E2245 and Test Method E2246.

<sup>5</sup> The boldface numbers in parentheses refer to the list of references at the end of this standard.

<sup>6</sup> The step heights are calibrated at NIST using a stylus instrument as specified in (2) and Appendix A of (3).

8.2.1 Before the data session, record the height of the step height standard at six locations, three spread out evenly along each side of the step height standard. Use six, 3-D data sets to accomplish this task.

8.2.2 After the data session, record the height of the step height standard at six locations, three spread out evenly along each side of the step height standard. Use six, 3-D data sets to accomplish this task.

8.2.3 Calculate the mean value of the twelve measurements.

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

$$cal_z = cert / mean \quad (3)$$

NOTE 8—Multiply the  $z$ -data values obtained during the data session by  $cal_z$  to obtain calibrated  $z$ -data values.

## 9. Procedure (1)

9.1 To obtain the endpoints of an in-plane length measurement for a surface-micromachined structure, four steps are taken: (1) select four transitional edges, (2) obtain a 3-D data set, (3) ensure alignment, and (4) determine the endpoints.

NOTE 9—See Appendix X1 for the modifications to this procedure for a bulk-micromachined structure. Also, situations may arise (for example, when the transitional edges are greater than 8  $\mu\text{m}$  in height) where a surface-micromachined structure should be treated as a bulk-micromachined structure using the procedure in Appendix X1.

### 9.2 Select Four Transitional Edges:

9.2.1 Select two transitional edges that define the in-plane length measurement (such as Edges “1” and “2” in Fig. 2).

NOTE 10—These are the first and second transitional edges. The first transitional edge has  $x$  (or  $y$ ) values that are less than the  $x$  (or  $y$ ) values associated with the second transitional edge.

9.2.2 Select two transitional edges to ensure alignment (for example, Edges “1” and “2” in Fig. 2). These transitional edges should be aligned parallel or perpendicular to the  $x$ - (or  $y$ -) axis of the interferometer. Therefore, they are typically edges that are the same, edges that are parallel, or edges that are perpendicular to those in 9.2.1 that define the in-plane length measurement.

### 9.3 Obtain a 3-D Data Set:

9.3.1 Orient the sample in the interferometer’s  $x$ -direction, if possible, if the interferometer’s pixel-to-pixel spacing is smaller in the  $x$ -direction than in the  $y$ -direction. Otherwise, an orientation in the  $y$ -direction is acceptable.

9.3.2 Obtain a 3-D data set that contains 2-D data traces perpendicular to the four transitional edges in 9.2, if possible.

9.3.2.1 Use the most powerful objective possible (while choosing the appropriate field of view lens, if applicable) given the sample areas to be investigated.

9.3.2.2 Select the detector array size that achieves the best lateral resolution.

9.3.2.3 Visually align the transitional edges in the field of view using crosshairs (if available).

9.3.2.4 Adjust the intensity with respect to the brightest layer of interest.

9.3.2.5 Eliminate any tilt in the sample by nulling the fringes on the top of the exposed underlying layer that is symmetrically located with respect to the in-plane length measurement.

9.3.2.6 Recheck the sample alignment.

9.3.2.7 Take an average of at least three measurements to comprise one 3-D data set. Level the 3-D data set, with respect to the top of the underlying layer, with regions chosen to be symmetrically located with respect to the in-plane length measurement. The  $z$  values of the data points along the top of the underlying layer are expected to lie between  $\pm 40$  nm.

### 9.4 Ensure Alignment:

9.4.1 Choose two, 2-D data traces (within the leveled 3-D data set in 9.3.2.7) for each selected transitional edge in 9.2.2.

NOTE 11—Each trace passes through and is perpendicular to at least one of the selected transitional edges for ensuring alignment. If possible, choose traces that are sufficiently separated (such as Traces “a” and “e” on either side of the fixed-fixed beam in Fig. 2, as shown in Fig. 4). In this example, Traces “a” and “e” can be used for both Edge “1” and Edge “2.”

9.4.2 Calibrate the 2-D data traces in the  $x$ - (or  $y$ -) and  $z$ -directions.

9.4.3 Obtain  $x_{upper}$  and  $x_{lower}$  for the two selected transitional edges in the alignment traces using the procedures given in 9.4.4 and 9.4.5. Therefore, eight values are obtained.

#### 9.4.4 Procedure to Find $x_{upper}$ :

9.4.4.1 Locate two points (“g” and “h”) on either side of the transitional edge (such as, Edge “1” in Fig. 4) being examined. Choose Point “g” to be located beyond the upper part of the transitional edge. Choose Point “h” to be located beyond the lower part of the transitional edge.

NOTE 12—Point “g” has a  $z$ -data value that is higher than the  $z$ -data value for Point “h.”

9.4.4.2 Examine the out-of-plane  $z$ -data values one-by-one going from Point “h” to Point “g” in Fig. 4.

9.4.4.3 Along the upper half of the transition, the  $x$  value associated with the first  $z$  value, which is less than 300 nm from the next  $z$  value is called  $x_{upper}$ .

NOTE 13—The difference in the  $z$  value of two neighboring points along the transitional edge is large (that is, typically greater than 500 nm). Along the anchor lip, this difference is a lot less (that is, typically less than 100 nm). The 300 nm criteria allows for an anchor lip that is not flat, rougher surfaces, and other phenomena. The 300 nm criteria may need to be modified, for example, when higher magnification lenses are used or for peculiarities in the sample or the 2-D data trace being examined, or both.

#### 9.4.5 Procedure to Find $x_{lower}$ :

9.4.5.1 Examine the  $z$ -data values one-by-one. However, this time go from Point “g” to Point “h” in Fig. 4.

9.4.5.2 Skip over the data points until a  $z$  value is obtained that is less than 75 nm.

NOTE 14—The  $z$  values of the data points along the top of the underlying layer are expected to lie between  $\pm 40$  nm. Choosing the first  $z$  value that is less than 75 nm allows for poor leveling, rougher surfaces, and other phenomena. The 75 nm criteria may need to be modified for peculiarities in the sample or the 2-D data trace being examined, or both.

9.4.5.3 The  $x$  value associated with the newly found  $z$  value is  $x_{lower}$ .

9.4.6 Compare the two values for  $x_{upper}$  in the two alignment traces for one of the transitional edges selected in 9.2.2.

9.4.7 For this same transitional edge, compare the two values for  $x_{lower}$  in the two alignment traces.

9.4.8 Compare the two values for  $x_{upper}$  in the two alignment traces for the other transitional edge selected in 9.2.2.