Designation: E 2244 – 02

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

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 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:*

E 2245 Test Method for Residual Strain Measurements of Thin, Reflecting Films Using an Optical Interferometer[2]

E 2246 Test Method for Strain Gradient Measurements of Thin, Reflecting Films Using an Optical Interferometer[2]

3. Terminology

3.1 *Definitions:*

3.1.1 *2-D data trace*, *n*—a two-dimensional data trace that is extracted from a topographical 3-D data set and that is parallel to the *xz*- or *yz*-plane of the interferometer.

3.1.1.1 *Discussion*—The height of the sample is measured along the *z*-axis of the interferometer. The interferometer's *x*-axis (as shown in Figs. 1 and 2) is typically aligned parallel or perpendicular to the transitional edges to be measured.

3.1.2 *3-D data set*, *n*—a three-dimensional data set with a topographical *z*-data 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 the mechanical layer makes contact with the underlying layer (see Fig. 2).

3.1.4 *anchor lip*, *n*—in a surface-micromachining process, the extension of the mechanical layer around the edges of the anchor (see Fig. 2).

3.1.5 *bulk micromachining, adj*—a MEMS fabrication process where the substrate is removed at specified locations, which can create structures suspended in air.

3.1.6 *cantilever, n*—a test structure that consists of a beam suspended in air and anchored or supported at one end.

3.1.7 *fixed-fixed beam*, *n*—a test structure that consists of a beam suspended in air and anchored or supported at both ends (see Figs. 1 and 2, and Fig. X1.1).

3.1.8 *in-plane length measurement*, *n*—a length (or deflection) measurement made parallel to the underlying layer (or the *xy*-plane).

3.1.9 *interferometer*, *n*—a non-contact optical instrument (such as shown in Fig. 3) used to obtain topographical 3-D data sets.

3.1.10 *mechanical layer*, *n*—in a surface-micromachining process, the patterned layer (as shown in Fig. 2) that is anchored to the underlying layer where cuts are designed in the sacrificial layer and that is suspended in air where no cuts are designed in the sacrificial layer.

3.1.11 *MEMS*, *adj*—microelectromechanical systems.

3.1.12 *sacrificial layer*, *n*—in a surface-micromachining process, the layer fabricated between the mechanical layer and the underlying layer. This layer is removed after fabrication. If cuts are designed in this sacrificial layer (as shown in Fig. 2),

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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] *Annual Book of ASTM Standards*, Vol 03.01.

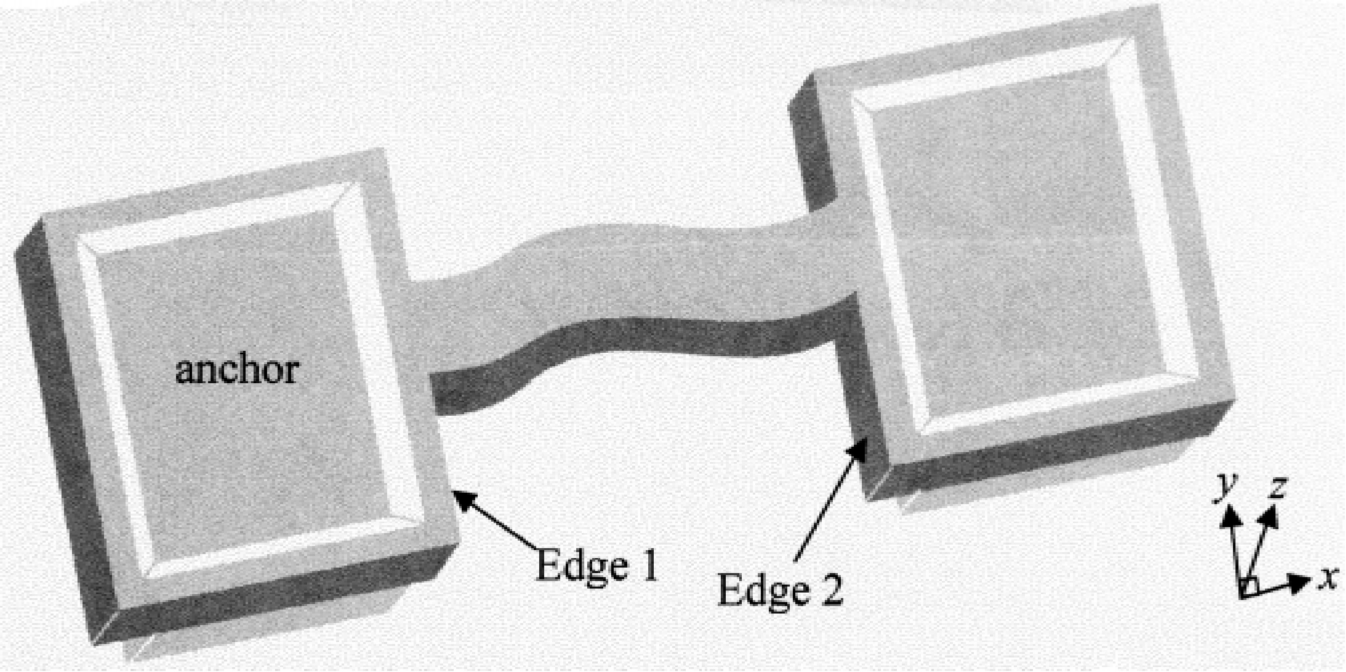
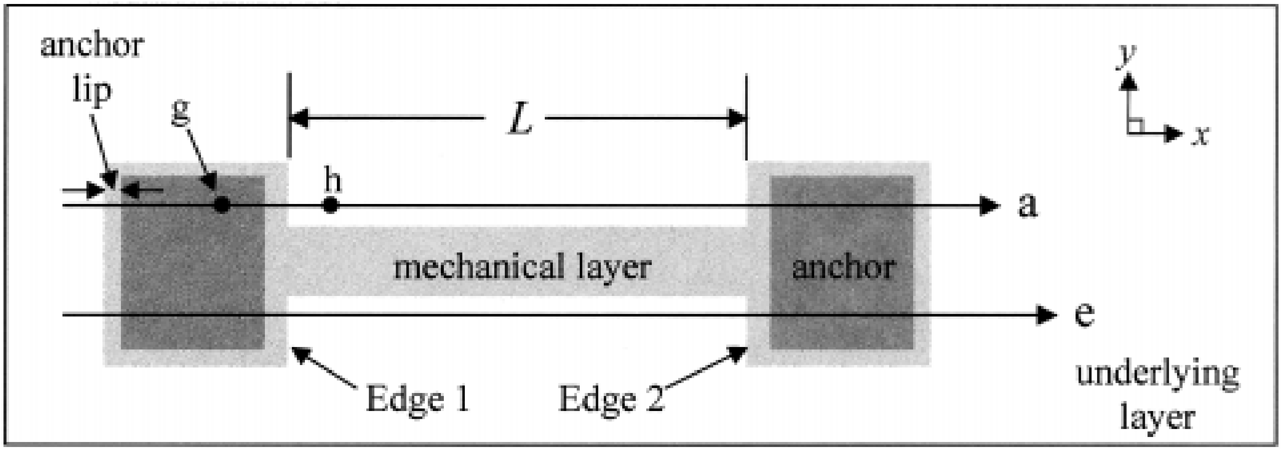


FIG. 1 Three-Dimensional View of Surface-Micromachined Fixed-Fixed Beam



NOTE 1—The underlying layer is beneath this test structure.

NOTE 2—The mechanical layer is included in both the light and dark gray areas.

NOTE 3—The dark gray areas (the anchors) are the designed cuts in the sacrificial layer. This is where the mechanical layer contacts the underlying layer.

NOTE 4—The light gray area is suspended in air after fabrication.

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

an anchor is created allowing the mechanical layer to contact the underlying layer in that region.

3.1.13 *substrate*, *n*—the thick, starting material in a MEMS fabrication process.

3.1.14 *support region*, *n*—in a bulk-micromachining process, the region that marks the end of the suspended structure. This region is suspended in air, attached to the substrate, or both.

3.1.15 *surface micromachining*, *adj*—a MEMS fabrication process where thin, sacrificial layers are removed, which can create structures suspended in air.

3.1.16 *test structure*, *n*—a structure (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.

3.1.17 *transitional edge*, *n*—an edge of a MEMS structure (such as Edge "1" in Fig. 2) that is characterized by a distinctive out-of-plane vertical displacement (as shown in Fig. 4).

3.1.18 *underlying layer*, *n*—in a surface-micromachining process, the layer directly beneath the mechanical layer after the sacrificial layer is removed.

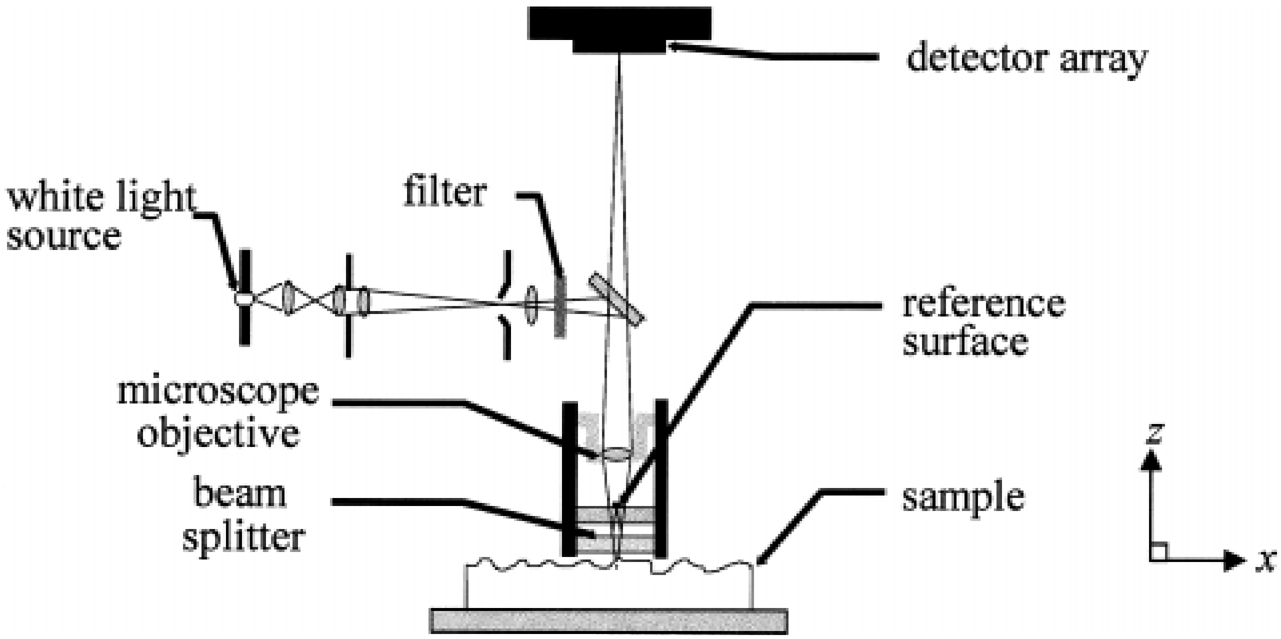


FIG. 3 Sketch of Optical Interferometer

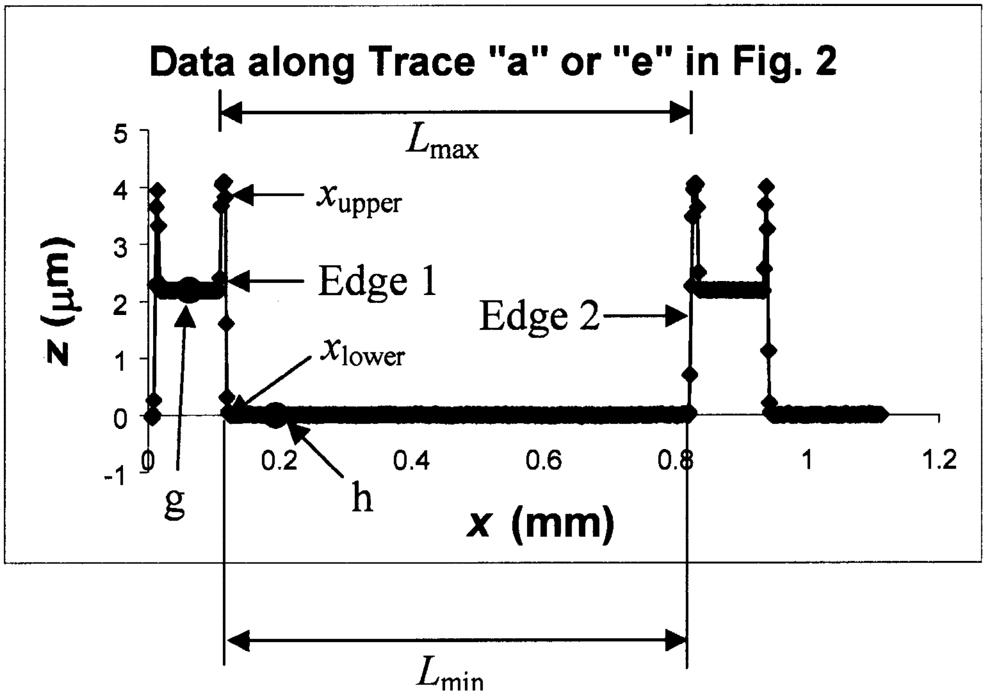


FIG. 4 2-D Data Trace Used to Find $x1_{min}$, $x1_{max}$, $x2_{min}$, and $x2_{max}$

3.2 *Symbols:*

3.2.1 *For Calibration*:

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-µm 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-µm grid ruler

3.2.2 *For Alignment*:

$x1_{lower}$ = the x-data value along Edge "1" (such as shown in Fig. 4) locating the lower part of the transition

$x1_{upper}$ = the x-data value along Edge "1" (such as shown in Fig. 4) locating the upper part of the transition

$x2_{lower}$ = the x-data value along Edge "2" (such as shown in Fig. 4) locating the lower part of the transition

$x2_{upper}$ = the x-data value along Edge "2" (such as shown in Fig. 4) locating the upper part of the transition

x_{lower} = the x-data value along the transitional edge of interest locating the lower part of the transition (see Fig. 4)

x_{upper} = the x-data value along the transitional edge of interest locating the upper part of the transition (see Fig. 4)

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 2-D data trace of interest (such as, Trace "a" or "e" in Fig. X1.1, as shown in Fig. X1.2)

u_c = the combined standard uncertainty value (that is, the estimated standard deviation of the result)[3]

$x1_{max}$ = the smaller of the two x values ($x1_{lower}$ or $x1_{upper}$) used to calculate L_{max}

$x1_{min}$ = the larger of the two x values ($x1_{lower}$ or $x1_{upper}$) 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}

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

$z_{upper\text{-}t}$ = 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 *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. 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.)

4.2 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}.

4.3 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 [4]

6.1 *Non-contact Optical Interferometer*, capable of obtaining a topographical 3-D data set and has software that can export a 2-D data trace. Fig. 3 is a sketch of a suitable non-contact optical 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 from 0.1 nm to at least 10 µm higher than the step height to be measured.

NOTE 1—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 Ruler*, for calibrating the interferometer in the xy-plane.

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.

TABLE 1 Interferometer Pixel-to-Pixel Spacing Requirements

Magnification, ×	Pixel-to-pixel spacing, µm
5	< 1.57
10	< 0.83
20	< 0.39
40	< 0.21
80	< 0.11

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[3] Taylor, B. N. and Kuyatt, C. E., "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," *NIST Technical Note 1297*, National Institute of Standards and Technology, September 1994.

[4] The same apparatus is used as in Test Method E 2245 and Test Method E 2246.

NOTE 2—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 [5]

8.1 Calibrate the interferometer in the *x*- and *y*-directions using a 10-µm-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-x* as measured on the interferometer's screen.

8.1.1.2 Orient the ruler in the *y*-direction using crosshairs, if available. Record *ruler-y* as measured on the interferometer's screen.

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

$$cal\text{-}x = ruler\text{-}x \;/\; inter\text{-}x \tag{1}$$

and

$$cal\text{-}y = ruler\text{-}y \;/\; inter\text{-}y \tag{2}$$

NOTE 3—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.

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

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

NOTE 4—Obtain at least five data sets representative of the field of view.

8.1.2.9 For each 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 5—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* (and/or *y*) values for pertinent pixels within the field of view.

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 6—Calibrating the step height at NIST[6] lowers the total uncertainty in the certified value.

8.2.1 Before the data session, record the height of the step height standard at six locations, three on 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 on 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:

$$cal\text{-}z = cert \;/\; mean \tag{3}$$

NOTE 7—Multiply the *z*-data values obtained during the data session by *cal-z* to obtain calibrated *z*-data values.

9. Procedure [7]

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 8—See Appendix X1 for the modifications to this procedure for a bulk-micromachined structure.

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 9—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 *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.

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[5] The same calibration procedure is used as in Test Method E 2245 and Test Method E 2246.

[6] The step heights are calibrated at NIST using a stylus instrument as specified in Song, J. F. and Vorburger, T. V., "Standard Reference Specimens in Quality Control of Engineering Surfaces," *J. Res. Natl. Inst. Stand. Technol.*, Vol 96, No. 3, May-June 1991, pp. 271-289 and Appendix A of Vorburger, T. V., Evans, C. J., and Estler, W. T., "Rationale and Procedures for Development of a NASA Primary Metrology Laboratory for Large Optics," *NISTIR 6710*, National Institute of Standards and Technology, March 2001.

[7] Marshall, J. C., "MEMS Length and Strain Measurements Using an Optical Interferometer," *NISTIR 6779*, National Institute of Standards and Technology, August 2001.

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.

9.4 *Ensure Alignment*:

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

NOTE 10—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 11—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 12—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 2-D data trace being examined.

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 13—The *z* values of the data points along the top of the underlying layer are expected to lie between ±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 2-D data trace being examined.

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.

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

9.4.10 If more than half of the comparisons performed in 9.4.6-9.4.9, inclusive, result in compared values that are not identical, rotate the sample slightly, obtain another 3-D data set as detailed in 9.3, and repeat the steps in 9.4.

NOTE 14—The compared values correspond to discrete pixel locations. Therefore, obtaining identical *x* values between two traces is not an insurmountable task. However, if alignment cannot be achieved as specified above (for example, when higher magnification lenses are used), visually align the sample within the field of view of the interferometer.

9.5 *Determine the Endpoints*:

9.5.1 Choose the 2-D data trace(s) within the 3-D data set to determine *L* (such as Trace “a” or “e” in Fig. 2). These traces pass through and are perpendicular to Edge “1,” Edge “2,” or both.

9.5.2 Calibrate the 2-D data trace(s) in the *x*- (or *y*-) and *z*-directions, if not already done.

9.5.3 Obtain $x1_{max}$ and $x1_{min}$ using the procedures in 9.4.4 and 9.4.5 for Edge “1.”

9.5.4 Obtain $x2_{max}$ and $x2_{min}$ using the procedures in 9.4.4 and 9.4.5 for Edge “2.”

10. Calculation

10.1 *L* is calculated from the endpoints obtained in 9.5.3 and 9.5.4 for a surface-micromachined structure (or in X1.5.3 and X1.5.4 for a bulk-micromachined structure).

10.2 Calculate L_{min} and L_{max} using the following two equations:

$$L_{min} = x2_{min} - x1_{min} \tag{4}$$

$$L_{max} = x2_{max} - x1_{max} \tag{5}$$

10.3 Calculate *L* using the following equation:

$$L = (L_{min} + L_{max}) / 2 \tag{6}$$

10.4 With 99.7 % confidence assuming a Gaussian distribution, the value for *L* is between L_{min} and L_{max}. Therefore,

$$L = (L_{min} + L_{max}) / 2 \pm (L_{max} - L_{min}) / 2 \tag{7}$$

10.5 Calculate u_c using the following equation:

$$u_c = (L_{max} - L_{min}) / 6 \tag{8}$$

10.6 For surface-micromachined structures, if the transitional edges defining *L* are oriented in the same direction and have similar slopes and magnitudes; also, calculate *L* using a different formula.

10.6.1 If the values for x_{lower} are more definitive than the values for x_{upper}, use the following equation:

$$L = x2_{lower} - x1_{lower} \tag{9}$$

NOTE 15—The value is more definitive if it more accurately locates the abrupt transition.

NOTE 16—If the values for x_{upper} are more definitive than the values for x_{lower}, use the following equation:

$$L = x2_{upper} - x1_{upper} \quad (10)$$

10.6.2 Calculate L_{min} and L_{max} using the following two equations:

$$L_{min} = L - 2sep \quad (11)$$

$$L_{max} = L + 2sep \quad (12)$$

10.6.3 With 99.7 % confidence assuming a Gaussian distribution, the value for L is between L_{min} and L_{max}. Therefore,

$$L = (x2_{lower} - x1_{lower}) \pm (L_{max} - L_{min}) / 2 \quad (13)$$

or

$$L = (x2_{lower} - x1_{lower}) \pm 2sep \quad (14)$$

10.6.4 Calculate u_c using one of the following equations:

$$u_c = (L_{max} - L_{min}) / 6 \quad (15)$$

or

$$u_c = 2sep / 3 \quad (16)$$

10.6.5 Choose the resulting value for L (that is, that calculated in 10.3 or that calculated in 10.6.1) that yields the smaller value for u_c (as calculated in 10.5 or as calculated in 10.6.4, respectively).

11. Report

11.1 Report the results as follows:[3] The length is believed to lie in the interval $L \pm u_c$ with a level of confidence of approximately 68 % assuming a Gaussian distribution.

12. Precision and Bias

12.1 In the spring of 1999, ASTM conducted a round robin experiment[7] that included the measurements of in-plane lengths and deflections. Both optical interferometers and optical microscopes were used to take these measurements. Twelve laboratories participated in the round robin with the laboratories using their own measurement methods. Significant variations were found when the laboratories measured the same devices. For example, for a designed 196-µm long fixed-fixed beam, the measured in-plane lengths among the laboratories ranged from 190 to 224.6 µm. This is a 34.6-µm range in the in-plane length measurement, which can be decreased by at least an order of magnitude.

12.2 For a designed 196-µm long fixed-fixed beam, it is expected that the length, L, will be 196 ± 0.3 µm after fabrication. Therefore, for the next round robin, with the use of this test method, it is expected that the measurements will lie in the interval $L \pm u_c$ (where $u_c = 0.53$ µm) with a level of confidence of approximately 68 % assuming a Gaussian distribution. The variations in the community measurements will be significantly tightened.

12.3 *Precision*—To be determined in the next round robin experiment.

12.4 *Bias*—To be determined in the next round robin experiment.

13. Keywords

13.1 cantilevers; combined standard uncertainty; deflection measurements; fixed-fixed beams; interferometry; length measurements; microelectromechanical systems; MEMS; polysilicon; residual strain; strain gradient; test structure

APPENDIX

(Nonmandatory Information)

X1. OBTAINING THE ENDPOINTS OF AN IN-PLANE LENGTH MEASUREMENT FOR A BULK-MICROMACHINED STRUCTURE

X1.1 To obtain the endpoints of an in-plane length measurement for a bulk-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 X1.1—The substrate etching in a bulk-micromachining process can be considered custom. Different etchants are used and for varying lengths of time. Therefore, the procedure that follows may need to be modified for the given application.

NOTE X1.2—In the procedure that follows, refer to Figs. X1.1 and X1.2 instead of Fig. 2 and Fig. 4, respectively. Also, replace the words "anchor lip" with the words "support region."

X1.2 *Select Four Transitional Edges:*

X1.2.1 Follow the steps in 9.2 with the following modification:

X1.2.2 If the edges of the etched out cavity are jagged, Edges "1" and "2" in Fig. X1.1 will not be appropriate for ensuring alignment. Select other edges, preferably in the field of view, for this purpose.

X1.3 *Obtain a 3-D Data Set:*

X1.3.1 Follow the steps in 9.3 with the following modification:

X1.3.2 Eliminate any tilt in the sample by nulling the fringes on the top of flat regions of the sample that are symmetrically located with respect to the in-plane length measurement.

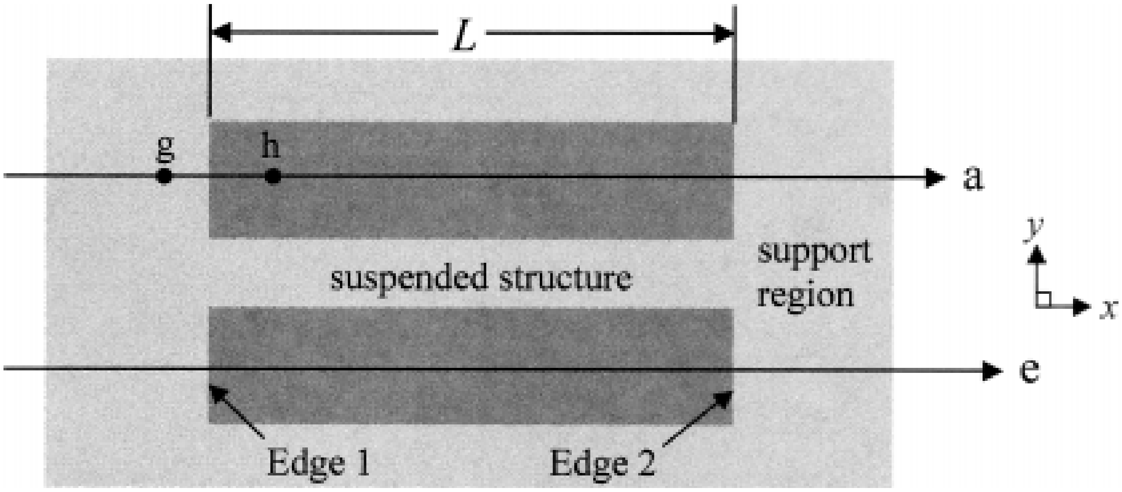
X1.4 *Ensure Alignment:*

X1.4.1 Follow the steps in 9.4 with the following modifications:

X1.4.2 Obtain x_{upper} for the two selected transitional edges in the alignment traces using the procedure given in 9.4.4. Therefore, four values are obtained.

X1.4.3 Skip 9.4.5, 9.4.7, and 9.4.9.

NOTE X1.3—If the edges of the etched out cavity are jagged and these are the only ones available to ensure alignment, it may not be possible to ensure alignment by comparing values along these edges. If this is the



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

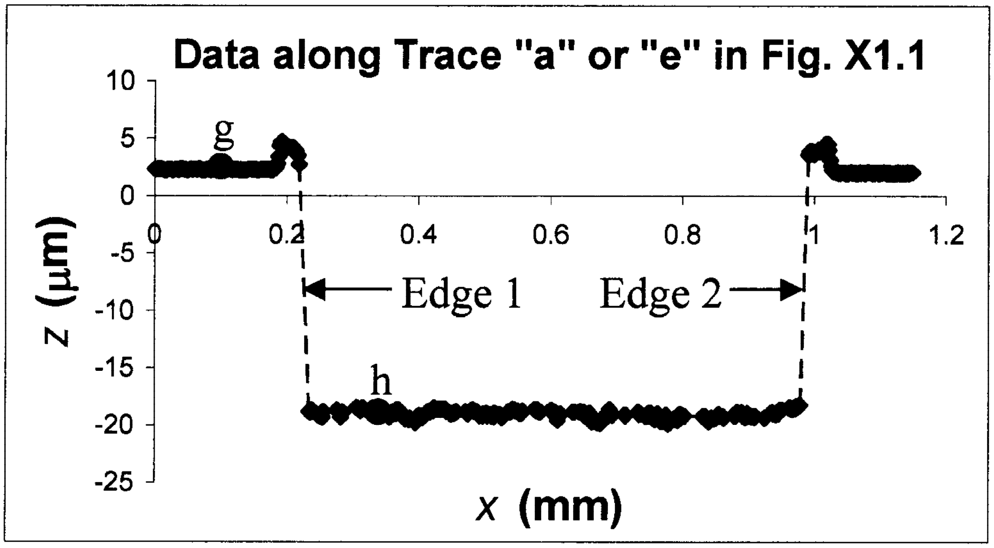
NOTE 2—The dark gray areas are the visible parts of the micromachined cavity.

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 ensure alignment.

NOTE 5—A 2-D data trace (“a” or “e”) is used to determine *L*.

FIG. X1.1 Top View of Bulk-Micromachined Fixed-Fixed Beam



NOTE—Data points are missing along and near Edges “1” and “2.”

FIG. X1.2 2-D Data Trace Used to Determine *L*

case, make sure the sample is visually aligned within the field of view of the interferometer.

X1.5 *Determine the Endpoints:*

X1.5.1 Follow the steps in 9.5 with the following modifications:

X1.5.2 The edges of the etched out cavity may be jagged, therefore, choose the trace or traces to represent the endpoints to be measured.

X1.5.3 Obtain $x1_{max}$ and $x1_{min}$ using the procedures in 9.4.4 and X1.5.5 for Edge “1.”

X1.5.4 Obtain $x2_{max}$ and $x2_{min}$ using the procedures in 9.4.4 and X1.5.5 for Edge “2.”

X1.5.5 There are four procedures that follow to find x_{lower} (choose the first one that is appropriate):

X1.5.5.1 If there are no missing pertinent data points along or near the transitional edge, examine the *z*-data values one-by-one going from Point “g” to Point “h” in Fig. X1.2. Skip over the data points until a *z* value is obtained that is associated with the bottom of the etched out cavity. The *x* value associated with the newly found *z* value is x_{lower}.

X1.5.5.2 Choose the bottommost *z* value that is available along the transitional edge. Record the *z*-data value (that is, z_{upper}) associated with x_{upper} (as obtained in 9.4.4). Subtract from z_{upper} the thickness of the support region, $t_{support}$, where it is intersected by the 2-D data trace. Call the resultant value $z_{upper\text{-}t}$. If the chosen z value along the transitional edge is less than $z_{upper\text{-}t}$ minus 500 nm (that is, $z_{upper\text{-}t\text{-}500}$), then the x value associated with the chosen z value is x_{lower}.

NOTE X1.4—The 500 nm criteria allows for phenomena associated with measurements taken along transitional edges and any effects due to secondary fringes.

X1.5.5.3 Locate the data point in the etched out cavity that is closest to the transitional edge. Call this point (x_{cavity}, z_{cavity}). Determine $z_{upper\text{-}t\text{-}500}$. Interpolate to find $x_{upper\text{-}t\text{-}500}$ using the following equation:

$$x_{uppper-t-500} = x_{upper} + (x_{cavity} - x_{upper})(z_{upper-t-500} - z_{upper}) / (z_{cavity} - z_{upper}) \tag{X1.1}$$

If $| x_{upper} - x_{upper\text{-}t\text{-}500} | \leq 14$ µm, record $x_{upper\text{-}t\text{-}500}$ as x_{lower}.

X1.5.5.4 Add or subtract (as appropriate) 14 µm to or from x_{upper} to get x_{lower}.

X1.6 Calculate the length, L, by following the steps in Section 10.

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