Designation: E 2246 – 02

Standard Test Method for Strain Gradient Measurements of Thin, Reflecting Films Using an Optical Interferometer[1]

This standard is issued under the fixed designation E 2246; 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 the strain gradient in thin, reflecting films. It applies only to films, such as found in microelectromechanical systems (MEMS) materials, which can be imaged using an interferometer. Measurements from cantilevers that are touching the underlying layer are not accepted.

1.2 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.

1.3 *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 2244 Test Method for In-Plane Length Measurements of Thin, Reflecting Films Using an Optical Interferometer[2]

E 2245 Test Method for Residual Strain 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. 1-3) 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 Figs. 1 and 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 Figs. 2 and 3).

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 (see Figs. 1-3, and Fig. X1.1).

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.

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. 4) 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 *out-of-plane, adj*—perpendicular (in the *z*-direction) to the underlying layer.

3.1.13 *out-of-plane measurements, n*—measurements taken on structures that are curved out-of-plane in the *z*-direction.

3.1.14 *residual strain, n*—in a surface-micromachining process, the strain present in the mechanical layer after fabrication yet before the sacrificial layer is removed. In a bulk-micromachining process, the strain present in the suspended layer after fabrication yet before the substrate is removed at specified locations.

3.1.15 *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), an anchor is created allowing the mechanical layer to contact the underlying layer in that region.

3.1.16 *stiction, n*—in a surface-micromachining process, a structure exhibits this when a non-anchored portion of the

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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.

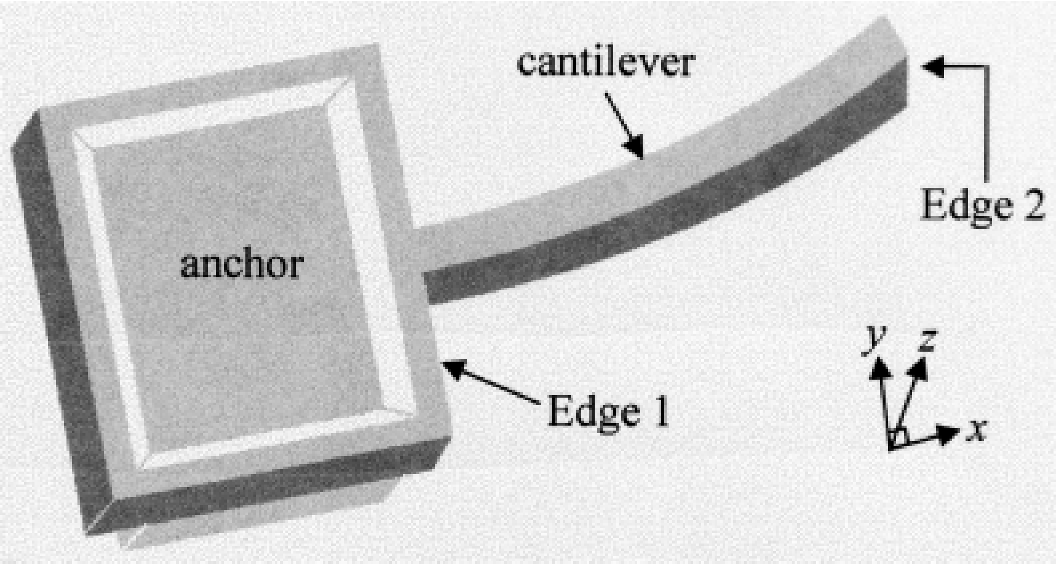
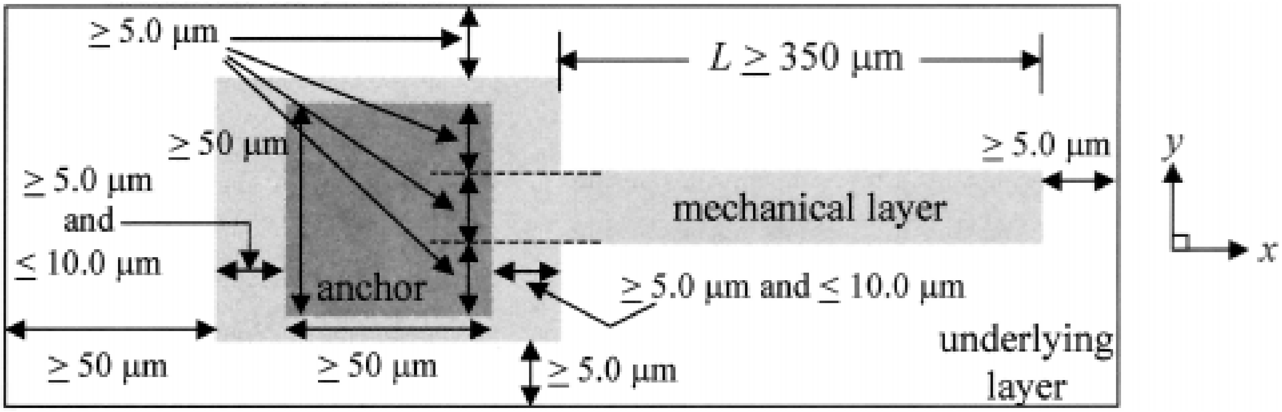


FIG. 1 Three-Dimensional View of Surface-micromachined Cantilever



NOTE 1—The underlying layer is beneath the entire test structure.

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

NOTE 3—The dark gray area (the anchor) is the designed cut 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.

FIG. 2 Design Dimensions for Cantilever in Fig. 1

mechanical layer adheres to the top of the underlying layer.

3.1.17 *strain gradient*, *n*—the positive difference in the strain between the top and bottom of a cantilever divided by its thickness.

3.1.17.1 *Discussion*—Consider a surface-micromachining process. The strain gradient is present in the cantilever before the sacrificial layer is removed. After the sacrificial layer is removed, the cantilever bows out-of-plane in the plus or minus *z*-direction (as shown in Fig. 1). The strain gradient in this cantilever is zero. Examining the out-of-plane measurements of the cantilever after the sacrificial layer is removed allows for the calculation of the strain gradient present in the cantilever before the sacrificial layer is removed.

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

3.1.19 *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.

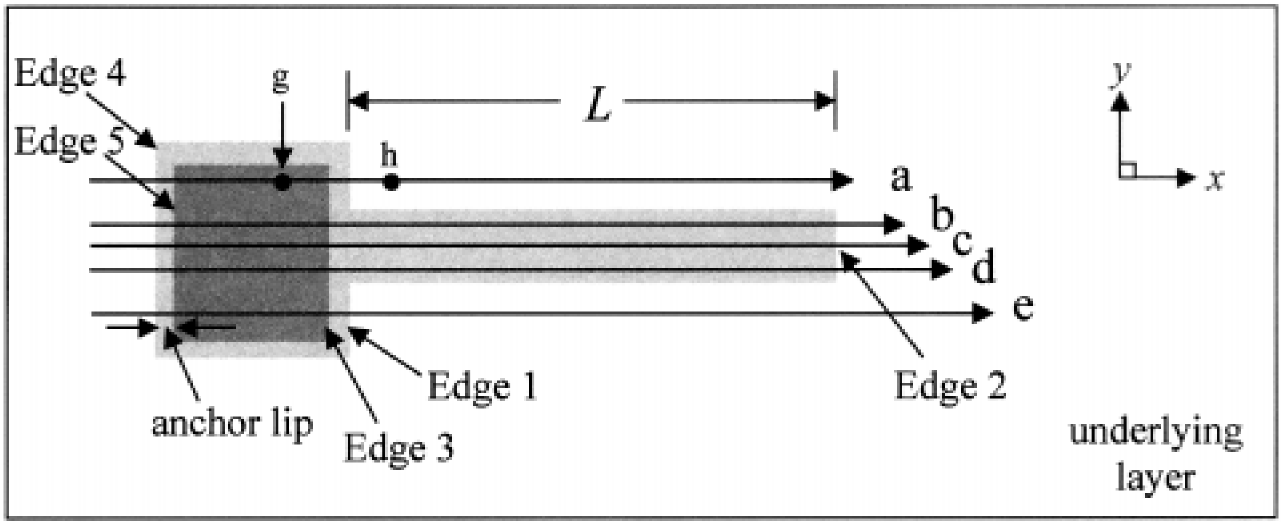
3.1.20 *surface micromachining*, *adj*—a MEMS fabrication process where thin, sacrificial layers are removed, which can create structures suspended in air.

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

3.1.22 *transitional edge*, *n*—an edge of a MEMS structure (such as Edge "1" in Fig. 3) that is characterized by a distinctive out-of-plane vertical displacement (as shown in Fig. 5).

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

3.2 *Symbols:*



NOTE 1—The 2-D data traces ("a" and "e") are used to ensure alignment.

NOTE 2—Trace "c" is used to determine the strain gradient and ascertain if the cantilever is adhered to the top of the underlying layer.

NOTE 3—Traces "b," "c," and "d" are used in the calculation of u_W.

FIG. 3 Top View of Surface-micromachined Cantilever

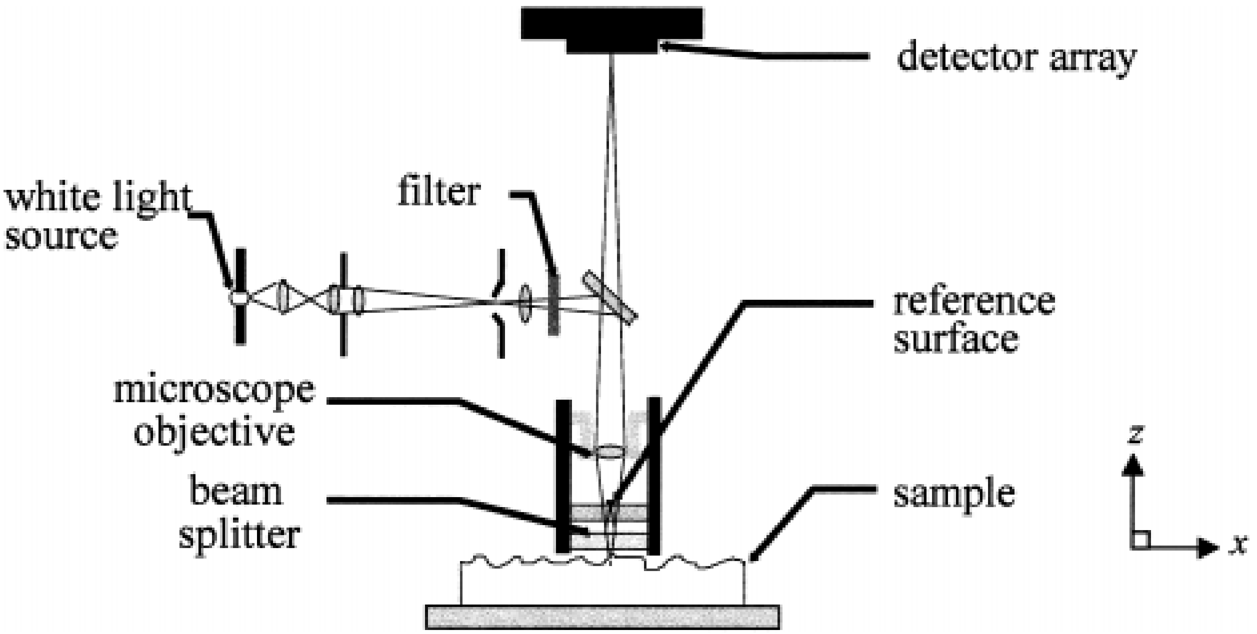


FIG. 4 Sketch of Optical Interferometer

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*:

L = the in-plane length measurement of the cantilever (see Fig. 2 or Fig. 3)

$x1_{lower}$ = the *x*-data value along Edge "1" (such as shown in

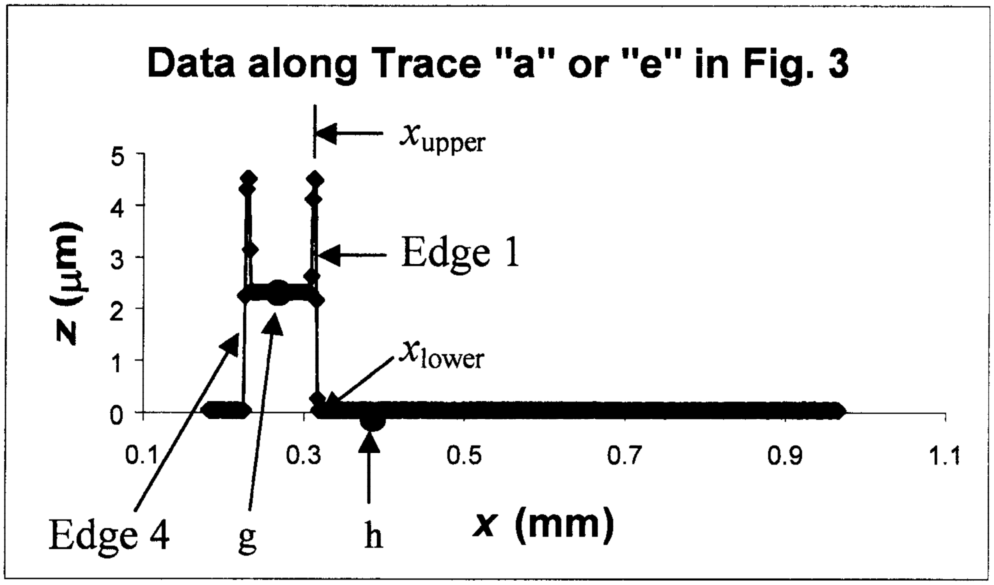


FIG. 5 2-D Data Trace Used to Find $x1_{lower}$, $x1_{upper}$, $x4_{lower}$ and $x4_{upper}$

Fig. 5) locating the lower part of the transition

$x1_{upper}$ = the *x*-data value along Edge "1" (such as shown in Fig. 5) locating the upper part of the transition

$x3_{lower}$ = the *x*-data value along Edge "3" (such as shown in Fig. X1.2) locating the lower part of the transition

$x3_{upper}$ = the *x*-data value along Edge "3" (such as shown in Fig. X1.2) locating the upper part of the transition

$x4_{lower}$ = the *x*-data value along Edge "4" (such as shown in Fig. 5) locating the lower part of the transition

$x4_{upper}$ = the *x*-data value along Edge "4" (such as shown in Fig. 5) 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. 5)

x_{upper} = the *x*-data value along the transitional edge of interest locating the upper part of the transition (see Fig. 5)

3.2.3 *For Strain Gradient Calculations*:

a = the *x*- (or *y*-) coordinate of the origin of the circle of radius R_{int}. This circle models the out-of-plane shape in the *z*-direction of the topmost surface of the cantilever

b = the *z*-coordinate of the origin of the circle of radius R_{int}. This circle models the out-of-plane shape in the *z*-direction of the topmost surface of the cantilever

R_{int} = the radius of the circle modeling the shape of the topmost surface of the cantilever as measured with the interferometer **(1)**[3]

s = equals 1 for cantilevers deflected in the minus *z*-direction, and equals −1 for cantilevers deflected in the plus *z*-direction

s_g = the strain gradient. Three data points (such as shown in Fig. 6) are used for this calculation

s_{g0} = the strain gradient when the residual strain equals zero

t = the thickness of the suspended layer, such as shown in Fig. X2.1 **(2-4)** for a surface-micromachining process

$t_{support}$ = 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)

$x1_{ave}$ = the average of $x1_{lower}$ and $x1_{upper}$

$x2_{ave}$ = the average of $x2_{lower}$ and $x2_{upper}$

$x2_{lower}$ = the *x*-data value along Edge "2" (as shown in Fig. 6) locating the lower part of the transition

$x2_{upper}$ = the *x*-data value along Edge "2" (as shown in Fig. 6) locating the upper part of the transition

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 *For Combined Standard Uncertainty Calculations*:

$s_{g\text{-}high}$ = in determining the combined standard uncertainty value for the strain gradient measurement, the highest value for s_g given the specified variations

$s_{g\text{-}low}$ = in determining the combined standard uncertainty value for the strain gradient measurement, the lowest value for s_g given the specified variations

u_{1pt} = the component in the combined standard uncertainty calculation that is due to the measurement uncertainty of one data point

u_c = the combined standard uncertainty value (that is, the estimated standard deviation of the result) **(5)**.

u_W = the component in the combined standard uncertainty calculation that is due to the measurement uncertainty across the width of the cantilever.

$w_{1/2}$ = the half width of the interval from $s_{g\text{-}low}$ to $s_{g\text{-}high}$

3.2.5 *For Adherence to the Top of the Underlying Layer*:

A = the minimum thickness of the mechanical layer as measured from the top of the mechanical layer in the anchor area (or region #2 in Fig. X2.2) to the top of the underlying layer (as shown in Fig. X2.1) and as specified in the reference **(4)**

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

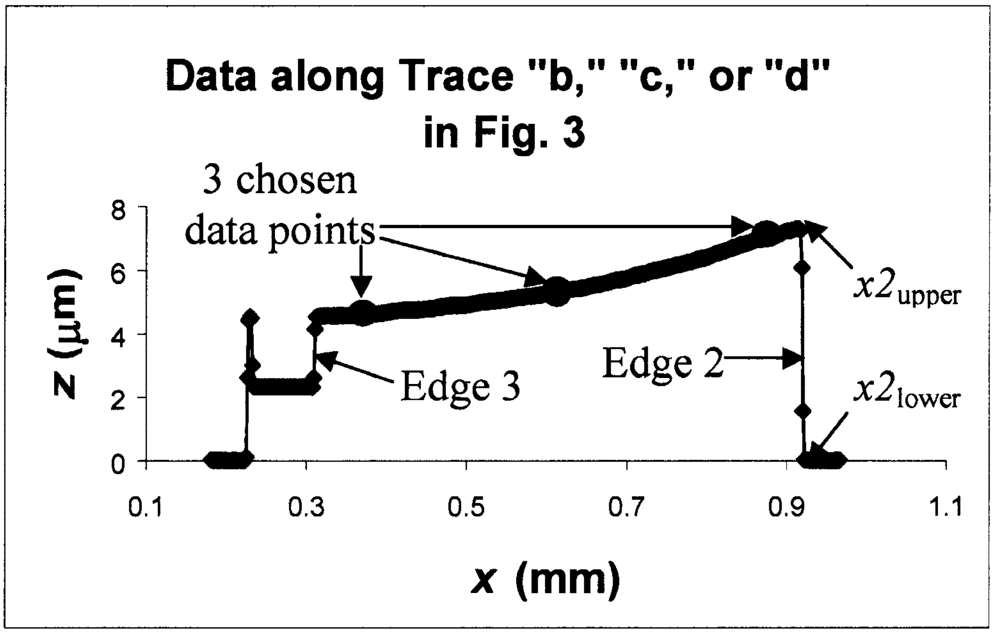

FIG. 6 2-D Data Trace Used to Find $x2_{lower}$, $x2_{upper}$, and the Three Data Points

H = the anchor etch depth (as shown in Fig. X2.1). The amount the underlying layer is etched away in the z-direction during the patterning of the sacrificial layer.

J = this dimension (as shown in Fig. X2.1) incorporates j_a, j_b, j_c, and j_d, as shown in Figs. X2.3 and X2.4 **(4)**

j_a = the roughness of the underside of the suspended, mechanical layer in the z-direction (as shown in Figs. X2.3 and X2.4). This is due to the roughness of the topside of the sacrificial layer.

j_b = the tilting component of the suspended, mechanical layer (as shown in Figs. X2.3 and X2.4)

j_c = the height in the z-direction of any residue present between the bottom of the suspended, mechanical layer and the top of the underlying layer (as shown in Figs. X2.3 and X2.4)

j_d = the roughness of the topside of the underlying layer (as shown in Figs. X2.3 and X2.4)

$z_{reg\#1}$ = the z value (as shown in Fig. X2.2) of the point of maximum deflection along the cantilever beam with respect to the anchor lip

$z_{reg\#2}$ = a representative z value (as shown in Fig. X2.2) of the group of points in region #2 within the large anchor area

3.2.6 *Discussion*—The symbols above are used throughout this test method. However, 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 The circular function models the out-of-plane shape of cantilevers. Three data points (such as shown in Fig. 6) define the circular function. The strain gradient is calculated from the radius of this circle.

4.2 To obtain three data points representative of the shape of a surface-micromachined cantilever: (*1*) select two transitional edges, (*2*) obtain a 3-D data set, (*3*) ensure alignment, and (*4*) select three data points. This procedure is presented in Appendix X1 for a bulk-micromachined cantilever.

4.3 To determine the strain gradient: (*1*) solve three equations for three unknowns, (*2*) plot the function with the data, and (*3*) calculate the strain gradient.

5. Significance and Use

5.1 Strain gradient values are an aid in the design and fabrication of MEMS devices.

6. Interferences

6.1 Measurements from cantilevers that are touching the underlying layer (as ascertained in Appendix X2) are not accepted.

7. Apparatus [4]

7.1 *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. 4 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.

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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[4] The same apparatus is used as in Test Method E 2244 and Test Method E 2245 and reference **(1)**.

7.2 *A 10*-µm-*grid Ruler*, for calibrating the interferometer in the *xy*-plane.

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

8. Test Units

8.1 *Cantilever Test Structures Fabricated in Either a Surface-micromachining or Bulk-micromachining Process*—The design of a representative surface-micromachined cantilever is specified below.

8.1.1 The cantilever shall be wide enough (for example, 5-µm wide, as shown in Fig. 2) such that obtaining a 2-D data trace (such as Trace "c" in Fig. 3) along its length is not a difficult task.

8.1.2 The cantilever shall be long enough (for example, $L \geq 350$ µm, as shown in Fig. 2) such that it exhibits out-of-plane curvature in the *z*-direction (as shown in Fig. 1).

8.1.3 The anchor lip between Edges "1" and "3" in Fig. 3 and between Edges "4" and "5" shall be wide enough to include at least three data points. If the pixel-to-pixel spacing is 1.56 µm, then this anchor lip should be at least 3.2 times greater (or 5.0 µm, as shown in Fig. 2). At the same time, it should be less than or equal to 10.0-µm wide.

8.1.4 The cut in the sacrificial layer that defines the anchor should be at least 50 by 50 µm (as shown in Fig. 2) to determine if the cantilever has adhered to the top of the underlying layer as ascertained in Appendix X2.

8.1.5 The anchor shall extend beyond the width of the cantilever in the ± *y*-directions (for example, at least 5.0 µm, as shown in Fig. 2) such that obtaining Traces "a" and "e" in Fig. 3 is not a difficult task.

8.1.6 There should be only one cantilever for each anchor (as shown in Fig. 2).

8.1.7 The underlying layer shall be un-patterned beneath the mechanical layer and should extend at least 5.0 µm beyond the outermost edges of the patterned, mechanical layer (as shown in Fig. 2). However, the underlying layer should extend at least 50 µm beyond the anchor lip in the minus *x*-direction (as shown in this figure) to ascertain if the cantilever has adhered to the top of the underlying layer, if necessary.

NOTE 1—Any tilt in the sample is eliminated by leveling the interferometric optics with respect to the top of the exposed underlying layer. The exposed underlying layer straddling the cantilever in Fig. 2 is used for this purpose. Therefore, no other structures should be designed in these areas.

8.1.8 A sufficient number of cantilevers (preferably of different lengths) should be fabricated in order to obtain at least one cantilever after fabrication, which exhibits out-of-plane curvature in the *z*-direction and which has not adhered to the top of the underlying layer.

9. Calibration [5]

9.1 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.

9.1.1 *For Non-reflective Rulers*:

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

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

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

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

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

NOTE 2—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.

9.1.2 *For Reflective Rulers*:

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

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

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

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

9.1.2.5 Recheck the sample alignment.

9.1.2.6 Take an average of at least three measurements to comprise one 3-D data set.

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

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

NOTE 3—Obtain at least five data sets representative of the field of view.

9.1.2.9 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.

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

9.1.2.11 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 4—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.

9.1.2.12 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.

9.2 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 5—Calibrating the step height at NIST[6] lowers the total uncertainty in the certified value.

9.2.1 Before the data session, record the height of the step height standard at six locations, three on each side of the step

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[5] The same calibration procedure is used as in Test Method E 2244 and Test Method E 2245 and reference **(1)**.

[6] The step heights are calibrated at NIST using a stylus instrument as specified in **(6)** and Appendix A of **(7)**.

height standard. Use six, 3-D data sets to accomplish this task.

9.2.2 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.

9.2.3 Calculate the mean value of the twelve measurements.

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

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

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

10. Procedure

10.1 To obtain three data points **(1)** representative of the shape of a surface-micromachined cantilever that is curved out-of-plane in the *z*-direction, four steps are taken: (*1*) select two transitional edges, (*2*) obtain a 3-D data set, (*3*) ensure alignment, and (*4*) select three data points.

NOTE 7—See Appendix X1 for the modifications to this procedure for a bulk-micromachined cantilever.

10.2 *Select Two Transitional Edges*:

10.2.1 Select two transitional edges to ensure alignment (for example, Edges "1" and "4" in Fig. 3). These transitional edges should be aligned parallel or perpendicular to the *x*- (or *y*-) axis of the interferometer.

10.3 *Obtain a 3-D Data Set*:

10.3.1 Orient the in-plane length, *L*, of the cantilever 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.

10.3.2 Obtain a 3-D data set that contains 2-D data traces (*a*) parallel to the in-plane length of the cantilever and (*b*) perpendicular to the two selected transitional edges in 10.2.1.

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

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

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

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

10.3.2.5 Eliminate any tilt in the sample by nulling the fringes on the top of the exposed underlying layer that straddles the cantilever.

10.3.2.6 Recheck the sample alignment.

10.3.2.7 Take an average of at least three measurements to comprise one 3-D data set.

10.3.2.8 From the 3-D data set, extract Trace "c" in Fig. 3.

10.3.2.9 In Trace "c," examine the data associated with the suspended portion of the cantilever. If the cantilever bends towards the underlying layer and there is a question as to whether or not it has adhered to the top of the underlying layer, calibrate the data trace in the *x*- (or *y*-) and *z*-directions and follow the steps in Appendix X2 at this point.

10.4 *Ensure Alignment*:

10.4.1 From the 3-D data set in 10.3.2.7, choose Traces "a" and "e" (in Fig. 3, as shown in Fig. 5).

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

10.4.3 Obtain x_{upper} and x_{lower} for Edges "1" and "4" in Traces "a" and "e" using the procedures given in 10.4.4 and 10.4.5. Therefore, eight values are obtained.

10.4.4 *Procedure to Find* x_{upper}:

10.4.4.1 Locate two points ("g" and "h") on either side of the transitional edge being examined (such as, Edge "1" in Fig. 5). 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 8—Point "g" has a *z*-data value that is higher than the *z*-data value for Point "h."

10.4.4.2 Examine the out-of-plane *z*-data values one-by-one going from Point "h" to Point "g" in Fig. 5.

10.4.4.3 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 9—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.

10.4.5 *Procedure to Find* x_{lower}:

10.4.5.1 Examine the *z*-data values one-by-one. However, this time go from Point "g" to Point "h" in Fig. 5.

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

NOTE 10—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.

10.4.5.3 The *x* value associated with the newly found *z* value is x_{lower}.

10.4.6 Compare the two values for $x1_{upper}$ in Traces "a" and "e."

10.4.7 Compare the two values for $x1_{lower}$ in Traces "a" and "e."

10.4.8 Compare the two values for $x4_{upper}$ in Traces "a" and "e."

10.4.9 Compare the two values for $x4_{lower}$ in Traces "a" and "e."

10.4.10 If more than half of the comparisons performed in 10.4.6-10.4.9, inclusive, result in compared values that are not identical, rotate the sample slightly, obtain another 3-D data set as detailed in 10.3, and repeat the steps in 10.4.

NOTE 11—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.

10.5 *Obtain Three Data Points Representative of the Shape of the Cantilever*:

10.5.1 Choose a centrally located 2-D data trace (within the

3-D data set) along the cantilever (such as Trace "c" in Fig. 3, as shown in Fig. 6).

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

10.5.3 Eliminate the data values at both ends of the trace that will not be included in the modeling (such as all data values outside and including Edges "2" and "3" in Fig. 6 with the *x* values of all the remaining data points being greater than or equal to $x1_{ave}$). The equation for $x1_{ave}$ is as follows:

$$x1_{ave} = (x1_{lower} + x1_{upper}) / 2 \tag{4}$$

10.5.4 Choose three representative data points (sufficiently separated) within this abbreviated data trace. Call these data points (x_1, z_1), (x_2, z_2), and (x_3, z_3) such that $x_1 < x_2 < x_3$.

11. Calculation

11.1 Given the three data points from 10.5.4, three steps are used to determine the strain gradient:[7] (*1*) solve three equations for three unknowns, (*2*) plot the function with the data, and (*3*) calculate the strain gradient.

11.2 *Solve Three Equations for Three Unknowns*:

11.2.1 Solving the three circular equations:

$$z_1 = b + s\,[R_{int}{}^2 - (x_1 - a)^2]^{1/2} \tag{5}$$

$$z_2 = b + s\,[R_{int}{}^2 - (x_2 - a)^2]^{1/2} \tag{6}$$

$$z_3 = b + s\,[R_{int}{}^2 - (x_3 - a)^2]^{1/2} \tag{7}$$

results in the following equations for *a*, *b*, and R_{int}:

$$a = (a_{num1} + a_{num2}) / a_{den} \tag{8}$$

$$b = z_1 - Q' \tag{9}$$

$$R_{int} = [(x_1 - a)^2 + Q^2]^{1/2} \tag{10}$$

where

$$a_{num1} = z_2 x_1{}^2 - z_2 z_3{}^2 + z_2 z_1{}^2 - z_2 x_3{}^2 + z_1 z_3{}^2 + z_1 x_3{}^2 \tag{11}$$

$$a_{num2} = -z_3 x_1{}^2 + z_3 x_2{}^2 + z_3 z_2{}^2 - z_3 z_1{}^2 - z_1 x_2{}^2 - z_1 z_2{}^2 \tag{12}$$

$$a_{den} = 2\,(x_2 z_3 - x_1 z_3 - x_2 z_1 + x_1 z_2 - x_3 z_2 + x_3 z_1) \tag{13}$$

$$Q = \pm\, Q' = \pm\,[(x_1 - a)^2 - (x_2 - a)^2 - (z_2 - z_1)^2] / [2\,(\,z_2 - z_1)] \tag{14}$$

11.3 *Plot the Function with the Data*:

11.3.1 Plot the abbreviated data trace obtained in 10.5.3 (or X1.5.2) along with the following equation:

$$z = b + s\,[R_{int}{}^2 - (x - a)^2]^{1/2} \tag{15}$$

where

$$x1_{ave} \leq x \leq x2_{ave} \tag{16}$$

$$x2_{ave} = (x2_{lower} + x2_{upper}\,) / 2 \tag{17}$$

and $x1_{ave}$ is given in Eq 4.

11.3.2 If one of the three chosen data points in 10.5.4 is not representative of the data, choose another data point or alter its *z* value and repeat the analysis beginning at 11.2.

11.4 Calculate the strain gradient using one of the following equations:

$$s_g \approx 1 / R_{int} \tag{18}$$

or

$$s_{g0} = 1 / [R_{int} - s\,(t / 2)] \tag{19}$$

11.5 Calculate u_c using the method presented in Annex A1.

12. Report

12.1 Report the results as follows **(5)**: Since it can be assumed that the possible estimated values are approximately uniformly distributed (as specified in Annex A1) with approximate standard deviation u_c, the strain gradient is believed to lie in the interval $s_g \pm u_c$ with a level of confidence of approximately 68 % assuming a Gaussian distribution.

13. Precision and Bias

13.1 In the spring of 1999, ASTM conducted a round robin experiment **(1, 8)** that included out-of-plane deflection measurements of fixed-fixed beams and cantilevers. These measurements indicate the magnitude and direction of the most deflected point of the test structure with respect to the anchor lip(s). 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. The reported deflection values of one fixed-fixed beam test structure ranged from 0.24 µm deflected down to 0.8 µm deflected up. Two laboratories considered this structure as being flat. (It is recognized that the spread in the measured deflected values could be due in part to change in positioning during the weekly transport between laboratories.) Similar discrepancies also existed in the measurements done on cantilever test structures.

13.2 For the next round robin, with the use of this test method, it is expected that the variations in the community measurements will be significantly tightened.

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

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

14. Keywords

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

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[7] By inserting the three data points into the correct locations on the appropriate NIST Web page (*http://www.eeel.nist.gov/812/test-structures/index.htm*), steps 1 and 3 can be performed on-line in a matter of seconds.

ANNEX

(Mandatory Information)

A1. CALCULATION OF COMBINED STANDARD UNCERTAINTY

A1.1 To calculate u_c, find u_{1pt} and u_W.

A1.1.1 Determine u_{1pt}:

A1.1.1.1 Vary z_2 from 10.5.4 ± 20 nm. Record $s_{g\text{-}low}$ and $s_{g\text{-}high}$.

NOTE A1.1—Plus or minus 20 nm includes variations due to surface roughness and measurement uncertainties at room temperature in a surface-micromachining process. This variation is expected to be larger in a bulk-micromachining process and at elevated temperatures. As fabrication processes improve and measurement uncertainties decrease, the specified variation will decrease as well.

A1.1.1.2 Calculate $w_{1/2}$ using the following equation:

$$w_{1/2} = (s_{g\text{-}high} - s_{g\text{-}low}) / 2 \tag{A1.1}$$

A1.1.1.3 Calculate u_{1pt} assuming a uniform (that is, rectangular) probability distribution using the following equation:

$$u_{1pt} = w_{1/2} / 3^{1/2} = w_{1/2} / 1.732 \tag{A1.2}$$

NOTE A1.2—The measurement uncertainty for each of the three data points chosen in 10.5.4 is assumed to be the same.

A1.1.2 Determine u_W:

A1.1.2.1 Find s_g for Traces "b," "c," and "d" in Fig. 3 (or Fig. X1.1), if not already done. Record $s_{g\text{-}low}$ and $s_{g\text{-}high}$.

A1.1.2.2 Calculate $w_{1/2}$ using Eq A1.1.

A1.1.2.3 Calculate u_W assuming a uniform probability distribution using the following equation:

$$u_W = w_{1/2} / 3^{1/2} = w_{1/2} / 1.732 \tag{A1.3}$$

A1.2 Calculate u_c using one of the following equations:

$$u_c = [3(u_{1pt})^2 / 3 + (u_W)^2]^{1/2} \tag{A1.4}$$

or

$$u_c = [(u_{1pt})^2 + (u_W)^2]^{1/2} \tag{A1.5}$$

NOTE A1.3—Note in Eq A1.4 that $(u_{1pt})^2$ is multiplied by three to account for the three chosen data points. It is then divided by three to account for using an average of three measurements as specified in 10.3.2.7.

APPENDIXES

(Nonmandatory Information)

X1. MODIFICATIONS TO THE PROCEDURE FOR A BULK-MICROMACHINED CANTILEVER

X1.1 To obtain three data points representative of the shape of a bulk-micromachined cantilever that is curved out-of-plane in the *z*-direction, four steps are taken: (*1*) select two transitional edges, (*2*) obtain a 3-D data set, (*3*) ensure alignment, and (*4*) select three data points.

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 Fig. X1.1, Fig. X1.2, and Fig. X1.3 instead of Fig. 3, Fig. 5, and Fig. 6, respectively. Also, replace the words "anchor lip" with the words "support region."

X1.2 *Select Two Transitional Edges:*

X1.2.1 Follow the steps in 10.2 with the following modification:

X1.2.2 Refer to Edges "1" and "3" in Fig. X1.1 instead of Edges "1" and "4" in Fig. 3.

NOTE X1.3—If the edges of the etched out cavity are jagged, Edges "1" and "3" 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 10.3 with the following modifications

X1.3.2 Refer to Edges "1" and "3" in Fig. X1.1 instead of Edges "1" and "4" in Fig. 3.

X1.3.3 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 cantilever.

X1.3.4 Skip 10.3.2.8 and 10.3.2.9.

X1.4 *Ensure Alignment:*

X1.4.1 Follow the steps in 10.4 with the following modifications:

X1.4.2 Obtain x_{upper} for Edges "1" and "3" (not Edges "1" and "4") in Traces "a" and "e" using the procedure given in 10.4.4. Therefore, four values are obtained.

X1.4.3 Skip 10.4.5, 10.4.7, and 10.4.9.

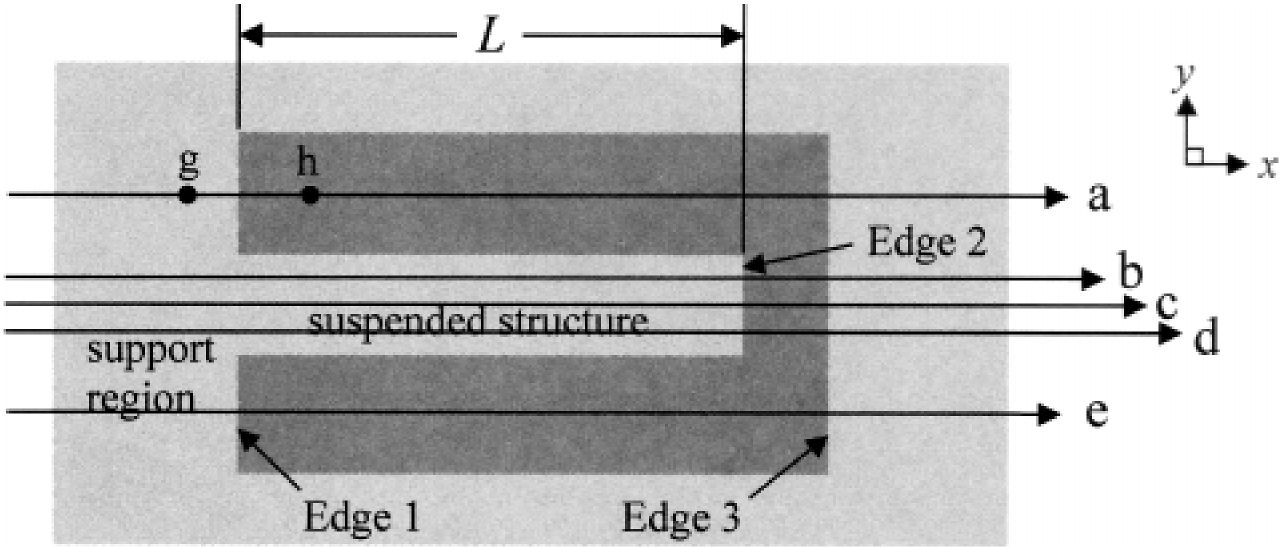
X1.4.4 Replace $x4_{upper}$ with $x3_{upper}$.

NOTE X1.4—If the edges of the etched out cavity are jagged and these are the only edges available to ensure alignment, it may not be possible to ensure alignment by comparing values along these edges. If this is the case, make sure the sample is visually aligned within the field of view of the interferometer.

X1.5 *Select Three Data Points:*

X1.5.1 Follow the steps in 10.5 with the following modifications:

X1.5.2 Eliminate the data values at both ends of the trace that will not be included in the modeling (such as all data values outside and including Edge "2" in Fig. X1.3 with the *x* values of all the remaining data points being greater than or



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.

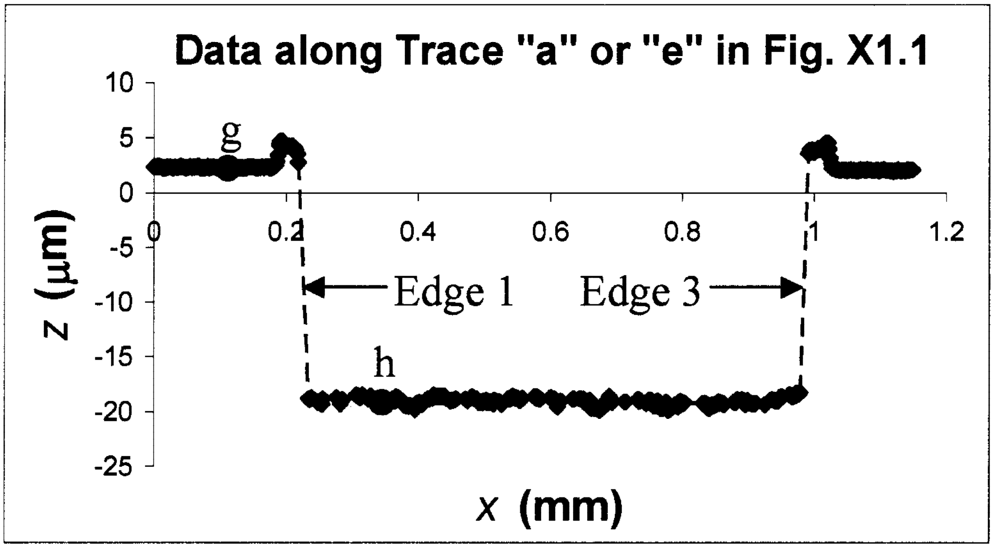
NOTE 3—The remaining light gray area around the outside of the visible portion of the cavity is suspended in air, attached underneath to the substrate, or both.

NOTE 4—The 2-D data traces (“a” and “e”) are used to ensure alignment.

NOTE 5—Trace “c” is used to determine the strain gradient.

NOTE 6—Traces “b,” “c,” and “d” are used in the calculation of u_W.

FIG. X1.1 Top View of Bulk-Micromachined Cantilever



NOTE—Data points are missing along and near Edges “1” and “3.”

FIG. X1.2 2-D Data Trace Used to Ensure Alignment

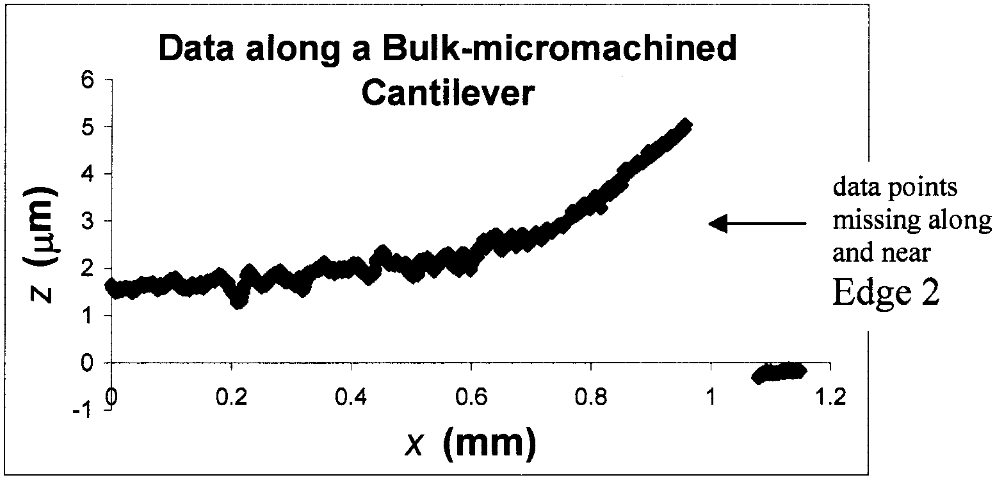
equal to $x1_{ave}$). Use Eq 4 to find $x1_{ave}$. Follow the procedure in 10.4.4 to find $x1_{upper}$.

X1.5.3 There are four procedures that follow to find x_{lower} (choose the first one that is appropriate):

X1.5.3.1 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}.

X1.5.3.2 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 10.4.4). 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 X1.5—The 500 nm criteria allows for phenomena associated with



NOTE—This is a 2-D data trace (“b,” “c,” or “d”) along a cantilever similar to that shown in Fig. X1.1.

FIG. X1.3 2-D Data Trace Used in Strain Gradient Calculation

measurements taken along transitional edges and any effects due to secondary fringes.

X1.5.3.3 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:

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

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

X1.5.3.4 Add or subtract (as appropriate) 14 µm to or from x_{upper} to get x_{lower}.

X1.6 Calculate the strain gradient, s_g, by following the steps in Section 11.

X2. ADHERENCE OF SURFACE-MICROMACHINED CANTILEVER TO UNDERLYING LAYER

X2.1 Determine if the surface-micromachined cantilever (shown in Fig. X2.1) is adhered to the top of the underlying layer **(1,4)**.

X2.1.1 From 10.3.2.7, choose a 2-D data trace (such as Trace “c” in Fig. 3) along the cantilever including its large anchor area.

X2.1.2 Plot the calibrated 2-D data trace (as shown in Fig. X2.2).

X2.1.3 Locate and record $z_{reg\#1}$.

X2.1.4 If neighboring points have similar z values (as shown in Fig. X2.2) such that a “flat” region exists, define this group of points as region #1.

X2.1.5 Define region #2 as a group of points within the large anchor area, as shown in Fig. X2.2. Record $z_{reg\#2}$.

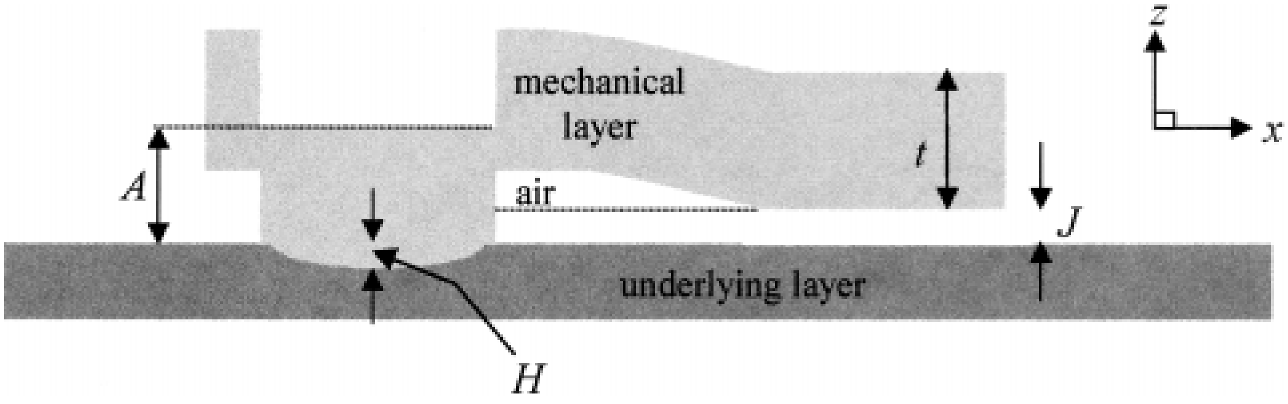
X2.1.6 Calculate B_1 as defined by the following equation:

$$B_1 = z_{reg\#1} - z_{reg\#2} \qquad \text{(X2.1)}$$

X2.1.7 Calculate B_2 as defined by one of the following equations:

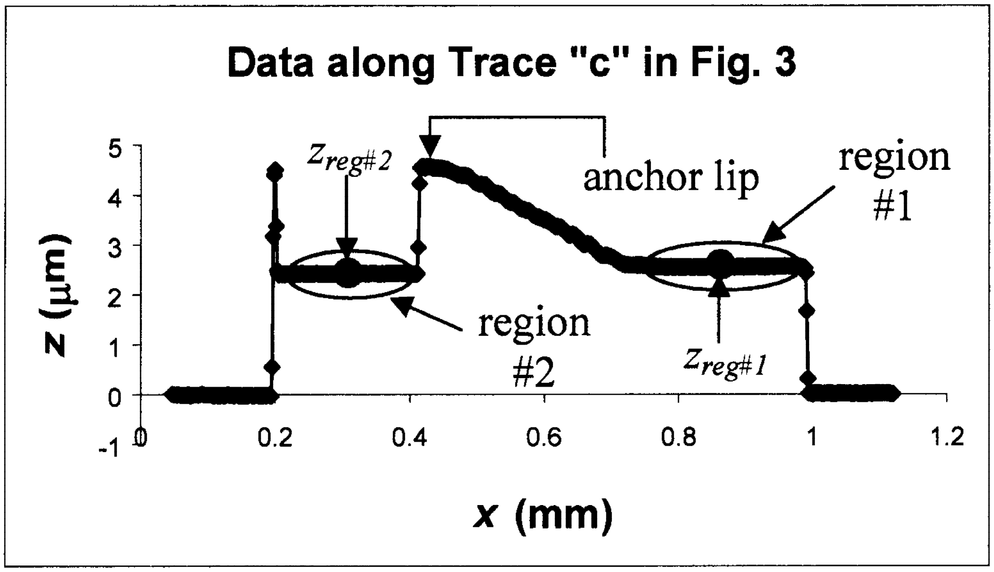
$$B_2 = H + J \qquad \text{(X2.2)}$$

or



NOTE—See Figs. X2.3 and X2.4 for the component parts of dimension *J*.

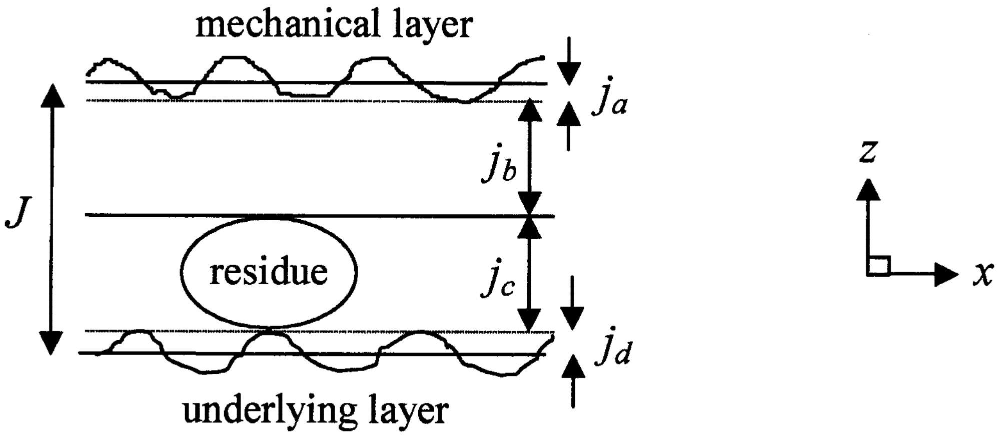
FIG. X2.1 Cross-sectional Side View of Cantilever Adhered to Top of Underlying Layer



NOTE—This is an example of stiction.

FIG. X2.2 2-D Data Trace of Cantilever in Fig. X2.1

$$J = j_a + j_b + j_c + j_d$$



NOTE—This view is along the length of the cantilever where it has adhered to the top of the underlying layer.

FIG. X2.3 Component Parts of *J* in Fig. X2.1

$$B_2 = t - A + J \quad \text{(X2.3)}$$

NOTE X2.1—Referring to Fig. X2.1, use Eq X2.2 if H is known more precisely than the quantity ($t - A$). Otherwise, use Eq X2.3 to find B_2.

X2.1.8 The cantilever is adhered to the top of the underlying layer if:

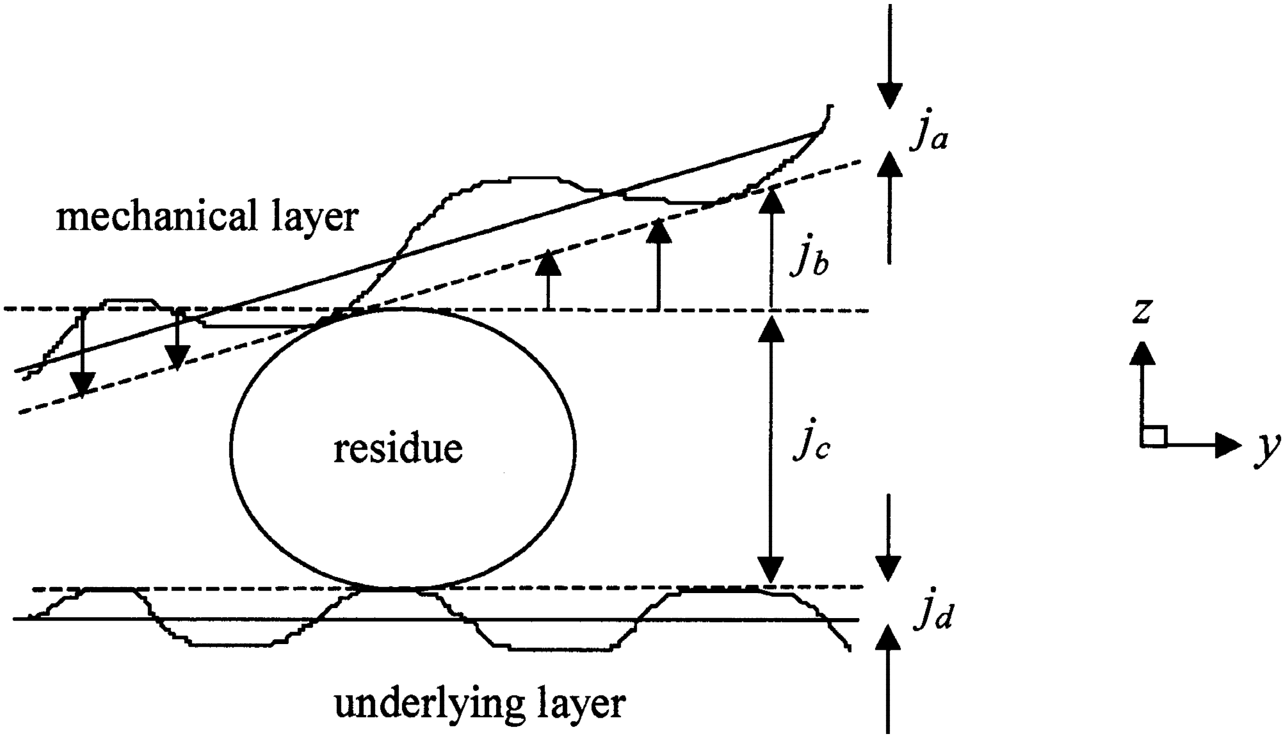
NOTE X2.2—The adherence criteria that follows will become more precise as fabrication processes and measurements improve.

X2.1.8.1 Twenty points or more are within region #1 and $B_1 \leq B_2 + 120$ nm, or

NOTE X2.3—It is believed that the existence of a substantial "flat" region that alters the cantilever's natural shape is the primary indicator of an adhered cantilever.

X2.1.8.2 Less than 20 points are within region #1 and $B_1 \leq B_2 + 100$ nm.

NOTE X2.4—Determining if the cantilever is adhered at one point along the length of the cantilever is a difficult task. Therefore, this criteria errs on the conservative side.



NOTE—This view is along the width of the cantilever.

FIG. X2.4 Component Parts of *J* in Fig. X2.1 and Fig. X2.3

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