Designation: E2246 – 11$^{\varepsilon 1}$

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

This standard is issued under the fixed designation E2246; 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.

ε¹ NOTE—Reference (1) was editorially revised in September 2013.

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 optical interferometer, also called an interferometric microscope. Measurements from cantilevers that are touching the underlying layer are not accepted.

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

1.3 *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:*[2]

E2244 Test Method for In-Plane Length Measurements of Thin, Reflecting Films Using an Optical Interferometer

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

E2444 Terminology Relating to Measurements Taken on Thin, Reflecting Films

E2530 Practice for Calibrating the *Z*-Magnification of an Atomic Force Microscope at Subnanometer Displacement Levels Using Si*(111)* Monatomic Steps (Withdrawn 2015)[3]

2.2 *SEMI Standard:*[4]

MS2 Test Method for Step Height Measurements of Thin Films

3. Terminology

3.1 *Definitions:*

3.1.1 The following terms can be found in Terminology E2444.

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

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

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

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

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

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

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

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

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

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

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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.

Current edition approved Nov. 1, 2011. Published January 2012. Originally approved in 2002. Last previous edition approved in 2005 as E2246 – 05.

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

[3] The last approved version of this historical standard is referenced on www.astm.org.

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

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

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

3.1.11 *MEMS, adj*—microelectromechanical systems.

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

3.1.13 *residual strain, n*—in a MEMS process, the amount of deformation (or displacement) per unit length constrained within the structural layer of interest after fabrication yet before the constraint of the sacrificial layer (or substrate) is removed (in whole or in part).

3.1.14 *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.

3.1.15 *stiction, n*—adhesion between the portion of a structural layer that is intended to be freestanding and its underlying layer.

3.1.16 *(residual) strain gradient, n*—a through-thickness variation (of the residual strain) in the structural layer of interest before it is released.

3.1.16.1 *Discussion*—If the variation through the thickness in the structural layer is assumed to be linear, it is calculated to be the positive difference in the residual strain between the top and bottom of a cantilever divided by its thickness. Directional information is assigned to the value of "*s*."

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

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

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

3.1.20 *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.

3.1.21 *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.

3.1.22 *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.

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

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

3.2 *Symbols:*

3.2.1 *For Calibration:*

σ_{6same} = the maximum of two uncalibrated values (σ_{same1} and σ_{same2}) where σ_{same1} is the standard deviation of the six step height measurements taken on the physical step height standard at the same location before the data session and σ_{same2} is the standard deviation of the six measurements taken at this same location after the data session

σ_{cert} = the certified one sigma uncertainty of the physical step height standard used for calibration

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

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

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

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

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

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

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

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

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

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

x_{res} = the calibrated resolution of the interferometric microscope in the *x*-direction

$\bar{z}_{6same}$ = the uncalibrated average of the six calibration measurements from which σ_{6same} is found

z_{drift} = the uncalibrated positive difference between the average of the six calibration measurements taken before the data session (at the same location on the physical step height standard used for calibration) and the average of the six calibration measurements taken after the data session (at this same location)

z_{lin} = over the instrument's total scan range, the maximum relative deviation from linearity, as quoted by the instrument manufacturer (typically less than 3 %)

z_{res} = the calibrated resolution of the interferometric microscope in the *z*-direction

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

3.2.2 *For Strain Gradient Calculations:*

α = the misalignment angle

a = the *x*- (or *y*-) coordinate of the origin of the circle of radius R_{int}. An arc of this circle models the out-of-plane shape in the *z*-direction of the surface of the cantilever that is measured with the interferometric microscope

b = the *z*-coordinate of the origin of the circle of radius R_{int}. An arc of this circle models the out-of-plane shape in the

z-direction of the surface of the cantilever that is measured with the interferometric microscope

L = the in-plane length measurement of the cantilever

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

R_{int} = the radius of the circle with an arc that models the shape of the surface of the cantilever that is measured with the interferometric microscope

s = equals 1 for cantilevers deflected in the minus z-direction of the interferometric microscope, and equals –1 for cantilevers deflected in the plus z-direction

s_g = the strain gradient as calculated from three data points

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

$s_{gcorrection}$ = the strain gradient correction term for the given design length

t = the thickness of the suspended, structural layer

$x1_{ave}$ = the calibrated average of $x1_{uppera}$ and $x1_{uppere}$

$x1_{uppert}$ = the calibrated x-value along Edge 1 locating the upper corner of the transitional edge using Trace t

$x2_{uppert}$ = the calibrated x-value along Edge 2 locating the upper corner of the transitional edge using Trace t

y_t = the calibrated y-value associated with Trace t

3.2.3 *For Combined Standard Uncertainty Calculations:*

$\sigma_{repeat(samp)}$ = the relative strain gradient repeatability standard deviation as obtained from cantilevers fabricated in a process similar to that used to fabricate the sample

R_{ave} = the calibrated surface roughness of a flat and leveled surface of the sample material calculated to be the average of three or more measurements, each measurement taken from a different 2-D data trace

R_{tave} = the calibrated peak-to-valley roughness of a flat and leveled surface of the sample material calculated to be the average of three or more measurements, each measurement taken from a different 2-D data trace

$s_{g\text{-}high}$ = 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_{sg} = the expanded uncertainty of a strain gradient measurement

u_{cert} = the component in the combined standard uncertainty calculation for strain gradient that is due to the uncertainty of the value of the physical step height standard used for calibration

$u_{correction}$ = the component in the combined standard uncertainty calculation for strain gradient that is due to the uncertainty of the correction term

u_{csg} = the combined standard uncertainty of a strain gradient measurement

u_{drift} = the component in the combined standard uncertainty calculation for strain gradient that is due to the amount of drift during the data session

u_{linear} = the component in the combined standard uncertainty calculation for strain gradient that is due to the deviation from linearity of the data scan

u_{noise} = the component in the combined standard uncertainty calculation for strain gradient that is due to interferometric noise

u_{Rave} = the component in the combined standard uncertainty calculation for strain gradient that is due to the sample's surface roughness

$u_{repeat(samp)}$ = the component in the combined standard uncertainty calculation for strain gradient that is due to the repeatability of measurements taken on cantilevers processed similarly to the one being measured

$u_{repeat(shs)}$ = the component in the combined standard uncertainty calculation for strain gradient that is due to the repeatability of measurements taken on the physical step height standard

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

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

u_{xres} = the component in the combined standard uncertainty calculation for strain gradient that is due to the resolution of the interferometric microscope in the x-direction

u_{zres} = the component in the combined standard uncertainty calculation for strain gradient that is due to the resolution of the interferometric microscope in the z-direction

3.2.4 *For Round Robin Measurements:*

L_{des} = the design length of the cantilever

n = the number of repeatability or reproducibility measurements

s_{gave} = the average strain gradient value for the repeatability or reproducibility measurements that is equal to the sum of the s_g values divided by n

u_{cgave} = the average combined standard uncertainty value for the strain gradient measurements that is equal to the sum of the u_{csg} values divided by n

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

A = in a surface micromachining process, the minimum thickness of the structural layer of interest as measured from the top of the structural layer in the anchor area to the top of the underlying layer

H = in a surface micromachining process, the anchor etch depth, which is the amount the underlying layer is etched away in the interferometric microscope's minus z-direction during the patterning of the sacrificial layer

J = in a surface micromachining process, the positive distance (equal to the sum of j_a, j_b, j_c, and j_d) between the bottom of the suspended, structural layer and the top of the underlying layer

j_a = in a surface micromachining process, half the peak-to-peak value of the roughness of the underside of the suspended, structural layer in the interferometric microscope's z-direction. This is due to the roughness of the topside of the sacrificial layer.

j_b = in a surface micromachining process, the tilting component of the suspended, structural layer that accounts for the deviation in the distance between the bottom of the suspended, structural layer and the top of the underlying layer that is not due to residue or the roughness of the surfaces. This component can be positive or negative.

j_c = in a surface micromachining process, the height in the interferometric microscope's z-direction of any residue present between the bottom of the suspended, structural layer and the top of the underlying layer

j_d = in a surface micromachining process, half the peak-to-peak value of the surface roughness of the topside of the underlying layer

$z_{reg\#1}$ = in a surface micromachining process, the interferometric z value of the point of maximum deflection along the cantilever with respect to the anchor lip

$z_{reg\#2}$ = in a surface micromachining process, a representative interferometric z value of the group of points 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 (or the subscript of the symbols) above that start with the letter "x."

4. Summary of Test Method

4.1 A surface-micromachined cantilever is shown in Figs. 1-3. After fabrication, this cantilever bends in the out-of-plane z-direction. An optical interferometric microscope (such as shown in Fig. 4) is used to obtain a topographical 3-D data set. 2-D data traces beside the cantilever (such as Traces a and e shown in Fig. 3 and Fig. 5) and along the top of the cantilever (such as Traces b, c, and d shown in Fig. 3 and Fig. 6) are extracted from this 3-D data set for the strain gradient analysis.

4.2 Traces a and e are used to a) determine the misalignment angle, α, and b) ensure that the x-values obtained along the cantilever in Traces b, c, and d are indeed along the cantilever and not on the anchor lip.

4.3 A circular arc models the out-of-plane shape of cantilevers. Three data points (such as shown in Fig. 6) define the circular function for each data trace (b, c, and d) after the data points have been modified for any misalignment. The strain gradient for each data trace is calculated from the radius of this circle. The strain gradient is the average of the strain gradient values calculated from Traces b, c, and d.

4.3.1 For Traces b, c, and d, to obtain three data points representative of the shape of a surface-micromachined cantilever: *(1)* select a transitional edge, *(2)* align the transitional edge in the field of view, *(3)* obtain a 3-D data set, *(4)* determine the attachment location of the cantilever, and *(5)* for Traces b, c, and d, obtain three data points representative of the shape of the cantilever. (This procedure may need to be modified for a bulk-micromachined cantilever.)

4.3.2 To determine the strain gradient for each data trace (b, c, and d): *(1)* account for any misalignment, *(2)* solve three equations for three unknowns for Trace c, *(3)* plot the function with the data from Trace c, *(4)* calculate the strain gradient for Trace c, and *(5)* repeat steps 2 through 4 for Traces b and d. The strain gradient is calculated as the average of the three strain gradient values obtained from the three data traces.

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

4.5 Appendix X1 is used to determine if the cantilever has adhered to the top of the underlying layer.

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 X1) are not accepted.

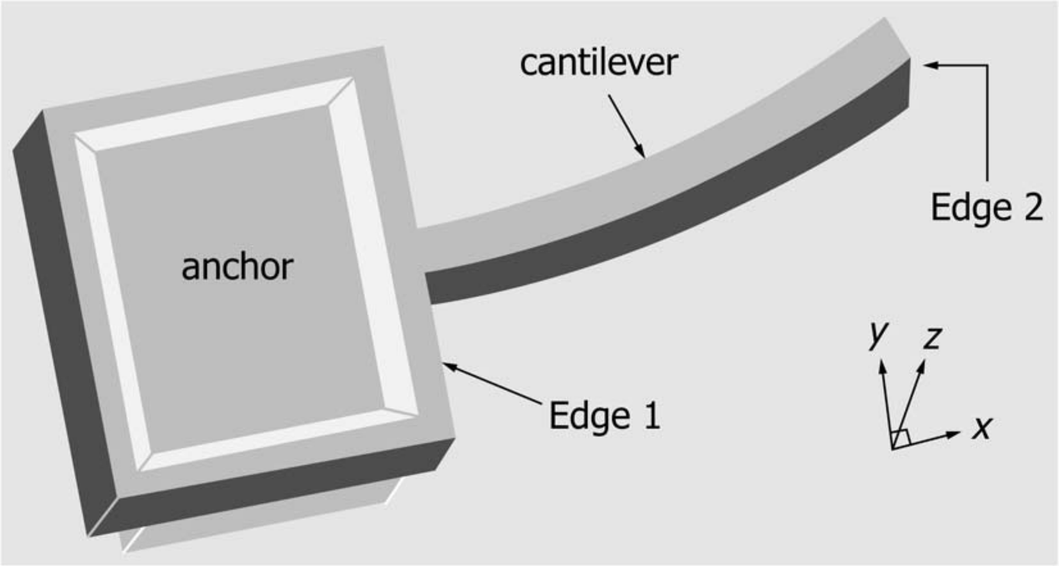
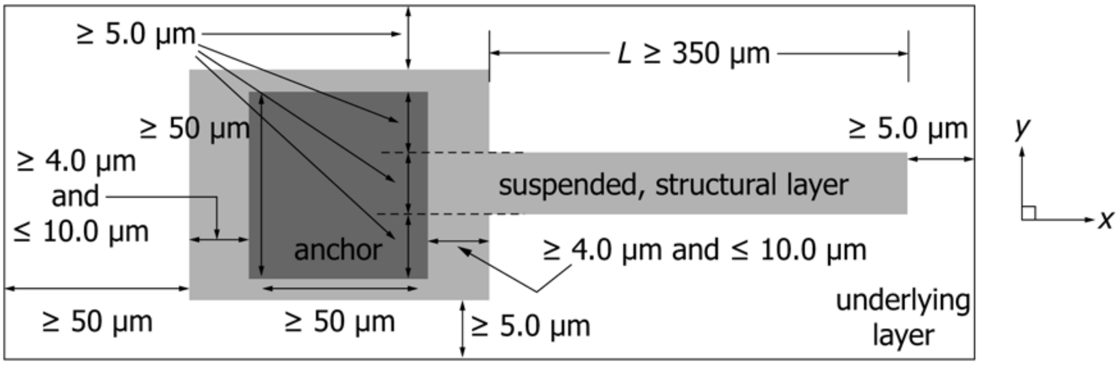


FIG. 1 Three-Dimensional View of Surface-micromachined Cantilever



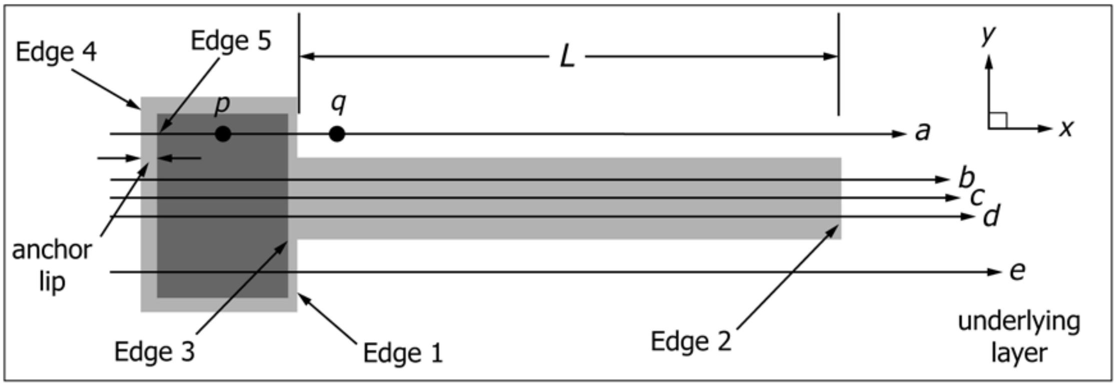
NOTE 1—The underlying layer is beneath the entire test structure.

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 area (the anchor) is the designed cut in the sacrificial layer. This is where the structural layer contacts the underlying layer.

FIG. 2 Design Dimensions for Cantilever in Fig. 1



NOTE 1—The 2-D data traces (a and e) are used to calculate the misalignment angle, α.

NOTE 2—Trace b, c, and d are used to determine the strain gradient and calculate u_W. They can also be used to ascertain if the cantilever is adhered to the top of the underlying layer if enough data points are measured on the top of the underlying layer to the left of the anchor.

FIG. 3 Top View of Surface-micromachined Cantilever

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

7.1 *Non-contact Optical Interferometric Microscope,* capable of obtaining a topographical 3-D data set and exporting a 2-D data trace. Fig. 4 is a schematic of such an interferometric microscope. However, any non-contact optical interferometric microscope that has pixel-to-pixel spacings as specified in Table 1 and that is capable of performing the test procedure with a vertical resolution less than 1 nm is permitted. The interferometric microscope must be capable of measuring step heights to at least 5 µm higher than the 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.

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

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

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

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

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.

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[5] The same apparatus is used (or can be used) in Test Method E2244, Test Method E2245, and SEMI Test Method MS2.

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

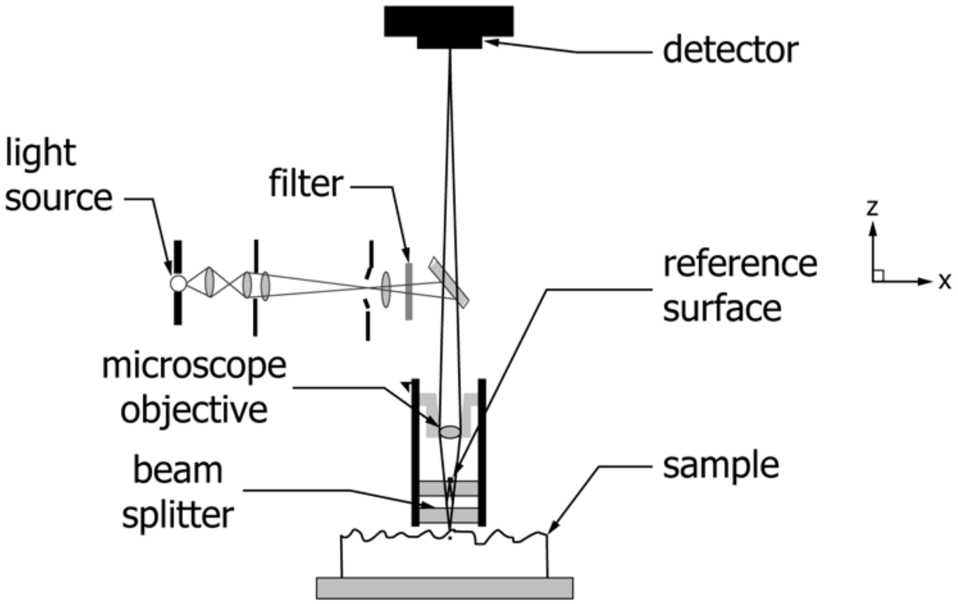

FIG. 4 Schematic of an Optical Interferometric Microscope

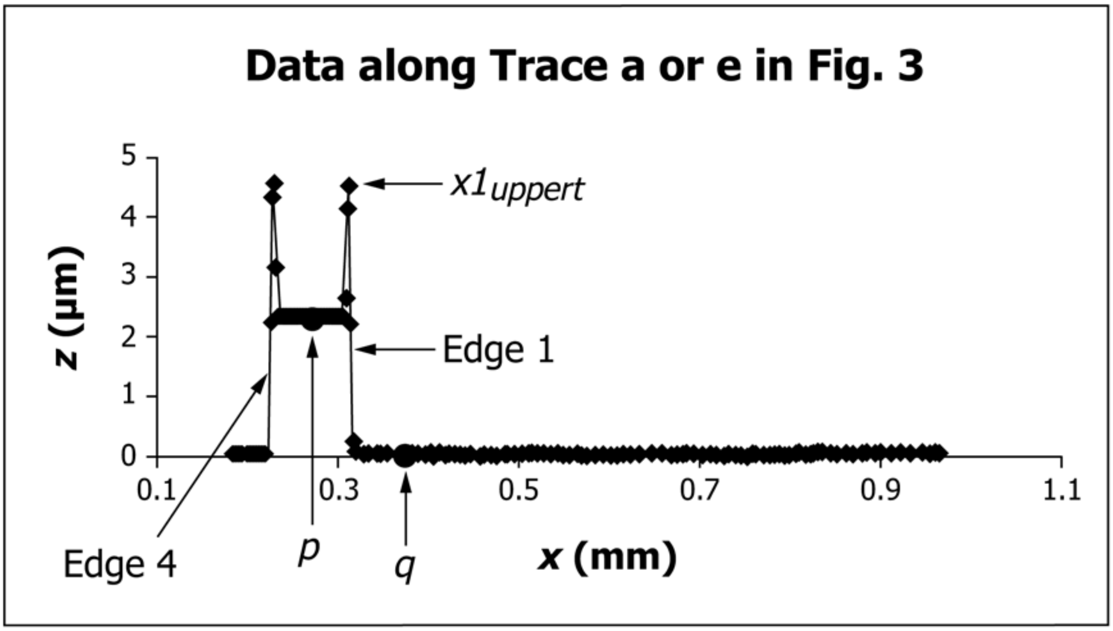

FIG. 5 2-D Data Trace Used to Find $x1_{uppert}$

8.1.1 The cantilever shall be wide enough (for example, 5-μm wide, as shown in Fig. 2) so 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) so that it exhibits out-of-plane curvature in the *z*-direction (as shown in Fig. 1 and Fig. 6).

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 two data points (three would be better). If the pixel-to-pixel spacing is 2.00 μm, then this anchor lip should be at least two times greater (or 4.0 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 μm 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 X1.

NOTE 2—If one or more "posts" are used in the anchor area, a post layer is not considered the underlying layer. The post or posts connect the underlying layer to the sample material, in which case replace the words "cut in the sacrificial layer" with the words "post or posts."

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.

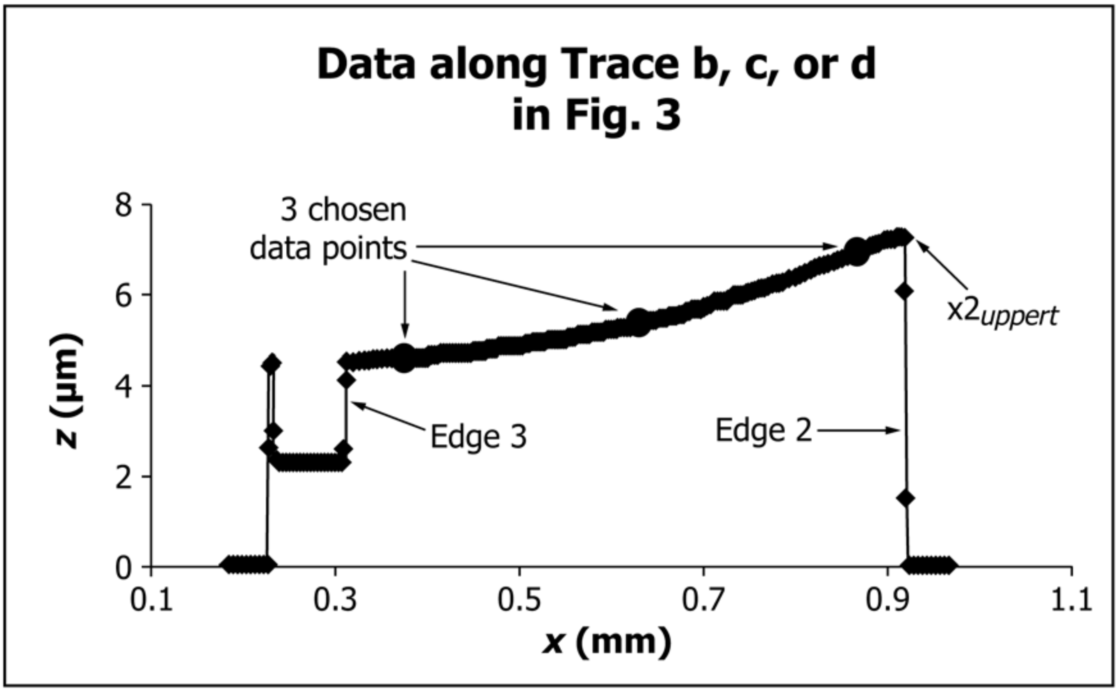

FIG. 6 2-D Data Trace Used to Find Three Data Points

TABLE 1 Interferometric Microscope Pixel-to-Pixel Spacing Requirements

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

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

8.1.7 The underlying layer should be un-patterned beneath the structural layer of interest and should extend at least 5.0 µm beyond the outermost edges of this patterned structural layer (as shown in Fig. 2). The underlying layer should also 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. This assumes that a backside etch is not used to eliminate stiction concerns.

NOTE 3—Any tilt in the sample (or the sample data) is initially eliminated (or eliminated) by leveling the interferometric optics (or the 3-D data set) with respect to the top of the exposed underlying layer (or with respect to the top of flat regions of the sample). If the exposed underlying layer straddling the cantilever in Fig. 2 is used for this purpose, 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.

8.1.9 If a backside etch is used to eliminate stiction concerns, consult the fabrication service or facility for appropriate design considerations. Avoid or minimize having any layer edges in or coincident with both the designed cantilever and the fabricated cantilever. It is also recommended that any resulting vertical transitions in the cantilever be as close to the anchor as possible.

8.1.10 If two layers of polysilicon are used within an anchor design, a more rigid and reliable attachment of the cantilever to the anchor will result. Consult the fabrication service or facility for design considerations.

9. Calibration[7] (1-3)

9.1 Calibrate the interferometric microscope 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.

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

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

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

$$cal_x = \frac{ruler_x}{scope_x} \tag{1}$$

and

$$cal_y = \frac{ruler_y}{scope_y} \tag{2}$$

NOTE 4—Multiply the *x*- and *y*-data values obtained during the data

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[7] The same calibration procedure is used as in Test Method E2244 and Test Method E2245. A similar calibration in the z-direction is used in SEMI Test Method MS2.

session by the appropriate calibration factor to obtain calibrated *x*- and *y*-data values.

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

NOTE 5—Having the physical step height standard calibrated at NIST[8] lowers the total uncertainty in the certified value.

9.2.1 Before the data session:

9.2.1.1 Take six measurements of the height of the physical step height standard using six 3-D data sets to accomplish this task. These measurements should be taken spread out evenly along the physical step height standard, being careful to obtain these measurements within the certified range (both along the length and width) of the physical step height standard. If single-sided step height measurements are taken, three measurements should be taken along each side of the physical step height standard. Record $\bar{z}_{before}$, the mean value of the six measurements, and σ_{before}, the standard deviation of the six measurements.

9.2.1.2 Take six measurements of the height of the physical step height standard (using six 3-D data sets) at the same location on the physical step height standard, being careful to obtain these measurements within the certified range (both along the length and width) of the physical step height standard. Record $\bar{z}_{same1}$, the mean value of the six measurements and σ_{same1}, the standard deviation of the six measurements.

9.2.2 After the data session:

9.2.2.1 Repeat 9.2.1.1 recording $\bar{z}_{after}$ as the mean value of the six measurements and σ_{after} as the standard deviation of the six measurements.

9.2.2.2 Repeat 9.2.1.2 at the same location as the measurements taken before the data session recording $\bar{z}_{same2}$ as the mean value of the six measurements and σ_{same2} as the standard deviation of the six measurements.

9.2.3 Determine the *z*-calibration factor:

9.2.3.1 Calculate the mean value of the twelve measurements, $\bar{z}_{ave}$, from 9.2.1.1 and 9.2.2.1 using the following equation:

$$\bar{z}_{ave} = \frac{\bar{z}_{before} + \bar{z}_{after}}{2} \tag{3}$$

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

$$cal_z = \frac{cert}{\bar{z}_{ave}} \tag{4}$$

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

9.2.4 Obtain the additional parameters that will be used in Annex A1 for the combined standard uncertainty calculations.

9.2.4.1 Calculate z_{drift} using the following equation:

$$z_{drift} = \left|\bar{z}_{same1} - \bar{z}_{same2}\right| \tag{5}$$

9.2.4.2 Calculate $\bar{z}_{6same}$ and σ_{6same} using the following equations:

$$\text{if } \sigma_{same1} \geq \sigma_{same2}, \text{ then } \sigma_{6same} = \sigma_{same1} \text{ and } \bar{z}_{6same} = \bar{z}_{same1} \tag{6}$$

and

$$\text{if } \sigma_{same1} < \sigma_{same2}, \text{ then } \sigma_{6same} = \sigma_{same2} \text{ and } \bar{z}_{6same} = \bar{z}_{same2} \tag{7}$$

9.2.4.3 Record σ_{cert}, z_{lin} , x_{res}, and z_{res} as defined in 3.2.1 for use in Annex A1.

9.2.4.4 Obtain R_{tave} and R_{ave} as defined in 3.2.3 for use in Annex A1.

10. Procedure (1-3)

10.1 To obtain three data points representative of the shape of a surface-micromachined cantilever that is curved out-of-plane in the *z*-direction, five steps are taken: *(1)* select a transitional edge, *(2)* align the transitional edge in the field of view, *(3)* obtain a 3-D data set, *(4)* determine the attachment location of the cantilever, and *(5)* for Traces b, c, and d, obtain three data points representative of the shape of the cantilever.

NOTE 7—The procedure that follows may need to be modified for the given cantilever. For a bulk-micromachining process, refer to Fig. 7, Fig. 8, and Fig. 9 instead of Fig. 3, Fig. 5, and Fig. 6, respectively. The bulk micromachined cantilever in Fig. 7 consists of four oxide layer thicknesses (**1**) and this test method uses a single-layer cantilever model. Therefore, the resulting strain gradient would be considered an effective strain gradient. Also, replace the words "anchor lip" with the words "support region." Additional modifications may also need to be made as appropriate, for example, when considering a surface-micromachined cantilever with a backside etch.

10.2 *Select a Transitional Edge:*

10.2.1 Select a transitional edge to use to calculate the misalignment angle, α. Typically the edge that locates the attachment point of the cantilever to the anchor lip (for example, Edge 1 in Fig. 3) is chosen.

10.3 *Align the Transitional Edge in the Field of View:*

10.3.1 Align the transitional edge from 10.2.1 parallel or perpendicular to the *x*- (or *y*-) axis of the interferometric microscope. If the interferometric microscope's pixel-to-pixel spacing is smaller in the *x*-direction than in the *y*-direction, it is preferable to orient the sample such that the length of the cantilever is in the *x*-direction.

NOTE 8—For the procedure that follows, it is assumed that the free end of the cantilever has *x* (or *y*) values that are larger than the *x* (or *y*) values of the fixed end of the cantilever. If this is not the case, multiply all the *x*-values by –1.

10.4 *Obtain a 3-D Data Set:*

10.4.1 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 selected transitional edge in 10.2.1.

10.4.1.1 Record the room temperature and relative humidity for informational purposes.

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

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

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

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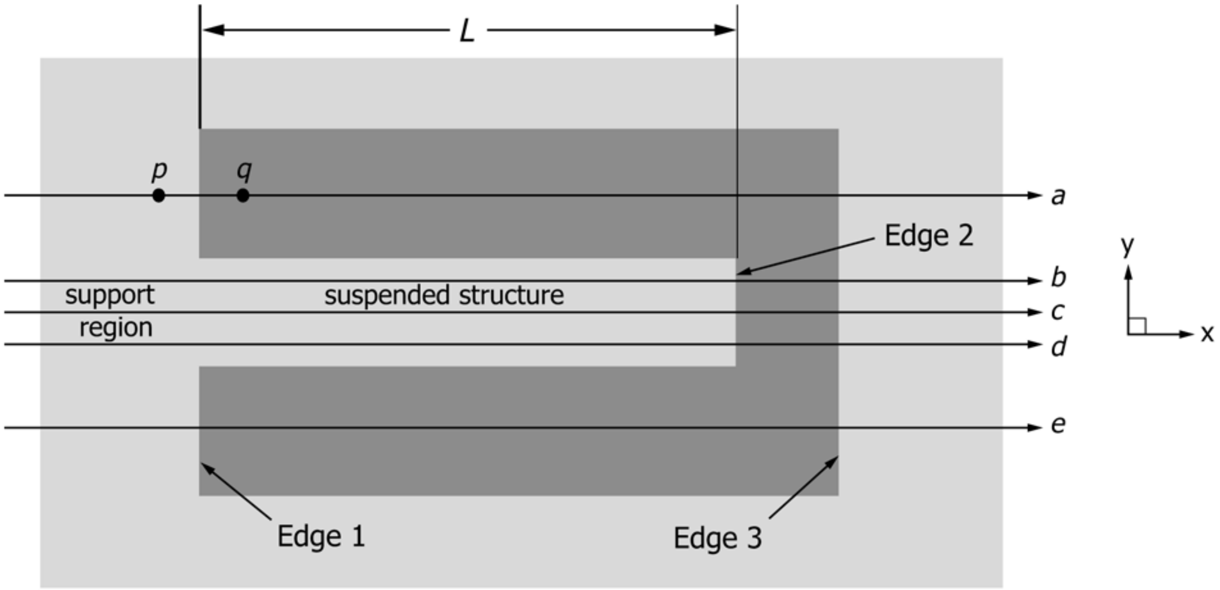
[8] Physical step height standards are calibrated at NIST as specified in (**4**), Appendix A of (**5**), and Test Method E2530.



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

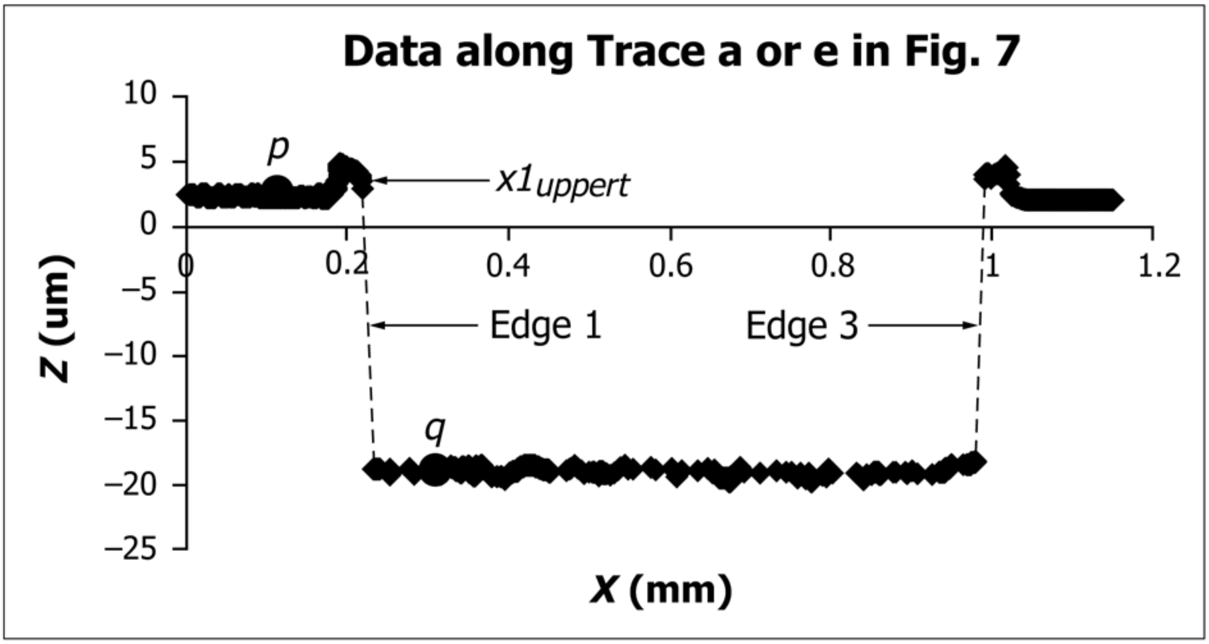
NOTE 2—The dark gray areas are the visible parts of the micromachined cavity.

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 calculate the misalignment angle, α.

NOTE 5—Traces b, c, and d are used to determine the strain gradient and u_W.

FIG. 7 Top View of Bulk-Micromachined Cantilever

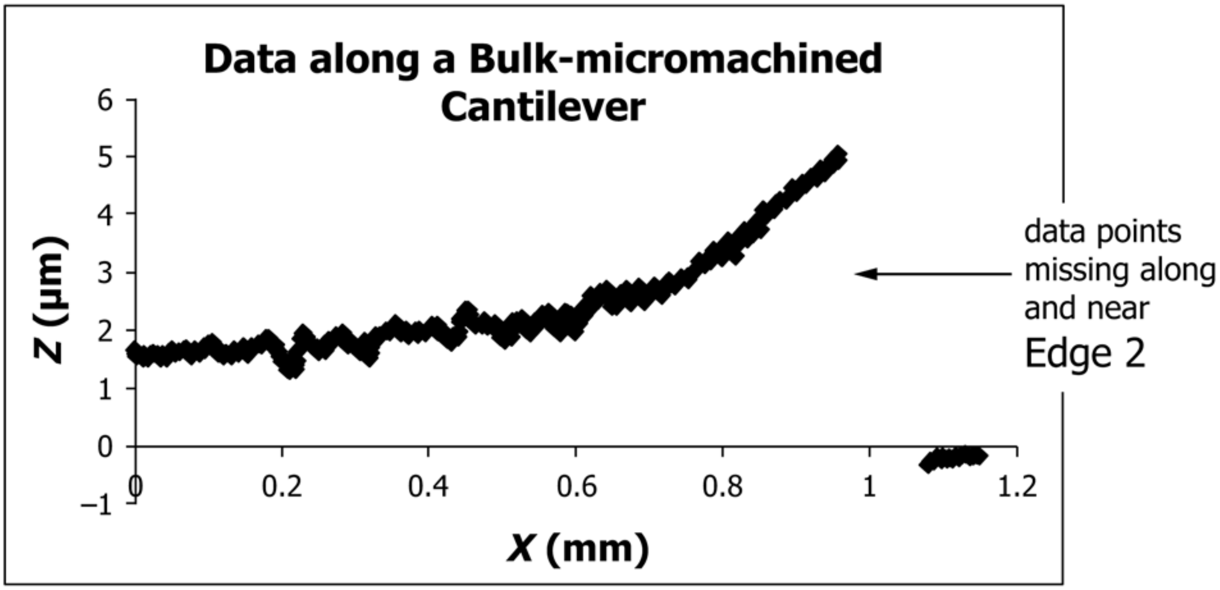


NOTE 1—Data points are missing along and near Edges 1 and 3.

FIG. 8 2-D Data Trace Used to Find $x1_{uppert}$

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

10.4.1.6 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 (for example, on the top of the exposed underlying layer in Fig. 3 that straddles the cantilever). The fringes are typically nulled for the measurement; however, if fringes are present, it is recommended that they be parallel to the length of the cantilever.



NOTE 1—This is a 2-D data trace (*b*, *c*, or *d*) along a cantilever similar to that shown in Fig. 7.

FIG. 9 2-D Data Trace Used in Strain Gradient Calculation

10.4.1.7 Recheck the sample alignment and bring the fringes to just past the topmost structure within the field of view.

10.4.1.8 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 sample that are symmetrically located with respect to the cantilever (for example, with respect to the top of the exposed underlying layer in Fig. 3, with regions chosen to be symmetrically located with respect to the cantilever).

10.4.1.9 From the leveled 3-D data set, extract Traces a, b, c, d, and e as shown in Fig. 3. Calibrate these data traces in the *x*- (or *y*-) and *z*-directions.

NOTE 9—In a bulk-micromachining process, the edges of the etched out cavity may be jagged, therefore, choose Traces a and e that contain representative endpoints.

10.4.1.10 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, follow the steps in Appendix X1 at this point. For a bulk-micromachining process, continue from 10.1 with another cantilever.

10.5 *Determine the Attachment Location of the Cantilever:*

10.5.1 Examine the calibrated Traces a and e from 10.4.1.9. These traces pass through and are perpendicular to Edge 1.

10.5.2 From each of these data traces, obtain $x1_{uppert}$ and $n1_t$, using the procedures in 10.5.3 and 10.5.4, respectively, where the subscript *t* identifies the data trace (*a* or *e*).

10.5.3 *To obtain* x_{uppert}*:*

10.5.3.1 Locate two points *p* and *q*, as shown in Fig. 5, on either side of the transitional edge (Edge 1 in this case) being examined.

10.5.3.2 Examine the out-of-plane *z*-data values one by one going from Point p to Point q (or from Point q to Point p).

10.5.3.3 Record the *x*-value of the data point that most appropriately locates the upper corner of the transitional edge as x_{uppert}, or $x1_{uppert}$ in this case because it is associated with Edge 1.

10.5.4 *To obtain* n_t *(for informational purposes only):*

10.5.4.1 The uncertainty associated with the identification of x_{uppert} is $\pm n_t x_{res} cal_x$, where x_{res} is the uncalibrated resolution of the interferometric microscope in the *x*-direction. An integer value is typically recorded for n_t. If it is easy to pick one point in 10.5.3.3 with an *x*-value that accurately identifies the *x*-value of the upper corner of the transitional edge, record n_t as 1. If the identification of the *x*-value of this corner point could be off by one data point, record n_t as 2, if it could be off by two data points, record n_t as 3, and so on. If n_t is larger than 4, extract another 2-D data trace repeating from 10.4.1.9, or obtain another 3-D data set repeating from 10.4.1. (This criterion may need to be modified for the given structure.)

10.5.5 For the data traces (*a* and *e*) record the calibrated *y* values (y_a and y_e) where $y_a > y_e$.

10.5.6 Calculate $x1_{ave}$ using the following equation:

$$x1_{ave} = \frac{x1_{uppera} + x1_{uppere}}{2} \tag{8}$$

10.6 *For Traces b, c, and d, Obtain Three Data Points Representative of the Shape of the Cantilever:*

10.6.1 For one of the data traces along the top of the cantilever (such as, Trace c, shown in Fig. 3 and Fig. 6) 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 $x1_{ave}$).

10.6.2 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 $x_1 < x_2 < x_3$.

NOTE 10—If the cantilever is curved out-of-plane in the *z*-direction such that it loops back over the top of the cantilever, the three data points can be taken along the cantilever before the presence of the bottom of the cantilever is detected by the interferometric microscope or the three data points can be taken from the bottom of the cantilever, in which case the value for "*s*" should be multiplied by minus 1.

10.6.3 Repeat the above (that is, 10.6.1 and 10.6.2) for Traces b and d.

11. Calculation (1-3)

11.1 Five steps are used to calculate the strain gradient for each data trace (*b*, *c*, and *d*): *(1)* account for any misalignment, *(2)* solve three equations for three unknowns for Trace c, *(3)* plot the function with the data from Trace c, *(4)* calculate the strain gradient for Trace c, and *(5)* repeat steps 2 through 4 for Traces b and d. The strain gradient is calculated as the average of the three strain gradient values obtained from the three data traces.[9]

11.2 *Account for Any Misalignment:*

11.2.1 Calculate the misalignment angle, α, as shown in Fig. 10 between Edge 1 and a line drawn perpendicular to Traces a and e, using the following equation:

$$\alpha = \tan^{-1}\left[\frac{\Delta x}{\Delta y}\right] \tag{9}$$

where

$$\Delta x = x1_{uppera} - x1_{uppere} \tag{10}$$

and

$$\Delta y = y_a - y_e \ (\text{with } y_a > y_e) \tag{11}$$

NOTE 11—An alternate edge, such as Edge 4 in Fig. 5, may be used to calculate the misalignment angle, α, instead of Edge 1 if $(n4_a + n4_e) < (n1_a + n1_e)$ as long as $x1_{ave} < x_1$.

11.2.2 Using the values obtained in 10.5 and 10.6 (namely, $x1_{ave}$, x_1, x_2, and x_3) determine *f*, *g*, *h*, and *i*, respectively, as seen in Fig. 11, along the *v*-axis (the axis parallel to the length of the cantilever). Do this for each data trace (*b*, *c*, and *d*) using the following equations:

$$f = x1_{ave} \tag{12}$$

$$g = (x_1 - f)\cos\alpha + f \tag{13}$$

$$h = (x_2 - f)\cos\alpha + f \tag{14}$$

and

$$i = (x_3 - f)\cos\alpha + f \tag{15}$$

The *z*-values of the data points along the cantilever remain the same, which assumes no curvature across the width of the cantilever. The data points along the cantilever (as seen in Fig. 12) are (g, z_1), (h, z_2), and (i, z_3).

11.3 *Solve Three Equations for Three Unknowns for Trace c:*

11.3.1 Solving the three circular equations:

$$z_1 = b + s\sqrt{R_{int}^2 - (g - a)^2} \tag{16}$$

$$z_2 = b + s\sqrt{R_{int}^2 - (h - a)^2} \tag{17}$$

and

$$z_3 = b + s\sqrt{R_{int}^2 - (i - a)^2} \tag{18}$$

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

$$a = \frac{a_{num1} + a_{num2}}{a_{den}} \tag{19}$$

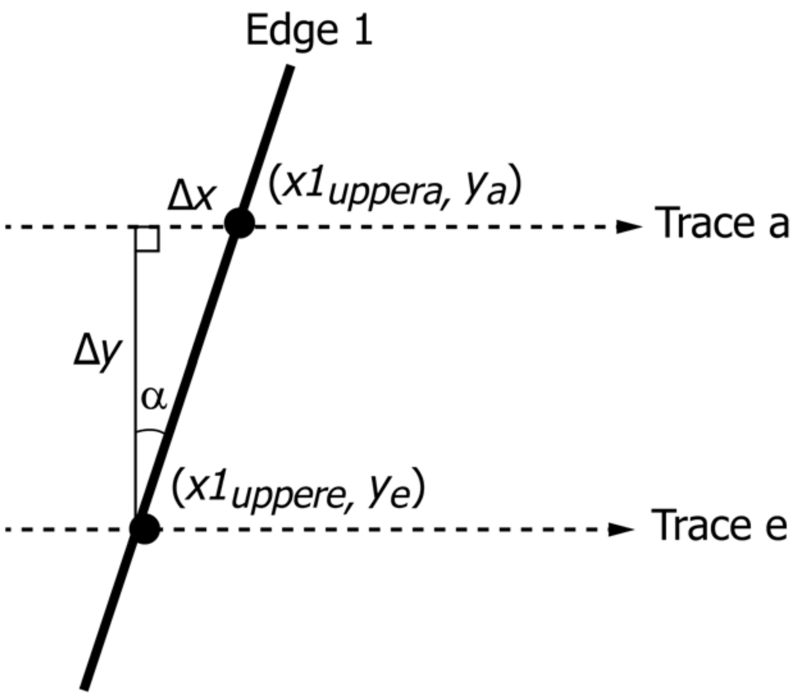


FIG. 10 Sketch Depicting the Misalignment Angle, α

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[9] By inserting the three data points into the correct locations on the appropriate NIST MEMS Calculator Web page, steps 1, 2, 4, and 5 can be performed on-line in a matter of seconds. The MEMS Calculator Web Site (Standard Reference Database 166) is accessible via the NIST Data Gateway (http://srdata.nist.gov/gateway/) with the keyword "MEMS Calculator."

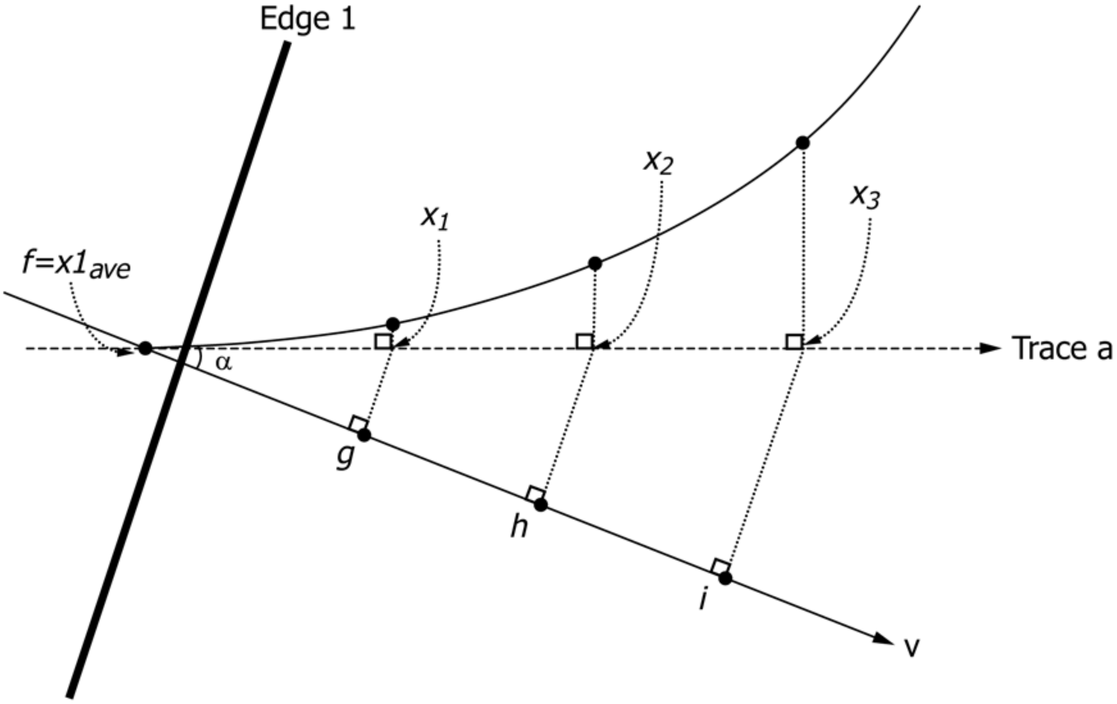


FIG. 11 Sketch Used to Derive the Appropriate *v*-Values (*f*, *g*, *h*, and *i*) Along the Length of the Cantilever

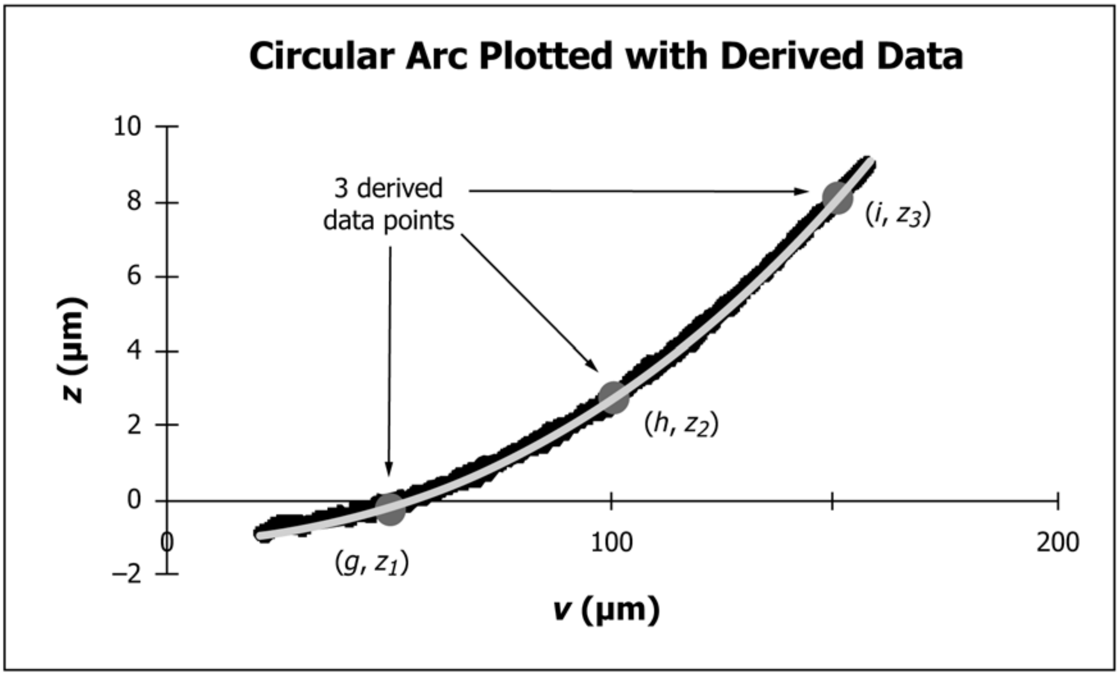


FIG. 12 A Comparison Plot of the Model with the Data

$$b = z_1 - Q' \tag{20}$$

and

$$R_{int} = \sqrt{(g - a)^2 + Q^2} \tag{21}$$

where

$$a_{num1} = z_2 g^2 - z_2 z_3^2 + z_2 z_1^2 - z_2 i^2 + z_1 z_3^2 + z_1 i^2 \tag{22}$$

$$a_{num2} = -z_3 g^2 + z_3 h^2 + z_3 z_2^2 - z_3 z_1^2 - z_1 h^2 - z_1 z_2^2 \tag{23}$$

$$a_{den} = 2(hz_3 - gz_3 - hz_1 + gz_2 - iz_2 + iz_1) \tag{24}$$

and

$$Q = \pm Q' = \pm \frac{[(g - a)^2 - (h - a)^2 - (z_2 - z_1)^2]}{2(z_2 - z_1)} \tag{25}$$

11.4 *Plot the Function with the Data from Trace c:*

11.4.1 Given the abbreviated data trace from 10.6.1, convert the *x*-values to *v*-values [where $v = (x - f)\cos\alpha + f$] and plot the resulting data along with the model using the following equation (see Fig. 12):

$$z = b + s\sqrt{R_{int}^{2} - (v - a)^{2}} \tag{26}$$

where

$$f \leq v \leq j \tag{27}$$

where j is the calibrated v-value associated with the upper corner of Edge 2 in Trace c (as seen in Fig. 6), and calculated, if necessary, using the following equation:

$$j = (x2_{uppert} - f)\cos\alpha + f \tag{28}$$

NOTE 12—An estimate for j is all that is needed for the plot.

11.4.2 If one of the three chosen data points in 10.6.2 does not provide an adequate fit of the curve to the data, choose another data point or alter its z value and repeat the analysis beginning at 11.2.2.

11.5 *Calculate the Strain Gradient for Trace c:*

11.5.1 Calculate the strain gradient for Trace c using one of the following equations:

$$s_{gt} \approx \frac{1}{R_{int}} + s_{gcorrection} \tag{29}$$

or

$$s_{g0t} = \frac{1}{\left[R_{int} - s\left(\frac{t}{2}\right)\right]} + s_{gcorrection} \tag{30}$$

where s_{g0t} is the strain gradient when the residual strain equals zero and where t is the thickness of the suspended, structural layer **(1, 6-8)**. The subscript t in s_{gt} and s_{g0t} refers to the data trace. The strain gradient correction term, $s_{gcorrection}$, corrects for variations associated with length and is also assumed to correct for deviations from the ideal cantilever geometry and/or composition **(1)**.

11.5.1.1 To obtain $s_{gcorrection}$ associated with a given length cantilever in a given process, obtain strain gradient measurements from different length cantilevers with three different cantilevers measured at each length. Plot s_g versus L_{des}. Typically, for the longer cantilevers $s_{gcorrection} = 0\ \text{m}^{-1}$ or a value that corrects for deviations from the ideal cantilever geometry and/or composition. The values of $s_{gcorrection}$ for the other cantilever lengths can be extracted from this plot.

11.6 *Repeat 11.3 through 11.5 for Traces b and d.*

11.7 *Calculate the strain gradient as the average of the strain gradient values obtained from Traces b, c, and d as follows:*

$$s_g = \frac{s_{gb} + s_{gc} + s_{gd}}{3} \tag{31}$$

If a bulk-micromachined cantilever consisting of multiple layers (see Note 7) was measured, s_g would be considered an effective strain gradient.

11.8 Calculate u_{csg}, the combined standard uncertainty **(9, 10)** for the strain gradient measurement, using the method presented in Annex A1.

12. Report

12.1 Report the results as follows **(9, 10)**: Since it can be assumed that the estimated values of the uncertainty components are either approximately uniformly or Gaussianly distributed (as specified in Annex A1) with approximate combined standard uncertainty u_{csg}, the strain gradient is believed to lie in the interval $s_g \pm u_{csg}$ (expansion factor k=1) representing a level of confidence of approximately 68 %.

13. Precision and Bias

13.1 In the spring of 1999, ASTM conducted a round robin experiment **(2, 11)** that included out-of-plane deflection measurements of fixed-fixed beams and cantilevers fabricated in a surface-micromachining process. 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 *The Round Robin*—The MEMS Length and Strain Round Robin Experiment took place from August 2003 to January 2005 **(3, 12)**. Eight independent laboratories participated in this round robin experiment using test chips fabricated in a surface-micromachining process. With the use of this test method, the variations in the community measurements were significantly tightened, assuming any change in positioning of the sample during transport between the laboratories remained the same.

13.3 *Precision*—The repeatability and reproducibility data for strain gradient are presented in Table 2. In this table, n indicates the number of measurements and s_{gave} is the average of the strain gradient repeatability or reproducibility measurements results. For the repeatability measurements only, $\sigma_{repeat(samp)}$ (the relative standard deviation of the repeatability strain gradient measurements) is listed next (for use in A1.13). Then, the $\pm 2\sigma_{sg}$ limits are listed where σ_{sg} is the standard deviation of the strain gradient measurements. The last four entries in this table are four different calculations of the average combined standard uncertainty (as detailed in the table notes).

13.3.1 As expected, the $\pm 2\sigma_{sg}$ limits for the repeatability data (that is, ±25 %) are better than the $\pm 2\sigma_{sg}$ limits for the reproducibility data (that is, ±37 %) for the same span of design lengths. This can be due to the repeatability measurements being taken at the same laboratory using the same instrument by the same operator. It is interesting to note that the u_{csgave} value for the reproducibility measurements is slightly lower than the comparable u_{csgave} value for the repeatability measurements for the same span of design lengths.

13.3.2 The strain gradient repeatability data is plotted versus test structure orientation in Fig. 13. In this plot, there is no obvious orientation dependence.

TABLE 2 Repeatability and Reproducibility Data[A]

	Repeatability Results L_{des} = 500 to 650 µm	Repeatability Results L_{des} = 400 to 750 µm	Reproducibility Results L_{des} = 500 to 650 µm
1. n	24	48	6
2. s_{gave}	4.71 m^{-1}	4.97 m^{-1}	4.67 m^{-1}
3. $\sigma_{repeat(samp)}$	13 %	20 %	—
4. ±2σ_{sg} limits	±1.2 m^{-1} (±25 %)	±2.0 m^{-1} (±40 %)	±1.7 m^{-1} (±37 %)
5. u_{csgave}[B]	0.73 m^{-1} (14 %)	0.84 m^{-1} (17 %)	0.56 m^{-1} (12 %)
6. u_{csgave}[C]	0.47 m^{-1} (10 %)	0.56 m^{-1} (11 %)	—
7. u_{csgave}[D]	0.44 m^{-1} (9.5 %)	0.52 m^{-1} (11 %)	—
8. u_{csgave}[E]	0.74 m^{-1} (16 %)	1.12 m^{-1} (23 %)	—

[A] Taken on test chips fabricated in a surface-micromachining process.

[B] As determined using Test Method E 2246–02. For the u_{csg} calculation, the u_{samp} and u_{zcal} components were combined into one component. As such, for this component, assuming a uniform (that is, rectangular) probability distribution, the limits were represented by a ±20 nm variation in the z-value of the data points. Also, $u_{zres} = u_{xcal} = u_{xres} = 0$ m^{-1}. (See Test Method E2246–05 for the definitions of the uncertainty components.)

[C] As determined using Test Method E2246–05.

[D] As determined using Eq A1.1 with $u_{repeat(samp)} = 0$ m^{-1}.

[E] As determined using Eq A1.1.

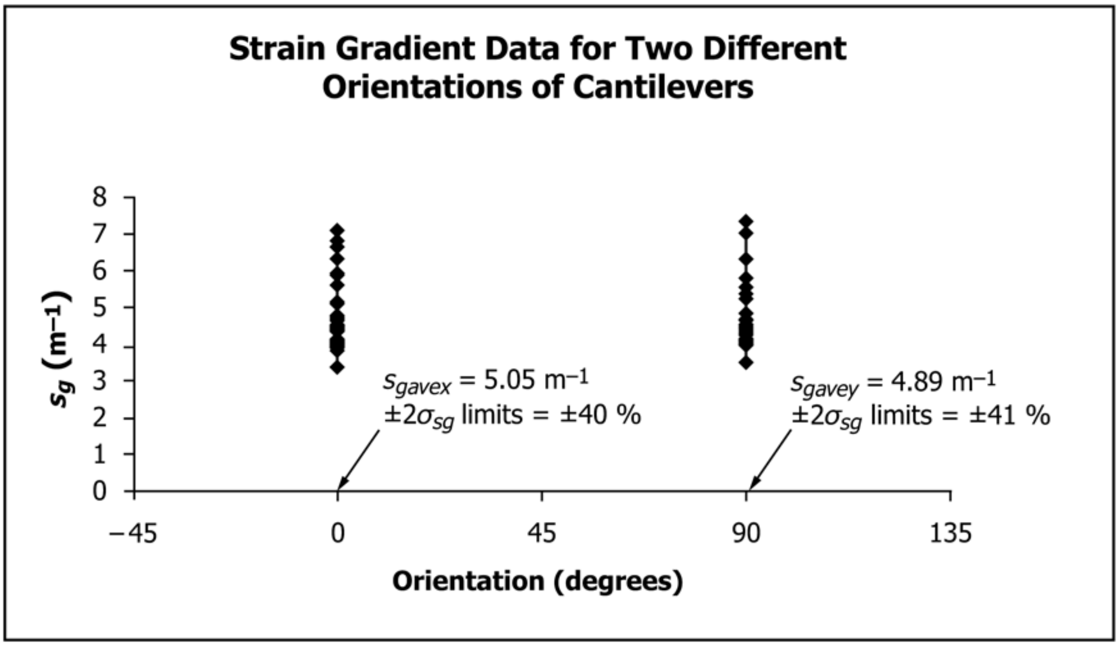


FIG. 13 Strain Gradient Repeatability Data Plotted versus Test Structure Orientation

13.3.3 The strain gradient repeatability data is plotted versus L_{des} in Fig. 14. In this plot, the data indicate there is a decrease in the strain gradient for increasing length (for L_{des} = 400 µm to 600 µm) then it levels off (L_{des} = 600 µm to 750 µm).

13.4 *Bias*—No information can be presented on the bias of the procedure in this test method for measuring strain gradient because there is not a certified MEMS material for this purpose.

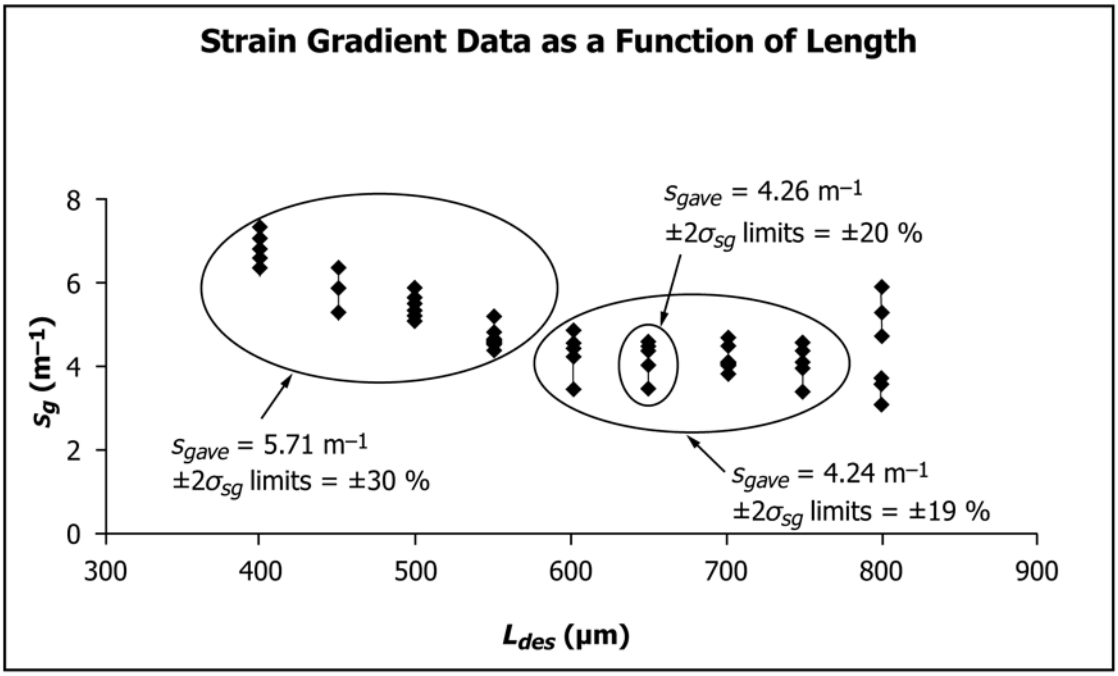


FIG. 14 Strain Gradient Repeatability Data Plotted versus L_{des}

14. Keywords

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

ANNEX

(Mandatory Information)

A1. CALCULATION OF COMBINED STANDARD UNCERTAINTY

A1.1 Calculate u_{csg}, the combined standard uncertainty for the strain gradient measurement (**9**, **10**), using the following equation:[9]

$$u_{csg} = \sqrt{\begin{array}{l} u_w^2 + u_{zres}^2 + u_{xcal}^2 + u_{xres}^2 + u_{Rave}^2 + u_{noise}^2 + u_{cert}^2 \\ + u_{repeat(shs)}^2 + u_{drift}^2 + u_{linear}^2 + u_{correction}^2 + u_{repeat(samp)}^2 \end{array}} \tag{A1.1}$$

where u_W, u_{zres}, u_{xcal}, u_{xres}, u_{Rave}, u_{noise}, u_{cert}, $u_{repeat(shs)}$, u_{drift}, u_{linear}, $u_{correction}$, and $u_{repeat(samp)}$ are found below in A1.2 through A1.13, respectively, as summarized in Table A1.1. These can be considered Type B components, except where noted.

A1.2 Determine u_W:

A1.2.1 Calculate u_W as the standard deviation of the strain gradient values (s_{gb}, s_{gc}, and s_{gd}) obtained in Section 11.

A1.3 Determine u_{zres}:

A1.3.1 For each data trace (b, c, and d) obtain three strain gradient values for the three different sets of inputs given in Table A1.2 using d=(1/2)z_{res} where z_{res} was recorded in 9.2.

A1.3.2 For each data trace, record $s_{g\text{-}low}$ and $s_{g\text{-}high}$ and calculate u_{zrest} using the equation given in Table A1.1, which assumes a uniform distribution.

A1.3.3 Calculate u_{zres} as the average of the three values obtained for u_{zrest}.

A1.4 Determine u_{xcal}:

A1.4.1 Calculate cal_{xmax} and cal_{xmin} using the equations given in Table A1.1, where σ_{xcal} and $ruler_x$ were obtained in 9.1.

A1.4.2 For each data trace, determine s_{gt} assuming cal_{xmax} is the x-calibration factor.

TABLE A1.1 Determination of the Uncertainty Components

Uncertainty Component	Method to Obtain $s_{g\text{-}high}$ and $s_{g\text{-}low}$, if applicable	G or U[A] / A or B[B]	equation
1. u_w	—	G / A	$u_w = STDEV(s_{gb}, s_{gc}, s_{gd})$
2. u_{zres}	using d=(1/2)z_{res} in Table A1.2	U / B	$u_{zrest} = \frac{\lvert s_{g-high} - s_{g-low}\rvert}{2\sqrt{3}}$
			$u_{zres} = \frac{u_{zresb} + u_{zresc} + u_{zresd}}{3}$
3. u_{xcal}	using cal_{xmin} for cal_x where $cal_{xmin} = cal_x - 3\sigma_{xcal} cal_x / ruler_x$	G / B	$u_{xcalt} = \frac{\lvert s_{g-high} - s_{g-low}\rvert}{6}$
	and using cal_{xmax} for cal_x where $cal_{xmax} = cal_x + 3\sigma_{xcal} cal_x / ruler_x$		$u_{xcal} = \frac{u_{xcalb} + u_{xcalc} + u_{xcald}}{3}$
4. u_{xres}	using d=(1/2)$x_{res}\cos(\alpha)$ in Table A1.3	U / B	$u_{xrest} = \frac{\lvert s_{g-high} - s_{g-low}\rvert}{2\sqrt{3}}$
			$u_{xres} = \frac{u_{xresb} + u_{xresc} + u_{xresd}}{3}$
5. u_{Rave}	using d=3σ_{Rave} in Table A1.2 where	G / B	$u_{Ravet} = \frac{\lvert s_{g-high} - s_{g-low}\rvert}{6}$
	$\sigma_{Rave} = \frac{1}{6} R_{ave}$		$u_{Rave} = \frac{u_{Raveb} + u_{Ravec} + u_{Raved}}{3}$
6. u_{noise}	using d=3σ_{noise} in Table A1.2 where	G / B	$u_{noiset} = \frac{\lvert s_{g-high} - s_{g-low}\rvert}{6}$
	$\sigma_{noise} = \frac{1}{6} (R_{tave} - R_{ave})$		$u_{noise} = \frac{u_{noiseb} + u_{noisec} + u_{noised}}{3}$
7. u_{cert}	using d=3$(z_x - z_1)\sigma_{cert}/cert$ in Table A1.4 where	G / B	$u_{certt} = \frac{\lvert s_{g-high} - s_{g-low}\rvert}{6}$
	z_x is the column heading		$u_{cert} = \frac{u_{certb} + u_{certc} + u_{certd}}{3}$
8.$u_{repeat(shs)}$	using d=3$(z_x - z_1)\sigma_{6same}/\bar{z}_{6same}$ in Table A1.4 where	G / B	$u_{repeat(shs)t} = \frac{\lvert s_{g-high} - s_{g-low}\rvert}{6}$
	z_x is the column heading		$u_{repeat(shs)} = \frac{u_{repeat(shs)b} + u_{repeat(shs)c} + u_{repeat(shs)d}}{3}$
9. u_{drift}	using d=$(z_x - z_1) z_{drift} cal_z/(2cert)$ in Table A1.4 where	U / B	$u_{driftt} = \frac{\lvert s_{g-high} - s_{g-low}\rvert}{2\sqrt{3}}$
	z_x is the column heading		$u_{drift} = \frac{u_{driftb} + u_{driftc} + u_{driftd}}{3}$
10. u_{linear}	using d=$(z_x - z_1) z_{lin}$ in Table A1.4 where	U / B	$u_{lineart} = \frac{\lvert s_{g-high} - s_{g-low}\rvert}{2\sqrt{3}}$
	z_x is the column heading		$u_{linear} = \frac{u_{linearb} + u_{linearc} + u_{lineard}}{3}$

TABLE A1.1 *Continued*

Uncertainty Component	Method to Obtain $s_{g\text{-}high}$ and $s_{g\text{-}low}$, if applicable	G or U[A] / A or B[B]	equation
11. $u_{correction}$	—	G / B	$u_{correction} = u_{correctiont} = \frac{\lvert s_{gcorrection} \rvert}{3}$
12. $u_{repeat(samp)}$	—	G / A	$u_{repeat(samp)t} = \sigma_{repeat(samp)}\ s_{gt}$ $u_{repeat(samp)} = \frac{u_{repeat(samp)b} + u_{repeat(samp)c} + u_{repeat(samp)d}}{3}$

[A] "G" indicates a Gaussian distribution and "U" indicates a uniform distribution.

[B] Type A or Type B analysis.

TABLE A1.2 Three Sets of Inputs to Determine u_{zrest}, u_{Ravet}, and u_{noiset}

	z_1	z_2	z_3
1	z_1	z_2	z_3
2	$z_1 + d$	$z_2 - d$	$z_3 + d$
3	$z_1 - d$	$z_2 + d$	$z_3 - d$

A1.4.3 For each data trace, determine s_{gt} assuming cal_{xmin} is the x-calibration factor.

A1.4.4 For each data trace, record $s_{g\text{-}low}$ and $s_{g\text{-}high}$ and calculate u_{xcalt} using the equation given in Table A1.1, which assumes a Gaussian distribution.

A1.4.5 Calculate u_{xcal} as the average of the three values obtained for u_{xcalt}.

A1.5 Determine u_{xres}:

A1.5.1 For each data trace (b, c, and d) obtain seven strain gradient values for the seven different sets of inputs given in Table A1.3 using d=(1/2)x_{res}cos(α) where x_{res} was recorded in 9.2.

A1.5.2 For each data trace, record $s_{g\text{-}low}$ and $s_{g\text{-}high}$ and calculate u_{xrest} using the equation given in Table A1.1, which assumes a uniform distribution.

A1.5.3 Calculate u_{xres} as the average of the three values obtained for u_{xrest}.

A1.6 Determine u_{Rave}:

A1.6.1 Calculate σ_{Rave} as one-sixth the value of R_{ave}, where R_{ave} was obtained in 9.2.

A1.6.2 For each data trace (b, c, and d) obtain three strain gradient values for the three different sets of inputs given in Table A1.2 using d=3σ_{Rave}.

TABLE A1.3 Seven Sets of Inputs to Determine u_{xrest}

	g	h	i
1	g	h	i
2	$g + d$	h	$i - d$
3	$g - d$	h	$i + d$
4	$g + d$	$h + d$	$i - d$
5	$g + d$	$h - d$	$i - d$
6	$g - d$	$h + d$	$i + d$
7	$g - d$	$h - d$	$i + d$

A1.6.3 For each data trace, record $s_{g\text{-}low}$ and $s_{g\text{-}high}$ and calculate u_{Ravet} using the equation given in Table A1.1, which assumes a Gaussian distribution.

A1.6.4 Calculate u_{Rave} as the average of the three values obtained for u_{Ravet}.

A1.7 Determine u_{noise}:

A1.7.1 Calculate σ_{noise}, the standard deviation of the noise measurement, as one-sixth the value of R_{tave} minus R_{ave}, where R_{tave} and R_{ave} were obtained in 9.2.

A1.7.2 For each data trace (b, c, and d) obtain three strain gradient values for the three different sets of inputs given in Table A1.2 using d=3σ_{noise}.

A1.7.3 For each data trace, record $s_{g\text{-}low}$ and $s_{g\text{-}high}$ and calculate u_{noiset} using the equation given in Table A1.1, which assumes a Gaussian distribution.

A1.7.4 Calculate u_{noise} as the average of the three values obtained for u_{noiset}.

A1.8 Determine u_{cert}:

A1.8.1 For each data trace (b, c, and d) obtain three strain gradient values for the three different sets of inputs given in Table A1.4 using d=3(z_x–z_1)σ_{cert}/$cert$ where z_x is the column heading and where σ_{cert} was recorded in 9.2.

A1.8.2 For each data trace, record $s_{g\text{-}low}$ and $s_{g\text{-}high}$ and calculate u_{certt} using the equation given in Table A1.1, which assumes a Gaussian distribution.

A1.8.3 Calculate u_{cert} as the average of the three values obtained for u_{certt}.

A1.9 Determine $u_{repeat(shs)}$:

A1.9.1 For each data trace (b, c, and d) obtain three strain gradient values for the three different sets of inputs given in Table A1.4 using d=3(z_x–z_1)σ_{6same}/$\bar{z}_{6same}$ where z_x is the column heading and where σ_{6same} and $\bar{z}_{6same}$ were found in 9.2.

TABLE A1.4 Three Sets of Inputs to Determine u_{certt}, $u_{repeat(shs)t}$, u_{driftt}, and $u_{lineart}$

	z_1	z_2	z_3
1	z_1	z_2	z_3
2	z_1	$z_2 + d$	$z_3 + d$
3	z_1	$z_2 - d$	$z_3 - d$

A1.9.2 For each data trace, record $s_{g\text{-}low}$ and $s_{g\text{-}high}$ and calculate $u_{repeat(shs)t}$ using the equation given in Table A1.1, which assumes a Gaussian distribution.

A1.9.3 Calculate $u_{repeat(shs)}$ as the average of the three values obtained for $u_{repeat(shs)t}$.

A1.10 Determine u_{drift}:

A1.10.1 For each data trace (*b*, *c*, and *d*) obtain three strain gradient values for the three different sets of inputs given in Table A1.4 using $d=(z_x-z_1)z_{drift}cal_z/(2cert)$ where z_x is the column heading and where z_{drift} was found in 9.2.

A1.10.2 For each data trace, record $s_{g\text{-}low}$ and $s_{g\text{-}high}$ and calculate u_{driftt} using the equation given in Table A1.1, which assumes a uniform distribution.

A1.10.3 Calculate u_{drift} as the average of the three values obtained for u_{driftt}.

A1.11 Determine u_{linear}:

A1.11.1 For each data trace (*b*, *c*, and *d*) obtain three strain gradient values for the three different sets of inputs given in Table A1.4 using $d=(z_x-z_1)z_{lin}$ where z_x is the column heading and where z_{lin} was recorded in 9.2.

A1.11.2 For each data trace, record $s_{g\text{-}low}$ and $s_{g\text{-}high}$ and calculate $u_{lineart}$ using the equation given in Table A1.1, which assumes a uniform distribution.

A1.11.3 Calculate u_{linear} as the average of the three values obtained for $u_{lineart}$.

A1.12 Determine $u_{correction}$:

A1.12.1 Calculate $u_{correction}$ using the equation given in Table A1.1.

A1.13 Determine $u_{repeat(samp)}$:

A1.13.1 Obtain $\sigma_{repeat(samp)}$, the strain gradient relative repeatability standard deviation for cantilevers fabricated in a process similar to that used to fabricate the sample. (Table 2 provides values for $\sigma_{repeat(samp)}$ for a surface-micromachining process used to fabricate the round robin test chips (**3**) specified in 13.2.)

A1.13.1.1 Determine $\sigma_{repeat(samp)}$, if not known, from at least twelve 3-D data sets of a given cantilever from which twelve values of s_g are calculated. The standard deviation of these measurements divided by the average of the twelve strain gradient values is equated with $\sigma_{repeat(samp)}$.

A1.13.2 For each data trace, calculate $u_{repeat(samp)t}$ using the equation given in Table A1.1.

A1.13.3 Calculate $u_{repeat(samp)}$ as the average of the three values obtained for $u_{repeat(samp)t}$.

A1.14 The expanded uncertainty for strain gradient, U_{sg}, is calculated using the following equation:

$$U_{sg} = ku_{csg} = 2u_{csg} \tag{A1.2}$$

where the *k* value of 2 approximates a 95 % level of confidence.

APPENDIX

X1. ADHERENCE OF SURFACE-MICROMACHINED CANTILEVER TO UNDERLYING LAYER

X1.1 Determine if the surface-micromachined cantilever (shown in Fig. X1.1) is adhered to the top of the underlying layer (**2, 7**).

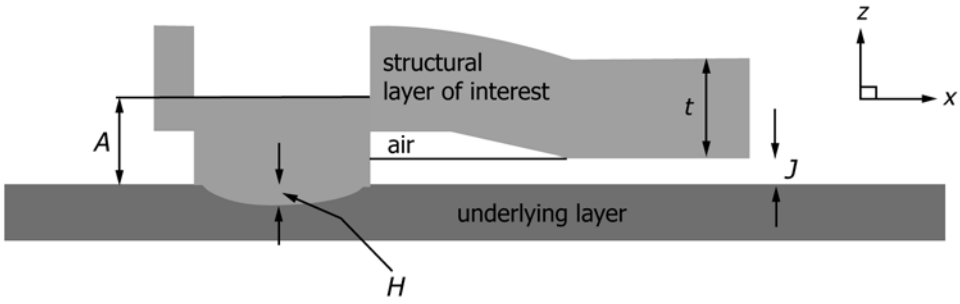
X1.1.1 From 10.4.1.9, choose a calibrated 2-D data trace (such as Trace c in Fig. 3) along the cantilever including its large anchor area and the exposed underlying layer to the far side of the anchor.

Note X1.1—It may be necessary to obtain two 3-D data sets. One of the data sets would include the cantilever and the anchor to the left of the cantilever and the other data set would include that same anchor and the underlying layer to the left of that anchor.

X1.1.2 Plot the calibrated 2-D data trace (as shown in Fig. X1.2).

X1.1.3 Locate and record $z_{reg\#1}$ as defined in 3.2.5.

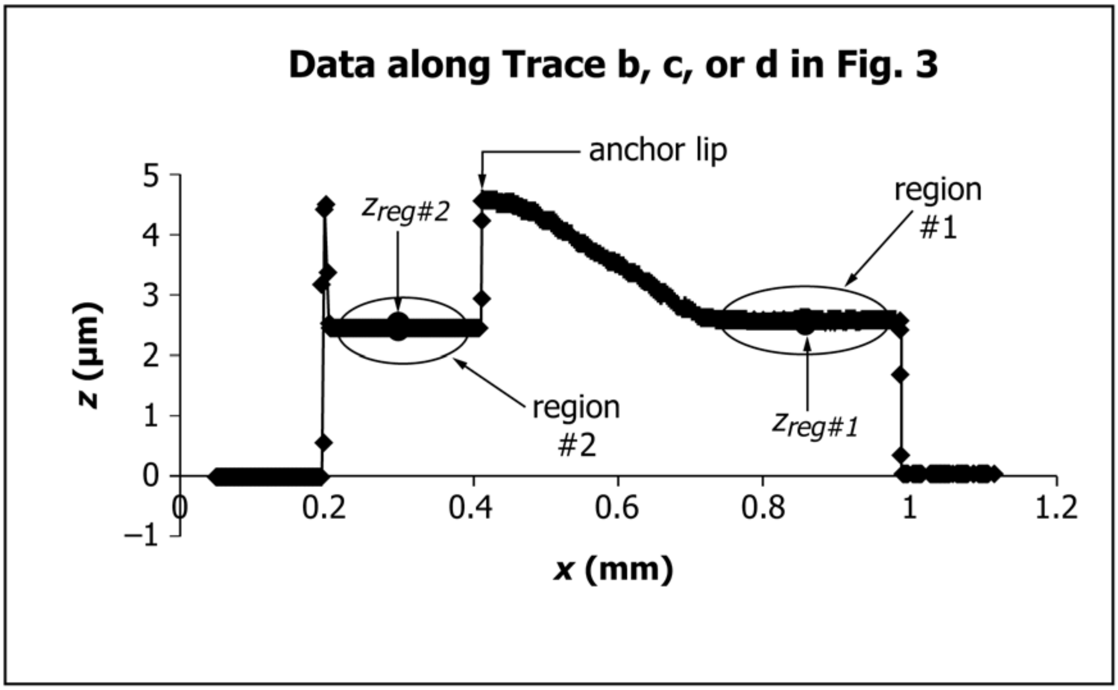
X1.1.4 If neighboring points have similar *z* values (as shown in Fig. X1.2) such that a "flat" region exists, define this group of points as region #1.



Note 1—See Fig. X1.2 for a corresponding interferometric 2-D data trace.

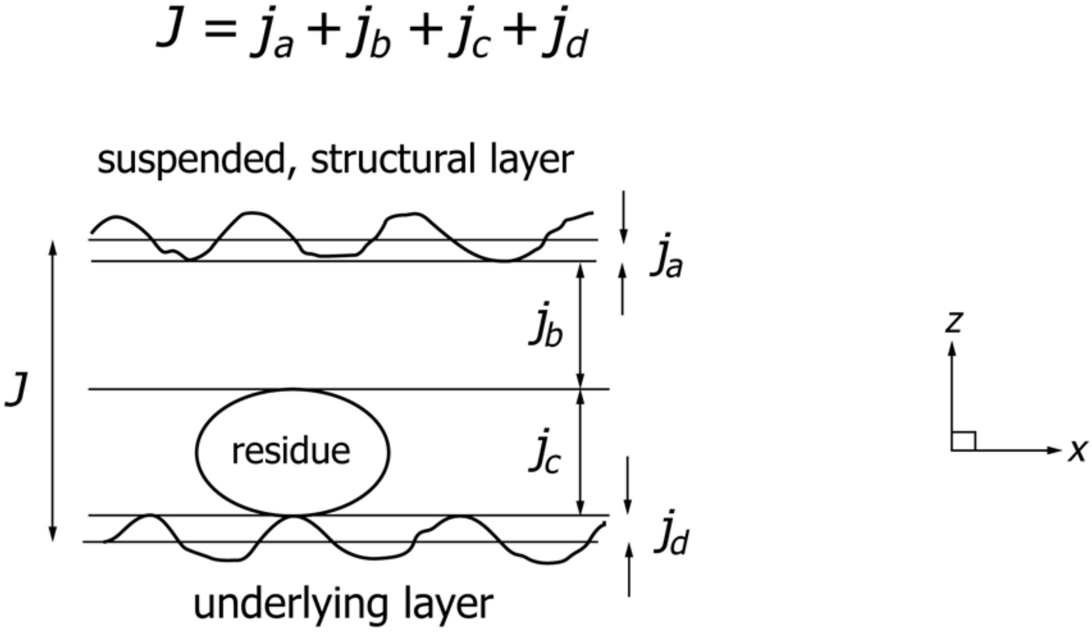
Note 2—See Fig. X1.3 and Fig. X1.4 for the component parts of dimension *J*.

FIG. X1.1 Cross-sectional Side View of Cantilever Adhered to Top of Underlying Layer



NOTE 1—This is an example of stiction.

FIG. X1.2 2-D Data Trace of Cantilever in Fig. X1.1



NOTE 1—This view is along the length of the cantilever where it has adhered to the top of the underlying layer.

FIG. X1.3 Component Parts of *J* in Fig. X1.1

X1.1.5 Define region #2 as a group of points within the large anchor area, as shown in Fig. X1.2. Record $z_{reg\#2}$ as defined in 3.2.5.

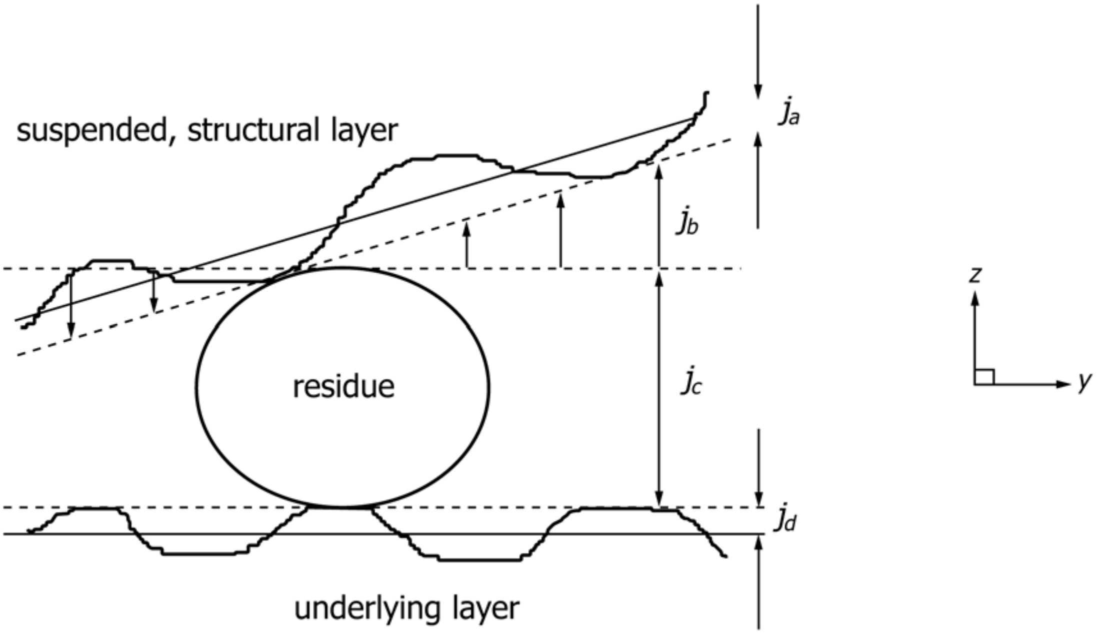
X1.1.6 If the process is such that there are one or more posts in the anchor area of thickness t_1, t_2, t_3, and so on, corresponding to posts 1, 2, 3, and so on, then the cantilever is adhered to the top of the underlying layer if $z_{reg\#2}$ minus $z_{reg\#1}$ plus 100 nm is greater than or equal to the sum of the post thicknesses. This criterion errs on the conservative side. If the process does not have posts in the anchor area, continue with X1.1.7.

X1.1.7 Calculate B_1 as defined by the following equation:

$$B_1 = z_{reg\#1} - z_{reg\#2} \tag{X1.1}$$

X1.1.8 Calculate B_2 as defined by one of the following equations:

$$B_2 = H + J \tag{X1.2}$$



NOTE 1—This view is along the width of the cantilever.

FIG. X1.4 Component Parts of *J* in Fig. X1.1 and Fig. X1.3

or

$$B_2 = t - A + J \tag{X1.3}$$

where *A*, *H*, and *J* in Fig. X1.1 are defined in 3.2.5 and where *t* is the thickness of the suspended, structural layer.

NOTE X1.2—SEMI Test Method MS2 can be used to obtain *A* (as shown in Fig. X1.1) from data taken along three 2-D data traces.

NOTE X1.3—Referring to Fig. X1.1, use Eq X1.2 if *H* is known more precisely than the quantity (*t* – *A*). Otherwise, use Eq X1.3 to find B_2.

X1.1.9 Repeat X1.1.2 to X1.1.8 for Traces b and d.

X1.1.10 The cantilever is adhered to the top of the underlying layer if the criterion specified in X1.1.10.1 or X1.1.10.2 is satisfied for any of the 2-D data traces along the cantilever.

NOTE X1.4—The adherence criteria that follows will become more precise as fabrication processes and measurements improve.

X1.1.10.1 Twenty points or more are within region #1 and $B_1 \leq B_2 + 120$ nm.

NOTE X1.5—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.

X1.1.10.2 Less than 20 points are within region #1 and $B_1 \leq B_2 + 100$ nm.

NOTE X1.6—Determining if the cantilever is adhered at one point along the length of the cantilever is a difficult task. Therefore, this criterion errs on the conservative side.

REFERENCES

(1) Cassard, J. M., Geist, J., Vorburger, T. V., Read, D. T., Gaitan, M., and Seiler, D. G., "User's Guide for RM 8096 and 8097: The MEMS 5-in-1, 2013 Edition," NIST Special Publication 260-177, National Institute of Standards and Technology (2013); available at http://dx.doi.org/10.6028/NIST.SP.260-177.

(2) Marshall, J. C., "MEMS Length and Strain Measurements Using an Optical Interferometer," NISTIR 6779, National Institute of Standards and Technology, August 2001.

(3) Marshall, J. C., Scace, R. I., Baylies, W. A., "MEMS Length and Strain Round Robin Results with Uncertainty Analysis," NISTIR 7291, National Institute of Standards and Technology, January 2006.

(4) 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.

(5) 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.

(6) Gupta, R. K., Osterberg, P. M., and Senturia, S. D., "Material Property Measurements of Micromechanical Polysilicon Beams," *Microlithography and Metrology in Micromachining II*, SPIE, Vol 2880, October 14-15, 1996, pp. 39-45.

(7) Jensen, B. D., de Boer, M. P., Masters, N. D., Bitsie, F., and LaVan, D. A., "Interferometry of Actuated Microcantilevers to Determine Material Properties and Test Structure Nonidealities in MEMS," *Journal of Microelectromechanical Systems*, Vol 10 , September 2001, pp. 336-346.

(8) Marshall, J. C., "New Optomechanical Technique for Measuring Layer Thickness in MEMS Processes," *Journal of Microelectromechanical Systems*, Vol 10, March 2001, pp. 153-157.

(9) 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, Sept. 1994.

(10) EURACHEM/CITAC Guide CG 4: Quantifying Uncertainty in Analytical Measurement, Second Edition, QUAM: 2000.1.

(11) Masters, N. D., de Boer, M. P., Jensen, B. D., Baker, M. S., and Koester, D., "Side-by-Side Comparison of Passive MEMS Strain Test Structures under Residual Compression," Mechanical Properties of Structural Films, ASTM STP 1413, ASTM, 2001, pp. 168-200.

(12) Marshall, J. C., Secula, E. M., and Huang, J., "Round Robin for Standardization of MEMS Length and Strain Measurements," SEMI Technology Symposium: Innovations in Semiconductor Manufacturing (STS: ISM), SEMICON West 2004, San Francisco, CA, July 12-14, 2004.

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