Designation: E2245 – 11$^{\varepsilon 1}$

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

This standard is issued under the fixed designation E2245; 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.

ε[1] NOTE—Reference (1) was editorially revised in September 2013.

1. Scope

1.1 This test method covers a procedure for measuring the compressive residual strain in thin films. It applies only to films, such as found in microelectromechanical systems (MEMS) materials, which can be imaged using an optical interferometer, also called an interferometric microscope. Measurements from fixed-fixed beams 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

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

E2444 Terminology Relating to Measurements Taken on Thin, Reflecting Films

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the Z-Magnification of an Atomic Force Microscope at Subnanometer Displacement Levels Using Si*(111)* Monatomic Steps (Withdrawn 2015)[3]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

[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 December 2011. Originally approved in 2002. Last previous edition approved in 2005 as E2245 – 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_{noise} = the standard deviation of the noise measurement, calculated to be one-sixth the value of R_{tave} minus R_{ave}

σ_{Rave} = the standard deviation of the surface roughness measurement, calculated to be one-sixth the value of R_{ave}

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 In-plane Length Measurement:*

α = the misalignment angle

L = the in-plane length measurement of the fixed-fixed beam

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

$v1_{end}$ = one endpoint of the in-plane length measurement

$v2_{end}$ = another endpoint of the in-plane length measurement

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

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

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

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

3.2.3 *For Residual Strain Measurement:*

$\delta_{\varepsilon rcorrection}$ = the relative residual strain correction term

ε_r = the residual strain

A_F = the amplitude of the cosine function used to model the first abbreviated data trace

A_S = the amplitude of the cosine function used to model the second abbreviated data trace

L_0 = the calibrated length of the fixed-fixed beam if there are no applied axial-compressive forces

L_c = the total calibrated length of the curved fixed-fixed beam (as modeled with two cosine functions) with $v1_{end}$ and $v2_{end}$ as the calibrated v values of the endpoints

L_{cF} = the calibrated length of the cosine function modeling the first curve with $v1_{end}$ and i as the calibrated v values of the endpoints

L_{cS} = the calibrated length of the cosine function modeling the second curve with i and $v2_{end}$ as the calibrated v values of the endpoints

$L_{e'}$ = the calibrated effective length of the fixed-fixed beam calculated as a straight-line measurement between v_{eF} and v_{eS}

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

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

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

t = the thickness of the suspended, structural layer

v_{eF} = the calibrated v value of the inflection point of the cosine function modeling the first abbreviated data trace

v_{eS} = the calibrated v value of the inflection point of the cosine function modeling the second abbreviated data trace

3.2.4 *For Combined Standard Uncertainty Calculations:*

$\varepsilon_{r\text{-}high}$ = in determining the combined standard uncertainty value for the residual strain measurement, the highest value for ε_r given the specified variations

$\varepsilon_{r\text{-}low}$ = in determining the combined standard uncertainty value for the residual strain measurement, the lowest value for ε_r given the specified variations

$\sigma_{Lrepeat(samp)'}$ = the in-plane length repeatability standard deviation (for the given combination of lenses for the given interferometric microscope) as obtained from test structures fabricated in a process similar to that used to fabricate the sample and when the transitional edges face each other

$\sigma_{repeat(samp)}$ = the relative residual strain repeatability standard deviation as obtained from fixed-fixed beams 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

$U_{\varepsilon r}$ = the expanded uncertainty of a residual strain measurement

$u_{c\varepsilon r}$ = the combined standard uncertainty of a residual strain measurement

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

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

u_L = the component in the combined standard uncertainty calculation for residual strain that is due to the measurement uncertainty of L

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

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

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

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

$u_{repeat(shs)}$ = the component in the combined standard uncertainty calculation for residual strain 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 residual strain that is due to variations across the width of the fixed-fixed beam

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

u_{xres} = the component in the combined standard uncertainty calculation for residual strain that is due to the resolution of the interferometric microscope in the *x*-direction as pertains to the data points chosen along the fixed-fixed beam

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

3.2.5 *For Round Robin Measurements:*

ε_{rave} = the average residual strain value for the repeatability or reproducibility measurements that is equal to the sum of the ε_r values divided by *n*

L_{des} = the design length of the fixed-fixed beam

n = the number of repeatability or reproducibility measurements

$u_{c\varepsilon rave}$ = the average combined standard uncertainty value for the residual strain measurements that is equal to the sum of the $u_{c\varepsilon r}$ values divided by *n*

3.2.6 *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 fixed-fixed beam with respect to an 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

3.2.7 *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 fixed-fixed beam is shown in Figs. 1-3. After fabrication, this fixed-fixed beam 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 fixed-fixed beam (such as Traces a', a, e, and e', shown in Fig. 3 and Fig. 5) and along the top of the fixed-fixed beam (such as Traces b, c, and d, shown in Fig. 3 and Fig. 6) are extracted from this 3-D data set for the residual strain analysis.

4.2 The residual strain is determined from measurements of the in-plane length and the curved length of the fixed-fixed

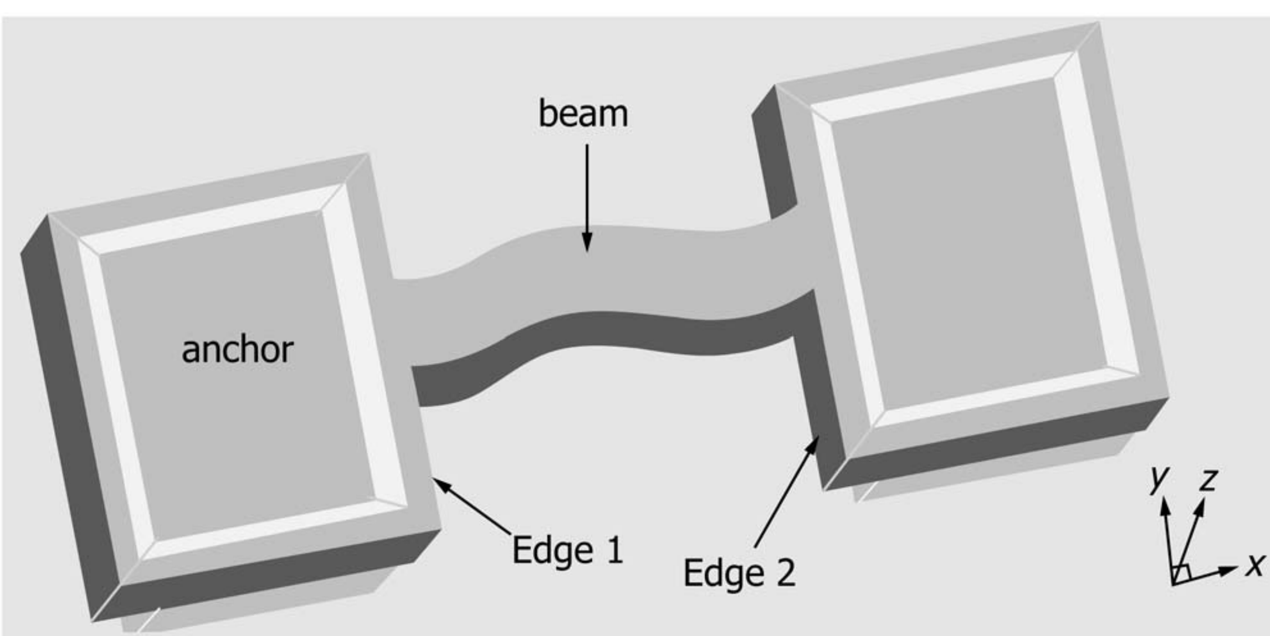
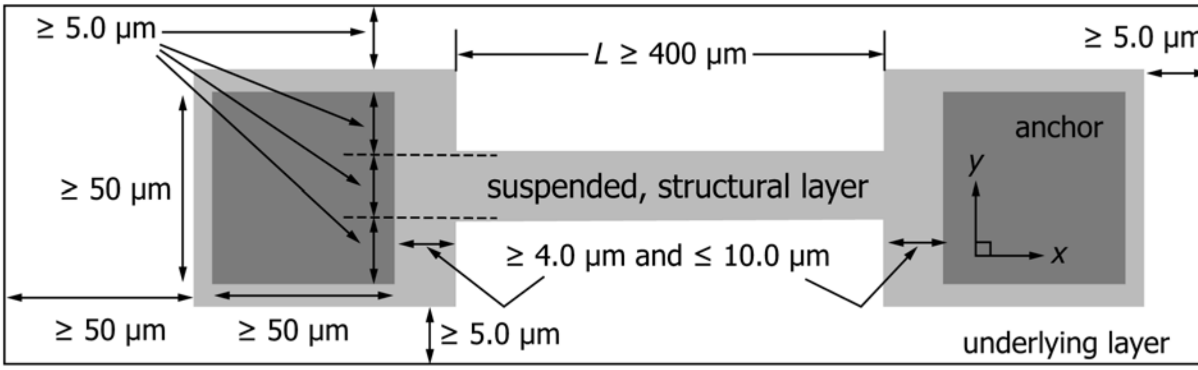


FIG. 1 Three-Dimensional View of Surface-Micromachined Fixed-Fixed Beam



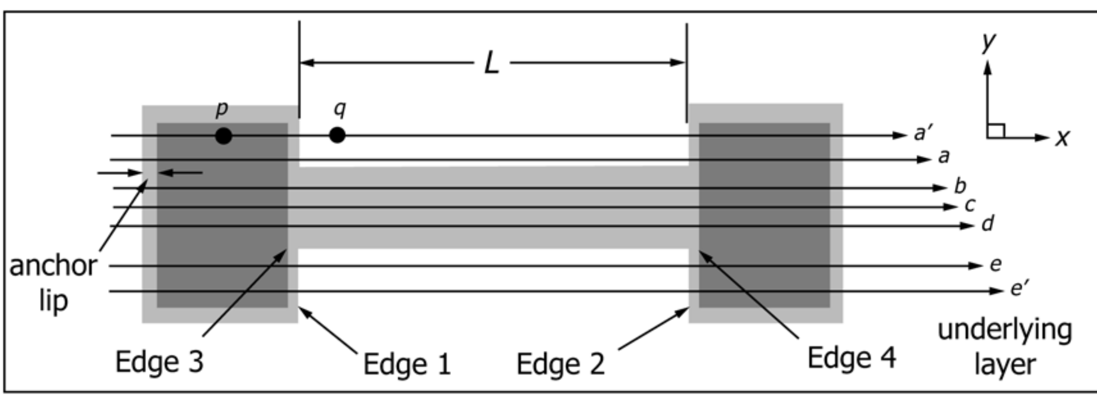
NOTE 1—The underlying layer is beneath this test structure.

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

NOTE 3—The light gray area is suspended in air after fabrication.

NOTE 4—The dark gray areas (the anchors) are the designed cuts in the sacrificial layer. This is where the structural layer contacts the underlying layer.

FIG. 2 Design Dimensions for Fixed-Fixed Beam in Fig. 1



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

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

NOTE 3—Traces b, c, and d are used to determine the residual strain and calculate u_W. They can be used to ascertain if the fixed-fixed beam 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 Fixed-Fixed Beam

beam. The in-plane length is determined between Edges 1 and 2 (shown in Fig. 3) using Traces a', a, e, and e' in a similar manner as specified in Test Method E2244. For Traces b, c, and d, the curved length of the fixed-fixed beam is determined with two cosine functions modeling the out-of-plane shape of the fixed-fixed beam. These functions are merged at the minimum or maximum deflection. Three data points are chosen to define each cosine function. The residual strain is the average of the residual strain values calculated for Traces b, c, and d.

4.3 For a surface-micromachined fixed-fixed beam, to obtain three data points that define each cosine function: *(1)* select the two transitional edges, *(2)* align the transitional edges in the field of view, *(3)* obtain a 3-D data set, *(4)* determine the endpoints of the in-plane length measurement and associated uncertainties, and *(5)* for Traces b, c, and d, obtain three data points that define each cosine function. (This procedure may need to be modified for a bulk-micromachined fixed-fixed beam.)

4.4 To calculate the residual strain for each data trace (*b*, *c*, and *d*): *(1)* account for any misalignment, *(2)* determine the in-plane length of the fixed-fixed beam and the endpoints, *(3)* for Trace c, solve three equations for three unknowns to obtain each cosine function, *(4)* plot the functions with the data from Trace c, *(5)* calculate the length of the curved fixed-fixed beam for Trace c, *(6)* calculate the residual strain for Trace c, and *(7)* repeat steps 3 through 6 for Traces b and d. The residual strain is calculated as the average of the three residual strain values obtained from the three data traces.

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

4.6 Appendix X1 is used to determine if the fixed-fixed beam has adhered to the top of the underlying layer.

5. Significance and Use

5.1 Residual strain measurements are an aid in the design and fabrication of MEMS devices. The value for residual strain can be used in Young's modulus calculations.

6. Interferences

6.1 Measurements from fixed-fixed beams that are touching the underlying layer (as ascertained in Appendix X1) are not accepted.

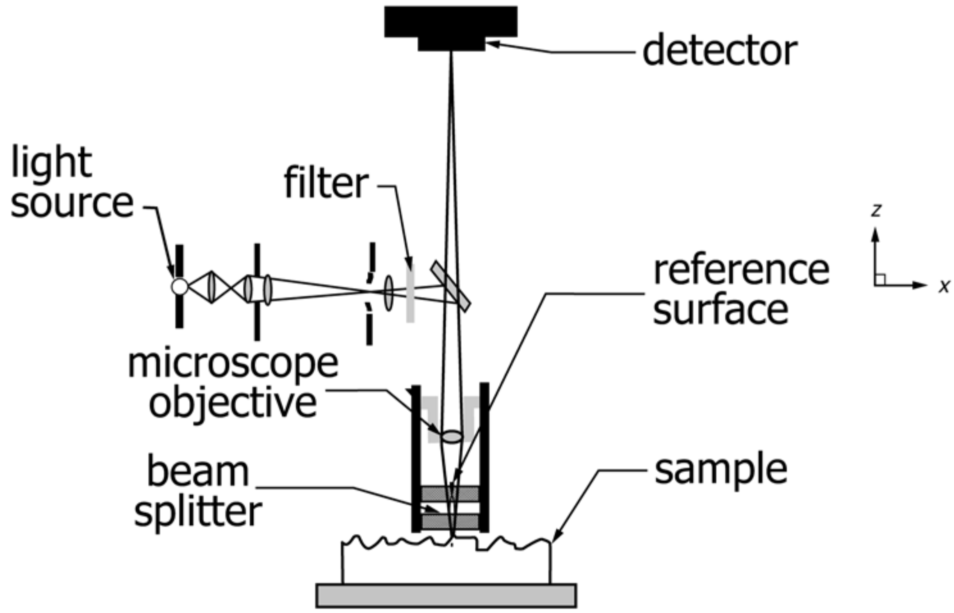


FIG. 4 Schematic of an Optical Interferometric Microscope

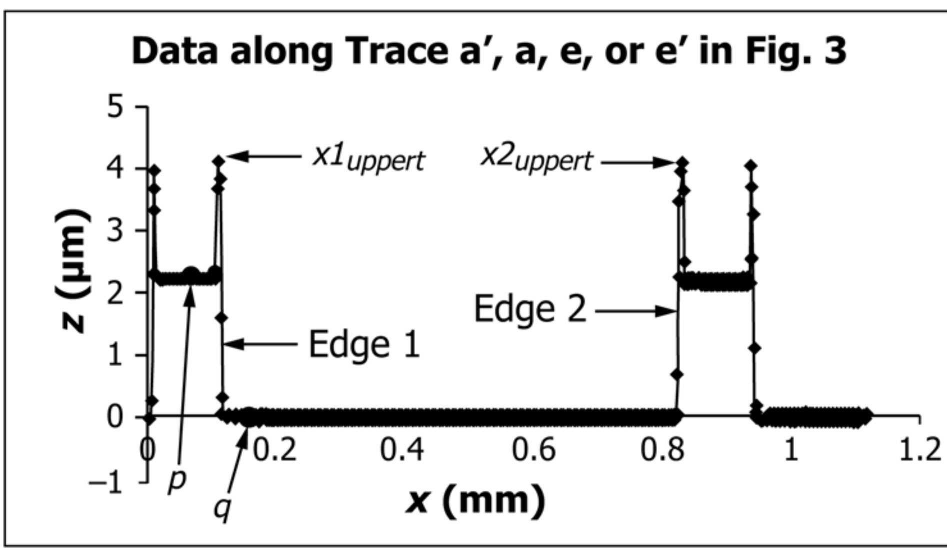


FIG. 5 2-D Data Trace Used to Find $x1_{uppert}$ and $x2_{uppert}$

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.

[5] The same apparatus is used (or can be used) in Test Method E2244, Test Method E2246, and SEMI Test Method MS2.

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

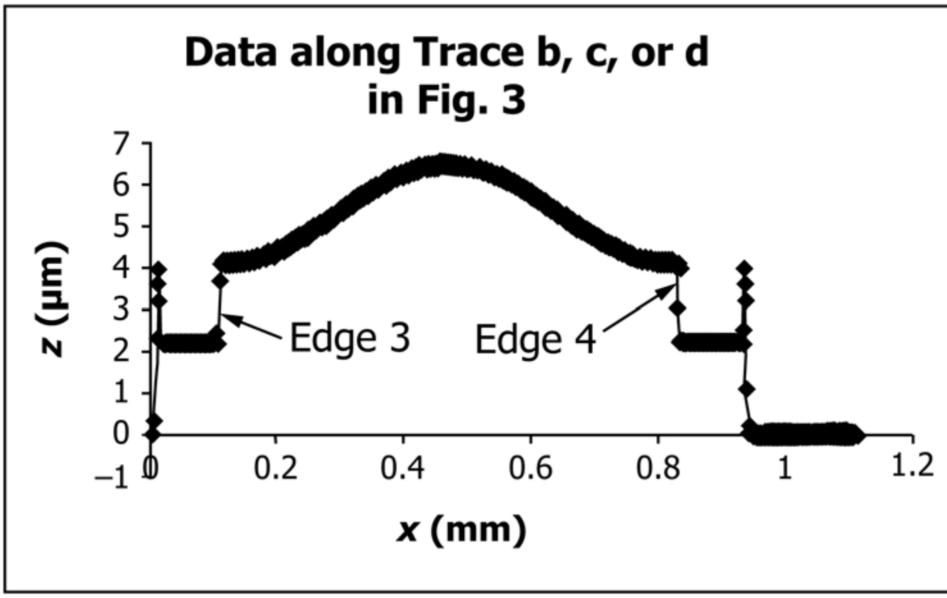


FIG. 6 2-D Data Trace Along a Fixed-Fixed Beam

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

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 *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 *Fixed-fixed Beam Test Structures Fabricated in Either a Surface-micromachining or Bulk-micromachining Process*—The design of a representative surface-micromachined fixed-fixed beam is specified below.

8.1.1 The fixed-fixed beam 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 fixed-fixed beam shall be long enough (for example, $L \geq 400$ 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). The approximate location of the two inflection points, created by this curvature, should be relatively easy to determine from a 2-D data trace (such as Trace b, c, or d in Fig. 3, as shown in Fig. 6) taken along the length of the beam.

8.1.3 The anchor lip between Edges 1 and 3 in Fig. 3 and between Edges 2 and 4 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 these anchor lips should be at least two times greater (or 4.0 µm, as shown in Fig. 2). At the same time, they 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 fixed-fixed beam has adhered to the top of the underlying layer as ascertained in Appendix X1. If a backside etch is used to eliminate stiction concerns, the interferometric optics (or the 3-D data set) can be leveled with respect to these anchors.

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

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

8.1.7 The underlying layer should be unpatterned 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 fixed-fixed beam 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 fixed-fixed beam in Fig. 2 is used for this purpose, no other structures should be designed in these areas.

8.1.8 A sufficient number of fixed-fixed beams (preferably of different lengths) should be fabricated in order to obtain at least one fixed-fixed beam 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 fixed-fixed beam and the fabricated fixed-fixed beam. It is also recommended that any resulting vertical transitions in the fixed-fixed beam be as close to an 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 fixed-fixed beam to the anchor will result. Consult the fabrication service or facility for appropriate 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 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:

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

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

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 3.2.4 for use in Annex A1.

[7] The same calibration procedure is used as in Test Method E2244 and Test Method E2246. A similar calibration in the *z*-direction is used in SEMI Test Method MS2.

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

10. Procedure (1-3)

10.1 For a surface-micromachined fixed-fixed beam, to obtain three data points that define each cosine function, five steps are taken: *(1)* select the two transitional edges, *(2)* align the transitional edges in the field of view, *(3)* obtain a 3-D data set, *(4)* determine the endpoints of the in-plane length measurement and associated uncertainties, and *(5)* for Traces b, c, and d, obtain three data points that define each cosine function.

NOTE 7—The procedure that follows may need to be modified for the given fixed-fixed beam. 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 fixed-fixed beam in Fig. 7 consists of four oxide layer thicknesses (**1**) and this test method uses a single-layered beam model. Therefore, the resulting residual strain would be considered an effective residual strain. Additional modifications may also need to be made as appropriate, for example, when considering a surface-micromachined fixed-fixed beam with a backside etch.

10.2 *Select the Two Transitional Edges:*

10.2.1 Select the two transitional edges that define the in-plane length measurement (for example, Edges 1 and 2 in Fig. 3). These are the first and second transitional edges.

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

10.3.1 Align the two transitional edges 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 in-plane length measurement is taken in the *x*-direction.

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

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 fixed-fixed beam and *(b)* perpendicular to the selected transitional edges 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).

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

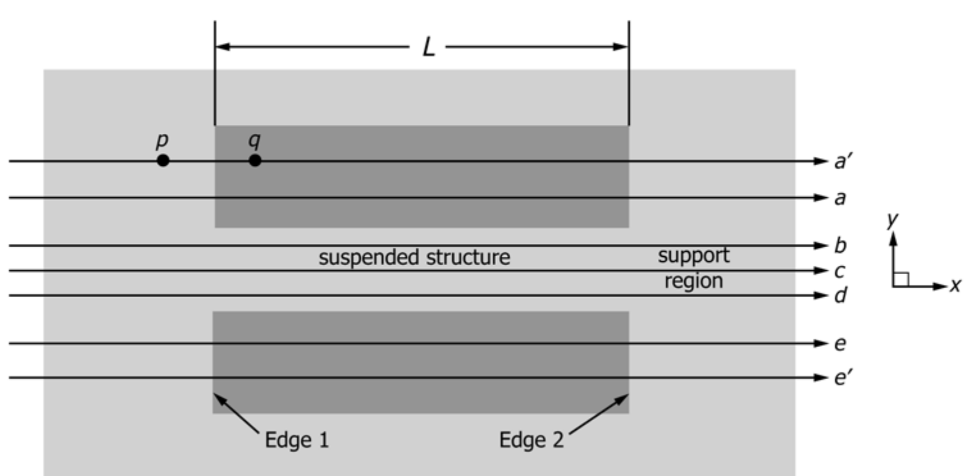
10.4.1.6 Eliminate any tilt in the sample by nulling the fringes on the top of flat regions of the sample that are symmetrically located with respect to the fixed-fixed beam (for example, on the top of the exposed underlying layer in Fig. 3 that straddles the fixed-fixed beam). The fringes are typically nulled for the measurement; however, if fringes are present, they should be perpendicular to the two transitional edges defining the in-plane length measurement.

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 fixed-fixed beam (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 fixed-fixed beam).

10.4.1.9 From the leveled 3-D data set, extract Traces a', a, b, c, d, e, 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



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

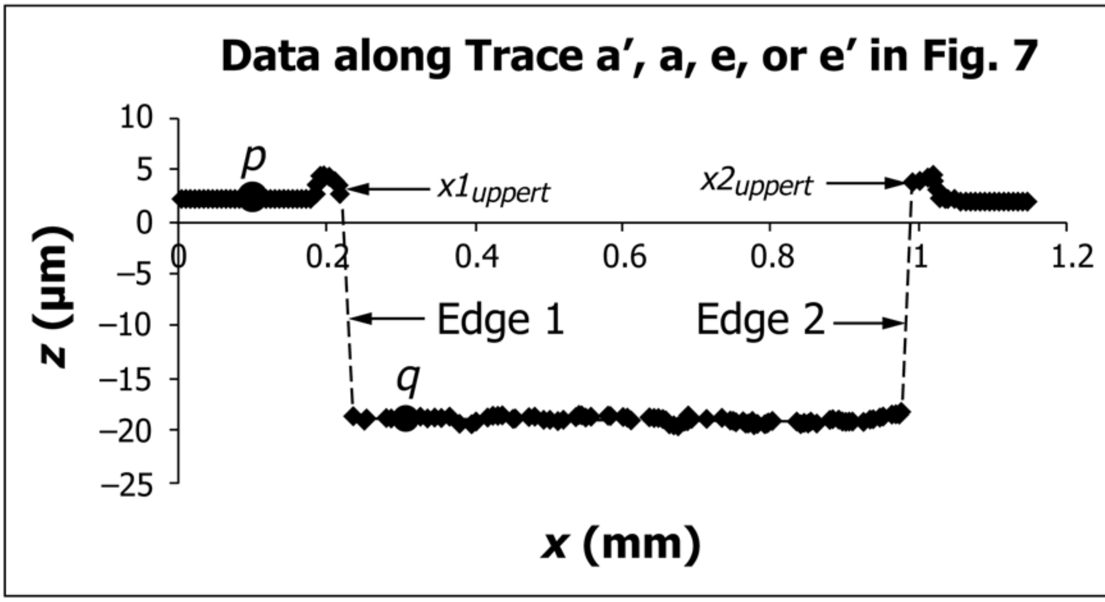
NOTE 2—The dark gray areas are the visible parts of the micromachined cavity.

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—Traces a' and e' are used to determine the misalignment angle, α. Traces *a'*, *a*, *e*, and *e'* are used to calculate *L*.

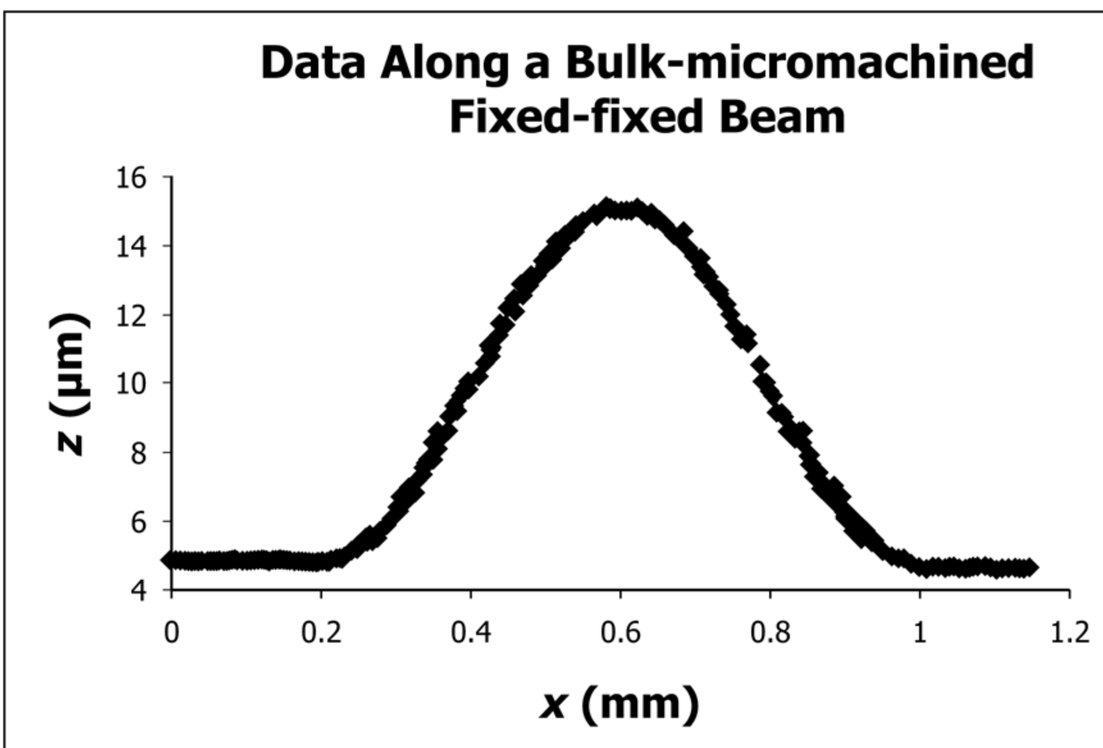
NOTE 5—Traces b, c, and d are used to calculate residual strain and u_W.

FIG. 7 Top View of Bulk-Micromachined Fixed-Fixed Beam



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

FIG. 8 2-D Data Trace Used to Find $x1_{uppert}$ and $x2_{uppert}$



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

NOTE 2—Some data points are missing along this trace.

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

cavity may be jagged, therefore, choose Traces a', a, e, and e' that contain representative endpoints.

10.4.1.10 In Trace c, examine the data associated with the suspended portion of the fixed-fixed beam. If the fixed-fixed beam 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 fixed-fixed beam.

10.5 *Determine the Endpoints of the In-Plane Length Measurement and Associated Uncertainties:*

10.5.1 Examine the calibrated Traces a', a, e, and e' from 10.4.1.9. These traces pass through and are perpendicular to Edge 1 and Edge 2.

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', a, e, 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*:*

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 From each data trace (a', a, e, or e') obtain $x2_{uppert}$ and $n2_t$, using the procedures in 10.5.3 and 10.5.4, respectively.

10.5.6 For the outermost data traces (a' and e') record the calibrated y values ($y_{a'}$ and $y_{e'}$) where $y_{a'} > y_{e'}$.

10.5.7 Calculate the calibrated endpoints (that is, $x1_{ave}$ and $x2_{ave}$) of the in-plane length measurement using the following equations:

$$x1_{ave} = \frac{x1_{uppera'} + x1_{uppera} + x1_{uppere} + x1_{uppere'}}{4} \tag{8}$$

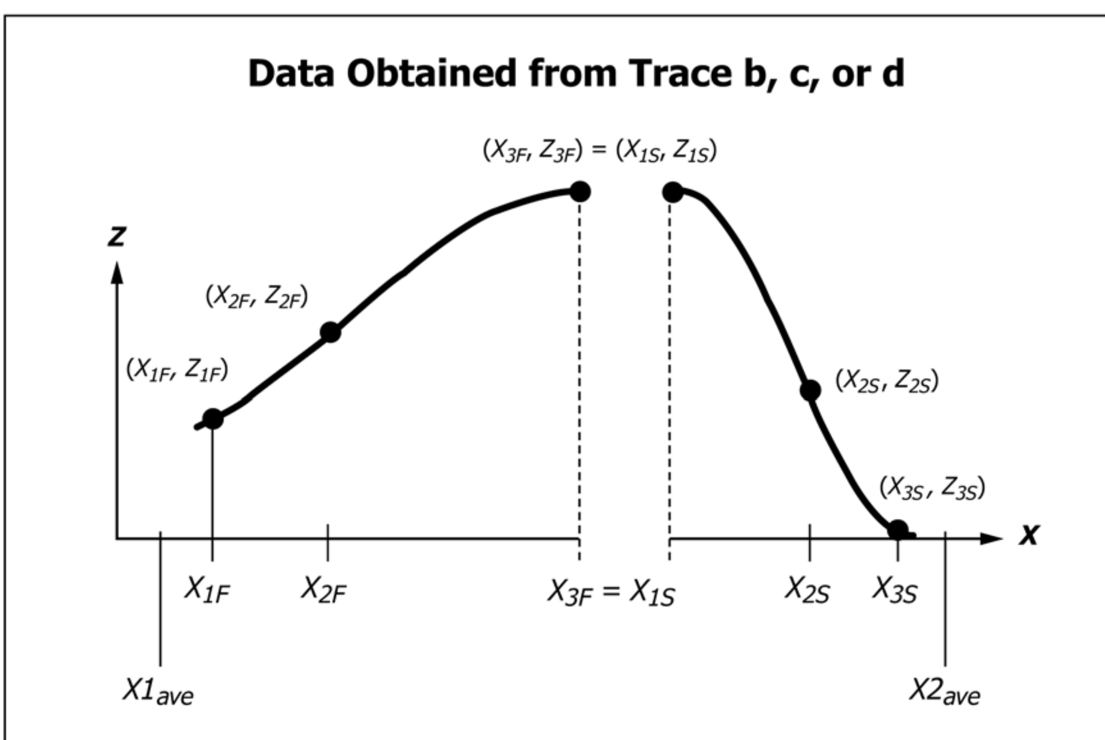
and

$$x2_{ave} = \frac{x2_{uppera'} + x2_{uppera} + x2_{uppere} + x2_{uppere'}}{4} \tag{9}$$

10.6 *For Traces b, c, and d, Obtain Three Data Points That Define Each Cosine Function:*

10.6.1 For one of the data traces along the top of the fixed-fixed beam (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 3 and 4 in Fig. 6 with the x values of all the remaining data points lying between $x1_{ave}$ and $x2_{ave}$).

10.6.2 Divide the remaining data into two abbreviated data traces (as shown in Fig. 10). The division should occur at the x (or y) value corresponding to the maximum (or minimum) z value. Include this data point in both data traces.



NOTE 1—The data above has been exaggerated.

FIG. 10 Two Abbreviated Data Traces

10.6.3 Choose three representative data points (with the subscript *F*) from the first abbreviated data trace, that is:

10.6.3.1 An initial data point (x_{1F}, z_{1F}) such that $x1_{ave} < x_{1F}$,

10.6.3.2 The last data point (x_{3F}, z_{3F}), and

10.6.3.3 A centrally located data point (x_{2F}, z_{2F}) such that $x_{1F} < x_{2F} < x_{3F}$ and such that it is located at or near the inflection point.

10.6.4 Choose three representative data points (with the subscript *S*) from the second abbreviated data trace, that is:

10.6.4.1 The first data point (x_{1S}, z_{1S}), where $x_{3F} = x_{1S}$,

10.6.4.2 A final data point (x_{3S}, z_{3S}) such that $x_{3S} < x2_{ave}$, and

10.6.4.3 A centrally located data point (x_{2S}, z_{2S}) such that $x_{1S} < x_{2S} < x_{3S}$ and such that it is located at or near the inflection point.

10.6.5 Repeat the above (that is, 10.6.1 through 10.6.4, inclusive) for Traces b and d.

11. Calculation (1-3)

11.1 Seven steps are used to calculate the residual strain for each data trace (b, c, and d): *(1)* account for any misalignment, *(2)* determine the in-plane length of the fixed-fixed beam and the endpoints, *(3)* for Trace c, solve three equations for three unknowns (for each abbreviated data trace) to obtain each cosine function, *(4)* plot the functions with the data from Trace c, *(5)* calculate the length of the curved fixed-fixed beam for Trace c, *(6)* calculate the residual strain for Trace c, and *(7)* repeat steps 3 through 6 for Traces b and d. The residual strain is calculated as the average of the three residual strain values obtained from the three data traces.[9]

11.2 *Account for Any Misalignment:*

11.2.1 The misalignment angle, α, is determined using the two outermost data traces [*a′* and *e′*, as seen in Fig. 3 and Fig. 11] and is calculated to be either α_1 or α_2 using either $\Delta x1$ or $\Delta x2$, respectively, where

$$\Delta x1 = x1_{uppera'} - x1_{uppere'} \quad (10)$$

and

$$\Delta x2 = x2_{uppera'} - x2_{uppere'} \quad (11)$$

Calculate α using the following equation:

$$\alpha = \tan^{-1}\left[\frac{\Delta x}{\Delta y}\right] \quad (12)$$

where

$$\Delta y = y_{a'} - y_{e'} \text{ (with } y_{a'} > y_{e'}) \quad (13)$$

In addition,

$$\text{if } n1_{a'} + n1_{e'} \leq n2_{a'} + n2_{e'}, \text{ then } \alpha = \alpha_1 \text{ and } \Delta x = \Delta x1 \quad (14)$$

$$\text{and if } n1_{a'} + n1_{e'} > n2_{a'} + n2_{e'}, \text{ then } \alpha = \alpha_2 \text{ and } \Delta x = \Delta x2 \quad (15)$$

11.2.2 Using the values obtained in 10.5 and 10.6 (namely, $x1_{ave}$, x_{1F}, x_{2F}, $x_{3F} = x_{1S}$, x_{2S}, x_{3S}, and $x2_{ave}$) determine *f*, *g*, *h*, *i*, *j*, *k*, and *l*, respectively, as seen in Fig. 12, along the *v*-axis (the axis used to measure the in-plane length of the fixed-fixed beam). Do this for each data trace (*b*, *c*, and *d*) using the following equations:

$$f = x1_{ave} \quad (16)$$

$$g = (x_{1F} - f)\cos\alpha + f \quad (17)$$

$$h = (x_{2F} - f)\cos\alpha + f \quad (18)$$

$$i = (x_{3F} - f)\cos\alpha + f = (x_{1S} - f)\cos\alpha + f \quad (19)$$

$$j = (x_{2S} - f)\cos\alpha + f \quad (20)$$

$$k = (x_{3S} - f)\cos\alpha + f \quad (21)$$

and

$$l = (x2_{ave} - f)\cos\alpha + f \quad (22)$$

The *z*-values of the data points along the beam remain the same, which assumes no curvature across the width of the fixed-fixed beam. The data points along the beam (as seen in Fig. 13) are (g, z_{1F}), (h, z_{2F}), (i, z_{3F}), or (i, z_{1S}), (j, z_{2S}), and (k, z_{3S}).

11.3 *Determine the In-plane Length of the Fixed-Fixed Beam and the Endpoints:*

11.3.1 Calculate the in-plane length of the fixed-fixed beam, *L*, using the following equation:

$$L = L_{align} + L_{offset} = l - f + L_{offset} = (x2_{ave} - x1_{ave})\cos\alpha + L_{offset} \quad (23)$$

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

[9] By inserting the inputs into the correct locations on the appropriate NIST MEMS Calculator Web page, steps 1, 2, 3, 5, 6, and 7 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."

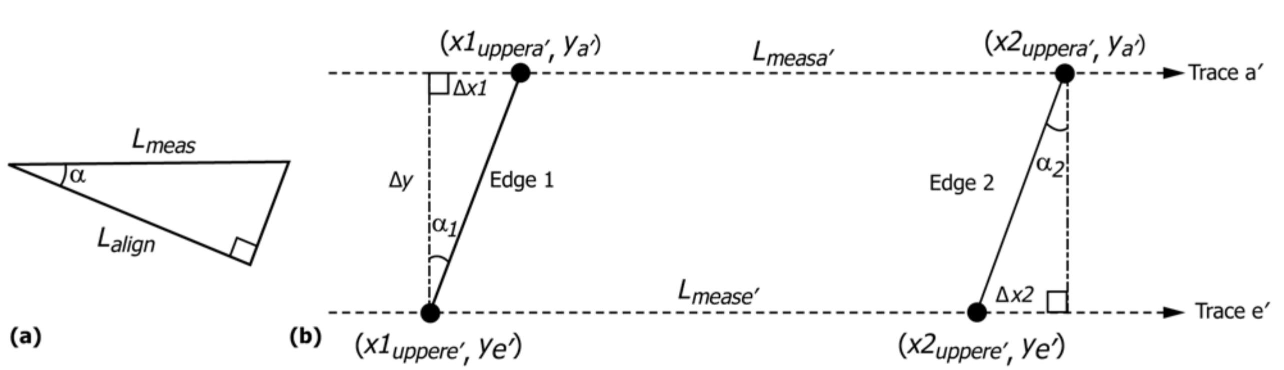


FIG. 11 Drawings Used to Determine a) the Misalignment Angle, α, and b) Δ*x1* and Δ*x2*

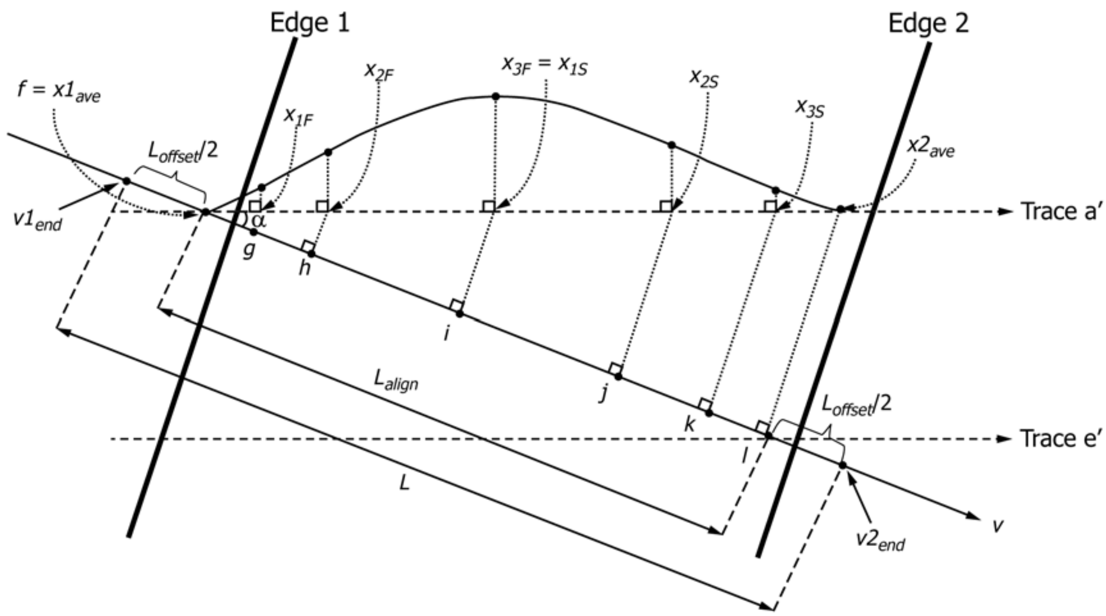


FIG. 12 The *v*-values (*f*, *g*, *h*, *i*, *j*, *k*, and *l*) Along the Length of the Beam

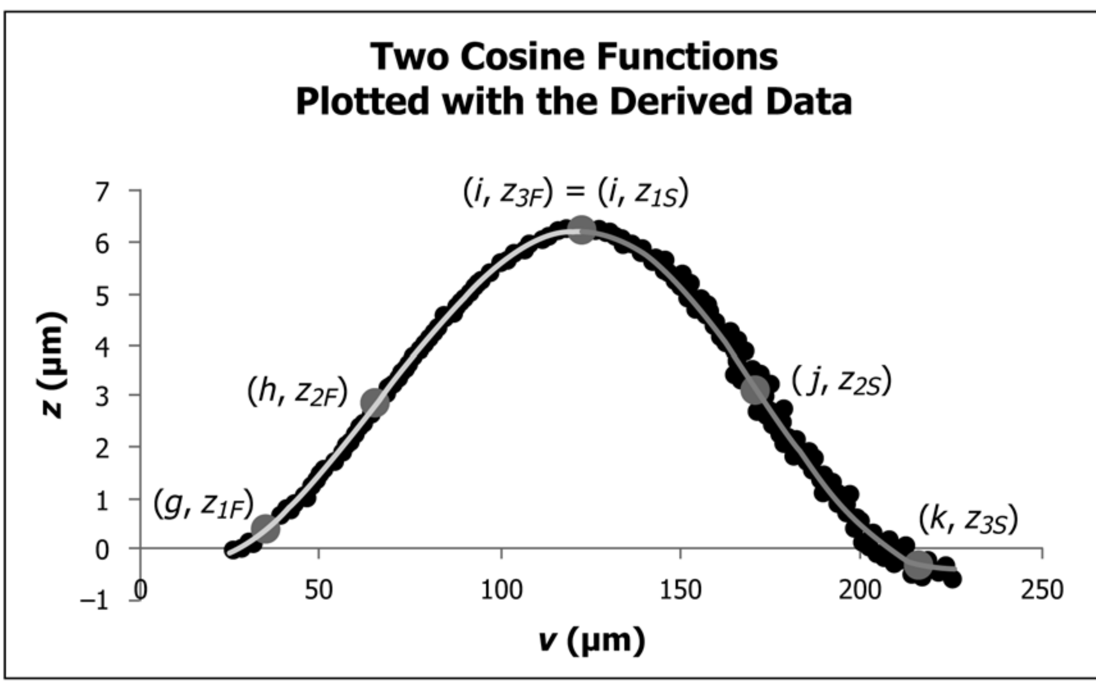


FIG. 13 A Comparison Plot of the Model with the Data

11.3.2 Calculate one endpoint, $v1_{end}$, of the in-plane length of the fixed-fixed beam using the following equation:

$$v1_{end} = f - \frac{1}{2}L_{offset} = x1_{ave} - \frac{1}{2}L_{offset} \quad (24)$$

11.3.3 Calculate the other endpoint, $v2_{end}$, of the in-plane length using the following equation:

$$v2_{end} = l + \frac{1}{2}L_{offset} = (x2_{ave} - f)\cos\alpha + f + \frac{1}{2}L_{offset} = (x2_{ave} - x1_{ave})\cos\alpha + x1_{ave} + \frac{1}{2}L_{offset} \quad (25)$$

11.4 *For the First Abbreviated Data Trace from Trace c, Solve Three Equations for Three Unknowns:*

11.4.1 The three equations are:

$$w = \pi + \frac{(\pi - w_{1F})(v - i)}{(i - g)} \quad (26)$$

$$z_{1F} = sA_F\cos(w_{1F}) + z_{3F} + sA_F \quad (27)$$

and

$$z_{2F} = sA_F\cos(w_{2F}) + z_{3F} + sA_F \quad (28)$$

or

$$w_{2F} = \pi + \frac{(\pi - w_{1F})\,(h - i)}{(i - g)} \tag{29}$$

$$A_F = \frac{s(z_{1F} - z_{3F})}{\cos(w_{1F}) + 1} \tag{30}$$

and

$$z_{2F} = \frac{(z_{1F} - z_{3F})\cos(w_{2F}) + z_{3F}\cos(w_{1F}) + z_{1F}}{\cos(w_{1F}) + 1} \tag{31}$$

NOTE 10—Eq 26 is a v-to-w transformation equation where the w-axis has π units.

11.4.2 Find the three unknowns (w_{1F}, w_{2F}, and A_F):

11.4.2.1 Assume $w_{1F} = 0$ and $w_{1F\Delta} = \pi/2$ where $w_{1F\Delta}$ is an assigned increment which gets smaller with each iteration, as shown in 11.4.2.6.

11.4.2.2 Solve Eq 29 to find w_{2F} .

11.4.2.3 Solve Eq 31 to find z_{2F} .

11.4.2.4 If the data value for z_{2F} (or z_{2Fdata}) is greater than the calculated value for z_{2F} (or z_{2Fcalc}), let $w_{1F} = w_{1F} + w_{1F\Delta}$ for upward bending fixed-fixed beams (that is, when $s = -1$).

NOTE 11—For downward bending fixed-fixed beams, let $w_{1F} = w_{1F} - w_{1F\Delta}$.

11.4.2.5 If z_{2Fdata} is less than z_{2Fcalc}, let $w_{1F} = w_{1F} - w_{1F\Delta}$ for upward bending fixed-fixed beams.

NOTE 12—For downward bending fixed-fixed beams, let $w_{1F} = w_{1F} + w_{1F\Delta}$.

11.4.2.6 Let $w_{1F\Delta} = w_{1F\Delta}/2$.

11.4.2.7 Repeat steps 11.4.2.2 – 11.4.2.6 until $z_{2Fcalc} = z_{2Fdata}$ to the preferred number of significant digits.

NOTE 13—Repeating these steps 100 times in a computer program undoubtedly accomplishes this task.

11.4.2.8 Solve Eq 30 for A_F.

11.5 *For the Second Abbreviated Data Trace from Trace c, Solve Three Equations for Three Unknowns:*

11.5.1 The three equations are:

$$w = w_{3S} + \frac{(w_{3S} - \pi)\,(v - k)}{(k - i)} \tag{32}$$

$$z_{2S} = sA_S\cos(w_{2S}) + z_{1S} + sA_S \tag{33}$$

and

$$z_{3S} = sA_S\cos(w_{3S}) + z_{1S} + sA_S \tag{34}$$

or

$$w_{2S} = w_{3S} + \frac{(w_{3S} - \pi)\,(j - k)}{(k - i)} \tag{35}$$

$$A_S = \frac{s(z_{3S} - z_{1S})}{\cos(w_{3S}) + 1} \tag{36}$$

and

$$z_{2S} = \frac{(z_{3S} - z_{1S})\cos(w_{2S}) + z_{1S}\cos(w_{3S}) + z_{3S}}{\cos(w_{3S}) + 1} \tag{37}$$

NOTE 14—Eq 32 is a v-to-w transformation equation where the w-axis has π units.

11.5.2 Find the three unknowns (w_{2S}, w_{3S}, and A_S):

11.5.2.1 Assume $w_{3S} = 2\pi$ and $w_{3S\Delta} = \pi/2$ where $w_{3S\Delta}$ is an assigned increment which gets smaller with each iteration, as shown in 11.5.2.6.

11.5.2.2 Solve Eq 35 to find w_{2S} .

11.5.2.3 Solve Eq 37 to find z_{2S} .

11.5.2.4 If the data value for z_{2S} (or z_{2Sdata}) is greater than the calculated value for z_{2S} (or z_{2Scalc}), let $w_{3S} = w_{3S} - w_{3S\Delta}$ for upward bending fixed-fixed beams (that is, when $s = -1$).

NOTE 15—For downward bending fixed-fixed beams, let $w_{3S} = w_{3S} + w_{3S\Delta}$.

11.5.2.5 If z_{2Sdata} is less than z_{2Scalc}, let $w_{3S} = w_{3S} + w_{3S\Delta}$ for upward bending fixed-fixed beams.

NOTE 16—For downward bending fixed-fixed beams, let $w_{3S} = w_{3S} - w_{3S\Delta}$.

11.5.2.6 Let $w_{3S\Delta} = w_{3S\Delta}/2$.

11.5.2.7 Repeat steps 11.5.2.2 – 11.5.2.6 until $z_{2Scalc} = z_{2Sdata}$ to the preferred number of significant digits.

NOTE 17—Repeating these steps 100 times in a computer program undoubtedly accomplishes this task.

11.5.2.8 Solve Eq 36 for A_S.

11.6 *Plot the Functions with the Data from Trace c:*

11.6.1 Given the two abbreviated data traces from 10.6.2, 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 equations (see Fig. 13):

$$z = sA_F\cos\left[\pi + \frac{(\pi - w_{1F})(v - i)}{i - g}\right] + z_{3F} + sA_F \tag{38}$$

where $v1_{end} \le v \le i$, and

$$z = sA_S\cos\left[w_{3S} + \frac{(w_{3S} - \pi)(v - k)}{k - i}\right] + z_{1S} + sA_S \tag{39}$$

where $i \le v \le v2_{end}$.

11.6.2 For each abbreviated data trace, if one of the three chosen data points in 10.6.3 or 10.6.4 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 11.1.

11.7 *Calculate the Length of the Curved Fixed-fixed Beam for Trace c:*

11.7.1 Calculate the length, L_{cF}, of the first curve (between $v1_{end}$ and i) as follows:

11.7.1.1 Obtain similar units (that is, π units) on both axes using the following equation:

$$u = A_{\pi-units}\cos(w) \tag{40}$$

where

$$A_{\pi-units} = A_F\frac{(\pi - w1_{end})}{(i - v1_{end})} \tag{41}$$

and $w1_{end}$ is the value for w when $v = v1_{end}$ in Eq 26.

11.7.1.2 Divide the curve along the w-axis into 100 equal segments between $w1_{end}$ and π.

NOTE 18—The value for $w1_{end}$ is chosen because this is the calibrated endpoint of the in-plane length (in terms of w) as found in Eq 24. The length of the curved fixed-fixed beam will ultimately be compared in the residual strain calculation with the in-plane length. Therefore, the endpoints of the in-plane length measurement are used to calculate the length of the curved fixed-fixed beam.

11.7.1.3 Calculate the length of each segment using the Pythagorean theorem as follows:

$$L_{seg} = \sqrt{(w_{next} - w_{last})^2 + (u_{next} - u_{last})^2} \quad (42)$$

11.7.1.4 Sum the lengths of the segments using the following equation:

$$L_{\pi-units} = \sum L_{seg} \quad (43)$$

11.7.1.5 Convert to the appropriate units using the following equation:

$$L_{cF} = L_{\pi-units} \frac{(i - v1_{end})}{(\pi - w1_{end})} \quad (44)$$

11.7.2 Calculate the length, L_{cS}, of the second curve (between i and $v2_{end}$) as follows:

11.7.2.1 Obtain similar units (that is, π units) on both axes using Eq 40 where

$$A_{\pi-units} = A_S \frac{(w2_{end} - \pi)}{(v2_{end} - i)} \quad (45)$$

and $w2_{end}$ is the value for w when $v = v2_{end}$ in Eq 32.

11.7.2.2 Divide the curve along the w-axis into 100 equal segments between π and $w2_{end}$.

NOTE 19—The value for $w2_{end}$ is chosen because this is the calibrated endpoint of the in-plane length (in terms of w) as found in Eq 25. The length of the curved fixed-fixed beam will ultimately be compared in the residual strain calculation with the in-plane length. Therefore, the endpoints of the in-plane length measurement are used to calculate the length of the curved fixed-fixed beam.

11.7.2.3 Calculate the length of each segment using the Pythagorean theorem as given in Eq 42.

11.7.2.4 Sum the lengths of the segments using Eq 43.

11.7.2.5 Convert to the appropriate units using the following equation:

$$L_{cS} = L_{\pi-units} \frac{(v2_{end} - i)}{(w2_{end} - \pi)} \quad (46)$$

11.7.3 Calculate the total calibrated length, L_c, of the curved fixed-fixed beam as follows:

$$L_c = L_{cF} + L_{cS} \quad (47)$$

11.8 *Calculate ε_{rt} for Trace c, where the subscript t refers to the data trace, using the following equation:*

$$\varepsilon_{rt} = \frac{L - L_0}{L_0}(1 + \delta_{\varepsilon correction}) \quad (48)$$

where $\delta_{\varepsilon rcorrection}$ is a relative residual strain correction term intending to correct for deviations from the ideal fixed-fixed beam geometry and/or composition (**1**), where L was determined in 11.3, and where the equation for L_0 is as follows:

$$L_0 = \frac{12L_c\left(\frac{L_c L'_e}{L}\right)^2}{12\left(\frac{L_c L'_e}{L}\right)^2 - \pi^2 t^2} \quad (49)$$

where t (**1, 6-8**) is the thickness of the suspended, structural layer, L_c was calculated in 11.7.3, and

$$L'_e = v_{eS} - v_{eF} \quad (50)$$

where

$$v_{eF} = \frac{\frac{\pi}{2}(g - i) + i(\pi - w_{1F})}{(\pi - w_{1F})} \quad (51)$$

and

$$v_{eS} = \frac{\left(\frac{3\pi}{2} - w_{3S}\right)(k - i) + k(w_{3S} - \pi)}{(w_{3S} - \pi)} \quad (52)$$

with w_{1F} determined in 11.4.2 and w_{3S} determined in 11.5.2.

NOTE 20—If the absolute value of $(h - v_{eF})$ is not less than 5 µm, choose another data point (x_{2F}, z_{2F}) such that the new value for h is closer to the just calculated value of v_{eF}, and repeat the steps beginning at 11.1. (This criterion may need to be modified for some data sets.)

NOTE 21—If the absolute value of $(j - v_{eS})$ is not less than 5 µm, choose another data point (x_{2S}, z_{2S}) such that the new value for j is closer to the just calculated value of v_{eS}, and repeat the steps beginning at 11.1. (This criterion may need to be modified for some data sets.)

11.9 *Repeat 11.4 to 11.8 for Traces b and d.:*

11.10 *Calculate the residual strain, ε_r, as the average of the residual strain values obtained from Traces b, c, and d, as follows:*

$$\varepsilon_r = \frac{\varepsilon_{rb} + \varepsilon_{rc} + \varepsilon_{rd}}{3} \quad (53)$$

If a bulk-micromachined fixed-fixed beam consisting of multiple layers (see Note 7) was measured, ε_r would be considered an effective residual strain.

11.11 Calculate $u_{c\varepsilon r}$, the combined standard uncertainty (**9, 10**) for the residual strain 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 $u_{c\varepsilon r}$, the residual strain is believed to lie in the interval $\varepsilon_r \pm u_{c\varepsilon r}$ (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 fabricated in a surface-micromachining process. These measurements indicate the magnitude and direction of the most deflected point of the fixed-fixed beam with respect to the anchor lips. 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.)

13.2 *The Round Robin*—The MEMS Length and Strain Round Robin Experiment took place from August 2003 to January 2005 (**1, 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 laboratories remained the same.

13.3 *Precision*—The repeatability and reproducibility data for residual strain are presented in Table 2. In this table, *n* indicates the number of measurements and ε_{rave} is the average of the residual strain repeatability or reproducibility measurement results. For the repeatability measurements only, $\sigma_{repeat(samp)}$ (the relative standard deviation of the repeatability residual strain measurements) is listed next (for use in A1.14). Then, the $\pm 2\sigma_{\varepsilon r}$ limits are listed where $\sigma_{\varepsilon r}$ is the standard deviation of the residual strain measurements. The last four entries in this table are four different calculations of the average combined standard uncertainty (as detailed in the table notes).

TABLE 2 Repeatability and Reproducibility Data[A]

	Repeatability Results L_{des} = 600 µm to 750 µm	Reproducibility Results L_{des} = 550 µm to 700 µm
1. *n*	24	6[B]
2. ε_{rave}	-41.65×10^{-6}	-44.0×10^{-6}
3. $\sigma_{repeat(samp)}$	5.7 %	—
4. ±2$\sigma_{\varepsilon r}$ limits	±4.7×10^{-6} (±11 %)	±8.8×10^{-6} (±20 %)
5. $u_{c\varepsilon rave}$[C]	0.77×10^{-6} (1.8 %)	1.1×10^{-6} (2.4 %)
6. $u_{c\varepsilon rave}$[D]	0.53×10^{-6} (1.3 %)	—
7. $u_{c\varepsilon rave}$[E]	0.57×10^{-6} (1.4 %)	—
8. $u_{c\varepsilon rave}$[F]	2.4×10^{-6} (5.9 %)	—

[A] Taken on test chips fabricated in a surface-micromachining process.
[B] Two of these measurements were taken from the same instrument by different operators.
[C] As determined using Test Method E2245–02. For the $u_{c\varepsilon r}$ calculation, the u_{samp} and u_{zcal} components were combined into one component. As such, for this component, the 100 % limits, assuming a uniform (that is, rectangular) probability distribution, were represented by a ±20 nm variation in the *z*-value of the data points. Also, $u_{zres} = u_{xcal} = u_{xres} = u_{xresL} = 0$. (See Test Method E2245–05 for the definitions of the uncertainty components.)
[D] As determined using Test Method E2245–05.
[E] As determined using Eq A1.1 with $u_{repeat(samp)}$=0.
[F] As determined using Eq A1.1.

13.3.1 As expected, the $\pm 2\sigma_{\varepsilon r}$ limits for the repeatability data (that is, ±11 %) are better than the $\pm 2\sigma_{\varepsilon r}$ limits for the reproducibility data (that is, ±20 %) for a somewhat comparable span of design lengths. And, the $u_{c\varepsilon rave}$ value for the reproducibility measurements is higher than the $u_{c\varepsilon rave}$ value for the repeatability measurements for a somewhat comparable 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.

13.3.2 The residual strain repeatability data is plotted versus test structure orientation in Fig. 14. In this plot, there is no obvious orientation dependence considering the values for ε_{rave} are approximately the same for the two different orientations. However, the $\pm 2\sigma_{\varepsilon r}$ limits for the data taken from the test structures with a 0 degree orientation are approximately half the $\pm 2\sigma_{\varepsilon r}$ limits for the data taken from the test structures with a 90 degree orientation.

13.3.3 The residual strain repeatability data is plotted versus L_{des} in Fig. 15. In this plot, the data indicate there is no obvious length dependence.

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

13.5 *Time*—Residual strain data was taken at the same laboratory on the same surface-micromachined test chip over a period of time. The chip was stored in a plastic storage container between measurements. A plot of residual strain versus time is given in Fig. 16 where the uncertainty bars correspond to ±12 % to represent the estimated expanded uncertainty values.

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

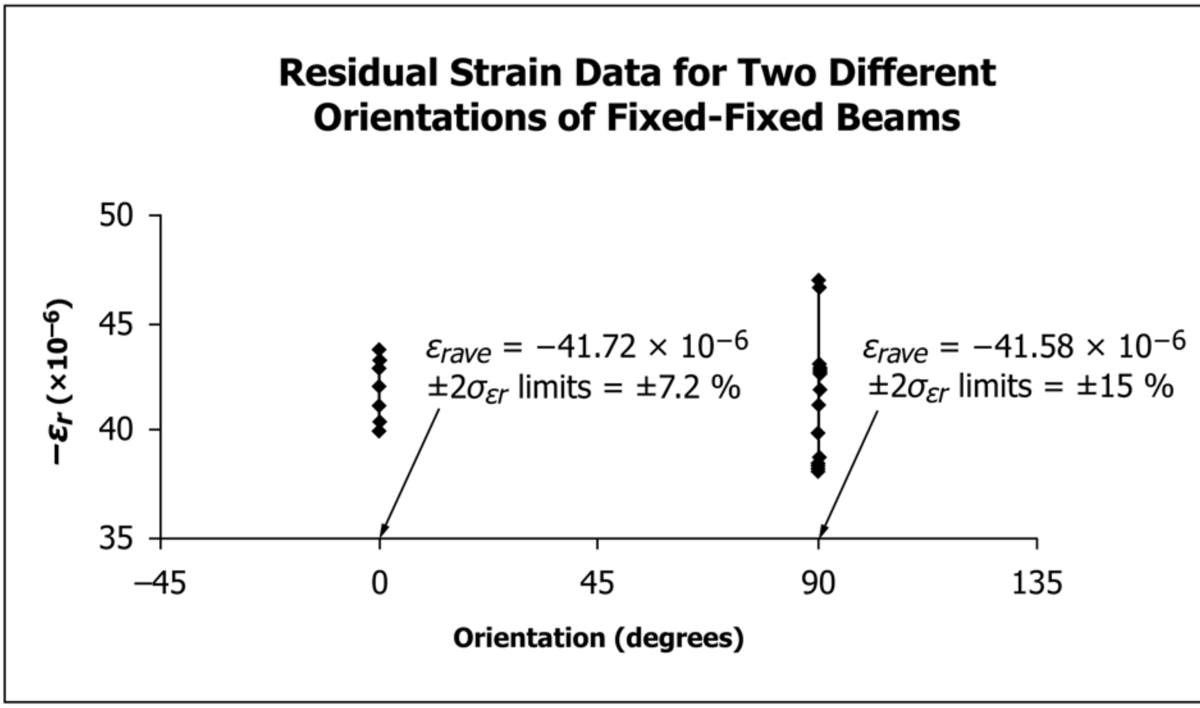
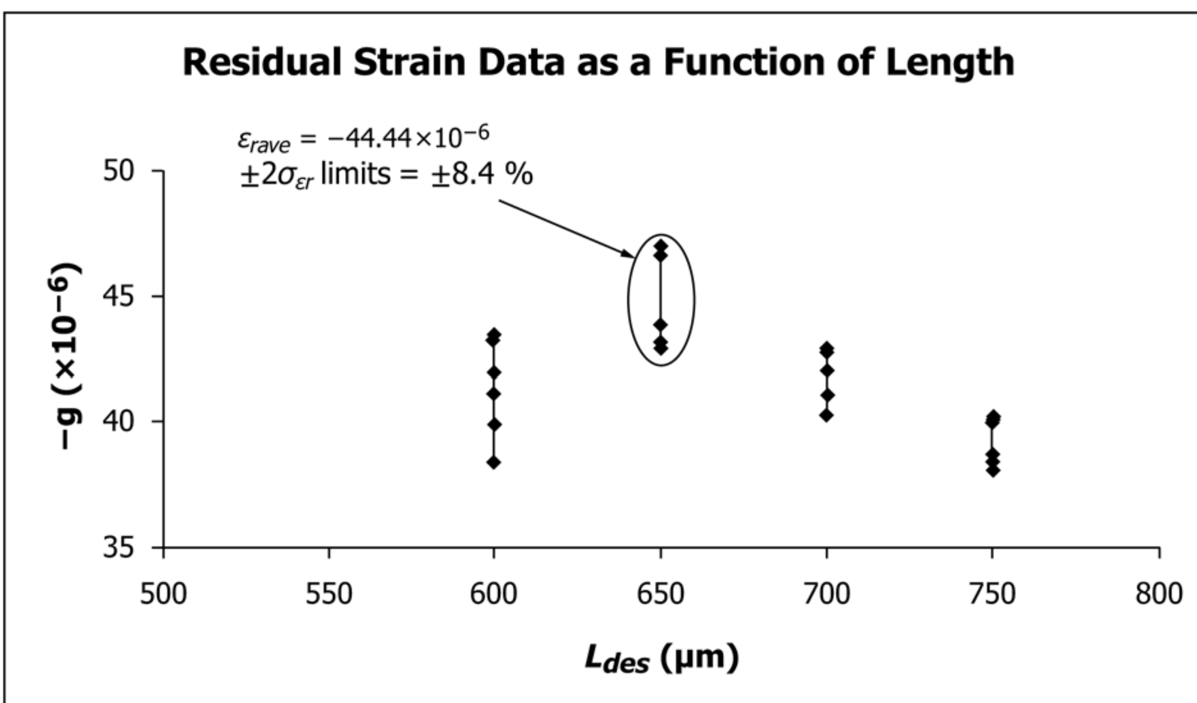


FIG. 14 Residual Strain Repeatability Data Plotted versus Test Structure Orientation



NOTE 1—This figure includes data for both fixed-fixed beam orientations.

FIG. 15 Residual Strain Repeatability Data Plotted versus L_{des}

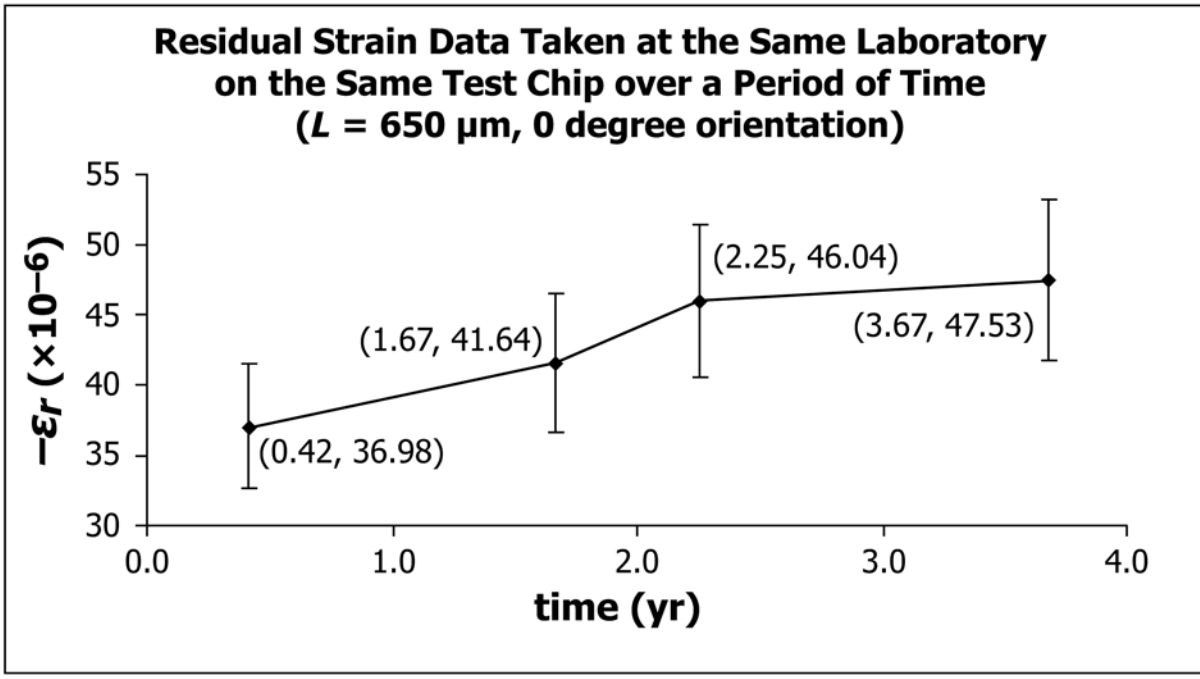


FIG. 16 Residual Strain Plotted Versus Time For Surface-Micromachined Chip

ANNEX

(Mandatory Information)

A1. CALCULATION OF COMBINED STANDARD UNCERTAINTY

A1.1 Calculate $u_{c\varepsilon r}$, the combined standard uncertainty for the residual strain measurement (**9**, **10**), using the following equation:[9]

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

where u_W, u_L, 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 A1.14, 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 residual strain values (ε_{rb}, ε_{rc}, and ε_{rd}) obtained in Section 11.

A1.3 Determine u_L:

A1.3.1 For Trace c, calculate ε_{rt} assuming L=L_{minuL} where the equation for L_{minuL} and the endpoints for L_{minuL} are given in Table A1.1. In this table, u_{cL} is the combined standard uncertainty for in-plane length as obtained using Test Method E2244 and $u_{cLnoxcal}$ is u_{cL} but without the in-plane length *x*-calibration component u_{Lxcal} (called u_{xcal} in Test Method E2244).

A1.3.2 Repeat A1.3.1 for Traces b and d.

A1.3.3 For Trace c, calculate ε_{rt} assuming L=L_{maxuL} where the equation for L_{maxuL} and the endpoints for L_{maxuL} are given in Table A1.1. Repeat for Traces b and d.

A1.3.4 For each data trace (*b*, *c*, and *d*), determine $\varepsilon_{r\text{-}high}$ and $\varepsilon_{r\text{-}low}$ and calculate u_{Lt} using the equation given in Table A1.1, which assumes a Gaussian distribution.

A1.3.5 Calculate u_L as the average of the three values obtained for u_{Lt}.

A1.4 Determine u_{zres}:

A1.4.1 For each data trace (*b*, *c*, and *d*) obtain seven residual strain values for the seven different sets of inputs given in Table A1.2 using d=(1/2)z_{res} where z_{res} was recorded in 9.2.

A1.4.2 For each data trace, record $\varepsilon_{r\text{-}low}$ and $\varepsilon_{r\text{-}high}$ and calculate u_{zrest} using the equation given in Table A1.1, which assumes a uniform distribution.

A1.4.3 Calculate u_{zres} as the average of the three values obtained for u_{zrest}.

A1.5 Determine u_{xcal}:

A1.5.1 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.

TABLE A1.1 Determination of the Uncertainty Components

Uncertainty Component	Method to Obtain $\varepsilon_{r\text{-}high}$ and $\varepsilon_{r\text{-}low}$, if applicable	G or U[A] / A or B[B]	equation
1. u_w	—	G / A	$u_w = STDEV(\varepsilon_{rb},\varepsilon_{rc},\varepsilon_{rd})$
2. u_L	using $L_{minuL}=L-3u_{cLnoxcal}$ for L and $L_{maxuL}=L+3u_{cLnoxcal}$ for L $u_{cLnoxcal} = \sqrt{u_{cL}^2 + u_{Lxcal}^2}$ endpoints for L_{minuL}: $v1_{end} + \frac{3}{2}u_{cLnoxcal}$ $v2_{end} - \frac{3}{2}u_{cLnoxcal}$ endpoints for L_{maxuL}: $v1_{end} - \frac{3}{2}u_{cLnoxcal}$ $v2_{end} + \frac{3}{2}u_{cLnoxcal}$	G / B	$u_{Lt} = \frac{\lvert \varepsilon_{r-high} - \varepsilon_{r-low} \rvert}{6}$ $u_L = \frac{u_{Lb} + u_{Lc} + u_{Ld}}{3}$
3. u_{zres}	using d=(1/2)z_{res} in Table A1.2	U / B	$u_{zrest} = \frac{\lvert \varepsilon_{r-high} - \varepsilon_{r-low} \rvert}{2\sqrt{3}}$ $u_{zres} = \frac{u_{zresb} + u_{zresc} + u_{zresd}}{3}$
4. u_{xcal}	using cal_{xmin} for cal_x where $cal_{xmin} = cal_x - 3\sigma_{xcal}cal_x / ruler_x$ and using cal_{xmax} for cal_x where $cal_{xmax} = cal_x + 3\sigma_{xcal}cal_x / ruler_x$	G / B	$u_{xcalt} = \frac{\lvert \varepsilon_{r-high} - \varepsilon_{r-low} \rvert}{6}$ $u_{xcal} = \frac{u_{xcalb} + u_{xcalc} + u_{xcald}}{3}$
5. u_{xres}	using d=(1/2)x_{res}cos(α) in Table A1.3	U / B	$u_{xrest} = \frac{\lvert \varepsilon_{r-high} - \varepsilon_{r-low} \rvert}{2\sqrt{3}}$ $u_{xres} = \frac{u_{xresb} + u_{xresc} + u_{xresd}}{3}$
6. u_{Rave}	using d=3σ_{Rave} in Table A1.2 where $\sigma_{Rave} = ⅙ R_{ave}$	G / B	$u_{Ravet} = \frac{\lvert \varepsilon_{r-high} - \varepsilon_{r-low} \rvert}{6}$ $u_{Rave} = \frac{u_{Raveb} + u_{Ravec} + u_{Raved}}{3}$
7. u_{noise}	using d=3σ_{noise} in Table A1.2 where $\sigma_{noise} = ⅙ (R_{tave} - R_{ave})$	G / B	$u_{noiset} = \frac{\lvert \varepsilon_{r-high} - \varepsilon_{r-low} \rvert}{6}$ $u_{noiset} = \frac{u_{noiseb} + u_{noisec} + u_{noised}}{3}$
8. u_{cert}	using d=3(z_{xx}–z_{1F})σ_{cert}/$cert$ in Table A1.4 where z_{xx} is the column heading	G / B	$u_{certt} = \frac{\lvert \varepsilon_{r-high} - \varepsilon_{r-low} \rvert}{6}$ $u_{cert} = \frac{u_{certb} + u_{certc} + u_{certd}}{3}$

TABLE A1.1 *Continued*

Uncertainty Component	Method to Obtain $\varepsilon_{r\text{-}high}$ and $\varepsilon_{r\text{-}low}$, if applicable	G or U[A] / A or B[B]	equation
9. $u_{repeat(shs)}$	using d=3(z_{xx}–z_{1F})σ_{6same}/$\bar{z}_{6same}$ in Table A1.4 where z_{xx} is the column heading	G / B	$u_{repeat(shs)t} = \frac{\lvert\varepsilon_{r-high} - \varepsilon_{r-low}\rvert}{6}$ $u_{repeat(shs)} = \frac{u_{repeat(shs)b} + u_{repeat(shs)c} + u_{repeat(shs)d}}{3}$
10. u_{drift}	using d=(z_{xx}–z_{1F})$z_{drift}cal_z$/(2$cert$) in Table A1.4 where z_{xx} is the column heading	U / B	$u_{driftt} = \frac{\lvert\varepsilon_{r-high} - \varepsilon_{r-low}\rvert}{2\sqrt{3}}$ $u_{drift} = \frac{u_{driftb} + u_{driftc} + u_{driftd}}{3}$
11. u_{linear}	using d=(z_{xx}–z_{1F})z_{lin} in Table A1.4 where z_{xx} is the column heading	U / B	$u_{lineart} = \frac{\lvert\varepsilon_{r-high} - \varepsilon_{r-low}\rvert}{2\sqrt{3}}$ $u_{linear} = \frac{u_{linearb} + u_{linearc} + u_{lineard}}{3}$
12. $u_{correction}$	—	G / B	$u_{correctiont} = \frac{\lvert\delta_{\varepsilon rcorrection}\varepsilon_{rt}\rvert}{3}$ $u_{correction} = \frac{u_{correctionb} + u_{correctionc} + u_{correctiond}}{3}$
13. $u_{repeat(samp)}$	—	G / A	$u_{repeat(samp)t} = \sigma_{repeat(samp)}\lvert\varepsilon_{rt}\rvert$ $u_{repeat(samp)} = \frac{u_{repeat(samp)b} + u_{repeat(samp)c} + u_{repeat(samp)d}}{3}$

[A] "G" indicates a Gaussian distribution and "U" indicates a uniform distribution.
[B] Type A or Type B analysis.

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

	z_{1F}	z_{2F}	$z_{3F} = z_{1S}$	z_{2S}	z_{3S}
1	z_{1F}	z_{2F}	z_{3F}	z_{2S}	z_{3S}
2	$z_{1F} + d$	z_{2F}	$z_{3F} - d$	z_{2S}	$z_{3S} + d$
3	$z_{1F} - d$	z_{2F}	$z_{3F} + d$	z_{2S}	$z_{3S} - d$
4	$z_{1F} + d$	$z_{2F} + d$	$z_{3F} - d$	$z_{2S} + d$	$z_{3S} + d$
5	$z_{1F} + d$	$z_{2F} - d$	$z_{3F} - d$	$z_{2S} - d$	$z_{3S} + d$
6	$z_{1F} - d$	$z_{2F} + d$	$z_{3F} + d$	$z_{2S} + d$	$z_{3S} - d$
7	$z_{1F} - d$	$z_{2F} - d$	$z_{3F} + d$	$z_{2S} - d$	$z_{3S} - d$

A1.5.2 For each data trace, determine ε_{rt} assuming cal_{xmin} is the x-calibration factor.

A1.5.3 For each data trace, determine ε_{rt} assuming cal_{xmax} is the x-calibration factor.

A1.5.4 For each data trace, record $\varepsilon_{r\text{-}low}$ and $\varepsilon_{r\text{-}high}$ and calculate u_{xcalt} using the equation given in Table A1.1, which assumes a Gaussian distribution.

A1.5.5 Calculate u_{xcal} as the average of the three values obtained for u_{xcalt}.

A1.6 Determine u_{xres}:

A1.6.1 For each data trace (b, c, and d) obtain seven residual strain 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.

A1.6.2 For each data trace, record $\varepsilon_{r\text{-}low}$ and $\varepsilon_{r\text{-}high}$ and calculate u_{xrest} using the equation given in Table A1.1, which assumes a uniform distribution.

A1.6.3 Calculate u_{xres} as the average of the three values obtained for u_{xrest}.

A1.7 Determine u_{Rave}:

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

	g	*h*	*i*	*j*	*k*
1	*g*	*h*	*i*	*j*	*k*
2	*g* + *d*	*h*	*i*	*j*	*k* – *d*
3	*g* – *d*	*h*	*i*	*j*	*k* + *d*
4	*g* + *d*	*h* + *d*	*i*	*j* – *d*	*k* – *d*
5	*g* + *d*	*h* – *d*	*i*	*j* + *d*	*k* – *d*
6	*g* – *d*	*h* + *d*	*i*	*j* – *d*	*k* + *d*
7	*g* – *d*	*h* – *d*	*i*	*j* + *d*	*k* + *d*

A1.7.1 Calculate σ_{Rave} as one-sixth the value of R_{ave}, where R_{ave} was obtained in 9.2.

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

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

A1.7.4 Calculate u_{Rave} as the average of the three values obtained for u_{Ravet}.

A1.8 Determine u_{noise}:

A1.8.1 Calculate σ_{noise}, the standard deviation of the noise measurement, as one-sixth the value of (R_{tave} – R_{ave}), where R_{tave} and R_{ave} were obtained in 9.2.

A1.8.2 For each data trace (*b*, *c*, and *d*), obtain seven residual strain values for the seven different sets of inputs given in Table A1.2 using d=3σ_{noise}.

A1.8.3 For each data trace, record $\varepsilon_{r\text{-}low}$ and $\varepsilon_{r\text{-}high}$ and calculate u_{noiset} using the equation given in Table A1.1, which assumes a Gaussian distribution.

A1.8.4 Calculate u_{noise} as the average of the three values obtained for u_{noiset}.

A1.9 Determine u_{cert}:

A1.9.1 For each data trace (*b*, *c*, and *d*), obtain three residual strain values for the three different sets of inputs given in Table A1.4 using $d=3(z_{xx}-z_{1F})\sigma_{cert}/cert$ where z_{xx} is the column heading and where σ_{cert} was recorded in 9.2.

A1.9.2 For each data trace, record $\varepsilon_{r\text{-}low}$ and $\varepsilon_{r\text{-}high}$ and calculate u_{certt} using the equation given in Table A1.1, which assumes a Gaussian distribution.

A1.9.3 Calculate u_{cert} as the average of the three values obtained for u_{certt}.

A1.10 Determine $u_{repeat(shs)}$:

A1.10.1 For each data trace (*b*, *c*, and *d*), obtain three residual strain values for the three different sets of inputs given in Table A1.4 using $d=3(z_{xx}-z_{1F})\sigma_{6same}/\bar{z}_{6same}$ where z_{xx} is the column heading and where σ_{6same} and $\bar{z}_{6same}$ were found in 9.2.

A1.10.2 For each data trace, record $\varepsilon_{r\text{-}low}$ and $\varepsilon_{r\text{-}high}$ and calculate $u_{repeat(shs)t}$ using the equation given in Table A1.1, which assumes a Gaussian distribution.

A1.10.3 Calculate $u_{repeat(shs)}$ as the average of the three values obtained for $u_{repeat(shs)t}$.

A1.11 Determine u_{drift}:

A1.11.1 For each data trace (*b*, *c*, and *d*), obtain three residual strain values for the three different sets of inputs given in Table A1.4 using $d=(z_{xx}-z_{1F})z_{drift}cal_z/(2cert)$ where z_{xx} is the column heading and where z_{drift} was found in 9.2.

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

A1.11.3 Calculate u_{drift} as the average of the three values obtained for u_{driftt}.

A1.12 Determine u_{linear}:

A1.12.1 For each data trace (*b*, *c*, and *d*), obtain three residual strain values for the three different sets of inputs given in Table A1.4 using $d=(z_{xx}-z_{1F})z_{lin}$ where z_{xx} is the column heading and where z_{lin} was recorded in 9.2.

A1.12.2 For each data trace, record $\varepsilon_{r\text{-}low}$ and $\varepsilon_{r\text{-}high}$ and calculate $u_{lineart}$ using the equation given in Table A1.1, which assumes a uniform distribution.

A1.12.3 Calculate u_{linear} as the average of the three values obtained for $u_{lineart}$.

A1.13 Determine $u_{correction}$:

A1.13.1 For each data trace, calculate $u_{correctiont}$ using the equation given in Table A1.1, where $\delta_{\varepsilon rcorrection}$ is a relative residual strain correction term intending to correct for deviations from the ideal fixed-fixed beam geometry and/or composition (**1**).

A1.13.2 Calculate $u_{correction}$ as the average of the three values obtained for $u_{correctiont}$.

A1.14 Determine $u_{repeat(samp)}$:

A1.14.1 Obtain $\sigma_{repeat(samp)}$, the residual strain relative repeatability standard deviation for fixed-fixed beams fabricated

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

	z_{1F}	z_{2F}	$z_{3F} = z_{1S}$	z_{2S}	z_{3S}
1	z_{1F}	z_{2F}	z_{3F}	z_{2S}	z_{3S}
2	z_{1F}	$z_{2F} + d$	$z_{3F} + d$	$z_{2S} + d$	$z_{3S} + d$
3	z_{1F}	$z_{2F} - d$	$z_{3F} - d$	$z_{2S} - d$	$z_{3S} - d$

in a process similar to that used to fabricate the sample. (Table 2 provides a value for $\sigma_{repeat(samp)}$ for a surface-micromachining process used to fabricate the round robin test chips (**3**) specified in 13.2.)

A1.14.1.1 Determine $\sigma_{repeat(samp)}$, if not known, from at least twelve 3-D data sets of a given fixed-fixed beam from which twelve values of ε_r are calculated. The standard deviation of these measurements divided by the average of the twelve values for ε_r is equated with $\sigma_{repeat(samp)}$.

A1.14.2 For each data trace, calculate $u_{repeat(samp)t}$ using the equation given in Table A1.1.

A1.14.3 Calculate $u_{repeat(samp)}$ as the average of the three values obtained for $u_{repeat(samp)t}$.

A1.15 The expanded uncertainty for residual strain, $U_{\varepsilon r}$, is calculated using the following equation:

$$U_{\varepsilon r} = ku_{c\varepsilon r} = 2u_{c\varepsilon r} \quad (A1.2)$$

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

APPENDIX

(Nonmandatory Information)

X1. ADHERENCE OF SURFACE-MICROMACHINED FIXED-FIXED BEAM TO UNDERLYING LAYER

X1.1 Determine if the surface-micromachined fixed-fixed beam (shown in Fig. X1.1) is adhered to the top of the underlying layer (**2, 8**).

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

NOTE X1.1—It may be necessary to obtain two 3-D data sets. One of the data sets would include the fixed-fixed beam and the anchor to the left of the beam 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 3.2.6.

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.

X1.1.5 Define region #2 as a group of points within the large anchor area shown in Fig. X1.2. Record $z_{reg\#2}$ as defined in 3.2.6.

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 fixed-fixed beam 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:

$$B_1 = z_{reg\#1} - z_{reg\#2} \quad (X1.1)$$

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

$$B_2 = H + J \quad (X1.2)$$

or

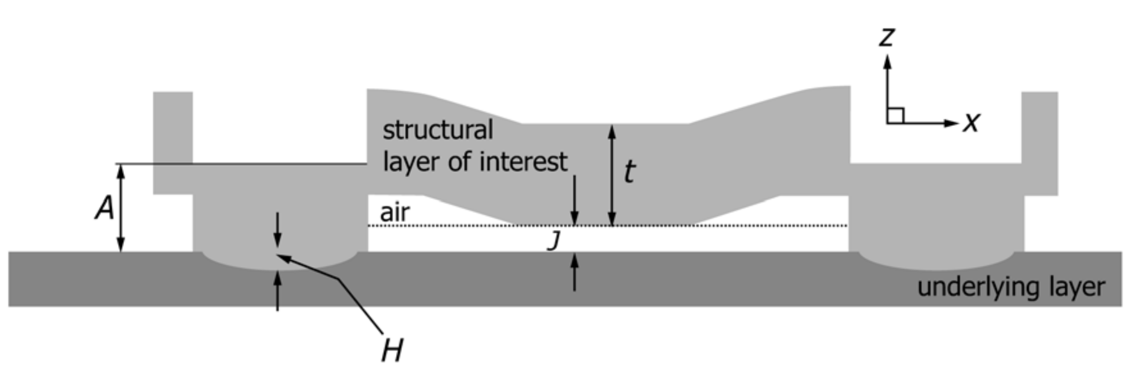
$$B_2 = t - A + J \quad (X1.3)$$

where A, H, and J in Fig. X1.1 are defined in 3.2.6 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.

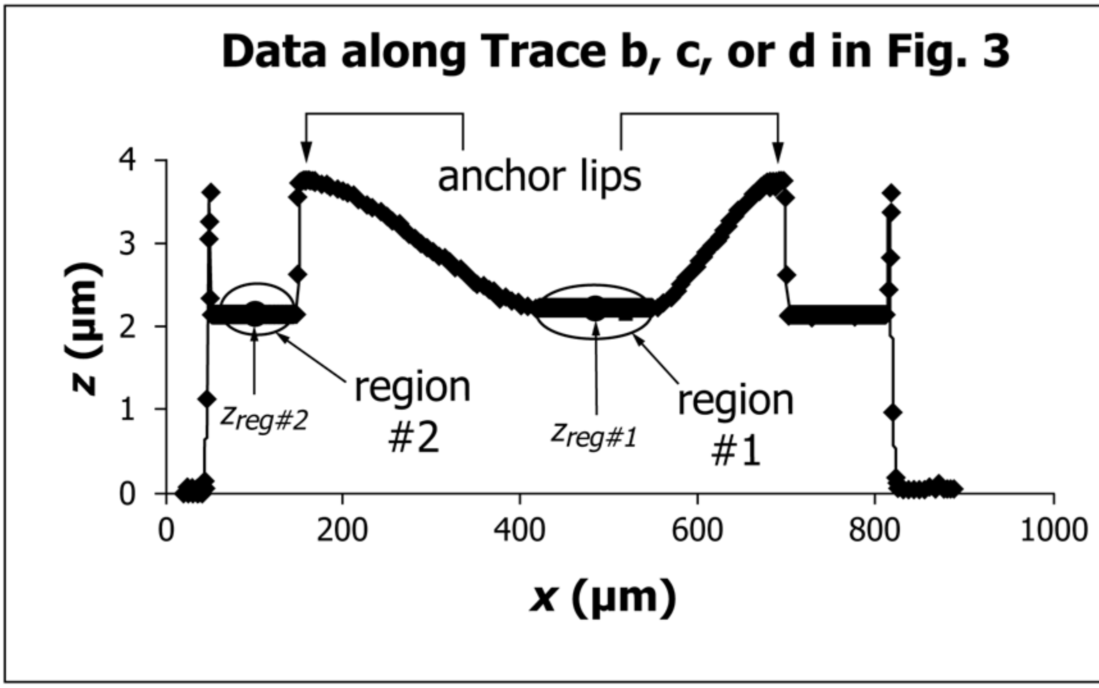
X1.1.9 Repeat X1.1.2 to X1.1.8 for Traces b and d.



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.

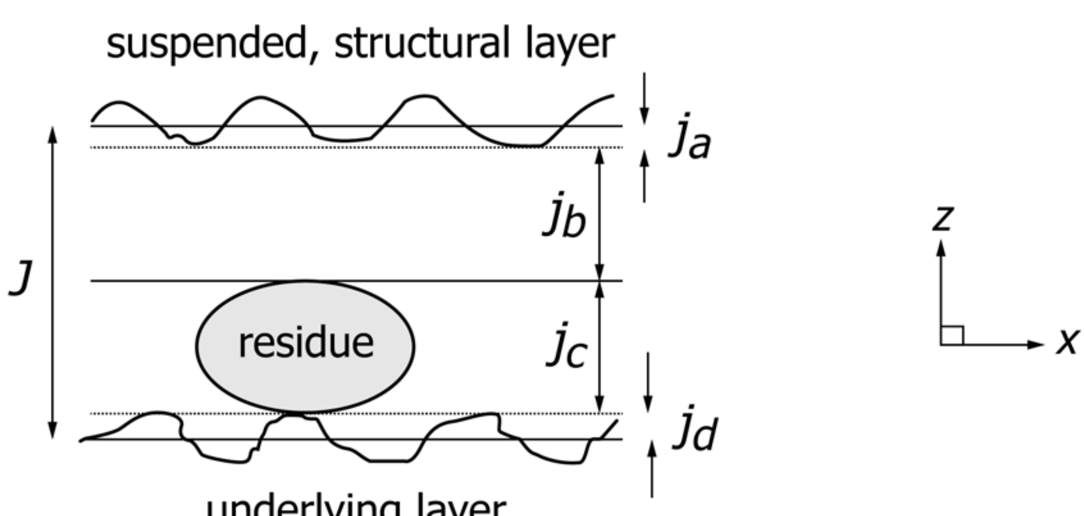
FIG. X1.1 Cross-Sectional Side View of Fixed-fixed Beam Adhered to Top of Underlying Layer



NOTE 1—This is an example of stiction.

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

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



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

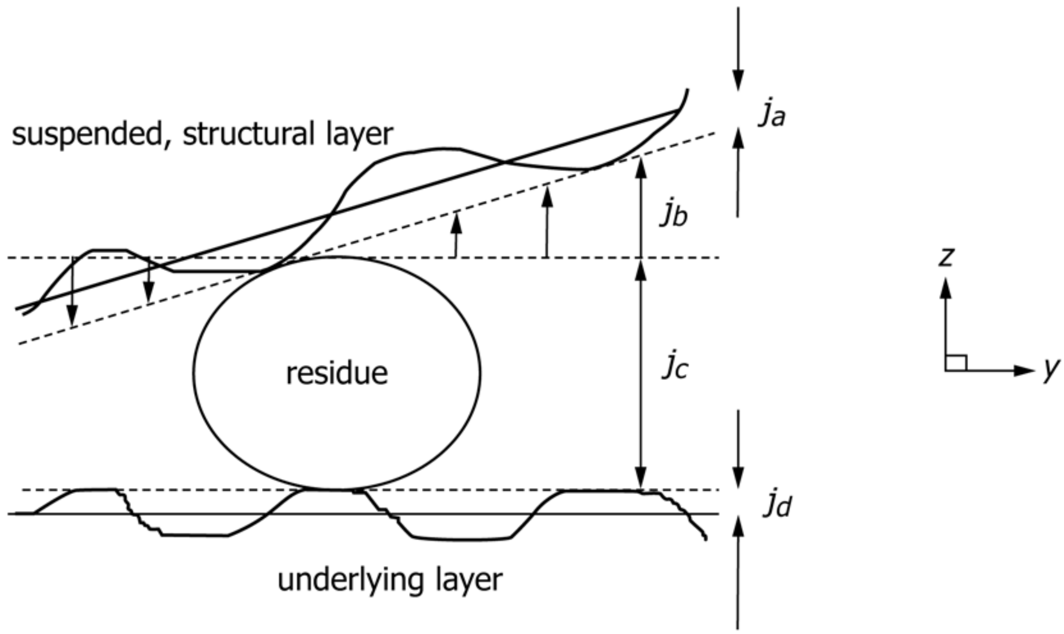
FIG. X1.3 Component Parts of *J* in Fig. X1.1

X1.1.10 The fixed-fixed beam 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 fixed-fixed beam.

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 beam's natural shape is the primary indicator of an adhered fixed-fixed beam.



NOTE 1—This view is along the width of the fixed-fixed beam.

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

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 fixed-fixed beam is adhered at one point along the length of the fixed-fixed beam is a difficult task. Therefore, this criterion errs on the conservative side.

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