Designation: E 2245 – 02

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

This standard is issued under the fixed designation E 2245; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers a procedure for measuring the 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 interferometer. Measurements from fixed-fixed beams that are touching the underlying layer are not accepted.

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

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

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

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

3. Terminology

3.1 *Definitions:*

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

3.1.1.1 *Discussion*—The height of the sample is measured along the *z*-axis of the interferometer. The interferometer's *x*-axis (as shown in Figs. 1-3) is typically aligned parallel or perpendicular to the transitional edges to be measured.

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

3.1.3 *anchor*, *n*—in a surface-micromachining process, the portion of the test structure where the mechanical layer makes contact with the underlying layer (see Figs. 1 and 2).

3.1.4 *anchor lip*, *n*—in a surface-micromachining process, the extension of the mechanical layer around the edges of the anchor (see Figs. 2 and 3).

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

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

3.1.7 *fixed-fixed beam*, *n*—a test structure that consists of a beam suspended in air and anchored or supported at both ends (see Figs. 1-3, and Fig. X1.1).

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

3.1.9 *interferometer*, *n*—a non-contact optical instrument (such as shown in Fig. 4) used to obtain topographical 3-D data sets.

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

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

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

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

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

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

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[1] This test method is under the jurisdiction of ASTM Committee E08 on Fatigue and Fracture and is the direct responsibility of Subcommittee E08.05 on Cyclic Deformation and Fatigue Crack Formation.

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

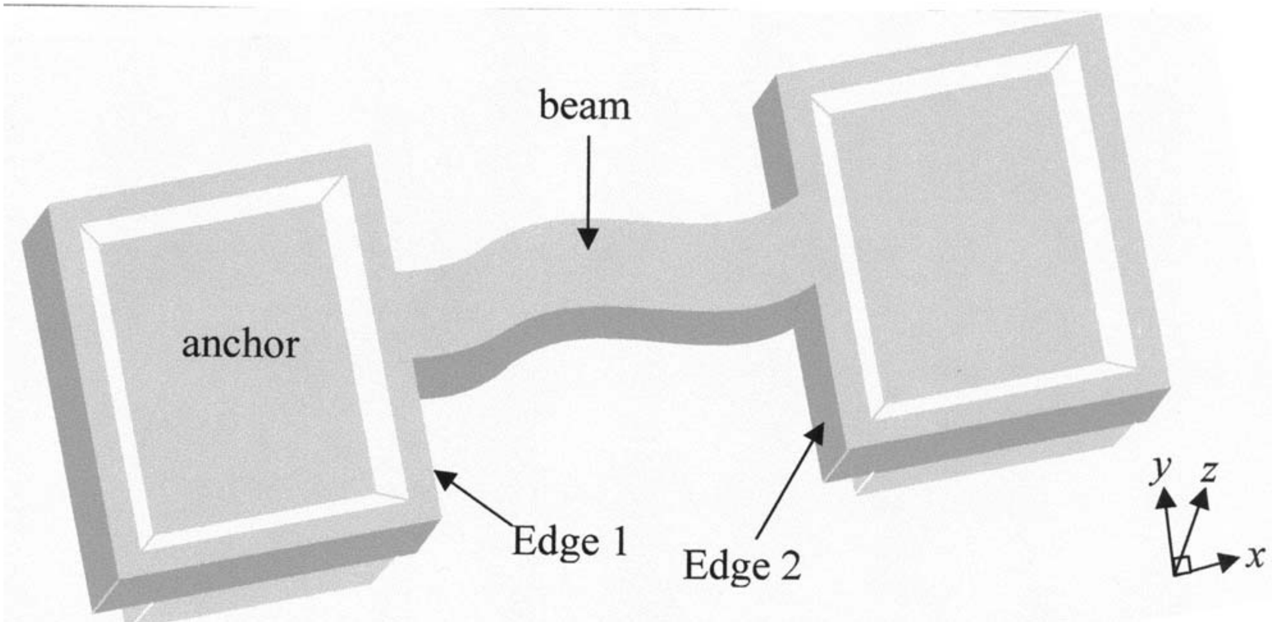
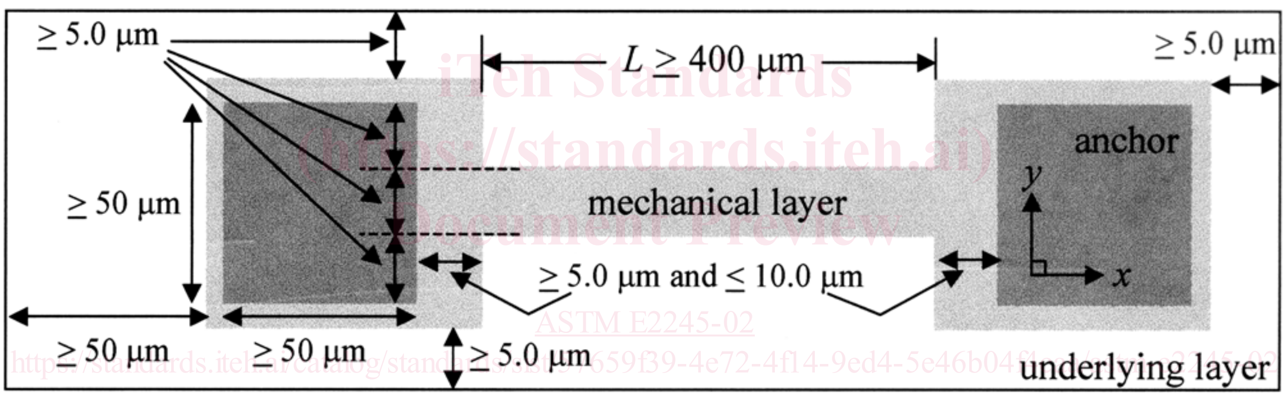


FIG. 1 Three-Dimensional View of Surface-Micromachined Fixed-Fixed Beam



NOTE 1—The underlying layer is beneath this test structure.
NOTE 2—The mechanical layer is included in both the light and dark gray areas.
NOTE 3—The dark gray areas (the anchors) are the designed cuts in the sacrificial layer. This is where the mechanical layer contacts the underlying layer.
NOTE 4—The light gray area is suspended in air after fabrication.

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

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

3.1.16 *stiction*, *n*—in a surface-micromachining process, a structure exhibits this when a non-anchored portion of the mechanical layer adheres to the top of the underlying layer.

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

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

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

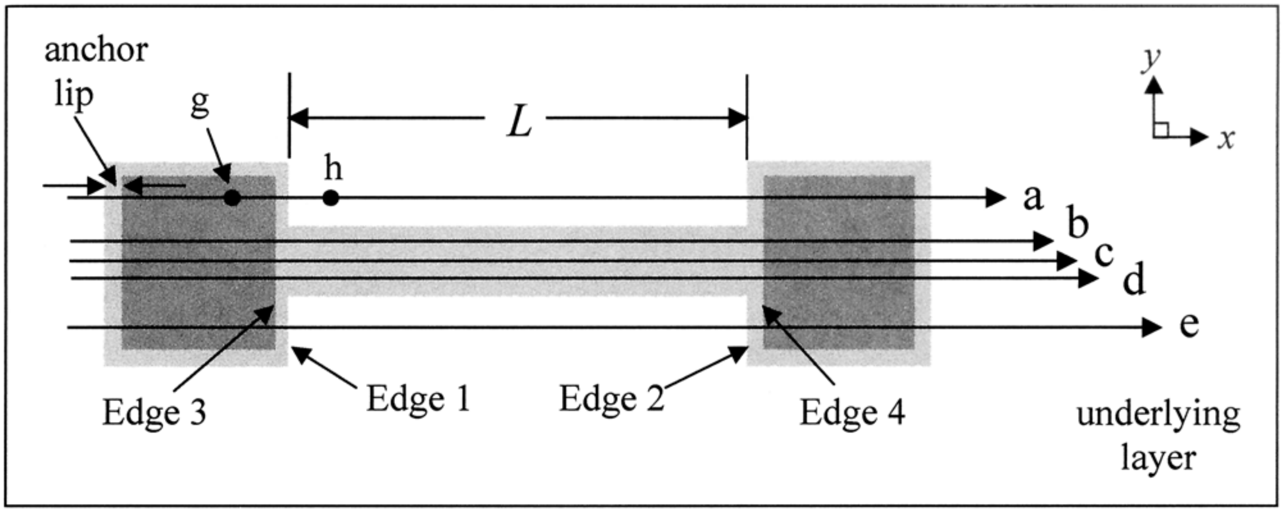
3.1.20 *surface micromachining*, *adj*—a MEMS fabrication process where thin, sacrificial layers are removed, which can create structures suspended in air.

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

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

3.2 *Symbols:*



NOTE 1—The 2-D data traces (“a” and “e”) are used to ensure alignment and determine *L*.

NOTE 2—Trace “c” is used to determine the residual strain and ascertain if the fixed-fixed beam is adhered to the top of the underlying layer.

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

FIG. 3 Top View of Fixed-Fixed Beam

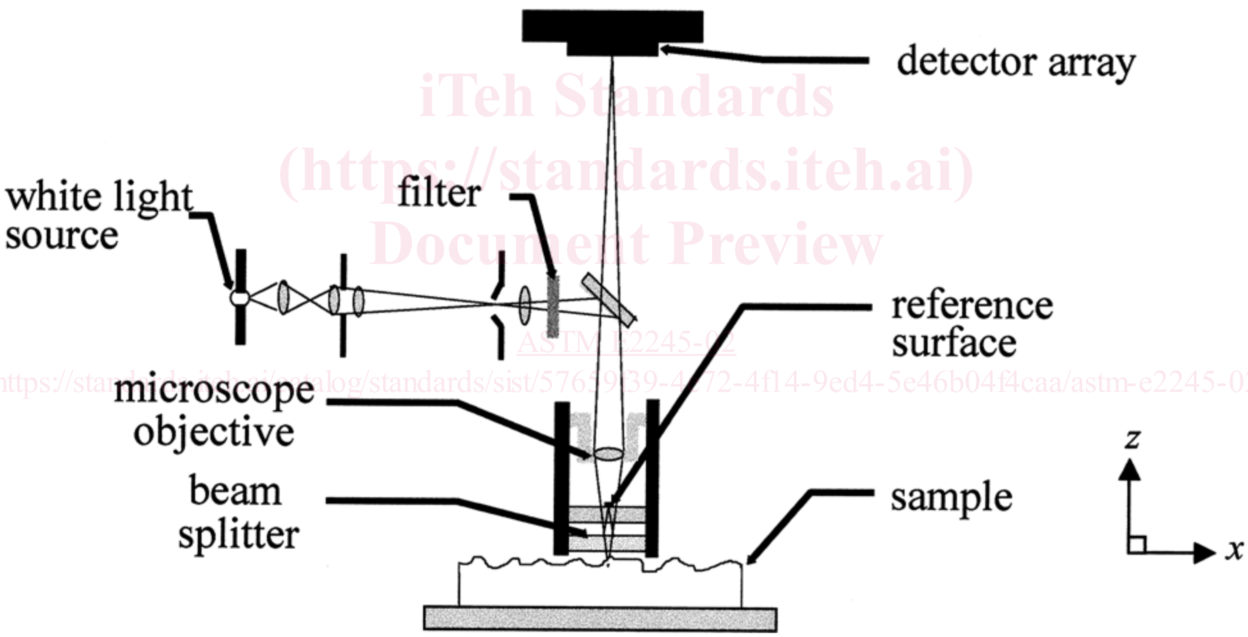


FIG. 4 Sketch of Optical Interferometer

3.2.1 *For Calibration*:

cal-x = the *x*-calibration factor of the interferometer for the given combination of lenses

cal-y = the *y*-calibration factor of the interferometer for the given combination of lenses

cal-z = the *z*-calibration factor of the interferometer for the given combination of lenses

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

inter-x = the interferometer’s maximum field of view in the *x*-direction for the given combination of lenses

inter-y = the interferometer’s maximum field of view in the *y*-direction for the given combination of lenses

mean = the mean value of the step-height measurements (on the double-sided step height standard) used to calculate *cal-z*

ruler-x = the interferometer’s maximum field of view in the *x*-direction for the given combination of lenses as measured with a 10-µm grid ruler

ruler-y = the interferometer’s maximum field of view in the *y*-direction for the given combination of lenses as measured with a 10-µm grid ruler

3.2.2 *For Alignment*:

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

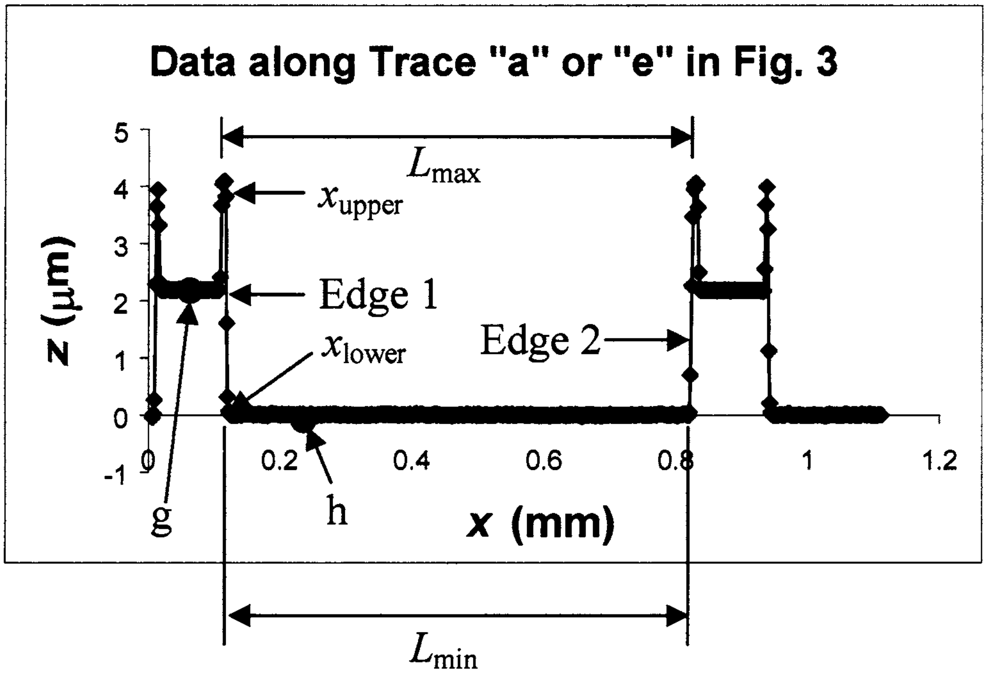


FIG. 5 2-D Data Trace Used to Find $x1_{min}$, $x1_{max}$, $x2_{min}$, and $x2_{max}$

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

$x2_{lower}$ = the x-data value along Edge "2" (such as shown in Fig. 5) locating the lower part of the transition

$x2_{upper}$ = the x-data value along Edge "2" (such as shown in Fig. 5) locating the upper part of the transition

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

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

3.2.3 *For In-plane Length Measurement*:

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

L_{max} = the maximum in-plane length measurement of the fixed-fixed beam (see Fig. 5)

L_{min} = the minimum in-plane length measurement of the fixed-fixed beam (see Fig. 5)

$x1_{ave}$ = an endpoint of the in-plane length measurement (that is, the average of $x1_{min}$ and $x1_{max}$)

$x1_{max}$ = the value for $x1_{upper}$ used in the calculation of L_{max}

$x1_{min}$ = the value for $x1_{lower}$ used in the calculation of L_{min}

$x2_{ave}$ = the other endpoint of the in-plane length measurement (that is, the average of $x2_{min}$ and $x2_{max}$)

$x2_{max}$ = the value for $x2_{upper}$ used in the calculation of L_{max}

$x2_{min}$ = the value for $x2_{lower}$ used in the calculation of L_{min}

3.2.4 *For Residual Strain Measurement*:

ϵ_r = in a surface-micromachining process, the residual strain present in the mechanical layer after fabrication yet before the sacrificial layer is removed. The data in Figs. 5 and 6 are used for this calculation. In a bulk-micromachining process, the residual strain present in the suspended layer after fabrication yet before the substrate is removed at specified locations.

A_F = the amplitude of the cosine function used to model curve #1 in Fig. 7

A_S = the amplitude of the cosine function used to model curve #2 in Fig. 7

L_c = the total length of the curved fixed-fixed beam (as modeled with two cosine functions) with $x1_{ave}$ and $x2_{ave}$ as the x values of the endpoints

L_{cF} = the length of the cosine function modeling curve #1 in Fig. 7 with $x1_{ave}$ and x_{3F} as the x values of the endpoints

L_{cS} = the length of the cosine function modeling curve #2 in Fig. 7 with x_{1S} and $x2_{ave}$ as the x values of the endpoints

L_e' = the effective length of the fixed-fixed beam. This is a straight-line measurement between x_{eF} and x_{eS}

L_0 = the length of the fixed-fixed beam if there were no applied axial-compressive force

s = equals 1 for fixed-fixed beams deflected in the $-z$-direction, and equals -1 for fixed-fixed beams deflected in the $+z$-direction

t = the thickness of the suspended layer, such as shown in Fig. X2.1 **(1-3)**[3] for a surface-micromachining process

$t_{support}$ = in a bulk-micromachining process, the thickness of the support region where it is intersected by the 2-D data trace of interest (such as, Trace "a" or "e" in Fig. X1.1, as shown in Fig. X1.2)

x_{eF} = the x value of the inflection point of the cosine function modeling curve #1 in Fig. 7

x_{eS} = the x value of the inflection point of the cosine function modeling curve #2 in Fig. 7

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

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

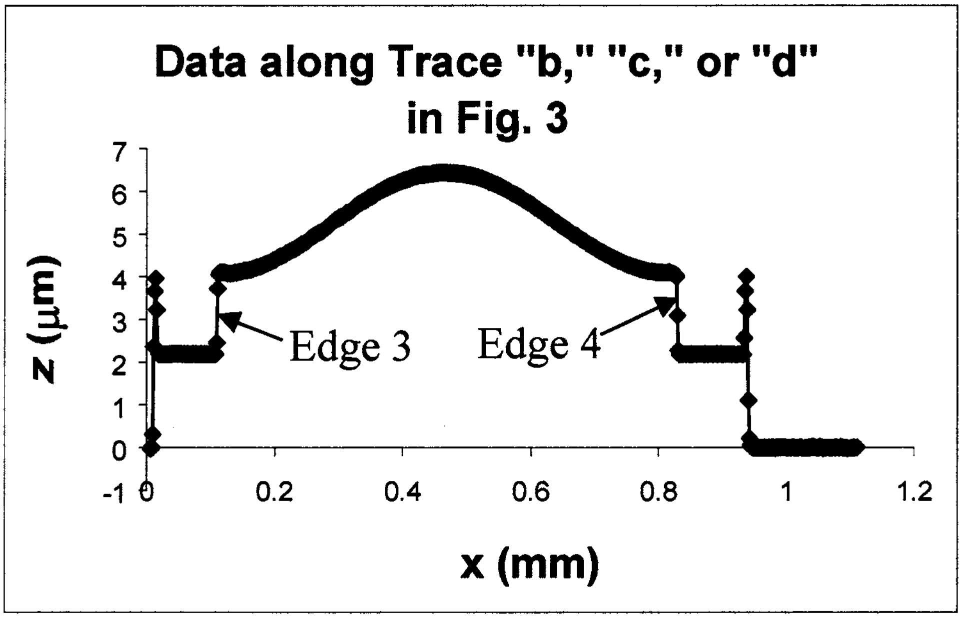
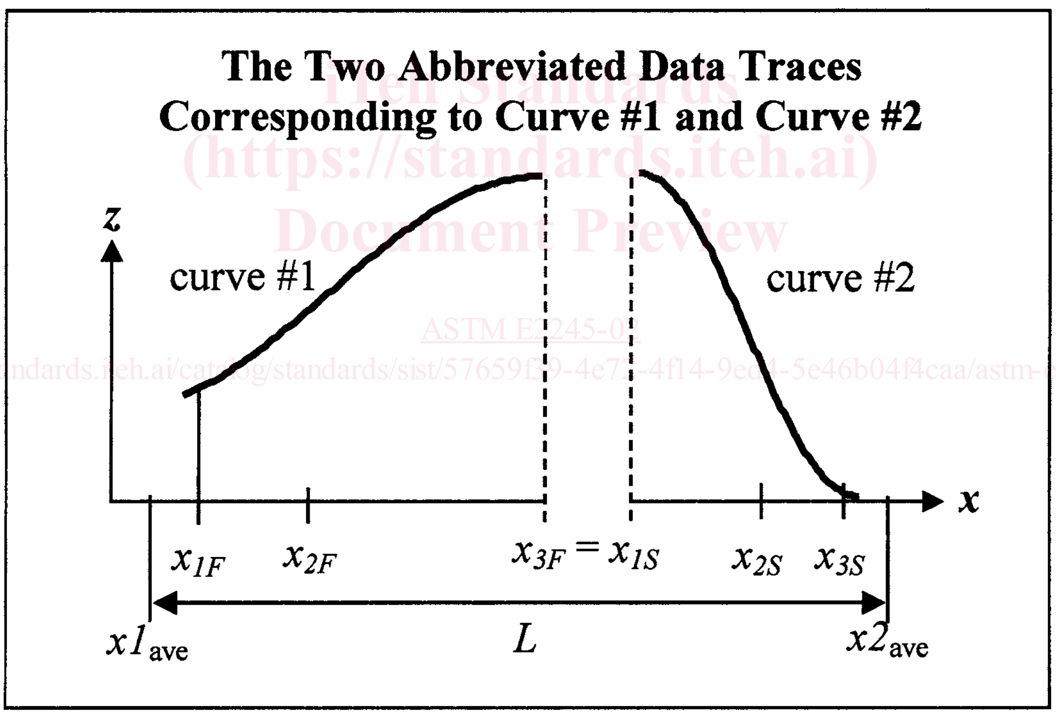


FIG. 6 2-D Data Trace Along a Fixed-Fixed Beam



NOTE—The data above has been exaggerated.

FIG. 7 First and Second Curves Used to Find Residual Strain

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

3.2.5 *For Combined Standard Uncertainty Calculations*:

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

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

$L_{c\text{-}max}$ = the total length of the curved fixed-fixed beam (as modeled with two cosine functions) with $x1_{max}$ and $x2_{max}$ as the x values of the endpoints

$L_{c\text{-}min}$ = the total length of the curved fixed-fixed beam (as modeled with two cosine functions) with $x1_{min}$ and $x2_{min}$ as the x values of the endpoints

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

u_c = the combined standard uncertainty value (that is, the estimated standard deviation of the result) **(4)**.

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

u_W = the component in the combined standard uncertainty calculation that is due to the measurement uncertainty across the width of the fixed-fixed beam

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

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

A = the minimum thickness of the mechanical layer as measured from the top of the mechanical layer in the anchor area (or region #2 in Fig. X2.2) to the top of the underlying layer (as shown in Fig. X2.1) and as specified in the reference **(3)**

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

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

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

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

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

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

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

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

3.2.7 *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 above that start with the letter "x."

4. Summary of Test Method

4.1 Two cosine functions model the out-of-plane shape of fixed-fixed beams. These functions are merged at the peak or valley deflection. Three data points are chosen to define each cosine function. The residual strain is calculated after the appropriate lengths are determined.

4.2 For a surface-micromachined fixed-fixed beam, to obtain three data points that define each cosine function: (*1*) select four transitional edges, (*2*) obtain a 3-D data set, (*3*) ensure alignment, (*4*) determine the endpoints of the in-plane length measurement, and (*5*) obtain three data points that define each cosine function. (This procedure is presented in Appendix X1 for a bulk-micromachined fixed-fixed beam.)

4.3 To calculate the residual strain: (*1*) solve three equations for three unknowns to obtain each cosine function, (*2*) plot the functions with the data, (*3*) calculate the length of the curved fixed-fixed beam, and (*4*) calculate the residual strain.

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 is 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 X2) are not accepted.

7. Apparatus [4]

7.1 *Non-contact Optical Interferometer*, capable of obtaining a topographical 3-D data set and has software that can export a 2-D data trace. Fig. 4 is a sketch of a suitable non-contact optical interferometer. However, any non-contact optical interferometer that has pixel-to-pixel spacings as specified in Table 1 and that is capable of performing the test procedure with a vertical resolution less than 1 nm is permitted. The interferometer must be capable of measuring step heights from 0.1 nm to at least 10 μm higher than the step height to be measured.

TABLE 1 Interferometer Pixel-to-Pixel Spacing Requirements

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

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

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

8. Test Units

8.1 *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) such that obtaining a 2-D data trace (such as Trace "c" in Fig. 3) along its length is not a difficult task.

8.1.2 The fixed-fixed beam shall be long enough (for example, $L \geq 400$ μm, as shown in Fig. 2) such that it exhibits out-of-plane curvature in the z-direction (as shown in Fig. 1).

8.1.3 The anchor lip between Edges "1" and "3" in Fig. 3 and between Edges "2" and "4" shall be wide enough to include at least three data points. If the pixel-to-pixel spacing

[4] The same apparatus is used as in Test Method E 2244 and Test Method E 2246 and **(5)**.