Designation: E2244 – 11$^{\varepsilon 1}$

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

This standard is issued under the fixed designation E2244; 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 in-plane lengths (including deflections) of patterned thin films. It applies only to films, such as found in microelectromechanical systems (MEMS) materials, which can be imaged using an optical interferometer, also called an interferometric microscope.

1.2 There are other ways to determine in-plane lengths. Using the design dimensions typically provides more precise in-plane length values than using measurements taken with an optical interferometric microscope. (Interferometric measurements are typically more precise than measurements taken with an optical microscope.) This test method is intended for use when interferometric measurements are preferred over using the design dimensions (for example, when measuring in-plane deflections and when measuring lengths in an unproven fabrication process).

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

1.4 The maximum in-plane length measured is determined by the maximum field of view of the interferometric microscope at the lowest magnification. The minimum deflection measured is determined by the interferometric microscope's pixel-to-pixel spacing at the highest magnification.

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

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E2245 Test Method for Residual Strain 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.

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

Current edition approved Nov. 1, 2011. Published December 2011. Originally approved in 2002. Last previous edition approved in 2005 as E2244 – 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.

3.1.5 *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).

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 *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.

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

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

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

3.1.17 *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.

3.1.18 *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.

3.1.19 *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.

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

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

3.2 *Symbols:*

3.2.1 *For Calibration:*

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

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

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

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

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

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

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

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

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

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

$\bar{z}_{ave}$ = 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

$\sigma_{repeat(samp)'}$ = 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 for the same or a similar type of measurement

L = the in-plane length measurement that accounts for misalignment and includes the in-plane length correction term, L_{offset}

L_{align} = the in-plane length, after correcting for misalignment, used to calculate *L*

L_{meas} = the measured in-plane length used to calculate L_{align}

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

$n1_t$ = 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.

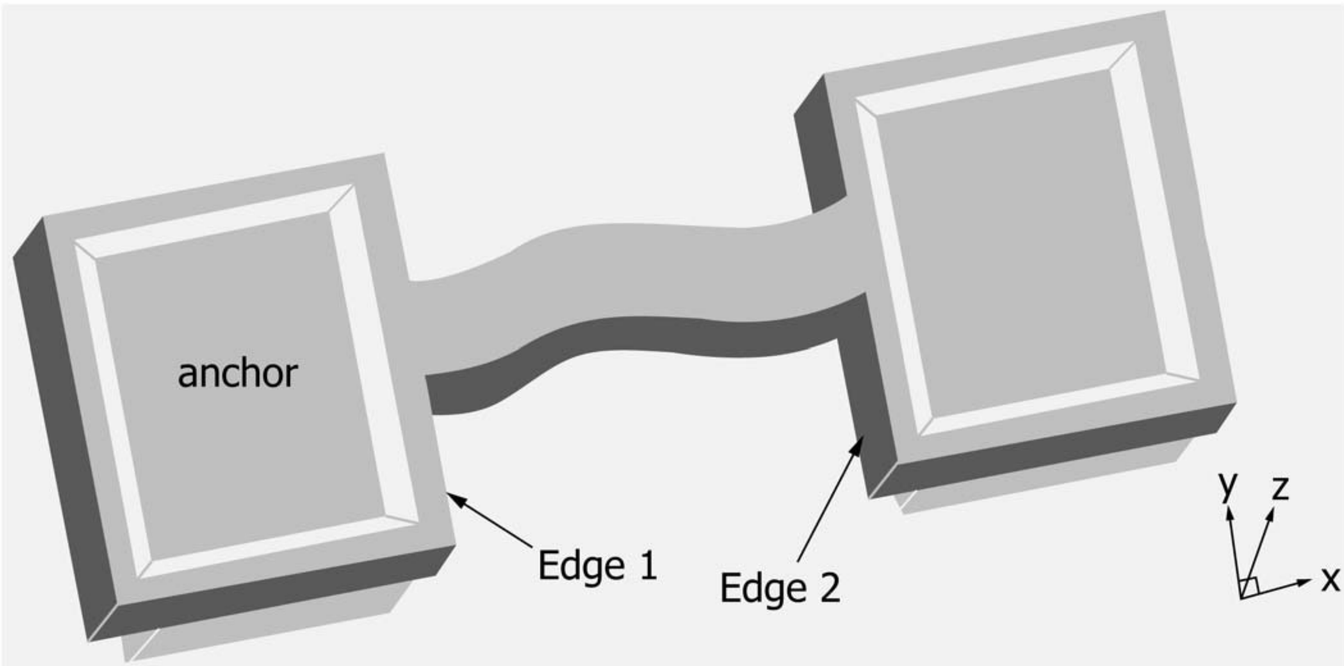


FIG. 1 Three-Dimensional View of Surface-Micromachined Fixed-Fixed Beam

U_L = the expanded uncertainty of an in-plane length measurement

u_{align} = the component in the combined standard uncertainty calculation for an in-plane length measurement that is due to alignment uncertainty

u_{cL} = the combined standard uncertainty for an in-plane length measurement

u_L = the component in the combined standard uncertainty calculation for an in-plane length measurement that is due to the uncertainty in the calculated length

u_{offset} = the component in the combined standard uncertainty calculation for an in-plane length measurement that is due to the uncertainty of the value for L_{offset}

$u_{repeat(L)}$ = the component in the combined standard uncertainty calculation for an in-plane length measurement that is due to the uncertainty of the four measurements taken on the test structure at different locations

$u_{repeat(samp)}$ = the component in the combined standard uncertainty calculation for an in-plane length measurement that is due to the repeatability of measurements taken on test structures processed similarly to the sample, using the same combination of lenses for the given interferometric microscope for the measurement, and for the same or a similar type of measurement

u_{xcal} = the component in the combined standard uncertainty calculation for an in-plane length measurement that is due to the uncertainty of the calibration in the *x*-direction

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

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

x_{res} = the uncalibrated resolution of the interferometric microscope in the *x*-direction for the given combination of lenses

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

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

3.2.3 *For Round Robin Measurements:*

ΔL = for the given value of L_{des}, L_{ave} minus L_{des}

ΔL_{ave} = the average value of ΔL over the given range of L_{des} values

L_{ave} = the average in-plane length value for the repeatability or reproducibility measurements that is equal to the sum of the L values divided by n

L_{des} = the design length

mag = the magnification used for the measurement

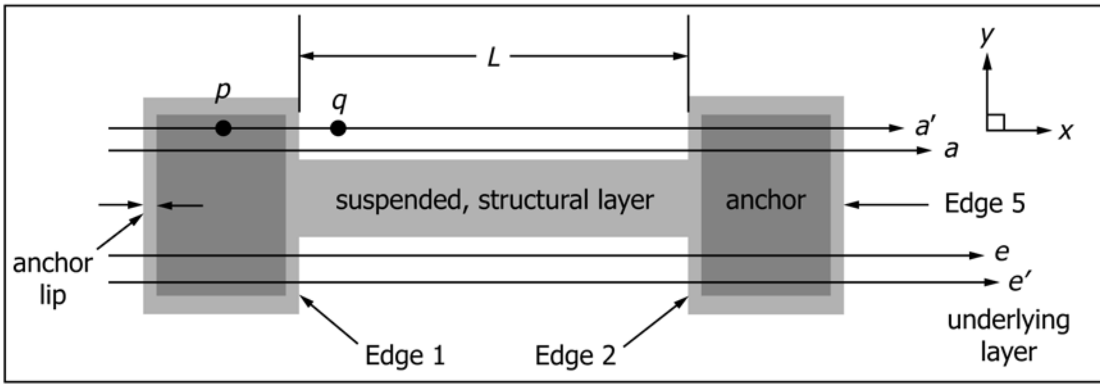
n = the number of repeatability or reproducibility measurements

u_{cLave} = the average combined standard uncertainty value for the in-plane length measurements that is equal to the sum of the u_{cL} values divided by n

3.2.4 *Discussion*—The symbols above are used throughout this test method. However, the letter "*D*" can replace the letter "*L*" in the symbols above when referring to in-plane deflection measurements, which would imply replacing the word "length" with the word "deflection." Also, 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 Any in-plane length measurement can be made if each end is defined by a transitional edge. Consider the surface-micromachined fixed-fixed beam shown in Figs. 1 and 2. An optical interferometric microscope (such as shown in Fig. 3) is used to obtain a topographical 3-D data set. Four 2-D data traces (one of which is shown in Fig. 4) are extracted from this 3-D data set for the analysis of the transitional edges of interest.



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.
NOTE 5—The 2-D data traces (*a′* and *e′*) are used to determine the misalignment angle, α.
NOTE 6—The 2-D data traces (*a′*, *a*, *e*, and *e′*) are used to determine *L*.

FIG. 2 Top View of Fixed-Fixed Beam in Fig. 1

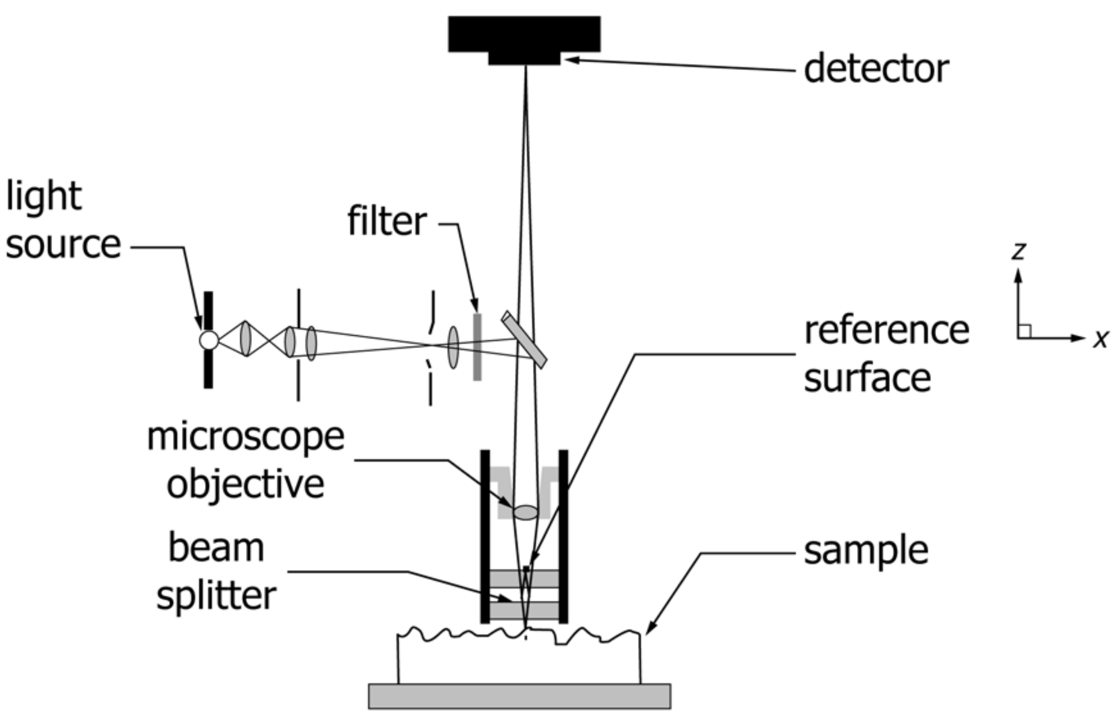


FIG. 3 Schematic of an Optical Interferometric Microscope

4.2 To obtain the endpoints of the in-plane length measurement for a surface-micromachined structure, four 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, and *(4)* obtain the endpoints and associated uncertainties. (This procedure may need to be modified for a bulk-micromachined structure.)

4.3 From each of the four data traces, the *x*-values ($x1_{uppert}$ and $x2_{uppert}$) are obtained at the transitional edges defining *L*, where the subscript *t* is *a*', *a*, *e*, or *e*' to identify Trace *a*', *a*, *e*, or *e*', respectively. The uncertainties ($n1_t$ and $n2_t$) associated with these *x*-values are also obtained. The misalignment angle, α, is calculated from the data obtained from the two outermost data traces (*a*' and *e*') along with the corresponding *y*-values ($y_{a'}$ and $y_{e'}$) associated with these traces. The in-plane length, *L*, is the average of the four calibrated values for ($x2_{uppert} - x1_{uppert}$) times cos(α) plus L_{offset}, the in-plane length correction term.

4.4 Alternatively for a surface-micromachining process, if the transitional edges that define *L* face the same way (for example, two right-hand edges) and have similar slopes and magnitudes, the values for $x1_{lowert}$ and $x2_{lowert}$ can be used instead of $x1_{uppert}$ and $x2_{uppert}$ if the sum of the uncertainties ($n1_t + n2_t$) for the lower values are typically less than the sum of the uncertainties for the upper values. Due to the similarities

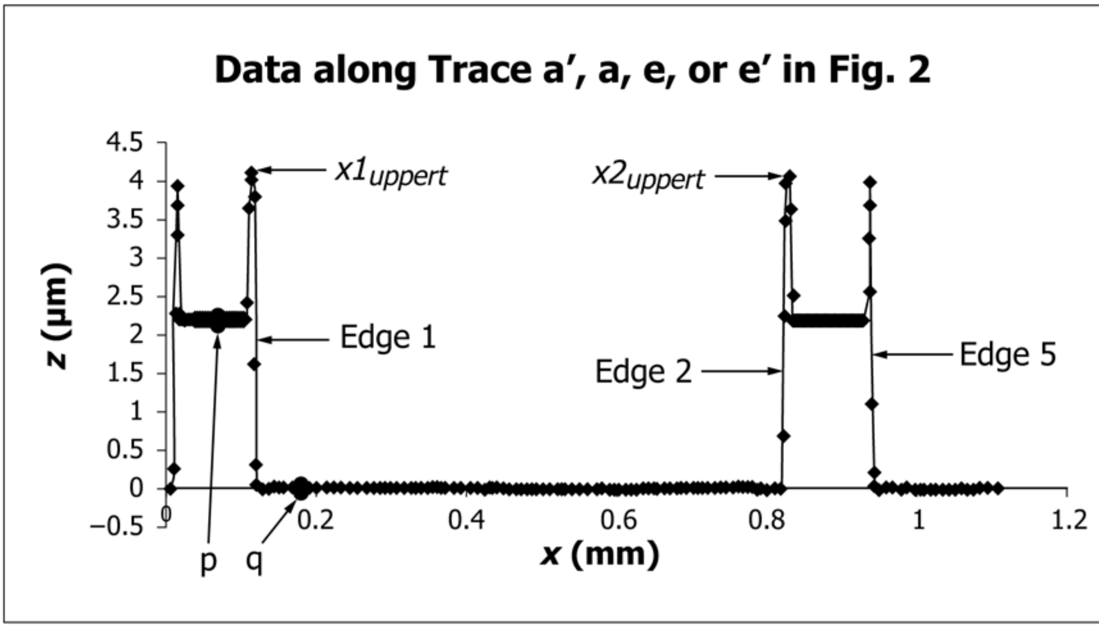


FIG. 4 2-D Data Trace Used to Find $x1_{uppert}$, $x2_{uppert}$, $n1_t$, and $n2_t$

of the edges involved, the length correction term, L_{offset}, is set equal to zero in the calculation of L.

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

5. Significance and Use

5.1 In-plane length measurements can be used in calculations of parameters, such as residual strain and Young's modulus.

5.2 In-plane deflection measurements are required for specific test structures. Parameters, including residual strain, are calculated given the in-plane deflection measurements.

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

6.1 *Non-contact Optical Interferometric Microscope,* capable of obtaining a topographical 3-D data set and exporting a 2-D data trace. Fig. 3 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 physical step height to be measured.

NOTE 1—Table 1 does not include magnifications at or less than 2.5× because the pixel-to-pixel spacings will be too large for this work, or the possible introduction of a second set of interferometric fringes in the data set at these magnifications can adversely affect the data, or both. Therefore, magnifications at or less than 2.5× shall not be used.

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 2—The 1 nm resolution is not mandatory for this test method. In reality, the vertical resolution can be as much as 5 nm. However, the constraint is supplied to alert the user of this instrumental constraint for out-of-plane measurements leading to residual strain, strain gradient, and step height calculations.

6.2 *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.

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

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

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

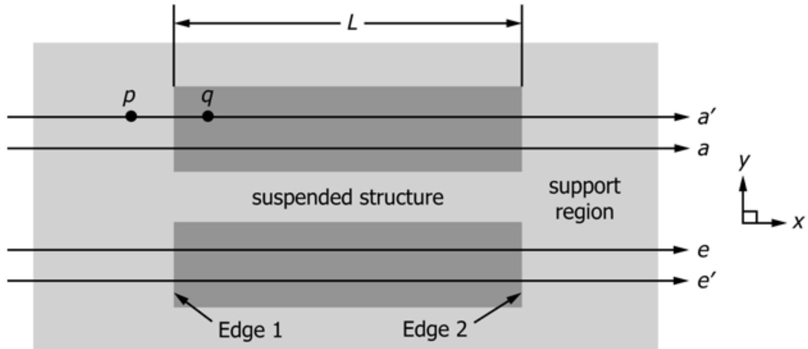
7. Test Units

7.1 The two transitional edges (for example, Edges 1 and 2 in Figs. 1 and 2) defining the in-plane length (or deflection) measurement.

NOTE 3—In a surface-micromachining process, if a transitional edge is on one side of an anchor lip, the anchor lip should be between 4.0 µm and 10.0 µm, inclusive.

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



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

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

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

NOTE 4—The 2-D data traces (*a′* and *e′*) are used to determine the misalignment angle, α.

NOTE 5—The 2-D data traces (*a′*, *a*, *e*, and *e′*) are used to determine *L*.

FIG. 5 Top View of Bulk-Micromachined Fixed-Fixed Beam

8. Calibration[7] (**1-3**)

8.1 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.

8.1.1 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}.

8.1.2 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}.

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

$$cal_x = \frac{ruler_x}{scope_x} \quad (1)$$

and

$$cal_y = \frac{ruler_y}{scope_y} \quad (2)$$

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.

8.2 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.

8.2.1 Before the data session, record 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.

8.2.2 After the data session, repeat 8.2.1. This step can be skipped if the instrument does not drift significantly during a data session.

8.2.3 Calculate the mean value, $\bar{z}_{ave}$, of the measurements obtained in 8.2.1 and 8.2.2.

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

$$cal_z = \frac{cert}{\bar{z}_{ave}} \quad (3)$$

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

9. Procedure (**1-3**)

9.1 To obtain the endpoints of an in-plane length measurement for a surface-micromachined structure, four 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, and *(4)* obtain the endpoints and associated uncertainties.

NOTE 7—The procedure that follows may need to be modified to obtain the required data. For a bulk-micromachining process, refer to Figs. 5 and 6 instead of Fig. 2 and Fig. 4, respectively, when possible.

9.2 *Select the Two Transitional Edges:*

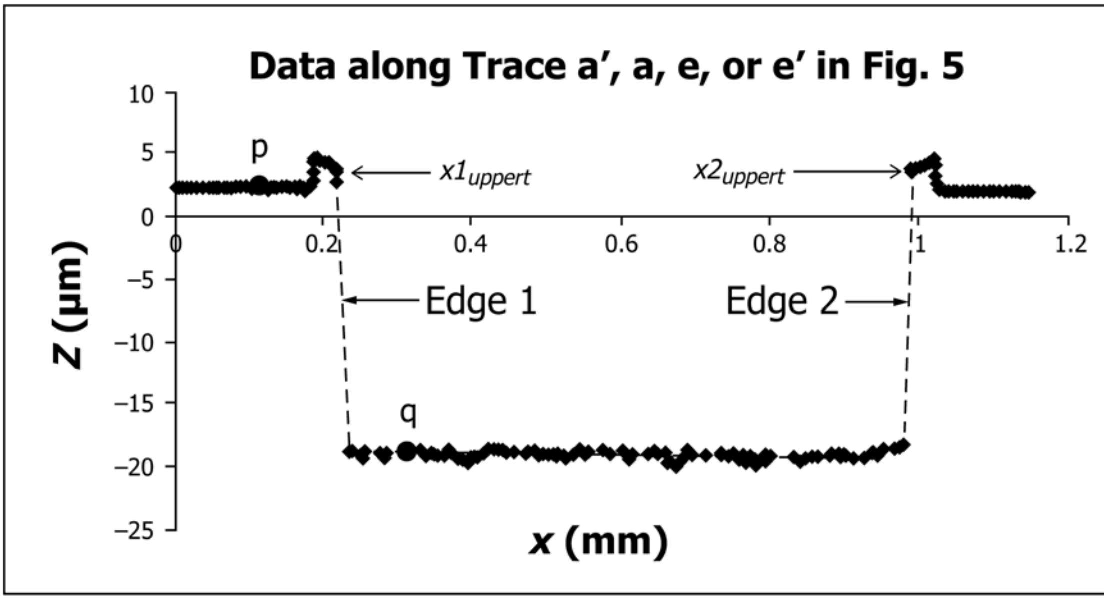
9.2.1 Select the two transitional edges that define the in-plane length measurement (such as Edges 1 and 2 in Fig. 2). These are the first and second transitional edges.

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

9.3.1 Align the two transitional edges from 9.2.1 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.

[7] The same calibration procedure is used as in Test Method E2245 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.



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

FIG. 6 2-D Data Trace Used to Find $x1_{uppert}$, $x2_{uppert}$, $n1_t$, and $n2_t$

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.

9.4 *Obtain a 3-D Data Set:*

9.4.1 Obtain a 3-D data set that contains 2-D data traces perpendicular to the two selected transitional edges in 9.2, if possible.

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

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

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

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

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

9.4.1.6 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 in-plane length measurement (for example, on the top of the exposed underlying layer in Fig. 2 that is symmetrically located with respect to the in-plane length measurement). 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.

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

9.4.1.8 Obtain a 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 in-plane length measurement (for example, with respect to the top of the underlying layer in Fig. 2, with regions chosen to be symmetrically located with respect to the in-plane length measurement).

9.5 *Obtain the Endpoints and Associated Uncertainties:*

9.5.1 For each transitional edge, extract four representative 2-D data traces (such as Traces *a'*, *a*, *e*, and *e'* in Fig. 2 for both Edge 1 and Edge 2) from the leveled 3-D data set in 9.4.1.8. These traces pass through and are perpendicular to Edge 1, Edge 2, or both.

NOTE 9—If eight 2-D data traces are extracted (four for each transitional edge), the data traces associated with the first transitional edge selected in 9.2.1 are called *a'*, *a*, *e*, and *e'*. The data traces associated with the second transitional edge selected in 9.2.1 are called *aa'*, *aa*, *ee*, and *ee'*.

NOTE 10—In a bulk-micromachining process, the edges of the etched out cavity may be jagged, therefore, choose the trace or traces from which to obtain representative endpoints.

9.5.2 For transitional edges that face opposite directions (such as, Edge 1 and Edge 2 in Fig. 2 and Fig. 4), for the four data traces associated with Edge 1, obtain $x1_{uppert}$ and $n1_t$, using the procedures in 9.5.3 and 9.5.4, respectively, where the subscript *t* identifies the data trace (such as, *a'*, *a*, *e*, or *e'*).

NOTE 11—If the desired in-plane length measurement involves a measurement from the lower corner of a transitional edge, replace "upper" with "lower."

9.5.3 *To obtain x_{uppert}:*

9.5.3.1 Locate two points *p* and *q*, as shown in Fig. 4, on either side of the transitional edge (Edge 1 in this case) being examined.

9.5.3.2 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*) in Fig. 4.

9.5.3.3 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.

9.5.4 *To obtain n_t:*

9.5.4.1 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

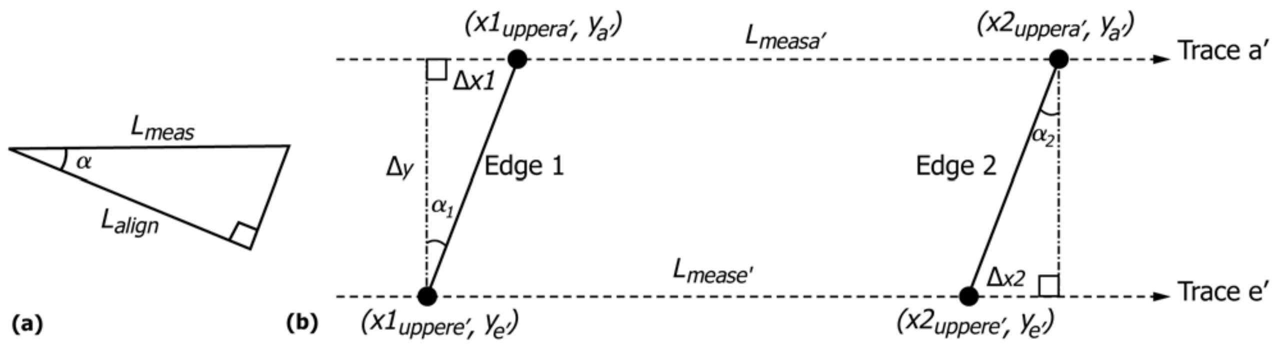


FIG. 7 Drawings Depicting a) the Misalignment Angle, α, and b) Misalignment Between Traces *a*′ and *e*′ and Edges 1 and 2 in Fig. 2 or Fig. 5

value is typically recorded for n_t. If it is easy to pick one point in 9.5.3.3 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 9.5.1, or obtain another 3-D data set repeating from 9.4.1. (This criteria may need to be modified for the given measurement.)

9.5.5 For transitional edges that face opposite directions (such as, Edge 1 and Edge 2 in Fig. 2 and Fig. 4), for the four data traces associated with Edge 2 (which may be the same data traces as used for Edge 1 in 9.5.2), obtain $x2_{uppert}$ and $n2_t$, using the procedures in 9.5.3 and 9.5.4, respectively.

9.5.6 For transitional edges that face the same direction and have similar slopes and magnitudes (such as, Edges 1 and 5 in Fig. 2 and Fig. 4), for each data trace, a measured *x*-value is obtained at the upper corner of each transitional edge (x_{uppert}) as specified in 9.5.3 or a measured *x*-value is obtained at the lower corner of each transitional edge (x_{lowert}) as also specified in 9.5.3 but replacing "upper" with "lower". The values for $n1_t$ and $n5_t$ are also obtained as specified in 9.5.4. The upper values are used unless $n1_t$+$n5_t$ for the lower values are typically smaller than those for the upper values.

9.5.7 For both transitional edges selected in 9.2 (for example, Edge 1 and Edge 2 in Fig. 2) record the *y* values of the two outermost data traces (for example, $y_{a'}$ and $y_{e'}$ for both Edge 1 and Edge 2, where $y_{a'} > y_{e'}$).

10. Calculation (1-3)

10.1 *L* is calculated from the data obtained in 9.5.[9]

10.2 For the selected transitional edges, such as Edges 1 and 2 in Fig. 2 and Fig. 4, calculate the measured in-plane length, L_{meas}, using one of the following two procedures:

NOTE 12—If lower values (as mentioned in 9.5.6) were obtained instead of upper values, the equations that follow should be modified accordingly.

10.2.1 If four 2-D data traces were extracted in 9.5.1 such that each trace can be used for both Edge 1 and Edge 2, calculate the measured in-plane length using the following equation:

$$L_{meas} = \frac{L_{measa'} + L_{measa} + L_{mease} + L_{mease'}}{4} \quad (4)$$

where

$$L_{meast} = (x2_{uppert} - x1_{uppert})cal_x \quad (5)$$

10.2.2 If eight 2-D data traces were extracted in 9.5.1 (four for Edge 1 and four for Edge 2), calculate L_{meas} using Eq 4 however:

$$L_{measa'} = (x2_{upperaa'} - x1_{uppera'})cal_x \quad (6)$$

$$L_{measa} = (x2_{upperaa} - x1_{uppera})cal_x \quad (7)$$

$$L_{mease} = (x2_{upperee} - x1_{uppere})cal_x \quad (8)$$

and

$$L_{mease'} = (x2_{upperee'} - x1_{uppere'})cal_x \quad (9)$$

10.3 To account for misalignment, calculate the aligned length, L_{align}, using the following equation:

$$L_{align} = L_{meas}\cos(\alpha) \quad (10)$$

where the misalignment angle, α, shown in Fig. 7(a), is determined in 10.3.1 or 10.3.2.

NOTE 13—The effect of the misalignment angle, α, is expected to be much smaller (almost negligible) for the shorter length measurements (≤ 200 µm at a magnification of 20×) than it is for the longer length measurements (≥ 500 µm at a magnification of 10×).

10.3.1 If four 2-D data traces were extracted in 9.5.1 such that each trace can be used for both Edge 1 and Edge 2, calculate the misalignment angle, α, shown in Fig. 7(a), which is typically determined using the two outermost data traces [*a*′ and *e*′ in this case, as seen in Fig. 2] and is calculated to be either α_1 or α_2 using either $\Delta x1$ or $\Delta x2$, respectively [as seen in Fig. 7(b)] where

$$\Delta x1 = x1_{uppera'} - x1_{uppere'} \quad (11)$$

and

$$\Delta x2 = x2_{uppera'} - x2_{uppere'} \quad (12)$$

Therefore, calculate α using the following equation:

[9] By inserting the inputs into the correct locations on the appropriate NIST MEMS Calculator Web Page, the calculations in this test method 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."

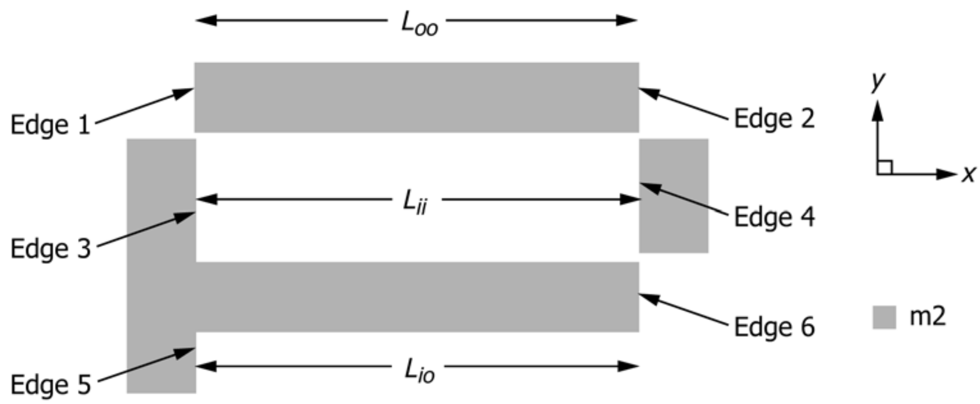


FIG. 8 CMOS Test Structure to Determine L_{offset}

$$\alpha = \tan^{-1}\left[\frac{\Delta xcal_x}{\Delta ycal_y}\right] \quad (13)$$

where

$$\Delta y = y_{a'} - y_{e'} \text{ with } y_{a'} > y_{e'} \quad (14)$$

in addition,

$$\text{if } n1_{a'} + n1_{e'} \leq n2_{a'} + n2_{e'}, \text{ then } \alpha = \alpha_1 \text{ and } \Delta x = \Delta x1 \quad (15)$$

$$\text{and if } n1_{a'} + n1_{e'} > n2_{a'} + n2_{e'}, \text{ then } \alpha = \alpha_2 \text{ and } \Delta x = \Delta x2 \quad (16)$$

10.3.2 If eight 2-D data traces were extracted in 9.5.1 (four for Edge 1 and four for Edge 2), calculate α using Eq 13 however:

$$\text{if } n1_{a'} + n1_{e'} \leq n2_{aa'} + n2_{ee'}, \quad (17)$$

$$\text{then } \Delta x = x1_{uppera'} - x1_{uppere'},$$

$$\text{and } \Delta y = y_{a'} - y_{e'}, \text{ where } y_{a'} > y_{e'}$$

$$\text{and if } n1_{a'} + n1_{e'} > n2_{aa'} + n2_{ee'}, \quad (18)$$

$$\text{then } \Delta x = x2_{upperaa'} - x2_{upperee'},$$

$$\text{and } \Delta y = y_{aa'} - y_{ee'}, \text{ where } y_{aa'} > y_{ee'}$$

10.4 Calculate the in-plane length, L, using the following equation:

$$L = L_{align} + L_{offset} \quad (19)$$

where L_{offset} is the in-plane length correction term (as calculated in 10.5) for the given type of in-plane length measurement on similar structures, when using similar calculations, and for a given magnification of a given interferometric microscope.

NOTE 14—For transitional edges that face the same direction and have similar slopes and magnitudes (such as, Edges 1 and 5 in Fig. 2 and Fig. 4), the in-plane length, L, is equated with L_{align} as given in Eq 10. This is due to the similarities of the edges involved.

10.5 Determine L_{offset} in one of the following two ways:

10.5.1 Obtain twelve 3-D data sets of a similar structure using the same magnification as used in 9.4. Calculate twelve values for L_{align} for this structure.

10.5.1.1 Calculate $L_{alignave}$ as the average of the twelve measurements of L_{align}.

10.5.1.2 Calculate L_{offset} as L_{des} minus $L_{alignave}$, where L_{des} is the design length.

10.5.2 Consider a test structure such as shown in Fig. 8 (where L_{des} is the same for L_{oo}, L_{ii}, and L_{io}). If the in-plane length between two m2 lines in the same CMOS process is being determined in 10.2, using the same magnification as used in 9.4, obtain four 3-D data sets of L_{ii} and L_{oo}. Calculate four values of L_{align} for L_{ii} and four values of L_{align} for L_{oo}.

NOTE 15—If the in-plane length between two m2 lines in a CMOS process is being determined, the transitional edges measured with the interferometer may be due to the contour of the oxide covering the m2 lines such that a measurement of L_{offset} is used as a correction term to provide a measurement between two m2 lines.

10.5.2.1 Calculate $L_{iialignave}$ as the average of the four values of L_{align} for L_{ii} and $L_{ooalignave}$ as the average of the four values of L_{align} for L_{oo}.

10.5.2.2 Calculate L_{offset} as $(L_{ooalignave} - L_{iialignave})/2$.

10.6 Calculate u_{cL}, the combined standard uncertainty **(6, 7)** for the in-plane length measurement, using the method presented in Annex A1.

11. Report

11.1 Report the results as follows **(6, 7)**: 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_{cL}, the length is believed to lie in the interval $L \pm u_{cL}$ (expansion factor k=1) representing a level of confidence of approximately 68 %.

12. Precision and Bias

12.1 In the spring of 1999, ASTM conducted a round robin experiment **(2)** that included the measurements of in-plane lengths and deflections. Both optical interferometers and optical microscopes were used to take these measurements on test chips fabricated in a surface-micromachining process. Twelve laboratories participated in the round robin with the laboratories using their own measurement methods. Significant variations were found when the laboratories measured the same devices. For example, for a designed 196-µm long fixed-fixed beam, the measured in-plane lengths among the laboratories ranged from 190 µm to 224.6 µm. This is a 34.6-µm range in the in-plane length measurement, which can be decreased by at least an order of magnitude.

TABLE 2 Repeatability Data[A] When the Transitional Edges Face Opposite Directions

Design Length (L_{des})	25 µm	80 µm	200 µm	500 µm	1000 µm
n	48	48	48	48	48
mag	80×	40×	20×	10×	5×
L_{ave}	24.37 µm	79.76 µm	199.10 µm	495.0 µm	995.5 µm
$\sigma_{repeat(samp)'}$	0.10 µm	0.086 µm	0.15 µm	0.80 µm	2.5 µm
$\pm 2\sigma_L$ limits	±0.20 µm (±0.81 %)	±0.17 µm (±0.22 %)	±0.30 µm (±0.15 %)	±1.6 µm (±0.32 %)	±5.0 µm (±0.50 %)
u_{Lave}[B]	0.23 µm (0.95 %)	1.0 µm (1.3 %)	0.95 µm (0.48 %)	1.7 µm (0.33 %)	3.2 µm (0.32 %)
u_{cLave}[C]	0.33 µm (1.3 %)	1.1 µm (1.4 %)	1.1 µm (0.54 %)	1.9 µm (0.39 %)	3.6 µm (0.36 %)
ΔL	–0.63 µm	–0.24 µm	–0.90 µm	–5.0 µm	–4.5 µm

[A] Taken on a test chip fabricated in a surface-micromachining process and analyzed using Data Sheet L.1.
[B] Where u_{Lave} is the sum of the u_L values divided by n.
[C] As determined using Test Method E 2244–05.

TABLE 3 Reproducibility Data[A] When the Transitional Edges Face Opposite Directions

Design Length (L_{des})	25 µm	80 µm	200 µm	500 µm	650 µm	1000 µm
n	7	7	6	6[B]	6	6[B]
mag	100×, 80×, 50×, 39×, 20×, 10×, w[C]	50×, 40×, 25×, 25×, 10×, 10×, w	25×, 20.4×, 20×, 10×, 10×, 10×	10.2×, 10×, 10×, 10×, 5×, 5×	25×, 7.8×, 5×, 5×, 5×, w	5×, 5×, 5×, 5×, 5×, 5×
L_{ave}	24.91 µm	79.70 µm	200.61 µm	497.8 µm	651.4 µm	999.8 µm
$\pm 2\sigma_L$ limits	±4.3 µm (±17 %)	±5.3 µm (±6.6 %)	±4.1 µm (±2.0 %)	±3.9 µm (±0.78 %)	±5.3 µm (±0.81 %)	±4.9 µm (±0.49 %)
u_{Lave}[D]	0.60 µm (2.4 %)	0.71 µm (0.89 %)	0.86 µm (0.43 %)	1.5 µm (0.30 %)	1.6 µm (0.25 %)	2.5 µm (0.25 %)
ΔL	–0.09 µm	–0.30 µm	0.61 µm	–2.2 µm	1.4 µm	–0.2 µm

[A] Taken on test chips fabricated in a surface-micromachining process and analyzed using Data Sheet L.1.
[B] Three of these measurements were taken from the same instrument by two different operators.
[C] The symbol "w" stands for "unknown." The magnification was not reported by the round robin participant.
[D] Where u_{Lave} is the sum of the u_L values divided by n.

12.2 *The Round Robin*—The MEMS Length and Strain Round Robin Experiment took place from August 2003 to January 2005 (**3, 8**). Eight independent laboratories participated in this round robin experiment using test chips fabricated in a surface-micromachining process. With the use of Test Method E2244–05, the variations in the community measurements were significantly tightened.

12.3 *Precision*—The repeatability and reproducibility data for in-plane length measurements are presented in Tables 2-5. The data in Tables 2 and 3 are for in-plane length measurements when the transitional edges face opposite directions. The data in Tables 4 and 5 are for in-plane length measurements when the transitional edges face the same direction. In these tables, n indicates the number of measurements, mag refers to the magnification, and L_{ave} is the average of the in-plane length repeatability or reproducibility measurement results. For the repeatability measurements only, $\sigma_{repeat(samp)'}$ (the standard deviation of the repeatability in-plane length measurements) is listed next. Then, in all four tables, the $\pm 2\sigma_L$ limits are listed, where σ_L is the standard deviation of the in-plane length measurements. Following this, the average of the repeatability or reproducibility standard uncertainty values (that is, u_{Lave} and/or u_{cLave}) are given. The last row in each table includes calculations of ΔL, where $\Delta L = L_{ave} - L_{des}$.

12.3.1 For the repeatability and reproducibility data in Tables 2 and 3, respectively (and also in Tables 4 and 5, respectively) the $\pm 2\sigma_L$ limits indicate that the reproducibility results (for example, ±2.0 % in Table 3 for L_{des}=200 µm) are much poorer than the corresponding repeatability results (that is, ±0.15 % in Table 2). This can be due to different magnifications used for the measurements (especially for smaller values of L_{des}), the calibrations of the instruments being slightly different, the use of different instruments, and a different person taking the measurements and analyzing the data.

TABLE 4 Repeatability Data[A] When the Transitional Edges Face the Same Direction

Design Length (L_{des})	60 µm	115 µm	235 µm	535 µm	1035 µm
n	48	48	48	48	48
mag	80×	40×	20×	10×	5×
L_{ave}	59.56 µm	115.96 µm	234.67 µm	532.2 µm	1035.0 µm
$\sigma_{repeat(samp)'}$	0.13 µm	0.19 µm	0.23 µm	0.25 µm	0.61 µm
$\pm 2\sigma_L$ limits	±0.27 µm (±0.45 %)	±0.39 µm (±0.33 %)	±0.47 µm (±0.20 %)	±0.50 µm (±0.094 %)	±1.2 µm (±0.12 %)
u_{Lave}[B]	0.067 µm (0.11 %)	0.14 µm (0.12 %)	0.26 µm (0.11 %)	0.54 µm (0.10 %)	1.1 µm (0.10 %)
u_{cLave}[C]	0.54 µm (0.91 %)	0.55 µm (0.47 %)	0.64 µm (0.27 %)	1.1 µm (0.21 %)	2.0 µm (0.20 %)
ΔL	–0.44 µm	0.96 µm	–0.33 µm	–2.8 µm	0.0 µm

[A] Taken on a test chip fabricated in a surface-micromachining process and analyzed using Data Sheet L.2.
[B] Where u_{Lave} is the sum of the u_L values divided by n.
[C] As determined using Test Method E 2244–05.

12.3.2 In comparing the repeatability data for transitional edges that face opposite directions (in Table 2) with the repeatability data for transitional edges that face the same direction (in Table 4), at a given magnification, the combined standard uncertainty values, u_{cLave}, stated as a percent and presented in the next to the last row of Table 4, are lower than those presented in the next to the last row of Table 2. This implies that it is preferable to obtain in-plane length measurements for transitional edges that face the same direction, if possible.

TABLE 5 Reproducibility Data[A] When the Transitional Edges Face the Same Direction

Design Length (L_{des})	60 µm	115 µm	235 µm	535 µm	1035 µm
n	6[B]	6	6[B]	6[C]	6[C]
mag	80×, 80×, 50×, 39×, 20×, 10×	40×, 25×, 25×, 25×, 10×, 10×	20.4×, 20×, 20×, 10×, 10×, 5×	10.2×, 10×, 10×, 10×, 5×, 5×	5.9×, 5×, 5×, 5×, 5×, 5×
L_{ave}	59.68 µm	115.34 µm	235.79 µm	533.8 µm	1035.1 µm
$\pm 2\sigma_L$ limits	±1.2 µm (±2.1 %)	±5.0 µm (±4.4 %)	±4.1 µm (±1.7 %)	±5.6 µm (±1.0 %)	±5.0 µm (±0.48 %)
u_{Lave}[D]	0.22 µm (0.37 %)	0.32 µm (0.27 %)	0.43 µm (0.18 %)	0.67 µm (0.13 %)	1.1 µm (0.10 %)
ΔL	–0.32 µm	0.34 µm	0.79 µm	–1.2 µm	0.1 µm

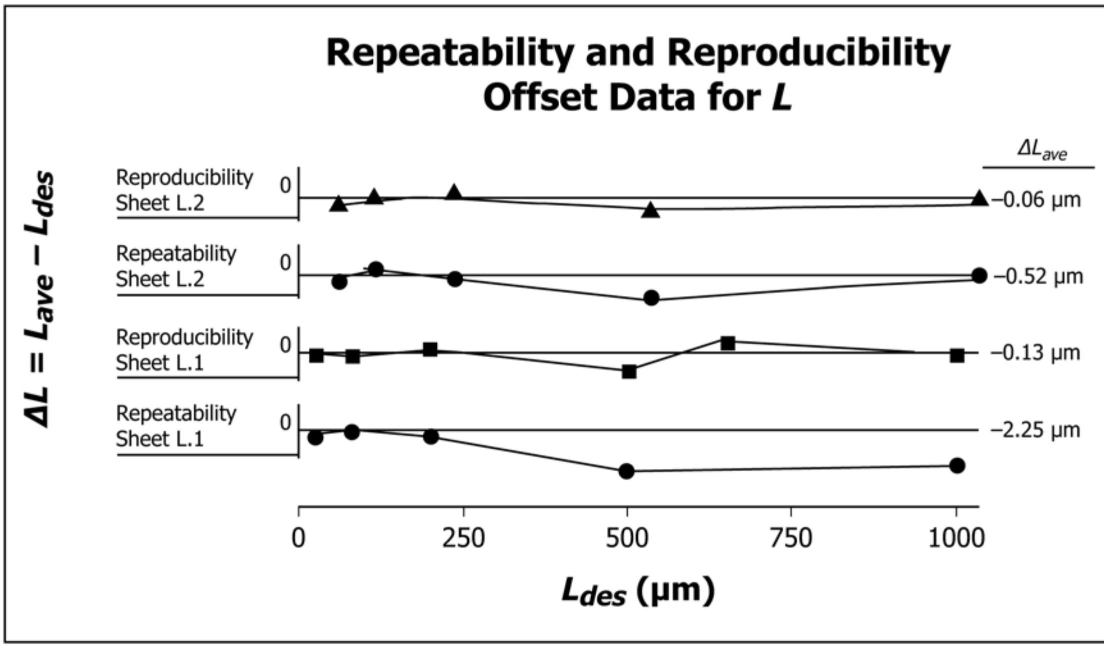
[A] Taken on test chips fabricated in a surface-micromachining process and analyzed using Data Sheet L.2.
[B] Two of these measurements were taken from the same instrument by different operators.
[C] Three of these measurements were taken from the same instrument by two different operators.
[D] Where u_{Lave} is the sum of the u_L values divided by *n*.

12.4 *Bias*—As specified in 8.1, the interferometric microscope is calibrated in the *x*- and *y*-directions using a 10-µm grid (or finer grid) ruler. If the calibration is not done at each magnification, a bias in the measurements is expected. The direction and degree of the resulting bias is different for each magnification of each interferometric microscope. Therefore, calibration of the interferometric microscope is considered mandatory for in-plane length measurements.

12.4.1 In Fig. 9, ΔL is plotted versus L_{des}, where $\Delta L = L_{ave} - L_{des}$. The data suggest no significant offsets associated with the length data except in the repeatability measurements that were done on transitional edges that face opposite directions. For these measurements, there is a tendency for measuring lower values of *L* for this laboratory for all magnifications and the degree of the resulting bias depends upon the magnification.

13. Keywords

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



NOTE 1—Sheet L.1 data is for measurements that are taken on transitional edges that face opposite directions.

NOTE 2—Sheet L.2 data is for measurements that are taken on transitional edges that face the same direction.

FIG. 9 ΔL Plotted versus L_{des}

ANNEX

(Mandatory Information)

A1. CALCULATION OF COMBINED STANDARD UNCERTAINTY

A1.1 Calculate u_{cL}, the combined standard uncertainty for the in-plane length measurement (**6, 7**), using the following equation:[9]

$$u_{cL} = \sqrt{u_L^2 + u_{repeat(L)}^2 + u_{xcal}^2 + u_{align}^2 + u_{offset}^2 + u_{repeat(samp)}^2} \quad (A1.1)$$

where u_L, $u_{repeat(L)}$, u_{xcal}, u_{align}, u_{offset}, and $u_{repeat(samp)}$ are described in A1.1.1 through A1.1.6, respectively.

A1.1.1 Calculate u_L, assuming the value for L lies between L_{minL} and L_{maxL} with 99.7 % nominal probability of coverage assuming a Gaussian distribution (and assuming $u_{repeat(L)}$, u_{xcal}, u_{align}, u_{offset}, and $u_{repeat(samp)}$ equal zero in Eq A1.1).

A1.1.1.1 If four 2-D data traces were extracted in 9.5.1 such that each trace can be used for both Edge 1 and Edge 2, calculate u_L using the following equation:

$$u_L = \frac{L_{maxL} - L_{minL}}{6} \quad (A1.2)$$

where

$$L_{minL} = L_{measmin}\cos(\alpha) + L_{offset} \quad (A1.3)$$

and

$$L_{measmin} = \frac{L_{measmina'} + L_{measmina} + L_{measmine} + L_{measmine'}}{4} \quad (A1.4)$$

and

$$L_{measmint} = L_{meast} - (n1_t + n2_t) x_{res} cal_x \quad (A1.5)$$

and similarly, where

$$L_{maxL} = L_{measmax}\cos(\alpha) + L_{offset} \quad (A1.6)$$

$$L_{measmax} = \frac{L_{measmaxa'} + L_{measmaxa} + L_{measmaxe} + L_{measmaxe'}}{4} \quad (A1.7)$$

$$L_{measmaxt} = L_{meast} + (n1_t + n2_t) x_{res} cal_x \quad (A1.8)$$

The uncertainty associated with the pixel resolution in the x-direction is assumed to be incorporated within this uncertainty component. This is a Type B component.

A1.1.1.2 If eight 2-D data traces were extracted in 9.5.1 (four for Edge 1 and four for Edge 2) calculate u_L as given in A1.1.1.1 using the following equations:

$$L_{measmina'} = L_{measa'} - (n1_{a'} + n2_{aa'}) x_{res} cal_x \quad (A1.9)$$

$$L_{measmina} = L_{measa} - (n1_a + n2_{aa}) x_{res} cal_x \quad (A1.10)$$

$$L_{measmine} = L_{mease} - (n1_e + n2_{ee}) x_{res} cal_x \quad (A1.11)$$

$$L_{measmine'} = L_{mease'} - (n1_{e'} + n2_{ee'}) x_{res} cal_x \quad (A1.12)$$

$$L_{measmaxa'} = L_{measa'} + (n1_{a'} + n2_{aa'}) x_{res} cal_x \quad (A1.13)$$

$$L_{measmaxa} = L_{measa} + (n1_a + n2_{aa}) x_{res} cal_x \quad (A1.14)$$

$$L_{measmaxe} = L_{mease} + (n1_e + n2_{ee}) x_{res} cal_x \quad (A1.15)$$

and

$$L_{measmaxe'} = L_{mease'} + (n1_{e'} + n2_{ee'})x_{res}cal_x \quad (A1.16)$$

A1.1.2 Calculate $u_{repeat(L)}$ using the following equation:

$$u_{repeat(L)} = \sigma_{repeat(L)}\cos(\alpha) \quad (A1.17)$$

or

$$u_{repeat(L)} = STDEV(L_{measa'}, L_{measa}, L_{mease}, L_{mease'})\cos(\alpha) \quad (A1.18)$$

This is considered a statistical Type A component.

A1.1.3 Calculate u_{xcal} using the following equation:

$$u_{xcal} = \left(\frac{\sigma_{xcal}}{ruler_x}\right)L_{meas}\cos(\alpha) \quad (A1.19)$$

for which it is assumed that u_{xcal} scales linearly with the aligned length [that is, $L_{meas}\cos(\alpha)$]. It is also assumed that the uncertainty of the calibration is due solely to the uncertainty of the calibration in the *x*-direction (in other words, the effect of σ_{ycal} on the misalignment angle, α, is considered negligible). Similarly, the effect of σ_{xcal} on the misalignment angle, α, is assumed to be negligible. This is a Type B component.

A1.1.4 Calculate u_{align}, assuming the value for L lies between $L_{minalign}$ and $L_{maxalign}$ assuming a uniform distribution (and assuming u_L, $u_{repeat(L)}$, u_{xcal}, u_{offset}, and $u_{repeat(samp)}$ equal zero in Eq A1.1), using the following equation:

$$u_{align} = \left|\frac{L_{maxalign} - L_{minalign}}{2\sqrt{3}}\right| \quad (A1.20)$$

where

$$L_{minalign} = L_{meas}\cos(\alpha_{min}) + L_{offset} \quad (A1.21)$$

and

$$\alpha_{min} = \tan^{-1}\left[\frac{\Delta x}{\Delta y}\frac{cal_x}{cal_y} - \frac{2x_{res}}{\Delta y}\frac{cal_x}{cal_y}\right] \quad (A1.22)$$

and similarly, where

$$L_{maxalign} = L_{meas}\cos(\alpha_{max}) + L_{offset} \quad (A1.23)$$

and

$$\alpha_{max} = \tan^{-1}\left[\frac{\Delta x}{\Delta y}\frac{cal_x}{cal_y} + \frac{2x_{res}}{\Delta y}\frac{cal_x}{cal_y}\right] \quad (A1.24)$$

where Δx and Δy are determined in 10.3. This is a Type B component.

A1.1.5 Calculate u_{offset} using the following equation:

$$u_{offset} = \frac{|L_{offset}|}{3} \quad (A1.25)$$

This value for u_{offset} is assumed to incorporate geometrical uncertainties along the applicable edges. This is a Type B component.

NOTE A1.1—When the transitional edges face the same direction and have similar slopes and magnitudes, $L_{offset} = u_{offset} = 0$.

A1.1.6 Calculate $u_{repeat(samp)}$ using the following equation:

$$u_{repeat(samp)} = \sigma_{repeat(samp)'} \quad (A1.26)$$

where $\sigma_{repeat(samp)'}$ is the repeatability standard deviation for in-plane length test structures taken on similarly processed test structures as the sample, using the same combination of lenses for the measurement, and using similar calculations. This is a Type A component.

NOTE A1.2—Table 2 and Table 4 (presented in Section 12) provide values for $\sigma_{repeat(samp)'}$ for a surface-micromachining process used to fabricate the round robin test chips (**3**).

A1.1.7 The expanded uncertainty for in-plane length, U_L, is calculated using the following equation:

$$U_L = ku_{cL} = 2u_{cL} \quad (A1.27)$$

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

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