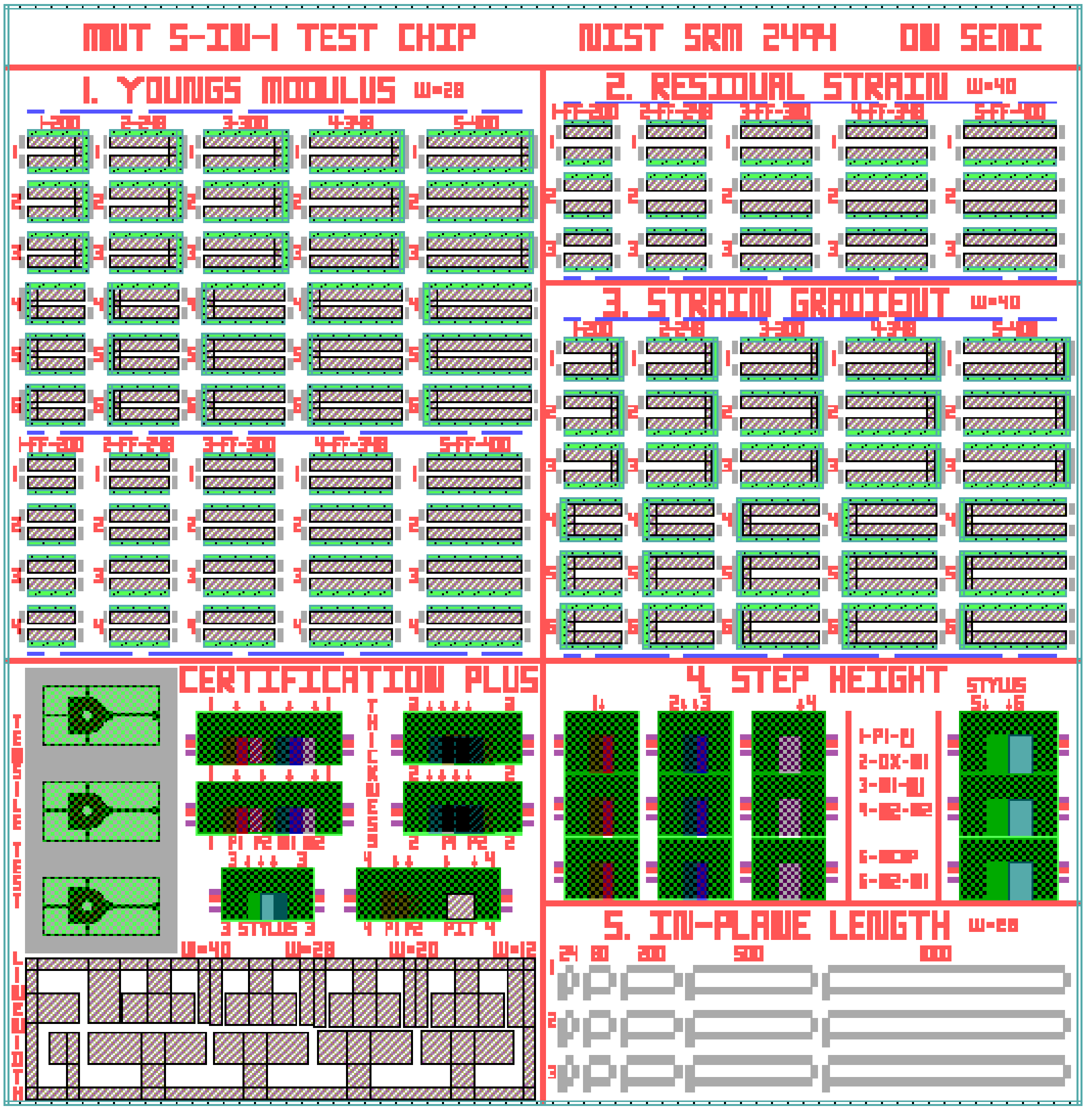
User's Guide for the
MNT 5-in-1 SRM
(*Revision 1*)



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USER'S GUIDE FOR THE MNT 5-IN-1 SRM

ABSTRACT

The Micro and Nano Technology (MNT) 5-in-1 standard reference material (SRM) contains microelectromechanical systems (MEMS) structures with five specific well-defined geometric and material properties: Young's modulus, step height, residual strain, strain gradient, and in-plane length. Test methods for measuring the first two of these properties have been standardized through the Semiconductor Equipment and Materials International (SEMI). Methods for measuring the remaining three properties have been standardized through the American Society for Testing and Materials (ASTM). The MNT 5-in-1 SRM will allow users of these standards to compare NIST measurements with their own, thereby validating their use of the documentary standards. The SRM utilizes the on-line data sheets on the National Institute of Standards and Technology (NIST) Semiconductor Electronics Division (SED) MEMS Calculator Web site (http://www.eeel.nist.gov/812/test-structures/MEMSCalculator.htm) to calculate the MEMS material properties.

Key words: ASTM, cantilevers, fixed-fixed beams, interferometry, length measurements, MEMS, residual strain, round robin, SEMI, step height measurements, strain gradient, test structures, vibrometry, Young's modulus measurements

USER'S GUIDE FOR THE MNT 5-IN-1 SRM

1. INTRODUCTION

The Micro and Nano Technology (MNT)[1] 5-in-1 standard reference material (SRM) contains test structures for the measurement of five geometric and material properties including: a) Young's modulus, b) step height, c) residual strain, d) strain gradient, and e) in-plane length. The measurements of the first two properties [1, 2] were standardized in the Semiconductor Equipment and Materials International (SEMI) and measurements of the last three properties [3-5] were standardized in the American Society for Testing and Materials (ASTM).

Two round robin experiments were held; the 2008–2009 SEMI MEMS Young's Modulus and Step Height Round Robin Experiment and the 2002 ASTM MEMS Length and Strain Round Robin Experiment. The purpose of these experiments was to obtain round robin precision and bias data for the five standard test methods and to educate the round robin participants concerning these test methods. The incorporation of the round robin data into the test methods had the effect of validating the standards. Therefore, the MNT 5-in-1 SRM is associated with five validated standard test methods.

A round robin user's guide was written for each round robin experiment. It is these user's guides combined together that form the bulk of this user's guide for the MNT 5-in-1 SRM; however, the purpose of this document is to facilitate measurements taken on the SRM to allow companies to compare their in-house measurements using the standard test methods with NIST measurements, thereby validating their use of the documentary standards.

The Young's modulus measurements are taken with an optical vibrometer,[2] stroboscopic interferometer, or comparable instrument. The other four measurements are taken with an optical interferometer or comparable instrument. For calculation of the MEMS material properties, these measurements are inputted on the pertinent on-line data sheet accessible via the National Institute of Standards and Technology (NIST) Semiconductor Electronics Division (SED) MEMS Calculator Web site (http://www.eeel.nist.gov/812/test-structures/MEMSCalculator.htm) [6].

Each MNT 5-in-1 SRM is accompanied by a certificate and five completed data analysis sheets using NIST measurements in the calculations. In-house measurements can then be compared with the NIST measurements supplied on these data analysis sheets to facilitate the validation of the use of the documentary standards.

The MNT 5-in-1 SRM is considered an SRM due to the measurement procedure using SEMI MS2 on step heights (which establishes traceability to an accurate realization of the micrometer) and due to the step height test structures (that were used in the round robin to assess the measurements in the standard test method). The certified step height value is accompanied by an uncertainty at a stated level of confidence. Contact the NIST

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[1] MEMS are also referred to as microsystems technology (MST) and micromachines.

[2] In this guide, commercial equipment or instruments may be identified. This does not imply recommendation or endorsement by the National Institute of Standards and Technology (NIST), nor does it imply that the equipment or instruments are the best available for the purpose.

SRM Program Office [7] to obtain an MNT 5-in-1 SRM, its certificate, and accompanying data analysis sheets.

Section 2 of this user's guide provides details associated with the MNT 5-in-1 SRM [e.g., details associated with the instruments, the MNT 5-in-1 SRM chip, the packaging of the MNT 5-in-1 SRM, the material available for the MNT 5-in-1 SRM, and the data analysis]. Sections 3 through 7 provide details concerning the measurements taken on the MNT 5-in-1 SRM chip. The summary is given in Section 8. Reproductions of the MEMS Calculator Web-based data analysis sheets [6] used for recording the MNT 5-in-1 SRM data and making calculations are given in the Appendices.

2. THE MNT 5-IN-1 SRM

This section provides details concerning the MNT 5-in-1 SRM. It is divided into five parts. Section 2.1 provides equipment specifications for the vibrometer, stroboscopic (or optical) interferometer, and comparable instruments, Section 2.2 describes the MNT 5-in-1 SRM chip, Section 2.3 describes the packaging of the MNT 5-in-1 SRM chip, Section 2.4 describes the material available for the MNT 5-in-1 SRM, and Section 2.5 discusses the data analysis.

2.1 *Equipment Specifications*

For the MNT 5-in-1 SRM, an optical vibrometer, stroboscopic interferometer, or comparable instrument is required for the Young's modulus measurements, as specified in subsection 2.1.1. For the residual strain, strain gradient, and in-plane length measurements, an optical interferometer is required, as specified in subsection 2.1.2. Step height measurements can be taken with an optical interferometer or comparable instrument.

2.1.1 *Vibrometer, Stroboscopic Interferometer, or Comparable Instrument Specifications*

For Young's modulus measurements, a non-contact optical vibrometer, non-contact optical stroboscopic interferometer, or an instrument comparable to one of these is required that is capable of non-contact measurements of surface motion. This subsection briefly describes the operation and specifications for a typical single beam laser vibrometer, a dual beam laser vibrometer, and a stroboscopic interferometer. The specifications can be applied to comparable instruments.

For a single beam laser vibrometer, a typical schematic is given in figure 1. A signal generator provides an excitation signal, which excites the sample via a piezoelectric transducer (PZT). The measurement beam is positioned to a scan point on the sample (by means of mirrors) and is reflected back. The reflected laser light interferes with the reference beam at the beam splitter. A photodetector records the interference signal, converting it into an electrical signal. The frequency difference between the beams is proportional to the instantaneous velocity of the vibration parallel to the measurement beam. (The Bragg cell is instrumental in determining the sign of the velocity.) The velocity decoder provides a voltage proportional to the instantaneous velocity.

A dual beam laser vibrometer incorporates two beams. The measurement beam is positioned to a scan point on the sample (for example, positioned near the tip of a cantilever). The reference beam emanates from the beam splitter (BS) shown in Figure 1 and is positioned to a point on the sample (for example, positioned on the support region at the base of the cantilever). The two scattered beams optically combine at the beam splitter where the reference beam is used to directly eliminate any movement of the sample also experienced by the measurement beam.

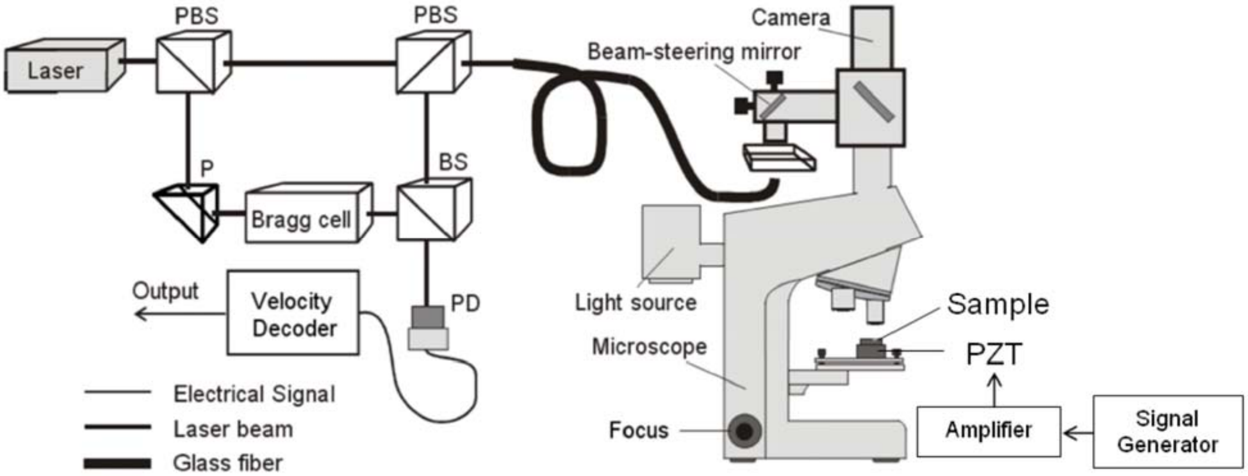

Figure 1. Schematic of a typical setup for a single beam laser vibrometer. (PBS indicates a polarizing beam splitter; BS indicates a beam splitter; P indicates a prism; and PD indicates a photodetector.)

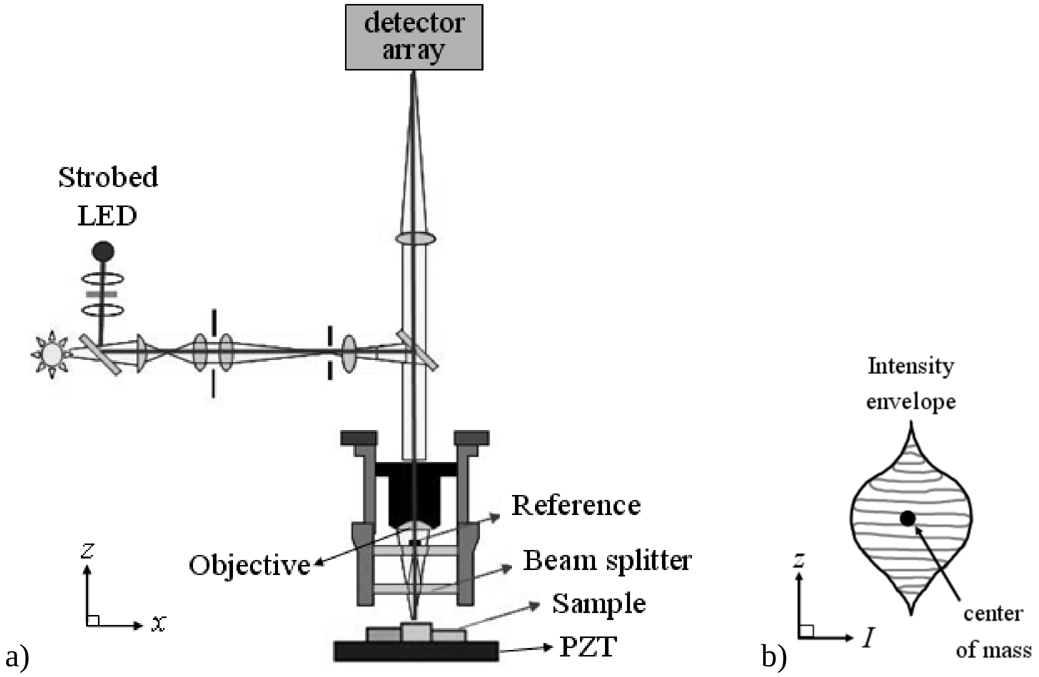

Figure 2. For a typical stroboscopic interferometer a) a schematic and b) an intensity envelope used to obtain a pixel's sample height

For a stroboscopic interferometer, a simplified schematic of a typical setup is shown in figure 2. When operated in the static mode, the interferometer is used to determine surface profiles. The incident light travels through the microscope objective to the beam splitter. Half of the light travels to the sample surface and then back to the beam splitter. The other half is reflected to a reference surface and then back to the beam splitter. These two paths of light recombine at the beam splitter to form interference light fringes. As the interferometer scans downward, an intensity envelope incorporating these fringes is determined by the software (see figure 2b). The peak contrast of the fringes, phase, or both are used in determining the sample height at that pixel location. The surface profile is found by collecting sample height data for each pixel within the FOV. When operated in the dynamic mode, the incident light is strobed at the same frequency as that used to actuate the device. The sample is actuated after securing it to the top of a PZT. The phase, frequency, and drive signal to the strobe and PZT are varied, performing a downward scan as is done for static devices at each combination to obtain successive 3D images as the sample cycles through its range of motion.

Specifications for the above instruments or a comparable instrument are as follows:

1. The microscope objective or objectives should be chosen to allow for sufficient resolution of the cantilever or fixed-fixed beam and a portion of the surrounding sample. The objective(s) should have a FOV that can encompass at least half of the length of the cantilever or fixed-fixed beam being measured. Typically, a 4× and a 20× objective will suffice.
2. The signal generator should be able to produce a waveform function (such as a periodic chirp function[3] or a sine wave function[4]) if applicable, such that from its use, a reproducible resonance frequency can be obtained and good 3-D oscillating images can be obtained such that it is obvious by inspection that the beam is in resonance.
3. The instrument shall be capable of producing a magnitude versus frequency plot from which the resonance frequency can be obtained.
4. The instrument should be capable of obtaining 3-D images of oscillations in order to ascertain if the correct frequency peak has been chosen as the beam's resonance frequency.
5. An estimate for the maximum frequency of the instrument needed for a resonating cantilever, $f_{caninit}$, is at least the value calculated using the following equation:[5]

$$f_{caninit} = \sqrt{\frac{E_{init} t^2}{38.330 \rho L_{can}^4}} \qquad (1)$$

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[3] The periodic chirp function enables quick results without averaging. For the periodic chirp function, sinusoidal signals (within the selected frequency range and of the same amplitude) are emitted simultaneously for all fast Fourier transform (FFT) lines. The periodic chirp function is periodic within the time window and the phases are adapted to maximize the energy of the resulting signal.

[4] The periodic chirp function produces a reproducible resonance frequency. A sine wave sweep function produces a resonance frequency that can be affected by the direction of the sweep if there is not a sufficient amount of time between measurements.

[5] By inserting the inputs into the correct locations on the appropriate NIST Web page [6], the given calculation can be performed on-line in a matter of seconds.

where E_{init} is an initial estimate for the Young's modulus value of the thin film layer, t is the thickness, ρ is the density, and L_{can} is the suspended cantilever length. An estimate for the maximum frequency of the instrument needed for a resonating fixed-fixed beam, $f_{ffbinithi}$, is at least the value calculated using the following equation:[6]

$$f_{ffbinithi} = \sqrt{\frac{E_{init} t^2}{0.946 \rho L_{ffb}^4}} \tag{2}$$

where L_{ffb} is the suspended fixed-fixed beam length.

6. An instrument that can make differential measurements (e.g., with the use of two laser beams) is recommended for use with fixed-fixed beams. It is also recommended for use with cantilevers, especially for estimated resonance frequencies less than 10 kHz and also if the value for p_{diff} as calculated in the following equation is greater than or equal to 2 %:[7]

$$p_{diff} = \left(1 - \sqrt{1 - \frac{1}{4Q^2}}\right) 100\% \,. \tag{3}$$

For a cantilever, the Q-factor, Q, in the above equation can be estimated using the following equation:[8]

$$Q = \left[\frac{W_{can}\sqrt{E_{init}\rho}}{24\mu}\right]\left(\frac{t}{L_{can}}\right)^2 \tag{4}$$

where μ is the viscosity (in air, μ =1.84e–5 Ns/m^2 at 20°C) and W_{can} is the suspended cantilever width.

2.1.2 *Interferometer or Comparable Instrument Specifications*

For residual strain, strain gradient, and in-plane length measurements, an optical interferometer is used which is capable of obtaining topographical 2-D data traces. (The stroboscopic interferometer operated in the static mode, as described in subsection 2.1.1, can be used for these measurements.) For step height measurements, an optical interferometer or comparable instrument is used.

Figure 3 is a schematic of a typical optical interferometer. However, any optical interferometer or comparable instrument that has pixel-to-pixel spacings as specified in Table 1,[9] if applicable, and that is capable of performing the test procedure with a vertical

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[6] Ibid.

[7] Ibid.

[8] Ibid.

[9] Table 1 does not include magnifications at or less than 2.5× for optical interferometry because the pixel-to-pixel spacings will be too large for this work or the possible introduction of a second set of

resolution less than 1 nm is permitted. The optical interferometer or comparable instrument must be capable of measuring step heights to at least 5 μm higher than the step heights to be measured and must be capable of extracting standard deviations.

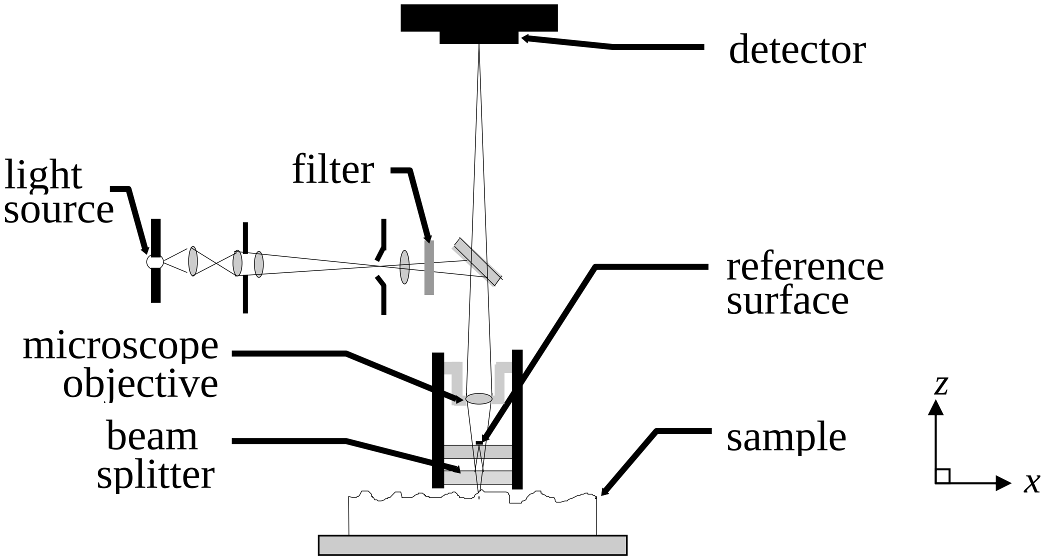

Figure 3. Schematic of an optical interferometer.

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

2.2 *MNT 5-in-1 SRM Chip*

The MNT 5-in-1 SRM Chips were fabricated on the 1.5 μm On Semiconductor process available through MOSIS [8]. The design for this chip is depicted in figure 4. As can be seen in this figure, the fabrication process designation is specified in the upper right hand corner. Participants can obtain the design file (in GDS-II format) for this MNT 5-in-1 SRM from the NIST SED MEMS Calculator Web site [6].

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interferometric fringes in the data set at these magnifications can adversely affect the data. Therefore, magnifications at or less than 2.5× shall not be used with optical interferometry.

For the MNT 5-in-1 SRM chip design shown in figure 4, one mechanical layer is used as the suspended portion of the applicable test structures. This layer consists of all oxide; namely, the field oxide, the deposited oxide before and after the metal1 deposition, and the glass layer. [The nitride cap (present atop the glass layer when the chips are received from MOSIS) was removed after fabrication using a CF_4+O_2 etch before a post-processing XeF_2 etch that released the beams.]

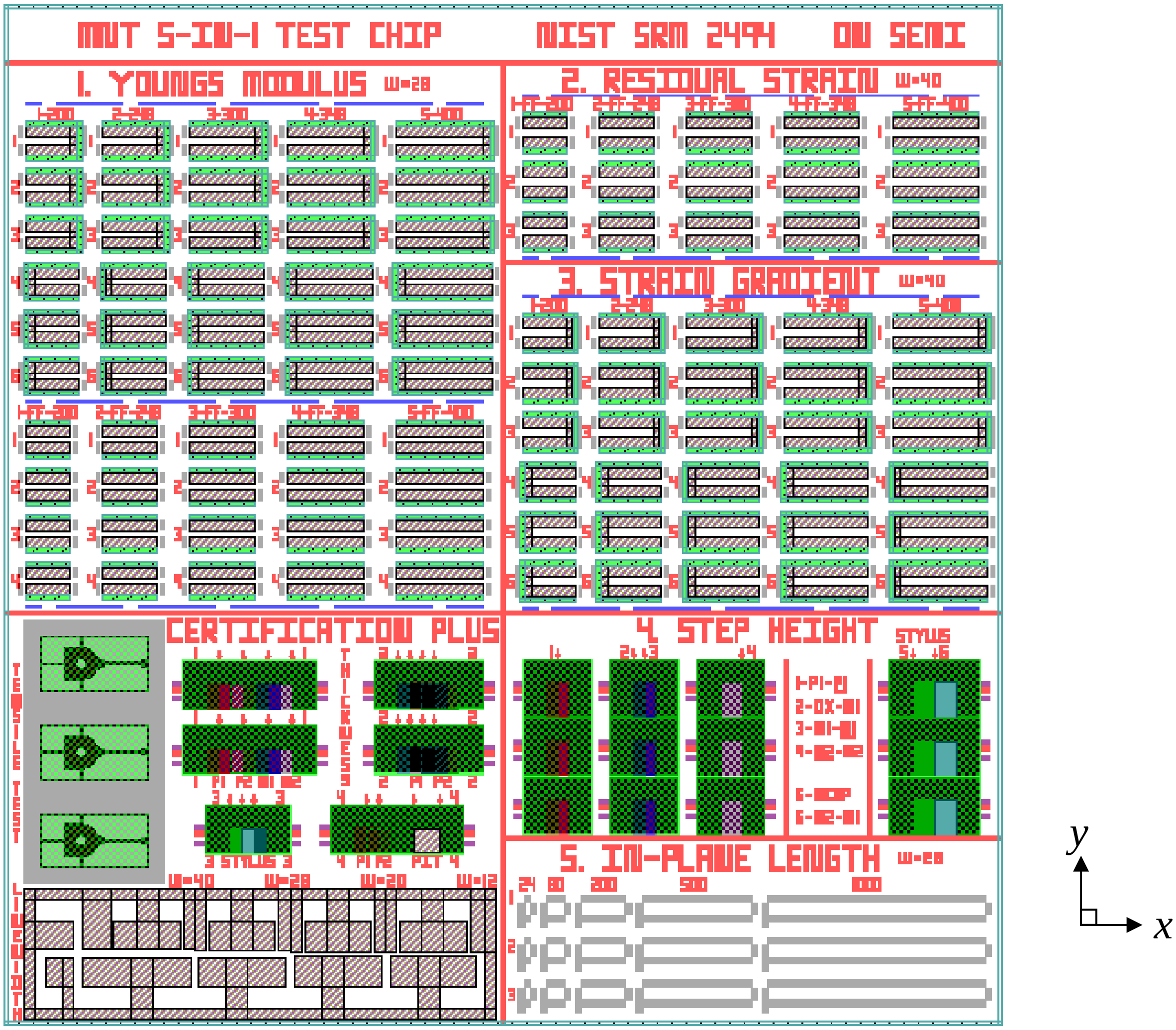

Figure 4. The MNT 5-in-1 SRM fabricated on the 1.5 μm On Semiconductor process through MOSIS.

As seen in figure 4, the test chip contains 6 groupings of test structures with the following labels:

1. Young’s Modulus,
2. Residual Strain,

3. Strain Gradient,
4. Step Height,
5. In-Plane Length, and
6. Certification Plus.

For the MNT 5-in-1 SRM, <u>we will only be concerned with the first through fifth groupings of test structures</u>. Grouping "1" contains the test structures (namely, cantilevers and fixed-fixed beams) for Young's modulus measurements. Grouping "2" contains fixed-fixed beams for residual strain measurements. Grouping "3" contains cantilevers for strain gradient measurements. Grouping "4" contains step height test structures for step height measurements. And, grouping "5" contains features for in-plane length measurements.

The Certification Plus section contains additional test structures (for example, tensile test structures, thickness test structures, and a linewidth test structure) that can be used to obtain additional geometrical and material properties (for example, the Young's modulus of the metal2 layer, the thicknesses of all the layers in the process, and the linewidth of select oxide beam widths, respectively) that may or may not complement the existing set of geometrical and material properties.

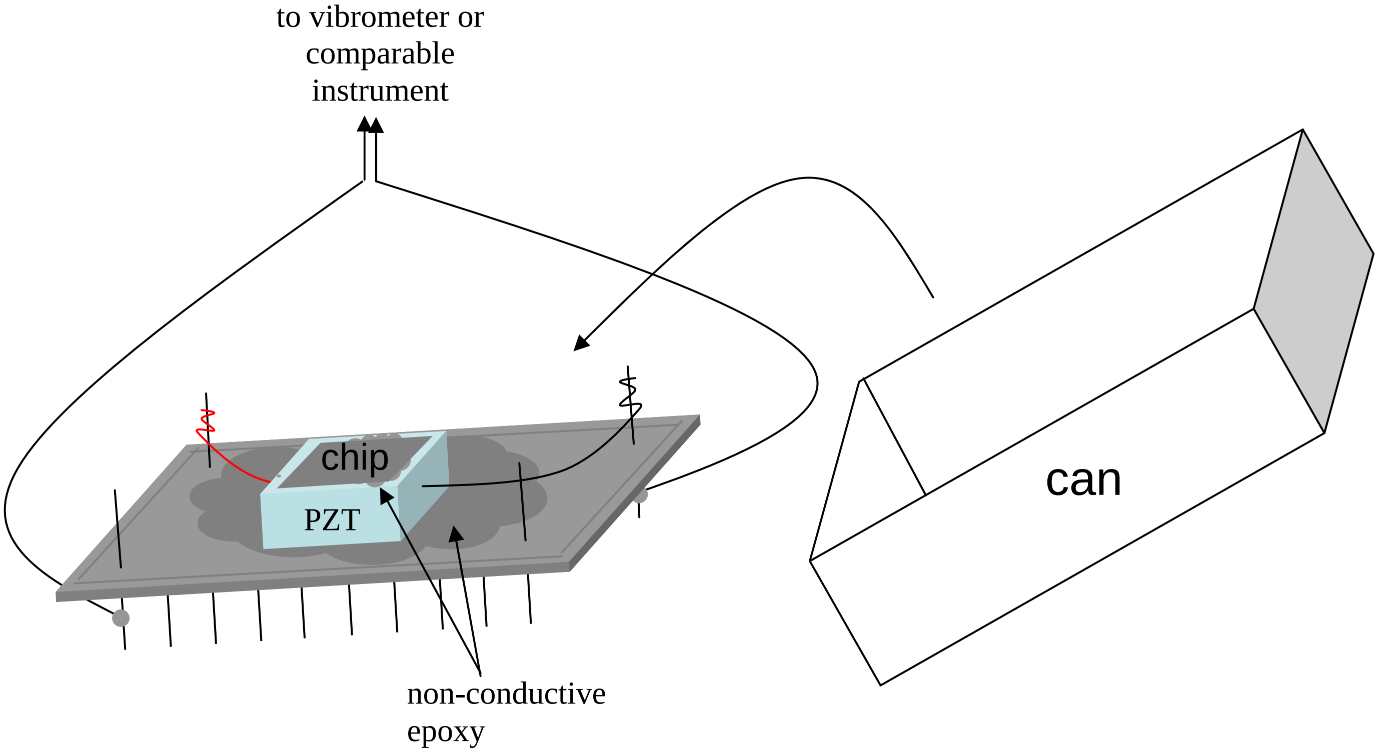

Figure 5. The packaged MNT 5-in-1 SRM

2.3 *Packaging of the MNT 5-in-1 SRM*

Each customer is given a packaged MNT 5-in-1 SRM, such as shown in figure 5. The SRM was packaged in the following way:

1. Starting with a hybrid package with a pin arrangement similar to that shown in figure 5, the PZT was secured to the top of the chip cavity using two thin layers of low stress, non-conducting epoxy. (The first layer of epoxy ensures that there will not be a conducting path between the package and the PZT.)
2. The PZT has the following properties:
   a. The dimensions of the PZT are approximately 5 mm by 5 mm and 2 mm in height.
   b. It is provided with a red and a black wire lead.
   c. It can achieve a 2.2 μm (±20 %) displacement at 100 V.
   d. It has an electrical capacitance of 250 nF (±20 %).
   e. It has a resonance frequency greater than 300 kHz, at which or above which it shall not be operated.
3. The two PZT wires were secured to their respective package connections.
4. The SRM chip was secured to the top of the PZT using two thin layers of a low stress non-conducting epoxy. (The first layer of epoxy ensures that there will not be a conducting path between the PZT and the SRM.)
5. The lid (or can) was placed on top of the package to protect the chip and the can was secured to the package with tape before shipment.

To take measurements on the MNT 5-in-1 SRM for comparison with the NIST measurements, the can is carefully removed. The residual strain, strain gradient, in-plane length, and step height measurements can now be taken. For Young's modulus measurements, to operate the PZT, the red wire should be driven with a voltage that is positive relative to the black wire. To ensure that you have successfully connected to the PZT, when activated at 10V and 7000 Hz, the PZT should be barely audible.

2.4 *Material Available for the MNT 5-in-1 SRM*

One of the best places from which to obtain information associated with the MNT 5-in-1 SRM is the MEMS Calculator Web site [6]. The symbol 5n1 is used on this web site to help you quickly find material associated with the MNT 5-in-1 SRM. From this web site you can obtain the following:

1. This user's guide,
2. The pertinent data analysis sheets (e.g., YM.1, RS.1, SG.1, SH.1, and L.1),
3. Ordering information for an MNT 5-in-1 SRM,
4. The design file and an accompanying tiff file of the MNT 5-in-1 SRM chip,
5. The list of the following two SEMI standard test methods [1,2] and three ASTM standard test methods [3-5] along with links for ordering information:
   - SEMI MS4, Test Method for Young's Modulus Measurements of Thin, Reflecting Films Based on the Frequency of Beams in Resonance,
   - ASTM E 2245, Test Method for Residual Strain Measurements of Thin, Reflecting Films Using an Optical Interferometer,
   - ASTM E 2246, Test Method for Strain Gradient Measurements of Thin, Reflecting Films Using an Optical Interferometer,

- SEMI MS2, Test Method for Step Height Measurements of Thin Films, and
- ASTM E 2244, Test Method for In-Plane Length Measurements of Thin, Reflecting Films Using an Optical Interferometer, and

6. Pertinent references for downloading.

Use the appropriate test method to guide you through the measurements. If you have difficulties understanding the technical underpinnings behind the steps in the standard test methods or if you would like to see how the standard can be used for possible future applications, you can consult the pertinent references [9-16] most of which can be downloaded from the web site.

When you order an MNT 5-in-1 SRM, you will receive the packaged chip along with a certificate and five completed data analysis sheets; one for each parameter. The data for these sheets were obtained at NIST. Therefore, to validate your use of the documentary standards, your in-house measurements can be compared with the measurements obtained at NIST.

2.5 *Data Analysis*

Sections 3 through 7, inclusive, of this guide provide the user with details concerning the measurements taken in the first through fifth groupings (for Young's modulus, residual strain, strain gradient, step height, and in-plane length measurements, respectively) of test structures on the MNT 5-in-1 SRM.

Table 2 can be used to navigate through this user's guide. It lists the grouping, the parameter associated with that grouping, the applicable section in this user's guide, the data sheet to use for that parameter, and the applicable appendix in this user's guide.

As an example, details concerning the Young's modulus measurements in the first grouping of test structures are discussed in Section 3 of this user's guide and are recorded in Data Analysis Sheet YM.1 [6] (a reproduction of which is given in Appendix A). The calculations are performed on-line by pressing the "Calculate and Verify" button located near the middle of the data analysis sheet. Any warnings flagged at the bottom of the data analysis sheet should be addressed before comparing your in-house measurements with the NIST measurements on the data analysis sheet supplied with the MNT 5-in-1 SRM. Any questions concerning these measurements can be directed to mems-support@nist.gov.

Table 2 – Grouping, Parameter, Section, Associated Data Sheet, and Appendix

Grouping on the MNT 5-in-1 SRM	Parameter	Section	Data Sheet	Appendix
1	Young's modulus	3	YM.1	A
2	Residual strain	4	RS.1	B
3	Strain gradient	5	SG.1	C
4	Step height	6	SH.1	D
5	In-plane length	7	L.1	E

3. GROUPING 1: YOUNG'S MODULUS MEASUREMENTS

In the first grouping of test structures on the MNT 5-in-1 SRM chip shown in figure 4, Young's modulus measurements are made. Cantilever and fixed-fixed beam test structures are provided for this purpose with 30 cantilevers grouped above 20 fixed-fixed beams on this chip; however, we will only be concerned with the cantilevers, such as shown in figure 6. Configurations for the cantilevers on the chip shown in figure 4 are given in Table 3.

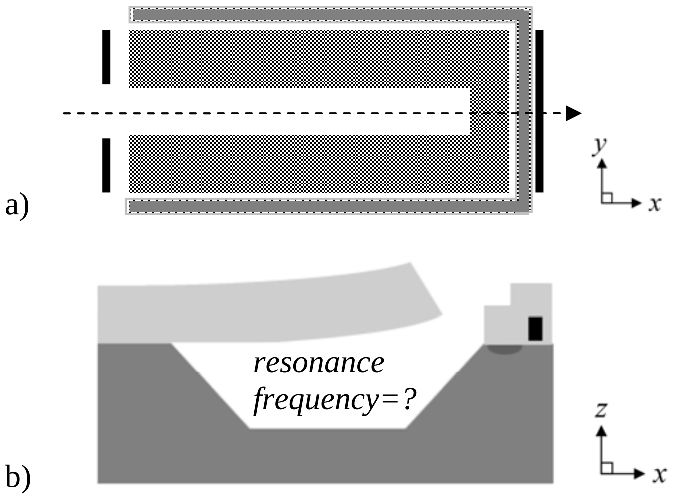

Figure 6. For a cantilever test structure on the test chip shown in figure 4
a) a design rendition and b) a cross section.

Table 3 – Cantilever Configurations for Young's Modulus Measurements

Test Structure	Width (in μm)	Length (in μm)	Mechanical Layer	Orientation	Quantity of Beams
Cantilevers	28	200, 248, 300, 348, 400	oxide	0°	3 of each length (or 15 beams)
				180°	3 of each length (or 15 beams)

As shown in Table 3, the cantilever design lengths are 200 μm, 248 μm, 300 μm, 348 μm, and 400 μm. The length of the cantilever (in micrometers) is given at the top of each column of cantilevers in figure 4 following the column number (i.e., 1 to 5). The cantilevers are designed at both a 0° and a 180° orientation[10] with the cantilevers having a 0° orientation being the first, second, and third cantilevers in each column and the cantilevers with a 180° orientation being the fourth, fifth, and sixth cantilevers in each

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[10] A 0° orientation implies that the length of the beam is parallel to the *x*-axis of the test chip, the axes of which are shown in figure 4 and again in figure 6, with the connection point of the cantilever having a smaller *x*-value than the x-values associated with the suspended portion of the cantilever.

column. Since there are 3 cantilevers designed at each length for each orientation, there are 15 oxide cantilevers with a 0° orientation and 15 oxide cantilevers with a 180° orientation.

To compare your in-house Young's modulus measurements with NIST measurements, you will need to fill out Data Analysis Sheet YM.1 once. (This data analysis sheet is accessible via the URL specified in the reference [6], a reproduction of which is given in Appendix A.) Your completed form can be compared with the completed data analysis sheet supplied with the MNT 5-in-1 SRM.

Data Analysis Sheet YM.1 requires measurements from one cantilever on the MNT 5-in-1 SRM Chip. The specific cantilever to be measured can be deduced from the data entered on the NIST-supplied Data Analysis Sheet YM.1 that accompanied the SRM chip. In particular, L_{can} (input #16 on Data Analysis Sheet YM.1) specifies the length of the cantilever (i.e., which column of cantilevers to examine in the first grouping of test structures on the SRM chip in figure 4) and *whichcan* (input #17) specifies which cantilever in the column to measure. [NOTE: For the SRM chip design in figure 4, *whichcan* entries of "first", "second", and "third" correspond to a 0° cantilever orientation, and *whichcan* entries of "fourth", "fifth", and "other" correspond to a 180° cantilever orientation. Therefore, the data (i.e., 0°, 90°, 180°, 270°, or other) supplied for *orient* (input #15) can be used as a form of verification.]

To determine an estimate for the resonance frequency of the cantilever (that may be a bit on the high side especially for shorter length cantilevers) do the following:

1. Access Data Analysis Sheet YM.1,
2. Supply inputs for:
   a. ρ (input #3),
   b. t (input #10),
   c. E_{init} (input #13), and
   d. L_{can} (input #16),
3. Press the "Calculate Estimates" button that appears before the Preliminary Estimates Table (Table 5) on the data analysis sheet, and
4. The value for $f_{caninit}$ (output #32) is the estimate for the resonance frequency.

For Young's modulus measurements taken with an optical vibrometer, stroboscopic interferometer, or comparable instrument, if the *x*-axis of the instrument provides a longer measurement range than the *y*-axis, align the length of the cantilever along the *x*-axis of the instrument.

For Data Analysis Sheet YM.1, the frequency resolution and three resonance frequency measurements are requested for the cantilever. Obtain these measurements using the highest magnification objective that is available and feasible (e.g., a 20× objective) following the steps in SEMI standard MS4 for measuring Young's modulus.

Press the "Reset this form" button located near the middle of the data analysis sheet, then record the raw, uncalibrated measurements. Press the "Calculate and Verify" button (also located near the middle of the data analysis sheet) to obtain the results for the cantilever being measured. Verify the data by checking to see that all the boxes in the verification section at the bottom of the data analysis sheet say "ok." If one or more of the boxes say "wait," address the issue, if necessary, by modifying the inputs and recalculating. After the data is successfully verified, print out the completed data analysis sheet to compare both the inputs and outputs with those on the NIST-supplied data analysis sheet. Any questions concerning the measurements and analysis can be directed to mems-support@nist.gov.

4. GROUPING 2: RESIDUAL STRAIN MEASUREMENTS

In the second grouping of test structures on the MNT 5-in-1 SRM chip shown in figure 4, residual strain measurements are made. All oxide fixed-fixed beams, as shown in figure 7, are provided for this purpose with a 0° orientation. The fixed-fixed beam design lengths are 200 μm, 248 μm, 300 μm, 348 μm, and 400 μm as given in Table 4. The length of the fixed-fixed beam (in micrometers) is given at the top of each column of fixed-fixed beams in figure 4 following the column number (i.e., 1 to 5) and the letters “FF” to indicate a fixed-fixed beam. There are 3 fixed-fixed beams designed at each length. Therefore, there are 15 fixed-fixed beams comprised of oxide.

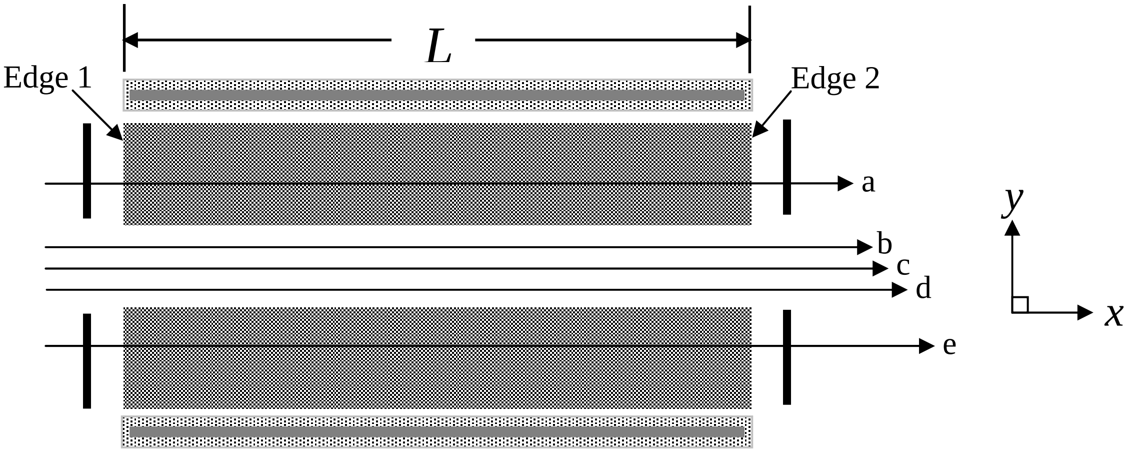

Figure 7. Top view of a fixed-fixed beam test structure.

Table 4 – Fixed-Fixed Beam Configurations for Residual Strain Measurements

Test Structure	Width (in μm)	Length (in μm)	Mechanical Layer	Orientation	Quantity of Beams
Fixed-Fixed Beams	40	200, 248, 300, 348, 400	oxide	0°	3 of each length (or 15 beams)

To compare your in-house residual strain measurements with NIST measurements, you will need to fill out Data Analysis Sheet RS.1 once. (This data analysis sheet is accessible via the URL specified in the reference [6], a reproduction of which is given in Appendix B.) Your completed form can be compared with the completed data analysis sheet supplied with the MNT 5-in-1 SRM.

Data Analysis Sheet RS.1 requires measurements from one fixed-fixed beam on the MNT 5-in-1 SRM chip. The specific fixed-fixed beam to be measured can be deduced from the data entered on the NIST-supplied Data Analysis Sheet RS.1 that accompanied the SRM chip. In particular, *design length* (input #3 on Data Analysis Sheet RS.1) specifies the design length of the fixed-fixed beam (i.e., which column of fixed-fixed beams to examine in the second grouping of test structures on the SRM chip in figure 4) and *which beam* (input #4) specifies which fixed-fixed beam in the column to measure.

Orient the fixed-fixed beam under the interferometric optics as shown in figure 7.[11] Obtain a 3-D data set using the highest magnification possible for the measurements. (For the given design lengths, the magnification should be at least 10×.) For Data Analysis Sheet RS.1, measurements are requested from Edges "1" and "2," as shown in figure 7, using Trace "a" or Trace "e." Data points along the fixed-fixed beam, as shown in figure 8, are requested from Traces "b," "c," and "d."

Following ASTM test method E2245 for measuring residual strain, record the raw, uncalibrated measurements on Data Analysis Sheet RS.1. Press the "Calculate and Verify" button (located near the center of the data analysis sheet) to obtain the results for the fixed-fixed beam being measured. Verify the data by checking to see that all the boxes in the verification section at the bottom of the data analysis sheet say "ok." If one or more of the boxes say "wait," address the issue, if necessary, by modifying the inputs and recalculating. After the data is successfully verified, print out the completed data analysis sheet to compare both the inputs and outputs with those on the NIST-supplied data analysis sheet. Any questions concerning the measurements and analysis can be directed to mems-support@nist.gov.

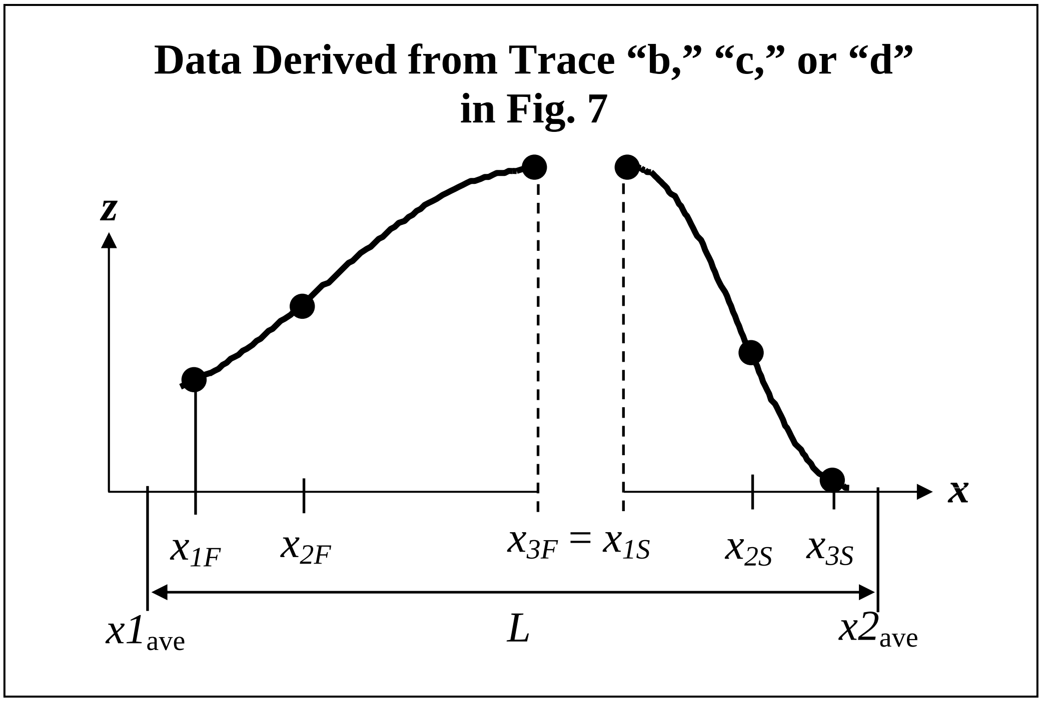

Figure 8. Two data sets derived from an abbreviated data trace along a fixed-fixed beam. The data in the figure above has been exaggerated.

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[11] This orientation assumes that the interferometer's pixel-to-pixel spacing in the *x*-direction is smaller than the pixel-to-pixel spacing in the *y*-direction.

5. GROUPING 3: STRAIN GRADIENT MEASUREMENTS

In the third grouping of test structures on the MNT 5-in-1 SRM chip shown in figure 4, strain gradient measurements are made. All oxide cantilevers, as shown in figure 9, are provided for this purpose with both a 0° and a 180° orientation. The cantilever design lengths are 200 μm, 248 μm, 300 μm, 348 μm, and 400 μm, as given in Table 5. The length of the cantilever (in micrometers) is given at the top of each column of cantilevers in figure 4 following the column number (i.e., 1 to 5). There are 3 cantilevers designed at each length for each orientation. Therefore, there are 15 oxide cantilevers with a 0° orientation and 15 oxide cantilevers with a 180° orientation.

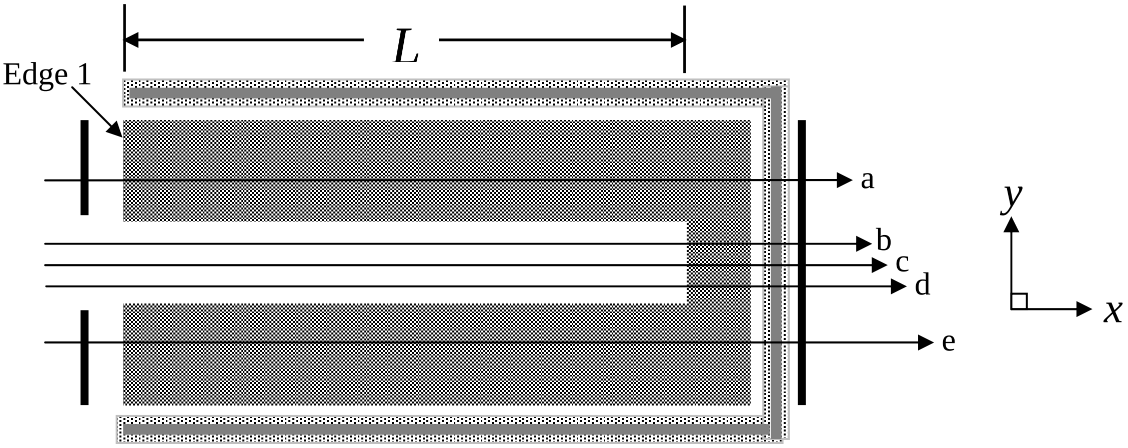

Figure 9. Top view of a cantilever test structure.

Table 5 – Cantilever Configurations for Strain Gradient Measurements

Test Structure	**Width (in μm)**	**Length (in μm)**	**Mechanical Layer**	**Orientation**	**Quantity of Beams**
Cantilevers	40	200, 248, 300, 348, 400	oxide	0°	3 of each length (or 15 beams)
				180°	3 of each length (or 15 beams)

To compare your in-house strain gradient measurements with NIST measurements, you will need to fill out Data Analysis Sheet SG.1 once. (This data analysis sheet is accessible via the URL specified in the reference [6], a reproduction of which is given in Appendix C.) Your completed form can be compared with the completed data analysis sheet supplied with the MNT 5-in-1 SRM.

Data Analysis Sheet SG.1 requires measurements from one cantilever on the MNT 5-in-1 SRM chip. The specific cantilever to be measured can be deduced from the data entered on the NIST-supplied Data Analysis Sheet SG.1 that accompanied the SRM chip. In particular, *design length* (input #2 on Data Analysis Sheet SG.1) specifies the design length of the cantilever (i.e., which column of cantilevers to examine in the third grouping of test structures on the SRM chip in figure 4) and *which cantilever* (input #3) specifies which cantilever in the column to measure. [NOTE: For the SRM chip design in figure 4, *which cantilever* entries of "first", "second", and "third" correspond to a 0° cantilever orientation, and *which cantilever* entries of "fourth", "fifth", and "other" correspond to a 180° cantilever orientation. Therefore, the data (i.e., 0°, 90°, 180°, 270°, or other) supplied for *orientation* (input #5) can be used as a form of verification.]

Orient the cantilever under the interferometric optics as shown in figure 9.[12] Obtain a 3-D data set using the highest magnification possible for the measurements. (For the given design lengths, the magnification should be at least 10×.) For Data Analysis Sheet SG.1, measurements are requested from Edge "1," as shown in figure 9, using Trace "a" or "e." Data points along the cantilever, as shown in figure 10, are requested from Traces "b," "c," and "d."

Following ASTM test method E2246 for measuring strain gradient, record the raw, uncalibrated measurements on Data Analysis Sheet SG.1. Press the "Calculate and Verify" button (located near the center of the data analysis sheet) to obtain the results for the cantilever being measured. Verify the data by checking to see that all the boxes in the verification section at the bottom of the data analysis sheet say "ok." If one or more of the boxes say "wait," address the issue, if necessary, by modifying the inputs and recalculating. After the data is successfully verified, print out the completed data analysis sheet to compare both the inputs and outputs with those on the NIST-supplied data analysis sheet. Any questions concerning the measurements and analysis can be directed to mems-support@nist.gov.

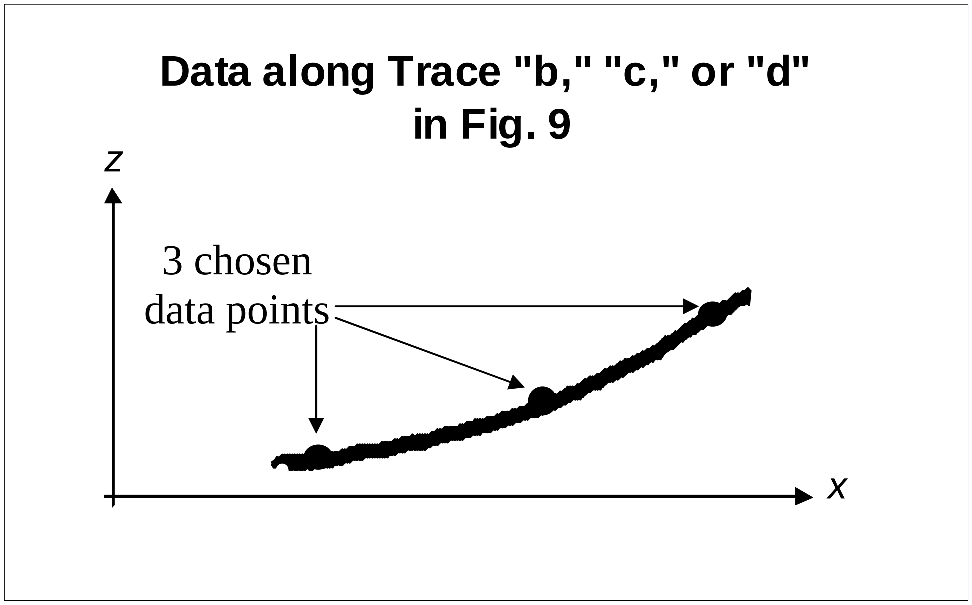

Figure 10. A 2-D data trace used to find three data points.

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[12] This orientation assumes that the interferometer's pixel-to-pixel spacing in the x-direction is smaller than the pixel-to-pixel spacing in the y-direction.

6. GROUPING 4: STEP HEIGHT MEASUREMENTS

In the fourth grouping of test structures on the MNT 5-in-1 SRM chip shown in figure 4, step height measurements are made. There are 4 distinct step height test structures (with 3 occurrences of each structure) from which 6 step height measurements are obtained. These 6 measurements can be used in calculations to determine the thickness of the oxide beams for the determination of Young's modulus in the first grouping of test structures.

The 4 distinct step height test structures can be seen in figure 11. The arrow(s) at the top of each test structure locate(s) the step(s) to be measured. As seen in this figure, one measurement is made on the first and third step height test structures and two measurements are made on the second and fourth step height test structures in order to obtain the beam oxide thickness.

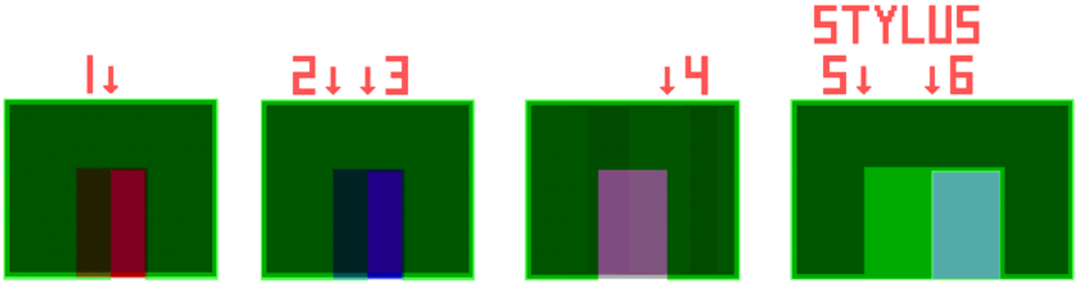

Figure 11. The four step height test structures used to determine the thickness of the oxide beams.

The first step height test structure (shown in figure 11) is a poly1 step going from active area to field oxide as can be seen in the cross section given in figure 12. The name of this step ($step1_{AB}$) and the other steps in this grouping of step height test structures are such that they match the names of similar steps in the thickness test structures (given in the Certification Plus section of this chip) from which the thicknesses of all the layers in the process can be obtained. Consult the reference [10] for more details.

The reference platform around three of the four sides of this first step height test structure (and the other test structures in figure 11) consists of the deposited oxides sandwiched between active area and metal2.

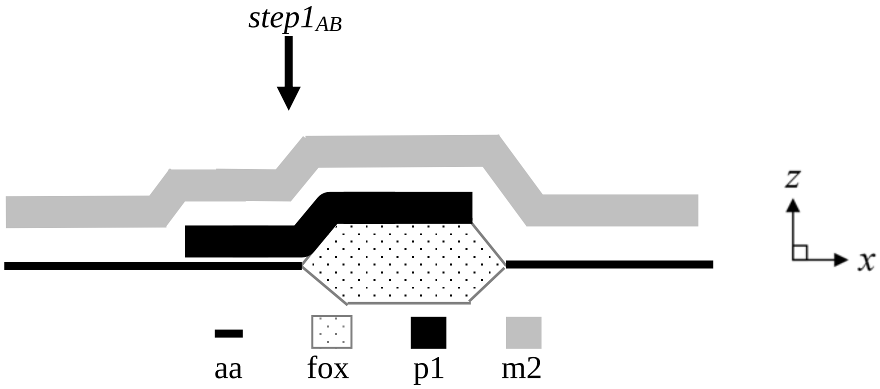

Figure 12. The cross section of the first step height test structure shown in figure 11.

The cross section of the second step height test structure (shown in figure 11) from which $step2_{rA}$ and $step1_{EF}$ are obtained is given in figure 13. The cross section of the third step height test structure from which $step1_{GH}$ is obtained is given in figure 14. And, the cross section of the fourth step height test structure from which $step3_{AB}(n)^{-}$ and $step3_{BC}$ are obtained is given in figure 15. The step heights (namely, $step1_{AB}$, $step2_{rA}$, $step1_{EF}$, $step1_{GH}$, $step3_{AB}(n)^{-}$, and $step3_{BC}$) obtained from the four step height test structures in this grouping of structures can be inputted in Data Analysis Sheet T.1 [6] along with other process specific data to obtain the thickness of the oxide beams for Young's modulus calculations.

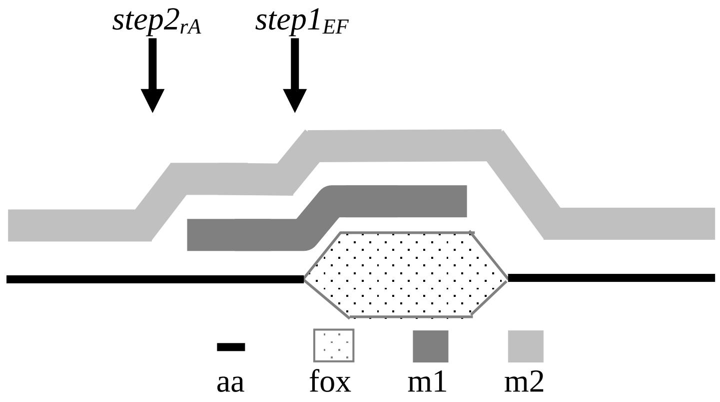

Figure 13. The cross section of the second step height test structure shown in figure 11.

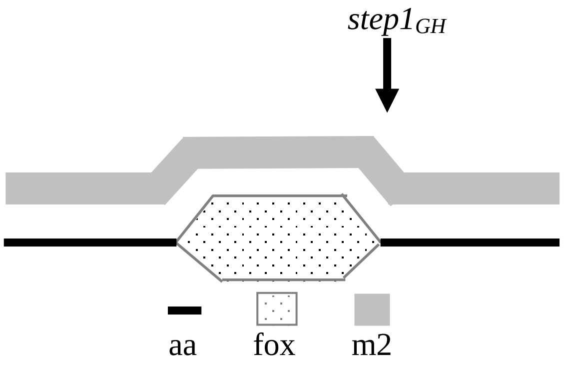

Figure 14. The cross section of the third step height test structure shown in figure 11.

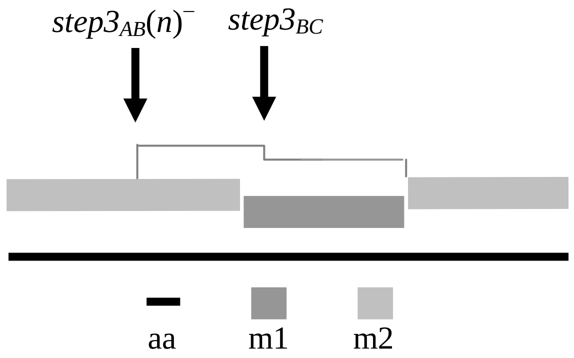

Figure 15. The cross section of the fourth step height test structure shown in figure 11.

To compare your in-house step height measurements with NIST measurements, you will need to fill out Data Analysis Sheet SH.1 once. (This data analysis sheet is accessible via the URL specified in the reference [6], a reproduction of which is given in Appendix D.) Your completed form can be compared with the completed data analysis sheet supplied with the MNT 5-in-1 SRM.

Data Analysis Sheet SH.1 requires measurements from one step height test structure on the MNT 5-in-1 SRM chip. The step height test structure to be measured can be deduced from the data entered on the NIST-supplied Data Analysis Sheet SH.1 that accompanied the SRM chip. In particular, *which* (input #2 on Data Analysis Sheet SH.1) specifies which of the six step height measurements to take in the fourth grouping of test structures on the SRM chip in figure 4. Therefore, the first measurement is taken from the first step height test structure, the second and third measurements are taken from the second step height test structure, the fourth measurement is taken from the third step height test structure, and the fifth and sixth measurements are taken from the fourth step height test structure. (Measurements from the fourth step height test structure should be taken with a stylus instrument or instrument not affected by the reflectivity of the sample surface, unless the chip is covered with a smooth reflective material before measurement.) Measurements can be taken from any one of the three identical test structures.

For the step height measurements taken with an optical interferometer or comparable instrument, orient the step height test structure under the instrument optics such that the *x*-axis of the test structure shown in figure 16 is parallel to the *x*-axis of the instrument.[13] The measurements should be obtained using the most powerful objective possible (while choosing the appropriate field of view lens, if applicable) given the sample areas to be investigated. The data is leveled and zeroed with respect to the surrounding reference platform.

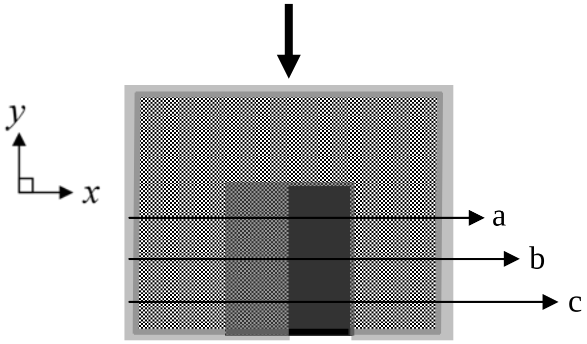

Figure 16. A design rendition of a step height test structure showing 2-D data traces “a,” “b,” and “c.”

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[13] This orientation assumes that the instrument’s pixel-to-pixel spacing in the *x*-direction is smaller than the pixel-to-pixel spacing in the *y*-direction.

Three 2-D data traces ("a," "b," and "c," as shown in figure 16) are used to obtain the step height measurement. Given the location of the arrow in figure 16, the platform height measurements and standard deviations from both of the central platforms along data traces "a," "b," and "c" are recorded. Therefore, twelve measurements are obtained (six from the first platform and six from the second platform).

Following SEMI MS2 for measuring step height, record the raw, uncalibrated measurements on Data Analysis Sheet SH.1. Press the "Calculate and Verify" button (located near the center of the data analysis sheet) to obtain the results for the step height test structure being measured. Verify the data by checking to see that all the boxes in the verification section at the bottom of the data analysis sheet say "ok." If one or more of the boxes say "wait," address the issue, if necessary, by modifying the inputs and recalculating. After the data is successfully verified, print out the completed data analysis sheet to compare both the inputs and outputs with those on the NIST-supplied data analysis sheet. Any questions concerning the measurements and analysis can be directed to mems-support@nist.gov.

7. GROUPING 5: IN-PLANE LENGTH MEASUREMENTS

In the fifth grouping of test structures on the MNT 5-in-1 SRM chip shown in figure 4, in-plane length measurements are made. There are features for five design lengths (24 µm, 80 µm, 200 µm, 500 µm, and 1000 µm) with the design length specified at the top of each column of features. There are 3 occurrences of each feature. At each length the following three types of in-plane length measurement can be obtained:

1. An outside edge-to-outside edge length measurement, as given by L_{oo} in figure 17, where Edge 1 and Edge 2 are considered outside edges,
2. An inside edge-to-inside edge length measurement, as given by L_{ii} in figure 17, where Edge 3 and Edge 4 are considered inside edges, and
3. An inside edge-to-outside edge length measurement, as given by L_{io} in figure 17, where Edge 5 is considered an inside edge and Edge 6 is considered an outside edge.

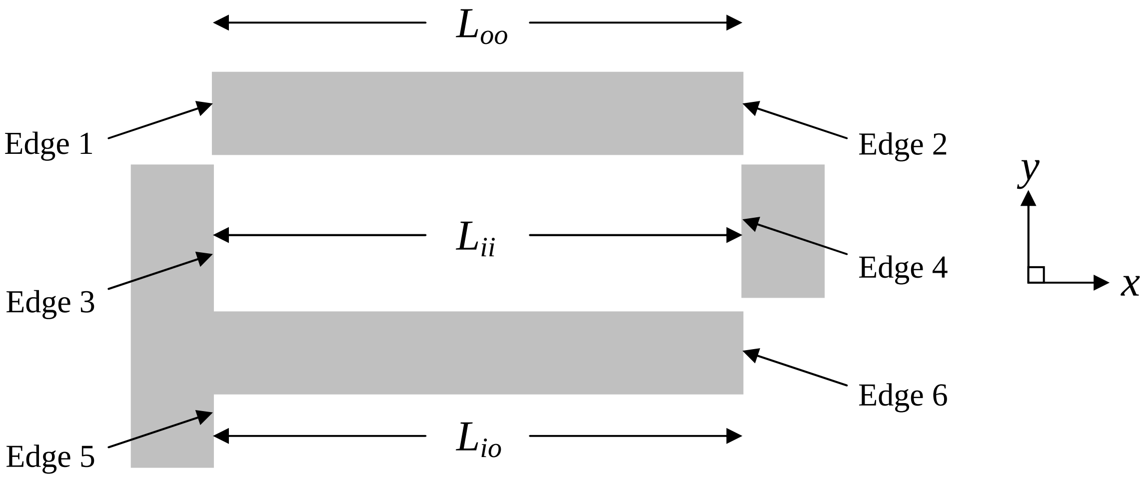

Figure 17. Features for in-plane length measurements.

Table 6 – Design Lengths for the Given Interferometric Magnifications

Magnification	**Calibrated Maximum Field of View (in the *x*-direction)**	**Design Lengths**
5×	1165.00 µm	1000 µm
10×	599.998 µm	500 µm
20×	287.00 µm	200 µm
40×	150.000 µm	80 µm
80×	75.0000 µm	24 µm

The in-plane length measurements are made with an optical interferometer. Many interferometers are purchased with five magnifications. Table 6 lists five magnifications along with a representative maximum field of view for that magnification. In the third column, the design lengths for the in-plane length measurements at that magnification are given. In most cases, this length is at least 70 μm less than the calibrated maximum field of view in the *x*-direction,[14] as given in the second column, for a representative interferometer.

To compare your in-house length measurements with NIST measurements, you will need to fill out one data analysis sheet that obtains one of the three length measurements (L_{oo}, L_{ii}, or L_{io}) shown in figure 17. The specific length to be measured can be deduced from the data analysis sheet supplied with the SRM chip and the data entered on that data analysis sheet. For example, if Data Analysis Sheet L.1 accompanied the SRM chip than an inside edge-to-inside edge length measurement, *Lii*, should be taken. (This data analysis sheet is accessible via the URL specified in the reference [6], a reproduction of which is given in Appendix E.) Also, *design length* (input #2 on Data Analysis Sheet L.1) specifies the design length (i.e., which column of features to examine in the fifth grouping of test structures on the SRM chip in figure 4). Any one of the 3 occurrences of the feature can be measured.

If Data Analysis Sheet L.3 accompanied the SRM chip, than an inside edge-to-outside edge length measurement, L_{io}, should be taken. And if Data Analysis Sheet L.4 accompanied the SRM chip, than an outside edge-to-outside edge length measurement, L_{oo}, should be taken.

Orient the chip under the interferometric optics as shown in figure 17 and obtain one 3-D data set.[15] Following ASTM test method E2244 for measuring in-plane lengths, record the raw, uncalibrated measurements on Data Analysis Sheet L.1, L.3, or L.4, as appropriate. Press the “Calculate and Verify” button (located near the center of the data analysis sheet) to obtain the results for the length being measured. Verify the data by checking to see that all the boxes in the verification section at the bottom of the data analysis sheet say “ok.” If one or more of the boxes say “wait,” address the issue, if necessary, by modifying the inputs and recalculating. After the data is successfully verified, print out the completed data analysis sheet to compare both the inputs and outputs with those on the NIST-supplied data analysis sheet. Any questions concerning the measurements and analysis can be directed to mems-support@nist.gov.

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[14] For this interferometer, the resolution in the *x*-direction is better than the resolution in the *y*-direction.

[15] This orientation assumes that the interferometer’s pixel-to-pixel spacing in the *x*-direction is smaller than the pixel-to-pixel spacing in the *y*-direction.

8. SUMMARY

In summary, this guide provided instructions for use with the MNT 5-in-1 SRM. In particular, it provided details associated with the following:

- Specifications of the equipment:
  - For the optical vibrometer, stroboscopic interferometer, or comparable instrument used for Young's modulus measurements and
  - For the optical interferometer or comparable instrument used for residual strain, strain gradient, step height, and in-plane length measurements.
- Design of the MNT 5-in-1 SRM:
  - For a bulk-micromachined 1.5 μm On Semiconductor process through MOSIS.
- Packaging of the MNT 5-in-1 SRM
- Measurements taken with the validated standards:
  - SEMI MS4 for Young's modulus measurements using Data Sheet YM.1,
  - ASTM E 2245 for residual strain measurements using Data Sheet RS.1,
  - ASTM E 2246 for strain gradient measurements using Data Sheet SG.1,
  - SEMI MS2 for step height measurements using Data Sheet SH.1, and
  - ASTM E 2244 for in-plane length measurements using Data Sheet L.1.

Five data analysis sheets completed with data taken at NIST are provided with the MNT 5-in-1 SRM and its certificate so that the customer can compare their in-house measurements with measurements taken at NIST in order to validate their use of the documentary standards. Contact the NIST SRM Program Office [7] to obtain an MNT 5-in-1 SRM and accompanying material.

9. ACKNOWLEDGMENT

Acknowledgments go to the Test Structures Subgroup within the Micro and Nano Technology Project at NIST, the SEMI North American MEMS Standards Committee, and the ASTM Subcommittee E08.05 on Cyclic Deformation and Fatigue Crack Formation.

An acknowledgment also goes to the Office of Microelectronics Programs for supporting this work.

10. REFERENCES

[1] SEMI MS4, "Test Method for Young's Modulus Measurements of Thin, Reflecting Films Based on the Frequency of Beams in Resonance," (Visit http://www.semi.org for ordering information.)

[2] SEMI MS2, "Test Method for Step Height Measurements of Thin Films," (Visit http://www.semi.org for ordering information.)

[3] ASTM E08, "E 2244 Standard Test Method for In-Plane Length Measurements of Thin, Reflecting Films Using an Optical Interferometer," *Annual Book of ASTM Standards*, Vol. 03.01, 2006. (Also available via http://www.astm.org.)

[4] ASTM E08, "E 2245 Standard Test Method for Residual Strain Measurements of Thin, Reflecting Films Using an Optical Interferometer," *Annual Book of ASTM Standards*, Vol. 03.01, 2006. (Also available via http://www.astm.org.)

[5] ASTM E08, "E 2246 Standard Test Method for Strain Gradient Measurements of Thin, Reflecting Films Using an Optical Interferometer," *Annual Book of ASTM Standards*, Vol. 03.01, 2006. (Also available via http://www.astm.org.)

[6] The URL for the National Institute of Standards and Technology (NIST) Semiconductor Electronics Division (SED) MEMS Calculator Web site is http://www.eeel.nist.gov/812/test-structures/MEMSCalculator.htm.

[7] Contact the NIST SRM Program Office to obtain an MNT 5-in-1 SRM, its certificate, and accompanying data analysis sheets by visiting http://ts.nist.gov/measurementservices/referencematerials/index.cfm.

[8] The URL for the MOSIS Web site is http://www.mosis.org. MOSIS provides access to fabrication of prototype and low-volume production quantities of integrated circuits…by combining designs from many customers onto multi-project wafers,…decreasing the cost of each design.

[9] J. C. Marshall, D. L. Herman, P. T. Vernier, D. L. DeVoe, and M. Gaitan, "Young's Modulus Measurements in Standard IC CMOS Processes using MEMS Test Structures," *IEEE Electron Device Letters*, Vol. 28, No. 11, p. 960-963, 2007.

[10] J. C. Marshall and P. T. Vernier, "Electro-physical technique for post-fabrication measurements of CMOS process layer thicknesses," *NIST J. Res.*, Vol. 112, No. 5, p. 223-256, 2007.

[11] J. C. Marshall, "New Optomechanical Technique for Measuring Layer Thickness in MEMS Processes," *Journal of Microelectromechanical Systems*, Vol. 10, No. 1, March 2001, pp. 153-157.

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

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

[14] Marshall, J. C., "MEMS Length and Strain Measurements Using an Optical Interferometer," *NISTIR 6779*, National Institute of Standards and Technology, August 2001.

[15] An Assessment of the US Measurement System: Addressing Measurement Barriers to Accelerate Innovation, Appendix B, "Case Study – Measurement Needs Technology at Issue: Micro-/Nano-Technology", (NIST Special Publication 1048, page 309, 2006).

[16] Taylor, B. N. and Kuyatt, C. E., "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," *NIST Technical Note 1297*, National Institute of Standards and Technology, September 1994.

APPENDIX A – Data Analysis Sheet YM.1

Data analysis sheet for determining the Young’s modulus value of a thin film layer

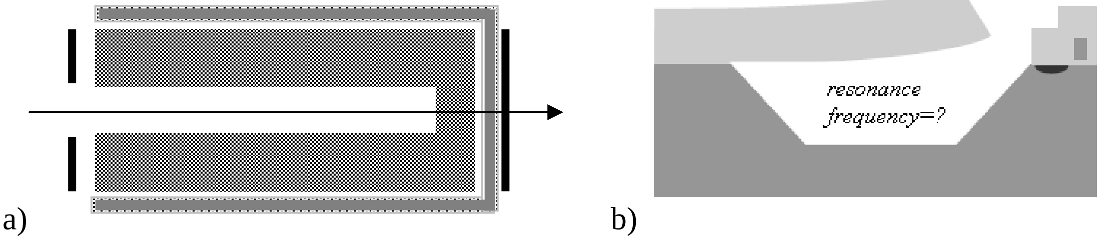

Figure YM.1.1. For CMOS cantilever a) a design rendition and b) a cross section

To obtain the following measurements, consult SEMI standard test method MS4 entitled “Test Method for Young’s Modulus Measurements of Thin, Reflecting Films Based on the Frequency of Beams in Resonance.”

IDENTIFYING INFORMATION:

date data taken (optional) = ☐ / ☐ / ☐
identifying words (optional) = ☐
instrument used (optional) = ☐
fabrication facility/process (optional) = ☐
test chip name (optional) = ☐
test chip number (optional) = ☐
root filename (optional) = ☐

Table 1 - Preliminary INPUTS			**Description**
1	*mag* =	☐ ×	magnification
2	*mat* =	poly1 ○ poly2 ○ SiO_2 ○ other ●	composition of the thin film layer
3*	ρ =	☐ g/cm^3	density of the thin film layer
4	σ_ρ =	☐ g/cm^3	one sigma uncertainty of the value of ρ
5*	μ =	☐ $\times 10^{-5}$ Ns/m^2	viscosity of the ambient surrounding the cantilever
6	σ_μ =	☐ $\times 10^{-5}$ Ns/m^2	one sigma uncertainty of the value of μ
7	*temp*=	☐ °C	temperature during measurement (should be held constant)
8*	*W* =	☐ μm	suspended beam width
9	σ_W =	☐ μm	one sigma uncertainty of the value of *W*
10*	*t* =	☐ μm	thickness of the thin film layer
11	σ_{thick} =	☐ μm	one sigma uncertainty of the value of *t*

12	d_{gap}=	µm	gap depth (distance between the bottom of the suspended beam and the underlying layer)
13*	E_{init} =	GPa	initial estimate for the Young's modulus value of the thin film layer

* The five starred entries in this table are required inputs for the calculations in the Preliminary Estimates Table.

Table 2 - Cantilever INPUTS			**Description**
14	*name* =		cantilever name (optional)
15	*orient* =	0° ○ 90° ○ 180° ○ 270° ○ other ●	orientation of the cantilever
16*	L_{can} =	µm	suspended cantilever length
17	*whichcan*=	first ○ second ○ third ○ fourth ○ fifth ○ other ●	which cantilever on the test chip, where "first" corresponds to the topmost cantilever in the column?
18	σ_L =	µm	one sigma uncertainty of the value of L_{can}
19	f_{resol} =	Hz	frequency resolution for the given set of measurement conditions
20	f_{meas1} =	kHz	first damped resonance frequency measurement, $f_{damped1}$ (or first undamped resonance frequency measurement, for example, if the measurements were performed in a vacuum)
21	f_{meas2} =	kHz	second damped resonance frequency measurement, $f_{damped2}$ (or second undamped resonance frequency measurement, for example, if the measurements were performed in a vacuum)
22	f_{meas3} =	kHz	third damped resonance frequency measurement, $f_{damped3}$ (or third undamped resonance frequency measurement, for example, if the measurements were performed in a vacuum)

* The starred entry in this table is a required input for the calculations in the Preliminary Estimates Table.

Table 3 - Fixed-Fixed Beam INPUTS (if cantilever not available)			**Description**
23	*name2* =		fixed-fixed beam name (optional)
24	*orient2* =	0° ○ 90° ○ other ●	orientation of the fixed-fixed beam
25*	L_{ffb} =	μm	suspended fixed-fixed beam length
26	*whichffb*=	first ○ second ○ third ○ fourth ○ fifth ○ other ●	which fixed-fixed beam on the test chip, where “first” corresponds to the topmost fixed-fixed beam in the column?
27	f_{ffb} =	kHz	average resonance frequency of the fixed-fixed beam

* The starred entry in this table is a required input for the calculations in the Preliminary Estimates Table.

Table 4 - Optional INPUTS			
For residual stress calculations:			**Description**
28	ε_r =	$\times 10^{-6}$	residual strain of the thin film layer (Compressive residual strain can be found using ASTM E 2245 and Data Sheet RS.1 or RS.2.)
29	$u_{\varepsilon r}$ =	$\times 10^{-6}$	combined standard uncertainty value for residual strain (For compressive residual strain, $u_{\varepsilon r}$ can be found using Data Sheet RS.1 or RS.2.)
For stress gradient calculations:			
30	s_g =	m^{-1}	strain gradient of the thin film layer (can be found using ASTM E 2246 and Data Sheet SG.1 or SG.2)
31	u_{sg} =	m^{-1}	combined standard uncertainty value for strain gradient (can be found using Data Sheet SG.1 or SG.2)

Input Sample Data Reset this form

Calculate Estimates Clear Output

Table 5 -Preliminary ESTIMATES*			**Description**
32	$f_{caninit}$ =	kHz	= SQRT [$E_{init}\, t^2$ / (38.330 $\rho\, L_{can}^4$)] (estimated resonance frequency of the cantilever)
33	$f_{ffbinithi}$ =	kHz	= SQRT [$E_{init}\, t^2$ / (0.946 $\rho\, L_{ffb}^4$)] (estimated upper bound for the resonance frequency of the fixed-fixed beam)
34	$f_{ffbinitlo}$ =	kHz	= SQRT [$E_{init}\, t^2$ / (4.864 $\rho\, L_{ffb}^4$)] (estimated lower bound for the resonance frequency of the fixed-fixed beam)
35	Q =		= $W\, t^2$ SQRT ($\rho\, E_{init}$) / (24 $\mu\, L_{can}^2$) (estimated Q-factor)
36	p_{diff} =	%	= {1 – SQRT [1–1 / (4 Q^2)]}×100 % should be < 2 % (estimated percent difference between the damped and undamped resonance frequency of the cantilever)

* The seven starred inputs in the first three tables are required for the calculations in this table.

Calculate and Verify Clear Output

OUTPUTS:

Table 6 - Frequency calculations:			**Description**
37	$f_{measave}$ =	kHz	= AVE [f_{meas1}, f_{meas2}, f_{meas3}] (average damped resonance frequency of the cantilever, $f_{dampedave}$, or average undamped resonance frequency of the cantilever if, for example, the measurements were performed in a vacuum)
38	$f_{undamped1}$ =	kHz	= $f_{damped1}$ / SQRT [1–1/(4Q^2)] (first undamped resonance frequency calculated from the cantilever's first damped resonance frequency measurement, if applicable)
39	$f_{undamped2}$ =	kHz	= $f_{damped2}$ / SQRT [1–1/(4Q^2)] (second undamped resonance frequency calculated from the cantilever's second damped resonance frequency measurement, if applicable)
40	$f_{undamped3}$ =	kHz	= $f_{damped3}$ / SQRT [1–1/(4Q^2)] (third undamped resonance frequency calculated from the cantilever's third damped resonance frequency measurement, if applicable)
41	f_{can} =	kHz	= AVE [$f_{undamped1}$, $f_{undamped2}$, $f_{undamped3}$] (average undamped resonance frequency of the cantilever assuming f_{meas1}, f_{meas2}, and f_{meas3} from

			the second table are damped resonance frequencies)
42	σ_{freq} =	☐ kHz	= STDEV [$f_{undamped1}$, $f_{undamped2}$, $f_{undamped3}$] (one sigma uncertainty of the value of f_{can} assuming f_{meas1}, f_{meas2}, and f_{meas3} from the second table are damped resonance frequencies)

1. Young's modulus calculation (as obtained from the cantilever assuming clamped-free boundary conditions):

   a. $E = 38.330\, \rho\, f_{can}^2 L_{can}^4 / t^2$ = ☐ GPa
   (Use this value if f_{meas1}, f_{meas2}, and f_{meas3} in the second table are damped resonance frequencies.)

   b. $E = 38.330\, \rho\, f_{measave}^2 L_{can}^4 / t^2$ = ☐ GPa
   (Use this value if f_{meas1}, f_{meas2}, and f_{meas3} in the second table are undamped resonance frequencies.)

   c. $u_c = \mathrm{SQRT}(u_{thick}^2 + u_\rho^2 + u_L^2 + u_{freq}^2 + u_{fresol}^2 + u_{damp}^2)$ = ☐ GPa
   u_{thick} = ☐ GPa
   u_ρ = ☐ GPa
   u_L = ☐ GPa
   u_{freq} = ☐ GPa*
   u_{fresol} = ☐ GPa
   u_{damp} = ☐ GPa*
   * assumes f_{meas1}, f_{meas2}, and f_{meas3} in the second table are damped resonance frequencies

2. Young's modulus calculation (as obtained from a fixed-fixed beam…not recommended):

   a. $E_{simple} = 4.864\, \rho\, f_{ffb}^2\, L_{ffb}^4 / t^2$ = ☐ GPa
   (as obtained from the fixed-fixed beam assuming simply-supported boundary conditions for both supports)

   b. $E_{clamped} = 0.946\, \rho\, f_{ffb}^2\, L_{ffb}^4 / t^2$ = ☐ GPa
   (as obtained from the fixed-fixed beam assuming clamped-clamped boundary conditions)

   c. $E = (E_{simple} + E_{clamped}) / 2$ = ☐ GPa (use this value, if must)

   d. $u_c = (E_{simple} - E_{clamped}) / 6$ = ☐ GPa

3. Report the results as follows: Since it can be assumed that the possible estimated values are either approximately uniformly distributed or Gaussian with approximate standard deviation u_c, the Young's modulus value is believed to lie in the interval $E \pm u_c$ with a level of confidence of approximately 68 % assuming a Gaussian distribution.

Table 7 - Optional OUTPUTS (using E and u_c from the cantilever and assuming f_{meas1}, f_{meas2}, and f_{meas3} in the second table are damped resonance frequencies)

For residual stress:			**Description**
43	σ_r =	☐ MPa	$= E\ \varepsilon_r$ (residual stress of the thin film layer)
44	$u_{\sigma r}$ =	☐ MPa	$= \mathrm{SQRT}\ [u_{E(\sigma r)}{}^2 + u_{\varepsilon r(\sigma r)}{}^2]$ (combined standard uncertainty value for residual stress)
45	$u_{E(\sigma r)}$ =	☐ MPa	$= [\ (E{+}3u_c)\lvert\varepsilon_r\rvert - (E{-}3u_c)\lvert\varepsilon_r\rvert\ ] / 6$ (component in the combined standard uncertainty calculation for residual stress that is due to the measurement uncertainty of E)
46	$u_{\varepsilon r(\sigma r)}$ =	☐ MPa	$= [\ E(\ \lvert\varepsilon_r\rvert + 3u_{\varepsilon r}) - E(\ \lvert\varepsilon_r\rvert - 3u_{\varepsilon r})\ ] / 6$ (component in the combined standard uncertainty calculation for residual stress that is due to the measurement uncertainty of ε_r)
For stress gradient:			
47	σ_g =	☐ GPa/m	$= E\ s_g$ (stress gradient of the thin film layer)
48	$u_{\sigma g}$ =	☐ GPa/m	$= \mathrm{SQRT}\ [u_{E(\sigma g)}{}^2 + u_{sg(\sigma g)}{}^2]$ (combined standard uncertainty value for stress gradient)
49	$u_{E(\sigma g)}$ =	☐ GPa/m	$= [\ (E + 3u_c)s_g - (E - 3u_c)s_g\ ] / 6$ (component in the combined standard uncertainty calculation for stress gradient that is due to the measurement uncertainty of E)
50	$u_{sg(\sigma g)}$ =	☐ GPa/m	$= [\ E(s_g + 3u_{sg}) - E(s_g - 3u_{sg})\ ] / 6$ (component in the combined standard uncertainty calculation for stress gradient that is due to the measurement uncertainty of s_g)

Modify the input data, given the information supplied in any flagged statement below, if applicable, then recalculate:

1. ☐ Please provide inputs to Tables 1 and 2 for calculations using data from a cantilever.
2. ☐ Please provide inputs to Table 3, ρ, W, t, and E_{init} for calculations using data from a fixed-fixed beam, if applicable.
3. ☐ The value for *mag* should be greater than or equal to 20×.
4. ☐ The value for ρ should be between 1.00 g/cm^3 and 5.00 g/cm^3.
5. ☐ The value for σ_ρ should be between 0.0 g/cm^3 and 0.10 g/cm^3.
6. ☐ The value for μ should be between 0.70×10^{-5} Ns/m^2 and 3.0×10^{-5} Ns/m^2.

7. ☐ The value for σ_μ should be between 0.0 Ns/m^2 and 0.05×10^{-5} Ns/m^2.
8. ☐ The value for *temp* should be between 15 °C and 30 °C.
9. ☐ The value for W should be greater than t and less than L_{can}.
10. ☐ The value for W should be greater than t and less than L_{ffb}, if inputted.
11. ☐ The value for σ_W should be between 0.0 μm and 2.0 μm.
12. ☐ The value for t should be between 0.000 μm and 10.000 μm.
13. ☐ The value for σ_{thick} should be between 0.0 μm and 0.3 μm.
14. ☐ Squeeze film damping expected for the cantilever since $d_{gap} < W / 3$.
15. ☐ The value for E_{init} should be between 10 GPa and 300 GPa.
16. ☐ The value for L_{can} should be between 0 μm and 1000 μm.
17. ☐ The value for σ_L should be between 0.0 μm and 2.0 μm.
18. ☐ The value for f_{resol} should be between 0 Hz and 50 Hz.
19. ☐ The values for f_{meas1}, f_{meas2}, and f_{meas3} should be between 5.00 kHz and 300.0 kHz.
20. ☐ If inputted, the value for L_{ffb} should be between 0 μm and 1000 μm.
21. ☐ If inputted, the value for f_{ffb} should be between 5.0 kHz and 1200 kHz.
22. ☐ If inputted, the value for ε_r should be between -100×10^{-6} and 100×10^{-6} and not equal to 0.0.
23. ☐ If inputted, the value for $u_{\varepsilon r}$ should be between 0.0 and 4.0×10^{-6}.
24. ☐ If inputted, the value for s_g should be between 0.0 m^{-1} and 20.0 m^{-1}.
25. ☐ If inputted, the value for u_{sg} should be between 0.0 m^{-1} and 2.0 m^{-1}.
26. ☐ The values for f_{meas1}, f_{meas2}, and f_{meas3} are not within 20 kHz of $f_{caninit}$.
27. ☐ If inputted, the value for f_{ffb} should be between $f_{ffbinitlo}$ and $f_{ffbinithi}$.
28. ☐ The value for p_{diff} should be between 0 % and 2 %.
29. ☐ The value for σ_{freq} should be between 0.0 kHz and 0.5 kHz, inclusive.
30. ☐ The value of E obtained from the cantilever should be within 20 GPa of E_{init}.
31. ☐ The values for u_{thick}, u_ρ, u_L, u_{freq}, u_{fresol}, and u_{damp} should be between 0 GPa and 5 GPa, inclusive.
32. ☐ The value of u_c obtained from the cantilever should be between 0 GPa and 10 GPa.
33. ☐ If applicable, the value of E obtained from the fixed-fixed beam should be within 30 GPa of E_{init}.
34. ☐ If applicable, the value of u_c obtained from the fixed-fixed beam should be between 0 GPa and 20 GPa.

Return to Main MEMS Calculator Page.

Email questions or comments to mems-support@nist.gov.

APPENDIX B – Data Analysis Sheet RS.1

Data analysis sheet for residual strain measurements

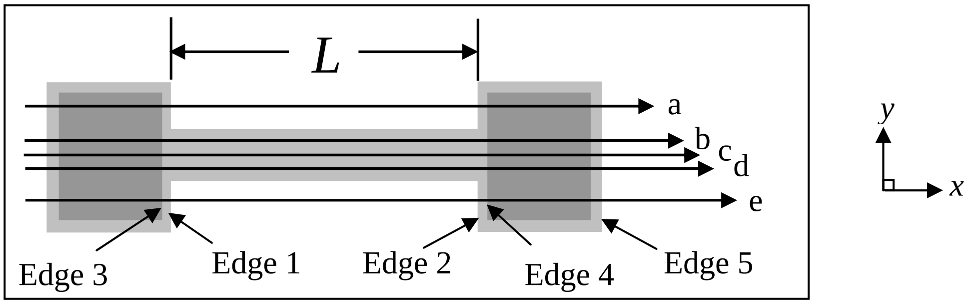

Figure RS.1.1. Top view of fixed-fixed beam used to measure residual strain.

To obtain the following measurements, consult ASTM standard test method E 2245 entitled “Standard Test Method for Residual Strain Measurements of Thin, Reflecting Films Using an Optical Interferometer.”

---

date data taken (optional) = ☐ / ☐ / ☐
identifying words (optional) =
instrument used (optional) =
fabrication facility/process (optional) =
test chip name/number (optional) =
filename of 3-D data set (optional) =
filename of 2-D data traces (optional) =

Table 1 - Preliminary ESTIMATES			**Description**
1	*material =*	Poly1 ○ Poly2 ○ stacked Poly1 and Poly2 ○ SiC-2 ○ SiC-3 ○ other ●	material
2	*t =*	☐ μm	beam thickness
3	*design length =*	☐ μm	design length
4	*which beam?*	First ○ Second ○ Third ○ Other ●	which fixed-fixed beam on the test chip?
5	*magnification =*	☐ ×	magnification
6	*orientation =*	0° ○ 90° ○ other ●	orientation of the fixed-fixed beam on the chip

7	*calx* =	☐	*x*-calibration factor (for the given magnification)
8	*interx* =	☐ μm	maximum field of view (for the given magnification)
9	σ_{xcal} =	☐ μm	one sigma uncertainty in a ruler measurement (for the given magnification)
10	x_{res} =	☐ μm	resolution of the interferometer in the *x*-direction
11	*calz* =	☐	*z*-calibration factor (for the given magnification)
12	*cert* =	☐ μm	certified value of physical step height used for calibration
13	σ_{zcal} =	☐ μm	standard deviation of step height measurements (on double-sided physical step height)
14	z_{res} =	☐ μm	resolution of the interferometer in the *z*-direction
15	R_{tave} =	☐ μm	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 of which is taken from a different 2-D data trace
16	*aligned?*	Yes ○ No ●	alignment ensured?
17	*leveled?*	Yes ○ No ●	data leveled?
18	*stiction?*	Yes ○ No ●	Is this fixed-fixed beam exhibiting stiction? (If it is exhibiting stiction, do not fill out the remainder of this form.)

Input Sample Data

Reset this form

Table 2 – INPUTS (uncalibrated values from Trace “a” or “e”)			**Notes**
19	$x1_{max}$ (i.e., $x1_{upper}$) =	☐ μm	
20	$x1_{min}$ (i.e., $x1_{lower}$) =	☐ μm	$(x1_{min} > x1_{max})$
21	$x2_{min}$ (i.e., $x2_{lower}$) =	☐ μm	$(x2_{min} > x1_{min})$
22	$x2_{max}$ (i.e., $x2_{upper}$) =	☐ μm	$(x2_{max} > x2_{min})$

Table 3 – INPUTS (uncalibrated values from Trace "b")			**Notes**
23	x_{1F} = ☐ µm	z_{1F} = ☐ µm	($x1_{\mathrm{ave}} \le x_{1F} * calx$)
24	x_{2F} = ☐ µm	z_{2F} = ☐ µm	(inflection point) ($x_{1F} < x_{2F} < x_{3F}$)
25	x_{3F} = ☐ µm	z_{3F} = ☐ µm	(most deflected point) ($x_{1S} = x_{3F}$; $z_{1S} = z_{3F}$)
26	x_{2S} = ☐ µm	z_{2S} = ☐ µm	(inflection point)
27	x_{3S} = ☐ µm	z_{3S} = ☐ µm	($x_{3S} * calx \le x2_{\mathrm{ave}}$) ($x_{1S} < x_{2S} < x_{3S}$)

Table 4 – INPUTS (uncalibrated values from Trace "c")			**Notes**
28	x_{1F} = ☐ µm	z_{1F} = ☐ µm	($x1_{\mathrm{ave}} \le x_{1F} * calx$)
29	x_{2F} = ☐ µm	z_{2F} = ☐ µm	(inflection point) ($x_{1F} < x_{2F} < x_{3F}$)
30	x_{3F} = ☐ µm	z_{3F} = ☐ µm	(most deflected point) ($x_{1S} = x_{3F}$; $z_{1S} = z_{3F}$)
31	x_{2S} = ☐ µm	z_{2S} = ☐ µm	(inflection point)
32	x_{3S} = ☐ µm	z_{3S} = ☐ µm	($x_{3S} * calx \le x2_{\mathrm{ave}}$) ($x_{1S} < x_{2S} < x_{3S}$)

Table 5 – INPUTS (uncalibrated values from Trace "d")			**Notes**
33	x_{1F} = ☐ µm	z_{1F} = ☐ µm	($x1_{\mathrm{ave}} \le x_{1F} * calx$)
34	x_{2F} = ☐ µm	z_{2F} = ☐ µm	(inflection point) ($x_{1F} < x_{2F} < x_{3F}$)
35	x_{3F} = ☐ µm	z_{3F} = ☐ µm	(most deflected point) ($x_{1S} = x_{3F}$; $z_{1S} = z_{3F}$)
36	x_{2S} = ☐ µm	z_{2S} = ☐ µm	(inflection point)
37	x_{3S} = ☐ µm	z_{3S} = ☐ µm	($x_{3S} * calx \le x2_{\mathrm{ave}}$) ($x_{1S} < x_{2S} < x_{3S}$)

[Calculate and Verify] [Clear Outputs]

OUTPUTS (calibrated values):

$x1_{\mathrm{ave}}$ = ☐ µm $x2_{\mathrm{ave}}$ = ☐ µm

L = ☐ µm

$L_{max} = (x2_{max} - x1_{max}) * calx$

$L_{min} = (x2_{min} - x1_{min}) * calx$

$u_{LL} = (L_{max} - L_{min}) / 6 =$ ☐ µm

$u_{Lxcal} = (\sigma_{xcal} / interx) * (L / calx) = \boxed{\qquad}$ μm
$u_{Lxres} = x_{res} * calx / 1.732 = \boxed{\qquad}$ μm
$u_{cL} = \mathrm{SQRT}[u_{LL}^2 + u_{Lxcal}^2 + u_{Lxres}^2] = \boxed{\qquad}$ μm
$s = \boxed{\qquad}$ fromTrace “c”
s = 1 (for downward bending fixed-fixed beams)
s = –1 (for upward bending fixed-fixed beams)

$A_F = \boxed{\qquad}$ μm from Trace “b”
$w_{1F} = \boxed{\qquad}$ from Trace “b”
$A_S = \boxed{\qquad}$ μm from Trace “b”
$w_{3S} = \boxed{\qquad}$ from Trace “b”
$x_{eF} = \boxed{\qquad}$ μm from Trace “b”
$x_{eS} = \boxed{\qquad}$ μm from Trace “b”
$\varepsilon_{r0} = \boxed{\qquad} \times 10^{-6}$ from Trace “b”
$\varepsilon_r = \boxed{\qquad} \times 10^{-6}$ from Trace “b”

$A_F = \boxed{\qquad}$ μm from Trace “c”
$w_{1F} = \boxed{\qquad}$ from Trace “c”
$A_S = \boxed{\qquad}$ μm from Trace “c”
$w_{3S} = \boxed{\qquad}$ from Trace “c”
$x_{eF} = \boxed{\qquad}$ μm from Trace “c”
$x_{eS} = \boxed{\qquad}$ μm from Trace “c”
$\varepsilon_{r0} = \boxed{\qquad} \times 10^{-6}$ from Trace “c”
$\varepsilon_r = \boxed{\qquad} \times 10^{-6}$ from Trace “c” (USE THIS VALUE)
$u_{samp} = \boxed{\qquad} \times 10^{-6}$ from Trace “c”
$u_W = \boxed{\qquad} \times 10^{-6}$ from two or three traces
$u_{xcal} = \boxed{\qquad} \times 10^{-6}$ from Trace “c”
$u_L = \boxed{\qquad} \times 10^{-6}$ from Trace “c”
$u_{zcal} = \boxed{\qquad} \times 10^{-6}$ from Trace “c”
$u_{zres} = \boxed{\qquad} \times 10^{-6}$ from Trace “c”
$u_{xres} = \boxed{\qquad} \times 10^{-6}$ from Trace “c”
$u_{xresL} = \boxed{\qquad} \times 10^{-6}$ from Trace “c”
$u_c = \mathrm{SQRT}[u_{samp}^2 + u_W^2 + u_{xcal}^2 + u_L^2 + u_{zcal}^2 + u_{zres}^2 + u_{xres}^2 + u_{xresL}^2]$
$u_c = \boxed{\qquad} \times 10^{-6}$ from two or three traces

$A_F = \boxed{\qquad}$ μm from Trace “d”
$w_{1F} = \boxed{\qquad}$ from Trace “d”
$A_S = \boxed{\qquad}$ μm from Trace “d”
$w_{3S} = \boxed{\qquad}$ from Trace “d”
$x_{eF} = \boxed{\qquad}$ μm from Trace “d”
$x_{eS} = \boxed{\qquad}$ μm from Trace “d”
$\varepsilon_{r0} = \boxed{\qquad} \times 10^{-6}$ from Trace “d”
$\varepsilon_r = \boxed{\qquad} \times 10^{-6}$ from Trace “d”

Report the results as follows: Since it can be assumed that the possible estimated values are either approximately uniformly distributed or Gaussian with approximate standard deviation u_c, the residual strain is believed to lie in the interval $\varepsilon_r \pm u_c$ with a level of confidence of approximately 68 % assuming a Gaussian distribution.

Modify the input data, given the information supplied in any flagged statement below, if applicable, then recalculate:

1. ☐ Please fill out the entire form.
2. ☐ The value for t should be between 0.000 μm and 10.000 μm.
3. ☐ The value for the design length should be between 0 μm and 1000 μm.
4. ☐ The measured value for L is more than $3u_{cL}$ from the design length.
5. ☐ Is the magnification appropriate given the design length?
6. ☐ Magnifications at or less than 2.5× shall not be used.
7. ☐ Is $0.95 < calx < 1.05$ but not equal to “1”? If not, recheck your x-calibration.
8. ☐ The value for *interx* should be between 0 μm and 1500 μm.
9. ☐ The value for σ_{xcal} should be between 0 μm and 4 μm.
10. ☐ The value for x_{res} should be between 0 μm and 2.00 μm.
11. ☐ Is $0.95 < calz < 1.05$ but not equal to “1”? If not, recheck your z-calibration.
12. ☐ The value for *cert* should be greater than 0 μm and less than 25 μm.
13. ☐ The value for σ_{zcal} should be between 0 μm and 0.050 μm.
14. ☐ The value for z_{res} should be greater than 0 μm and less than or equal to 0.005 μm.
15. ☐ The value for R_{tave} should be between 0 μm and 0.100 μm.
16. ☐ Alignment has not been ensured.
17. ☐ Data has not been leveled.
18. ☐ $x1_{\mathrm{min}}$ should be greater than $x1_{\mathrm{max}}$.
19. ☐ $x2_{\mathrm{min}}$ should be greater than $x1_{\mathrm{min}}$.
20. ☐ $x2_{\mathrm{max}}$ should be greater than $x2_{\mathrm{min}}$.
21. ☐ The calibrated values for $x1_{\mathrm{min}}$ and $x1_{\mathrm{max}}$ are greater than 10 μm apart.
22. ☐ The calibrated values for $x2_{\mathrm{min}}$ and $x2_{\mathrm{max}}$ are greater than 10 μm apart.
23. ☐ In Traces “b,” “c,” and “d,” the value for s is not the same.
24. ☐ $x1_{\mathrm{ave}}$ should be $\leq (x_{1F} * calx)$ in all traces.
25. ☐ $(x_{3S} * calx)$ should be $\leq x2_{\mathrm{ave}}$ in all traces.
26. ☐ In all traces, make sure $(x_{1F} < x_{2F} < x_{3F})$.
27. ☐ In all traces, make sure $(x_{1S} < x_{2S} < x_{3S})$.
28. ☐ For Trace “b,” $|[(x_{2F} * calx) - x_{eF}]| =$ ☐ μm. This should be < 5 μm.
    If not, choose (x_{2F}, z_{2F}) such that $(x_{2F} * calx)$ is closer to $x_{eF} =$ ☐ μm.
29. ☐ For Trace “b,” $|[(x_{2S} * calx) - x_{eS}]| =$ ☐ μm. This should be < 5 μm.
    If not, choose (x_{2S}, z_{2S}) such that $(x_{2S} * calx)$ is closer to $x_{eS} =$ ☐ μm.
30. ☐ For Trace “c,” $|[(x_{2F} * calx) - x_{eF}]| =$ ☐ μm. This should be < 5 μm.
    If not, choose (x_{2F}, z_{2F}) such that $(x_{2F} * calx)$ is closer to $x_{eF} =$ ☐ μm.
31. ☐ For Trace “c,” $|[(x_{2S} * calx) - x_{eS}]| =$ ☐ μm. This should be < 5 μm.
    If not, choose (x_{2S}, z_{2S}) such that $(x_{2S} * calx)$ is closer to $x_{eS} =$ ☐ μm.
32. ☐ For Trace “d,” $|[(x_{2F} * calx) - x_{eF}]| =$ ☐ μm. This should be < 5 μm.
    If not, choose (x_{2F}, z_{2F}) such that $(x_{2F} * calx)$ is closer to $x_{eF} =$ ☐ μm.

33. ☐ For Trace “d,” $\left|[(x_{2S} * calx) - x_{eS}]\right|$ = ☐ µm. This should be < 5 µm.
If not, choose (x_{2S}, z_{2S}) such that (x_{2S} * $calx$) is closer to x_{eS} = ☐ µm.

Return to Main MEMS Calculator Page.

Email questions or comments to mems-support@nist.gov.

APPENDIX C – Data Analysis Sheet SG.1

Data analysis sheet for strain gradient measurements

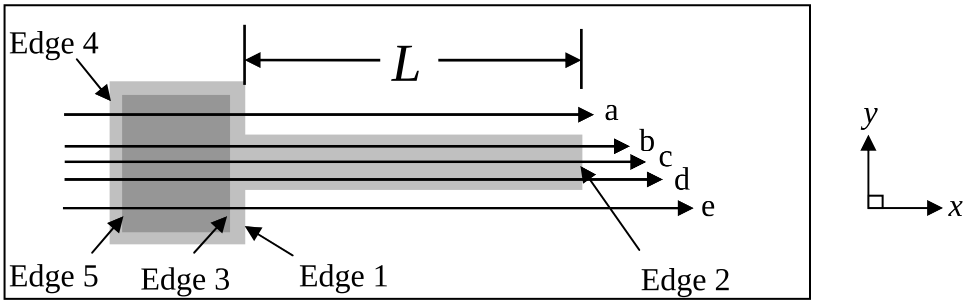

Figure SG.1.1. Top view of cantilever test structure used to measure strain gradient.

To obtain the following measurements, consult ASTM standard test method E 2246 entitled “Standard Test Method for Strain Gradient Measurements of Thin, Reflecting Films Using an Optical Interferometer.”

---

date data taken (optional) = ☐ / ☐ / ☐
identifying words (optional) = ☐
instrument used (optional) = ☐
fabrication facility/process (optional) = ☐
test chip name/number (optional) = ☐
filename of 3-D data set (optional) = ☐
filename of 2-D data traces (optional) = ☐
☐ ☐
☐ ☐

Table 1 - Preliminary ESTIMATES			**Description**
1	*material =*	Poly1 ○ Poly2 ○ stacked Poly1 and Poly2 ○ SiC-2 ○ SiC-3 ○ other ●	material
2	*design length =*	☐ μm	design length
3	*which cantilever?*	First ○ Second ○ Third ○ Fourth ○ Fifth ○ Other ●	which cantilever on the test chip?
4	*magnification =*	☐ ×	magnification
		0° ○ 90° ○	

5	*orientation* =	180° ○ 270° ○ other ●	orientation of the cantilever on the chip
6	*calx* =		*x*-calibration factor (for the given magnification)
7	*interx* =	µm	maximum field of view (for the given magnification)
8	σ_{xcal} =	µm	one sigma uncertainty in a ruler measurement (for the given magnification)
9	x_{res} =	µm	resolution of the interferometer in the *x*-direction
10	*calz* =		*z*-calibration factor (for the given magnification)
11	*cert* =	µm	certified value of double-sided physical step height used for calibration
12	σ_{zcal} =	µm	standard deviation of step height measurements (on double-sided physical step height)
13	z_{res} =	µm	resolution of the interferometer in the *z*-direction
14	R_{tave} =	µm	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 of which is taken from a different 2-D data trace
15	*aligned?*	Yes ○ No ●	alignment ensured?
16	*leveled?*	Yes ○ No ●	data leveled?
17	*stiction?*	Yes ○ No ●	Is this cantilever exhibiting stiction? (If it is exhibiting stiction, do not fill out the remainder of this form.)

Input Sample Data

Reset this form

Table 2 – INPUTS (uncalibrated values from Trace “a” or “e”)			**Notes**
18	$x1_{max}$ (i.e., $x1_{upper}$) =	µm	
19	$x1_{min}$ (i.e., $x1_{lower}$) =	µm	($x1_{min} > x1_{max}$)

Table 3 – INPUTS (uncalibrated values from Trace "b")			**Notes**
20	x_1 = µm	z_1 = µm	$(x1_{\text{ave}} \le x_1 * calx)$
21	x_2 = µm	z_2 = µm	$(x1_{\text{ave}} \le x_2 * calx)$
22	x_3 = µm	z_3 = µm	$(x1_{\text{ave}} \le x_3 * calx)$

Table 4 – INPUTS (uncalibrated values from Trace "c")			**Notes**
23	x_1 = µm	z_1 = µm	$(x1_{\text{ave}} \le x_1 * calx)$
24	x_2 = µm	z_2 = µm	$(x1_{\text{ave}} \le x_2 * calx)$
25	x_3 = µm	z_3 = µm	$(x1_{\text{ave}} \le x_3 * calx)$

Table 5 – INPUTS (uncalibrated values from Trace "d")			**Notes**
26	x_1 = µm	z_1 = µm	$(x1_{\text{ave}} \le x_1 * calx)$
27	x_2 = µm	z_2 = µm	$(x1_{\text{ave}} \le x_2 * calx)$
28	x_3 = µm	z_3 = µm	$(x1_{\text{ave}} \le x_3 * calx)$

Calculate and Verify Clear Outputs

OUTPUTS (calibrated values):

$x1_{\text{ave}}$ = µm
s = from Trace "c"
s = 1 (for downward bending cantilevers or if data was taken from the bottom of an upward bending cantilever)
s = −1 (for upward bending cantilevers unless data was taken from the bottom of an upward bending cantilever)

R_{int} = µm from Trace "b"
a = µm from Trace "b"
b = µm from Trace "b"
s_g = m^{-1} from Trace "b"

R_{int} = µm from Trace "c"
a = µm from Trace "c"
b = µm from Trace "c"
s_g = m^{-1} from Trace "c" (USE THIS VALUE)
u_W = m^{-1} from two or three traces
u_{samp} = m^{-1} from Trace "c"

u_{xcal} = ☐ m^{-1} from Trace “c”
u_{zcal} = ☐ m^{-1} from Trace “c”
u_{zres} = ☐ m^{-1} from Trace “c”
u_{xres} = ☐ m^{-1} from Trace “c”
u_c = SQRT[$u_W^2 + u_{samp}^2 + u_{xcal}^2 + u_{zcal}^2 + u_{zres}^2 + u_{xres}^2$]
u_c = ☐ m^{-1} from two or three traces

R_{int} = ☐ μm from Trace “d”
a = ☐ μm from Trace “d”
b = ☐ μm from Trace “d”
s_g = ☐ m^{-1} from Trace “d”

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

Modify the input data, given the information supplied in any flagged statement below, if applicable, then recalculate:

1. ☐ Please fill out the entire form.
2. ☐ The value for the design length should be between 0 μm and 1000 μm.
3. ☐ Is the magnification appropriate given the design length?
4. ☐ Magnifications at or less than 2.5× shall not be used.
5. ☐ Is 0.95< *calx* < 1.05 but not equal to “1”? If not, recheck your *x*-calibration.
6. ☐ The value for *interx* should be between 0 μm and 1500 μm.
7. ☐ The value for σ_{xcal} should be between 0 μm and 4 μm.
8. ☐ The value for x_{res} should be between 0 μm and 2.00 μm.
9. ☐ Is 0.95 < *calz* < 1.05 but not equal to “1”? If not, recheck your *z*-calibration.
10. ☐ The value for *cert* should be greater than 0 μm and less than 25 μm.
11. ☐ The value for σ_{zcal} should be between 0 μm and 0.050 μm.
12. ☐ The value for z_{res} should be greater than 0 μm and less than or equal to 0.005 μm.
13. ☐ The value for R_{tave} should be between 0 μm and 0.100 μm.
14. ☐ Alignment has not been ensured.
15. ☐ Data has not been leveled.
16. ☐ $x1_{\text{min}}$ should be greater than $x1_{\text{max}}$.
17. ☐ The calibrated values for $x1_{\text{min}}$ and $x1_{\text{max}}$ are greater than 10 μm apart.
18. ☐ In Trace “b,” the calibrated values of x_1, x_2, and x_3 should be $\geq x1_{\text{ave}}$.
19. ☐ In Trace “c,” the calibrated values of x_1, x_2, and x_3 should be $\geq x1_{\text{ave}}$.
20. ☐ In Trace “d,” the calibrated values of x_1, x_2, and x_3 should be $\geq x1_{\text{ave}}$.
21. ☐ In Traces “b,” “c,” and “d,” the value for *s* is not the same.

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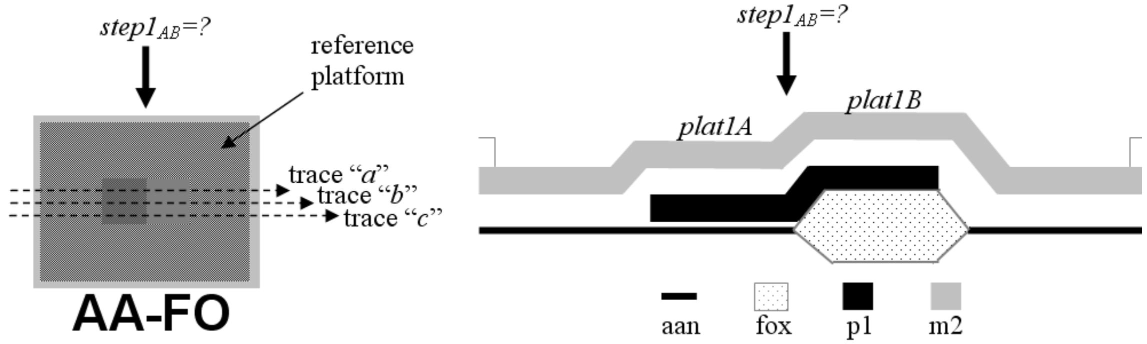
APPENDIX D – Data Analysis Sheet SH.1

Data analysis sheet for step height measurements from one step height test structure.



a) b)

Figure SH.1.1. For a CMOS step height test structure: a) a design rendition and b) a cross-section.

To obtain the following measurements, consult SEMI standard test method MS2 entitled "Test Method for Step Height Measurements of Thin Films."

---

date data taken (optional) = ☐ / ☐ / ☐
identifying words (optional) = ☐
instrument used (optional) = ☐
fabrication facility (optional) = ☐
test chip name/number (optional) = ☐
filename of 3-D data set (optional) = ☐

Table 1 - Preliminary INPUTS			
Data Set Prelims			**Description**
1	*proc* =	MUMPs ○ CMOS ● other ○	which process?
2	*which* =	first ● second ○ third ○ fourth ○ fifth ○ other ○	which step height measurement, test structure, or quad?
3	*orient* =	0° ● 90° ○ 180° ○ 270° ○ other ○	orientation of the test structure on the test chip
4	*mag* =	☐ ×	magnification
5	*align* =	Yes ○ No ●	alignment ensured?

6	*level* =	Yes ○ No ●	data leveled?
7	*cert* =	☐ µm	certified value of physical step height used for calibration
8	s_{cert} =	☐ µm	certified one sigma uncertainty of certified physical step height used for calibration
9	z_{repeat} =	☐ µm	maximum uncalibrated range of the six calibration measurements taken before the data session at the same location on the physical step height or after the data session at the same location on the physical step height (whichever is larger)
10	$\bar{z}_6$ =	☐ µm	the uncalibrated average of the six calibration measurements from which z_{repeat} was found
11	z_{drift} =	☐ µm	uncalibrated drift in the calibration data (i.e., 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 and the average of the six calibration measurements taken after the data session at the same location on the physical step height)
12	cal_z =	☐	the *z*-calibration factor = the certified value of the physical step height divided by the average of the twelve calibration measurements taken at the same location on the physical step height
13	z_{perc} =	☐ %	if applicable, over the instrument's total scan range, the maximum percent deviation from linearity, as quoted by the instrument manufacturer (typically less than 3 %)
14	$\sigma_{roughNX}$=	☐ µm	the uncalibrated surface roughness of *platNX* measured as the smallest of all the values obtained for $\sigma_{platNXt}$. (However, if the surfaces of *platNX*, *platNY*, and *platNr* all have identical compositions, then it is measured as the smallest of all the values obtained for $\sigma_{platNXt}$, $\sigma_{platNYt}$, and $\sigma_{platNrDt}$ in which case $\sigma_{roughNX}$=$\sigma_{roughNY}$.)
15	$\sigma_{roughNY}$=	☐ µm	the uncalibrated surface roughness of *platNY* measured as the smallest of all the values obtained for $\sigma_{platNYt}$. (However, if the surfaces of *platNX*, *platNY*, and *platNr* all have identical compositions, then it is measured as the smallest of all the values obtained for $\sigma_{platNXt}$, $\sigma_{platNYt}$, and $\sigma_{platNrDt}$ in which case $\sigma_{roughNX}$=$\sigma_{roughNY}$.)

Input Sample Data Reset this form

Calculate and Verify Clear Outputs

Nomenclature:

“*N*” refers to the test structure number (“*1*,” “*2*,” “*3*,” etc.),
“*X*” and “*Y*” refer to the platform letter (“*A*,” “*B*,” “*C*,” etc.),
“*r*” indicates a reference platform,
“*D*” directionally indicates which reference platform, and
“*t*” indicates which data trace (“*a*,” “*b*,” or “*c*”).

Table 2 – Platform INPUTS and CALCULATIONS								
Uncalibrated PLATFORM INPUTS (in μm)						**Calibrated CALCULATIONS (in μm)**		
1	$platNXa$ =		**7**	$platNYa$ =		**13**	$stepN_{XYa}$ =	
2	$platNXb$ =		**8**	$platNYb$ =		**14**	$stepN_{XYb}$ =	
3	$platNXc$ =		**9**	$platNYc$ =		**15**	$stepN_{XYc}$ =	
4	$\sigma_{platNXa}$ =		**10**	$\sigma_{platNYa}$ =				
5	$\sigma_{platNXb}$ =		**11**	$\sigma_{platNYb}$ =		**16**	$\sigma_{platNXave}$ =	
6	$\sigma_{platNXc}$ =		**12**	$\sigma_{platNYc}$ =		**17**	$\sigma_{platNYave}$ =	

NOTE 1: $stepN_{XYt} = cal_z * (platNYt – platNXt)$
NOTE 2: $\sigma_{platNXave} = cal_z *$ AVE$(\sigma_{platNXa}, \sigma_{platNXb}, \sigma_{platNXc})$
NOTE 3: $\sigma_{platNYave} = cal_z *$ AVE$(\sigma_{platNYa}, \sigma_{platNYb}, \sigma_{platNYc})$

Table 3 - Calibrated OUPTUTS (in μm)								
	$stepN_{XY}$	u_{Lstep}	u_{Wstep}	u_{cert}	u_{repeat}	u_{drift}	u_{linear}	u_c
18								

NOTE 4: $stepN_{XY}$ = AVE $(stepN_{XYa}, stepN_{XYb}, stepN_{XYc})$
NOTE 5: u_{Lstep} = SQRT$[(\sigma_{platNXave} – cal_z*\sigma_{roughNX})^2+(\sigma_{platNYave} – cal_z*\sigma_{roughNY})^2]$
NOTE 6: $u_{Wstep} = s_{stepNXY}$ = STDEV$(stepN_{XYa}, stepN_{XYb}, stepN_{XYc})$
NOTE 7: $u_{cert} = |s_{cert} * stepN_{XY} / cert|$
NOTE 8: $u_{repeat} = |z_{repeat} * stepN_{XY} / (2 * 1.732 * \bar{z}_6)|$
NOTE 9: $u_{drift} = |(z_{drift} * cal_z) * stepN_{XY} / (2 * 1.732 * cert)|$
NOTE 10: $u_{linear} = |z_{perc} * stepN_{XY} / (1.732)|$
NOTE 11: u_c = SQRT$(u_{Lstep}^2 + u_{Wstep}^2 + u_{cert}^2 + u_{repeat}^2 + u_{drift}^2 + u_{linear}^2)$

Report the results as follows: Since it can be assumed that the possible estimated values are either approximately uniformly distributed or Gaussian with approximate standard deviation u_c, the step height is believed to lie in the interval $stepN_{XY} \pm u_c$ with a level of confidence of approximately 68 % assuming a Gaussian distribution.

Modify the input data, given the information supplied in any flagged statement below, if applicable, then recalculate:

1. wait Please completely fill out the Preliminary Inputs Table.
2. Is the magnification appropriately greater than 2.5×?
3. wait Alignment has not been ensured.
4. wait Data has not been leveled.
5. The value for *cert* should be between 0.000 μm and 15.000 μm.
6. The value for s_{cert} should be between 0.000 μm and 0.100 μm.
7. The value for z_{repeat} should be between 0.000 μm and 0.050 μm.

8. ☐ The value for $\bar{z}_6$ should be between ($cert$–0.100 µm)/cal_z and ($cert$+0.100 µm)/cal_z.
9. ☐ The value for z_{drift} should be between 0.000 µm and 0.050 µm, inclusive.
10. ☐ The value for cal_z should be between 0.900 and 1.100, but not equal to 1.000.
11. ☐ The value for z_{perc} should be between 0.0 % and 3.0 %, inclusive.
12. ☐ The values for $\sigma_{roughNX}$ and $\sigma_{roughNY}$ should be greater than 0.0 µm and less than or equal to the smallest measured value for $\sigma_{platNXt}$ and $\sigma_{platNYt}$, respectively.
13. ☐ All the platform inputs have not been provided.
14. ☐ More platform inputs are required for standard deviation calculations.
15. ☐ The values for $platNXt$ and $platNYt$ should be between –2.500 µm and 2.500 µm.
16. ☐ The values for $\sigma_{platNXt}$ and $\sigma_{platNYt}$ should be between 0.00 µm and 0.025 µm, inclusive.
17. ☐ The value for $stepN_{XY}$ should be between –2.500 µm and 2.500 µm.
18. ☐ The values for u_{Lstep} and u_{Wstep} should be less than 0.025 µm.

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APPENDIX E – Data Analysis Sheet L.1

Data analysis sheet for in-plane length measurements with two ends anchored (or for an inside edge-to-inside edge length measurement)

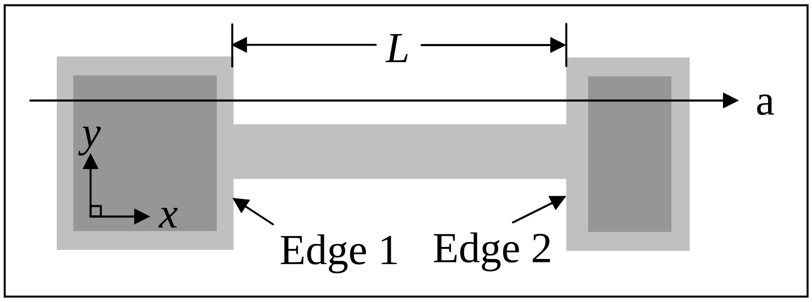

Figure L.1.1. Top view of a fixed-fixed beam test structure depicting the measurement to be made, where Edge 1 and Edge 2 are considered inside edges.

To obtain the following measurements, consult ASTM standard test method E2244 entitled “Standard Test Method for In-Plane Length Measurements of Thin, Reflecting Films Using an Optical Interferometer.”

---

date data taken (optional) = ☐ / ☐ / ☐
identifying words (optional) = ☐
instrument used (optional) = ☐
fabrication facility/process (optional) = ☐
test chip name/number (optional) = ☐
filename of 3-D data set (optional) = ☐
filename of 2-D data trace (optional) = ☐

Table 1 - Preliminary ESTIMATES			**Description**
1	*material* =	Poly1 ○ Poly2 ○ stacked Poly1 and Poly2 ○ SiC-2 ○ SiC-3 ○ other ●	material
2	*design length* =	☐ μm	design length
3	*magnification* =	☐ ×	magnification
4	*orientation* =	0° ○ 90° ○ other ●	orientation on the chip
5	*calx* =	☐	*x*-calibration factor (for the given magnification)
6	*interx* =	☐ μm	interferometer’s maximum field of view (for the given magnification)
7	σ_{xcal} =	☐ μm	one sigma uncertainty in a ruler measurement (for the given

			magnification)
8	x_{res} =	µm	resolution of the interferometer in the *x*-direction
9	*calz* =		*z*-calibration factor (for the given magnification)
10	*aligned?*	Yes ○ No ●	alignment ensured?
11	*leveled?*	Yes ○ No ●	data leveled?

Input Sample Data Reset this form

Table 2 – INPUTS (uncalibrated values)			**Notes**
12	$x1_{max}$ (i.e., $x1_{upper}$) =	µm	
13	$x1_{min}$ (i.e., $x1_{lower}$) =	µm	($x1_{min} > x1_{max}$)
14	$x2_{min}$ (i.e., $x2_{lower}$) =	µm	($x2_{min} > x1_{min}$)
15	$x2_{max}$ (i.e., $x2_{upper}$) =	µm	($x2_{max} > x2_{min}$)

Calculate and Verify Clear Outputs

Table 3 – OUTPUTS (calibrated values)			**Equation**
16	L_{min} =	µm	$L_{min} = (x2_{min} - x1_{min}) * calx$
17	L_{max} =	µm	$L_{max} = (x2_{max} - x1_{max}) * calx$
18	L =	µm	in-plane length $L = (L_{min} + L_{max}) / 2$
19	u_L =	µm	$u_L = (L_{max} - L_{min}) / 6$
20	u_{xcal} =	µm	$u_{xcal} = (\sigma_{xcal} / interx) * (L / calx)$
21	u_{xres} =	µm	$u_{xres} = x_{res} * calx / 1.732$
22	u_c =	µm	combined standard uncertainty $u_c = \mathrm{SQRT}[u_L^2 + u_{xcal}^2 + u_{xres}^2]$

Report the results as follows: Since it can be assumed that the possible estimated values are either approximately uniformly distributed or Gaussian with approximate standard deviation u_c, the length is believed to lie in the interval $L \pm u_c$ with a level of confidence of approximately 68 % assuming a Gaussian distribution.

Modify the input data, given the information supplied in any flagged statement below, if applicable, then recalculate:

1. ☐ Please fill out the entire form.
2. ☐ The design length should be between 0 µm and 1050 µm.

3. ☐ The measured value for L is more than $3u_c$ from the design length.
4. ☐ Is the magnification appropriate given the design length ?
5. ☐ Magnifications at or less than 2.5× shall not be used.
6. ☐ Is $0.95 < calx < 1.05$ but not equal to “1”? If not, recheck your x-calibration.
7. ☐ The value for *interx* should be between 0 μm and 1500 μm.
8. ☐ The value for σ_{xcal} should be between 0 μm and 4 μm.
9. ☐ The value for x_{res} should be between 0 μm and 1.57 μm.
10. ☐ Is $0.95 < calz < 1.05$ but not equal to “1”? If not, recheck your z-calibration.
11. ☐ Alignment has not been ensured.
12. ☐ Data has not been leveled.
13. ☐ $x1_{\text{min}}$ should be greater than $x1_{\text{max}}$.
14. ☐ $x2_{\text{min}}$ should be greater than $x1_{\text{min}}$.
15. ☐ $x2_{\text{max}}$ should be greater than $x2_{\text{min}}$.
16. ☐ The calibrated values for $x1_{\text{min}}$ and $x1_{\text{max}}$ are greater than 10 μm apart.
17. ☐ The calibrated values for $x2_{\text{min}}$ and $x2_{\text{max}}$ are greater than 10 μm apart.

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