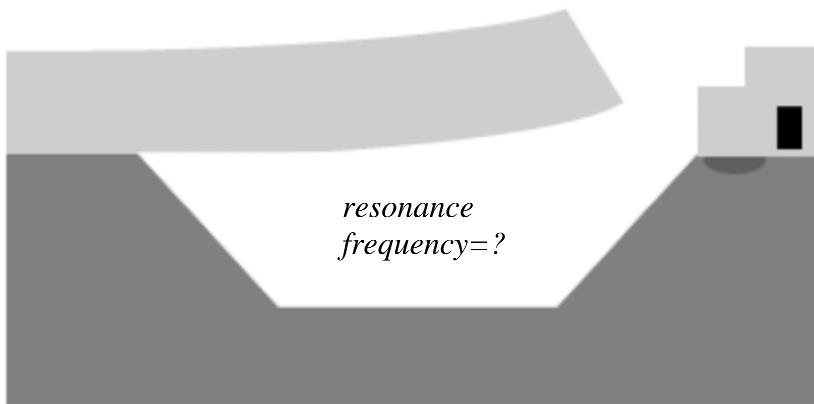
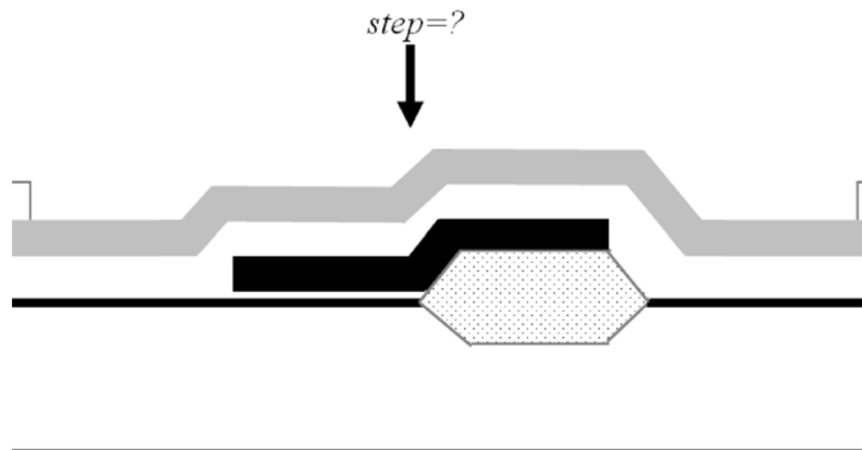
# User's Guide for the MEMS Young's Modulus and Step Height Round Robin Experiment (*Revision 1*)



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# USER'S GUIDE FOR THE MEMS YOUNG'S MODULUS AND STEP HEIGHT ROUND ROBIN EXPERIMENT

## ABSTRACT

This is the User's Guide for the MicroElectroMechanical Systems (MEMS) Young's Modulus and Step Height Round Robin Experiment. It provides details concerning the test equipment, the Round Robin Test Chips, the round robin measurements taken on these chips, and the submission of the data. The round robin measurements include Young's modulus measurements taken with an optical vibrometer, stroboscopic interferometer or comparable instrument and step height measurements taken with an optical interferometer or comparable instrument using the procedures in two Semiconductor Equipment and Materials International (SEMI) standard test methods. The purpose of the MEMS Young's Modulus and Step Height Round Robin Experiment is to educate the round robin participants concerning these test methods and to provide round robin results for the test methods.

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

USER'S GUIDE FOR THE
MEMS YOUNG'S MODULUS AND STEP HEIGHT ROUND ROBIN EXPERIMENT

## 1. INTRODUCTION

For the MicroElectroMechanical Systems (MEMS)[1] Young's Modulus and Step Height Round Robin Experiment, an optical vibrometer, stroboscopic interferometer, or comparable instrument is used to take Young's modulus measurements and an optical interferometer or comparable instrument is used to take step-height measurements. Two Semiconductor Equipment and Materials International (SEMI) standard test methods have been written for these measurements. The test methods have a mandatory section entitled "Precision and Bias" that reports round robin results using the test method. The purpose of the MEMS Young's Modulus and Step Height Round Robin Experiment is to educate the round robin participants and to provide round robin results for these Precision and Bias Statements.

Section 2 provides details concerning the MEMS Young's Modulus and Step Height Round Robin Experiment [e.g., details associated with the optical vibrometer, optical interferometer, or comparable instruments, the Round Robin Test Chip, the material available for the experiment, and the submission of the data]. Sections 3 and 4 provide details concerning the round robin measurements taken on the Round Robin Test Chip. The summary is given in Section 5. Reproductions of the Web-based data analysis sheets [1] used for recording the round robin data and making calculations are given in the Appendices.

## 2. MEMS YOUNG'S MODULUS AND STEP HEIGHT ROUND ROBIN EXPERIMENT

This section provides details concerning the MEMS Young's Modulus and Step Height Round Robin Experiment. It is divided into five parts. Section 2.1 provides equipment specifications for the optical vibrometer,[2] optical interferometer, and comparable instruments, Section 2.2 describes the Round Robin Test Chip, Section 2.3 describes the packaged Round Robin Test Chip, Section 2.4 describes the material available for the experiment, and Section 2.5 discusses the submission of the round robin data.

### 2.1 *Equipment Specifications*

For the MEMS Young's Modulus and Step Height Round Robin Experiment, 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 step height

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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.

measurements, an optical interferometer or comparable instrument is required, as specified in subsection 2.1.2.

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

For Young's modulus measurements, an optical vibrometer, stroboscopic interferometer, or comparable instrument is used 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 scattered back. The reflected laser light interferes with the reference beam at the beam splitter. A photodetector records the interfered scattered light, converting the interference signal 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.

For a dual beam laser vibrometer, along with the measurement beam, an additional beam (the reference beam) which emanates from the beam splitter is positioned to a point on the sample (by means of mirrors) and is scattered back. Once again, the two beams optically combine at the beam splitter; however, this time the reference beam is instrumental in subtracting out any movement of the sample also experienced by the measurement beam.

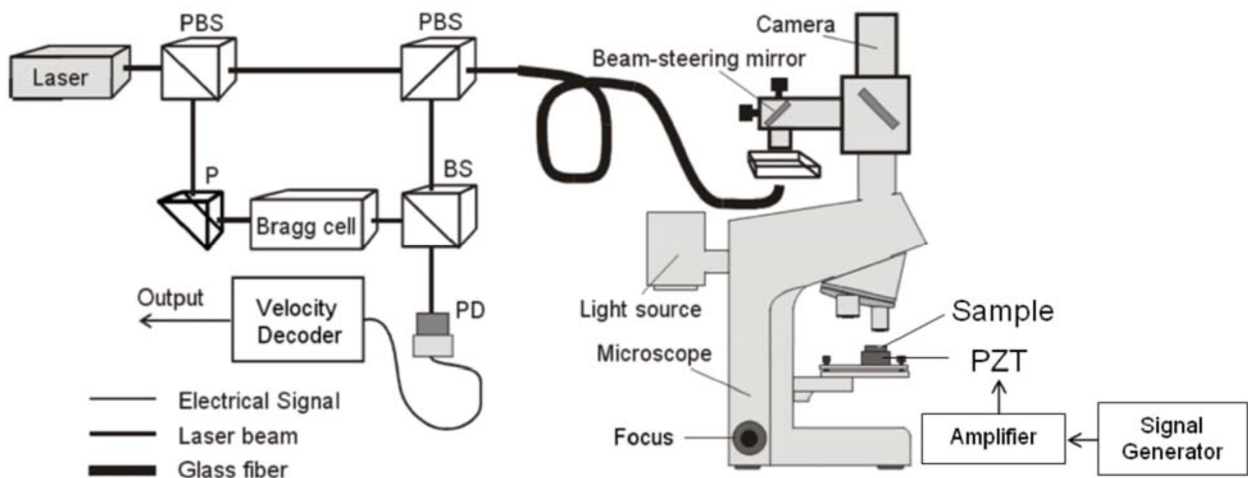


Figure 1. Schematic of a typical setup for a single beam laser vibrometer. (PBS indicates a polarizing beam splitter; BS indicates a beam splitter; P indicates a prism; and PD indicates a photodetector.)

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 interferometric 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 is 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 that is used to actuate the device. The sample is actuated by placing it on 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.

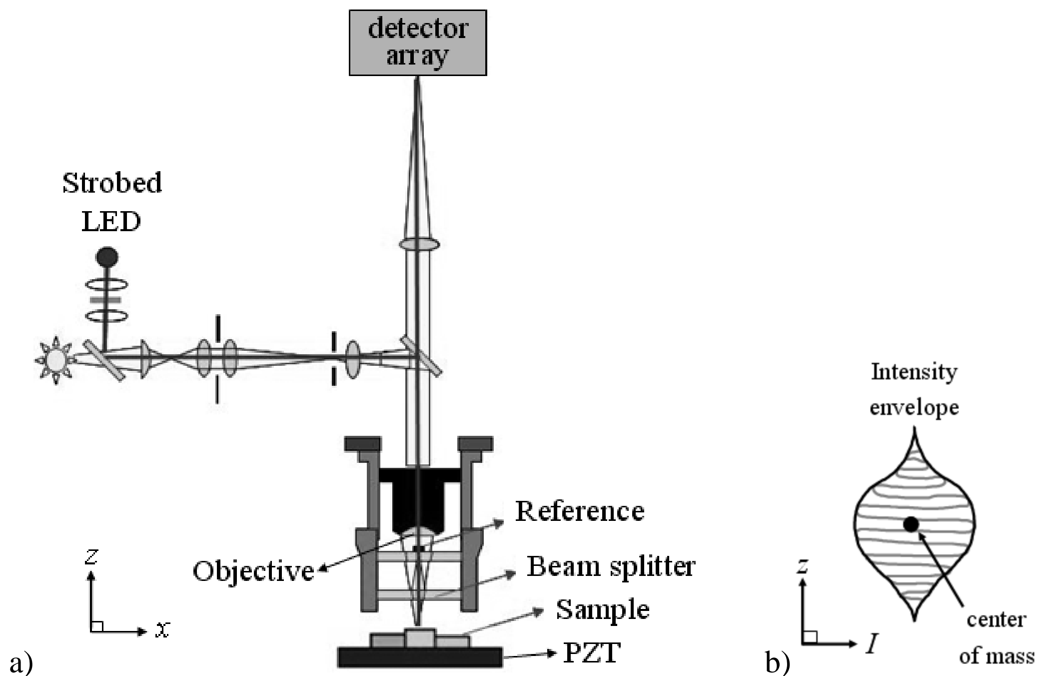


Figure 2. For a typical stroboscopic interferometer a) a schematic and b) an intensity envelope used to obtain a pixel's sample height

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

1. At least two magnification objectives (such as, 4× and 20×) should be provided with the instrument.

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 cantilever 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 shall be capable of obtaining 3-D images of oscillations in order to ascertain if the correct frequency peak has been chosen as the cantilever'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]

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

   where $E_{init}$ is an initial estimate for the Young's modulus value of the thin film layer, $t$ is the thickness, $\rho$ 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, if the value for $p_{diff}$ as calculated in the following equation is greater than or equal to 2 %:[7]

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

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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 [1], the given calculation can be performed on-line in a matter of seconds.
[6] Ibid.
[7] Ibid.

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

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

where $\mu$ is the viscosity (in air, $\mu$ =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 step height measurements, an optical interferometer or comparable instrument is used which is capable of obtaining topographical 2-D data traces. 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 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. (This optical interferometer can also be used for measurements taken with ASTM E 2244, ASTM E 2245, and ASTM E 2246.)

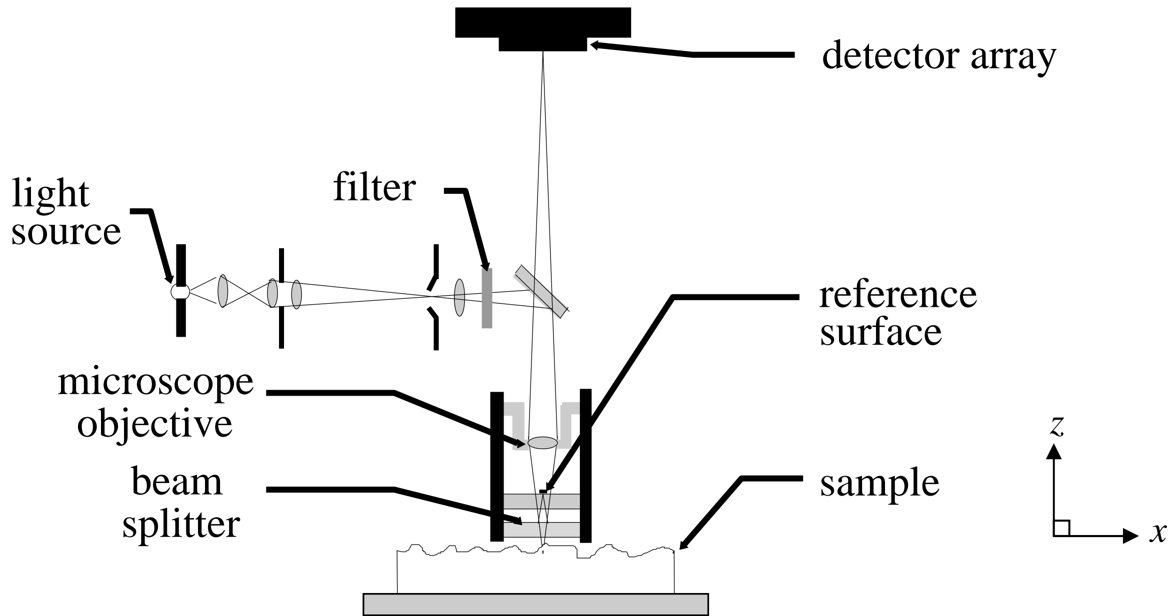



Figure 3. Schematic of an optical interferometer.

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

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 *Round Robin Test Chip*

The MEMS Round Robin Test Chip was fabricated on the 1.5 μm AMIS process available through MOSIS [2]. The design for this test 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 round robin test chip from the Semiconductor Electronics Division (SED) MEMS Calculator Web site [1].

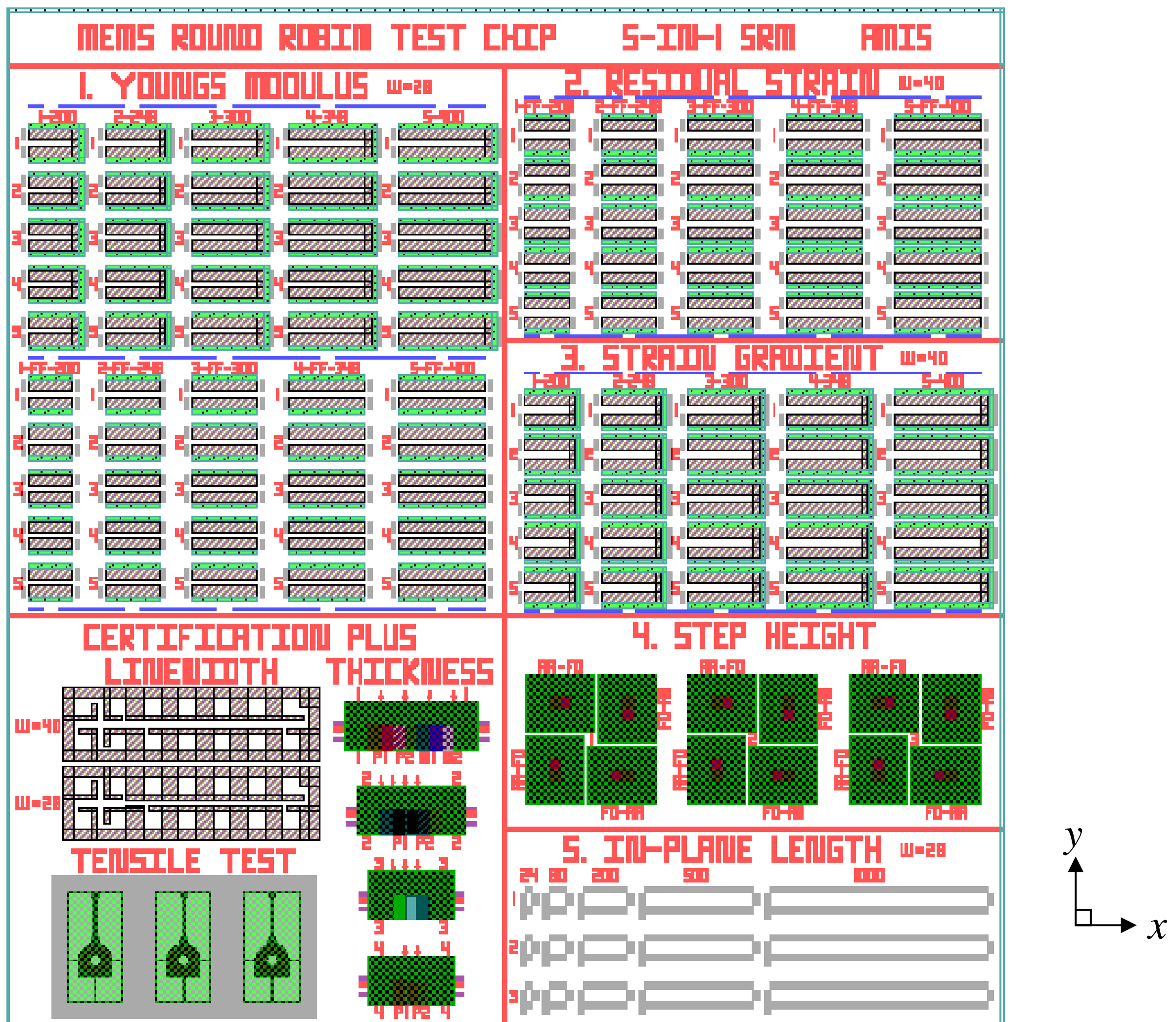



Figure 4. The round robin test chip fabricated on the 1.5 μm AMIS process through MOSIS.

For the round robin 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 has been removed.

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.

However, for the MEMS Young's Modulus and Step Height Round Robin Experiment, we will only be concerned with the first and fourth groupings of test structures. Grouping "1" contains all of the test structures (namely cantilevers and fixed-fixed beams) required for a Young's modulus measurement. Grouping "4" contains the step height test structures required for step-height measurements.

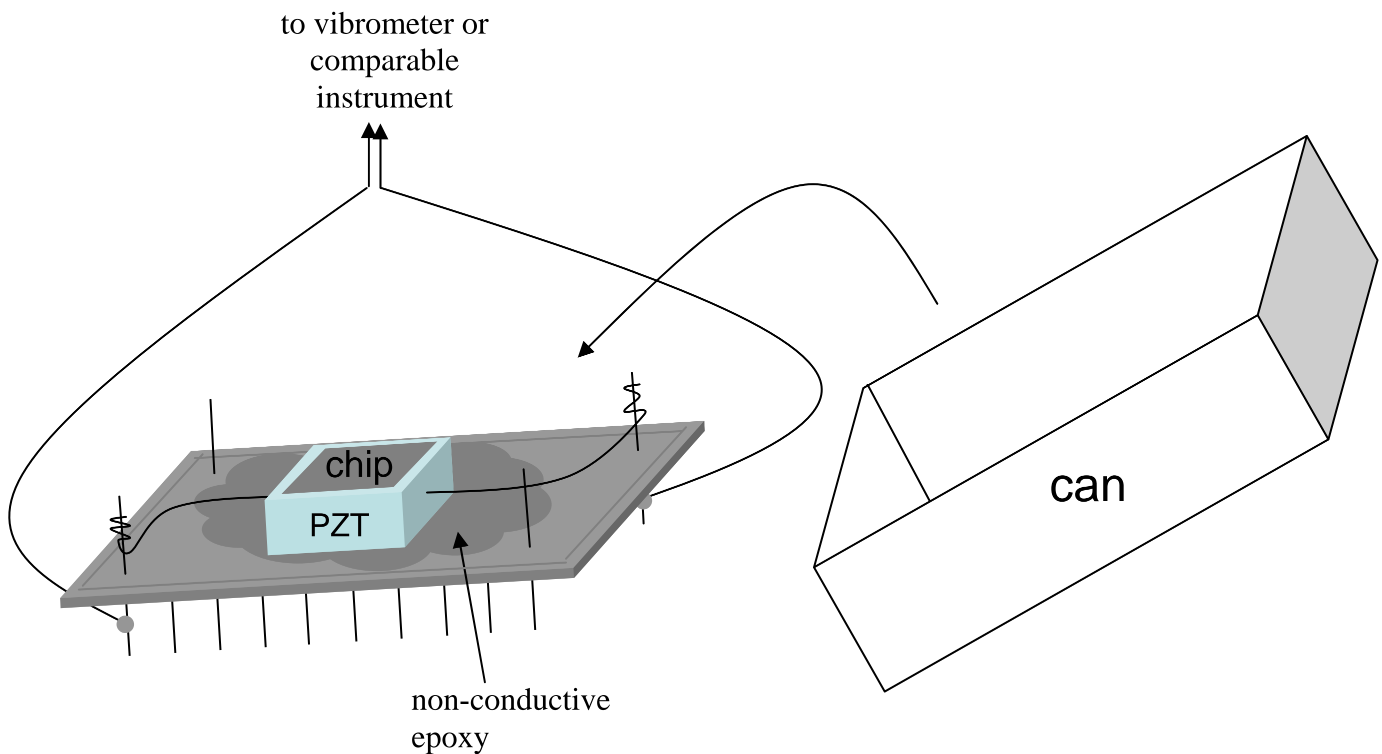



Figure 5. The packaged Round Robin Test Chip

2.3 *Packaged Round Robin Test Chip*

Each round robin participant will receive a packaged Round Robin Test Chip, as shown in figure 5. The packaged part was put together in the following way:

1. Starting with the package, a thin layer of low stress, non-conducting epoxy

was spread on the bottom of the package.

2. The PZT was placed on top of this epoxy and the epoxy was allowed to dry, thus securing the PZT to the package. 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 two wire leads (as seen in figure 5) for connection to the package.
   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 different package pins.
4. The test chip was secured to the top of the PZT using a low stress non-conducting epoxy.
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 the round robin measurements, the can is carefully removed. For Young's modulus measurements, in order to activate the PZT, electrical connections are made to the two pins that the PZT wires are connected. 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 Experiment*

Two SEMI standard test methods [3,4] have been written. They are:

- MS4, Test Method for Young's Modulus Measurements of Thin, Reflecting Films Based on the Frequency of Beams in Resonance and
- MS2, Test Method for Step-Height Measurements of Thin, Reflecting Films Using an Optical Interferometer

and they are available both electronically [3,4] and on CD-ROM. A copy of each standard undergoing revision will be mailed in the packet of material that is sent to the round robin participant.

Use the appropriate test method to guide you through the measurements.[10] The test method for Young's modulus measurements is used for the measurements in the first grouping of test structures (as located in Section 2.2). The test method for step height measurements is used for the fourth grouping of test structures (as located in Section 2.2).

If the user would like to see how the standard can be used or possible future applications, he or she can consult the references [5,6], which can be downloaded from the Semiconductor Electronics Division (SED) MEMS Calculator Web site [1].

2.5 *Submission of the Round Robin Data*

Sections 3 and 4 of this guide provide the participant with details concerning the measurements taken in the first and fourth groupings (for Young's modulus measurements and step-height measurements, respectively) of test structures on the test

[10] It is important that the round robin participants use the same procedures. The collected data will be reported in the Precision and Bias Statement towards the end of the appropriate standard test method.

chip. The raw, uncalibrated Young's modulus measurements are recorded in Data Analysis Sheet YM.1 [1] (a reproduction of which is given in Appendix A) and the raw, uncalibrated step-height measurements are recorded in Data Analysis Sheet SH.1 [1] (a reproduction of which is given in Appendix B). The calculations are performed on-line by pressing the "Calculate and Verify" button on the data analysis sheet. The participant is advised to correct any warnings given at the bottom of the data analysis sheet, after which this form can be printed out and mailed to the MEMS Young's Modulus and Step Height Round Robin Coordinator at the following address:

MEMS Young's Modulus and Step Height Round Robin Coordinator
100 Bureau Dr., Stop 8120
Gaithersburg, MD 20899-8120

For the MEMS Young's Modulus and Step Height Round Robin Experiment, the following number of completed data analysis sheets are requested:

1. Data Analysis Sheet YM.1 – 3 data sheets are requested – (see Section 3)
2. Data Analysis Sheet SH.1 – 2 data sheets are requested – (see Section 4)

Consult the appropriate section in the above list for more details. Results from these data analysis sheets will be included in the Precision and Bias Statement for the pertinent standard.

The completed data analysis sheets will be made available, upon request, to other robin-robin participants. Identifying information concerning whose data it is will be kept confidential. Therefore, it is expected that the round robin participant add no identifiers within their submitted data analysis sheets.

## 3. GROUPING 1: YOUNG'S MODULUS MEASUREMENTS

In the first grouping of test structures on the Round Robin Test Chip shown in figure 4, Young's modulus measurements are made. Cantilever and fixed-fixed beam test structures are provided for this purpose; however, in this round robin experiment we will only be concerned with the cantilevers, such as shown in figure 6. Configurations for the cantilevers are given in Table 2.

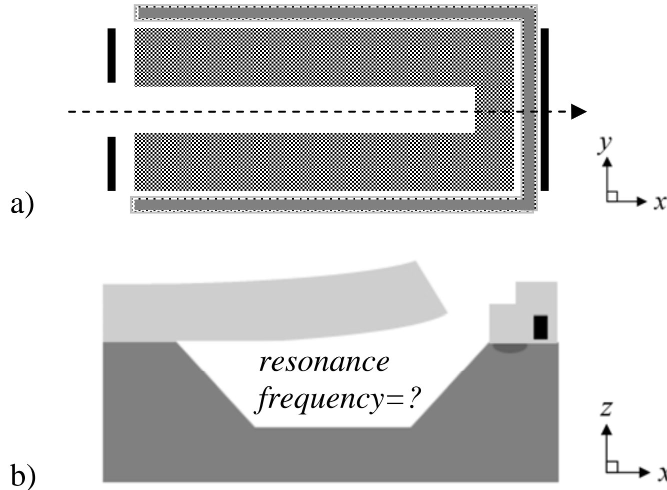



Figure 6. For a cantilever test structure on the test chip shown in figure 4 a) a design rendition and b) a cross section.

Table 2 – Cantilever Configurations

| **Test Structure** | **Width (in µm)** | **Length (in µm)** | **Orientation** | **Mechanical Layer** | **Quantity of Beams** |
|---|---|---|---|---|---|
| Cantilevers | 28 | 200, 248, 300, 348, 400 | 0 degree | oxide | 5 of each length (or 25 beams) |

As shown in Table 2, the cantilever design lengths are 200 µm, 248 µm, 300 µm, 348 µm, and 400 µm. The beams are designed at only a 0 degree orientation.[11] There are five cantilevers designed at each length. Therefore, there are twenty-five oxide cantilevers with a 0 degree orientation.

Measurements for Data Analysis Sheet YM.1 are requested for the MEMS Young's Modulus and Step Height Round Robin Experiment. More specifically, measurements from three oxide cantilevers on the Round Robin Test Chip are requested. (Therefore, 3 completed forms using Data Analysis Sheet YM.1 will be submitted to the round robin coordinator.) The participant will be informed of the cantilevers to be measured in a letter accompanying the packaged Round Robin Test Chip.

[11] A 0 degree 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.

For Young's modulus measurements taken with an optical vibrometer (or comparable instrument), orient the test chip with respect to the instrument such that as much of the length of the cantilever as possible appears within the measurement area of the instrument. Typically, the *x*-axis of the instrument provides a longer measurement range. If this is the case, align the length of the cantilever along the *x*-axis of the instrument.

For each Data Analysis Sheet YM.1 that is filled out, three resonance frequency measurements are requested from one cantilever. Obtain these measurements using the highest magnification objective that is available and feasible (e.g., a 20× objective).

Following SEMI standard MS4 for measuring Young's modulus, record the raw, uncalibrated measurements on Data Analysis Sheet YM.1. This data analysis sheet is accessible via the URL specified in the reference [1]. (A reproduction of Data Analysis Sheet YM.1 is given in Appendix A.) 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, modify the inputs as appropriate, and recalculate. After the data is successfully verified, print out the completed data analysis sheet.

Three completed forms using Data Analysis Sheet YM.1 are requested. (Therefore, the three completed forms will each provide a unique set of results.) The round robin results from these data analysis sheets will be reported in the Precision and Bias Statement for SEMI standard MS4. Mail the completed data analysis sheets to the MEMS Young's Modulus and Step Height Round Robin Coordinator at the address given in Section 2.5.

4. GROUPING 4: STEP HEIGHT MEASUREMENTS

In the fourth grouping of test structures on the Round Robin Test Chip shown in figure 4, step height measurements are made. Step height test structures are provided for this purpose as shown in figure 7 for a metal2-over-poly1 step from active area to field oxide. The surrounding reference platform consists of the deposited oxides and metal2 over active area.

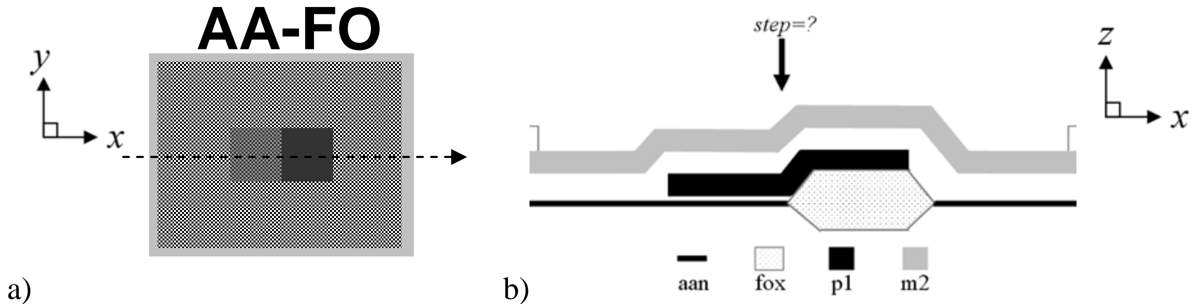



Figure 7. For the step height test structure on the test chip shown in figure 4 with a 0 degree orientation a) a design rendition and b) its cross section.

There are four orientations (0 degree, 90 degree, 180 degree, and 270 degree) of each step height test structure and these orientations are grouped in quads as shown in figure 8. For the Round Robin Test Chip Design in figure 4 there are three quads. The quad number is given in the center of the quad. Therefore, quad 2 (out of 3) is shown in figure 8.

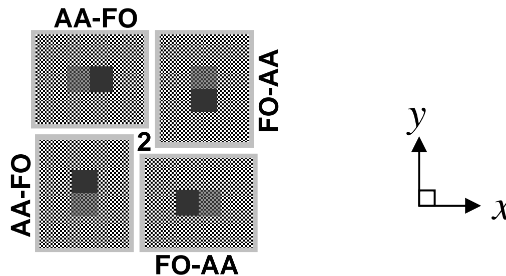



Figure 8. A design rendition of quad #2 from figure 4.

Measurements from Data Analysis Sheet SH.1 are requested for the MEMS Young's Modulus and Step Height Round Robin Experiment. More specifically, measurements from two step height test structures on the Round Robin Test Chip are requested. (Therefore, 2 completed forms using Data Analysis Sheet SH.1 will be submitted to the round robin coordinator.) The participant will be informed of the step

height test structures to be measured in a letter accompanying the packaged Round Robin Test Chip.

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 9 is parallel to the *x*-axis of the instrument.

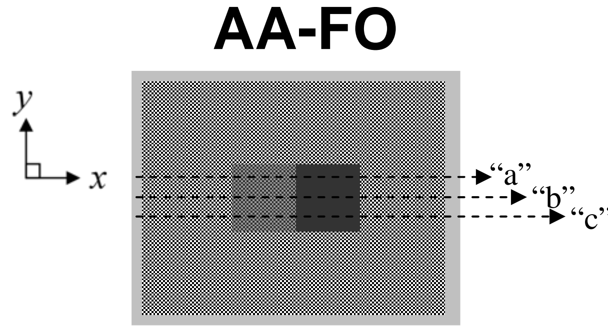



Figure 9. A design rendition of a step height test structure showing 2-D data traces "a," "b," and "c."

For each Data Analysis Sheet SH.1 that is filled out, three 2-D data traces ("a," "b," and "c," as shown in figure 9) are used to obtain the step height measurements. The platform height measurements and standard deviations from both of the central platforms in data traces "a," "b," and "c" are recorded. Therefore, twelve measurements are obtained (six from the first platform and six from the second platform). The height measurements are with respect to the height of the surrounding reference platform that is used to level and zero the data. Obtain these measurements using the most powerful objective possible (while choosing the appropriate field of view lens, if applicable) given the sample areas to be investigated.

Following SEMI standard MS2 for measuring step heights, record the raw, uncalibrated measurements on Data Analysis Sheet SH.1. This data analysis sheet is accessible via the URL specified in the reference [1]. (A reproduction of Data Analysis Sheet SH.1 is given in Appendix B.) Press the "Calculate and Verify" button (located near the center of the data analysis sheet) to obtain the results for the step height 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, modify the inputs as appropriate, and recalculate. After the data is successfully verified, print out the completed data analysis sheet.

Two completed forms using Data Analysis Sheet SH.1 are requested. (Therefore, the two completed forms will each provide a unique set of results.) The round robin results from these data analysis sheets will be reported in the Precision and Bias Statement for SEMI standard MS2. Mail the completed data analysis sheets to the MEMS Young's Modulus and Step Height Round Robin Coordinator at the address given in Section 2.5.

## 5. SUMMARY

In summary, this guide provided instructions for the MEMS Young's Modulus and Step Height Round Robin Experiment. In particular, it provided details associated with the following:

- Equipment specifications:
  - For the optical vibrometer, stroboscopic interferometer, or comparable instrument used for Young's modulus measurements
  - For the optical interferometer or comparable instrument used for step height measurements
- The packaged round robin test chip:
  - For a bulk-micromachined 1.5 μm AMIS process through MOSIS
- The standards being validated:
  - SEMI MS4 for Young's modulus measurements
  - SEMI MS2 for step height measurements
- The data submission process using:
  - Data Sheet YM.1 for Young's modulus measurements
  - Data Sheet SH.1 for step height measurements

In addition, the specific round robin Young's modulus measurements were discussed and the specific round robin step height measurements were discussed. The results of this round robin will be incorporated within the pertinent sections of the standards being validated.

## 6. ACKNOWLEDGMENT

The round robin participants who have volunteered to participate in this round robin experiment are wholeheartedly acknowledged. Without them, the standards cannot be validated. Besides NIST, the list of participants currently includes (but is not limited to) the following companies and university listed alphabetically: Berkeley, Polytec Inc., SIOS, Veeco Metrology, and Zygo Corporation. It is hoped that the participants in this round robin experiment benefit from the educational experience the round robin experiment provides and that the standards can be used in their future work.

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

## 7. REFERENCES

[1] The URL for selecting the appropriate data analysis sheet for the round robin and for downloading pertinent files (such as, the design file for the round robin test chip) is http://www.eeel.nist.gov/812/test-structures/MEMSCalculator.htm.

[2] 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.

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

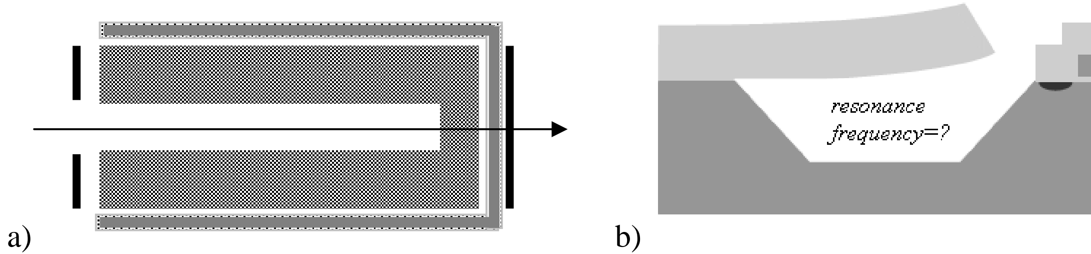
[4] SEMI MS2, "Test Method for Step-Height Measurements of Thin, Reflecting Films Using an Optical Interferometer," http://www.semi.org for ordering information.

[5] 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.

[6] 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.

APPENDIX A – Data Analysis Sheet YM.1

**Data analysis sheet for determining the Young's modulus value of a thin film layer from the resonance frequency of a single-layered cantilever**




a) b)

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) = ☐
type of instrument (optional) = ☐
fabrication facility/process (optional) = ☐
test chip name (optional) = ☐
test chip number (optional) = ☐

| Preliminary INPUTS | | | Description |
|---|---|---|---|
| **1** | *mag* = | ☐ × | magnification |
| **2** | *mat* = | poly1 ○<br>poly2 ○<br>$SiO_2$ ○<br>other ● | composition of the thin film layer |
| **3*** | $\rho$ = | ☐ g/cm$^3$ | density of the thin film layer |
| **4** | $\sigma_\rho$ = | ☐ g/cm$^3$ | the one sigma uncertainty of the value of $\rho$ |
| **5*** | $\mu$ = | ☐ $\times 10^{-5}$Ns/m$^2$ | the viscosity of the ambient surrounding the cantilever |
| **6** | $\sigma_\mu$ = | ☐ $\times 10^{-5}$Ns/m$^2$ | the one sigma uncertainty of the value of $\mu$ |
| **7*** | $W$ = | ☐ μm | suspended width |
| **8** | $\sigma_W$ = | ☐ μm | the one sigma uncertainty of the value of $W$ |
| **9*** | $t$ = | ☐ μm | thickness of the thin film layer |
| **10** | $\sigma_{thick}$ = | ☐ μm | the one sigma uncertainty of the value of $t$ |
| **11*** | $E_{init}$ = | ☐ GPa | an 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.

| Cantilever INPUTS | | | Description |
|---|---|---|---|
| **1** | *name* = | [ ] | cantilever name (optional) |
| **2** | *orient* = | 0 degree ○<br>90 degree ○<br>180 degree ○<br>270 degree ○<br>other ● | orientation of the cantilever |
| **3*** | $L_{can}$ = | [ ] μm | suspended cantilever length |
| **4** | *whichcan*= | first ○<br>second ○<br>third ○<br>fourth ○<br>fifth ○<br>other ● | which cantilever on the test chip, where “first” corresponds to the topmost cantilever in the column? |
| **5** | $\sigma_L$ = | [ ] μm | the one sigma uncertainty of the value of $L_{can}$ |
| **6** | $f_{resol}$ = | [ ] Hz | the frequency resolution for the given set of measurement conditions |
| **7** | $f_{meas1}$ = | [ ] kHz | the first damped resonance frequency measurement, $f_{damped1}$ (or the first undamped resonance frequency measurement, for example, if the measurements were performed in a vacuum) |
| **8** | $f_{meas2}$ = | [ ] kHz | the second damped resonance frequency measurement, $f_{damped2}$ (or the second undamped resonance frequency measurement, for example, if the measurements were performed in a vacuum) |
| **9** | $f_{meas3}$ = | [ ] kHz | the third damped resonance frequency measurement, $f_{damped3}$ (or the 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.

| Fixed-Fixed Beam INPUTS (for 2nd and 3rd $u_c$ calculation) | | | Description |
|---|---|---|---|
| **1** | *name2* = | [ ] | fixed-fixed beam name (optional) |
| **2** | *orient2* = | 0 degree ○<br>90 degree ○<br>180 degree ○<br>270 degree ○<br>other ● | orientation of the fixed-fixed beam |
| **3*** | $L_{ffb}$ = | [ ] μm | suspended fixed-fixed beam length |

| | | | |
|---|---|---|---|
| **4** | *whichffb=* | first ○<br>second ○<br>third ○<br>fourth ○<br>fifth ○<br>other ● | which fixed-fixed beam on the test chip, where "first" corresponds to the topmost fixed-fixed beam in the column? |
| **5** | $f_{ffb}$ = | [ ] kHz | the 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.

| **Optional INPUTS** | | | |
|---|---|---|---|
| **For residual stress calculations:** | | | **Description** |
| **1** | $\varepsilon_r$ = | [ ] $\times 10^{-6}$ | the residual strain of the thin film layer<br>(Compressive residual strain can be found using ASTM E 2245 and Data Sheet RS.1 or RS.2.) |
| **2** | $u_{\varepsilon r}$ = | [ ] $\times 10^{-6}$ | the combined standard uncertainty value for residual strain<br>(For compressive residual strain, $u_{\varepsilon r}$ can be found using Data Sheet RS.1 or RS.2.) |
| **For stress gradient calculations:** | | | |
| **3** | $s_g$ = | [ ] $m^{-1}$ | the strain gradient of the thin film layer<br>(can be found using ASTM E 2246 and Data Sheet SG.1 or SG.2) |
| **4** | $u_{sg}$ = | [ ] $m^{-1}$ | the combined standard uncertainty value for strain gradient<br>(can be found using Data Sheet SG.1 or SG.2) |

Input Sample Data Reset this form

Calculate Estimates Clear Output

| **Preliminary ESTIMATES*** | | | **Description** |
|---|---|---|---|
| **1** | $f_{caninit}$ = | [ ] kHz | = SQRT [$E_{init}$ $t^2$ / (38.330 $\rho$ $L_{can}^4$)]<br>(the estimated resonance frequency of the cantilever) |
| **2** | $f_{ffbinithi}$ = | [ ] kHz | = SQRT [$E_{init}$ $t^2$ / (0.946 $\rho$ $L_{ffb}^4$)]<br>(the estimated upper bound for the resonance frequency of the fixed-fixed beam) |

| | | | |
|---|---|---|---|
| **3** | $f_{ffbinitlo}$ = | [ ] kHz | = SQRT [ $E_{init}$ $t^2$ / (4.864 $\rho$ $L_{ffb}^4$)] (the estimated lower bound for the resonance frequency of the fixed-fixed beam) |
| **4** | $Q$ = | [ ] | = $W$ $t^2$ SQRT ($\rho$ $E_{init}$) / (24 $\mu$ $L_{can}^2$) (the estimated $Q$-factor) |
| **5** | $p_{diff}$ = | [ ] % | = {1 – SQRT [1–1 / (4 $Q^2$)]}×100 % should be $< 2$ % (the 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:**

| **Frequency calculations:** | | | **Description** |
|---|---|---|---|
| **1** | $f_{dampedave}$ = | [ ] kHz | = AVE [$f_{meas1}$, $f_{meas2}$, $f_{meas3}$] (the average damped resonance frequency of the cantilever, $f_{dampedave}$, or the average undamped resonance frequency of the cantilever if, for example, the measurements were performed in a vacuum) |
| **2** | $f_{undamped1}$ = | [ ] kHz | = $f_{damped1}$ / SQRT [1–1/(4$Q^2$)] (the first undamped resonance frequency calculated from the cantilever's first damped resonance frequency measurement, if applicable) |
| **3** | $f_{undamped2}$ = | [ ] kHz | = $f_{damped2}$ / SQRT [1–1/(4$Q^2$)] (the second undamped resonance frequency calculated from the cantilever's second damped resonance frequency measurement, if applicable) |
| **4** | $f_{undamped3}$ = | [ ] kHz | = $f_{damped3}$ / SQRT [1–1/(4$Q^2$)] (the third undamped resonance frequency calculated from the cantilever's third damped resonance frequency measurement, if applicable) |
| **5** | $f_{can}$ = | [ ] kHz | = AVE [$f_{undamped1}$, $f_{undamped2}$, $f_{undamped3}$] (the average undamped resonance frequency of the cantilever assuming $f_{meas1}$, $f_{meas2}$, and $f_{meas3}$ from the second table are damped resonance frequencies) |
| **6** | $\sigma_{freq}$ = | [ ] kHz | = STDEV [$f_{undamped1}$, $f_{undamped2}$, $f_{undamped3}$] (the 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.)

2. Minimum $u_c$ calculation (the smallest of the three values for $u_c$) = $u_c =$ [ ] GPa
(USE THIS VALUE)

   a. $u_c = \text{SQRT}(u_{thick}^2 + u_\rho^2 + u_L^2 + u_{freq}^2 + u_{fresol}^2 + u_{damp}^2) =$ [ ] GPa
   $u_{thick} =$ [ ] GPa
   $u_\rho =$ [ ] 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

   b. $u_c = (E_{simple} - E) / 3 =$ [ ] GPa
   $E_{simple} = 4.864\ \rho f_{ffb}^2 L_{ffb}^4 / t^2 =$ [ ] GPa
   (as obtained from the fixed-fixed beam assuming simply-supported boundary conditions for both supports)

   c. $u_c = (E - E_{clamped}) / 3 =$ [ ] GPa
   $E_{clamped} = 0.946\ \rho f_{ffb}^2 L_{ffb}^4 / t^2 =$ [ ] GPa
   (as obtained from the fixed-fixed beam assuming clamped-clamped boundary conditions)

| **Optional OUTPUTS** | | | |
|---|---|---|---|
| **For residual stress:** | | | **Description** |
| **1** | $\sigma_r =$ | [ ] MPa | $= E\ \varepsilon_r$ (the residual stress of the thin film layer) |
| **2** | $u_{\sigma r} =$ | [ ] MPa | $= \text{SQRT}\ [u_{E(\sigma r)}^2 + u_{\varepsilon r(\sigma r)}^2]$ (the combined standard uncertainty value for residual stress) |
| **3** | $u_{E(\sigma r)} =$ | [ ] MPa | $= [\ (E+3u_c)\lvert\varepsilon_r\rvert - (E-3u_c)\lvert\varepsilon_r\rvert\ ] / 6$ (the component in the combined standard uncertainty calculation for residual stress that is due to the measurement uncertainty of $E$) |

| | | | |
|---|---|---|---|
| **4** | $u_{\varepsilon r(\sigma r)}$ = | [ ] MPa | = [ $E$( \|$\varepsilon_r$\| + 3$u_{\varepsilon r}$) – $E$( \|$\varepsilon_r$\| – 3$u_{\varepsilon r}$) ] / 6 (the component in the combined standard uncertainty calculation for residual stress that is due to the measurement uncertainty of $\varepsilon_r$) |
| **For stress gradient:** | | | |
| **5** | $\sigma_g$ = | [ ] GPa/m | = $E\ s_g$ (the stress gradient of the thin film layer) |
| **6** | $u_{\sigma g}$ = | [ ] GPa/m | = SQRT [$u_{E(\sigma g)}{}^2 + u_{sg(\sigma g)}{}^2$] (the combined standard uncertainty value for stress gradient) |
| **7** | $u_{E(\sigma g)}$ = | [ ] GPa/m | = [ ($E$ + 3$u_c$)$s_g$ – ($E$ – 3$u_c$)$s_g$ ] / 6 (the component in the combined standard uncertainty calculation for stress gradient that is due to the measurement uncertainty of $E$) |
| **8** | $u_{sg(\sigma g)}$ = | [ ] GPa/m | = [ $E$($s_g$ + 3$u_{sg}$) – $E$($s_g$ – 3$u_{sg}$) ] / 6 (the 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 fill out the entire form.
2. [ ] Is the magnification appropriate given $L_{can}$ and $L_{ffb}$? The value for *mag* should be greater than or equal to 20×.
3. [ ] The value for $\rho$ should be between 1.00 g/cm$^3$ and 5.00 g/cm$^3$.
4. [ ] The value for $\sigma_\rho$ should be between 0.0 g/cm$^3$ and 0.10 g/cm$^3$.
5. [ ] The value for $\mu$ should be between 0.70×10$^{-5}$ Ns/m$^2$ and 3.0×10$^{-5}$ Ns/m$^2$.
6. [ ] The value for $\sigma_\mu$ should be between 0.0 Ns/m$^2$ and 0.05×10$^{-5}$ Ns/m$^2$.
7. [ ] The value for $W$ should be greater than $t$ and less than $L_{can}$ and $L_{ffb}$.
8. [ ] The value for $\sigma_W$ should be between 0.0 µm and 2.0 µm.
9. [ ] The value for $t$ should be between 0.000 µm and 10.000 µm.
10. [ ] The value for $\sigma_{thick}$ should be between 0.0 µm and 0.3 µm.
11. [ ] The value for $E_{init}$ should be between 10 GPa and 300 GPa.
12. [ ] The values for $L_{can}$ and $L_{ffb}$ should be between 0 µm and 1000 µm and $L_{ffb}$ need not equal $L_{can}$.
13. [ ] The value for $\sigma_L$ should be between 0.0 µm and 2.0 µm.
14. [ ] The value for $f_{resol}$ should be between 0 Hz and 50 Hz.
15. [ ] The values for $f_{meas1}$, $f_{meas2}$, and $f_{meas3}$ should be between 5.00 kHz and 300.0 kHz.
16. [ ] The value for $f_{ffb}$ should be between 5.0 kHz and 1200 kHz.
17. [ ] If inputted, the value for $\varepsilon_r$ should be between –100×10$^{-6}$ and 100×10$^{-6}$.

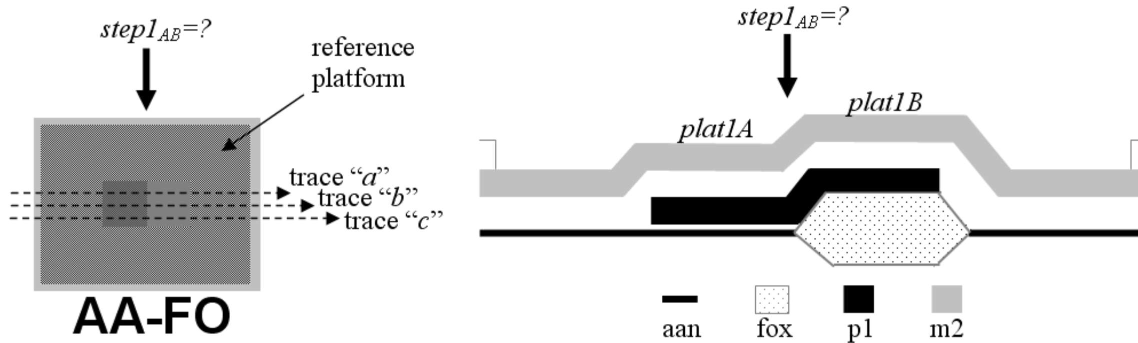
18. ☐ If inputted, the value for $u_{\varepsilon r}$ should be between 0.0 and $4.0\times10^{-6}$.
19. ☐ If inputted, the value for $s_g$ should be between 0.0 $m^{-1}$ and 20.0 $m^{-1}$.
20. ☐ If inputted, the value for $u_{sg}$ should be between 0.0 $m^{-1}$ and 2.0 $m^{-1}$.
21. ☐ The value for $p_{diff}$ should be between 0 % and 2 %.
22. ☐ The value for $\sigma_{freq}$ should be between 0.0 kHz and 0.5 kHz, inclusive.
23. ☐ The value of $E$ should be within 20 GPa of $E_{init}$.
24. ☐ The value of $E$ should be between $E_{clamped}$ and $E_{simple}$.
25. ☐ The values for $u_{thick}$, $u_{\rho}$, $u_L$, $u_{freq}$, $u_{fresol}$, and $u_{damp}$ should be between 0 GPa and 5 GPa, inclusive.
26. ☐ Each value of $u_c$ should be between 0 GPa and 30 GPa.
27. ☐ The smallest value of $u_c$ should be between 0 GPa and 10 GPa.

Return to Main MEMS Calculator Page.

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

APPENDIX B – 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, Reflecting Films Using an Optical Interferometer."

---

date data taken (optional) = [ ]
identifying words (optional) = [ ]
type of instrument (optional) = [ ]
filename of 3-D data set (optional) = [ ]

| **Preliminary INPUTS** | | | |
|---|---|---|---|
| **Data Set Prelims** | | | **Description** |
| **1** | *proc* = | MUMPs ○<br>On Semi ●<br>other ○ | which process? |
| **2** | *quad* = | first ●<br>second ○<br>third ○<br>fourth ○<br>fifth ○<br>other ○ | which quad of test structures, if applicable? |
| **3** | *orient* = | 0º ●<br>90º ○<br>180º ○<br>270º ○<br>other ○ | orientation of the test structure on the test chip |
| **4** | *mag* = | [ ] × | magnification |
| **5** | *align* = | Yes ○<br>No ● | alignment ensured? |

| | | | |
|---|---|---|---|
| **6** | *level* = | Yes ○<br>No ● | data leveled? |
| **7** | *cert* = | [ ] μm | certified value of step height standard |
| **8** | $s_{cert}$ = | [ ] μm | certified one sigma uncertainty of certified value of step height standard |
| **9** | $z_{repeat}$ = | [ ] μm | maximum uncalibrated range of the six calibration measurements taken before the data session at the same location on the step height standard or after the data session at the same location on the step height standard (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 step height standard and the average of the six calibration measurements taken after the data session at the same location on the step height standard) |
| **12** | $cal_z$ = | [ ] | the $z$-calibration factor = the certified value of the step height standard divided by the average of the twelve calibration measurements taken at the same location on the step height standard |
| **13** | $z_{perc}$ = | [ ] % | if applicable, the percent quoted by instrument manufacturer for the maximum deviation from linearity of the data scan over the total scan range |
| **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*").

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

| **Calibrated OUPTUTS (in μm)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $stepN_{XY}$ | $u_{Lstep}$ | $u_{Wstep}$ | $u_{cert}$ | $u_{repeat}$ | $u_{drift}$ | $u_{linear}$ | $u_c$ |
| **12** | | | | | | | | |

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($u_{Lstep}^2 + u_{Wstep}^2 + u_{cert}^2 + u_{repeat}^2 + u_{drift}^2 + u_{linear}^2$)

---

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 0.0 μm and 0.02 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 0.015 μm.

Return to Main MEMS Calculator Page.

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