

The MEMS 5-in-1 Reference Materials (RM 8096 and 8097)

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ABSTRACT¹

The Microelectromechanical Systems (MEMS) 5-in-1 Reference Material (RM) contains test structures for five standard test methods on one test chip, so companies can compare their in-house measurements taken on the RM with National Institute of Standards and Technology (NIST) measurements, thereby validating their use of the documentary standard test methods. Examples of NIST reference values are given for an RM 8096 monitor chip used at NIST for stability studies.

SUMMARY

The Microelectromechanical Systems (MEMS)² 5-in-1 is a reference device or more commonly called a National Institute of Standards and Technology (NIST) Reference Material (RM) that contains MEMS test structures on a test chip. The two RM chips (8096 and 8097) provide for both dimensional and material property measurements. RM 8096, as depicted in Fig. 1, was fabricated using a multi-user 1.5 μm complementary metal oxide semiconductor (CMOS) process [1]³ followed by a bulk-micromachining etch. Material properties of the composite oxide layer are reported on the RM Certificates. RM 8097, as depicted in Fig. 2, was fabricated using a polysilicon multi-user surface-micromachining MEMS process with a backside etch [2]. The material properties of the first or second polysilicon layer are reported on the RM Certificates.

The MEMS 5-in-1 contains MEMS test structures for use with five standard test methods on one test chip (from which its name is derived). The five standard test methods are for Young's modulus [3], step height [4], residual strain [5], strain gradient [6], and in-plane length [7] measurements. The first two of these five standard test methods have been published through the Semiconductor Equipment and

Materials International (SEMI). The remaining three standard test methods have been published through the American Society for Testing and Materials (ASTM) International. All five of these standard test methods include precision and bias data developed in round robin measurements.

The Certificates accompanying these RMs typically report eight properties. In addition to the five properties mentioned in the previous paragraph, residual stress, stress gradient, and thickness are also reported. The calculations for residual stress and stress gradient are provided in the Young's modulus standard test method, and the beam thickness calculations rely upon step height measurements using an electro-physical technique [8] for RM 8096 and using an opto-mechanical technique [9] for RM 8097, as described in the NIST Special Publication, SP 260-174 [10]. Therefore, to determine the eight properties, five standard test methods are used.

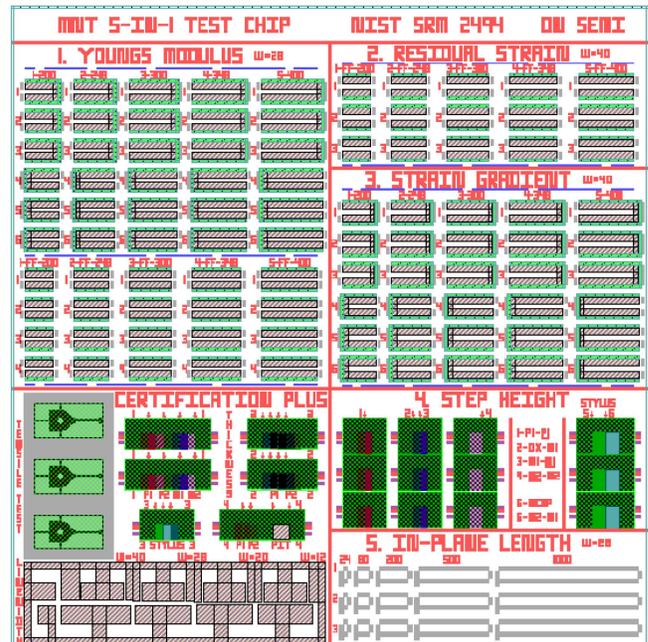


Fig. 1. The MEMS 5-in-1 test chip design for RM 8096. Measurements for the five standard test methods are taken in the applicable group of test structures. The chip dimensions are 4600 μm by 4700 μm .

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² MEMS are also referred to as microsystems technology (MST) and micromachines.

³ Commercial equipment, instruments, or processes may be identified. This does not imply recommendation or endorsement by NIST, nor does it imply that the equipment, instruments, or processes are the best available for the purpose.

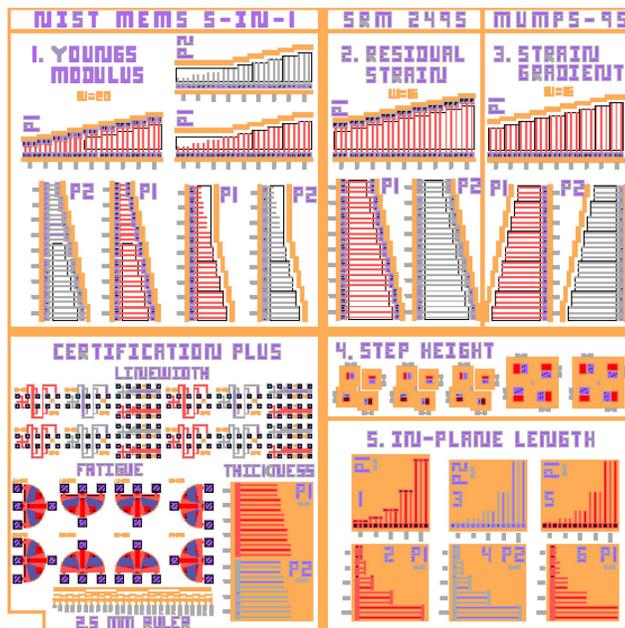


Fig. 2. A MEMS 5-in-1 test chip design for RM 8097. Measurements for the five standard test methods are taken in the applicable group of test structures. The chip dimensions are 1 cm by 1 cm.

NIST SP 260 [10] was written specifically for MEMS 5-in-1 chips.⁴ This SP instructs the user to follow the procedures in the applicable SEMI or ASTM standard test method in the taking of the measurements on the same test structures on which NIST measurements were taken. These test structures are located using data supplied by NIST on the data analysis sheets that accompany the RM. The data analysis sheets also show the measurements used to obtain the values listed on the Certificates. The purpose of each parameter along with the test structure and instrument used to obtain the parametric value is specified in Table 1. A brief description of the measurement methods is given in Table 2.

To calculate the MEMS parameters, measurements are initially input on the pertinent on-line data analysis sheet on the MEMS Calculator Web Site (Standard Reference Database 166) accessible via the NIST Data Gateway (<http://srdata.nist.gov/gateway/>) with the keyword “MEMS Calculator” [11]. Then, the “Calculate and Verify” button is clicked to obtain the results. The key parametric and combined standard uncertainty equations that are used are given in Table 2 to indicate the comprehensive nature of the analysis. A more complete understanding of these equations, including the identification and definition of the parameters used in the equations can be found in the SP 260 [10]. The data are verified by checking to see that all the

pertinent boxes in the verification section at the bottom of the data analysis sheet say “ok.” If one or more of the boxes say “wait,” the issue is addressed, if necessary, by modifying the inputs and recalculating.

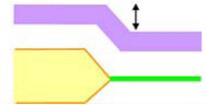
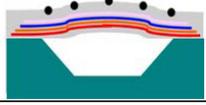
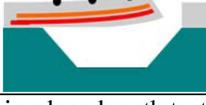
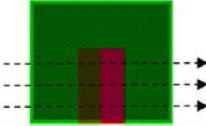
The SP 260 then suggests how the user’s measurements can be compared with the NIST measurements supplied on the RM Certificates (and the data analysis sheets) to validate their use of the documentary standard test methods.

The RM Certificate provides a NIST reference value for Young’s modulus, step height, residual strain, strain gradient, in-plane length, residual stress, stress gradient, and thickness. A NIST reference value is a best estimate of the true value provided on a NIST Certificate/Certificate of Analysis/Report of Investigation where all known or suspected sources of bias have not been fully investigated by NIST [12]. A NIST certified value would be reported for those parameters of which NIST has the highest confidence in the accuracy; *i.e.*, all known or suspected sources of bias have been fully investigated or accounted for by NIST. If one of the eight reported parameters were a certified value, then the test chip would be a standard reference material (SRM) as opposed to a reference material (RM).

Examples of NIST reference values are given in Table 3 for an RM 8096 monitor chip used at NIST for stability studies. An effective value is reported for a parameter if there are non-idealities associated with the geometry and/or composition of the test structure(s) used to take the measurements [10].

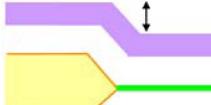
⁴ Actually, this NIST SP 260 was written for Standard Reference Materials (SRMs) 2494 and 2495. Therefore, for this SP, replace SRM 2494 and 2495 with RM 8096 and 8097, respectively, which have identical chip designs but only reference values are reported on the Certificates as indicated in a paragraph that follows.

TABLE 1
A LISTING OF EACH OF THE MEMS 5-IN-1 RM PARAMETERS, THE TEST STRUCTURE USED TO MEASURE IT, THE INSTRUMENT USED, AND THE PURPOSE FOR THE MEASUREMENT

	Parameter	Test Structure	Instrument ^a	Purpose
1.	Young's modulus	cantilever 	vibrometer	To use in the design and fabrication of MEMS devices and ICs
2.	Step height	step height test structure 	interferometric microscope	To determine thin film thickness values, which can be used in the determination of thin film material parameters, such as Young's modulus
3.	Residual strain	fixed-fixed beam 	interferometric microscope	To measure the strain present in parts of a microsystem before they relax after the removal of the stiff oxides that surround them during manufacturing
4.	Strain gradient	cantilever 	interferometric microscope	To determine the maximum distance that a MEMS component can be suspended, say, in air, before it begins to bend or curl
5.	In-plane length	in-plane length test structure 	interferometric microscope	For use when interferometric measurements are preferred over using the design dimensions (e.g., when measuring in-plane deflections and when measuring lengths in an unproven fabrication process)
6.	Residual stress	–	–	To improve the yield in CMOS fabrication processes since high values of residual stress can lead to failure mechanisms in ICs
7.	Stress gradient	–	–	To measure the through-thickness variation of the residual stress in the structural layer of interest before it is released
8a.	Thickness (RM 8096)	4 step height test structures 	interferometric microscope and stylus profilometer	Used in the determination of thin film material parameters, such as Young's modulus
8b.	Thickness (RM 8097)	cantilever exhibiting stiction 	interferometric microscope and stylus profilometer	Used in the determination of thin film material parameters, such as Young's modulus

^a A comparable instrument may also be used to obtain the parametric value.

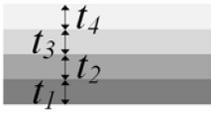
TABLE 2
SOME KEY PARAMETRIC AND COMBINED STANDARD UNCERTAINTY EQUATIONS
WITH A BRIEF DESCRIPTION OF THE METHOD

	Parameter ± Expanded Uncertainty ^a	Method and Key Parametric and Combined Standard Uncertainty Equations ^b
1.	Young's modulus ($E \pm 2u_{cE3}$) 	Calculated using the average resonance frequency of a cantilever oscillating out-of plane $E = (38.330 \rho f_{can}^2 L_{can}^4) / t^2$ where $f_{can} = f_{undampedave} + f_{correction}$ $u_{cE3} = E \left[2^2 (\sigma_{thick} / t)^2 + (\sigma_{\rho} / \rho)^2 + 4^2 (\sigma_L / L_{can})^2 + 2^2 (\sigma_{fcan} / f_{can})^2 \right]^{1/2}$ where $\sigma_{fcan} = [\sigma_{fundamped}^2 + \sigma_{fresol}^2 + \sigma_{freqcal}^2 + \sigma_{support}^2 + \sigma_{cantilever}^2]^{1/2}$
2.	Step height ($stepN_{XY} \pm 2u_{cSH1a}$) 	Obtained from multiple measurements taken along the width of a step height test structure $stepN_{XYt} = (platNYt - platNXt) cal_z$ (for one trace) $stepN_{XY} = (stepN_{XYa} + stepN_{XYb} + stepN_{XYc}) / 3$ $u_{cSH1a} = [u_{Lstep}^2 + u_{Wstep}^2 + u_{cert}^2 + u_{cal}^2 + u_{repeat(shs)}^2 + u_{drift}^2 + u_{linear}^2 + u_{repeat(samp)}^2]^{1/2}$
3.	Residual strain ($\epsilon_r \pm 2u_{cer3}$) 	The curved length of the fixed-fixed beam is determined from five data points extracted from one data trace along the length of the fixed-fixed beam. The in-plane length of the fixed-fixed beam is also measured. The residual strain for the data trace is calculated given these measurements and taking into account offset and misalignment. The residual strain is the average of the residual strain values obtained from multiple data traces. $\epsilon_{rt} = [(L - L_0) / L_0] (1 + \delta_{ercorrection})$ (for one trace) where $L_0 = [12 L_c (L_c L_e' / L)^2] / [12 (L_c L_e' / L)^2 \pi^2 t^2]$ $\epsilon_r = (\epsilon_{rb} + \epsilon_{rc} + \epsilon_{rd}) / 3$ $u_{cer3} = [u_W^2 + u_L^2 + u_{zres}^2 + u_{xcal}^2 + u_{xres}^2 + u_{Rave}^2 + u_{noise}^2 + u_{cert}^2 + u_{repeat(shs)}^2 + u_{drift}^2 + u_{linear}^2 + u_{correction}^2 + u_{repeat(samp)}^2]^{1/2}$
4.	Strain gradient ($s_g \pm 2u_{csg3}$) 	Three data points (from one data trace) are obtained along the length of the cantilever that bends out-of-plane. The strain gradient for this data trace is calculated using these data points and taking into account misalignment. The strain gradient is the average of the strain gradient values obtained from multiple data traces. $s_{gt} \approx 1 / (R_{int}) + s_{gcorrection}$ (for one trace) $s_g = (s_{gb} + s_{gc} + s_{gd}) / 3$ $u_{csg3} = [u_W^2 + u_{zres}^2 + u_{xcal}^2 + u_{xres}^2 + u_{Rave}^2 + u_{noise}^2 + u_{cert}^2 + u_{repeat(shs)}^2 + u_{drift}^2 + u_{linear}^2 + u_{correction}^2 + u_{repeat(samp)}^2]^{1/2}$
5.	In-plane length ($L \pm 2u_{cL0}$) 	Multiple key corner points are identified and recorded along with their uncertainties for an in-plane length calculation, taking into account offset and misalignment. $L_{meast} = (x2_{upper} - x1_{upper}) cal_x$ (for one trace) $L_{meas} = (L_{measa} + L_{measa} + L_{mease} + L_{mease}) / 4$ and $L_{align} = L_{meas} \cos \alpha$ $L = L_{align} + L_{offset}$ $u_{cL0} = [u_L^2 + u_{repeat(L)}^2 + u_{xcal}^2 + u_{align}^2 + u_{offset}^2 + u_{repeat(samp)}^2]^{1/2}$

^a Where $k=2$ for $\approx 95\%$ confidence

^b The key parametric and combined standard uncertainty equations are given to indicate the comprehensive nature of the analysis. For the definitive identification and definition of the parameters in each equation, consult [10].

TABLE 2, CONTINUED
 MORE KEY PARAMETRIC AND COMBINED STANDARD UNCERTAINTY EQUATIONS
 WITH A BRIEF DESCRIPTION OF THE METHOD

	Parameter ± Expanded Uncertainty ^a	Method and Key Parametric and Combined Standard Uncertainty Equations ^b
6.	Residual stress ($\sigma_r \pm 2u_{c\sigma r3}$)	Calculated given Young's modulus and residual strain $\sigma_r = E\varepsilon_r$ $u_{c\sigma r3} = \sigma_r \left[(u_{cE3} / E)^2 + (u_{c\varepsilon r3} / \varepsilon_r)^2 \right]^{1/2}$
7.	Stress gradient ($\sigma_g \pm 2u_{c\sigma g3}$)	Calculated given Young's modulus and strain gradient $\sigma_g = E s_g$ $u_{c\sigma g3} = \sigma_g \left[(u_{cE3} / E)^2 + (u_{cs g3} / s_g)^2 \right]^{1/2}$
8a.	Thickness for 8096 ($t_{SiO2} \pm 2u_{cSiO2}$) 	Calculated using the results of six step height measurements taken from four different step height test structures. $t_{SiO2} = t_1 + t_2 + t_3 + t_4 = X + Y = Z$ where $X = t_3 + t_4 - t_{imd(m2/m1)elec} = B + C - D + E$ and where $Y = Y_1, Y_2, Y_3, \text{ or } Y_4$ $Y_1 = t_{1d} + t_2 + t_{imd(m2/m1)elec} = M$ $Y_2 = t_{1c} + t_2 + t_{imd(m2/m1)elec} = A + K - L$ $Y_3 = t_{1b} + t_2 + t_{imd(m2/m1)elec} = A - J + O$ $Y_4 = t_{1a} + t_2 + t_{imd(m2/m1)elec} = A + F + O$ $u_{cSiO2} = u_n = \text{MIN}(u_{z1}, u_{z2}, u_{z3}, u_{z4})$ $t_{SiO2} = Z_n$
8b.	Thickness for 8097 ($\alpha \pm 2u_{c\alpha}$) 	Calculated from measurements of: a) the height of the anchor to the underlying layer (A) and b) the height of the stuck portion of the cantilever to the anchor (B). $C = A + B \quad \text{and} \quad u_{cC} = (u_{cSHA}^2 + u_{cSHB}^2)^{1/2}$ $J = B - H \quad \text{and} \quad u_{cJ} = (u_{cSHB}^2 + u_{cCH}^2)^{1/2} \quad \text{where} \quad u_{cCH} = \Delta H / 6$ $\alpha_a = A + H \quad \text{and} \quad u_{c\alpha a} = (u_{cSHA}^2 + u_{cCH}^2)^{1/2}$ $\alpha_b = C - J_{est} \quad \text{and} \quad u_{c\alpha b} = (u_{cC}^2 + u_{cJest}^2)^{1/2}$ $\alpha = \alpha_a, \text{ if } u_{c\alpha a} \leq u_{c\alpha b} \text{ or } J_{est} = 0$ $\alpha = \alpha_b, \text{ if } u_{c\alpha b} < u_{c\alpha a} \text{ and } J_{est} \neq 0$

^a Where $k=2$ for $\approx 95\%$ confidence

^b The key parametric and combined standard uncertainty equations are given to indicate the comprehensive nature of the analysis. For the definitive identification and definition of the parameters in each equation, consult [10].

TABLE 3
EXAMPLES OF NIST REFERENCE VALUES FOR RM 8096

Measurement	NIST Reference Value ± Expanded Uncertainty ($k=2$ for $\approx 95\%$ confidence)	Corresponding Range
Effective Young's modulus, E	62.2 GPa ± 10.9 GPa	51.3 GPa to 73.1 GPa
Step height, ^a $stepI_{XY}$	0.507 μm ± 0.166 μm	0.341 μm to 0.673 μm
Effective residual strain, ε_r	$-2.68 \times 10^{-3} \pm 0.20 \times 10^{-3}$	-2.88×10^{-3} to -2.48×10^{-3}
Effective strain gradient, s_g	891 $\text{m}^{-1} \pm 111 \text{m}^{-1}$	779 m^{-1} to 1002 m^{-1}
In-plane length, L	201.1 μm ± 3.0 μm	198.1 μm to 204.1 μm
Effective residual stress, σ_r	-167 MPa ± 32 MPa	-198 MPa to -135 MPa
Effective stress gradient, σ_g	55.4 TPa/m ± 11.9 TPa/m	43.5 TPa/m to 67.3 TPa/m
Thickness, t_{SiO_2}	2.58 μm ± 0.22 μm	2.36 μm to 2.80 μm

^a Other physical step height standards are available with lower uncertainty values and those should be used to calibrate instruments.

The results are reported in the following way: Since it can be assumed that the estimated values of the uncertainty components are either approximately uniformly or Gaussianly distributed, with the approximate expanded uncertainty U , the parametric value is believed to lie in the interval $NIST\ Value \pm U$ (expansion factor $k=2$) representing a level of confidence of approximately 95 %.

REFERENCES

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