

SEMI MS4-1107

STANDARD TEST METHOD FOR YOUNG'S MODULUS MEASUREMENTS OF THIN, REFLECTING FILMS BASED ON THE FREQUENCY OF BEAMS IN RESONANCE

This standard was technically approved by the global MEMS Committee. This edition was approved for publication by the global Audits and Reviews Subcommittee on September 5, 2007. It was available at www.semi.org in October 2007 and on CD-ROM in November 2007. Originally published 2007.

1 Purpose

1.1 Young's modulus is a material parameter that has been eluding the MEMS community for many years. Standardization of this parameter is necessary to bring the community into consensus as to how it should be measured in order to compare results. This test method enables the determination of Young's modulus for thin, reflecting films, based on the resonant frequency of cantilevers and fixed-fixed beams.

1.2 Young's modulus measurements are an aid in the design and fabrication of MEMS devices. For example, high values of residual stress can lead to failure mechanisms in IC's such as electromigration, stress migration, and delamination. So, methods for its characterization are of interest for IC process development and monitoring in order to improve the yield in CMOS fabrication processes. The residual stress of a thin film layer is calculated given the Young's modulus value obtained in this test method.

2 Scope

2.1 This test method covers a procedure for measuring Young's modulus in thin films. It applies only to films, such as found in microelectromechanical system (MEMS) materials, which can be imaged using a non-contact optical vibrometer or comparable instrument, which is capable of obtaining the resonant frequencies of beams oscillating out-of-plane. (As such, measurements from beams that are touching or touch the underlying layer are not accepted.) The resonant frequencies of a single-layered cantilever and fixed-fixed beam are used in Young's modulus and combined standard uncertainty calculations, respectively. These newly acquired values are then used in residual stress and stress gradient calculations.

2.2 The fabrication, including the post-processing etch, of the chips incorporating the beams is considered outside the scope of this test method. The determination of whether or not a beam is exhibiting stiction is considered outside the scope of this test method. The determination of the beam's length, width, thickness, and density is considered outside the scope of this test method.

2.3 If a laser beam is used, this test method only applies to Class 1 and Class 2 lasers.

NOTICE: This standard does not purport to address safety issues, if any, associated with its use. It is the responsibility of the users of this standard to establish appropriate safety and health practices and determine the applicability of regulatory or other limitations prior to use.

3 Limitations

3.1 The beams should be suspended high enough above the underlying layer such that the resonant frequency of the cantilevers or fixed-fixed beams is not altered by its presence. Squeeze film and other damping phenomena routinely lead to amplitude dependent resonant frequencies and shifts in the natural frequency of the system, which may limit the accuracy of the technique. The damping may not be evident in bulk-micromachining processes. It is dependent upon the depth of the cavity and the vicinity of the sides of the cavity to the beam. It is expected to be present in surface micromachining processes, however, the problem goes away if the measurement is performed in a vacuum.

3.2 For cantilevers, this test method assumes clamped-free boundary conditions, which implies that there is no undercutting of the beam. Therefore, this test method is limited to how accurate the assumption is in the use of clamped-free boundary conditions.

4 Referenced Standards and Documents

4.1 SEMI Standard

SEMI MS2 — Test Method for Step-Height Measurements of Thin, Reflecting Films Using an Optical Interferometer

4.2 ASTM Standards¹

ASTM E2244 — Standard Test Method for In-Plane Length Measurements of Thin, Reflecting Films Using an Optical Interferometer

ASTM E2245 — Standard Test Method for Residual Strain Measurements of Thin, Reflecting Films Using an Optical Interferometer

ASTM E2246 — Standard Test Method for Strain Gradient Measurements of Thin, Reflecting Films Using an Optical Interferometer

ASTM E2444 — Standard Terminology Relating to Measurements Taken on Thin, Reflecting Films. Referenced definitions reprinted, with permission, from the *Annual Book of ASTM Standards*, copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428.

4.3 ANSI Standard²

ANSI Z136.1 — Standard for the Safe Use of Lasers

NOTICE: Unless otherwise indicated, all documents cited shall be the latest published versions.

5 Terminology

5.1 Abbreviations and Acronyms

5.1.1 *CMOS* — complementary metal oxide semiconductor

5.1.2 *FFT* — fast Fourier transform

5.1.3 *FOV* — field of view

5.1.4 *LED* — light emitting diode

5.1.5 *MEMS* — microelectromechanical system

5.1.6 *PZT* — piezoelectric transducer

5.2 Definitions

5.2.1 *anchor* — in a surface-micromachining process, the portion of the test structure where a structural layer is intentionally attached to its underlying layer. [ASTM E2444]

5.2.2 *bulk micromachining* — a MEMS fabrication process where the substrate is removed at specified locations. [ASTM E2444]

5.2.3 *cantilever* — a test structure that consists of a freestanding beam that is fixed at one end. [ASTM E2444]

5.2.4 *fixed-fixed beam* — a test structure that consists of a freestanding beam that is fixed at both ends. [ASTM E2444]

5.2.5 *microelectromechanical systems* — in general, this term is used to describe micron-scale structures, sensors, actuators or the technologies used for their manufacture (such as, silicon process technologies), or combinations thereof. [ASTM E2444]

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² American National Standards Institute, Headquarters: 1819 L Street, NW, Washington, DC 20036, USA. Telephone: 202.293.8020; Fax: 202.293.9287. New York Office: 11 West 42nd Street, New York, NY 10036, USA. Telephone: 212.642.4900; Fax: 212.398.0023; <http://www.ansi.org>

5.2.6 *open area* — in a bulk-micromachining process, a region on the chip where the silicon surface is exposed to a selected ambient after fabrication but before the post-processing etch.

5.2.7 *residual strain* — in a MEMS process, the amount of deformation (or displacement) per unit length constrained within the structural layer of interest after fabrication yet before the constraint of the sacrificial layer (or substrate) is removed (in whole or in part). [ASTM E2444]

5.2.8 *residual stress* — remaining forces per unit area after the original cause(s) during fabrication have been removed.

5.2.9 *sacrificial layer* — a single thickness of material that is intentionally deposited (or added) then removed (in whole or in part) during the micromachining process, to allow freestanding microstructures. [ASTM E2444]

5.2.10 *stiction* — adhesion between the portion of a structural layer that is intended to be freestanding and its underlying layer. [ASTM E2444]

5.2.11 *(residual) strain gradient* — a through-thickness variation (of the residual strain) in the structural layer of interest before it is released. [ASTM E2444]

5.2.12 *(residual) stress gradient* — a through-thickness variation (of the residual stress) in the structural layer of interest before it is released.

5.2.13 *structural layer* — a single thickness of material present in the final MEMS device. [ASTM E2444]

5.2.14 *substrate* — the thick, starting material (often single crystal silicon or glass) in a fabrication process that can be used to build MEMS devices. [ASTM E2444]

5.2.15 *support region* — in a bulk-micromachining process, the area that marks the end of the suspended structure. [ASTM E2444]

5.2.16 *surface micromachining* — a MEMS fabrication process where micron-scale components are formed on a substrate by the deposition (or addition) and removal (in whole or in part) of structural and sacrificial layers. [ASTM E2444]

5.2.17 *test structure* — a component (such as, a fixed-fixed beam or cantilever) that is used to extract information (such as, the residual strain or the strain gradient of a layer) about a fabrication process. [ASTM E2444]

5.2.18 *thickness* — the height of one or more designated thin-film layers.

5.2.19 *underlying layer* — the single thickness of material directly beneath the material of interest. [ASTM E2444]

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

5.2.20 *vibrometer* — an instrument for non-contact measurements of surface motion.

5.2.21 *Young's modulus* — a parameter indicative of material stiffness and is equal to the stress divided by the strain when the material is loaded in uniaxial tension, assuming the strain is small enough such that it does not irreversibly stretch the material.

5.2.21.1 *Discussion* — It is also called the elastic modulus, the modulus of elasticity, and the tensile modulus.

5.3 Symbols

5.3.1 For Young's Modulus Measurements and Calculations:

5.3.1.1 μ — the viscosity of the ambient surrounding the cantilever.

5.3.1.2 ρ — density of the thin film layer.

5.3.1.3 E — calculated Young's modulus value obtained from the average undamped resonant frequency of a cantilever assuming clamped-free boundary conditions.

5.3.1.4 E_{init} — an initial estimate for the Young's modulus value of the thin film layer.

5.3.1.5 f_{can} — the average undamped resonant frequency of the cantilever.

5.3.1.6 L_{can} — suspended cantilever length.

5.3.1.7 Q — the oscillating quality factor of the cantilever.

5.3.1.8 t — thickness of the thin film layer.

5.3.1.9 W_{can} — suspended cantilever width.

5.3.2 For Combined Standard Uncertainty Calculations:

5.3.2.1 σ_ρ — the one sigma uncertainty of the value of ρ .

5.3.2.2 σ_{freq} — the one sigma uncertainty of the value of f_{can} .

5.3.2.3 σ_L — the one sigma uncertainty of the value of L_{can} .

5.3.2.4 σ_{thick} — the one sigma uncertainty of the value of t .

5.3.2.5 σ_W — the one sigma uncertainty of the value of W_{can} .

5.3.2.6 $E_{clamped}$ — calculated Young's modulus value obtained from the average resonant frequency of a fixed-fixed beam assuming clamped-clamped boundary conditions.

5.3.2.7 E_{max} — the maximum Young's modulus value as determined in an uncertainty calculation.

5.3.2.8 E_{min} — the minimum Young's modulus value as determined in an uncertainty calculation.

5.3.2.9 E_{simple} — calculated Young's modulus value obtained from the average resonant frequency of a fixed-fixed beam assuming simply-supported boundary conditions at both supports.

5.3.2.10 f_{ffb} — the average resonant frequency of the fixed-fixed beam.

5.3.2.11 f_{resol} — the frequency resolution for the given set of measurement conditions.

5.3.2.12 L_{ffb} — suspended fixed-fixed beam length.

5.3.2.13 p_{diff} — the estimated percent difference between the damped and undamped resonant frequency of the cantilever.

5.3.2.14 u_ρ — the component in the combined standard uncertainty calculation for Young's modulus that is due to the uncertainty of ρ .

5.3.2.15 u_c — the combined standard uncertainty value (that is, the estimated standard deviation of the result).

5.3.2.16 u_{damp} — the component in the combined standard uncertainty calculation for Young's modulus that is due to damping.

5.3.2.17 u_{freq} — the component in the combined standard uncertainty calculation for Young's modulus that is due to the measurement uncertainty of f_{can} .

5.3.2.18 u_{fresol} — the component in the combined standard uncertainty calculation for Young's modulus that is due to f_{resol} .

5.3.2.19 u_L — the component in the combined standard uncertainty calculation for Young's modulus that is due to the measurement uncertainty of L_{can} .

5.3.2.20 u_{thick} — the component in the combined standard uncertainty calculation for Young's modulus that is due to the measurement uncertainty of t .

5.3.3 For Residual Stress and Stress Gradient Calculations:

5.3.3.1 ε_r — the residual strain of the thin film layer.

5.3.3.2 σ_g — the stress gradient of the thin film layer.

5.3.3.3 σ_{gmax} — the maximum stress gradient value as determined in an uncertainty calculation.

5.3.3.4 σ_{gmin} — the minimum stress gradient value as determined in an uncertainty calculation.

5.3.3.5 σ_r — the residual stress of the thin film layer.

5.3.3.6 σ_{rmax} — the maximum residual stress value as determined in an uncertainty calculation.

5.3.3.7 σ_{rmin} — the minimum residual stress value as determined in an uncertainty calculation.

5.3.3.8 s_g — the strain gradient of the thin film layer.

5.3.3.9 $u_{\sigma(\sigma)}$ — the component in the combined standard uncertainty calculation for residual stress that is due to the measurement uncertainty of ε_r .

5.3.3.10 $u_{\sigma g}$ — the combined standard uncertainty value for stress gradient.

5.3.3.11 $u_{\sigma r}$ — the combined standard uncertainty value for residual stress.

5.3.3.12 $u_{E(\sigma g)}$ — the component in the combined standard uncertainty calculation for stress gradient that is due to the measurement uncertainty of E .

5.3.3.13 $u_{E(\sigma r)}$ — the component in the combined standard uncertainty calculation for residual stress that is due to the measurement uncertainty of E .

5.3.3.14 $u_{sg(\sigma g)}$ — the component in the combined standard uncertainty calculation for stress gradient that is due to the measurement uncertainty of s_g .

6 Summary of Method

6.1 This test method can be used to obtain Young's modulus measurements of thin films and their combined standard uncertainty values, u_c . A PZT is used to create out-of-plane excitations in cantilevers and fixed-fixed beams comprised of one layer (such as shown in Figure 1 through Figure 3). For each beam, an optical vibrometer or comparable instrument records a magnitude versus frequency plot from which the resonant frequencies are found.

6.2 The average undamped resonant frequency of the single-layered cantilever is calculated given the measured damped resonant frequencies. The Young's modulus value is calculated using the average undamped resonant frequency, assuming clamped-free boundary conditions, and assuming a density value.

6.3 The value for u_c is found in three different ways. As presented in Appendix 1, the smallest value for u_c is chosen from the following:

6.3.1 A calculation of u_c involving uncertainty components for the cantilever thickness, density, length, resonant frequency, frequency resolution, and damping.

6.3.2 A calculation of u_c assuming that the Young's modulus value obtained from the average resonant frequency of a fixed-fixed beam and assuming simply-supported boundary conditions at both supports is an extreme three sigma measurement for the Young's modulus measurement specified in ¶ 6.2.

6.3.3 A calculation of u_c assuming that the Young's modulus value obtained from the average resonant frequency of a fixed-fixed beam and assuming clamped-clamped boundary conditions is an extreme three sigma measurement for the Young's modulus measurement specified in ¶ 6.2.

6.4 Residual stress and stress gradient calculations for this thin film layer can be found in Appendix 2.

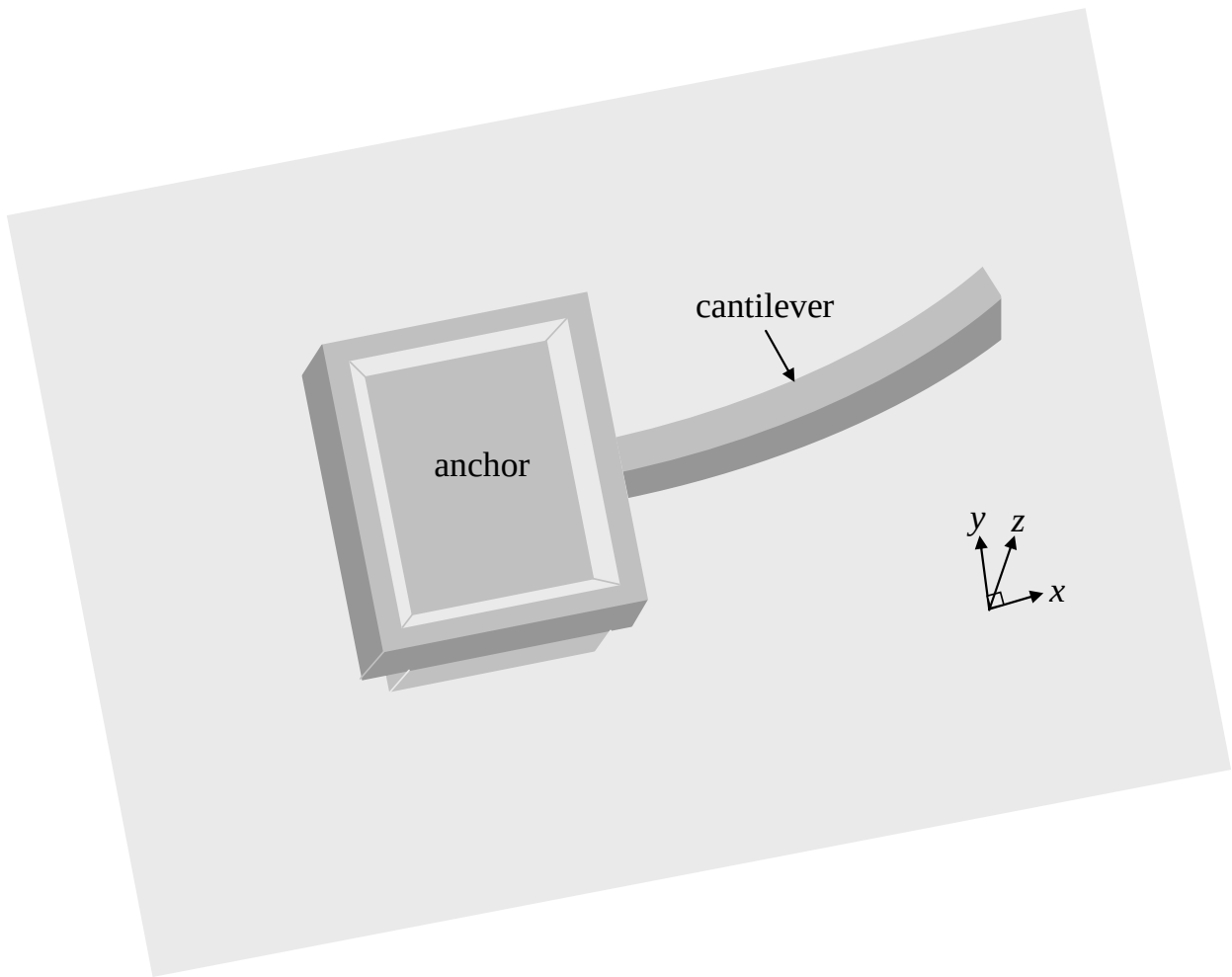
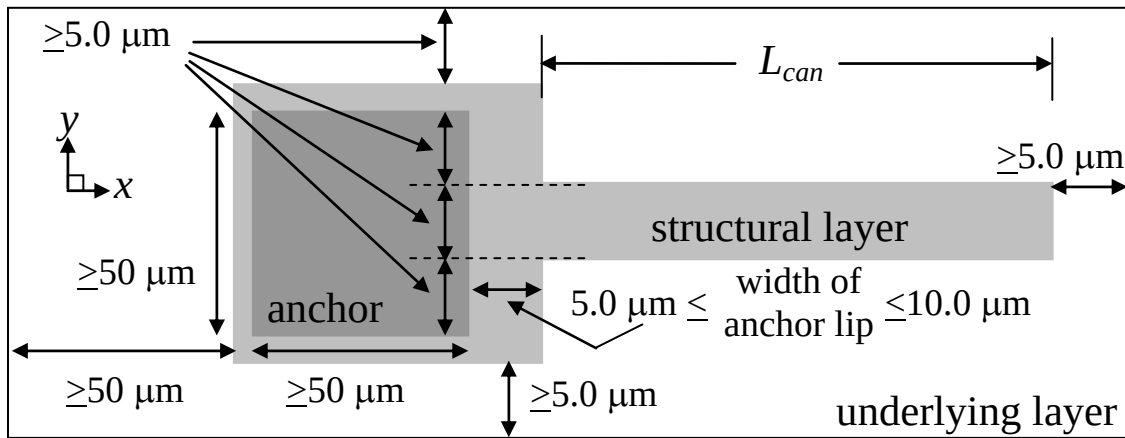


Figure 1
Three-Dimensional View of Surface-Micromachined Cantilever



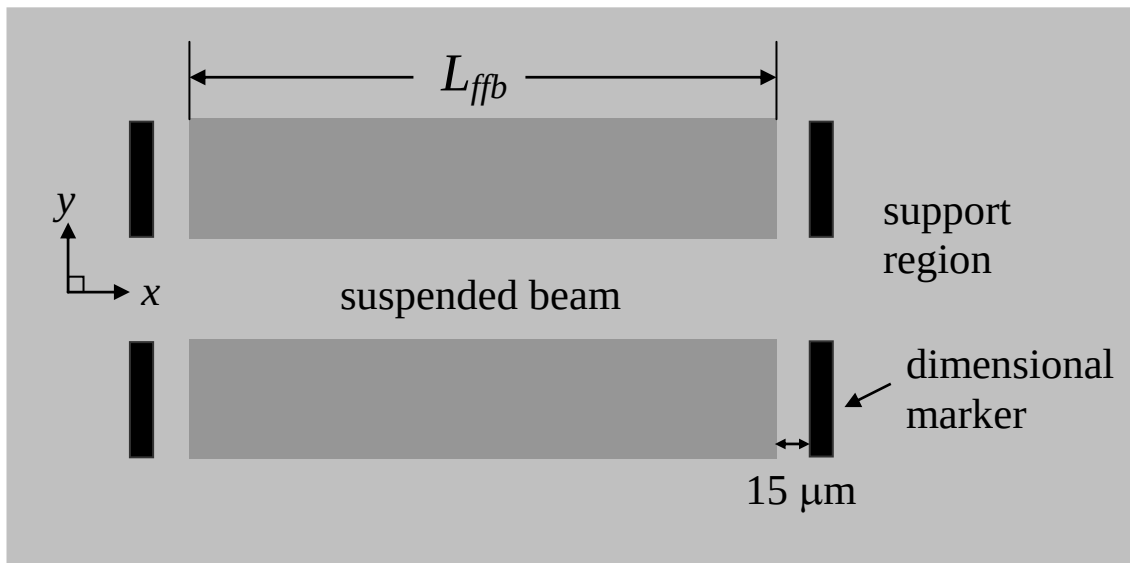
Note 1: The underlying layer is beneath the entire test structure.

Note 2: The structural layer is included in both the light and dark gray areas.

Note 3: The dark gray area (the anchor) is the designed cut in the sacrificial layer. This is where the structural layer contacts the underlying layer.

Note 4: The light gray area is suspended in air after fabrication.

Figure 2
Design Dimensions for Cantilever in Figure 1



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

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

NOTE 3: The remaining light gray area around the outside of the visible portion of the cavity and including the black dimensional markers is suspended in air, attached underneath to the substrate, or both.

NOTE 4: The black dimensional markers are typically made of polysilicon encompassed in oxide to obtain a more accurate measurement of L_{ffb} after the post-processing etch.

Figure 3
Top View of Bulk-Micromachined Fixed-Fixed Beam