SEMI MS4-0212
STANDARD TEST METHOD FOR YOUNG'S MODULUS MEASUREMENTS OF THIN, REFLECTING FILMS BASED ON THE FREQUENCY OF BEAMS IN RESONANCE

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1 Purpose

1.1 The absence of a generally accepted method to determine Young's modulus has provided a challenge to the MEMS community for many years. Without a standard measurement technique, measurements between different laboratories cannot be meaningfully compared. This Standard provides a test method to determine Young's modulus for thin, reflecting films, based on the average resonance frequency of a single-layered cantilever. It also provides a test method to determine Young's modulus based on the average resonance frequency of a single-layered fixed-fixed beam, but this method is only to be used if a cantilever is not available for measurement.

1.2 Young's modulus measurements are an aid in the design and fabrication of MEMS devices and ICs. For example, high values of residual stress can lead to failure mechanisms in ICs 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.[1] The residual stress of a thin film layer is calculated in this Test Method based on the Young's modulus value also 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 that can be imaged using a noncontact optical vibrometer, stroboscopic interferometer or comparable instrument that is capable of obtaining the resonance frequency of a beam oscillating out-of-plane. (Measurements from beams that are touching or touch the underlying layer are not acceptable.) The average resonance frequency of a single-layered cantilever is used in Young's modulus calculations. (If a cantilever is not available for measurement, the average resonance frequency of a single-layered fixed-fixed beam can be used, but this approach is not recommended due to a higher combined standard uncertainty value.) The Young's modulus value can then be used in calculations of residual stress and stress gradient.

2.2 The fabrication, including the etching steps required to release the beams, is considered outside the scope of this Test Method. The determination of the beam's length, width, thickness, and density, as well as whether the beam is exhibiting stiction is also considered outside the scope of this test method.

2.3 If the test instrument incorporates a laser, this Test Method only applies if the laser is Class 1 or Class 2.

NOTICE: SEMI Standards and Safety Guidelines do not purport to address all safety issues associated with their use. It is the responsibility of the users of the Documents to establish appropriate safety and health practices, and determine the applicability of regulatory or other limitations prior to use.

3 Limitations

3.1 To ensure that the resonance frequency of the cantilevers or fixed-fixed beams is not altered by squeeze film or other damping phenomena, the beams should be suspended high enough above the underlying layer such that its motion is not altered by the underlying layer. In other words, for cantilevers, the gap, *d*, between the suspended beam and the underlying layer should adhere to the following equation:[2]

$$d \geq \frac{W_{can}}{3}, \tag{1}$$

[1] Marshall, J. C., Herman, D. L., Vernier, P. T., DeVoe, D. L., and Gaitan, M. "Young's Modulus Measurements in Standard IC CMOS Processes using MEMS Test Structures." *IEEE Electron Devices Letters*, Vol. 28, No. 11 (November 2007): p. 960–63.

[2] Gregory T. A. Kovacs "Micromachined Transducers Sourcebook." McGraw-Hill, New York, NY (1998): p. 312.

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where W_{can} is the width of the cantilever. These damping phenomena are expected to be present in surface micromachining processes without the use of a backside etch, unless the measurement is performed in a vacuum. The damping may not be present 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. (Squeeze film and other damping phenomena routinely lead to amplitude dependent resonance frequencies and shifts in the natural frequency of the system, which may limit the accuracy of the technique.)

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 by the accuracy of this assumption.

4 Referenced Standards and Documents

4.1 *SEMI Standards and Safety Guidelines*

SEMI MS2 — Test Method for Step Height Measurements of Thin Films

4.2 *ANSI Standards*[3]

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

4.3 *ASTM Standards*[4]

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[5]

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 *CMP* — chemical mechanical planarization

5.1.3 *FFT* — fast Fourier transform

5.1.4 *FOV* — field of view

5.1.5 *IC* — integrated circuit

5.1.6 *LED* — light emitting diode

5.1.7 *MEMS* — microelectromechanical systems

5.1.8 *PZT* — piezoelectric transducer

5.2 *Definitions*

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

[3] 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

[4] American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, Pennsylvania 19428-2959, USA. Telephone: 610.832.9585; Fax: 610.832.9555; http://www.astm.org

[5] Referenced definitions reprinted, with permission, from the *Annual Book of ASTM Standards*, copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428.

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5.2.2 *bulk micromachining* — a MEMS fabrication process that removes the substrate at specified locations.

5.2.3 *cantilever* — a MEMS test structure that consists of a freestanding beam that is fixed at one end.

5.2.4 *fixed-fixed beam* — a MEMS test structure that consists of a freestanding beam that is fixed at both ends.

5.2.5 *interferometer* — a non-contact optical instrument used to obtain topographical data (such as 3-D data sets and 2-D data traces).

5.2.5.1 *Discussion* — The *z*-axis of the interferometer is used to measure the height of the sample. The *x*-axis is typically aligned parallel or perpendicular to the measured transitional edges.

5.2.6 *microelectromechanical systems* — a term used to describe micron-scale structures, sensors, actuators, and technologies used for their manufacture (such as, silicon process technologies), or combinations thereof.

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

5.2.8 *quality factor* — a measure of the sharpness of a resonance peak.

5.2.9 *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]

5.2.10 *residual stress* — the remaining forces per unit area within the structural layer of interest after the original cause(s) during fabrication have been removed yet before the constraint of the sacrificial layer (or substrate) is removed (in whole or in part).

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

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

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

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

5.2.15 *structural layer* — a single thickness of material that is present in the final MEMS device.

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

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

5.2.18 *surface micromachining* — a MEMS fabrication process where components are formed on a substrate by the deposition (or addition) and removal (in whole or in part) of structural and sacrificial layers.

5.2.19 *test structure* — a fabricated 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 the fabrication process.

5.2.20 *thickness* — the height in the *z*-direction of one or more designated thin film layers.

5.2.21 *transitional edge* — the side of a MEMS structure that is characterized by a distinctive out-of-plane vertical displacement as seen in a 2-D data trace.

5.2.22 *underlying layer* — the single thickness of material (which can be the substrate) located directly beneath the material of interest.

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

5.2.24 *Young's modulus* — a parameter indicative of material stiffness that 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 deform the material.

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

5.3 *Symbols*

5.3.1 *For Calibration*

5.3.1.1 σ_{meter} — for calibrating the time base of the instrument: the standard deviation of the measurements used to obtain f_{meter}.

5.3.1.2 cal_f — the calibration factor for a frequency measurement.

5.3.1.3 $f_{instrument}$ — for calibrating the time base of the instrument: the frequency setting for the calibration measurements (or the manufacturer's specification for the clock frequency).

5.3.1.4 f_{meter} — for calibrating the time base of the instrument: the calibrated average frequency of the calibration measurements (or the calibrated average clock frequency) taken with a frequency meter.

5.3.1.5 u_{certf} — for calibrating the time base of the instrument: the certified uncertainty of the frequency measurements as specified on the frequency meter's certificate.

5.3.1.6 u_{cmeter} — for calibrating the time base of the instrument: the uncertainty of the frequency measurements taken with the frequency meter.

5.3.2 *For Young's Modulus Measurements and Calculations*

5.3.2.1 μ — viscosity of the ambient surrounding the cantilever.

5.3.2.2 ρ — density of the thin film layer.

5.3.2.3 E — calculated Young's modulus value of the thin film layer.

5.3.2.4 $E_{clamped}$ — calculated Young's modulus value obtained from the average resonance frequency of a fixed-fixed beam assuming clamped-clamped boundary conditions.

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

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

5.3.2.7 f_{can} — average calibrated undamped resonance frequency of the cantilever, which includes the frequency correction term.

5.3.2.8 $f_{correction}$ — correction term for the cantilever's resonance frequency.

5.3.2.9 f_{ffb} — average uncalibrated resonance frequency of the fixed-fixed beam.

5.3.2.10 L_{can} — suspended cantilever length.

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

5.3.2.12 Q — oscillatory quality factor of the cantilever.

5.3.2.13 t — thickness of the thin film layer.

5.3.2.14 W_{can} — suspended cantilever width.

5.3.3 *For Combined Standard Uncertainty Calculations*

5.3.3.1 σ_μ — one sigma uncertainty of the value of μ.

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

5.3.3.3 $\sigma_{cantilever}$ — uncertainty in the cantilever's resonance frequency due to geometry and/or composition deviations from the ideal.

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5.3.3.4 σ_{Einit} — estimated standard deviation of E_{init}.

5.3.3.5 $\sigma_{freqcal}$ — the calibrated standard deviation of the frequency measurements (used to obtain f_{can}) that is due to the calibration of the time base for which the uncertainty is assumed to scale linearly.

5.3.3.6 σ_{fresol} — the calibrated standard deviation of the frequency measurements (used to obtain f_{can}) that is due to the frequency resolution.

5.3.3.7 $\sigma_{fundamped}$ — one sigma uncertainty of the calibrated undamped resonance frequency measurements.

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

5.3.3.9 $\sigma_{support}$ — the estimated uncertainty in the cantilever's resonance frequency due to a non-ideal support (or attachment conditions).

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

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

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

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

5.3.3.14 U_E — the expanded uncertainty of a Young's modulus measurement.

5.3.3.15 u_{cE} — combined standard uncertainty of a Young's modulus measurement as obtained from the resonance frequency of a cantilever.

5.3.3.16 u_E — uncertainty of a Young's modulus measurement as obtained from the resonance frequency of a fixed-fixed beam.

5.3.4 *For Residual Stress and Stress Gradient Calculations*

5.3.4.1 ε_r — residual strain of the thin film layer.

5.3.4.2 σ_g — stress gradient of the thin film layer.

5.3.4.3 σ_r — residual stress of the thin film layer.

5.3.4.4 s_g — strain gradient of the thin film layer.

5.3.4.5 $U_{\sigma g}$ — the expanded uncertainty of a stress gradient measurement.

5.3.4.6 $U_{\sigma r}$ — the expanded uncertainty of a residual stress measurement.

5.3.4.7 $u_{c\varepsilon r}$ — combined standard uncertainty value for residual strain.

5.3.4.8 $u_{c\sigma g}$ — combined standard uncertainty value for stress gradient.

5.3.4.9 $u_{c\sigma r}$ — combined standard uncertainty value for residual stress.

5.3.4.10 u_{csg} — combined standard uncertainty value for strain gradient.

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. A PZT is used in this test method to create out-of-plane excitations in beams (such as shown in Figures 1 and 2). For each beam, an optical vibrometer, stroboscopic interferometer, or comparable instrument records an excitation-magnitude versus frequency plot from which the resonance frequency is found.

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NOTE 1: Although this test method uses a PZT to excite the beams; it does not imply that a PZT is the only means available for excitation (e.g., thermal excitation[6] is possible). For alternate means of excitation, modifications will need to be made, as appropriate, to obtain the required data.

6.2 A single-layered cantilever is used to obtain the Young's modulus value of that layer. Three measurements of resonance frequency are taken and the average undamped resonance frequency of the cantilever is calculated. Given this value, the Young's modulus value is determined assuming clamped-free boundary conditions and assuming a density value. The combined standard uncertainty value, u_{cE}, is determined in Appendix 1.

6.3 If a cantilever is not available for measurement, a fixed-fixed beam can be used. (However, this approach is not recommended due to a higher resulting uncertainty value) Given the average resonance frequency of the fixed-fixed beam, two values of Young's modulus are calculated; one assuming simply-supported boundary conditions at both supports (E_{simple}) and one assuming clamped-clamped boundary conditions ($E_{clamped}$). Given these two Young's modulus values, the average Young's modulus is calculated and recorded as the Young's modulus value for the thin film layer. The uncertainty is calculated assuming E_{simple} and $E_{clamped}$ are three sigma values.

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

6.5 The procedure specified in the body of this Test Method is for use with an optical vibrometer or comparable instrument. The procedure specified in Appendix 3 is for use with a stroboscopic interferometer or comparable instrument.

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[6] Gabrielson, T.B. "Mechanical-Thermal Noise in Micromachined Acoustic and Vibration Sensors." *IEEE Transactions on Electron Devices*, Vol. 40, No. 5 (May 1993): pp. 903–09.

Oden, P.I. "Gravimetric sensing of metallic deposits using an end-loaded microfabricated beam structure." *Sensors and Actuators B*, 53 (1998): pp. 191–96.

Lawrence, E. M., Rembe, C. "MEMS Characterization using New Hybrid Laser Doppler Vibrometer/Strobe Video System." SPIE Proceedings Vol. 5343, Reliability, Testing, and Characterization of MEMS/MOEMS III (January 2003): pp. 45–54.

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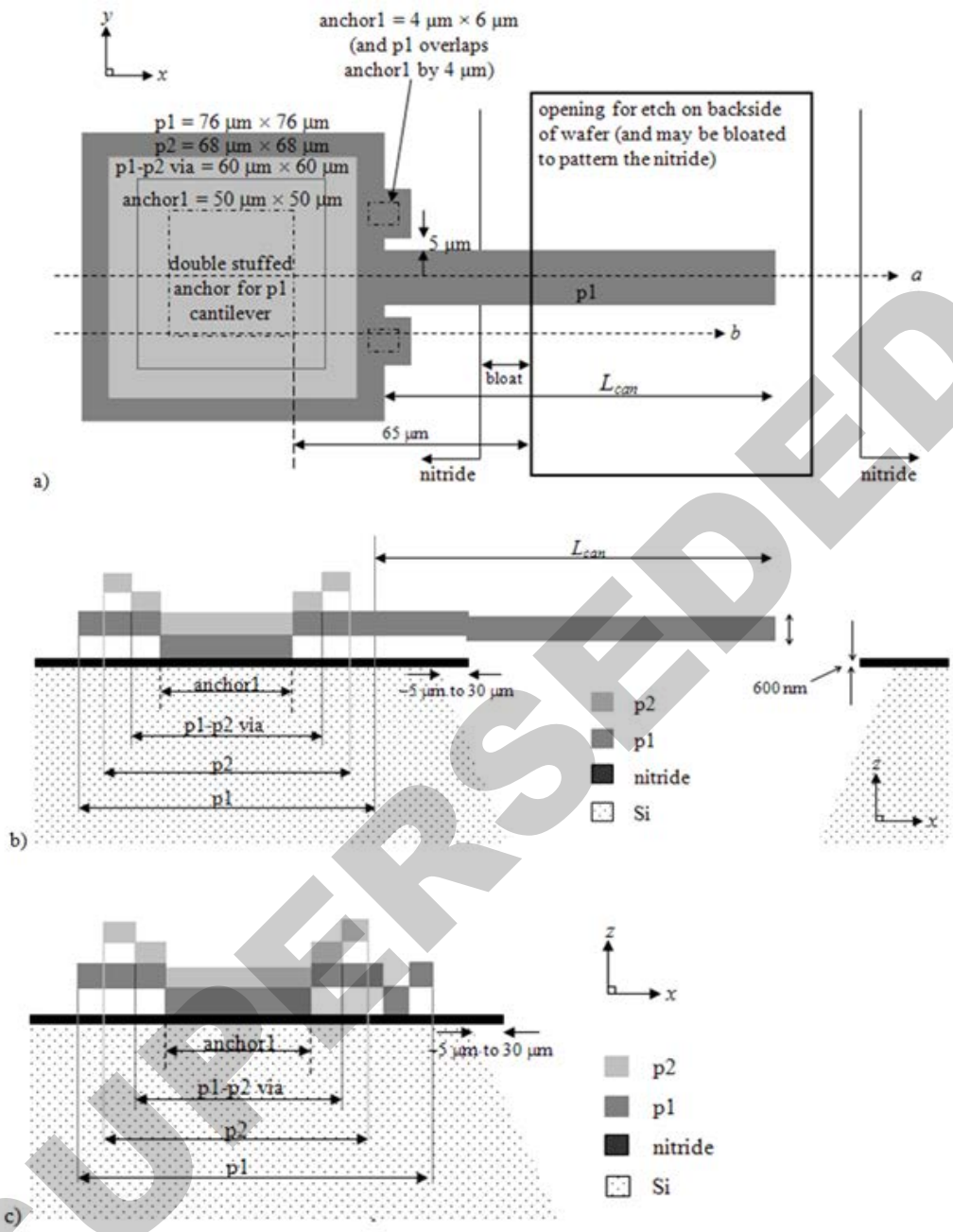

Figure 1
For Surface Micromachined Cantilever a) the Design Dimensions,
b) Cross Section along Trace a in a), and c) Cross Section along Trace b in a)

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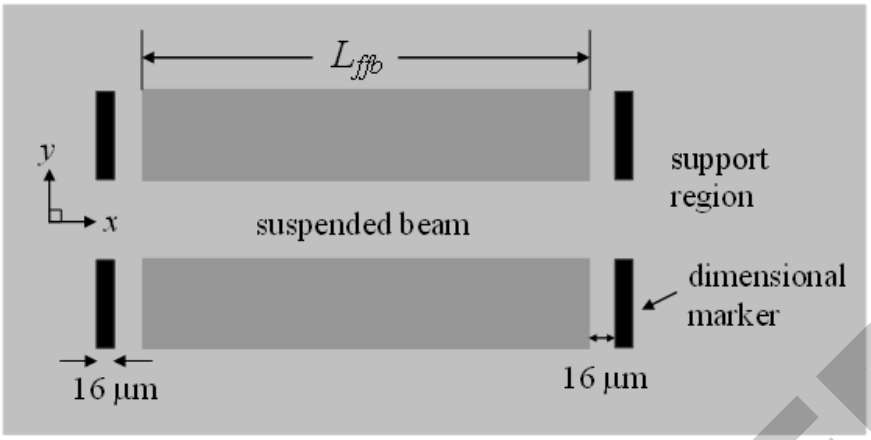

NOTE 1: The central beam is suspended above a micromachined cavity.
NOTE 2: The dark gray areas are the visible parts of the micromachined cavity.
NOTE 3: The remaining light gray area around the outside of the visible portion of the cavity and including the black dimensional markers is either suspended in air or attached underneath to the substrate.
NOTE 4: The black dimensional markers are typically made of polysilicon or metal encapsulated in oxide to obtain a more accurate measurement of L_{ffb} after the post-processing etch.

Figure 2
Top View of Bulk-Micromachined Fixed-Fixed Beam

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7 Interferences

7.1 *Stiction* — Measurements from beams that are touching the underlying layer are not accepted.

NOTE 2: To determine if a cantilever is adhered to the top of the underlying layer, consult ASTM E2246. To determine if a fixed-fixed beam is adhered to the top of the underlying layer, consult ASTM E2245. This is considered outside the scope of this Test Method.

7.2 *Damping* — Measurements from certain beams in certain ambient environments experience more damping than others. Measurements from these beams are not recommended. See ¶ 10.2.4 for some geometrical considerations.

8 Apparatus

8.1 *Noncontact Optical Vibrometer, Noncontact Optical Stroboscopic Interferometer, or an Instrument Comparable to One of These* — Capable of noncontact measurements of surface motion in the *z*-direction. Additional specifications for this instrument are given in ¶¶ 8.1.1 through 8.1.6.

NOTE 3: A schematic of a typical setup for a single beam laser vibrometer is shown in Figure 3. A signal generator provides an excitation signal, which excites the sample via a 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.

NOTE 4: 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 3 and is positioned to a point on the sample (e.g., 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.

NOTE 5: A simplified schematic of a typical setup for a stroboscopic interferometer is shown in Figure 4a. 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 4b). 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, in

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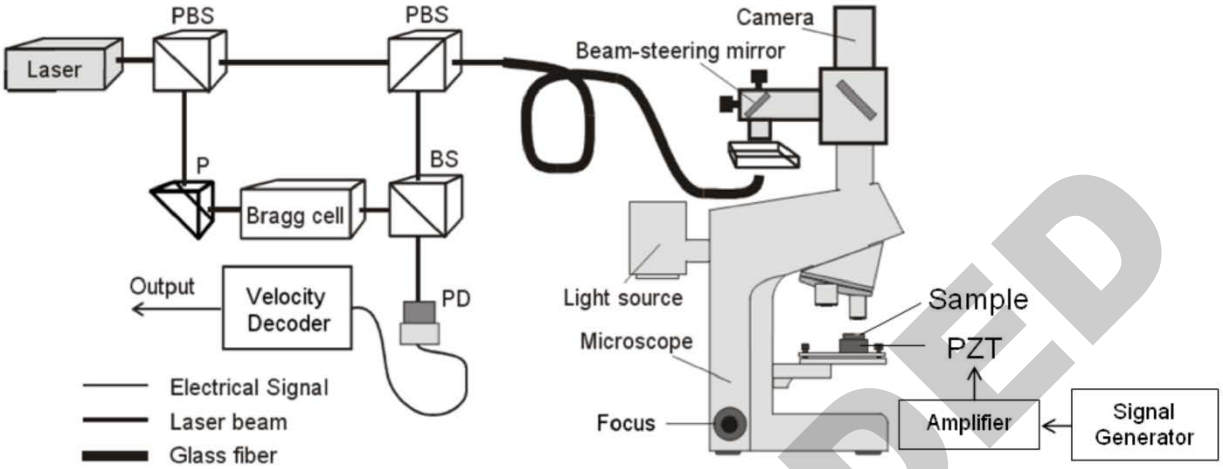
this Test Method, after securing it to the top of a PZT. The phase, frequency, and drive signal to the strobe and PZT are varied, performing a downward scan as is done for static devices at each combination to obtain successive 3-D images as the sample cycles through its range of motion.



NOTE: PBS indicates a polarizing beam splitter; BS indicates a beam splitter; P indicates a prism; and PD indicates a photodetector.

Figure 3
Schematic of a Typical Setup for a Single Beam Laser Vibrometer

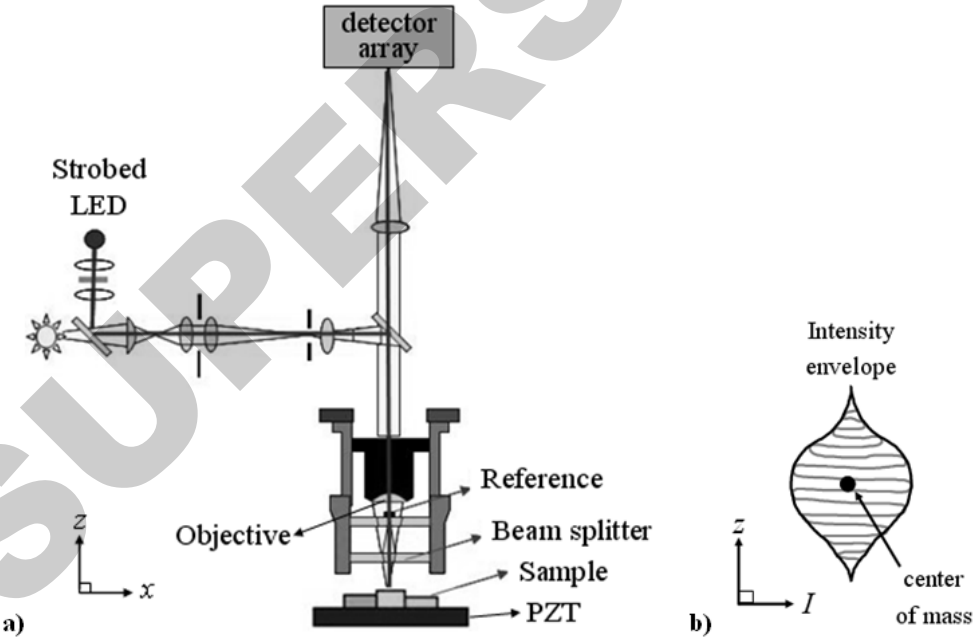


Figure 4
For a Typical Stroboscopic Interferometer a) a Schematic and b) an Intensity Envelope Used to Obtain a Pixel's Sample Height

8.1.1 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

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at least half of the length of the cantilever or fixed-fixed beam being measured. For the dimensions of the example beams described in this document, objectives of 4× and 20× will suffice.

8.1.2 The signal generator should be able to produce a waveform function (such as a periodic chirp function or a sine wave function) 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.

NOTE 6: The periodic chirp function mentioned above 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 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.

NOTE 7: 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.

8.1.3 The instrument shall be capable of producing a magnitude versus frequency plot from which the resonance frequency can be obtained.

8.1.4 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.

8.1.5 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:[7]

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

where details concerning the parameters in this equation can be found in §§ 5.3 and 13.7. 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:[7]

$$f_{ffbinithi} = \sqrt{\frac{E_{init} t^2}{0.946 \rho L_{ffb}^4}}, \tag{3}$$

where details concerning the parameters in this equation can be found in §§ 5.3 and 13.7.

8.1.6 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]

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

In the above equation, $f_{dampedn}$ is the nth calibrated damped resonance frequency measurement and $f_{undampedn}$ is the nth calibrated undamped resonance frequency to be discussed in § 14.1. For a cantilever, the Q-factor, Q, in Equation 4 can be estimated using the following equation:[7, 8]

[7] By inserting the inputs into the correct locations on the appropriate NIST MEMS Calculator Web Page, the calculations in this Test Method can be performed on-line in a matter of seconds. The MEMS Calculator Web Site (Standard Reference Database 166) is accessible via the NIST Data Gateway (http://srdata.nist.gov/gateway/) with the keyword "MEMS Calculator."

Also consult Cassard, J. M., Geist, J., Vorburger, T. V., Read, D. T., Gaitan, M., and Seiler, D. G. "Standard Reference Materials: User's Guide for RM 8096 and 8097: The MEMS 5-in-1, 2012 Edition." *NIST Special Publication 260-174*, National Institute of Standards and Technology, soon to be published."

[8] Kiesewetter, L., Zhang, J. – M., Houdeau, D., and Steckenborn, A. "Determination of Young's moduli of micromechanical thin films using the resonance method." *Sensors and Actuators A*, vol. 35 (1992) pp. 153–59.

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$$Q=\left[\frac{W_{can}\sqrt{E_{init}\rho}}{24\mu}\right]\left(\frac{t}{L_{can}}\right)^2, \quad (5)$$

where μ is the viscosity of the ambient (in air, μ=1.84e–5 Ns/m^2 at 20°C)[9] and W_{can} is the suspended width of the cantilever obtained in the most accurately available fashion. This is considered outside the scope of this Test Method. Details concerning the other parameters in this equation can be found in §§ 5.3 and 13.7.

8.2 *Amplifier (optional)* — With a gain of 10 and bandwidth of 8 kHz for the vibrometer and with a gain of 50 and bandwidth of 200 kHz for the stroboscopic interferometer, to amplify the excitation signal going to the PZT.

8.3 *Low Voltage PZT (with Two Wire Leads)* — To cause out-of-plane vibrations in the chip and excite the cantilevers and fixed-fixed beams on the chip. The dimensions of a representative PZT are approximately 5 mm by 5 mm and 2 mm in height. It can achieve a 2.2 µm (±20%) displacement at 100 V from DC to 100 kHz and has an electrical capacitance of 250 nF (±20%). It has a resonance frequency greater than 300 kHz, at which or above which it shall not be operated because it could damage the PZT. The red wire is driven with a voltage that is positive relative to the black wire.

8.4 *Low Stress Non-conducting Epoxy* — For mounting the chip to the top of the PZT, to allow movement and to not electrically short the PZT. It can also be used to permanently attach the PZT to the microscope slide or to a package.

8.5 *Microscope Slide* — Serves as a non-conductive substrate upon which the PZT is permanently mounted. An alternate mounting (e.g., within a package) can be used as long as the PZT is not electrically shorted.

8.6 *Solderless Breadboarding Socket (optional)* — To aid stability to the package sample assembly during setup and measurement, if applicable.

8.7 *Small Mirror* — To check the spot size of the measurement beam, if applicable.

8.8 *Frequency Meter* — With a resolution capability of at least 10 digit/sec, to calibrate the time base of the instrument.

8.9 *Oscilloscope (optional)* — To monitor waveforms, such as the drive signals to the PZT.

8.10 *Thermometer (optional)* — To record the temperature during measurement.

8.11 *Humidity Meter (optional)* — To record the relative humidity during measurement.

9 Safety Precaution

9.1 If the light source of the optical vibrometer, stroboscopic interferometer, or comparable instrument is a laser, do not look directly into the laser beam or into the reflected laser beam (see ANSI Z136.1). If a laser light source is used, this test method only applies to Class 1 and Class 2 lasers.

NOTE 8: Class 1 lasers are exempt from control measures because they do not emit harmful levels of radiation. However, as a general practice, unnecessary exposure to Class 1 laser light should be avoided.

NOTE 9: Class 2 lasers can cause eye damage through chronic exposure. When exposed to Class 2 laser light, the human eye will generally blink within 0.25 seconds, which protects the eye. However, eye damage can be caused by overcoming this blink reflex and staring into the laser.

10 Test Specimen

10.1 The design of a representative cantilever or fixed-fixed beam in a surface-micromachining process is specified below in § 10.2. For a bulk-micromachining process, the design is specified in § 10.3. The specific process steps, necessary to realize the beams specified in this section, are considered outside the scope of this Test Method.

[9] CRC Handbook of Chemistry and Physics, 91st Edition, 2010-2011 (on-line edition), Accessed August 15, 2011 at http://208.254.79.26/ (subscription required).

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