Specifying and Measuring Nanometer Surface Properties

a seminar prepared for the
American Society of Mechanical Engineers

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Specifying and Measuring Nanometer Surface Properties

1. **Specifying and Measuring Nanometer Surface Properties -** The 2002 edition of ASME B46.1 is the first national standard to address the specific issues associated with nanometer metrology. It has been eight years in the preparation.

2. **ASME B46.1-2002 -** Two new chapters are incorporated: Chapter 7 contains the nanometer metrology methods and Chapter 8 describes the performance limits of optical instruments often used in nanometer surface metrology. Accuracy was the principal concern of the committee since at the nanometer scale the metrology instruments are being used at, or near, their limits of stability, sensitivity or both. To encourage accuracy the metrologist is required to report the uncertainty of his measurements. He must also report the high and low limits to the passband. New calibration devices are incorporated in the standard. Step heights have been included as a surface parameter, in part because they are the preferred calibration devices (roughness calibration specimens are not recommended). Drift and curvature may be removed from the data. All contact and non-contact instruments are accommodated, including AFMs.

ASME B46.1-2002

New:

Chapter 7 *Nanometer Surface Texture and Step Heights*
Chapter 8 *Optical Methods for Nanometer Surface Metrology*

Accuracy, Accuracy, Accuracy

Measurement uncertainty to be reported
Passband reported
New calibration devices
Step height added as surface property
Drift and curvature may be removed from the data
All contact and non-contact instruments, including AFMs

3. **Accuracy -** The accuracy issue is well illustrated by a nanometer-scale roughness roundrobin sponsored by AMD in the mid-90s. The participants included nine industrial and academic metrology laboratories using all three of the most widely used atomic force microscopes (AFMs). In a comparison of the laboratories' measurements the highest and lowest values varied by a factor of 8.5 for the peak-to-valley roughness and a factor of 6.8 for the root-mean-square roughness. There is clearly a major problem in the calibration of the instruments. The five laboratories that have the best agreement still disagree by factors of 2.0 and 1.8.

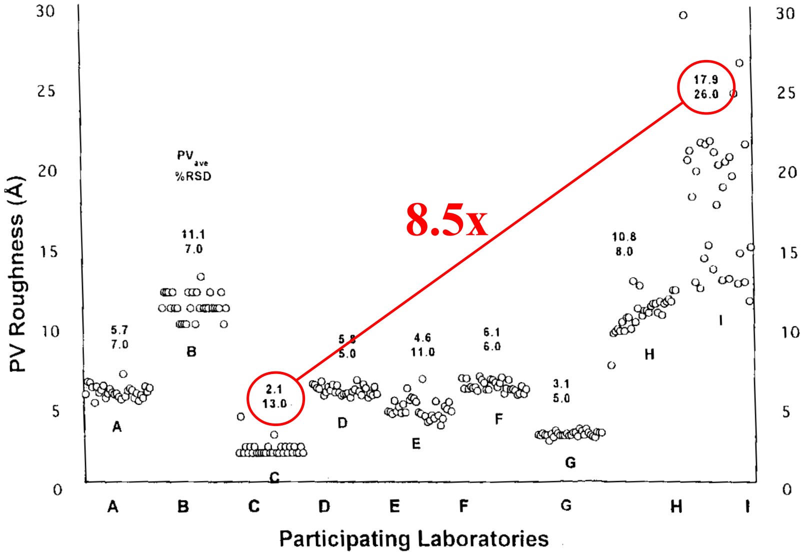
Accuracy

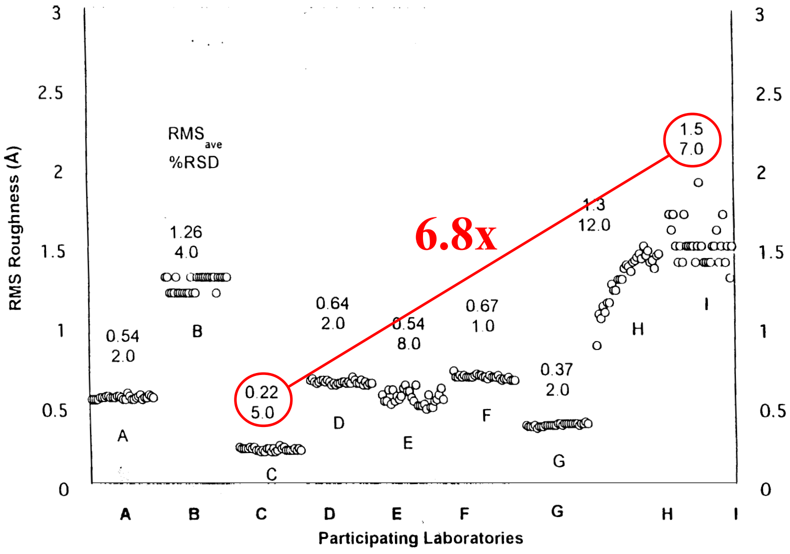
Instruments from:

- Digital Instruments
- Park Scientific
- Topometrix

Participants:

- 4 Semiconductor Manufacturers
- 3 Instrument Makers
- 1 University
- 1 Independent Lab





(After: Raheem, R., Advanced Micro Devices, Sunnyvale, California, 1996)

4. **Applications -** The industries needing good nanometer metrology include;

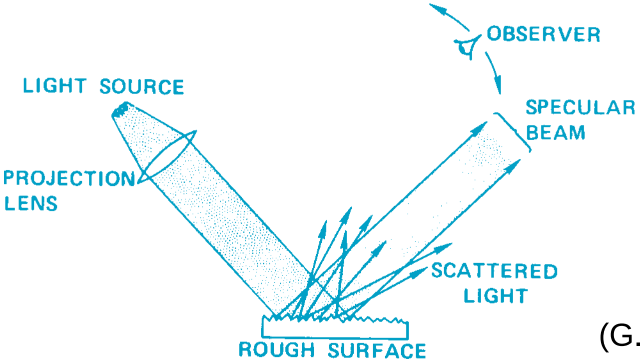
    a. Magnetic storage – The size of a written byte is controlled by the gap between the recording medium and the write head. The gap is maintained by the air that is drawn between them and the aerodynamics of the air draft is controlled by the roughness on both the head and the medium. High density recording requires closely controlled surface roughness so the gap is neither too large nor too small.
    b. Optical instruments – High performance optical instruments require very smooth surfaces to suppress light scattering that limits the contrast of the image at the focal plane.
    c. Semiconductors – Integrated circuits are requiring small features, line widths and film thickness. Since these are laid down in many overlaying layers very tight dimensional tolerances are required on each step of the process. Semiconductors also need a very smooth surface in the beginning.

Applications

Magnetic Disk Drives: head-to-disk air film controlled by roughness

(Hutchinson Technology)

Optical Instuments: low light scatter surfaces



(G. M. Bennett, L. Mattsson)

Semiconductors: Thin films, shallow etches, small features and smooth surfaces

(Digital Instruments)

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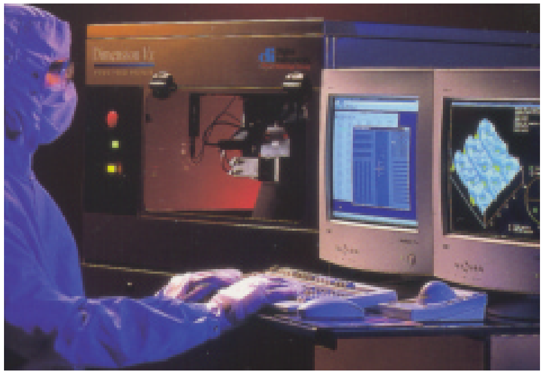
5. **Nanometer Metrology Instruments -** Both contact and non-contact instruments are used in nanometer surface metrology. Ted Vorburger described the linear voltage differential transformer (LVDT) often used in profiling instruments. The LVDT transducer is relatively stable but near the limits of its sensitivity at the nanometer scale. AFMs derive their metrology from piezoelectric transducers that scan the specimen in three directions. The surface height is derived from the transducer voltage by driving the Z-axis transducer to null the optical signal that is sensitive to the force on the tip of the probe. The phase measuring interferometric microscope also derives its metrology from a piezoelectric transducer. The microscope is driven in the Z direction by the transducer and the height of the surface is determined from the voltage on the transducer when the fringe appears. The piezoelectric transducer is relatively sensitive at the nanometer level but is unstable and requires frequent calibration.

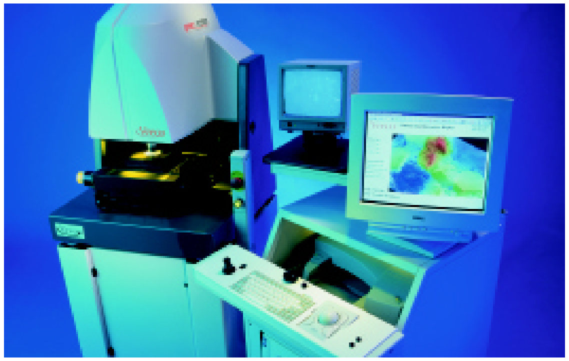
Nanometer Metrology Instruments

Contact Types

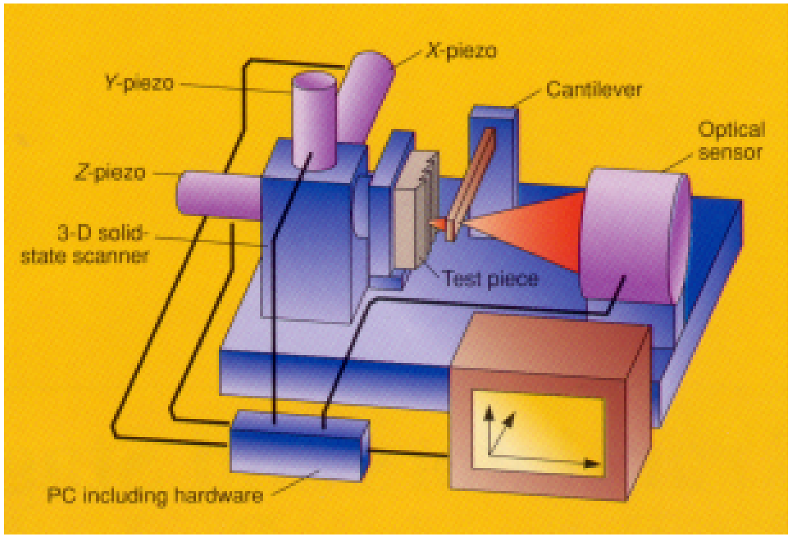
Non-contact Types



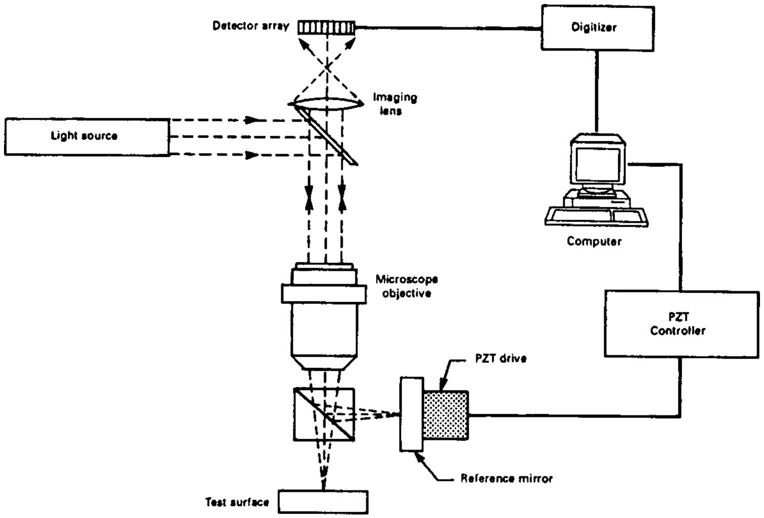
(Digital Instruments)



(Wyco)



(Queensgate)

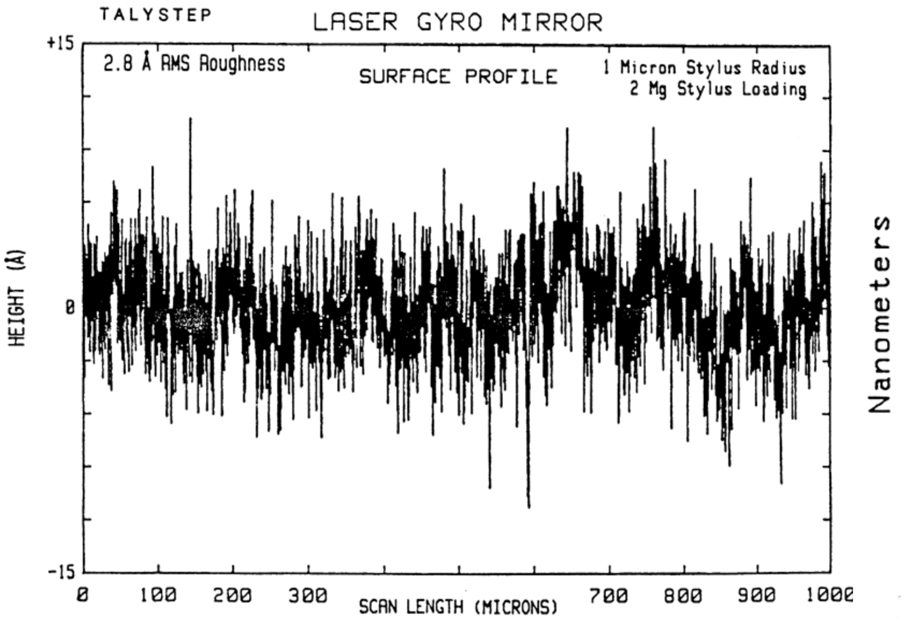


(D. Cohen)

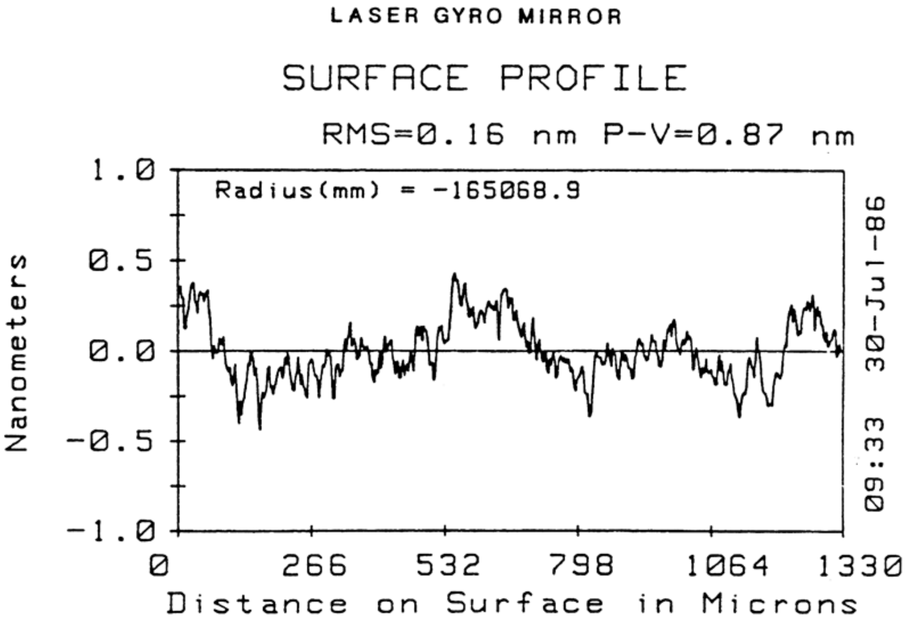
6. **Instrument Responses (1) -** The type of instrument used to make nanometer scale measurements may strongly affect the result. A stylus/probe instrument may be sensitive to much shorter wavelengths than an optical instrument. The difference may be nearly a factor of two in the indicated roughness. An LVDT transducer may also include more noise because it is being used near the limits of its sensitivity.

Instrument Responses (1)

Stylus/Probe
Profiler



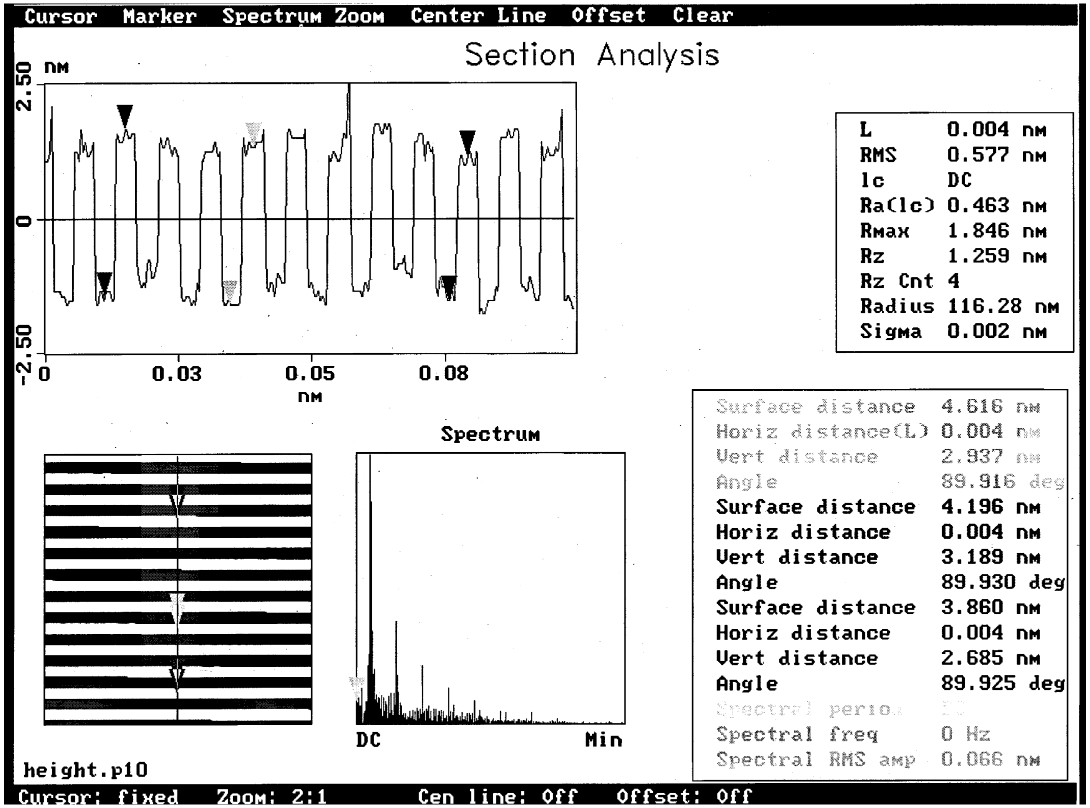
Interferometric
Profiler



(After T. Vorburger, from J. M. Bennett et al.)

7. **Instrument Responses (2) -** The instability of a piezoelectric transducer in an AFM is shown in a train of 3.70 nanometer steps generated by a Hewlett-Packard signal generator driving a calibrated displacement actuator. The steps were measured by an AFM. Three steps were selected for evaluation and their mean was about 14% high (4.22 nanometers) and their standard deviation was about 10% of the step size. The mean value may be corrected by calibration at-size. The uncertainty of the size of the feature may then be reduced by averaging more measurements.

Instrument Responses (2)



```
L         0.004 nm
RMS       0.577 nm
lc        DC
Ra(lc)    0.463 nm
Rmax      1.846 nm
Rz        1.259 nm
Rz Cnt    4
Radius    116.28 nm
Sigma     0.002 nm
```

```
Surface distance     4.616 nm
Horiz distance(L)    0.004 nm
Vert distance        2.937 nm
Angle                89.916 deg
Surface distance     4.196 nm
Horiz distance       0.004 nm
Vert distance        3.189 nm
Angle                89.930 deg
Surface distance     3.860 nm
Horiz distance       0.004 nm
Vert distance        2.685 nm
Angle                89.925 deg
Spectral period      DC
Spectral freq        0 Hz
Spectral RMS amp     0.066 nm
```

Nanoscope 5000

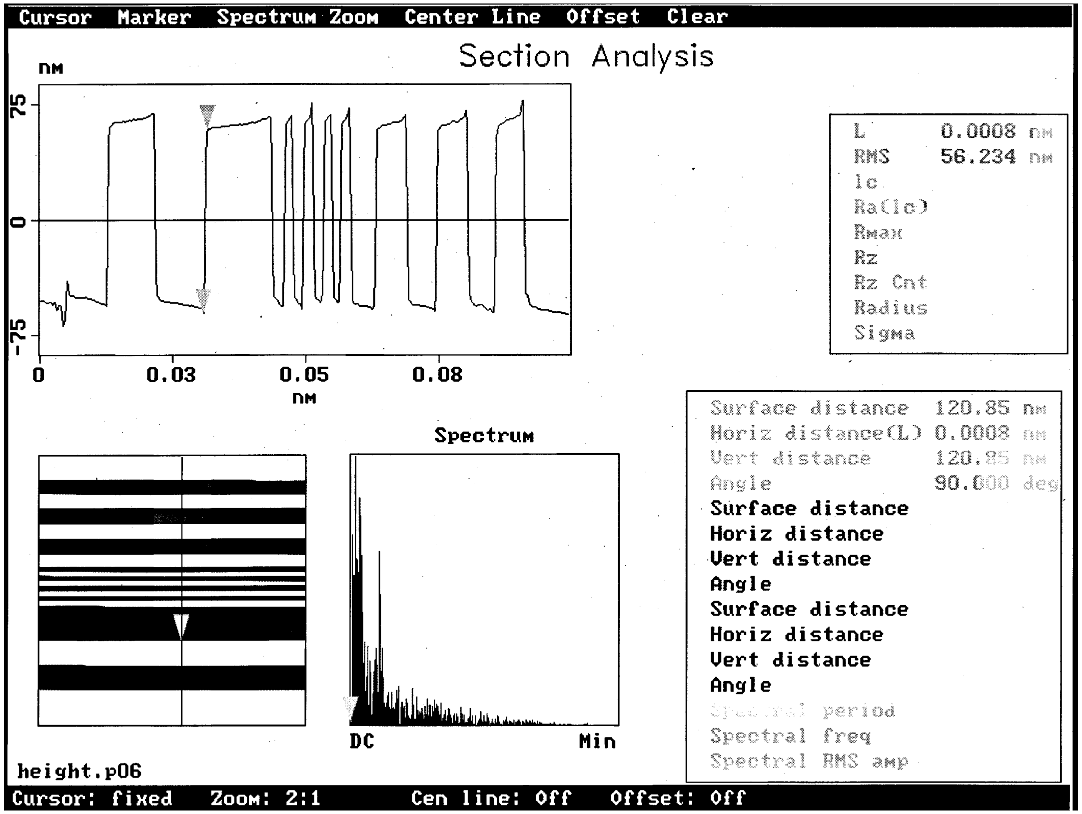
Train of 3.70 nm steps from the HECTOR^{tm} calibrated displacement actuator (0.0143 ampere from a Hewlett-Packard waveform generator).

		Error
Mean (3)	2.937 nm	-20.6%
Std. Dev. (3)	0.252 nm	6.8%

HECTOR and HECTOR-100 are trademarks of Alson E. Hatheway Inc.

8. **Instrument Responses (3) -** The same AFM was used to measure a 109.4 step produced by a calibrated displacement actuator. A single step was measured to be 120.85 nanometers, 10.4% high. Another form of instability is apparent in the data: the tops and bottoms of the steps should be flat but are seen to peak on the leading edge (note that time goes from right-to-left in the chart in the upper left corner). This drift characteristic is well known in these kinds of transducers. The amplitude value may be corrected by calibration at-size. The drift effects may be minimized by calibration at the time of measurement.

Instrument Responses (3)



```
L              0.0008 nm
RMS            56.234 nm
lc
Ra(lc)
Rmax
Rz
Rz Cnt
Radius
Sigma
```

```
Surface distance    120.85 nm
Horiz distance(L)   0.0008 nm
Vert distance       120.85 nm
Angle               90.000 deg
Surface distance
Horiz distance
Vert distance
Angle
Surface distance
Horiz distance
Vert distance
Angle
Spectral period
Spectral freq
Spectral RMS amp
```

Nanoscope 5000

Train of 109.4 nm steps from the HECTOR^{tm} calibrated displacement actuator

		Error
Step (1)	120.85 nm	+10.5%

Instability visible in plateaus and floors.

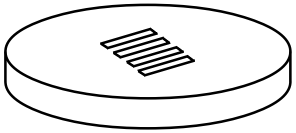
9. **Nanometer Calibration Devices -** Calibration for nanometer surface measurements must be performed with a known step height. Roughness calibration specimens are not recommended. There are three calibration devices currently available: Calibration Specimens are available in height above about 8 nanometers and with an uncertainty of about 0.1 nanometers; Single Silicon Atom Steps are available at a step size of 0.31 nanometers and an uncertainty of about 6.0%; Calibrated Displacement Actuators produce steps of any size between +100 and –100 (grooves) nanometers with an uncertainty of about 0.04%. Any calibration device must contain an estimate of its uncertainty.

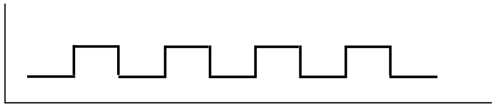
Nanometer Calibration Devices

Calibration Specimens

8.0 nanometers and larger

($U_{k=2}$ = ~0.1 nm)

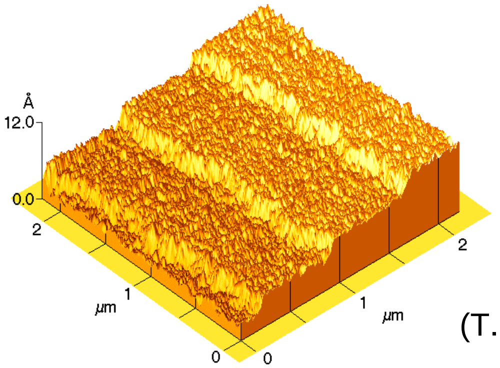


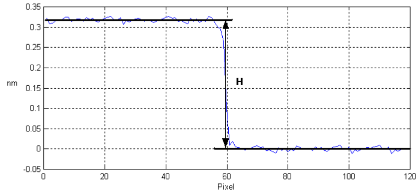


Single Silicon Atom Steps

0.31 nanometers

($U_{k=2}$ = 6.0%)



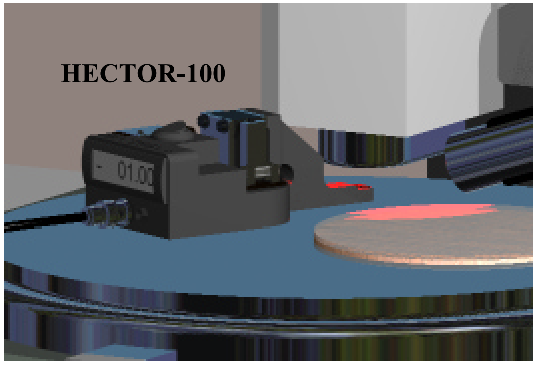


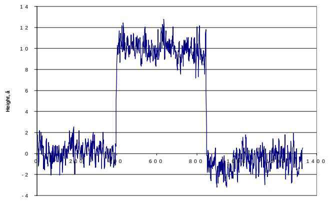
(T. Vorburger)

Calibrated Displacement Actuators

100 nanometers to 0.01 nanometer

($U_{k=2}$ = 0.04%)





(A. E. Hatheway)

Calibration device must include an evaluation of its uncertainty

10. **The Treatment of Uncertainty -** The report of the measurement must contain a statement of the uncertainty of the reported value. Uncertainty is to be treated in accordance with the ISO's "*Guide to the Expression of Uncertainty in Measurement*." Sources of uncertainty to be considered include the irregularity of the feature being measured, instrument stability and sensitivity limits, environmental influences and the calibration device. All sources of uncertainty should be considered. The uncertainty of the measurement should be small with respect to the size of the feature being measured. A "coverage factor" of 2.0 is used to determine the "expanded uncertainty" that is reported.

The Treatment of Uncertainty

Uncertainty

standard uncertainty = u = standard deviation of a measurement
expanded uncertainty = U = *k*u
coverage factor = *k* = 2.0 for B46.1 reporting

Sources of Uncertainty in a Measurement

Feature irregularity
Environment
Instrument
Calibration device

Types of Uncertainty

Evaluation by analysis, Type A
Evaluation by other methods, Type B

References: ***Guide to the Expression of Uncertainty in Measurement***
aka: *"GUM"*
Available from ISO
Methods for Improving Accuracy of Measurements
ASME b46.1, Project Team 29

11. **Annotations to the Report -** Some data processing is permitted before calculating surface parameters but must be noted in the report. If zero point drift is removed the reported value must be followed by the word “Leveled.” If curvature or other form is removed the reported value must be followed by the phrase “Form removed.” If other data processing procedures are used the reported value must be followed by the phrase “Other than GUM.” When non-analytical estimates of uncertainty are included the measurement uncertainty must be followed by the phrase “Included Type B components.”

Annotations to the Report

Zero Point Drift Correction

...the measured value shall be followed by the phrase "Leveled."

Curvature (Form) Removal

...the measured value shall be followed by the phrase "Form removed."

Other Data Processing Procedures

...the measurment uncertainty shall be followed by the phrase "Other than GUM."

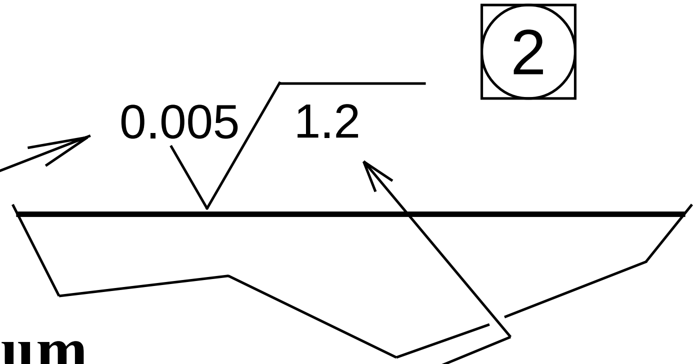
Non-analytical Estimates of Uncertainty (GUM)

...the measurement uncertainty shall be followed by the phrase "includes Type B components."

12. **Specifying Nanometer Surface Roughness -** A roughness specification may utilize the symbology of ASME Y14.36 but the short wavelength cutoff must be placed in a note. The note must also call out ASME B46.1, Chapter 7, if the methods for nanometer metrology are desired. Note: ASME B46.1 does not distinguish a threshold at which nanometer methodology is to be used, this must be determined by the engineer.

Specifying Nanometer Surface Roughness

② Measurement shall conform to ASME B46.1, Chapter 7. The short-wavelength cutoff, λ_s, shall be less than 0.8 micrometer.



The roughness, Ra, is a maximum value (0.005 micrometers).

The long-wavelength cutoff, λ_c, is shown (1.2 mm).

13. **Nanometer Surface Roughness Reports -** The report of the measurement of the surface parameter shows that the roughness is acceptable. The data were leveled (zero point drift was removed before calculating Ra) and the estimate of uncertainty included non-analytical components. The uncertainty was about 37.5% of the measured value.

Nanometer Surface Roughness Reports

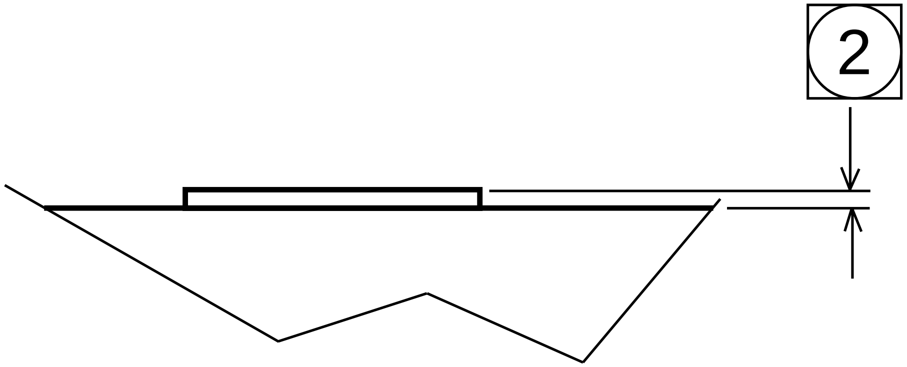
Sample: AX55654-A
The Measured Property: Ra
The Measured Value: 2.24 nm, Leveled
The Expanded Uncertainty (*k*=2) of the Measurement: .84 nm, includes Type B components
Transmission Band: 0.5 µm to 1200 µm
Date and Time: Dec. 12, 1999, 455PM
Name of Metrologist: John Smith

Note: $2.24 + 0.84 = 3.08$ nanometer < 0.005 micrometers
The Ra is acceptable

14. **Specifying Nanometer Step Heights -** A step height specification must be placed in the notes and referenced at the appropriate location on the drawing (there is no standard symbology for step heights). The note must call out ASME B46.1. Chapter 7 will be used since it is the only place step heights are measured in the standard. However, calling out Chapter 7 will reduce the possibility of using the wrong method.

Specifying Nanometer Step Heights

2 The thickness of the copper film shall be 0.005 ±0.001 micrometers. It shall be measured as a step height, Z_s, in accordance with ASME B46.1. The short-wavelength cutoff, λ_s, shall be less than 0.8 micrometer. The long-wavelength cutoff, λ_c, shall be 1.2 millimeters.



15. **Nanometer Step Height Reports -** The report of the measurement of the step height shows it to be unacceptable.

Nanometer Step Height Reports

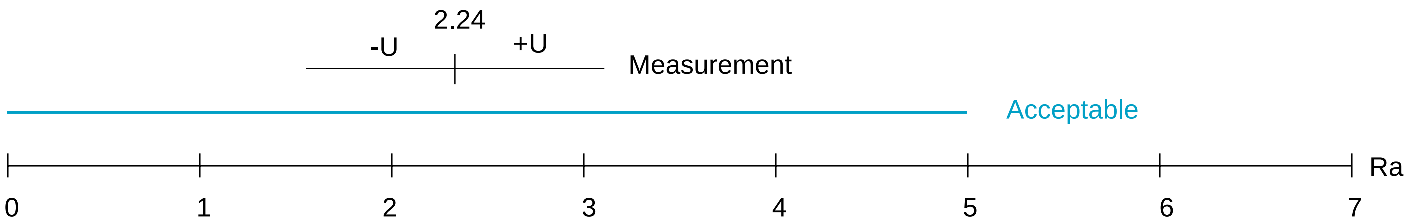
Sample: AX55654-B
The Measured Property: Z_s
The Measured Value: 2.24 nm, Leveled
The Expanded Uncertainty (k=2) of the Measurement: .84 nm, includes
Type B components
Transmission Band: 0.5 µm to 1200 µm
Date and Time: Dec. 12, 1999, 465PM
Name of Metrologist: John Smith

Note: 2.24 + 0.84 = 3.08 nanometer < 0.004 micrometers
The Z_s is <u>unacceptable</u>

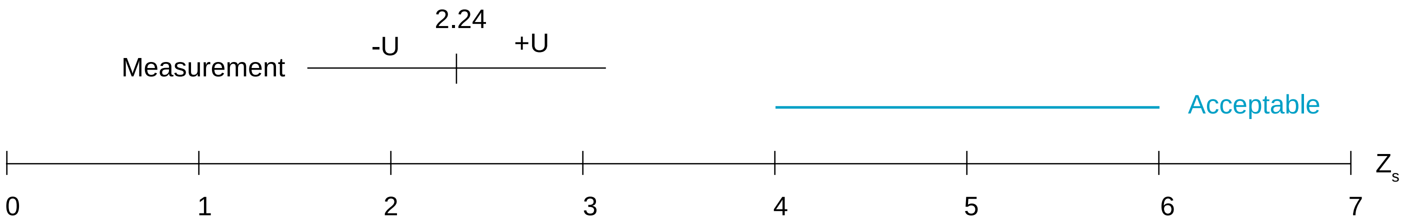
16. **Acceptance Criteria -** The reporting of uncertainty provides the designer and engineer with additional data about the quality of the measurements. Normal inspection will probably ignore the uncertainty and use the conventional criteria for evaluation unless another policy is instituted by the organization. Designers and engineers may specify (in the notes) the uncertainty associated with a measurement. Adjusting the tolerances may then assure that accepted surface measurements fall within the acceptable range of values.

Acceptance Criteria

1) Roughness:



2) Step Height:



The engineer may want to add an acceptable (maximum) uncertainty to the drawing notes.

17. **ASME B46.1-2003 Nanometer Summary -** Two new chapters have been incorporated: Chapter 7 contains the nanometer metrology methods and Chapter 8 describes the performance limits of optical instruments often used in nanometer surface metrology. Accuracy was the principal concern of the committee since at the nanometer scale the metrology instruments are being used at, or near, their limits of stability, sensitivity or both. To encourage accuracy the metrologist is required to report the uncertainty of his measurements. He must also report the high and low limits to the passband. New calibration devices are incorporated in the standard. Step heights have been included as a surface parameter, in part because they are the preferred calibration devices (roughness calibration specimens are not recommended). Drift and curvature may be removed from the data. All contact and non-contact instruments are accommodated, including AFMs.

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