Tools and Metrology at the NanoScale

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Outline

- *what is nanometrology?*
- *measurement needs*
- *instrumentation and material measures*
- *surface metrology*
- *traceability*
- *particle size*
- *linewidth standards*
- *high-resolution interferometry*
- *comparison and normative work*
- *conclusions*

"When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you can not measure it, when you can not express it in numbers, your knowledge is a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of Science, whatever the matter may be"

William Thomson (Lord Kelvin)

What is nanometrology?

Nanometrology is the science of measurement of the dimensions of objects or object features, separations or displacements in the range from 1 nm to 1000 nm

WGDM / DG7, 1998 Meeting

What is nanotechnology ?

Nanotechnology is the understanding and control of matter at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering, and technology, nanotechnology involves imaging, measuring, modeling, and manipulating matter at this length scale.

The National Nanotechnology Initiative (USA)– http://www.nano.gov/html/facts/whatIsNano.html

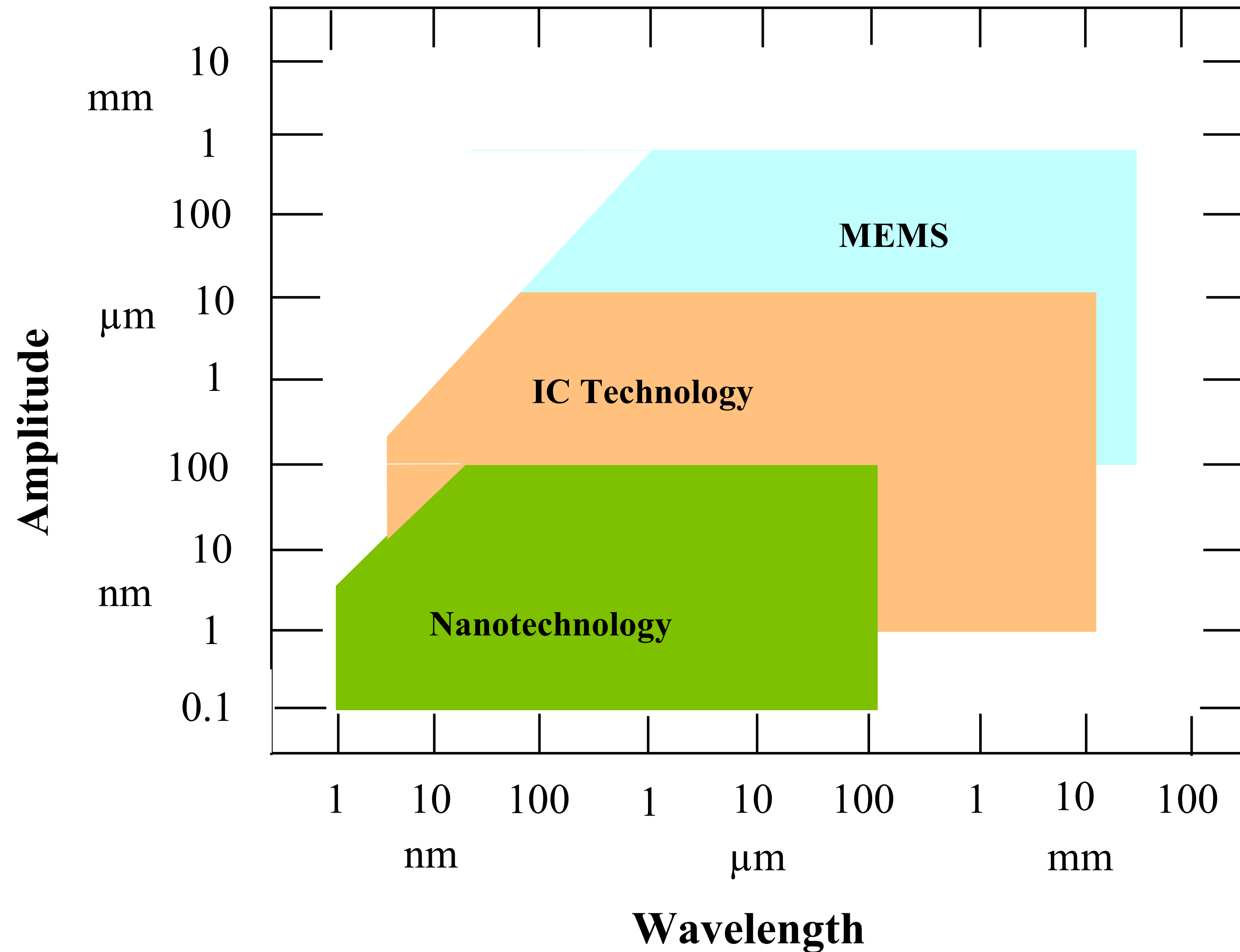
NNI – Strategic plan - Feb 2011 – Program Component Areas

4 Instrumentation , Research, Metrology, and Standards for Nanotechnology

R&D pertaining to the tools needed to advance nanotechnology research and commercialization, including next-generation instrumentation for characterization, measurement, synthesis, and design of materials, structures, devices, and systems. Also includes R&D and other activities related to development of standards, including standards for nomenclature, materials characterization and testing, and manufacture.

The National Nanotechnology Initiative (USA)– http://www.nano.gov/sites/default/files/pub_resource/2011_strategic_plan.pdf

Needs - AW space



Instrumentation

- ***electron Microscopy (SEM, STEM, TEM)***
- ***probe Microscopy (SPM family)***
- ***interference Microscopy***
- ***diffractometry, scatterometry, ellipsometry***
- ***x-ray and spectroscopic techniques***
- ***………….***

standards - material measures

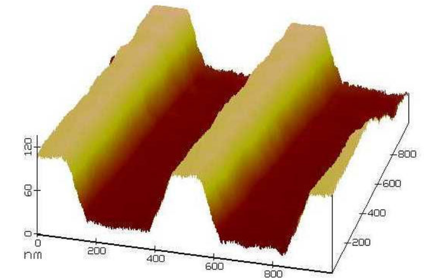
- traceability
- measurement techniques
- design

A list (not exhaustive) of available standards can be downloaded from http://www.nanoscale.de/standards.htm

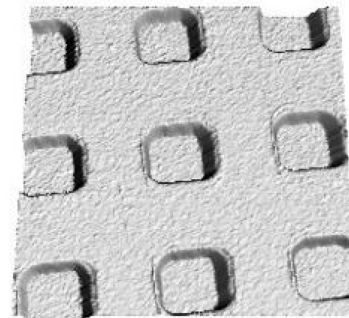
A) z - Axis: Single Step
B) z-Axis: Periodic Steps
C) z-Axis: Step Grating
D) x-, y-Axis: 1-Dimensional
E) x-, y-Axis: 2-Dimensional
F) 3D-Standards
G) Flatness
H) Thickness
I) Roughness
J) Critical Dimension
K) Tip Radius, Angle, Parallelity
L) Contour, Profile
M) Diameter, Roundness
N) Probing Force

Surface Metrology

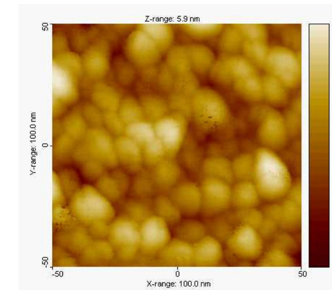
- ***Linewidth***
- ***Step Height***
- ***Roughness***
- ***Pitch***
- ***Thickness***
- ***Flatness***
- ***Grain size***
- ***Particle size***
- ***Critical dimensions (CD)***



UV grating on InP substrate



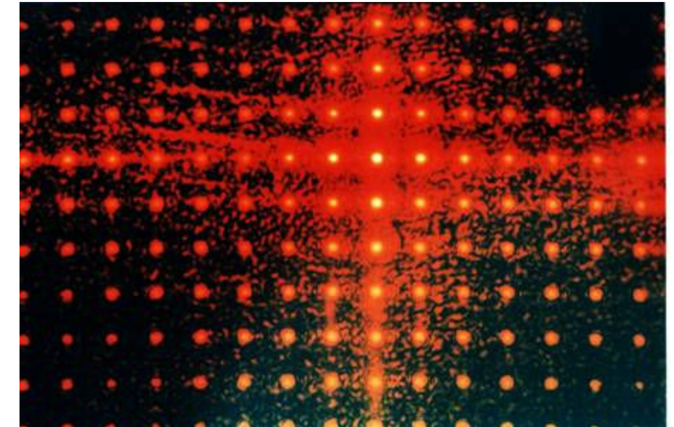
2D grid – 1 μm pitch

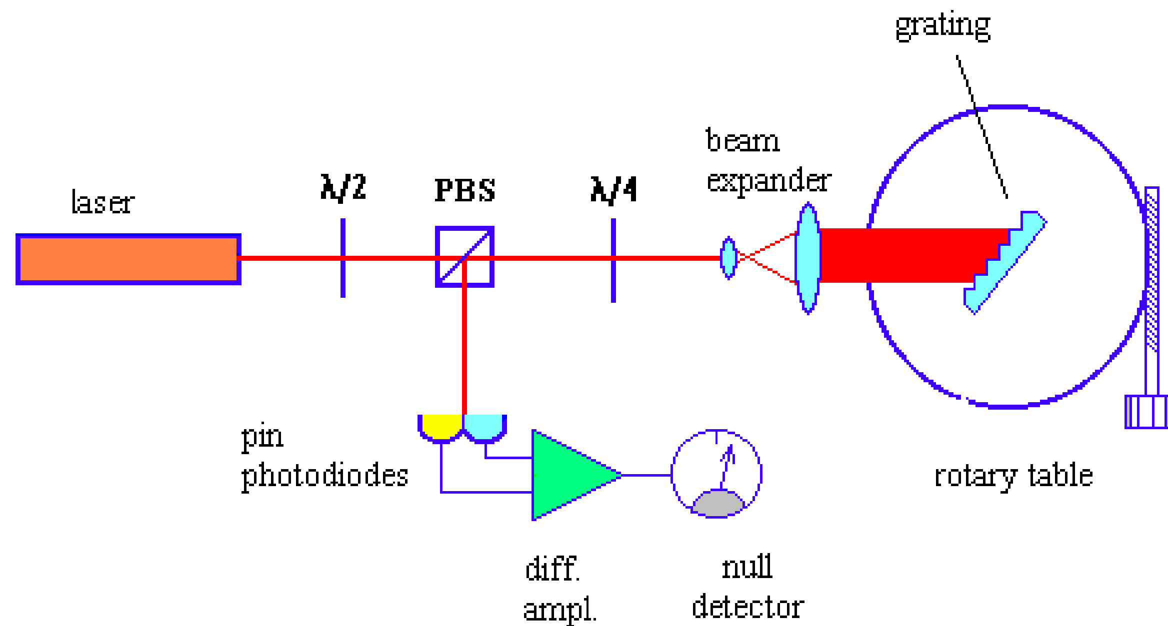


TiO_2 film (100nm x100 nm)

← ***ITRS Metrology 2011***
http:/public.itrs.net

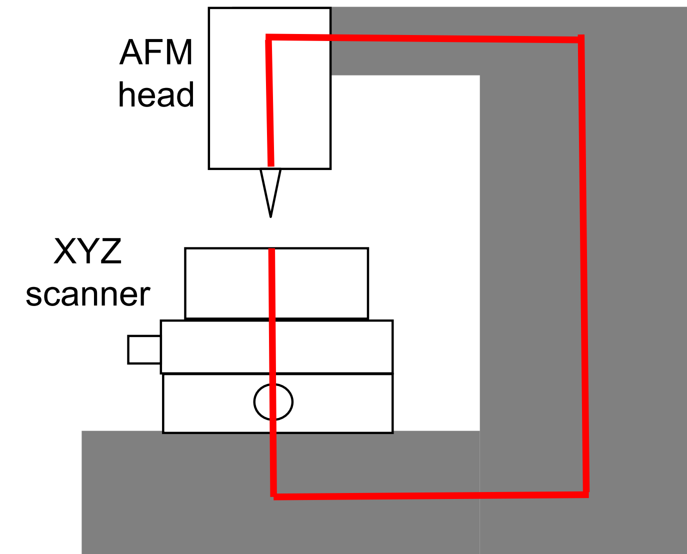
Diffractometer





high-accuracy measurements of the pitch of gratings and grids

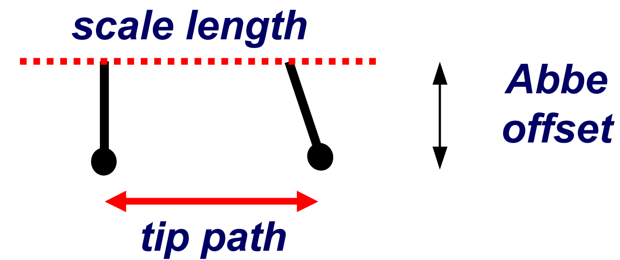
Metrological AFMs - design criteria



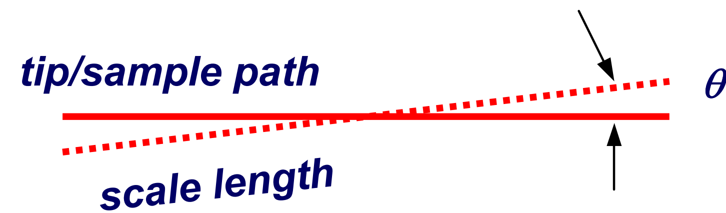
- ***reduced metrology loop***
- ***material***
  (low CTE, path compensation)
- ***xyz position/displacement sensors***
  (interferometric, capacitive, …)
- ***geometrical effects*** *(Abbé offsets, cosine error)*
- ***scanner design*** *(range, bandwidth, straightness, orthogonality, pitch, roll, yaw)*

geometrical effects

- *Abbé*



- *Cosine*

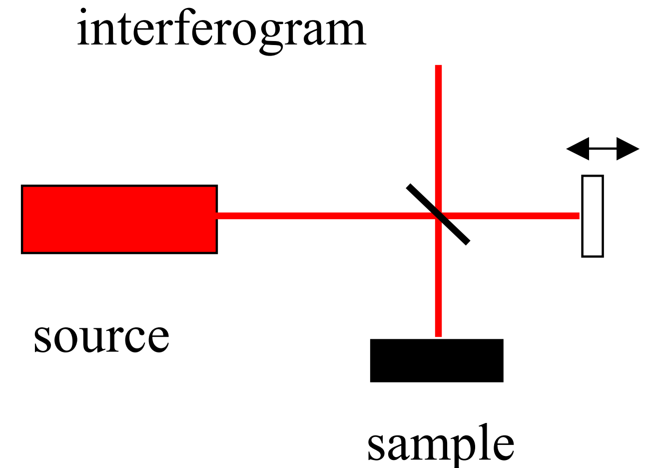


Metrological AFMs

- ***several labs and national metrology institutes (NMIs) have developed their own instruments;***
- ***different solutions depending on working range and metrology set-up***

H.-U. Danzebrink, et al., *Advances in Scanning Force Microscopy for Dimensional Metrology*, CIRP Annals – Manufacturing Technology 55 (2), 841, 2006

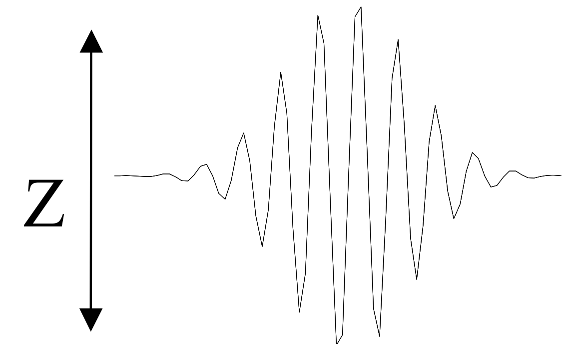
Interference microscopy



PSI – Phase Shifting Interferometry

- step-height < λ/2
- monocromatic sources
- phase interferograms are taken at given sub-λ steps

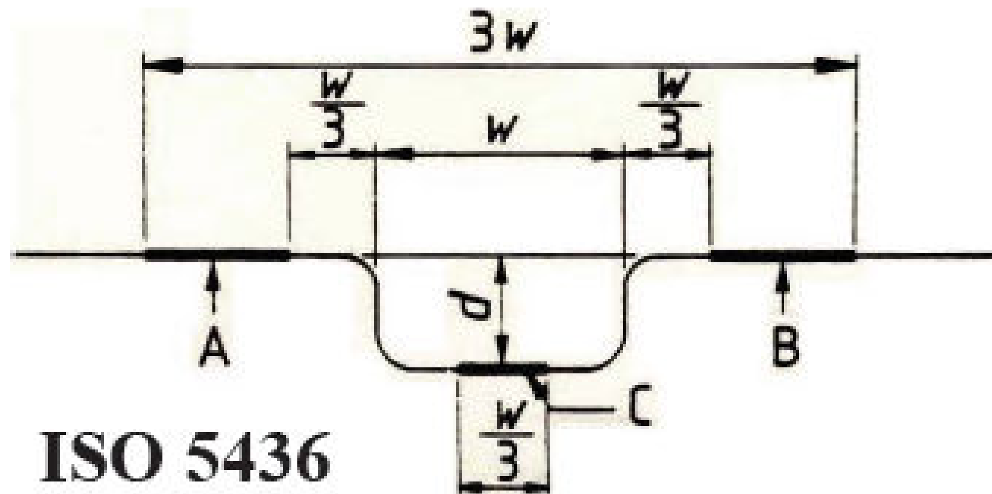
VSI – Vertical Scanning Interferometry

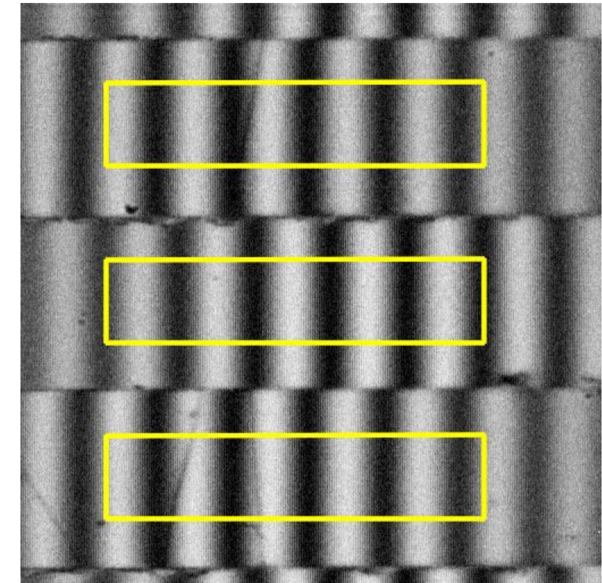


- white light or monocromatic sources
- position of the fringe envelop peak is detected while scanning the vertical axis
- on-board z-metrology

Interference microscopy

groove and step-height



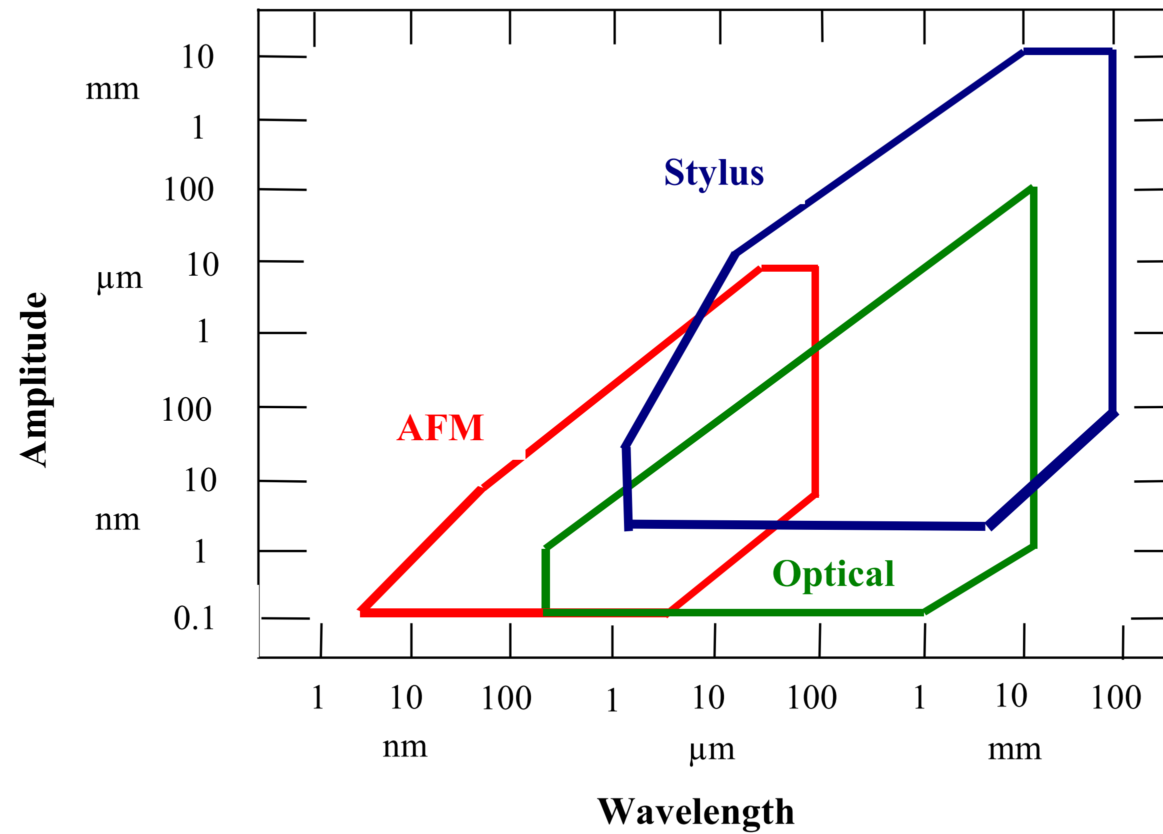


measurand: ***d***

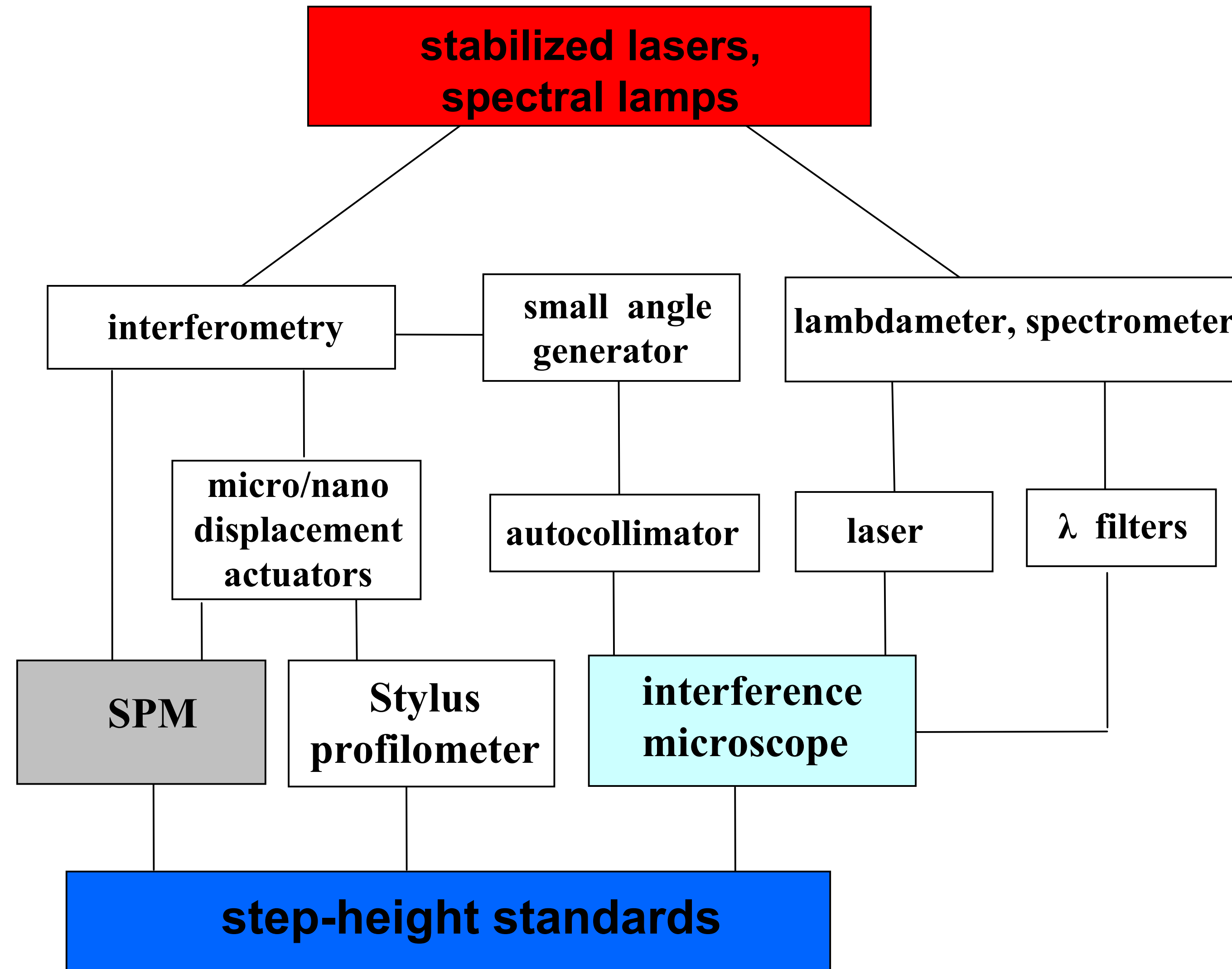
step-height / groove depth

Surface metrology

AW Space - instrumentation

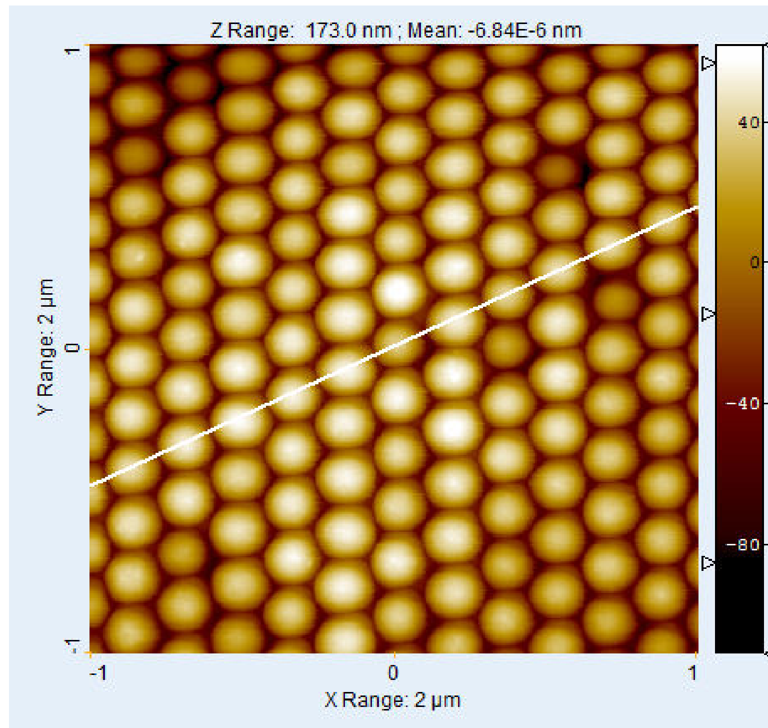


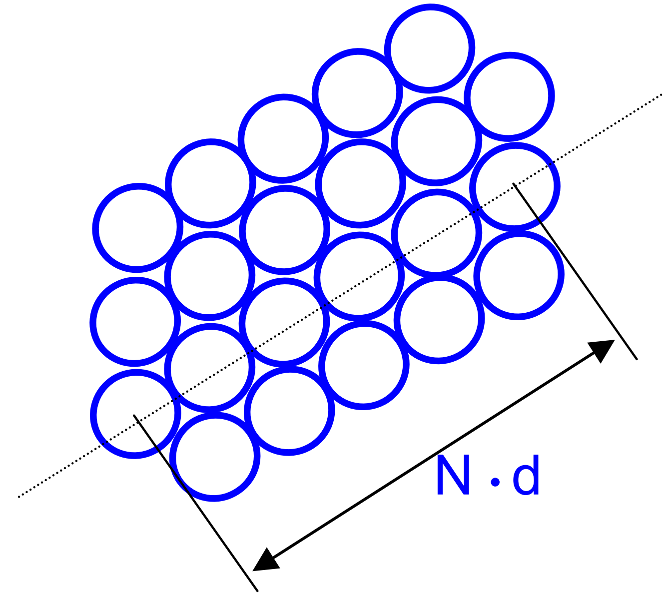
Traceability chain

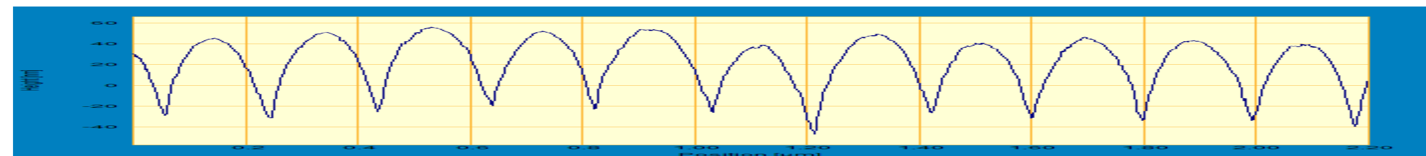


Particle size – mean diameter

AFM-based measurements



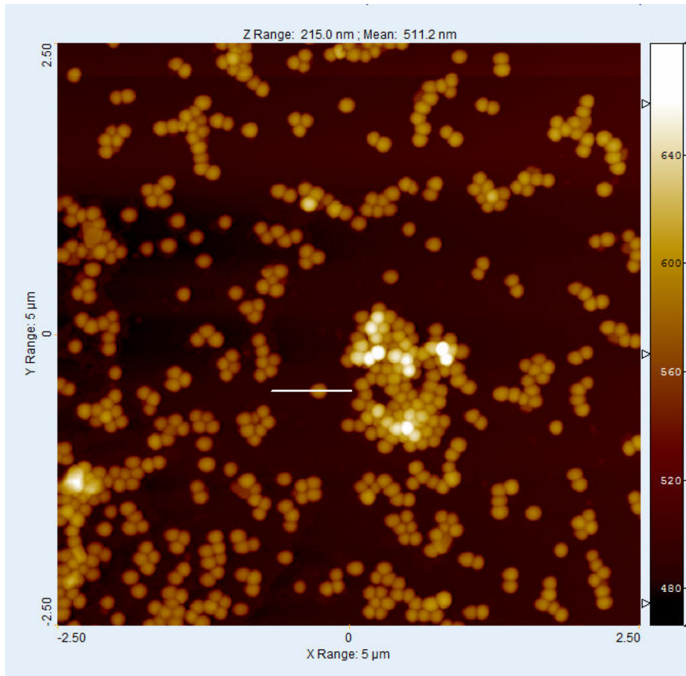




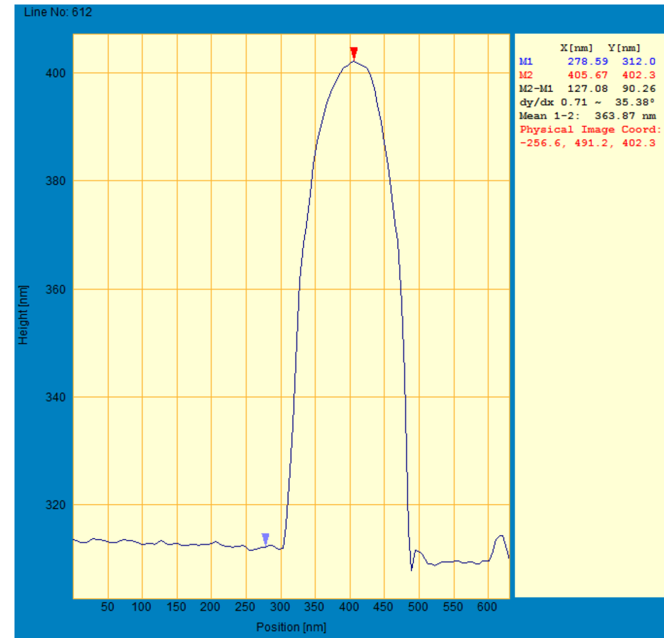
AFM image of polymer spheres having a nominal diameter of 200 nm

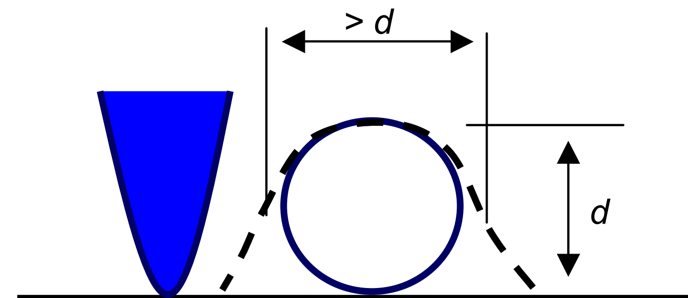
Particle size – mean diameter

AFM-based measurements



AFM image of polymer spheres having a nominal diameter of 100 nm





Particle size

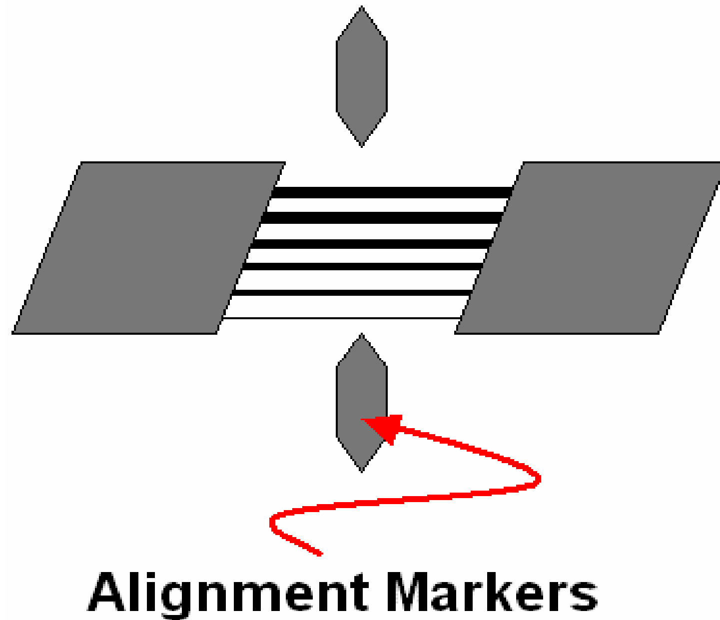
EURAMET joint research project "Traceable measurement of nanoparticle size" funded from the European Union's Seventh Framework Programme, ERA-NET Plus, under Grant Agreement No. 217257

http://www.euramet.org/fileadmin/docs/EMRP/JRP/iMERA-plus_JRPs_2010-06-22/T3.J1.1.pdf

F. Meli[1], et al., *Traceable size determination of nanoparticles, a comparison among European metrology institutes,* submitted to Meas. Sci. & Technol.

Linewidth standards

NIST 45



the standard is comprised of a number of patterns, many of them consisting of six line features of different widths (from 30 nm to 250 nm)

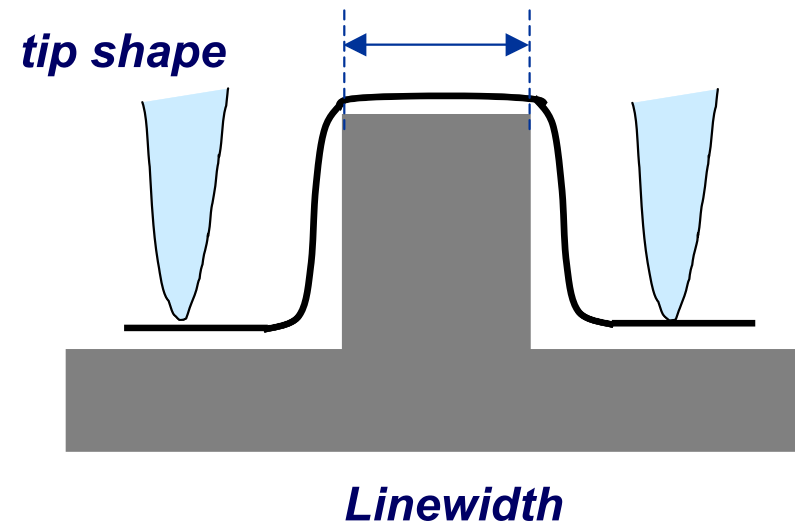
M.W. Cresswell, et al., RM 8111: *Development of a Prototype Linewidth Standard,* J. Res. Natl. Inst. Stand. Technol. **111**, 187-203 (2006)

Preliminary International Comparison on Nanometrology according to the Rules of the CCL Supplementary Comparison. Nano 6: AFM Linewidth Standards, coord. by NIST

Linewidth standards

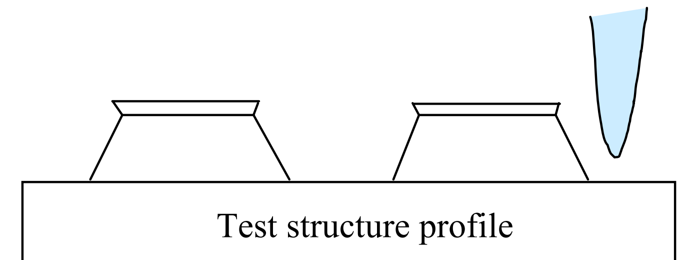
AFM-based measurements

- measurand (top or mid-height linewidth?)
- finite size and shape of the tip
- linewidth reconstruction error
- tip-shape estimation

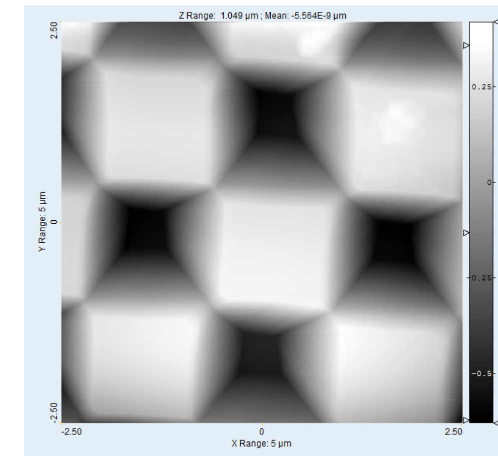


Linewidth standards

tip-shape estimation



- tip characterizer samples (with steep edges)
- blind tip estimation algorithm and suitable test samples
- tip specifications (manufacturer)
- other techniques (SEM micrographs, ..)



J. S. Villarrubia, *Algorithms for Scanned Probe Microscope Image Simulation, Surface Reconstruction, and Tip Estimation,* J. Res. Natl. Inst. Stand. Technol. 102, 425 (1997)

high-resolution interferometry
(position and displacement measurements)

Needs

- ***pattern placement measurements on photomasks***
- ***position control in wafer scanners***
- ***double patterning techniques demands a high reproducibility in positioning***

Interferometry

Error sources

- ***geometrical errors (Abbé, cosine)***
- ***ambient (air refractivity, material temperature, optics thermal drifts, dead-path)***
- ***laser wavelength***
- ***optical non-linearity (fringe-periodical phase error with sub-wavelength steps)***

NANOTRACE project - optical interferometers

- **two wavelength common path homodyne interferometer (CMI)**
- **differential Fabry-Perot Interferometer (UME)**
- **electro-opto-modulator linearized heterodyne interferometer (INRIM)**
- **separated beams heterodyne interferometer (PTB)**
- **non-linearity correction using a capacitive sensor (MIKES)**

***All tested against an X-ray interferometer* (NPL)**

M. Pisani et al., *Comparison of the performance of the next generation of optical interferometers,* submitted to Metrologia

EURAMET joint research project “NANOTRACE" funded from the European Union's Seventh Framework Programme, ERA-NET Plus, under Grant Agreement No. 21725 (7)
http://www.nanotrace.it/Home.aspx

Quantitative Microscopy

- ***traceable standards;***
- ***calibrated instruments;***
- ***measurement protocols;***
- ***consistent uncertainty budget;***
- ***written standards and good-practise guides to ensure the quality of measurements (ISO 17025)***

ISO/IEC 17025:2005 General requirements for the competence of testing and calibration laboratories

Supplementary Comparisons, Length, dimensional nanometrology
http://kcdb.bipm.org

- **CCL-S1 - Nano 4, lateral, 1D gratings, 290 and 700 nm pitch**
- **CCL-S2 - Nano 2, step-height, 20 … 800 nm**
- **CCL-S3 - Nano 3, linescale, 280 mm length**
- **CCL-S4 - Nano 5, lateral, 2D gratings, 300 and 700 nm pitch**
- **Nano 6 , linewidth standards < 500 nm, in progress**
- **EUROMET.L-S15, step-height, 7 ... 2000 nm**
- **APMP.L-S2, 1D gratings, 50 and 100 nm pitch**

Written Standards

under development by several standardization organizations

- *ISO/TC229 - Nanotechnologies*
- *CEN/TC352 - Nanotechnologies*
- *IEC/TC113 - Nanotechnology*
  - *JWGs ISO/TC229 IEC/TC113*

- *ISO/TC213 – GPS (Geometrical Product Specifications)*
  WG16 - Surface texture (ISO 25178 – areal texture)

Conclusions

- *quantitative measurements and traceable standards are needed to support the overall reliability of products*
- *several projects have been carried out by national Metrology Institutes and other labs to extend traceability and to improve measurement capabilities at the nanoscale*
- *consistency of measurements is demonstrated and periodically tested by inter-laboratory comparisons*
- *an agreed standardization framework is supported by pre-normative research*