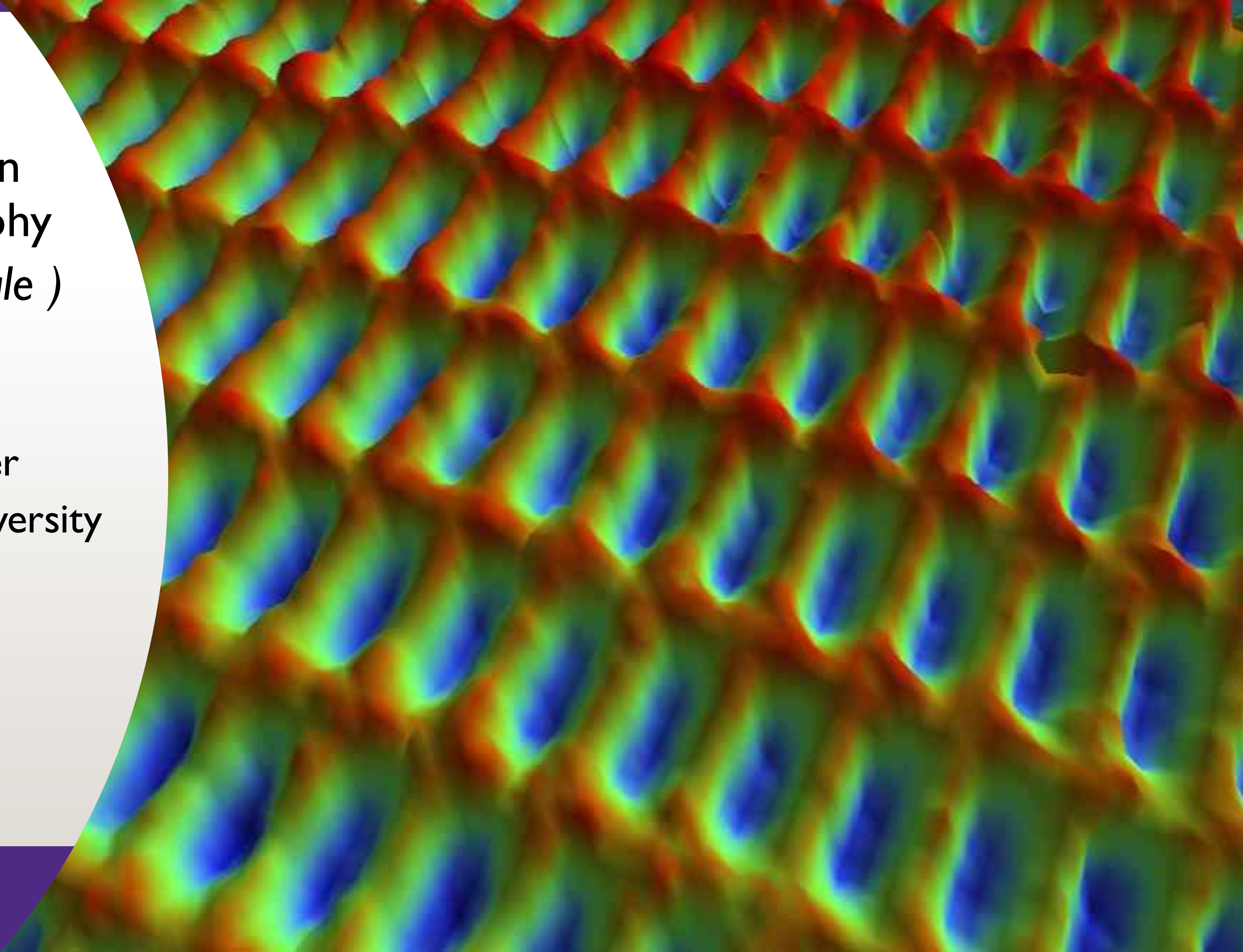
3D Characterization of Surface Topography

(From mm to nm scale)



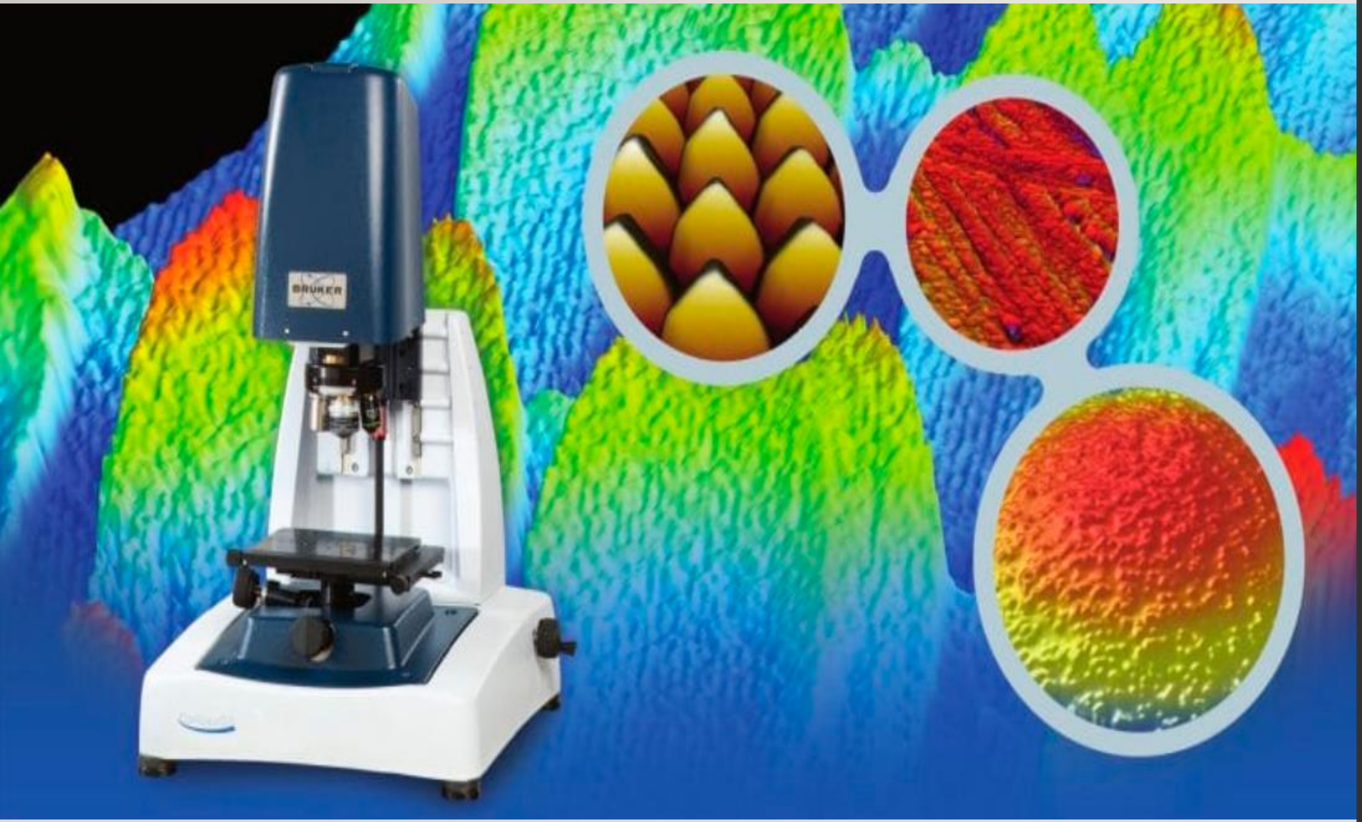
Xinqi Chen
Nuance Center
Northwestern University

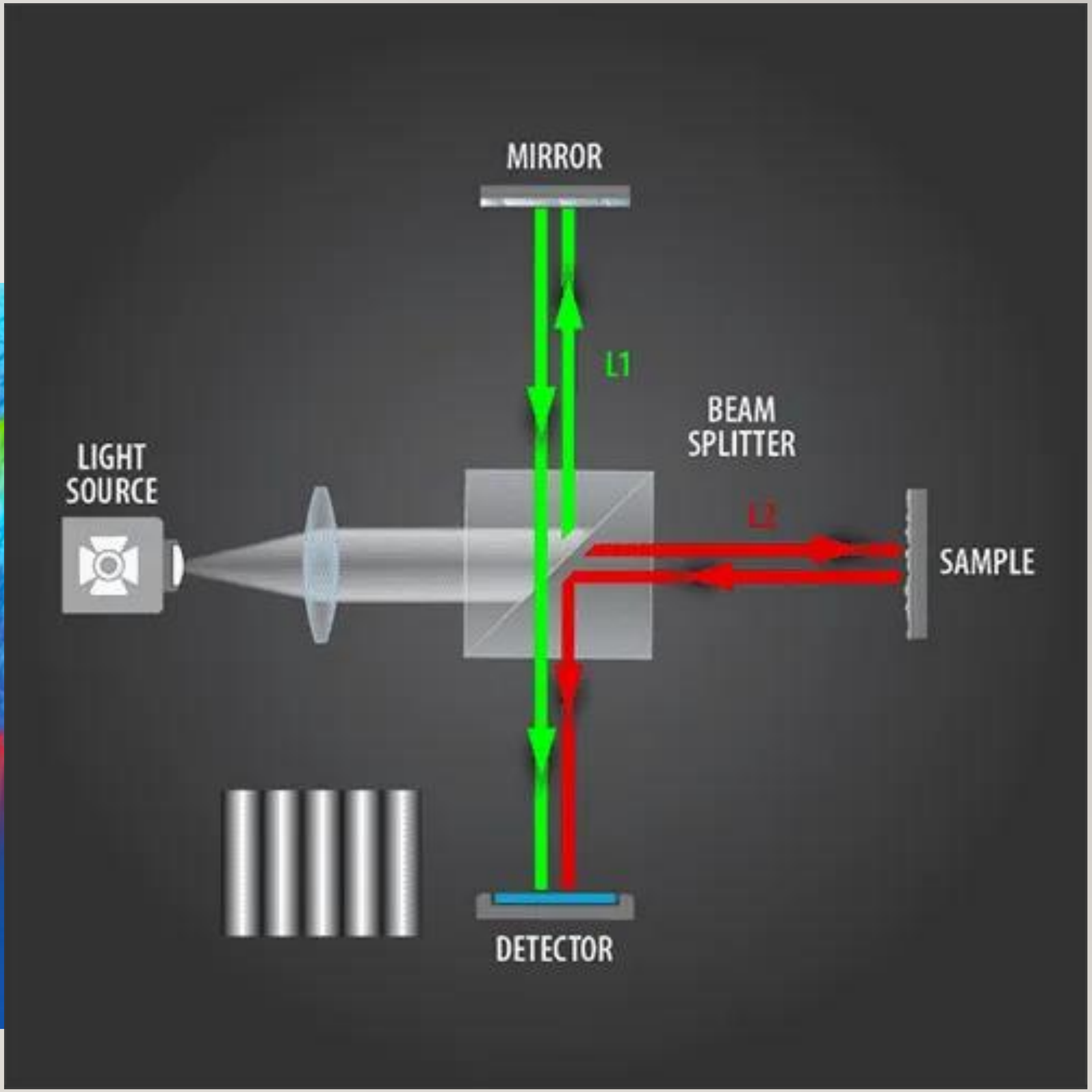
NUANCE
Northwestern University Atomic and Nanoscale Characterization Experimental Center

- 3D Optical Microscope (Optical Profilometer, Non-contact Profilometer, White Light Interferometry – WLI)
- Stylus Profilometer (Contact Profilometer)
- Atomic Force Microscope (AFM) (Scanning Probe Microscope)
- The Comparison of the Strength and Weakness

SEM? No quantitative height information

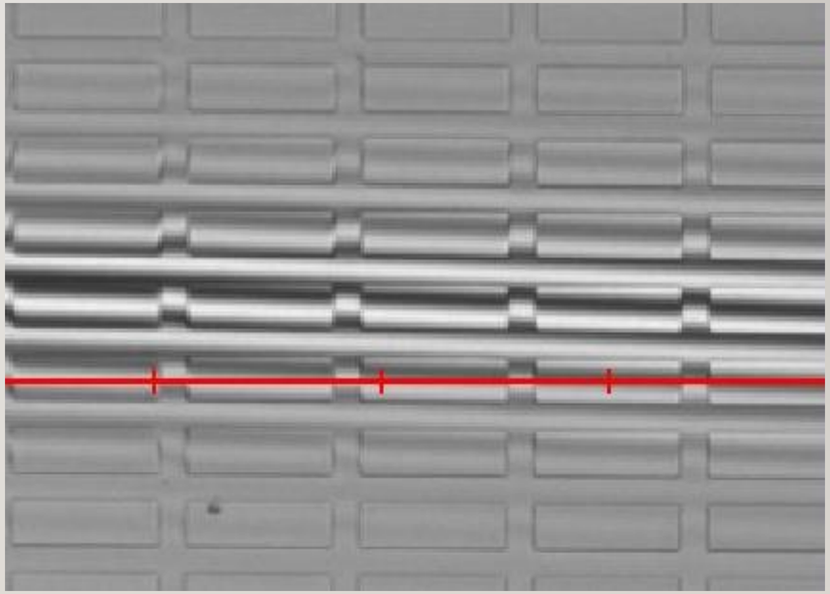
Bruker Contour GT Optical Profilometer (3D Optical Microscope)





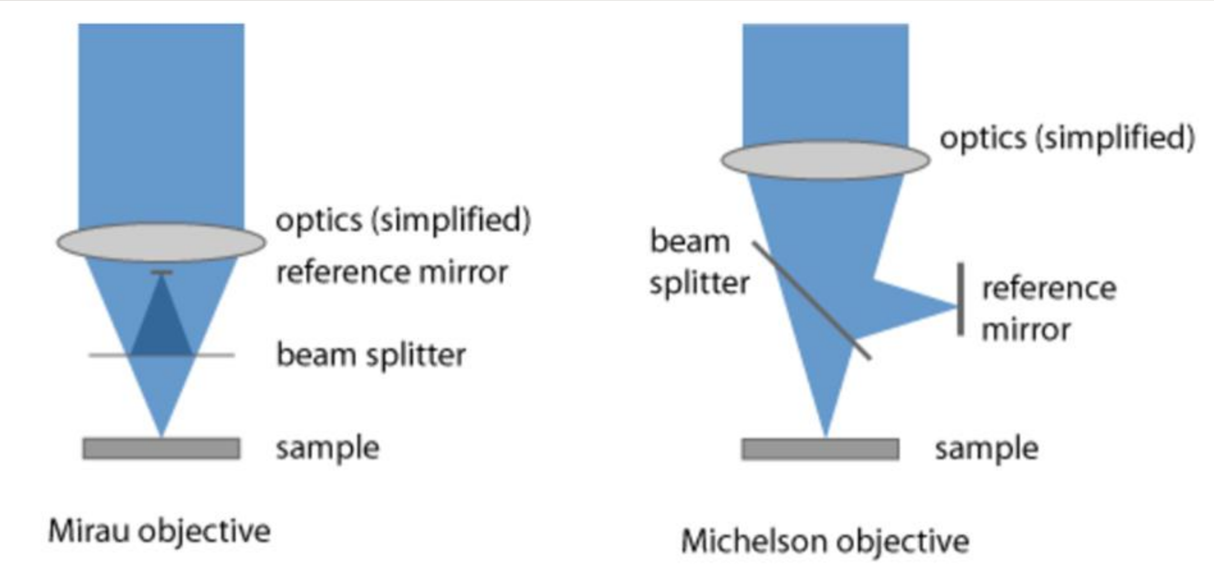
Working Principle of Profilometer
(Non - Contact Optical Profilometer)

- A light beam is split, reflecting from reference (known/flat) & test material.
- Constructive and destructive interference occurs
- Forms the light and dark bands known as interference fringes.
- The optical path differences are due to height variances in the test surface.
- Constructive interference areas as lighter and the destructive interference areas as darker.
- Light to dark fringes above represents one-half a wavelength of difference between the reference path and the test path.



<u>From the above Interference Image</u>:

- Lower portion is out of focus means less interference.
- Greatest contrast means best focus.

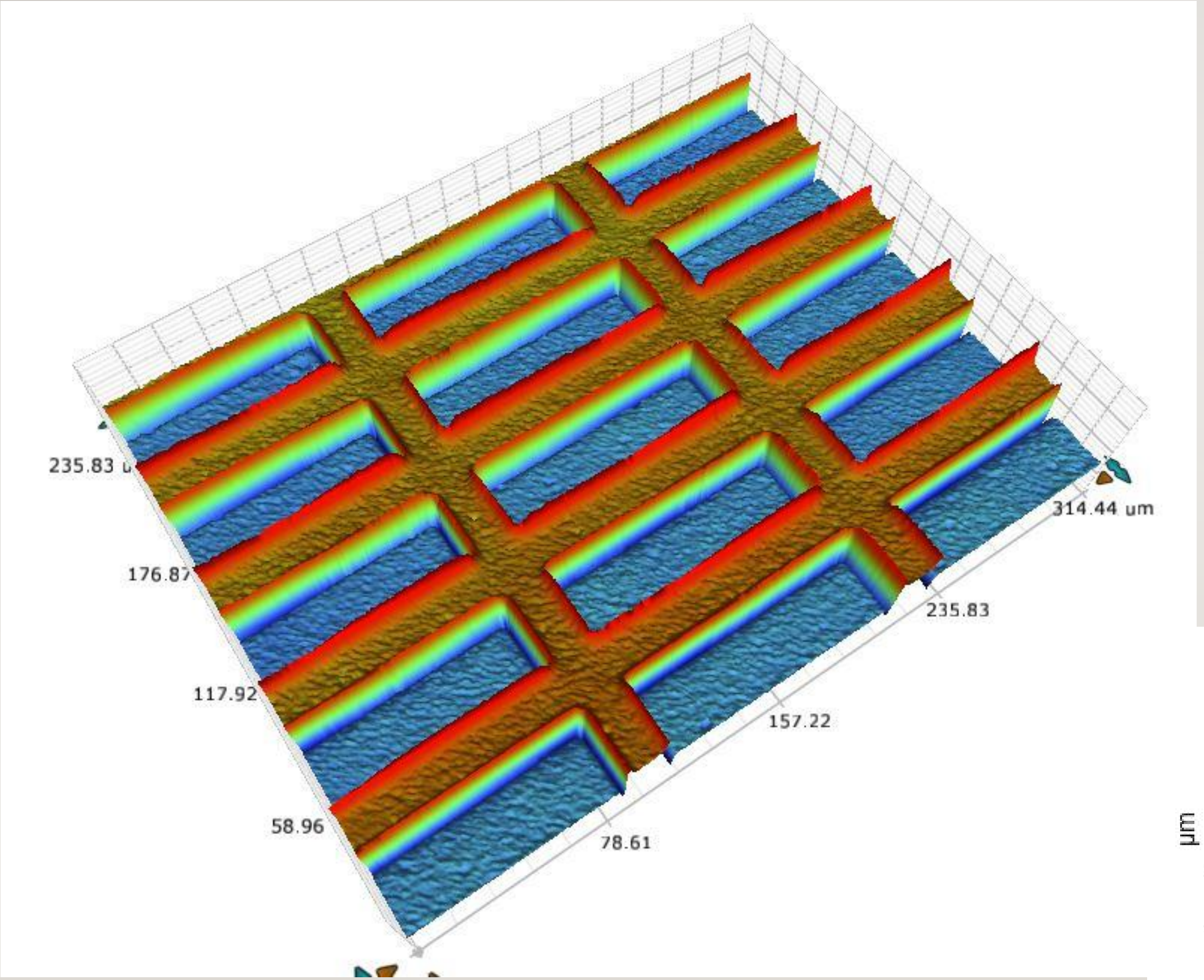


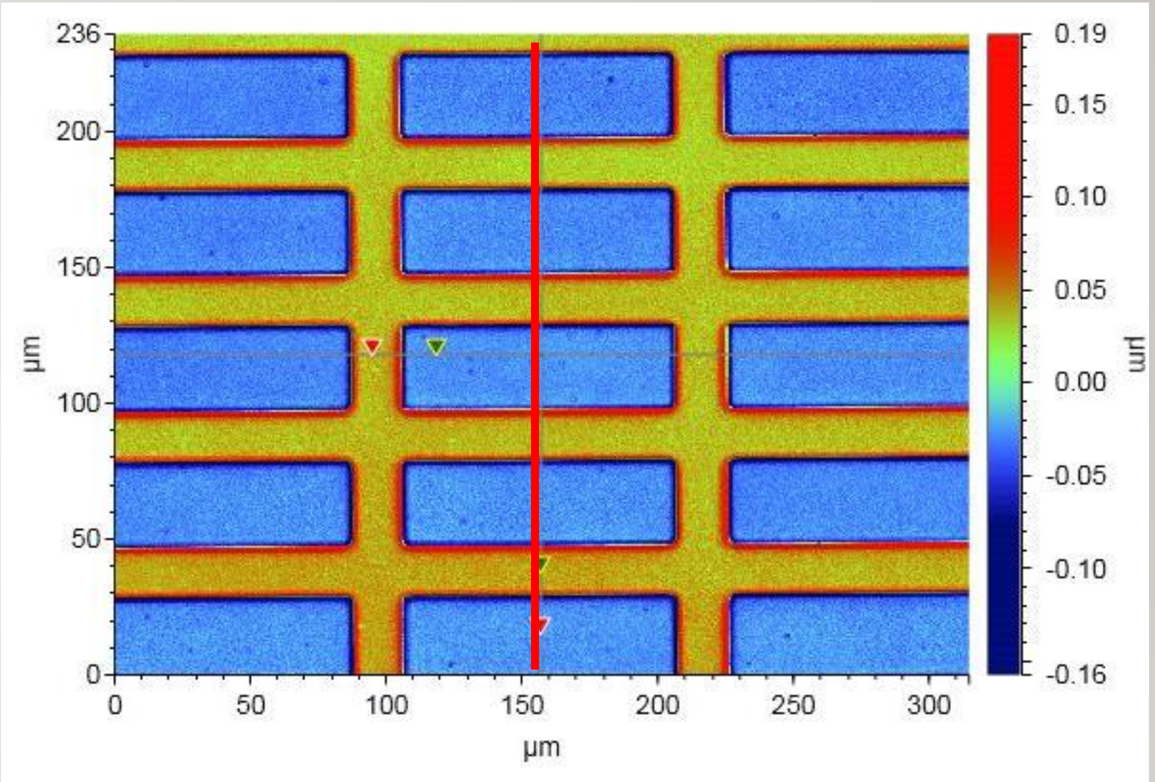
What does an optical profilometer measure?

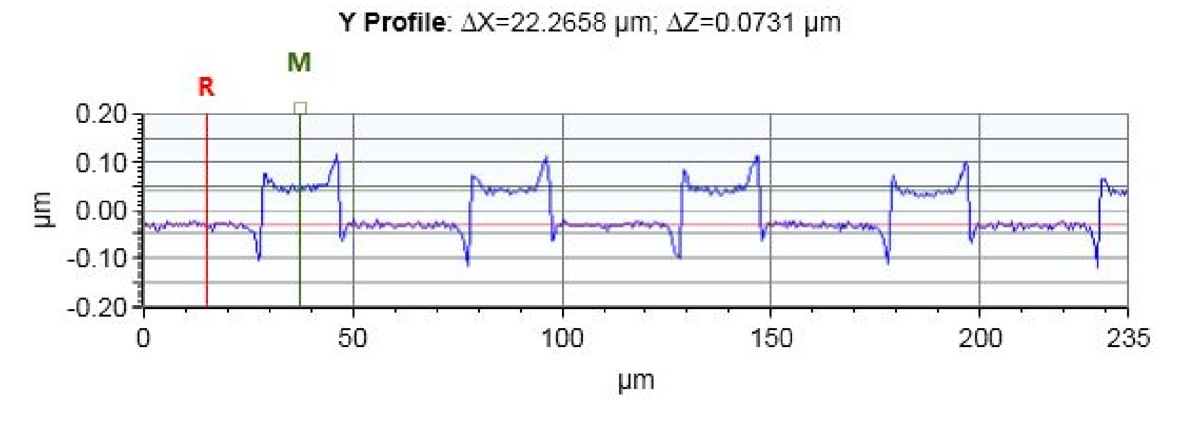
Surface roughness
Step height

- INTERFEROMETRY MODE
- In PSI (Phase Shift Interferometry), a few z-shifts corresponding to known phase shifts are applied; they allow the surface to be reconstructed (smooth surfaces, samples with little roughness and steps < 120 nm).
- In VSI (Vertical Scanning Interferometry), a vertical scan is performed and the fringe envelope is observed to find the maximum correlation between the waves or focus point (samples with roughness ranging from 50 nm to 1 µm, step heights greater than 120 nm).

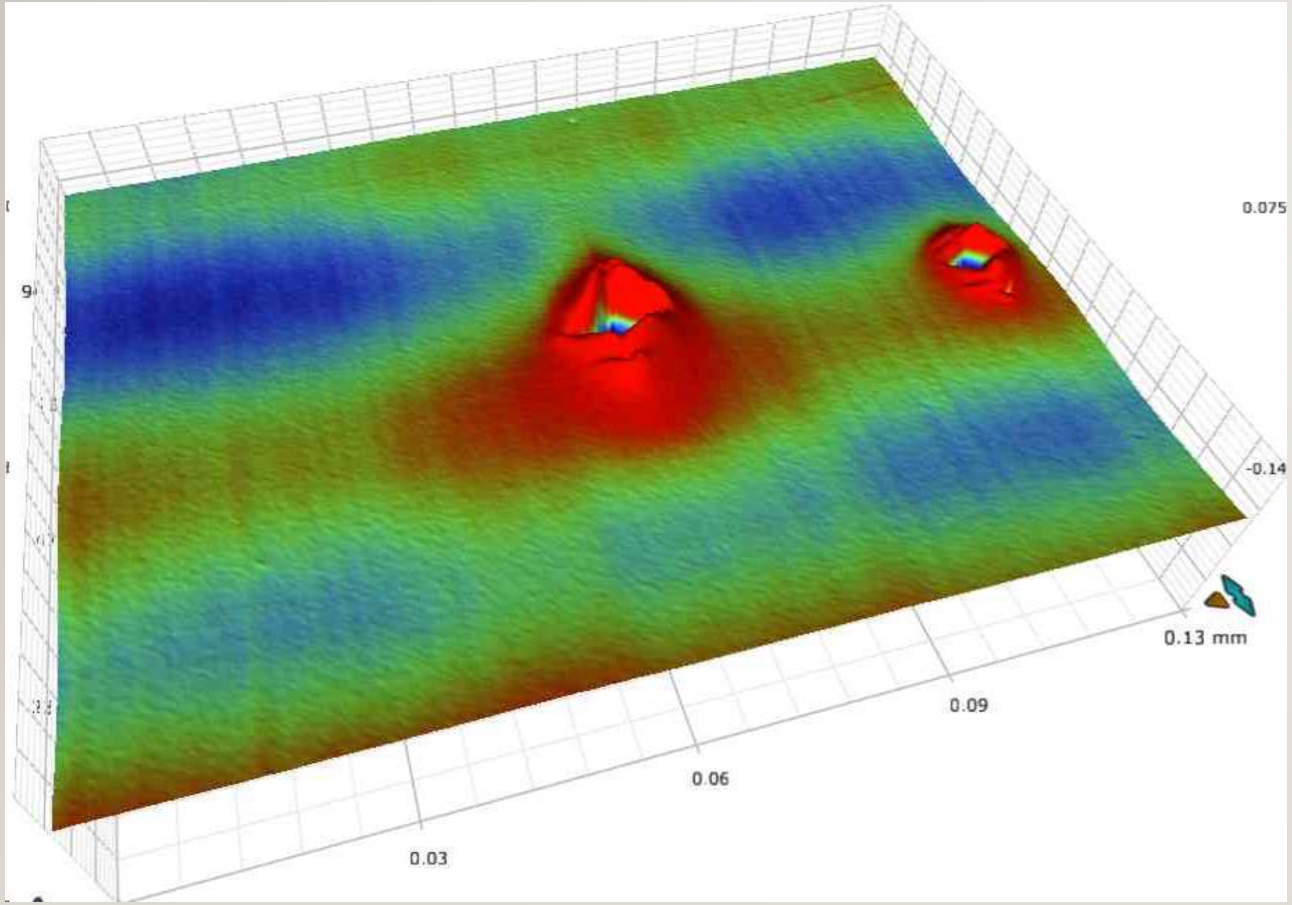
Silicon wafer with etched pattern



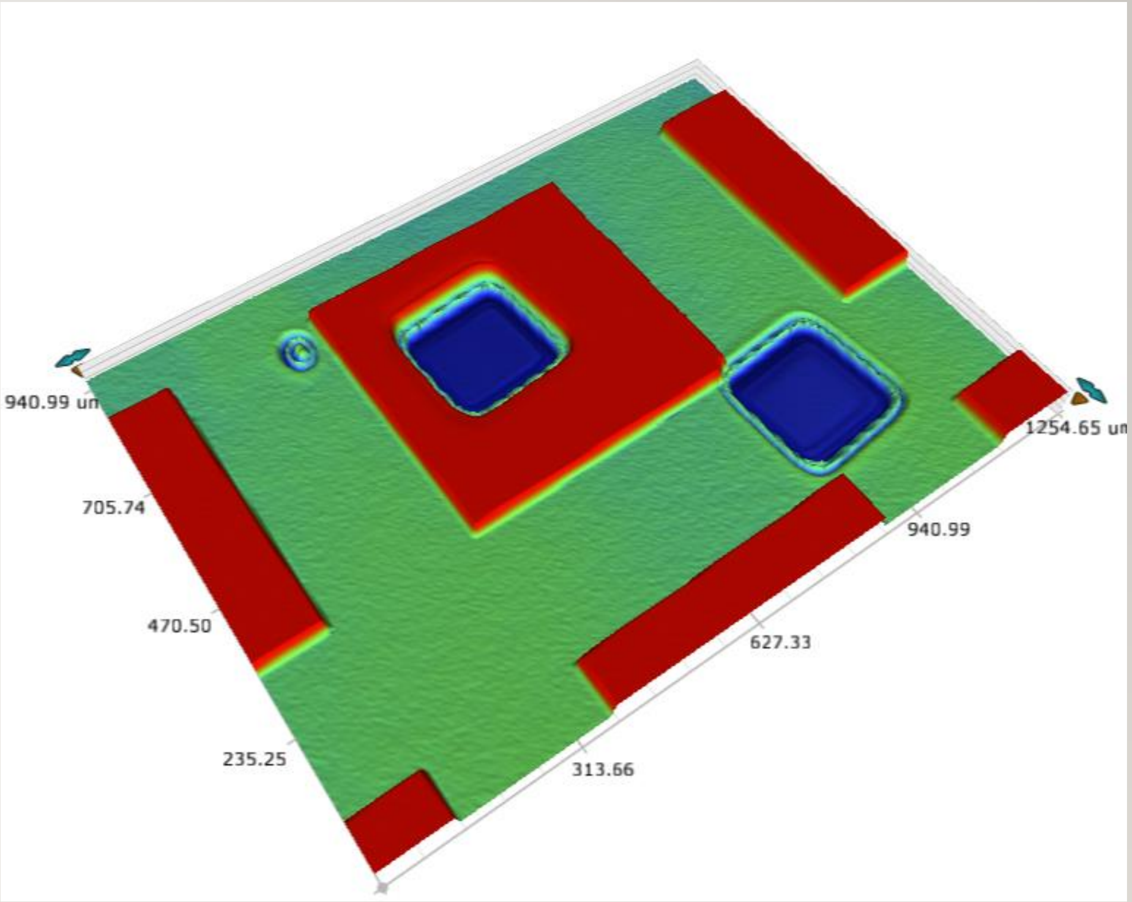




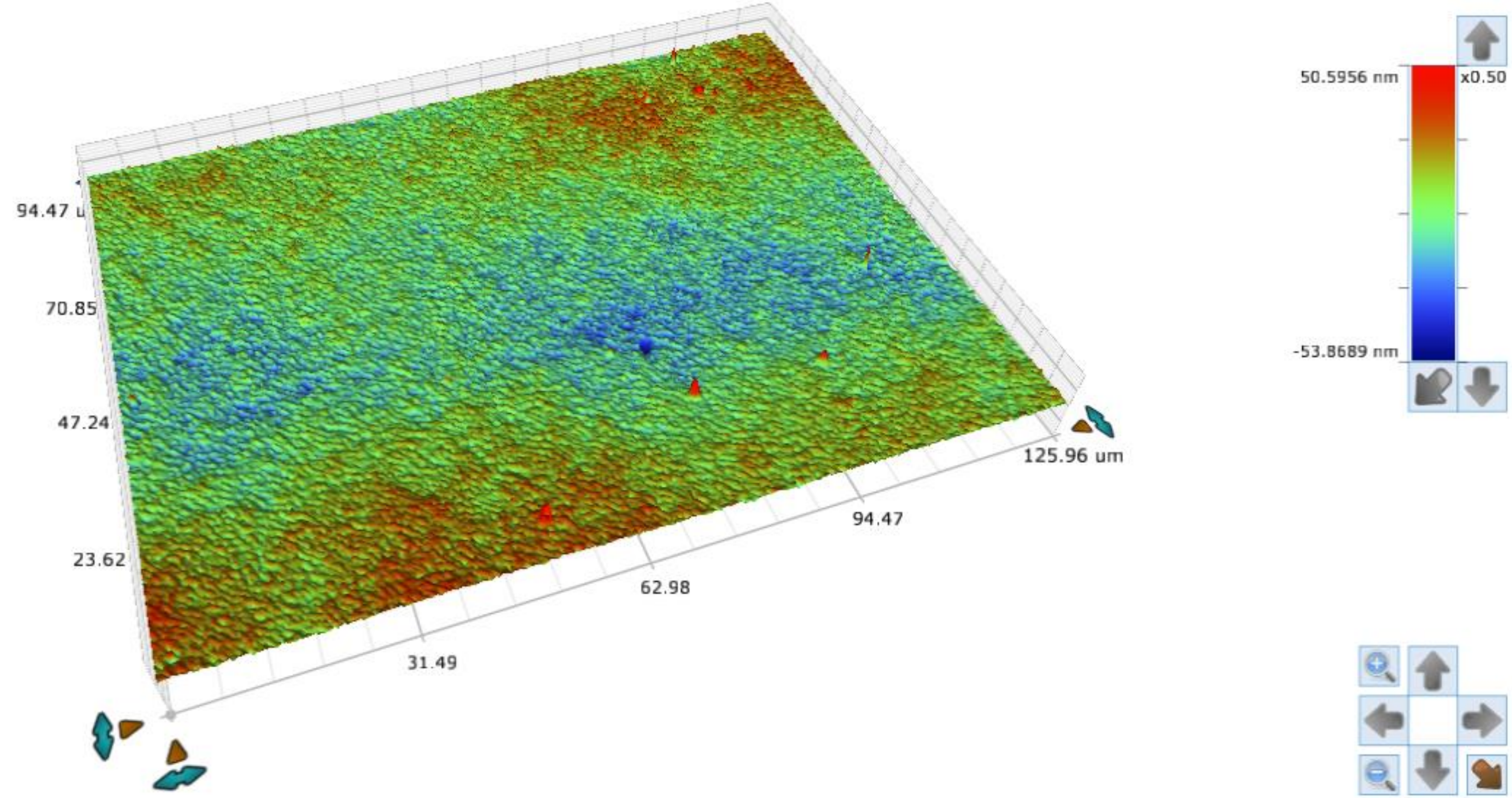
Crater made from nanoindentation

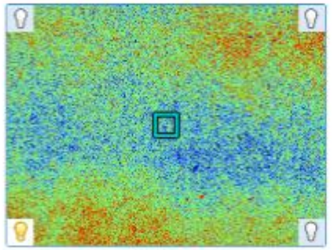


Crater made from SIMS depth profiling



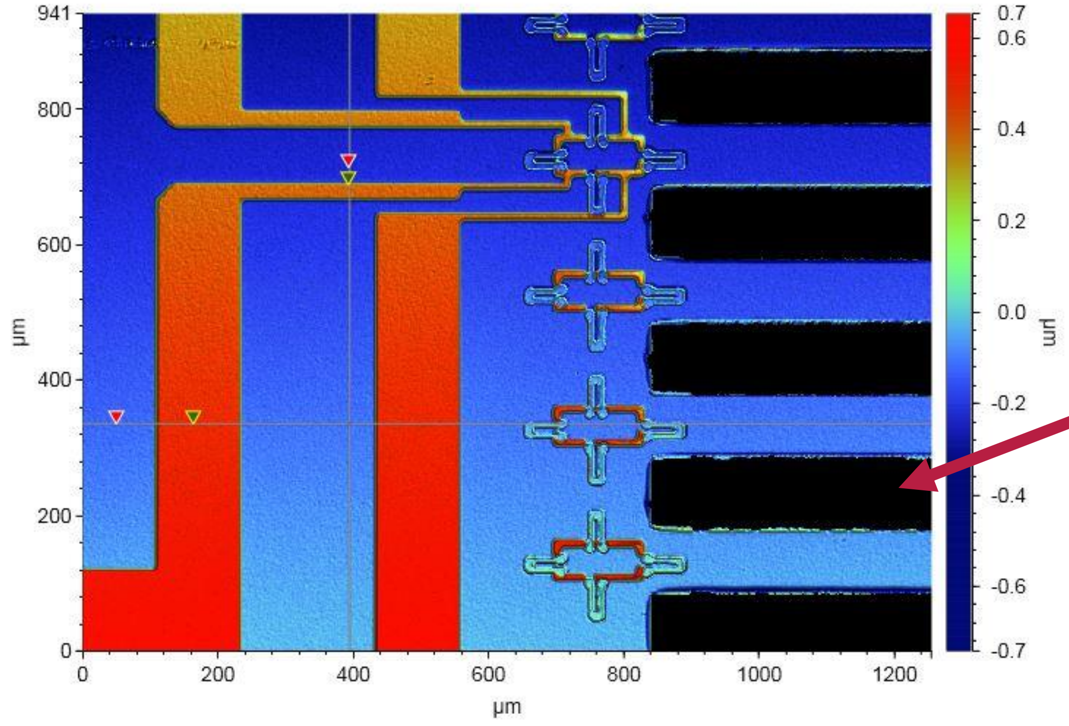
Cu/Ti film on Si wafer



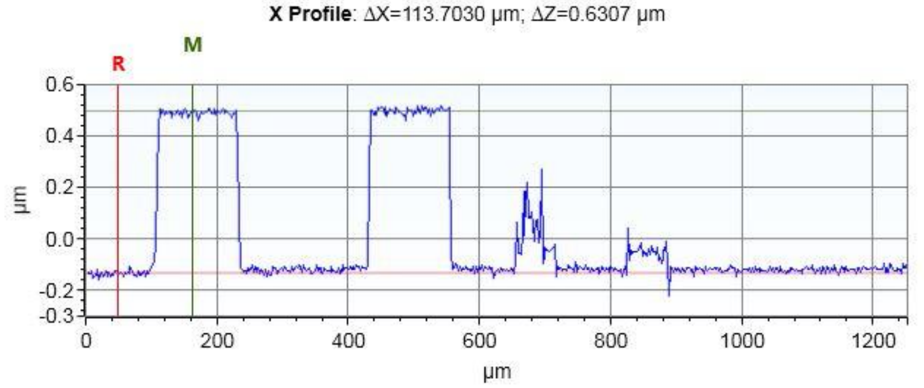


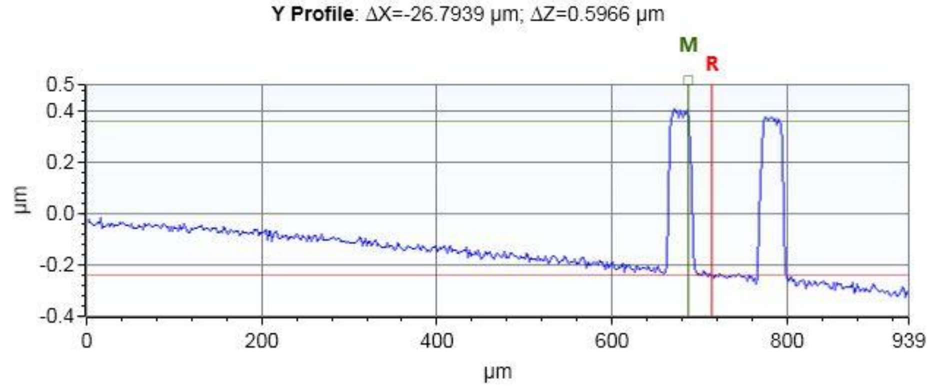
Analytical Results

Label	Value	Units
Average	0	nm
Data Points	307200	
Percent Data Points	100	%
Ra	3.734	nm
Rp	50.6	nm
Rq	4.693	nm
Rt	0.1	µm
Rv	-53.87	nm

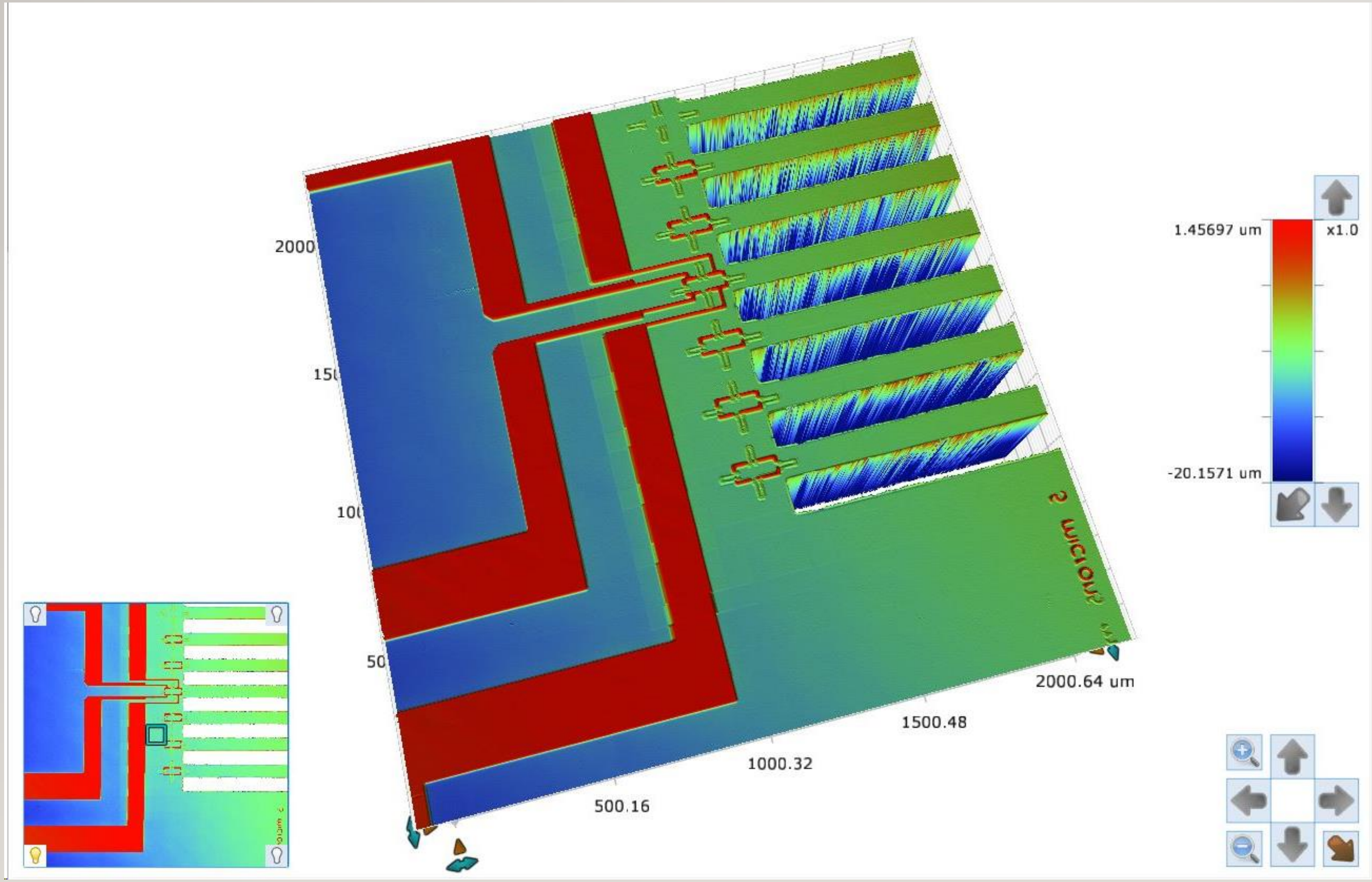


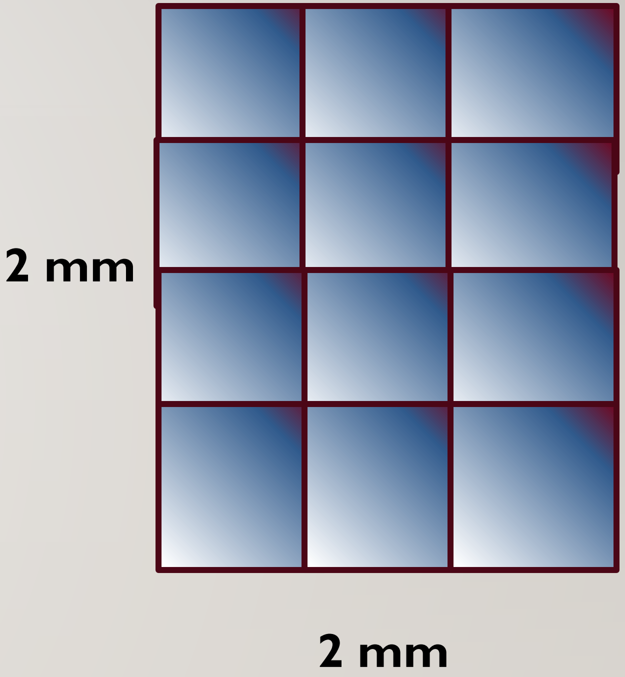
The wall is too sharp, and the bottom is too deep.
No height information





Stitching for mapping a big area





Optical Profilometer

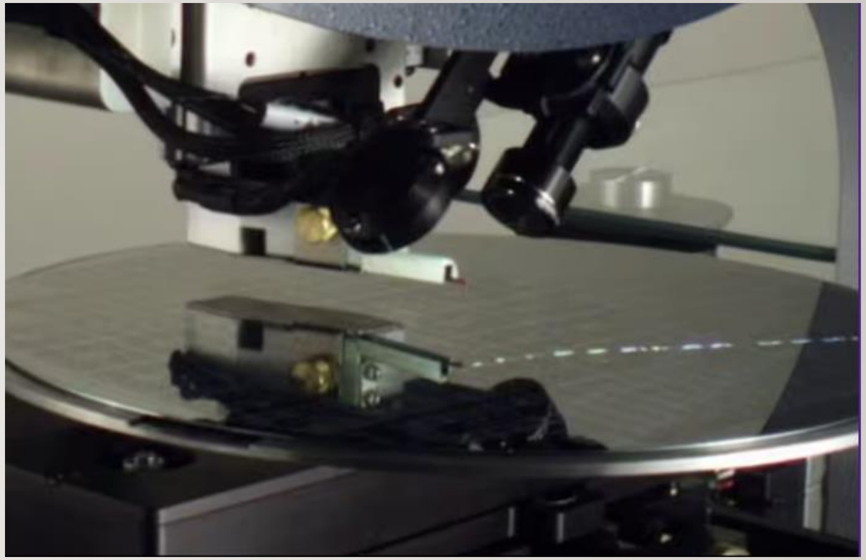
Advantages:

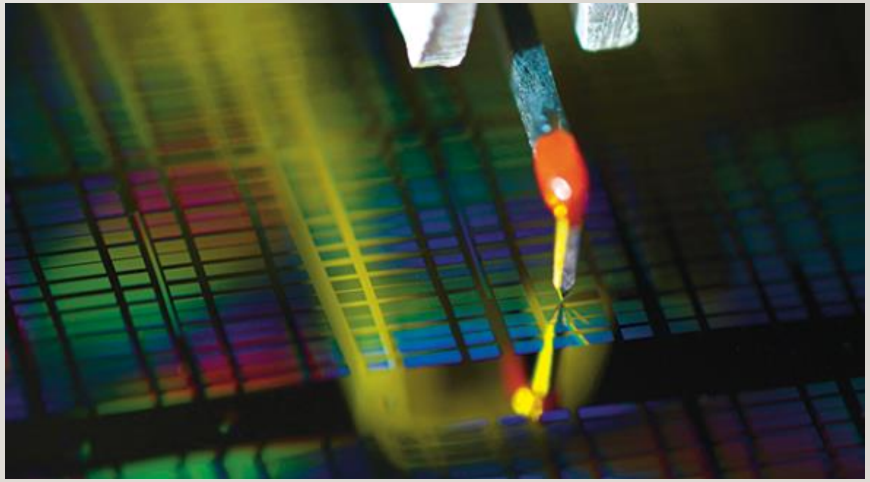
- Great vertical resolution in the nm level
- Lateral resolution ranges from a few micrometres down to 100 nm
- High Speed for 3D characterization
- No damage on surface wear or scratch
- Stitching capability to increase the maximum characterization size

Limitation:

- Limited by very large slopes, where the light is reflected away from the objective, unless the slope has enough texture to provide the light.

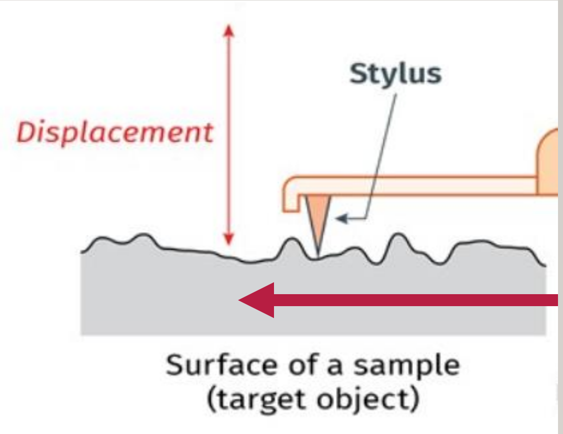
Stylus Profilometer





Stylus (contact) Profilometer

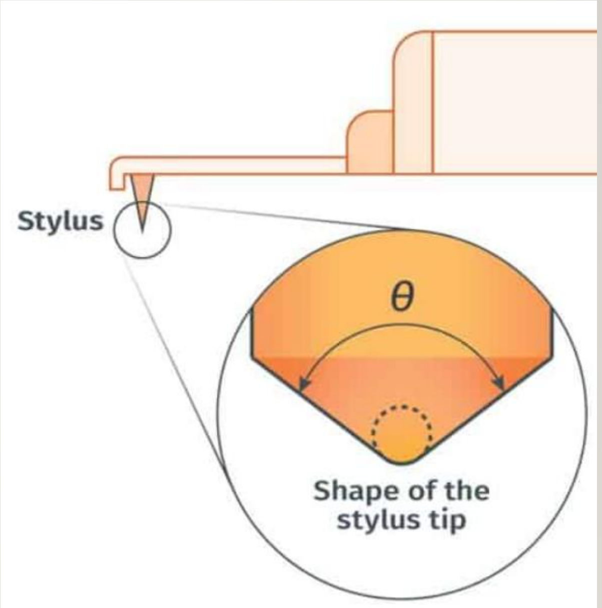
- The stylus profilometer provide repeatable, **reliable**, and accurate measurements- from traditional step height measurements and 2D roughness surface characterization to advanced 3D mapping and film stress analyses.

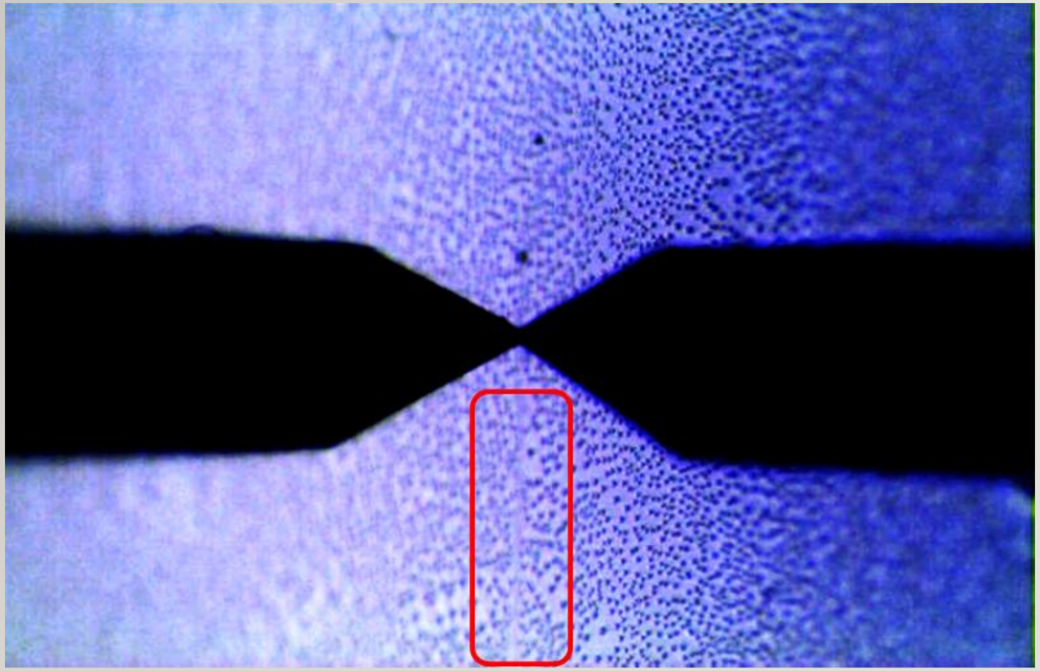


LVDT (Linear Variable Differential Transformer)

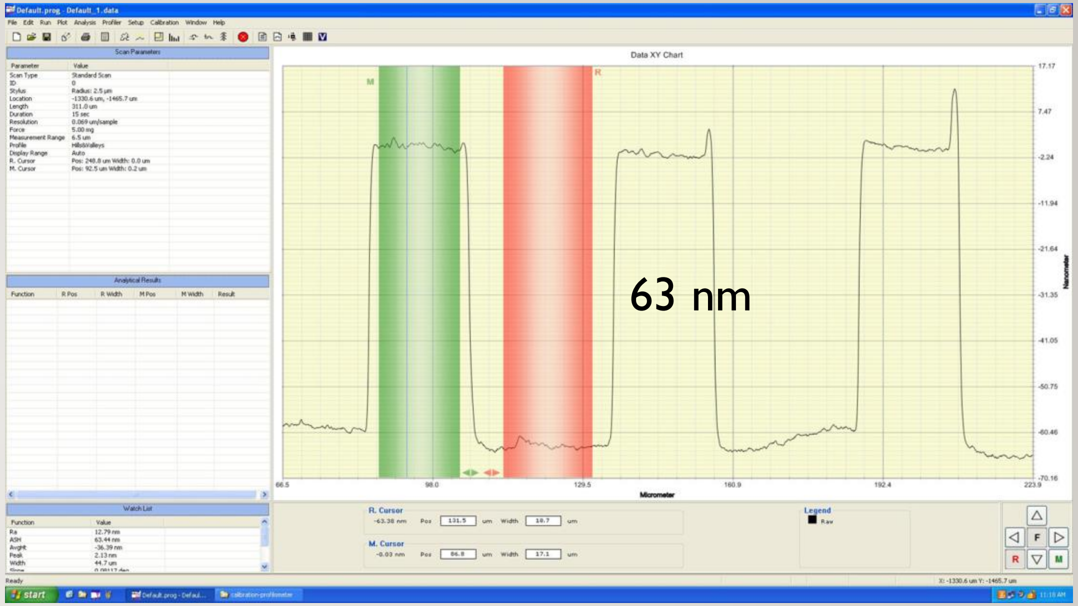
Stage movement direction

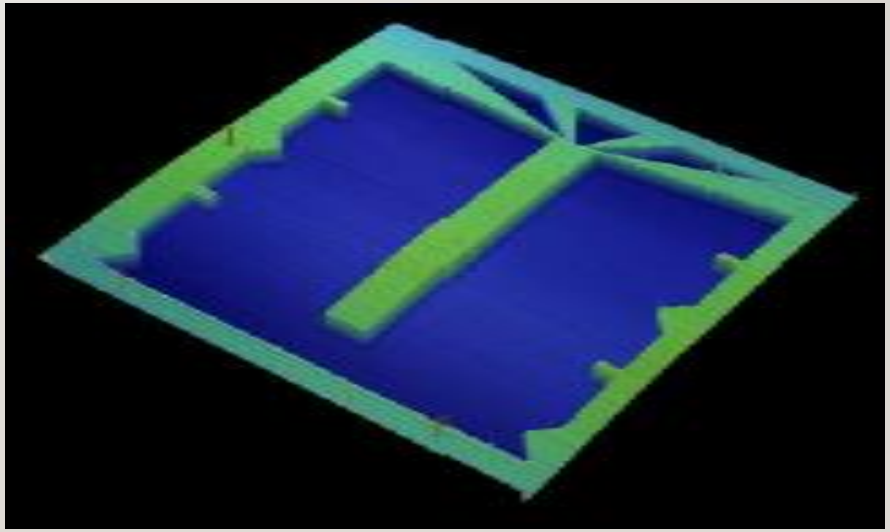
- A constant contact force is applied while the stylus moves laterally.
- The feedback controller lifts the stylus tip up or down to maintain constant force
- Tips are usually diamond. The tip radius dictates the lateral resolution.
- Tip radius ranges from 50 nm to 200 microns (**ours is 5 um**)





Surface scratch



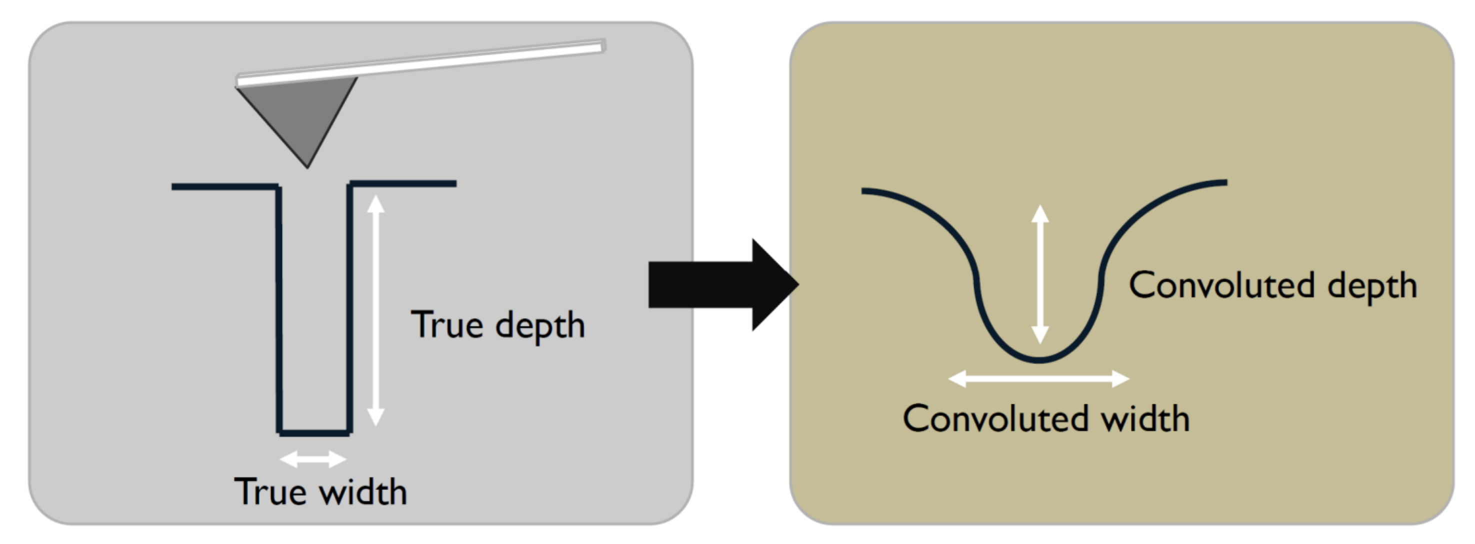


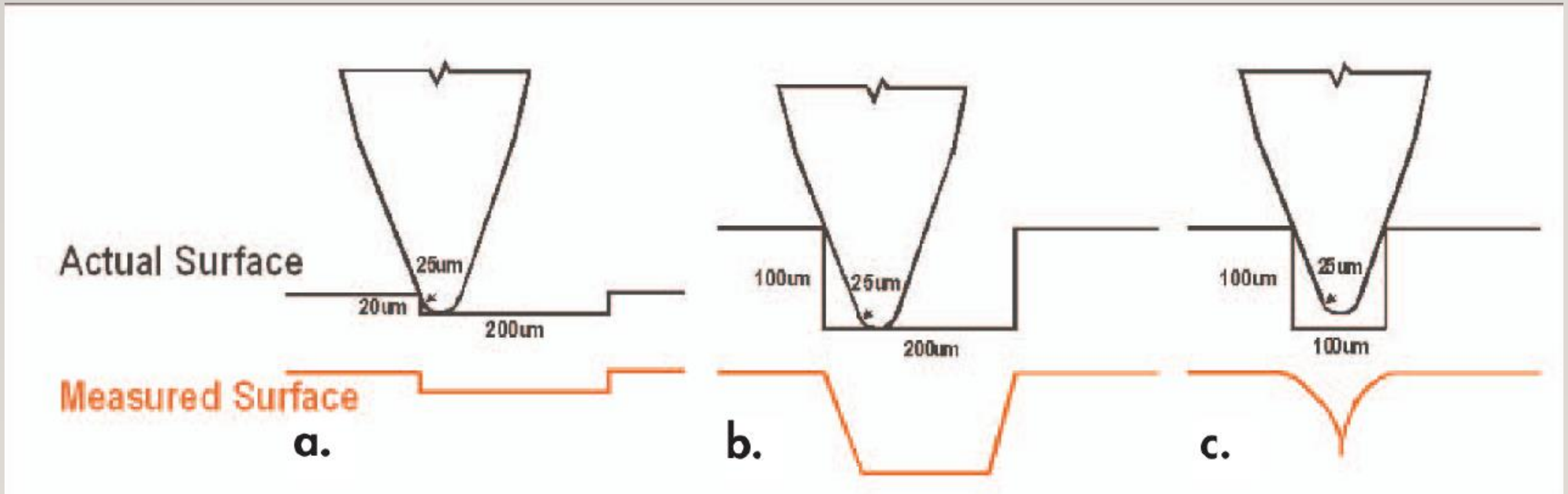
Very time consuming

Tip Radius and Convolution Effects

Radius of curvature of the tip defines the lateral resolution.

– Not only leads to convoluted x,y dimensions, can caused convoluted depth… effects surface roughness





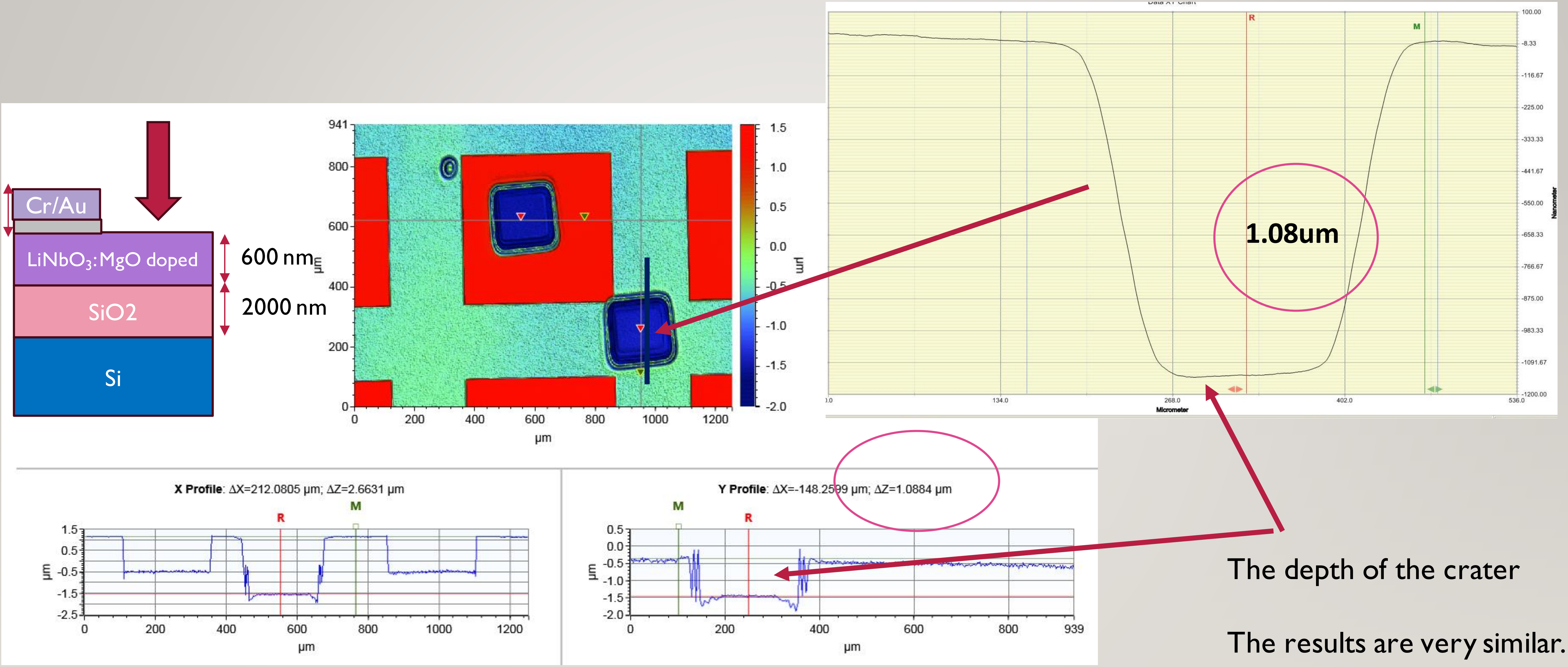
Features

- 3D topographical surface map rather than just traditional line scan
- Larger sample (up to 6 inches wafer) and longer scan (up to 55 mm)
- Vertical resolution - 1 ångström
- Vertical Range - 524 um
- Powerful and user-friendly software
- Stylus radius- 12.5 um, 5.0 um, 2.5 um

Data Information

- Step height
- Roughness
- Curvature measurement
- Film stress measurement

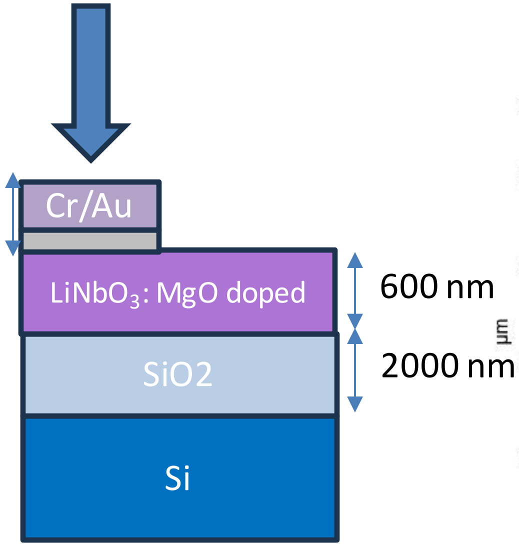
Data Collected from Optical and Stylus Profilometer

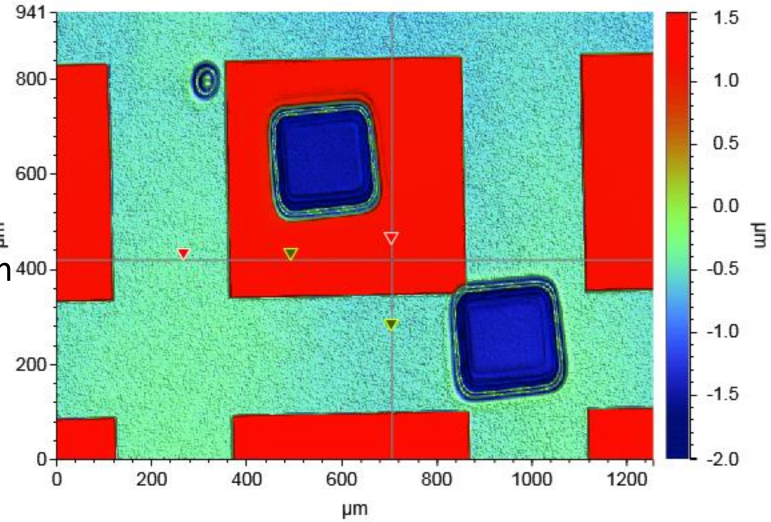


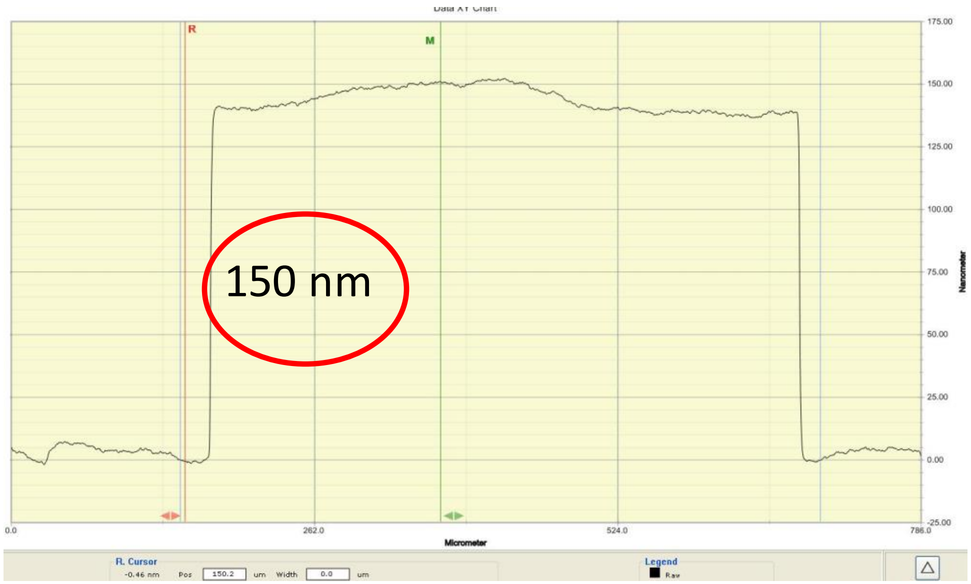
The depth of the crater

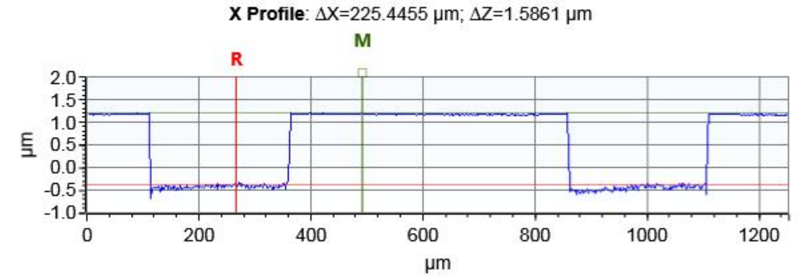
The results are very similar.

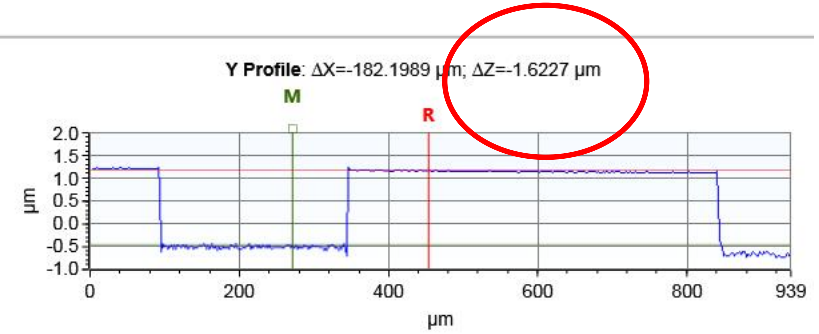
Error from Optical Profilometer





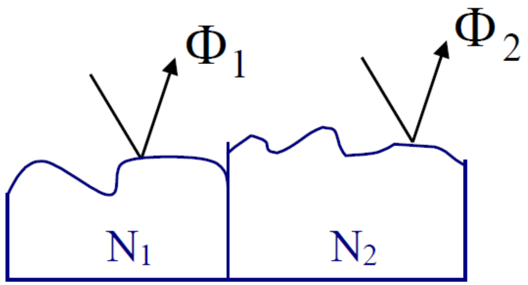






WHY?

Phase Change on Reflection



- Light, when reflected from materials, exhibits a phase change upon reflection
- Actual phase change is a function of the complex index of refraction: N= n – ik
- For a bulk material the phase change on reflection is given by:

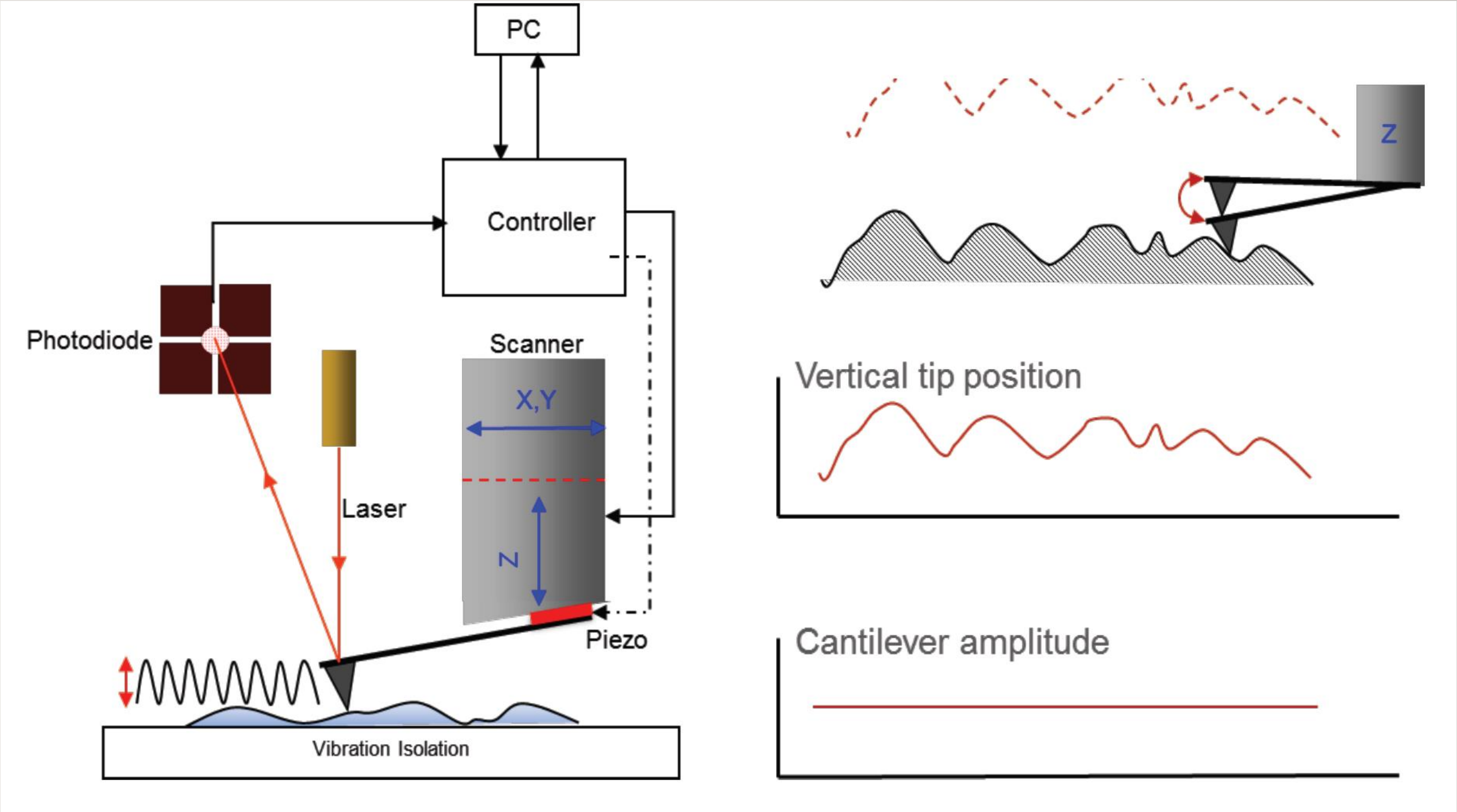
$$\Phi\ (n,k) = TAN^{-1}\ [\frac{2k}{1-k^2-n^2}]$$

Correction for the offset caused by the dessimilar materials

- Adjacent regions of dissimilar materials will have a constant offset due to difference in phase change on reflection
- The offset can be calculated once the n and k are known for both materials

$$\Delta h = \frac{\lambda}{4\pi}\ \Delta\Phi = \frac{\lambda}{4\pi}\left[\Phi\ (n_1,k_1) - \Phi\ (n_2,k_2)\right]$$

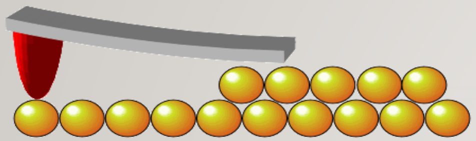
AFM (Atomic Force Microscopy)
SPM (Scanning Probe Microscopy)



- Cantilever is driven at its resonant frequency by a piezo.
- The amplitude is monitored by laser deflection.
- Constant amplitude is maintained by adjusting the z piezo up or down.

AFM Mode

contact mode



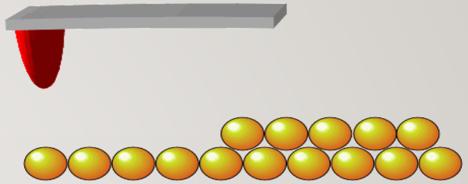
Tip angstroms from surface (repelled)

Constant force

Highest resolution

May damage surface

non-contact mode



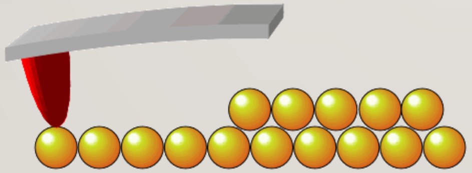
Tip hundreds of angstroms from surface (attracted)

Variable force measured

Lowest resolution

Non-destructive

tapping mode



Intermittent tip contact

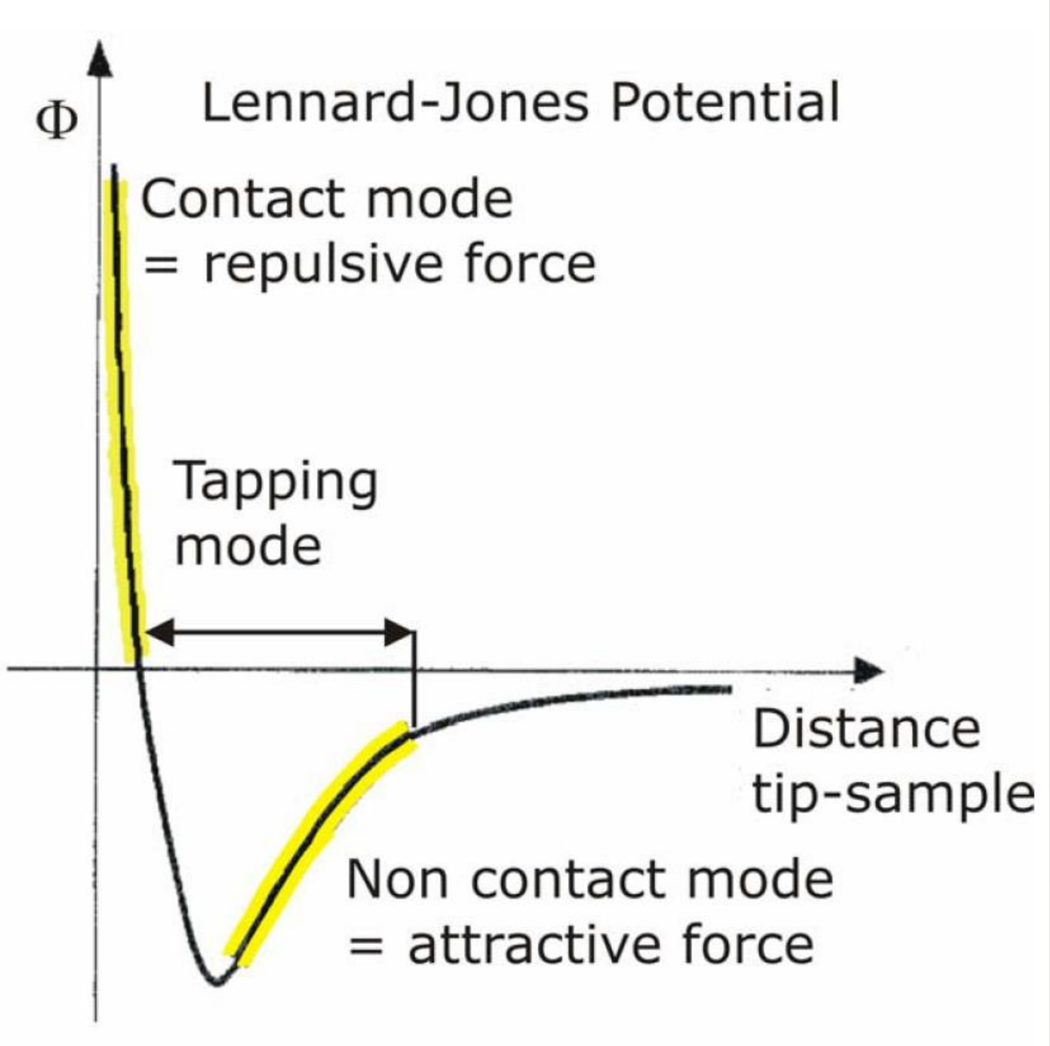
Variable force measured

Improved resolution

Non-destructive

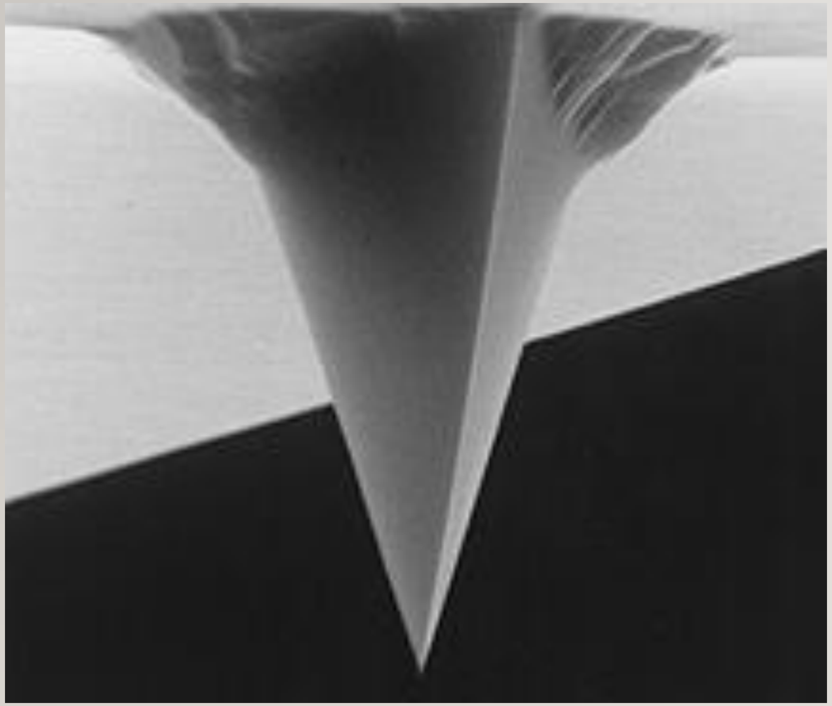
Tapping Mode

- A cantilever with attached tip is oscillated at its resonant frequency and scanned across the sample surface
- A constant oscillation amplitude (and thus a constant tip-sample interaction) are maintained during scanning. Typical amplitudes are 20-100 nm.
- Forces can be 200 pN or less
- The amplitude of the oscillations changes when the tip scans over bumps or depressions on a surface



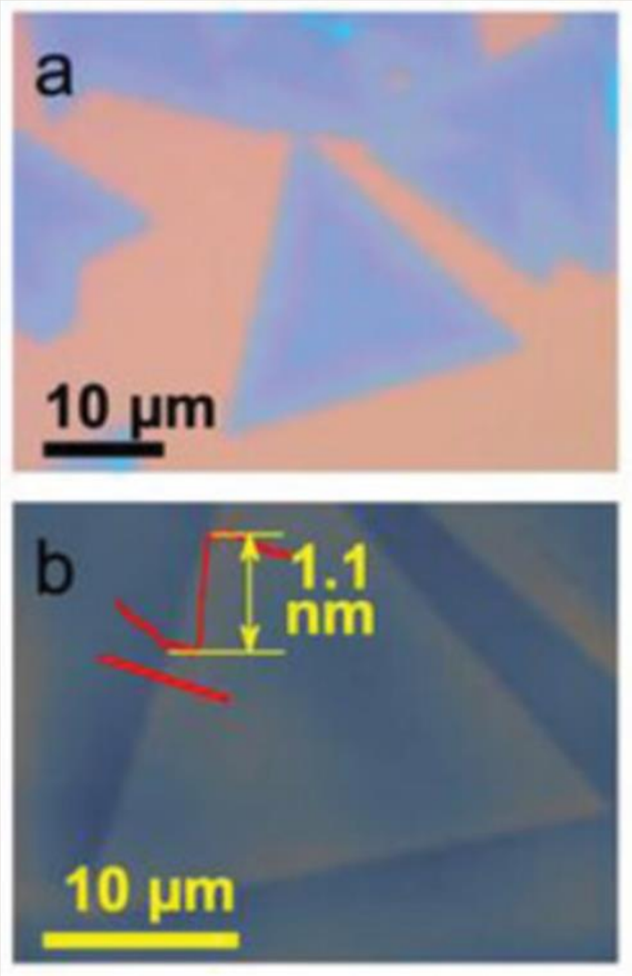
The development of TappingMode™ enabled researchers to image samples too fragile to withstand the lateral forces of Contact Mode and use scan speeds much higher than could be obtained in non-contact mode.

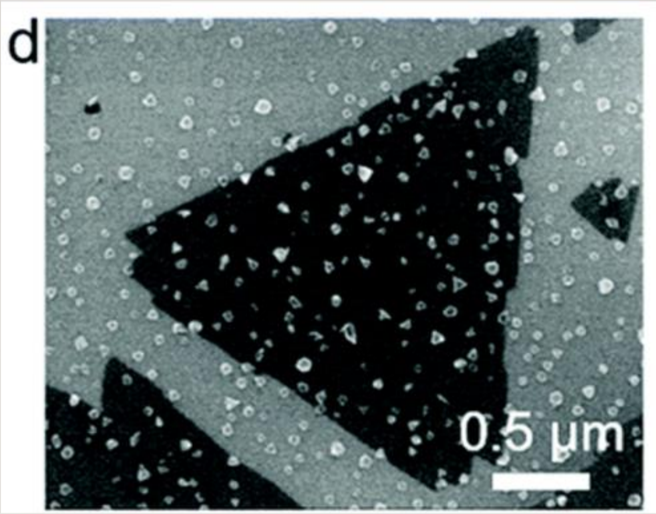
Microfabricated AFM cantilevers

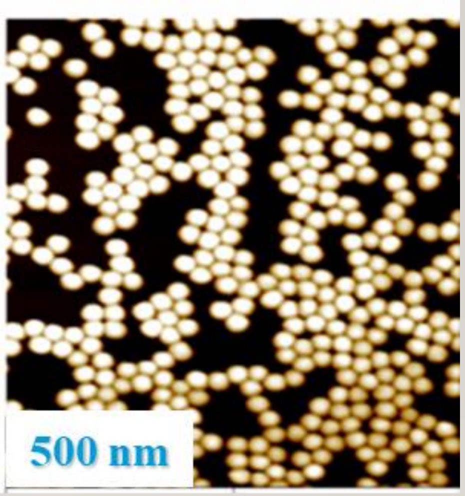


Radius$_{tip}$ ~ 1nm to 20nm

Only can be used for a few times



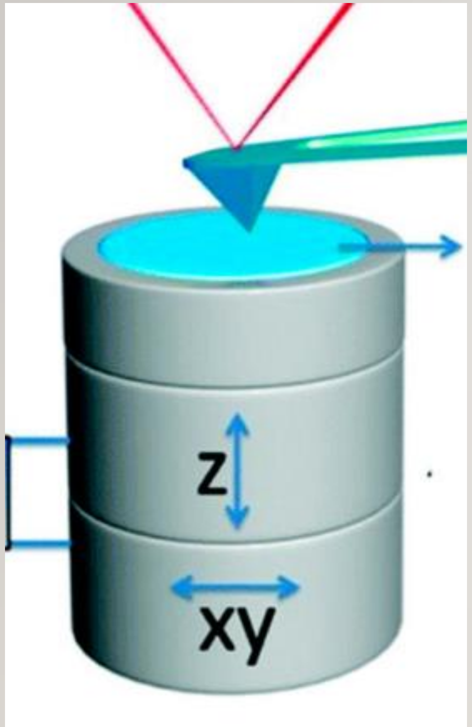




ZnS nanoparticles

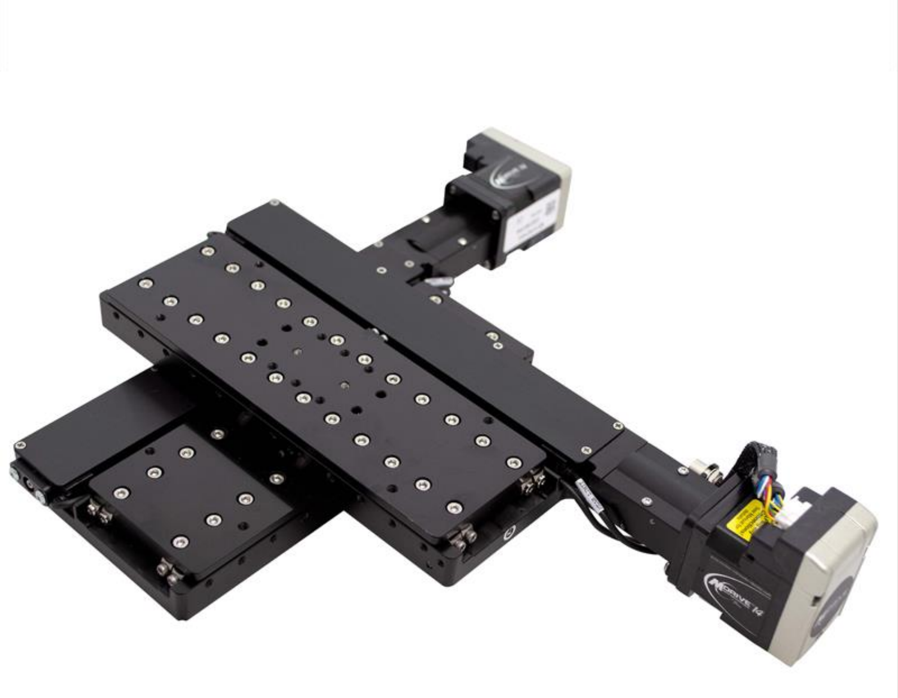
P. Yasaei, et al "Spatial Mapping of Hot-Spots at Lateral Heterogeneities in Monolayer Transition Metal Dichalcogenides." Advanced Materials 1808244 (2019)
Y. Li et al, MoS2-capped CuxS nanocrystals: a new heterostructured geometry of transition metal dichalcogenides for broadband optoelectronics. Materials Horizons 6 (3), 587-594. (2019)

Piezo stage used for AFM



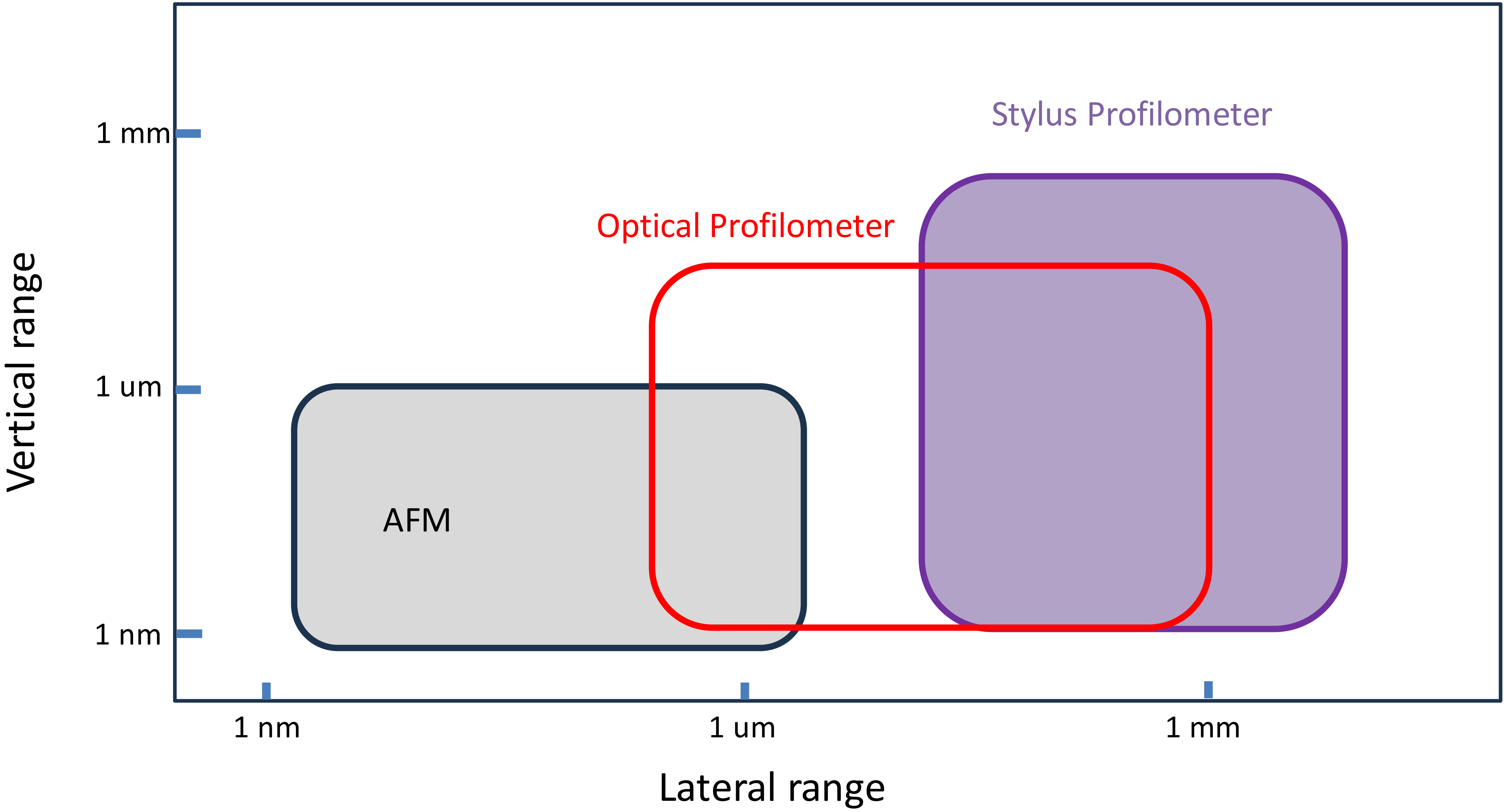
X and y translation precision
Smaller range

Motorized stage used for Profilometer



Huge x and y translation range
Poor precision

	Strength	Weakness
Stylus Surface Profiler (Contact profilometer)	Very fast and very easy (no setup and focus time, don't need changing tip) Vertical data are always reliable (no artifact) Huge vertical range (524 um) Great vertical resolution	Poor lateral resolution Contact mode, damage the soft surface Time consuming for 3D characterization
3D Optical Microscope (Optical profilometer)	Fast and easy Quick 3D characterization No contact, good for soft surface Great vertical resolution Better lateral resolution	Not work for low reflective surface Artifact is possible for dessimilar surface
Atomic Force Microscope (Tapping mode AFM)	Best lateral and vertical resolution Great for atomic layer film Great for soft surface	X, Y, Z range is very limited The tip should be replaced very frequently Setup and scanning take more time


Stylus Profilometer
Optical Profilometer
AFM
1 mm
1 um
1 nm
Vertical range
1 nm
1 um
1 mm
Lateral range

THANKS FOR YOUR ATTENTION

- QUESTIONS?

- XCHEN@NORTHWESTERN.EDU
- 847-491-5505