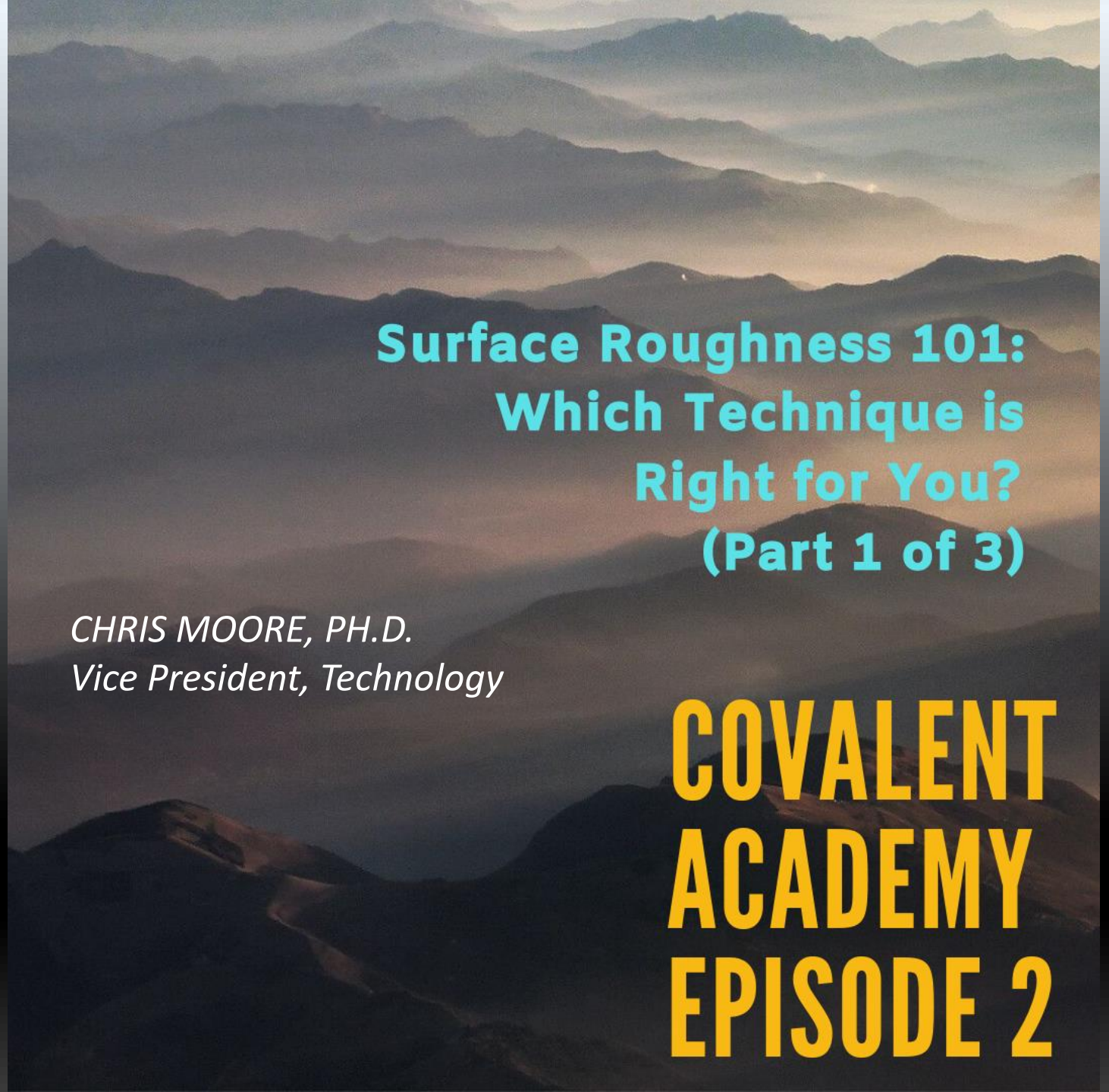

Surface Roughness 101:
Which Technique is
Right for You?
(Part 1 of 3)
CHRIS MOORE, PH.D.
Vice President, Technology
COVALENT
ACADEMY
EPISODE 2

Covalent Metrology



- **Founded 2016**
- **Testing, measurement & characterization** Platform
- **30 team members (13 PhDs)**
- **9,500 ft² lab in Sunnyvale**
- **1-Stop-Shop Source for Answers**
  - 30 instruments in-house
  - 6 partnerships with instrument makers
  - 11 partner labs
  - 6 corporate “tool shares”
- **>275 customers** (80% repeat)

Covalent Technical Groups and Organization

hello@covalentmetrology.com

Electron & Scanning Probe Microscopy

(SEM/TEM, AFM, EDS, EELS, Nanoindent, acoustic microscopy)

Surface Analysis

(XPS, Auger, ToF-SIMS, dSIMS)

Optical Microscopy & Spectroscopy

(Laser Confocal, White Light, Chromatic Aberration, Spectral Ellipsometry, UV-Vis-NIR Spectroscopy)

Materials/ PC Board FA

(Cross Sections, Inspections, Dye & Pry)

X-Ray Characterization

(XRD/XRR, XRF, µCT)

Chemical Analysis

(ICPMS, GCMS, FTIR, Raman, Solid & Solution NMR, 2D NMR)

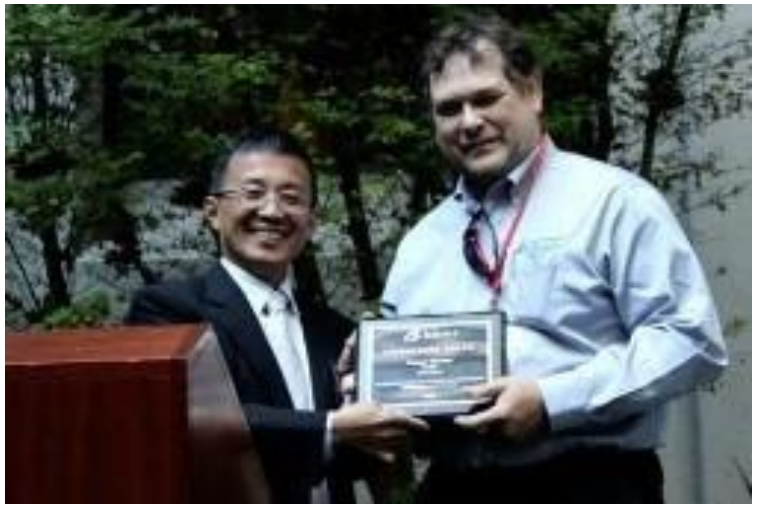
Nanoparticle Analysis

(DLS, PSA, Particle Zeta Potential)

Bulk Properties Characterization

(DSC, TGA, DMA, Rheometry, Tensile Test, Pencil Test, Surface Zeta Potential)

Dr. Chris Moore, VP Technology



- PhD Solid State Physics, University of Waterloo, 1983
- Extensive experience in metrology technology and systems
  - Lead teams that designed:
    - Optical tool UV to mid IR
    - High speed mapping X-ray
    - Photoluminescence
    - Non-contact electrical
    - Contact electrical tools
  - Worked with many other types of tools and imaging systems
- Experience in measuring or characterizing:
  - Semiconductor materials and devices
  - Compound materials and devices
  - Flat panel display
  - Solar cells and batteries
  - MEMS and micro-fluidics

Episode 2 Overview

COVALENT METROLOGY

- **General introduction**
  - Short discussion on surface characterization
  - Surface roughness: why does it matter?
  - How do you characterize surface roughness?
  - Different R values, what they mean, and some practical thoughts
- **An Overview of the Techniques**
  - Introduction
  - Plusses and minuses
- **How to Choose a Technique**
  - General guidelines
  - Specific needs
- **Next Episode**
- **Question and Answer**

How Do You Characterize a Surface?

Here are a few examples of how you can characterize a surface:

Mechanical

- **Roughness**
- Flatness
- Hardness
- Scratch resistance

Chemical

- Elemental Composition
- Chemical Bonding
- Contamination

Optical

- Color
- Reflection
- Scattering

Electrical

- Spreading Resistance

Physical

- Work Function
- Carrier Lifetime

Why Care about Surface Roughness?

Surface Roughness is one of the most common physical characteristics impacting device / product performances and yields across many, many applications.

Mechanical

- Adhesion and Bonding
- Grain Structure / Growth
- Friction
- Wettability

Chemical

- Reaction kinetics (surface area)

Optical

- Specular or Diffuse Reflectance
- Color

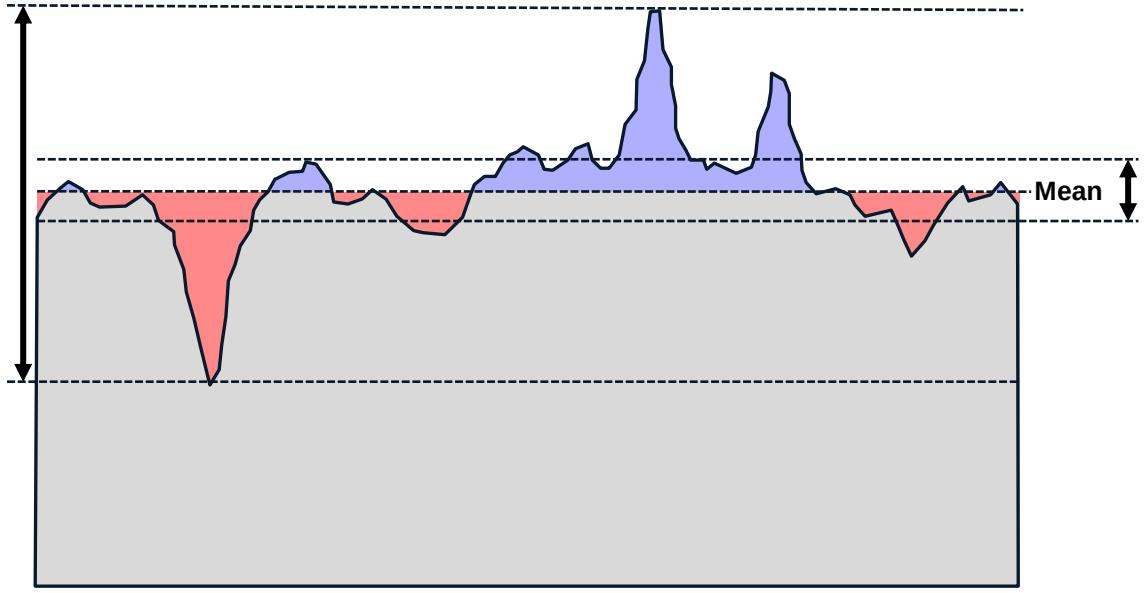
Electrical

- Coupling / Resistance

Physical

- Interdiffusion / Surface Area Effects

How To Characterize Roughness



- **Is this rough or smooth?**
  - Depends on your criteria (and where you look)
  - Roughness is quantified using a statistical analysis
    - At least 15 different ways to calculate roughness
- **What you measure depends on:**
  - Technology used
  - Area of measurement
  - Density of measured data
  - Statistical analysis used

Surface Parameters That Are Commonly Used

Surface Parameters	Definition
Ra, Sa	The arithmetic average of the absolute values of the profile height deviations from the mean line or surface
Rq,Sq	The root mean square average of the absolute values of the profile height deviations from the mean line or surface
Rsku,Sku	Kurtosis. A measure of the “tailedness” of the height distribution of a line or surface
Rp,Sp	The height of the highest single peak in a line or surface
Rv,Sv	The depth of the deepest single valley in a line or surface
Rz,Sz	The range between the average of the five highest peaks and the average of the five lowest in a line or surface. (Number in this depends on system software could be 1)

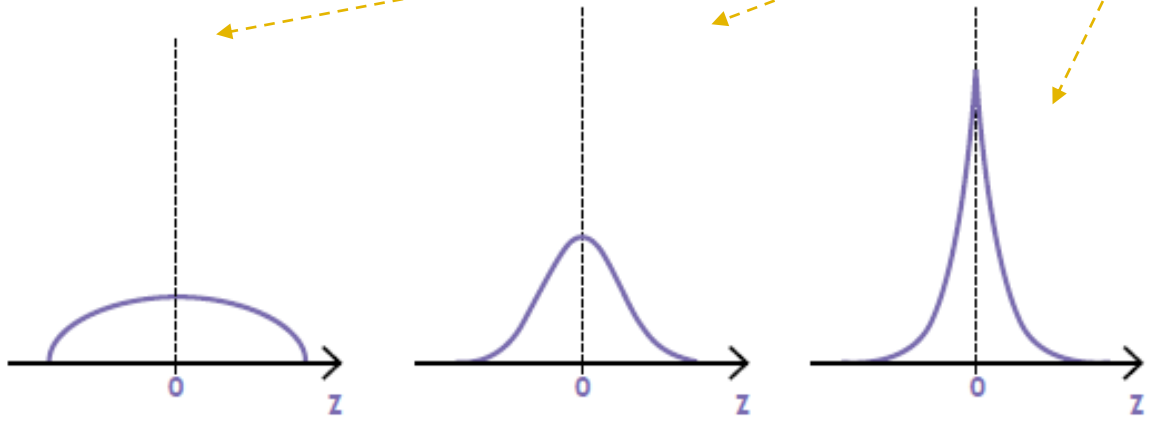
More on Sku

Kurtosis (Sku)

Sku value is a measure of the sharpness of the roughness profile.

$$Sku = \frac{1}{Sq^4}\left[\frac{1}{A}\iint_A Z^4(x,y)dxdy\right]$$

Statistical distribution of heights – this is not a representation of the surface itself



Sku<3 Sku=3 Sku>3

Sku<0 · · · · · · Height distribution is skewed above the mean plane.

Sku=0 · · · · · · Height distribution is normal distribution.
(Sharp portions and indented portions co-exist.)

Sku>0 · · · · · · Height distribution is spiked.

R Parameters versus S parameters

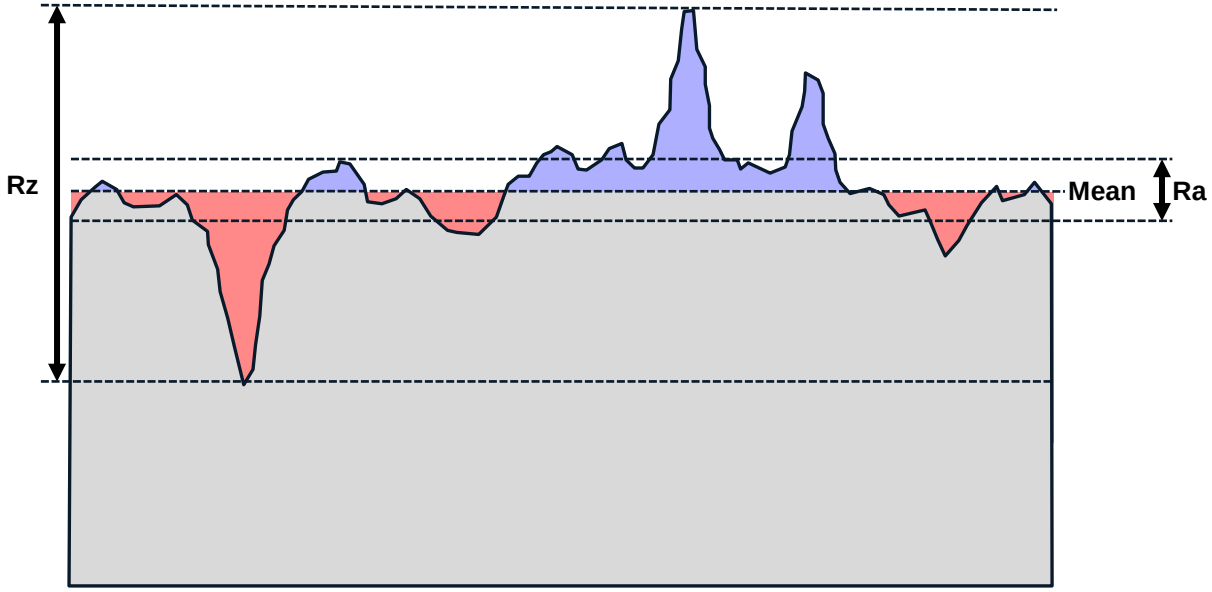
- Traditionally R values are measured along a line (i.e. from a line profile as 1D measurement)
  - Some analysis measure R along a series of lines to get “better” statistics
  - i.e. you are getting an average value of R for each line
  - R values are not unitless - need to say are we talking nm, mm, micro inches, …

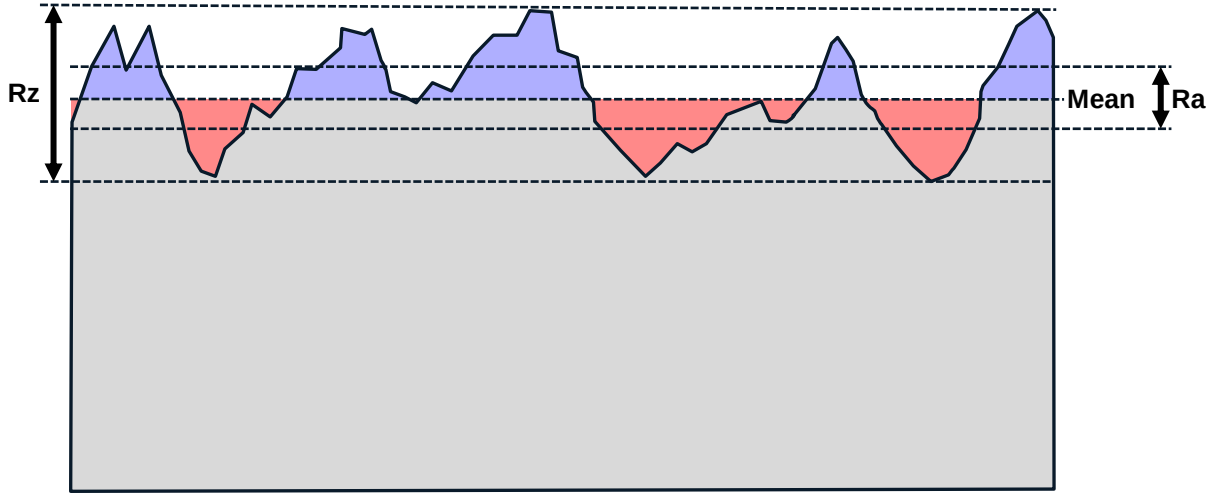
- S values are calculated in 2 dimensions (i.e. 2D measurement)
  - Although there can be a correspondence between the two for an isotropic material
  - It is not necessarily a given if the roughness has a directional component
  - S values are not unitless - need to say are we talking nm, mm, micro inches…

- For more information:
  - “2D Spatial Frequency Considerations in Comparing 1D Power Spectral Density Measurements” by Peter z. Takacs, Sam Barber, Eugene L. Church, Konstantine Kaznatcheev, Wayne R. McKinney, Valerly Y. Yashchuk. https://www.bnl.gov/isd/documents/71134.pdf

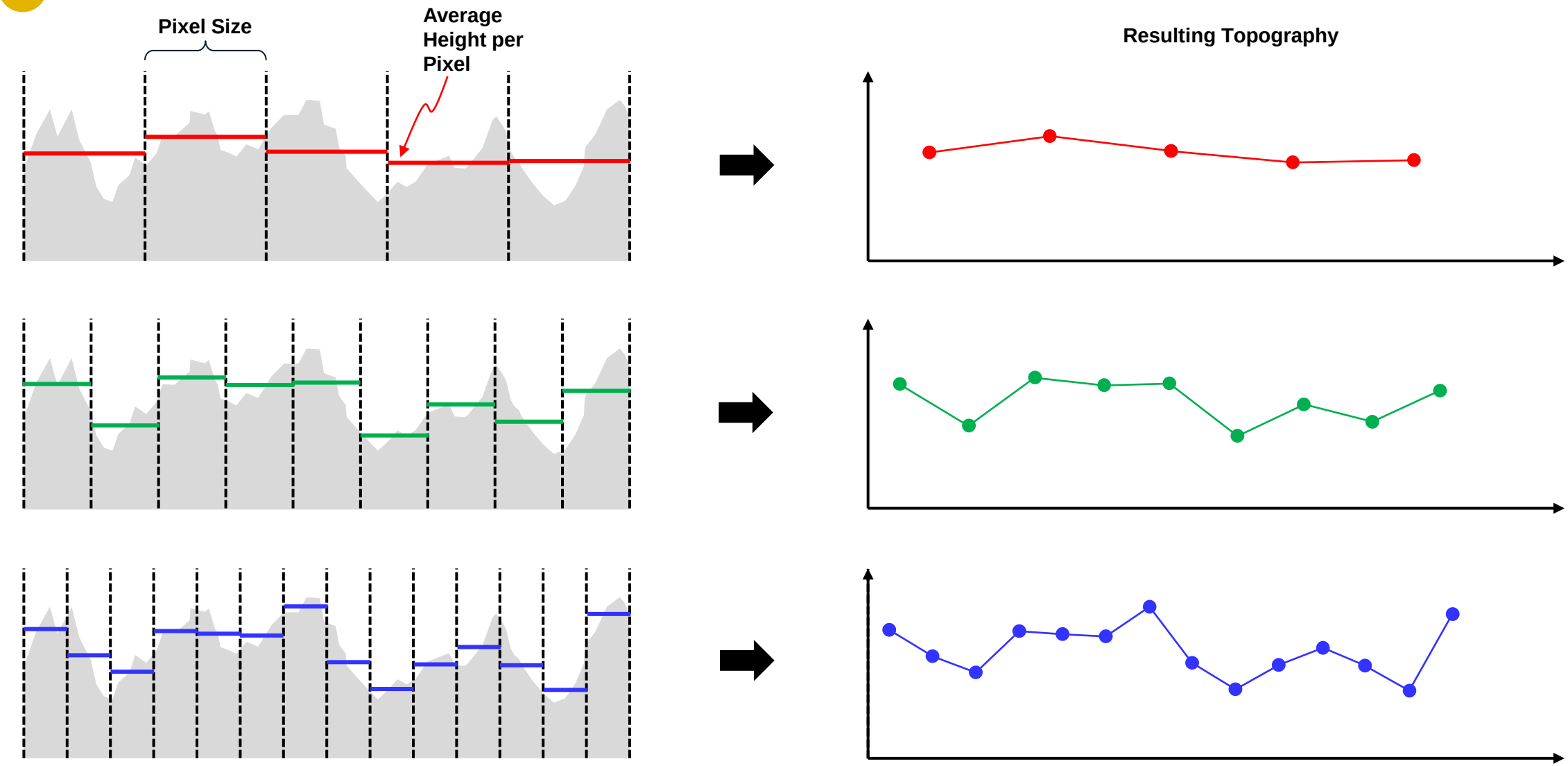
The Danger of Using R_a

Are these the same roughness?
They have the same R_a





In Roughness Size of measurement area matters



Indirect versus Direct Measurements

- **Direct**
  - **Produces an image or a profile**
    - AFM, microscopes, SEM …
    - Clear length scale

- **Indirect (not described in this series)**
  - **Uses a model to interpret measured data**
    - Spectroscopic Ellipsometry
    - Scatterometry
    - XRR (X-ray Reflectivity)

- **One can correlate two different methods (if both applicable) to give a similar result.**
  - Very seldom does the raw measurement give the same value
  - Even comparable instrument tool matching is difficult

Roughness Scale (Vertical Range)

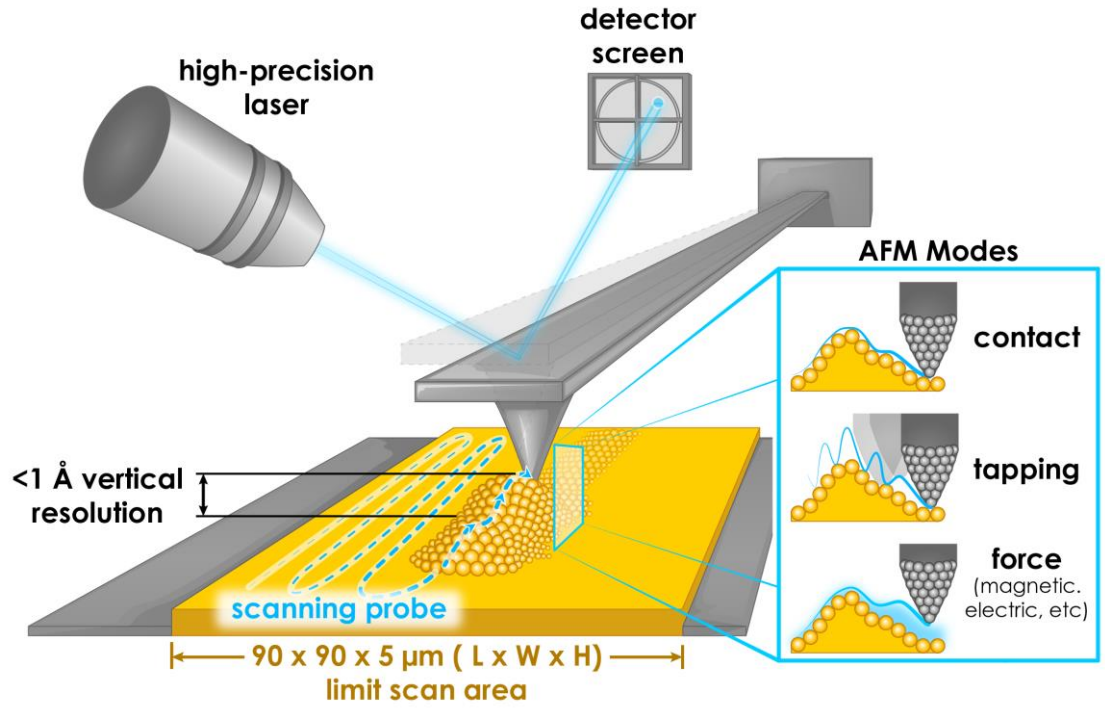
COVALENT METROLOGY

Scale	Atomic Force Microscopy (AFM)	White Light Interferometry	Transmission Electron Microscopy	Scanning Electron Microscopy	Chromatic Dispersion	Confocal Laser Microscopy	Patterned White Light	Stylus Profilometry	Depth of Field Microscopy
Sub nm	Yes		Yes						
nm	Yes	Yes	Yes		Sometimes	Sometimes		Sometimes (depends on tip)	
10's of nm	Yes	Yes	Yes	Yes	Yes	Yes		Yes	
Sub micron	Yes	Yes	Yes	Yes	Yes	Yes		Yes	Sometimes
10's of microns		Yes		Yes	Yes	Yes	Yes	Yes	Yes
Sub mm		Yes		Yes	Yes	Yes	Yes	Yes	Yes

AFM – Atomic Force Microscopy

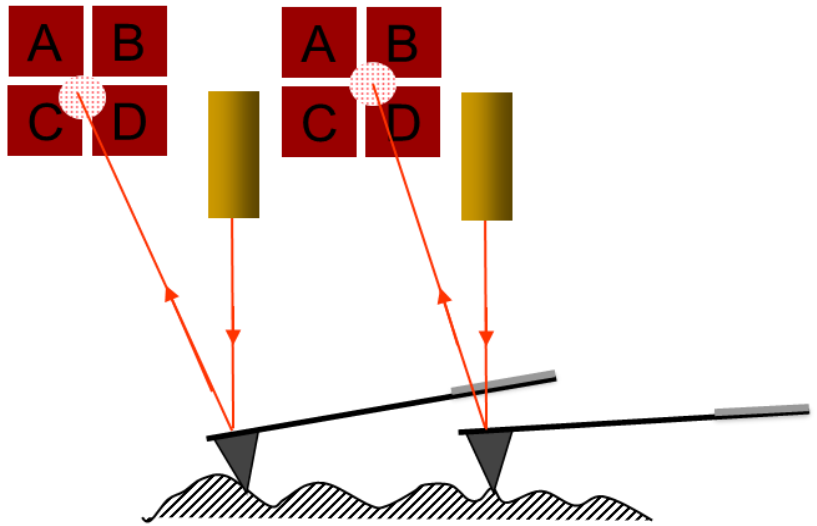
A more precise stylus profilometer

- **Basic operation:**
  - **Raster scan a microscopic probe over a sample**
    - “Atomic Force” – The source of the measurement is interatomic repulsion
- **Strengths:**
  - **Outputs 3D profile**
  - **Z Resolution < 1 nm**
  - **No special environment or sample preparation needed**

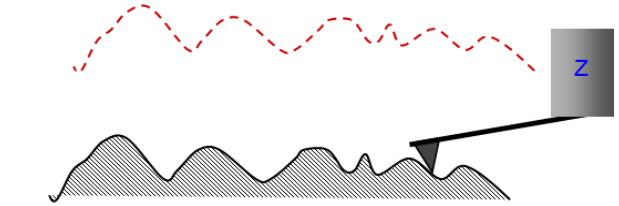


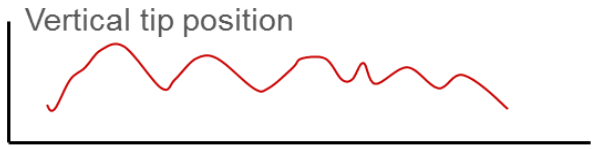
How an AFM Measures Roughness

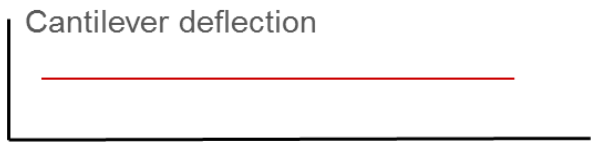
Contact Mode



Deflection: $\frac{(A+B)-(C+D)}{(A+B)+(C+D)}$







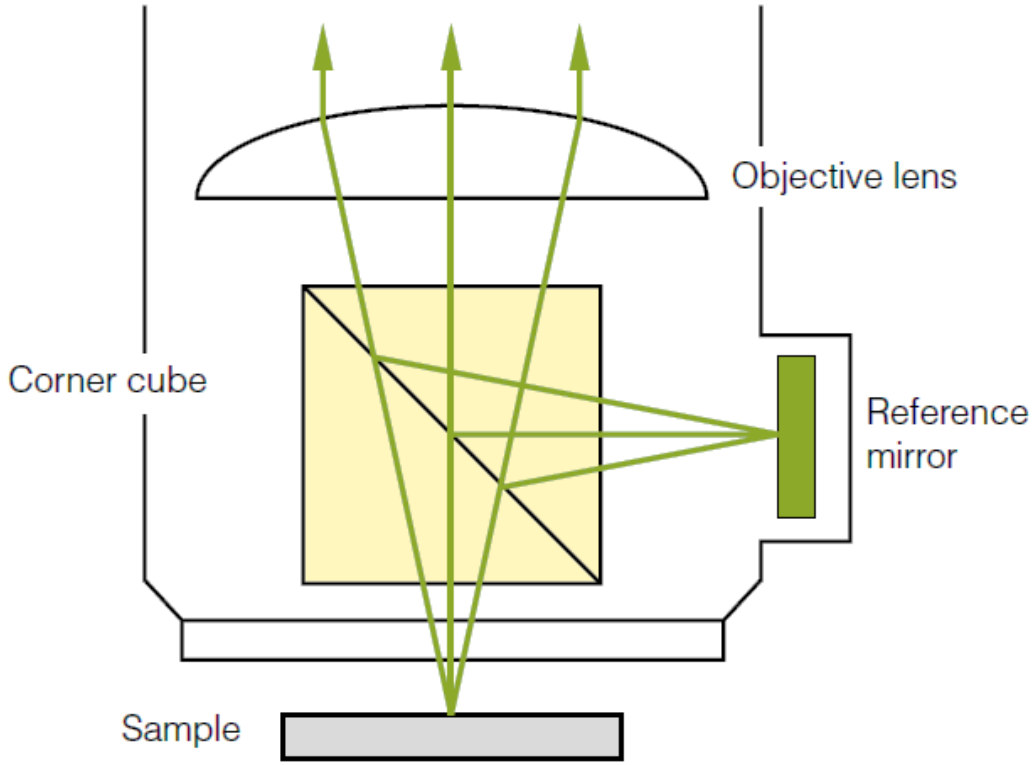
Pros
- Very high resolution

Cons
- Limited area scan
- Works poorly on soft materials
- Understanding tip effects & artifacts requires skilled operator

Working Principle
- Keep lever deflection constant
- Base for other modes like contact resonance, force modulation…

White Light Interferometry

White Light Interferometry (WLI)



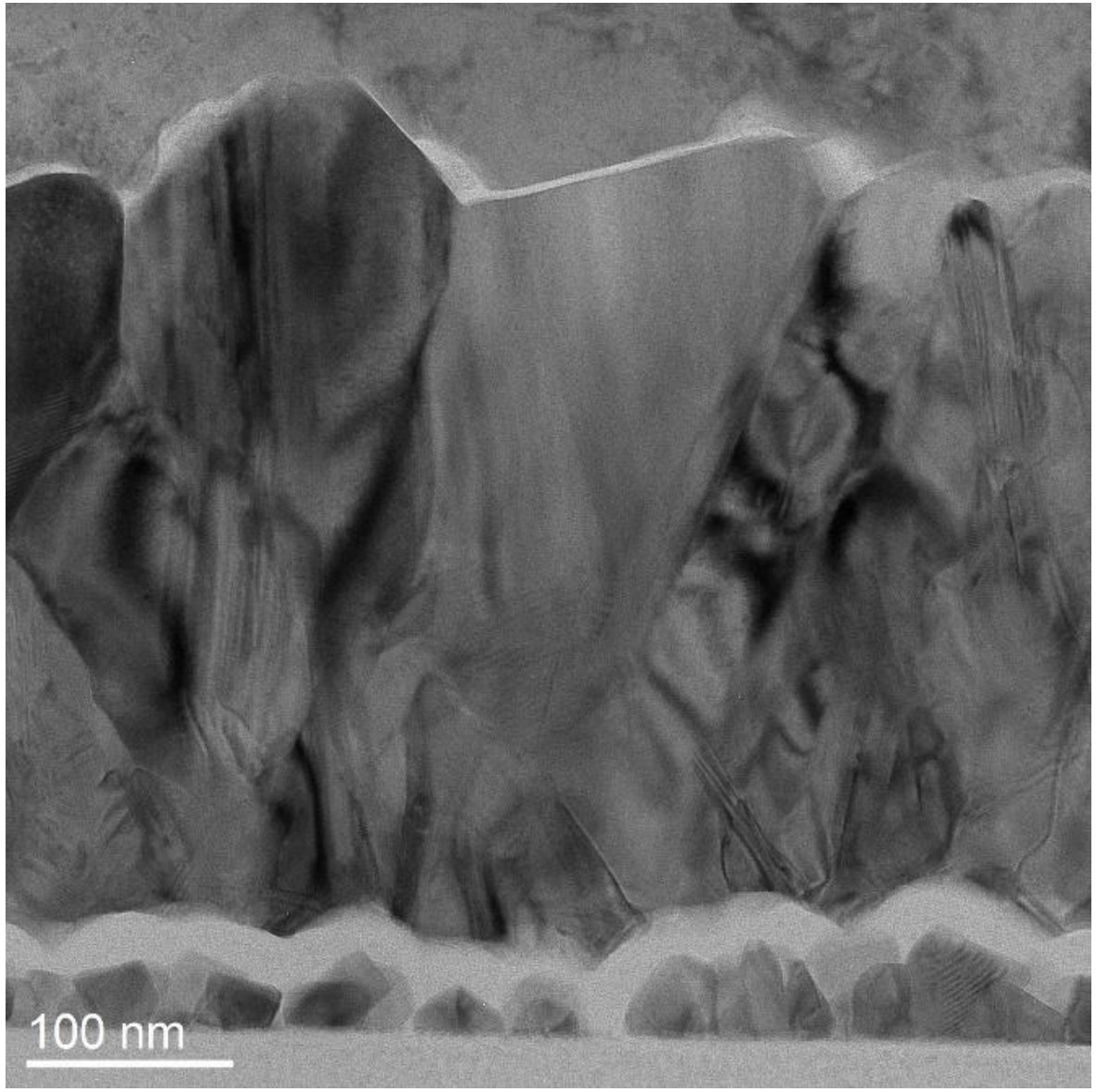
Pros

- Very high resolution
- Often lowest cost

Cons

- Limited area scan
- Can be difficult to interpret results
- Reflectivity of surface critical to accuracy
- Problems with acceptance angle

Transmission Electron Microscopy



Pros

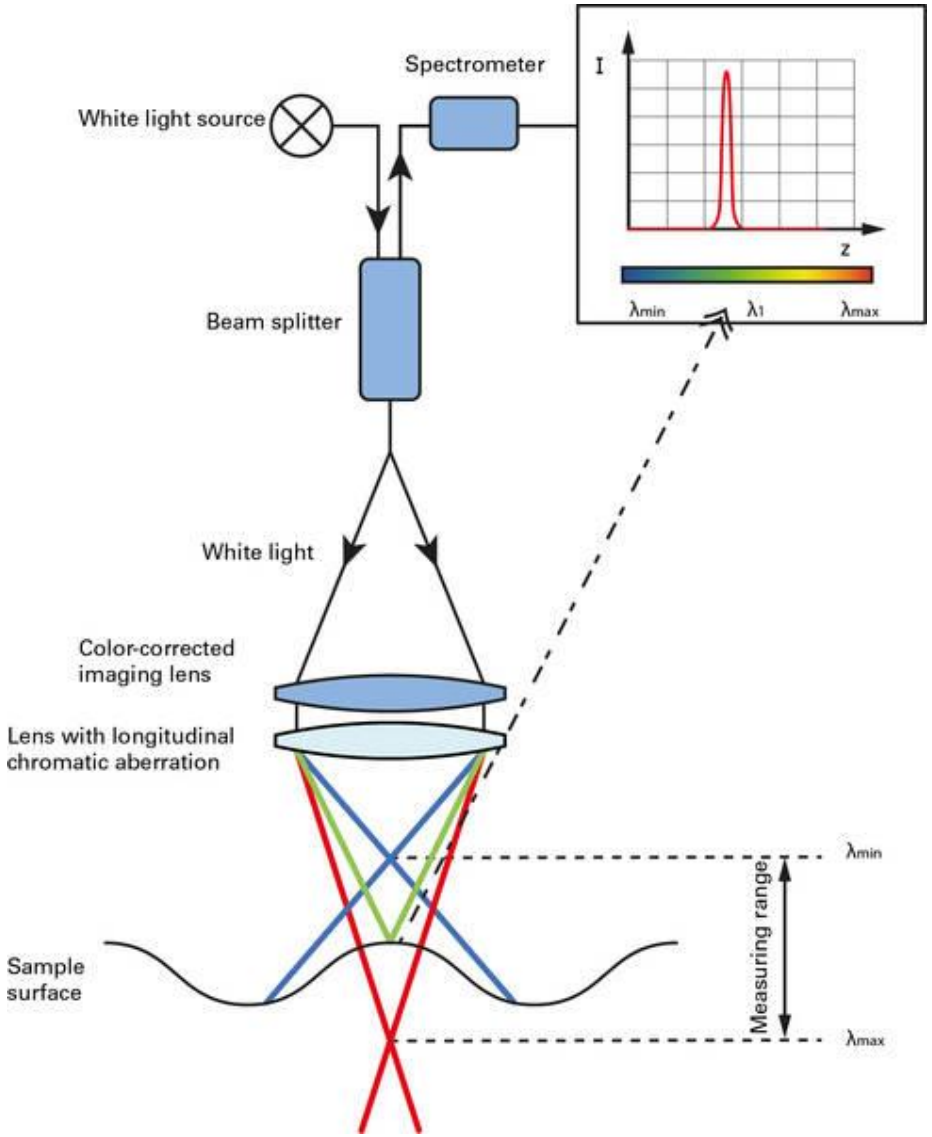
- Very high resolution
- Appeals to human psychology (looks pretty)

Cons

- Limited area scan
- Needs sample prep
- No statistics

More expensive than AFM or WLI (usually)

Chromatic Dispersion



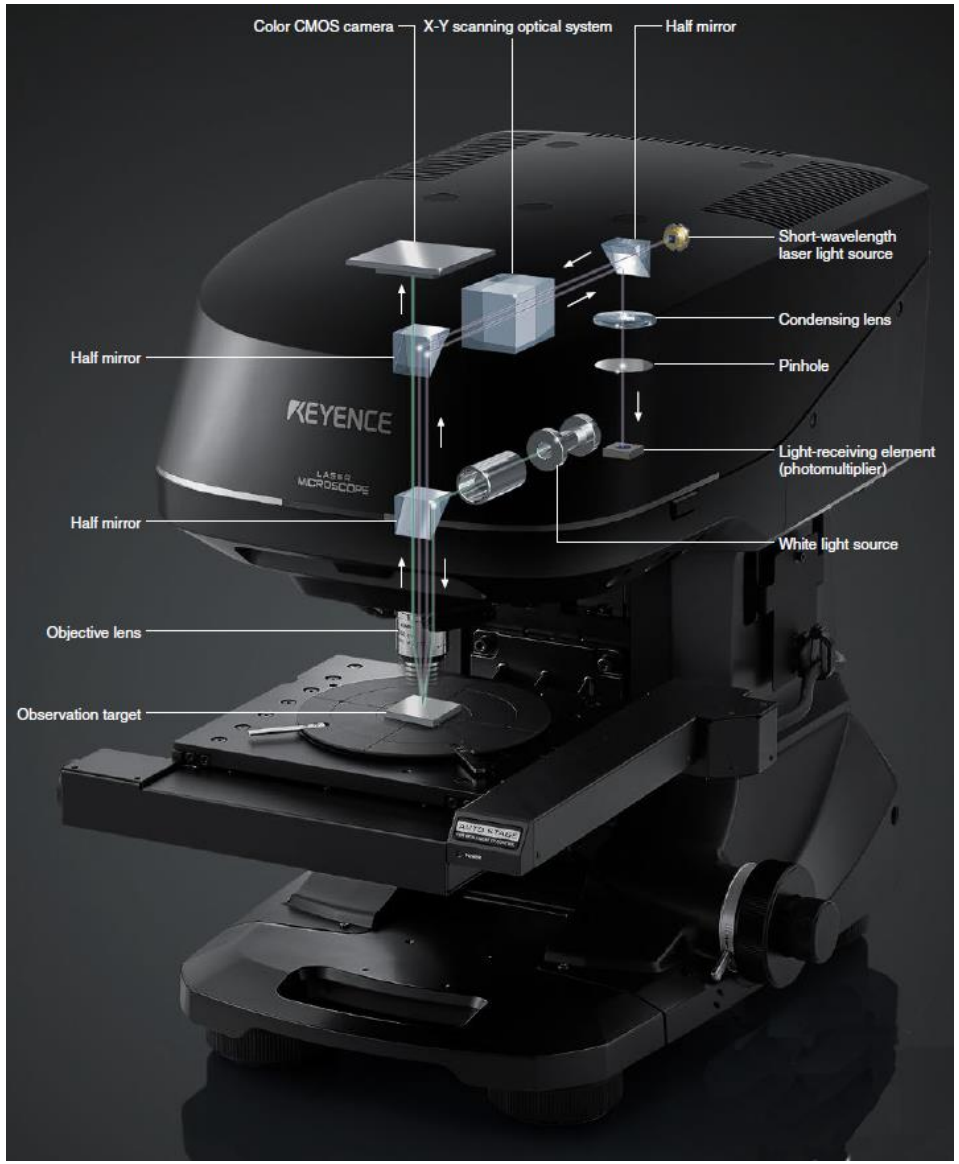
Pros

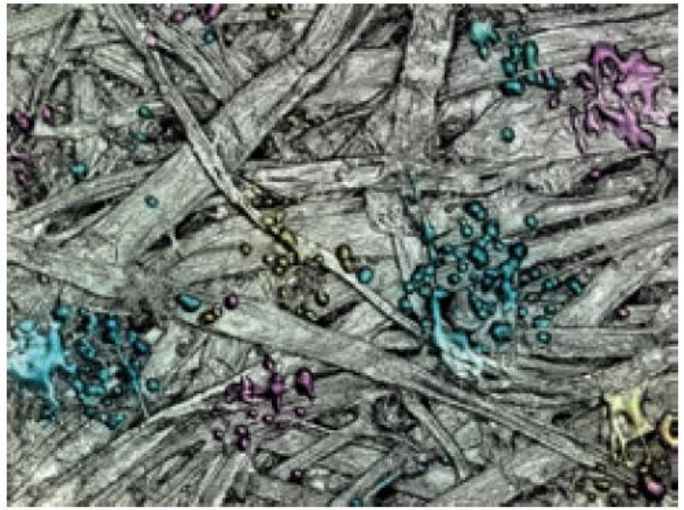
- High resolution
- Large sample area

Cons

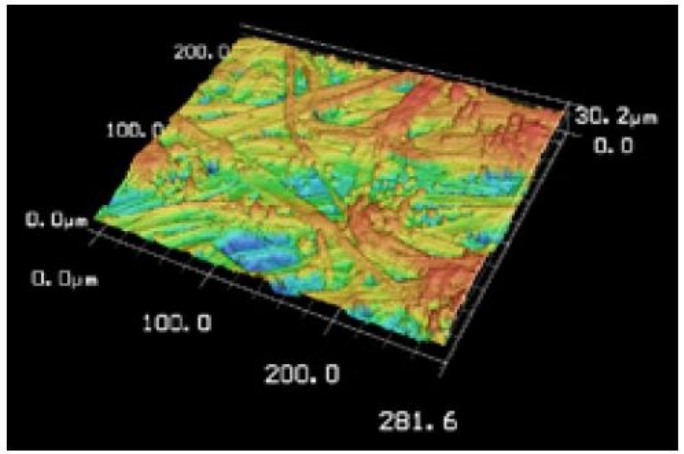
- Slower (scanning probe)
- Can be confused by transparent layers

Confocal Laser





Paper fiber 1000×



Pros

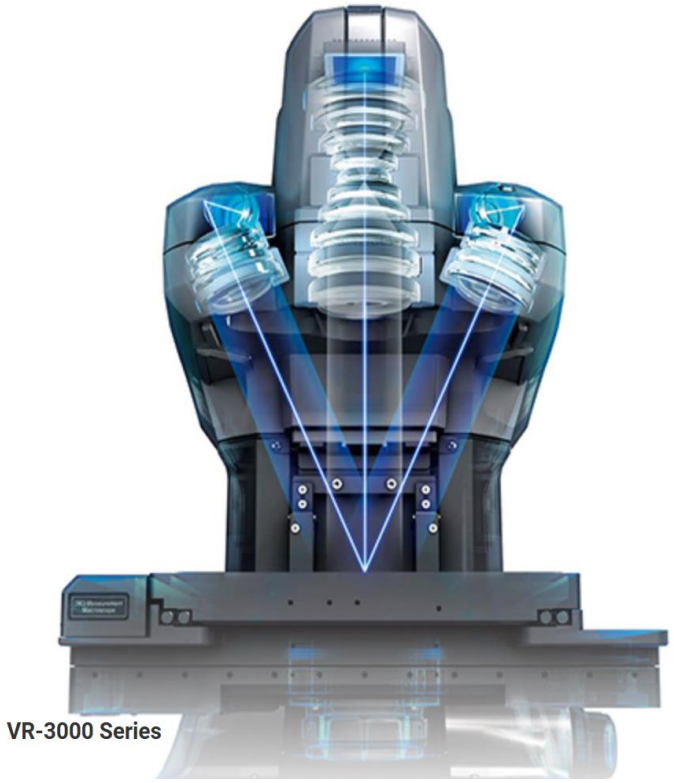
- Medium resolution
- Quantitative
  Often cost effective
- Produces visually appealing pictures

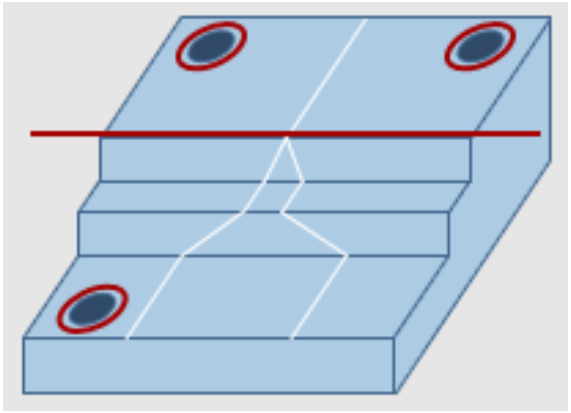
Cons

- Depends on surface reflectivity
- Difficult to stich large areas (data set too large)

Patterned White Light

Patterned White Light





Pros

- Wide area coverage
- Stitching works well
- Cost effective

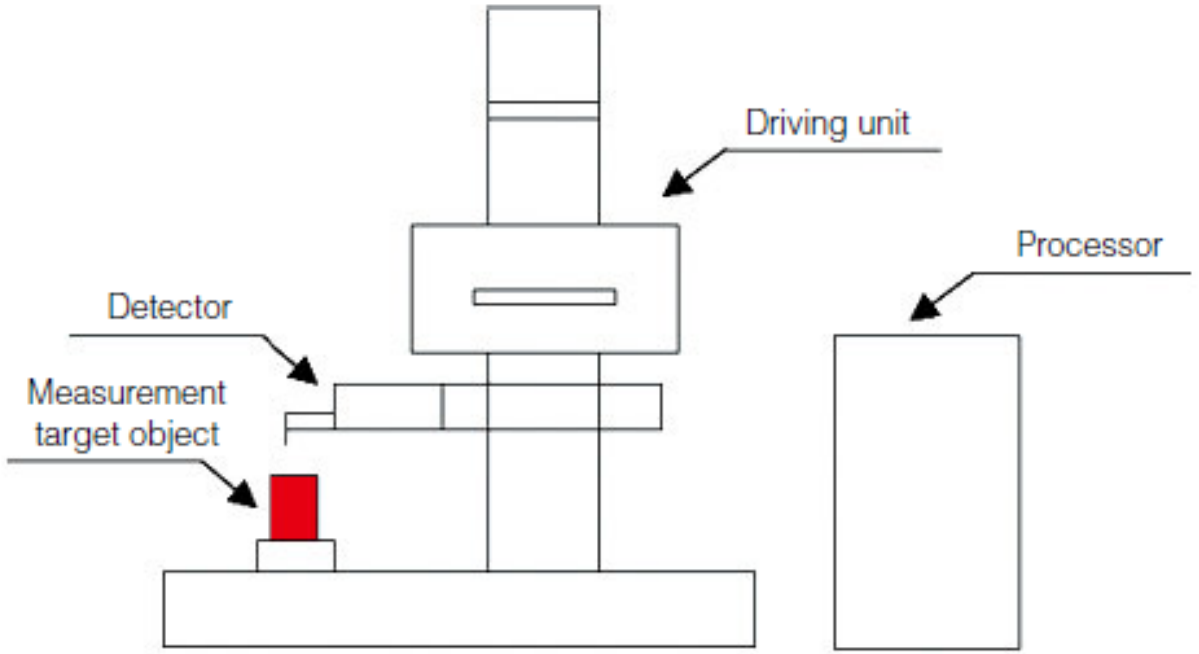
Cons

- Approx 5µm vertical resolution
- Does not work well on transparent samples
- Shadowing effects depending on sample geometry

Stylus Profilometer

COVALENT METROLOGY

Stylus Profilometer



Contact type surface roughness measuring system

Pros

- Medium resolution (depends on probe)
- Large scan
- Low cost

Cons

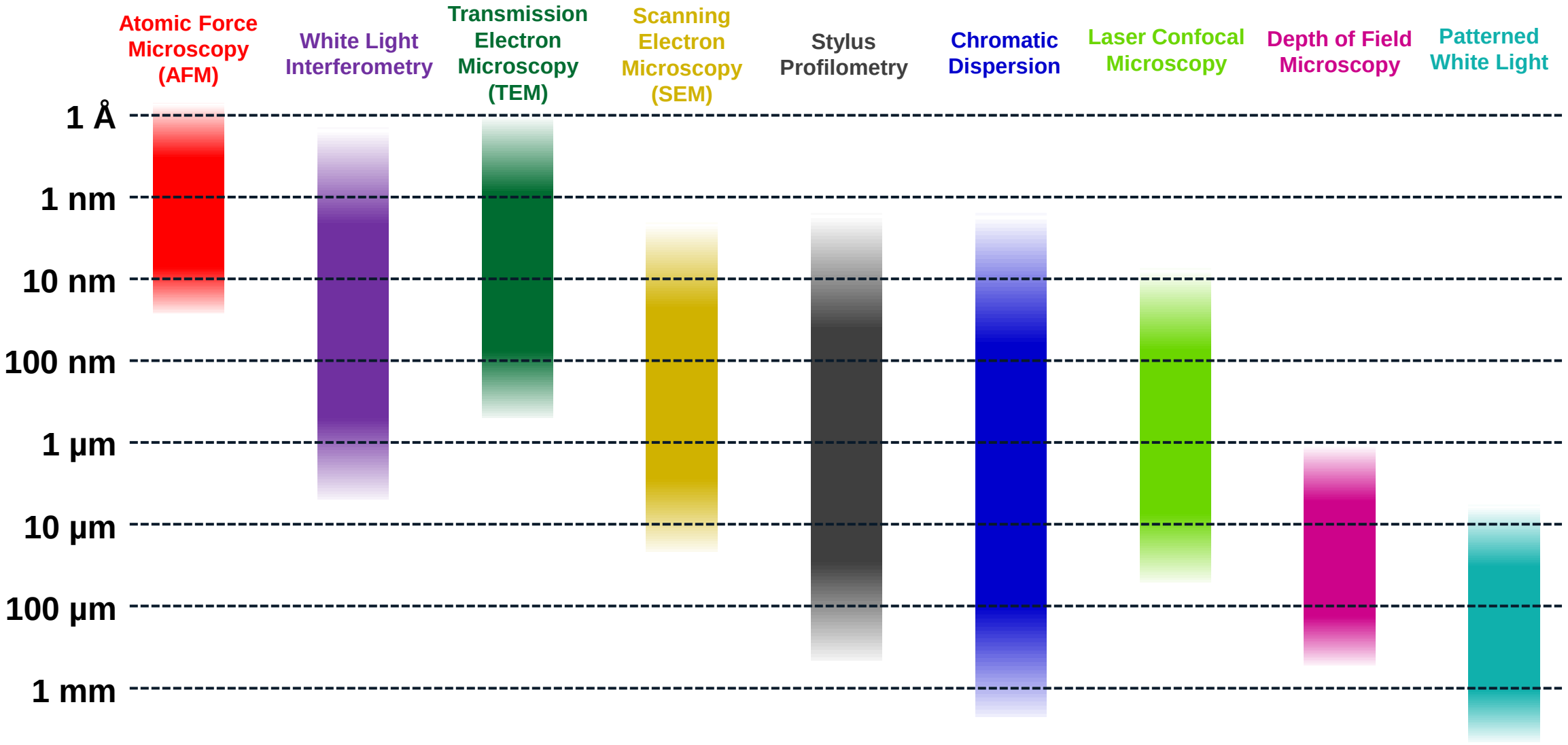
- Can damage soft samples
- Line scan (1D)

How Do You Choose a Technique?

- **Two Primary Considerations:**
  - ***(1) What scale is my surface roughness*** (the one most people think of)
    - Very smooth (Si wafer) sub nm roughness
    - Very rough forged or cut metal
    - Somewhere in between
  - ***(2) Over what area do I need a measurement*** (the one most people do not think of)
    - Few microns
    - Few mm
- **And a host of others**
  - ***How easy to damage the material?***
  - ***Is it sensitive to air?***
  - ***Flat or curved surface?***
  - ***How big is the sample?***
  - ***Is the sample conductive?***
  - ***Is the sample transparent?***
  - ***Are you looking for quantitative or qualitative results?***
  - ***Can the sample surface be touched?*** (subsequent use of sample)

Roughness Scale (Vertical Range)

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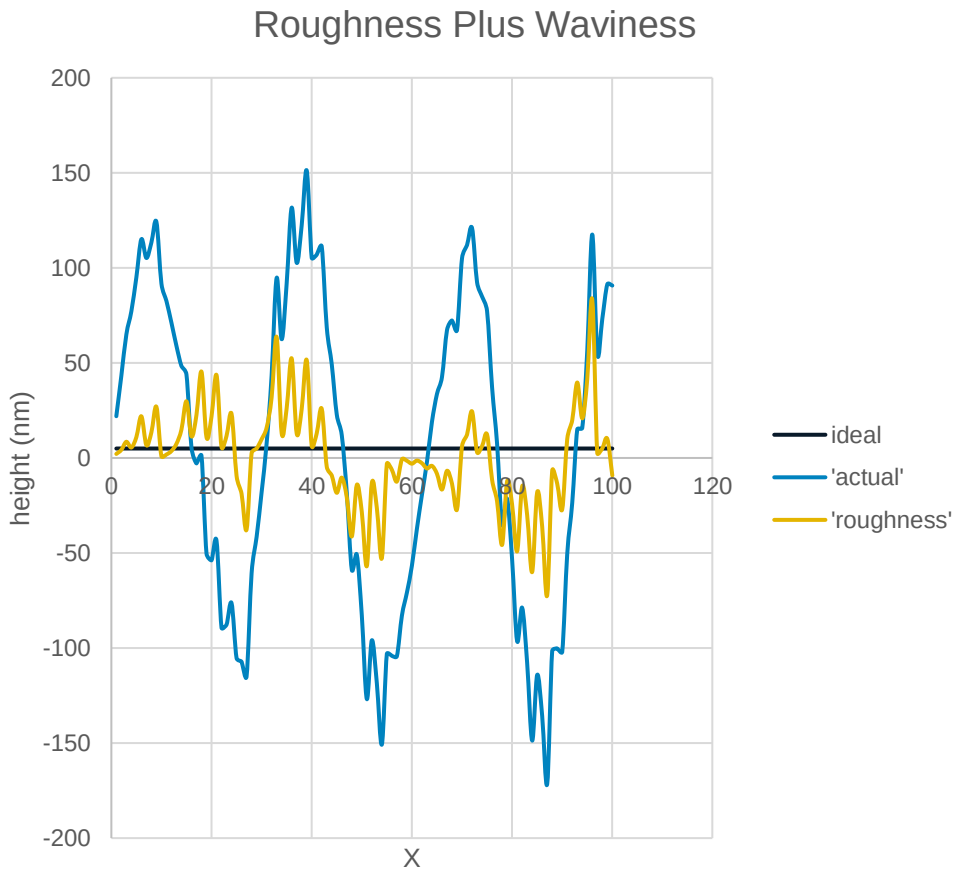


Roughness (In the eye of the beholder)

This sample's basic form is sinusoidal

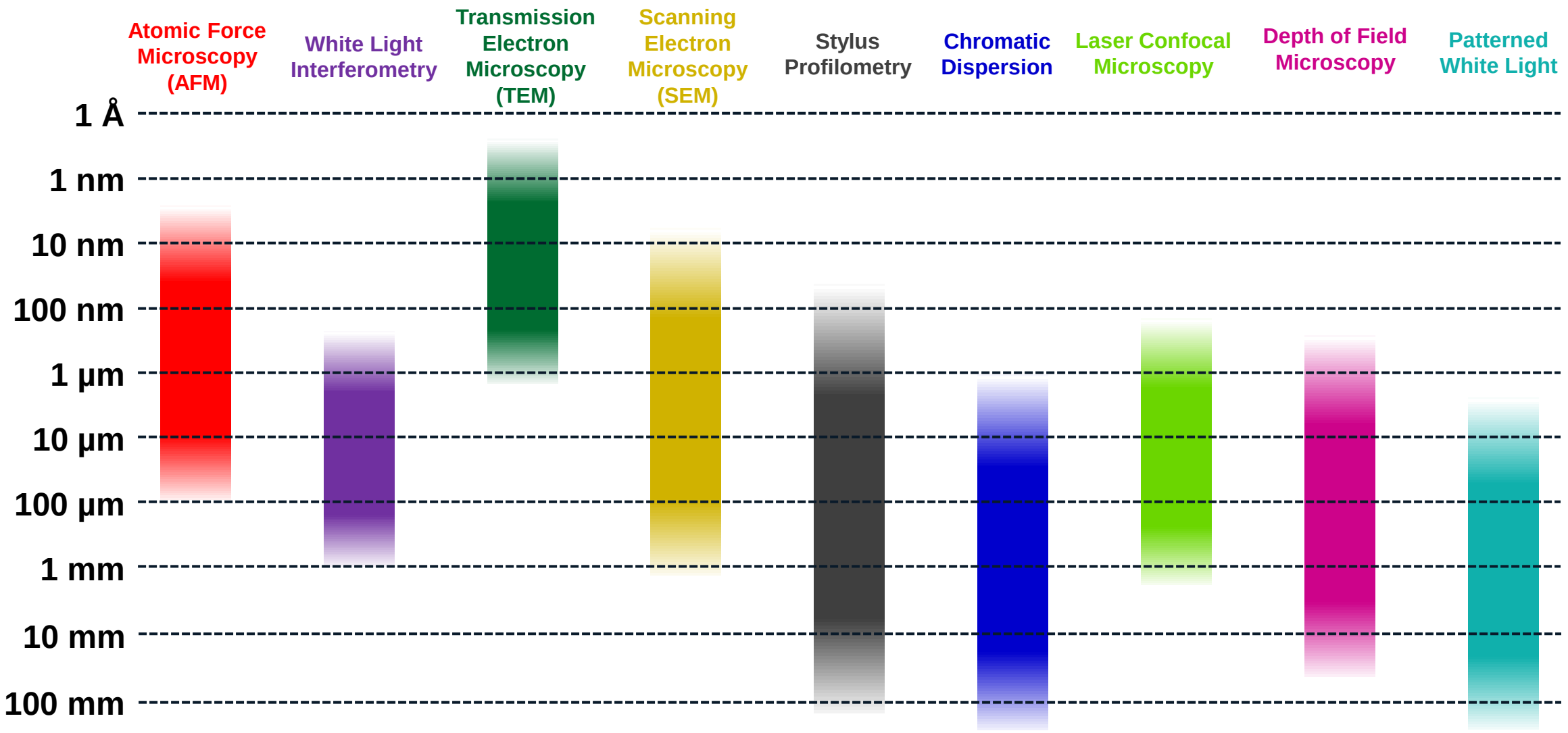


This sample is supposed to be flat



Roughness Scale (Horizontal Range)

COVALENT METROLOGY

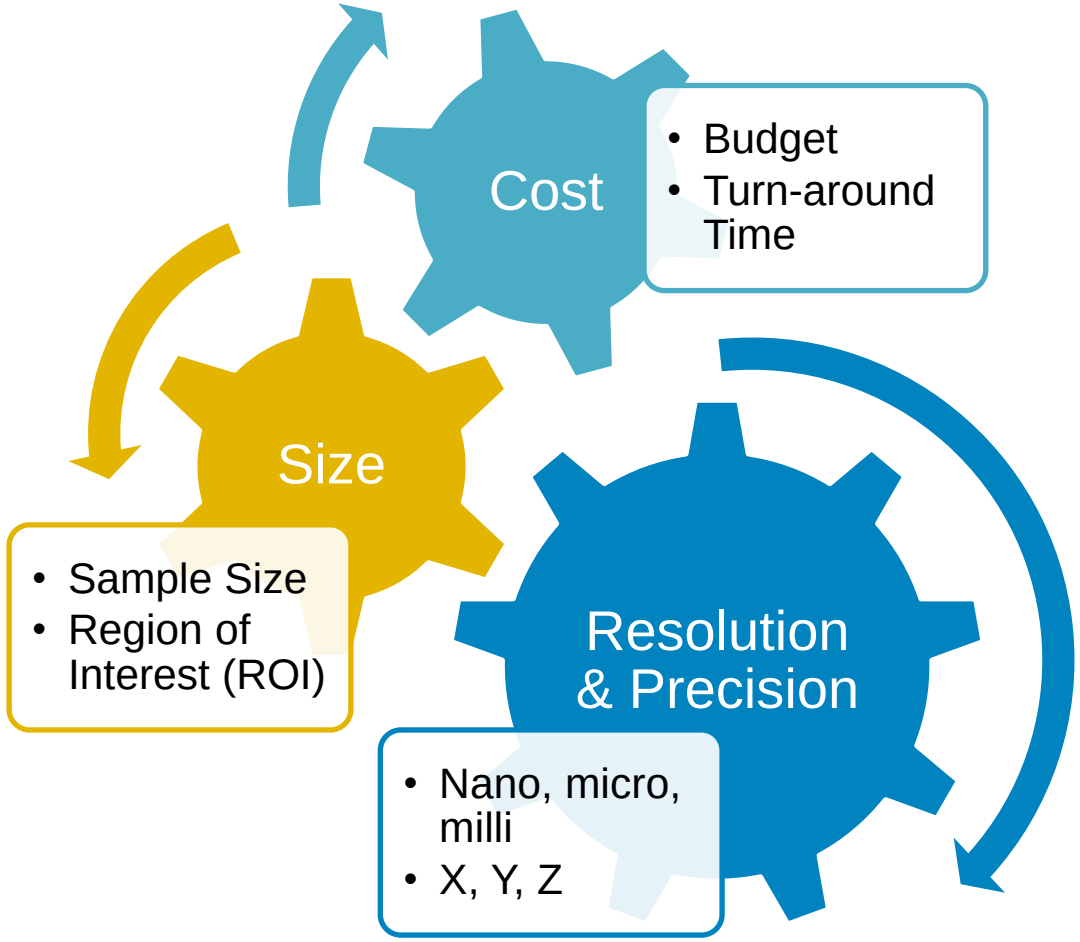


How Do I Choose?

- Scale and vertical precision often determine technology
- Sample size and area to be sampled can limit it
- **Cost is very often the dominant factor – Lowest cost to get "good enough" data**

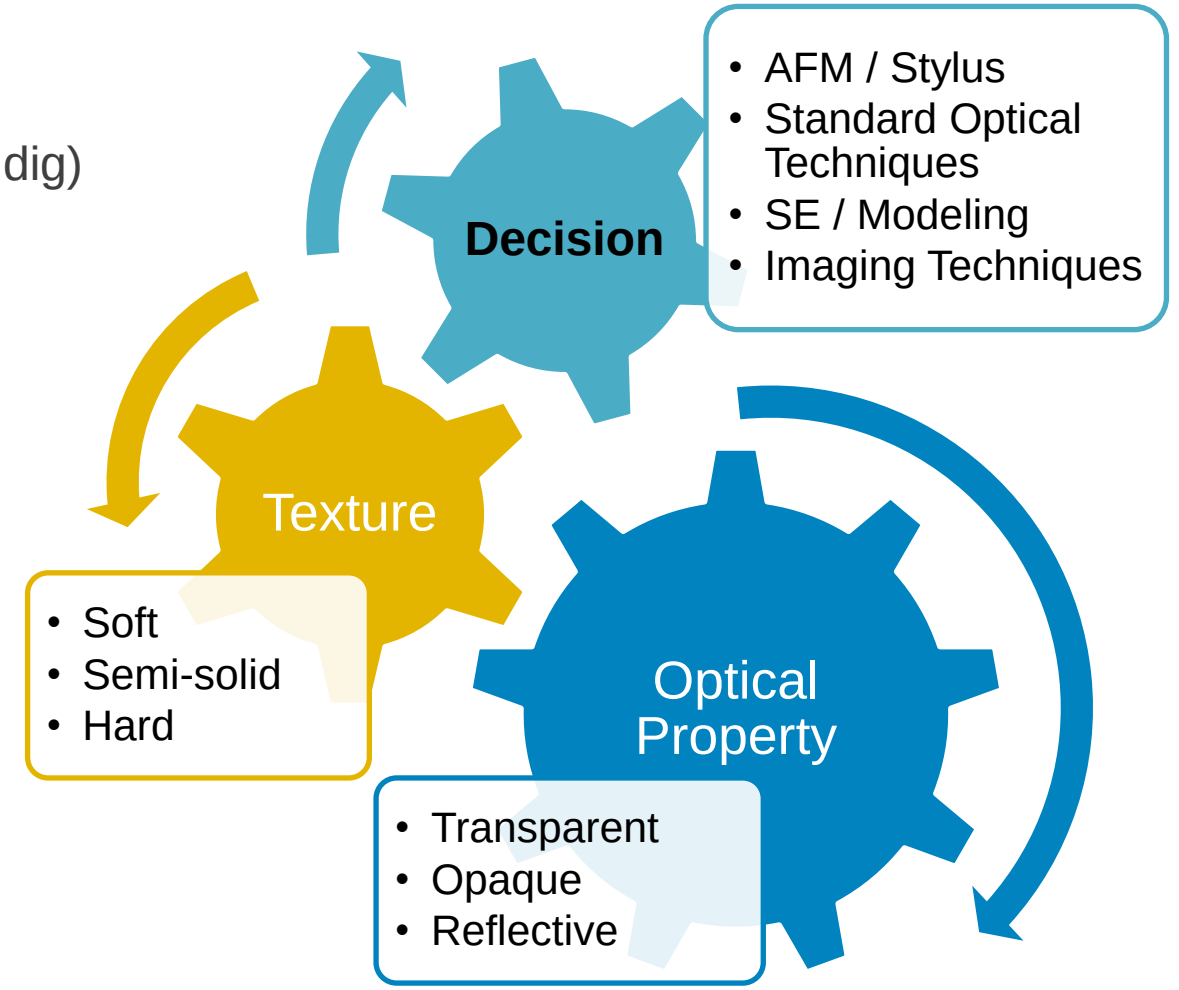
- Imaging techniques couple field of view with resolution
  - Larger the FOV the lower the resolution
  - On some tools can be overcome with stitching but very sample dependent
    - Very smooth (featureless samples) hard to stitch (no discernible features)

- Scanning techniques decouple FOV and resolution



How Do I Choose – Part 2

- Choice now depends on the details of the samples
  - Soft Samples
    - Do poorly with stylus materials (tend to scratch and dig)
      - AFM and stylus not suggested
    - Is it transparent
      - Can be difficult for standard optical techniques
      - May need an indirect approach (SE?)
  - Low Reflectivity Samples
    - Poor choice for most optical techniques except scattering measurements
    - Maybe good for stylus techniques or SEM
- Often a tradeoff between how much area can be sampled and what resolution is needed



Summary

Probe	"Stylus" Techniques		Optical				Electron Beam	
Technique	Atomic Force Microscopy	Stylus Profilometry	White Light Interferometry	Laser Scanning Confocal	Chromatic Confocal	3D White Light	Scanning Electron Microscopy	Transmission Electron Microscopy
You May Hear This Referred to As:	AFM or SPM	"Dektak"	Optical Profilometry	"Keyence"	"FRT"	“VR”	SEM or HRSEM	TEM
Key Manufacturers	Bruker	Bruker	Zygo	**Keyence**	FRT	**Keyence**	**ThermoFisher**	**ThermoFisher**
	Park Scientific	KLA	Bruker	Zeiss	Nanovea		JEOL	JEOL
	Asylum Research		PolyTec	Leica			Zeiss	Hitachi
	Anton Paar			Olympus			Hitachi	
	Molecular Vista			Nikon			Tescan	
	Many others						Nikon	
Substrate Size Limitations	200mm max to reach edges; 300m in center	Up to 300mm (Covalent @ 200mm)	Flexible, with fixtures	Flexible, with fixtures	Up to 300mm (Covalent @ 200mm)	Flexible, with fixtures	Most analytical services <200mm	Coupons
Field of View - Min to Max	200nm to 70µm	Not Applicable	160µm to 800µm	100µm to 1mm	Few um to 200mm	4mm to 24mm	1µm to 2mm	2nm to 10µm
Vertical Resolution	Å	nm	Å	nm	nm	Generally 3-5µm	nm	Å
Particular challenges	Sample should be smooth	No mapping	Reflectivity, +/- vertical ambiguity	Reflectivity, Steep Slopes	Steep Slopes	Resolution, shadowing, reflectivity	Non-conductive samples charging	Very small field of view
Cost @ Covalent	$175 / scan	$225 / hr	$275 / hr	$300 / hr	$300 / hr	$275 / hr	$275 / hr (standard res) $375 / hr (hi-res)	$900 / sample (standard sample)

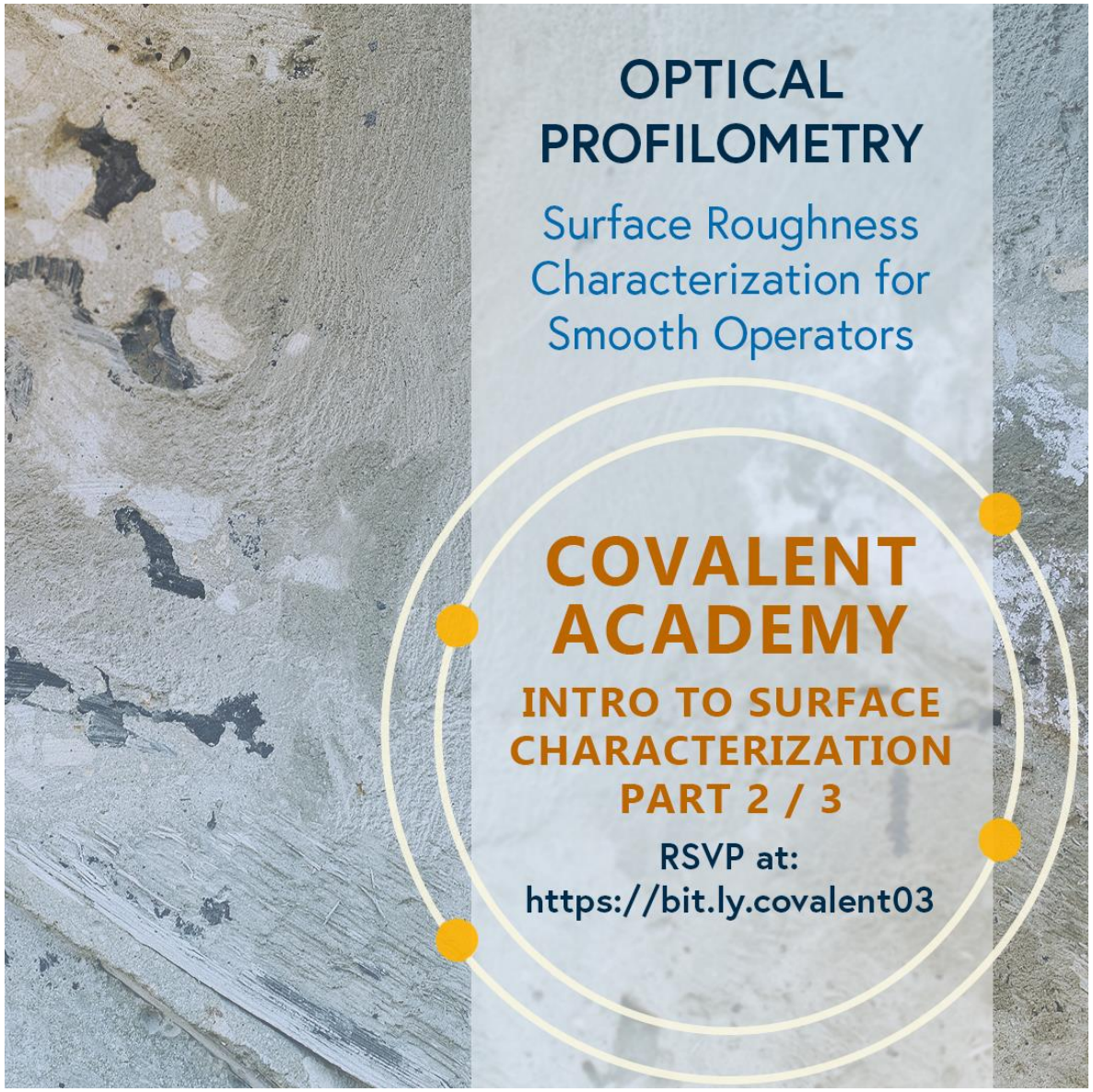
Acknowledgements

I would like to thank the following for their contributions to this talk

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Covalent Metrology	Doris Chun	Doris@covalentmetrology.com

Coming Episodes

- **Changing time to Thursday at 11am PDT**
- **Episode 3 (Part 2 of 3)**
  - Optical Profilometry – Surface Roughness Characterization for Smooth Operators
- **Episode 4 (Part 3 of 3)**
  - Stylus methods for measuring surface roughness



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