Metrology in Nanotechnology

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Oct. 18, 2016

Introduction

- We are now in a very exciting period of time when many new and disruptive technologies emerge across a wide range of industries.
- The new products with emerging technologies are generally smaller, lighter, stronger, more reliable and cheaper, which require better process control, and more up stream in the manufacturing processes.
- This trend brings not only good opportunities, but also new challenges to integrate various metrology tools into the advanced manufacturing processes.
- In this talk, I will review and compare several metrology tools that Bruker provides, and their applications in nanotechnology. I will also discuss about some of the challenges in integrating the tools into the manufacturing process.

Acknowledgements

- This presentation includes data and materials from various technical, application and sales presentations, which were contributed by many colleagues worldwide at Bruker.
- Some materials are from Bruker’s customers, who have gracefully shared their experiences with our equipment and agreed to help us demonstrate our equipment capabilities.
- The presenter would like to sincerely thank all people who have contributed to the materials included in this presentation.

Outline

- **Technology review**
- **Examples of imaging metrology applications**
  - *Wafer level package*
  - *Flexible films*
  - *MEMS*
- **Summary**

Bruker Nano Surfaces Division
Leading Metrology Technologies

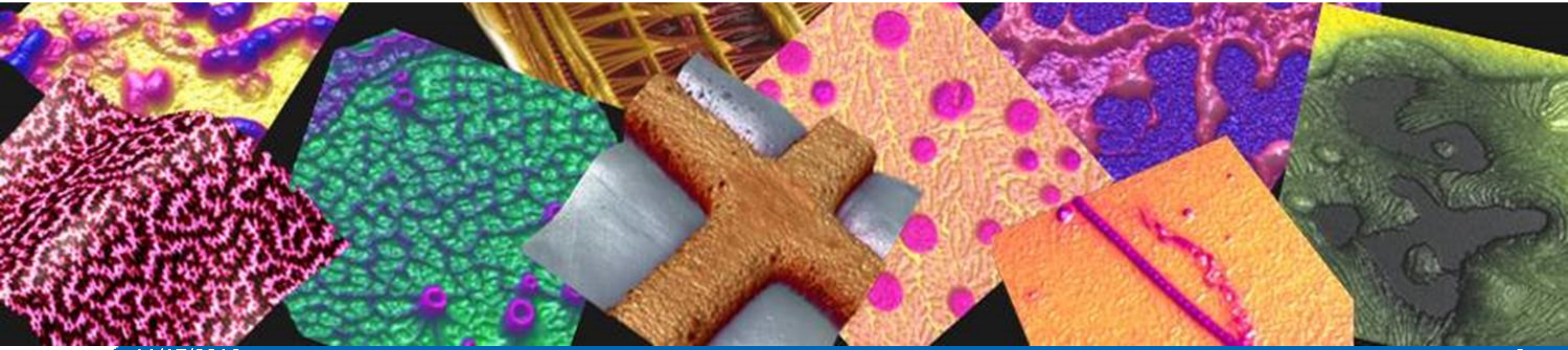
- **AFM, Scanning Probe Microscopy**

- **Optical Profilometry**

- **Stylus Profilometry**

Atomic Force Microscopes

- High resolution 3D surface imaging by rastering a nm size probe across surface
- Can also measure electrical, magnetic, mechanical, thermal & some chemical properties
- Primary application areas:
  - (Nano)materials Research
  - Biology/Life science Research
  - Semiconductor/Data Storage



Atomic Force Microscopy
Application-Optimized Models

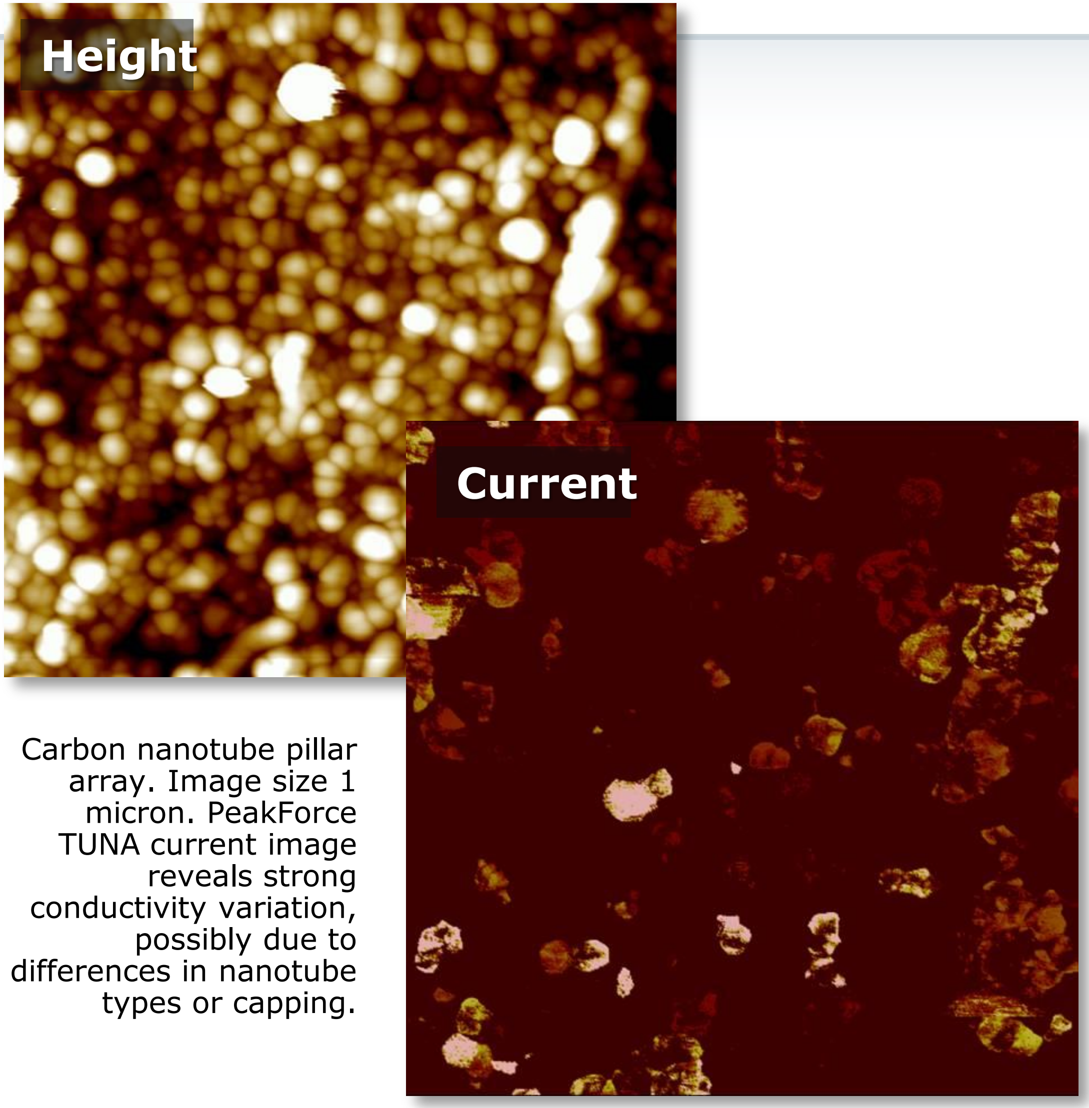
Entry-level Research

24/7 industrial

Life Science

High-End Research &
High Throughput

AFM
Vertical Carbon Nanotubes

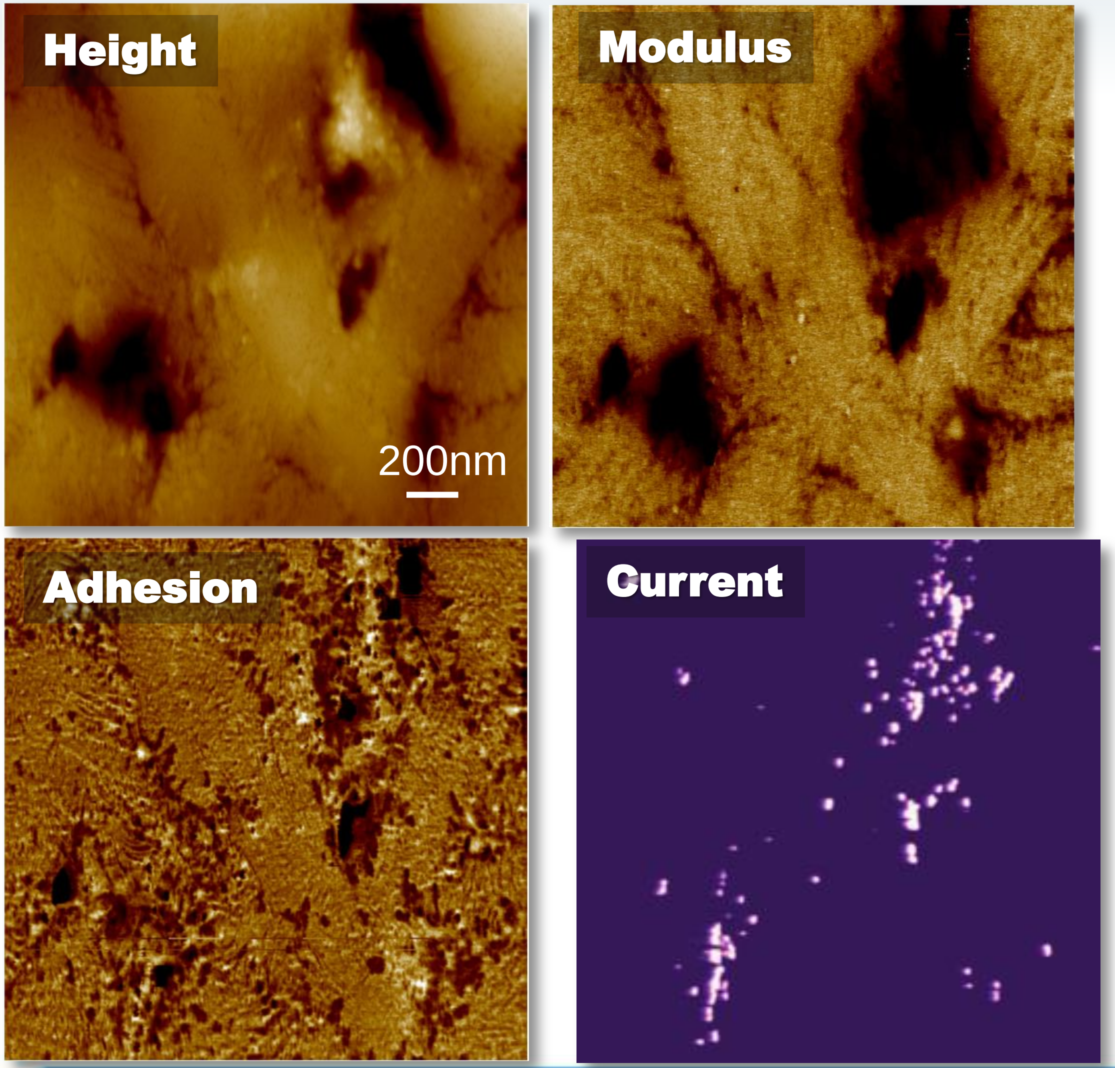


Carbon nanotube pillar array. Image size 1 micron. PeakForce TUNA current image reveals strong conductivity variation, possibly due to differences in nanotube types or capping.

Electrical investigation on previously impossible samples

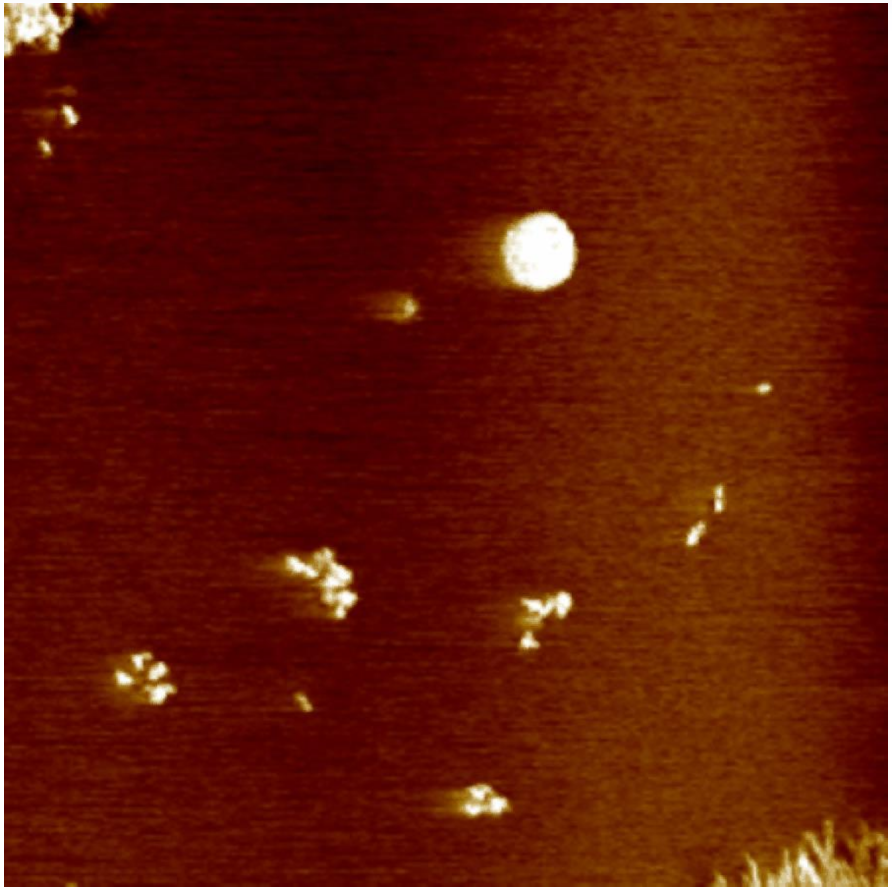
Electrical conductivity

Material Property Maps



Get quantitative and high resolution on modulus, adhesion, and conductivity.

Explore Real-Time Changes as Polymer Crystallizing

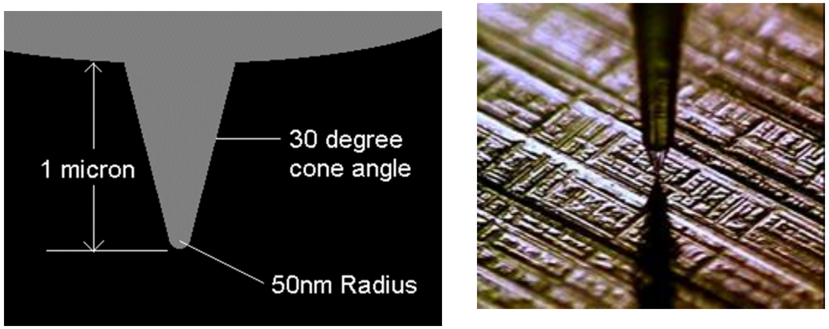


2.2 micron images, 100Hz, 256 x 256 pixels. Sample Courtesy: Dr. Jamie Hobbs University of Sheffield

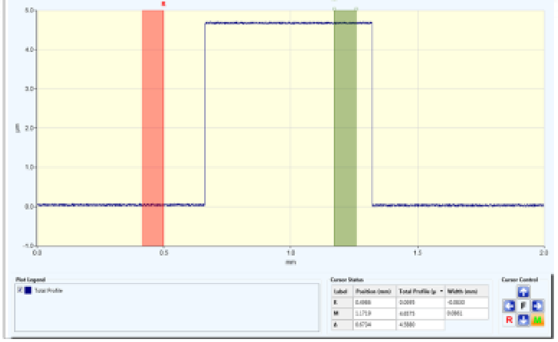
High speed AFM studies of PHBV crystallization show lamella spurting forward substantially faster than the macroscopic growth rate, then slowing or stopping. Growth is then controlled by the rate of lamella nucleation on dormant lamella, rather than by the growth rate of individual lamella (see Hobbs, Bruker).

Dektak Stylus Profilers

- Measures surface profile by moving stylus across sample.
- Low cost, easy to use.
- Primary applications:
  - Roughness
  - Step Height



50nm radius, FIB-etched diamond tips



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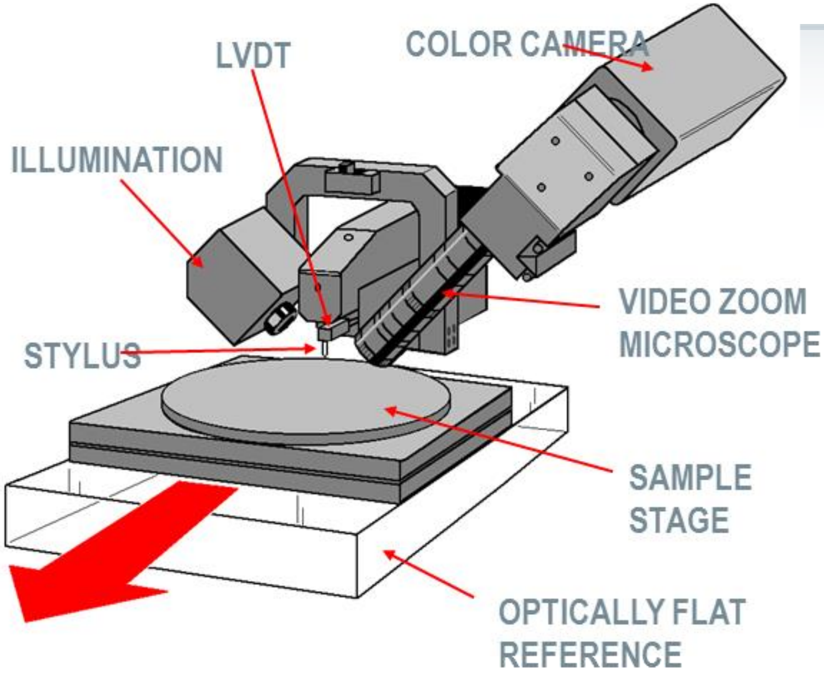
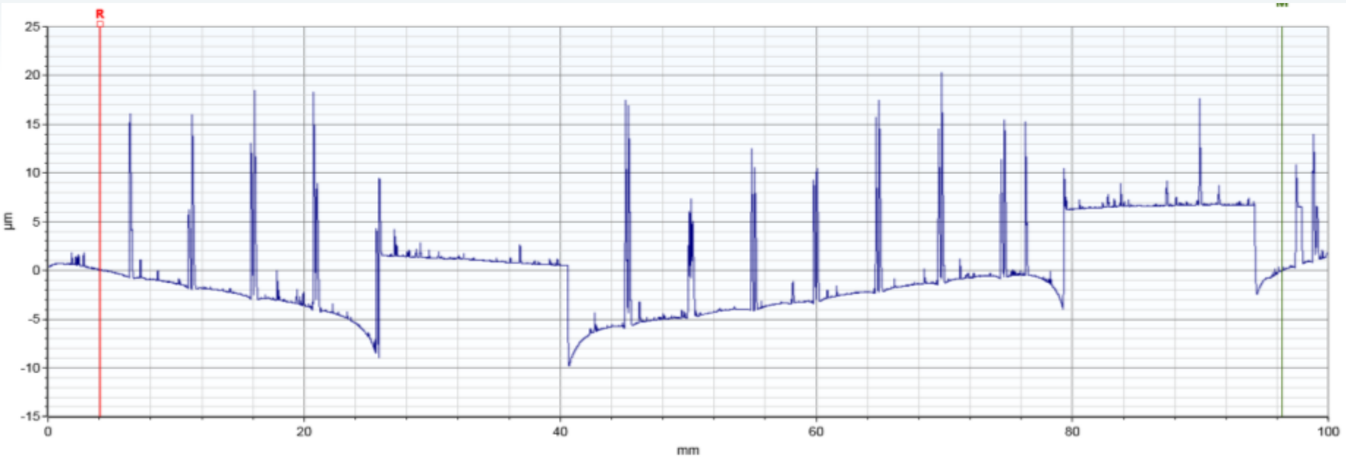
Stylus Profiler Capabilities

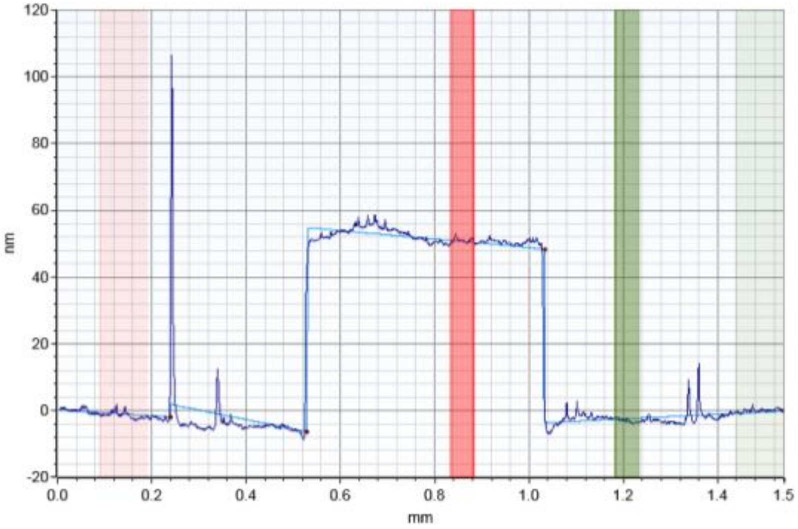
- **Large Part Ranges**
  - Wafers >200 mm
  - Parts up to 100mm tall
  - Sample thickness up to 50mm
  - Vertical scan range to 1mm
- **Low stylus force**
  - **Down to** 0.03mg
- **Step height repeatability**
  - **5** Å
- **Full XY automation for 3D Mapping**
- **Reference optical flat for best results in film stress measurement**



Stylus Profiler Capability Illustrations

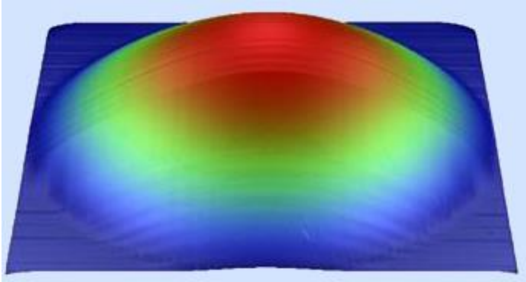


Full 4" wafer profile

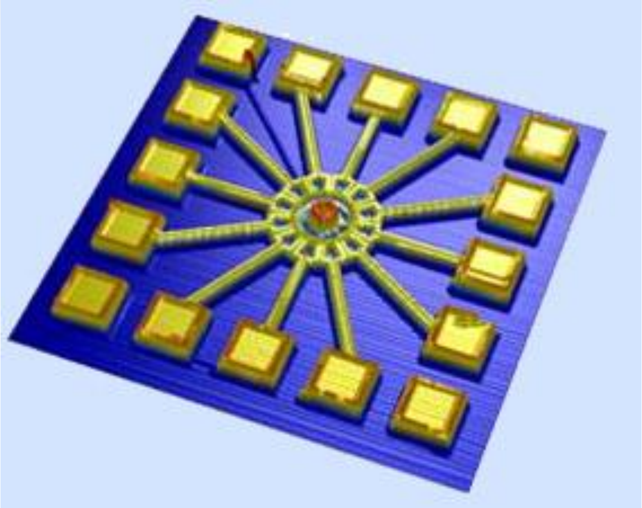


Same head covers step from ***1nm to 1mm*** with force range from ***0.03mg to 15mg***.

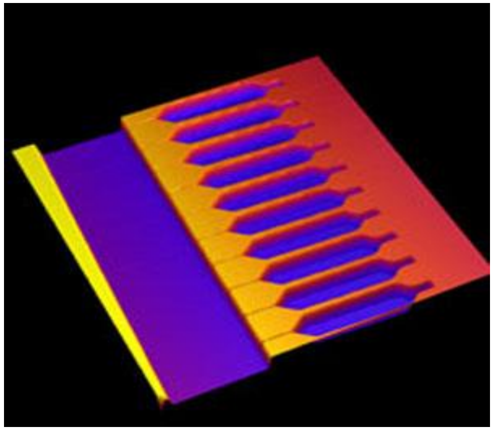
Stylus Profiler
3D Mapping Examples



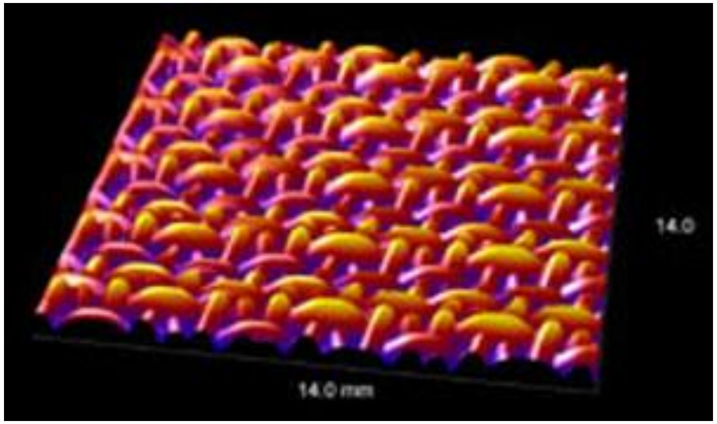
Optics



MEMS



Ink Jet Nozzles



Polyester Weave

Optical Interfometry Profilers

- 3D microscope for surface profiling based on White Light Interferometry (WLI)
- Non-contact, non-destructive
- Fast, accurate, and repeatable
- Sub-nanometer vertical resolution
- Image large areas at once

- Key application areas:
  - Automotive/Aerospace
  - Data Storage
  - Solar
  - MEMS
  - Semiconductor
  - LED, Optics
  - Medical
  - Precision Machining/Tribology

3D Optical Profilers

Table top to high end automation

ContourGT-I
Table top
automated

ContourGT-K
manual

ContourGT-X
Advanced automation
with wafer loader capability

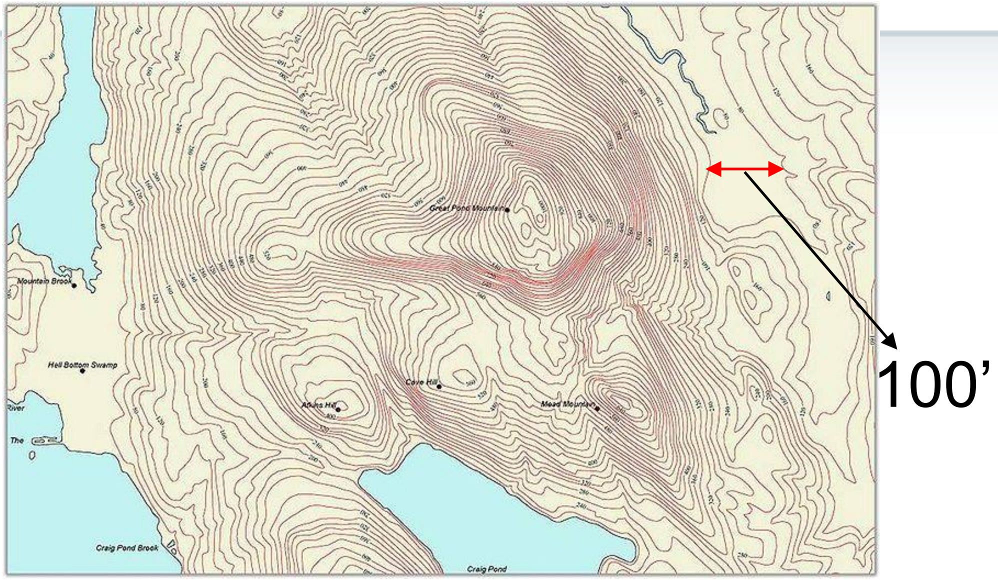
Dual 300mm FOUP
ContourGT-X ARM
Configuration

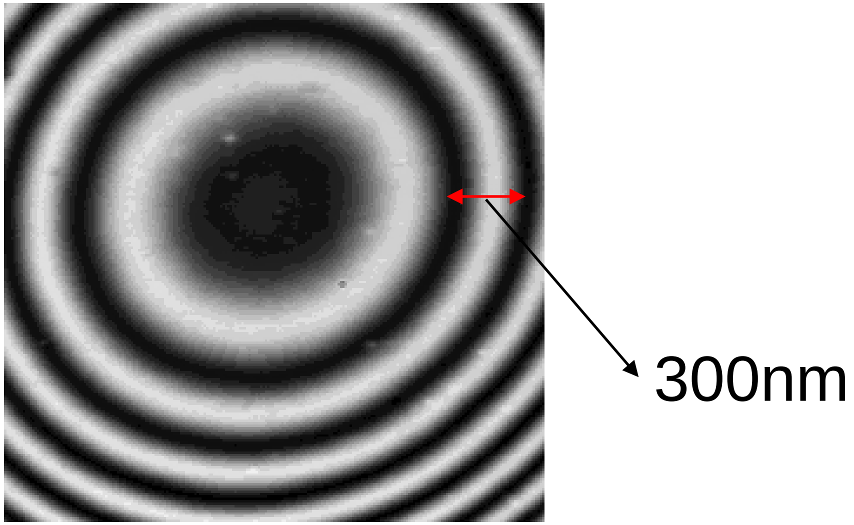
SP – flat panel ,
large substrate
and PCB

Interference fridges are similar to contour map lines

- On a contour map each line represents a fixed elevation.
- Typically the spacing is 100 feet
- Set by the mapmaker

- On an interferogram each line also represents a fixed height
- Spacing is 1/2 the wavelength of the light (typically 300nm in current instrument)
- Set by optics





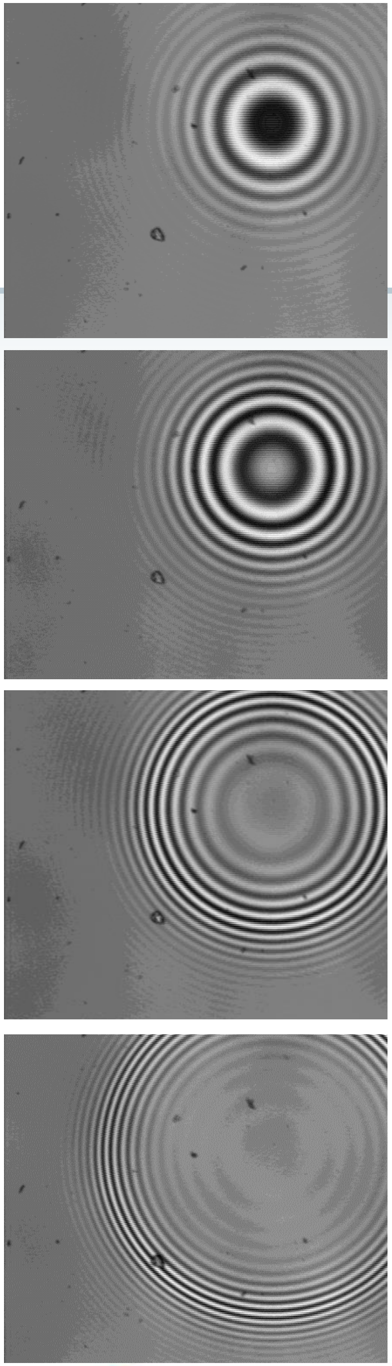
3D Optical Interferometry

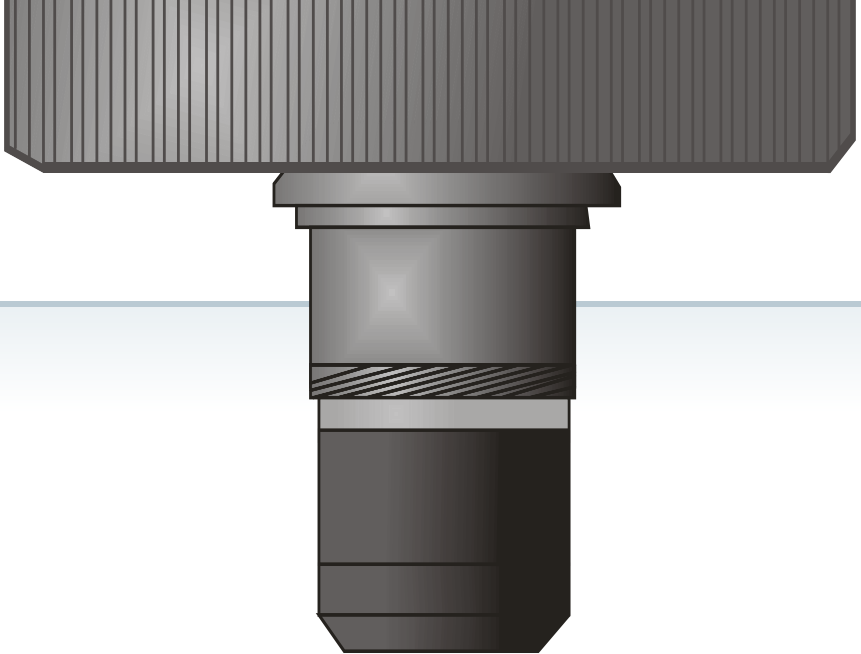
White Light Interferometry – WLI

- VSI – white light illumination
- Vertically scan through focus, looks for highest fringe contrast
- Vertical resolution ~3 nm
- Rough surfaces, steep steps
  - Height range: <10mm
  - Slope: <60deg +
- Speed: 5-80um/sec

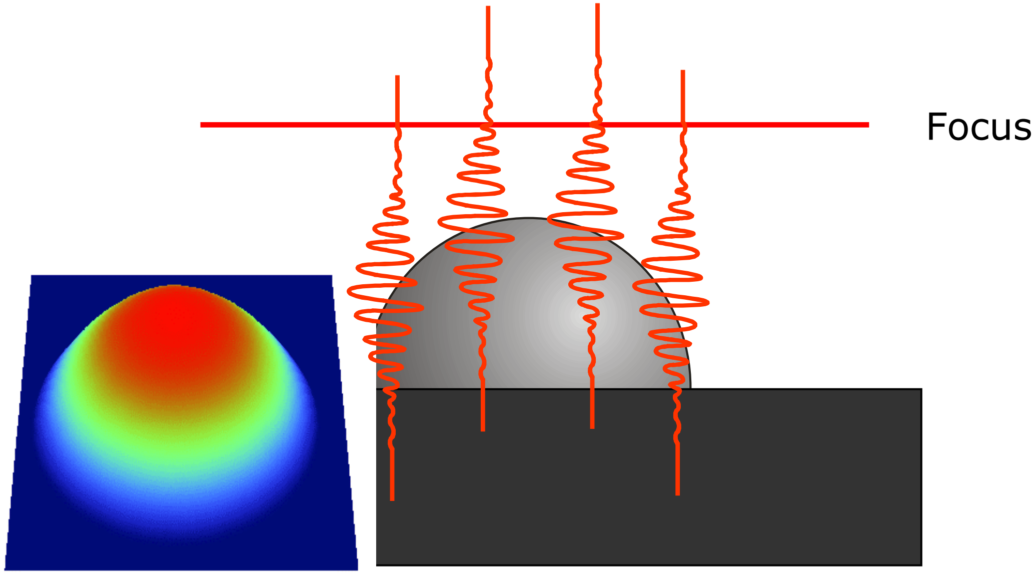
Phase Shifting Interferometry – PSI

- PSI – monochromatic illumination
- Calculates the phase of the fringes
- Vertical resolution <0.1 nm
- Optically smooth surfaces
  - Height range: <140nm
  - Ra: <30nm
- Speed: ~1 sec

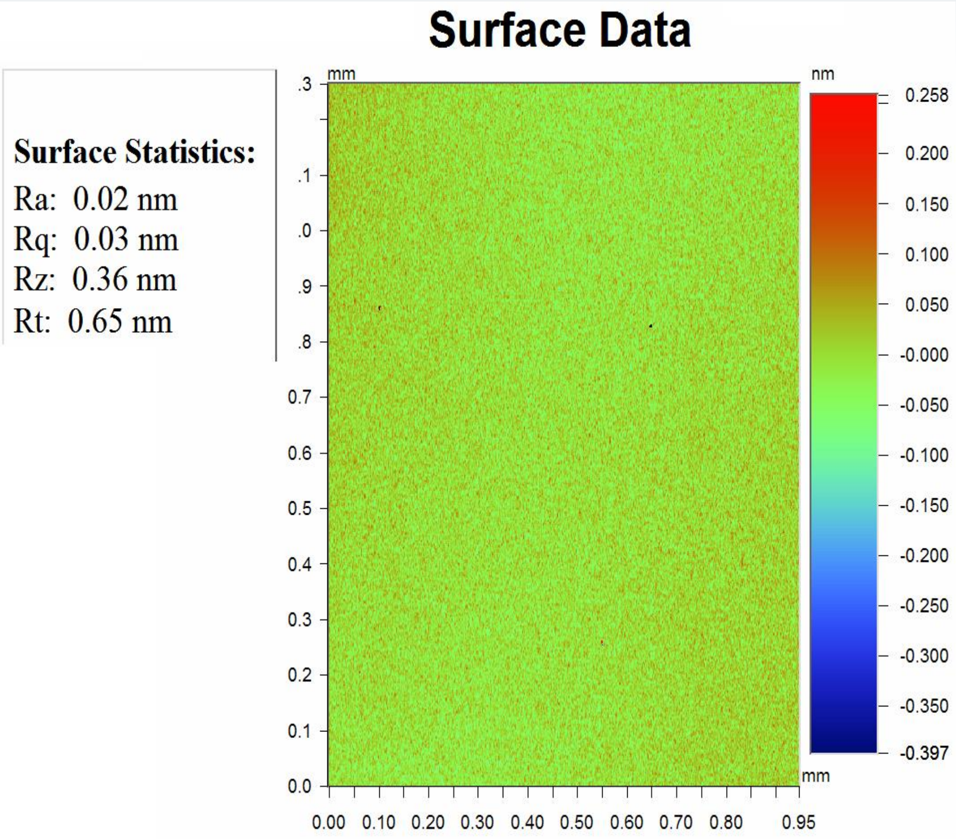




WLI Illustration

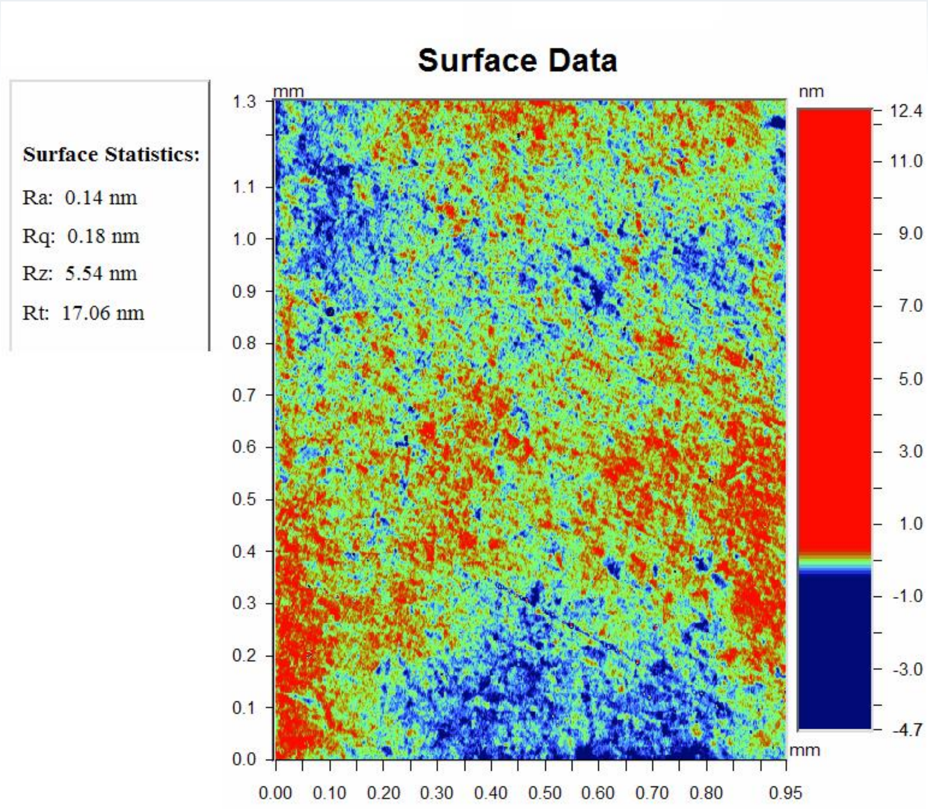


PSI – High Vertical Resolution


Surface Data

Surface Statistics:
Ra: 0.02 nm
Rq: 0.03 nm
Rz: 0.36 nm
Rt: 0.65 nm

- 0.02nm Ra, 0.7nm PV

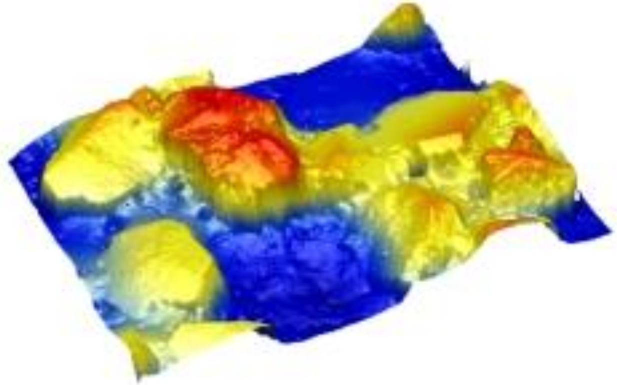

Surface Data

Surface Statistics:
Ra: 0.14 nm
Rq: 0.18 nm
Rz: 5.54 nm
Rt: 17.06 nm

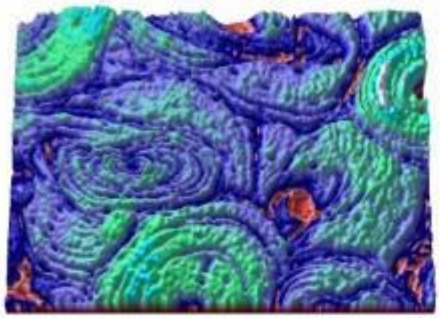
- SiC mirror with 0.14nm Ra
- 0.2nm deep scratches are visible

VSI –Versatile Applications

Metals

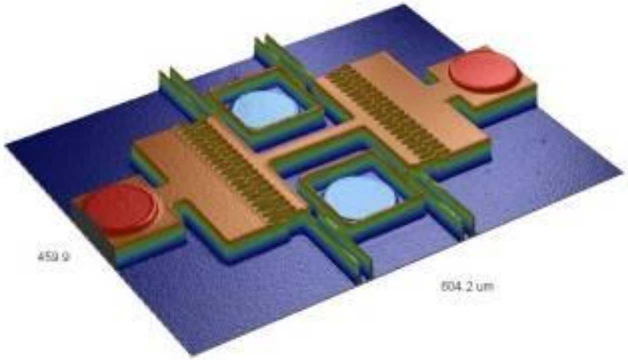


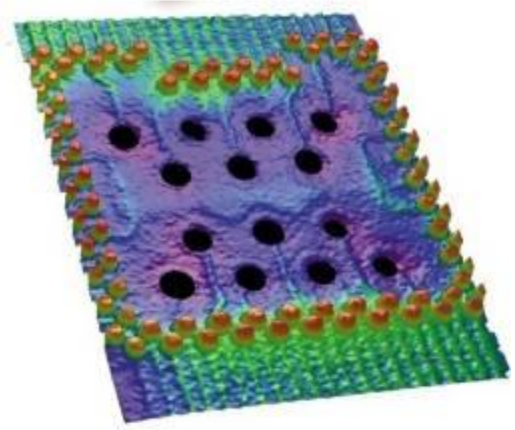
Life Sciences



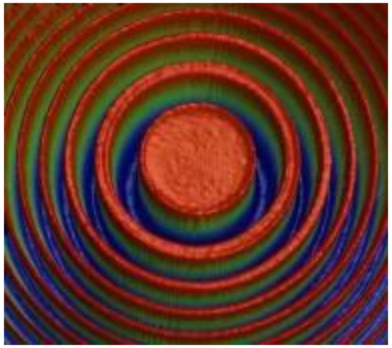
MEMS

(MicroElectroMechanical Systems)

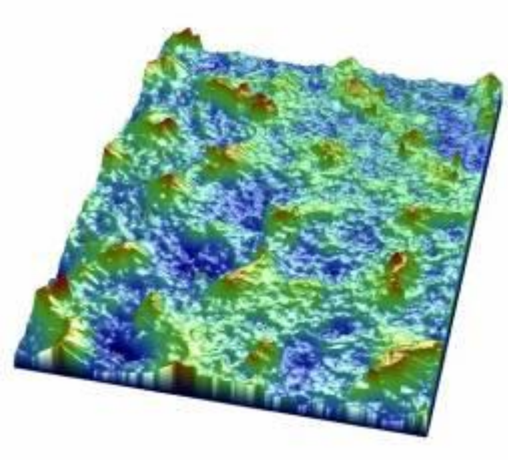




Semiconductors

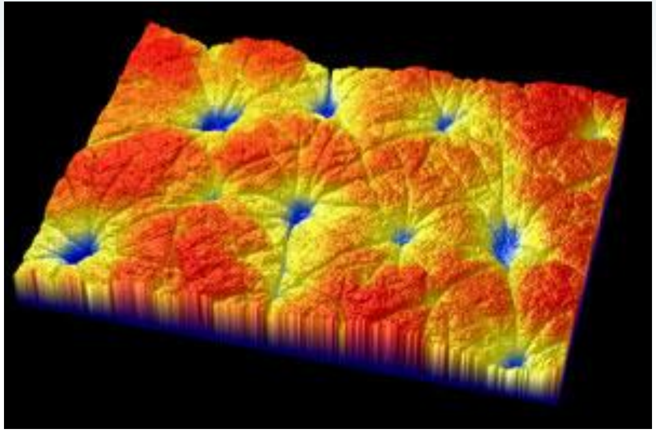


Optics

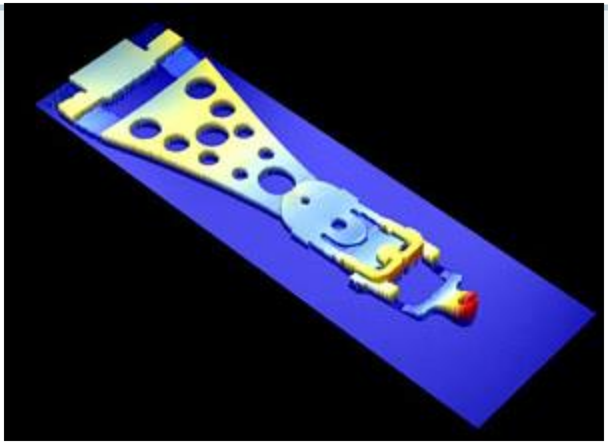


Materials

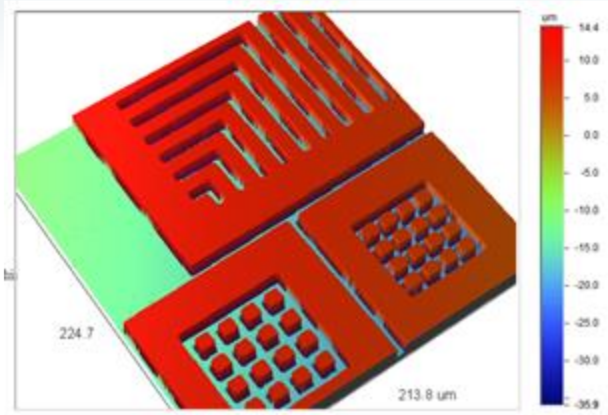
VSI –More Applications



Human Skin

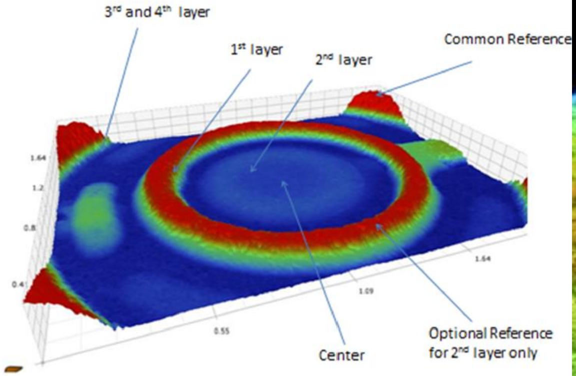


Hard disk suspension arm

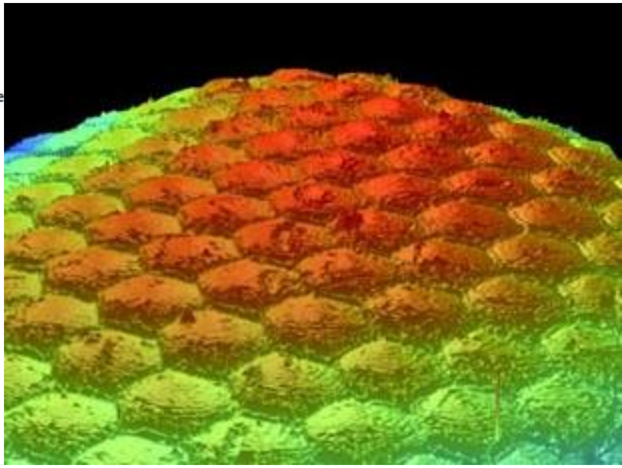


Electronic circuit

Cotton cloth, 1mm x 1mm



Microfluidic



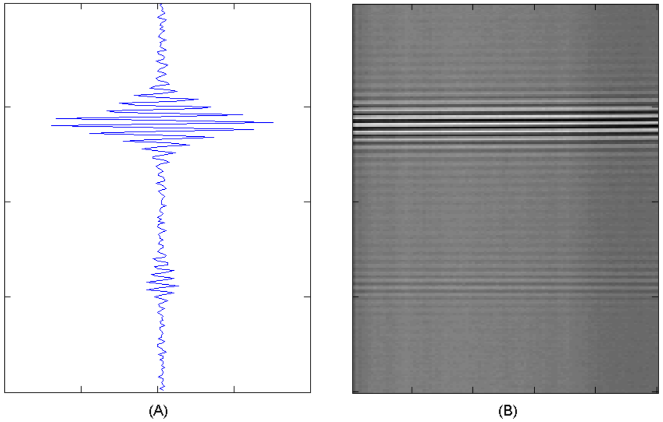
Grasshopper Eye
230um x 300um.

Stitching Enables Large Area Metrology

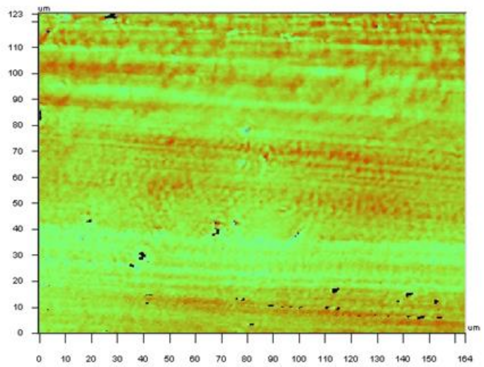
- Stitch up to 2000 fields together for large area imaging with high spatial resolution,
- Fields of view up to many square cm

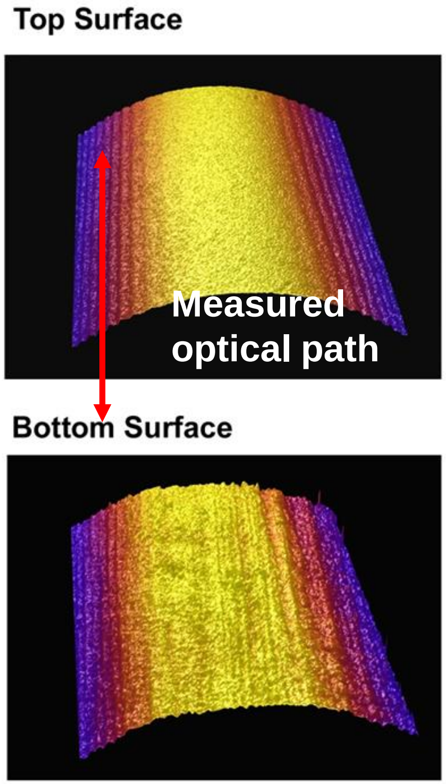
Transparent Film Thickness Measurement

- Interferometer create two sets of fridges at:
  - air/film interface
  - film/substrate interface.
- Position of the peaks, corrected for the film material, gives film thickness
- 400nm to 200 µm films can be characterized.
- Repeatability: 2-6nm
- Film Thickness and Surfaces Simultaneously Characterized



Film Thickness



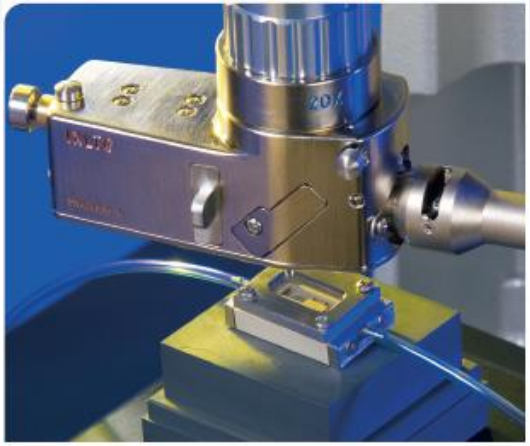


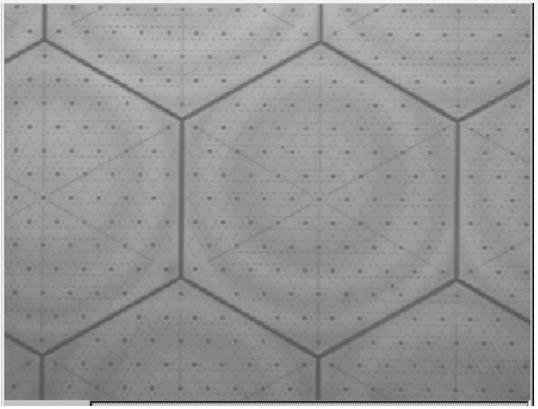
Unlike Stylus, Optical Techniques Do Not Require Steps

Measuring Through Transmissive Media (TTM)

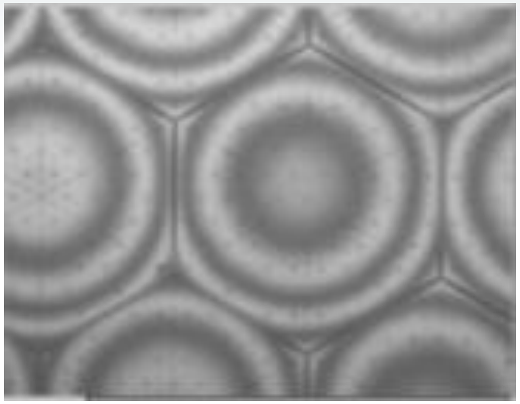
- Manufacturers need to understand how devices perform in their final state, often through packaging
- Environmental testing is also required, typically in test chambers under varying temperature, pressure, etc .
- Challenge: when measuring through transmissive media the optical path length differs between the two arms of interferometer:
  - Decreased fringe contrast
  - Difficult to make accurate measurements
- At low magnification compensation is possible by introducing a slide of similar material and thickness in the reference arm

Custom Objective Enable Measurement Through Glass



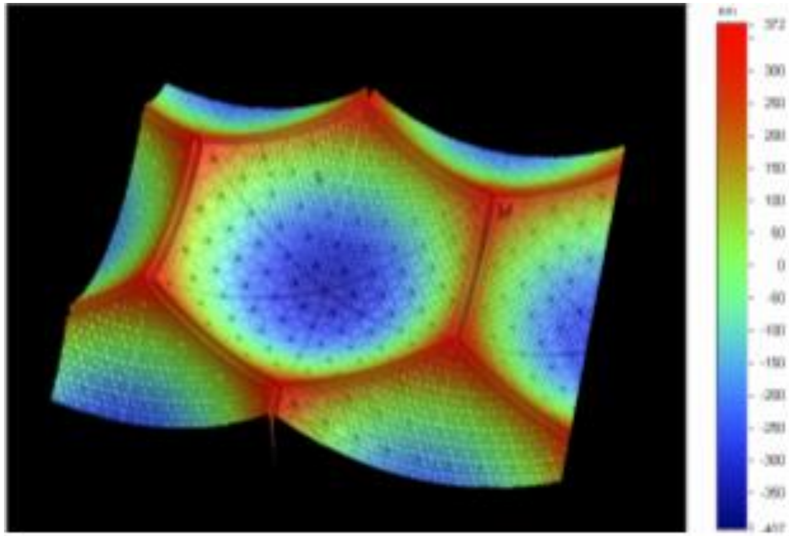


without compensation



with compensation

- Micro-mirror array imaged through the window (170um) of an environmental chamber



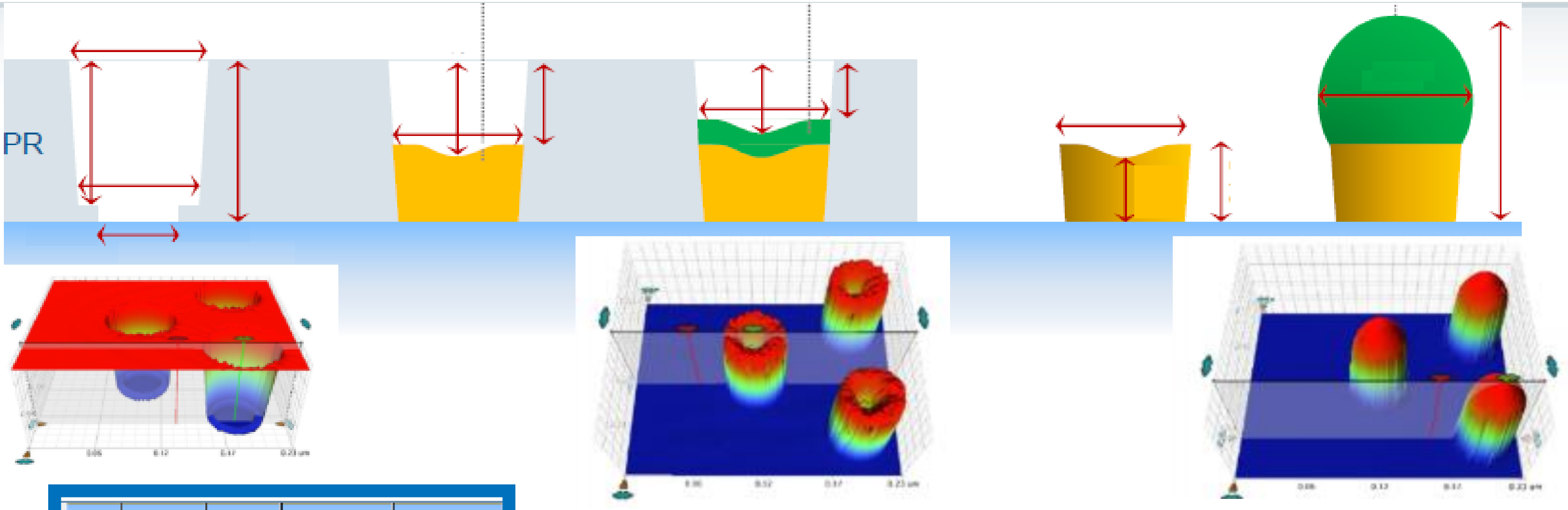
Courtesy Sandia National Laboratories.

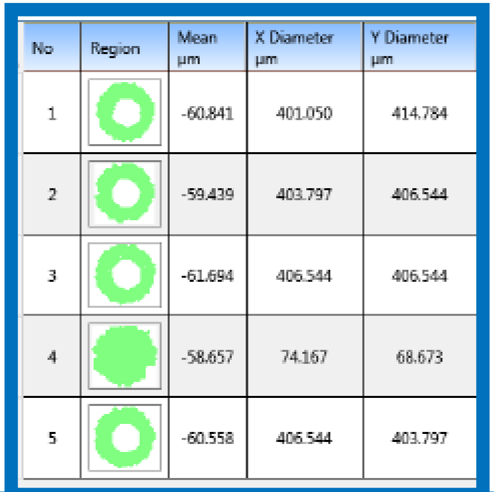
Wafer Level Packaging Process Monitoring

- ***Need to verify proper etch and plate dimensions for Cu traces, pillars in process across wafers***
- ***Fast feedback on process is not easily achieved via SEM (current workhorse)***
- Fast, non-contact solution available from Bruker for…

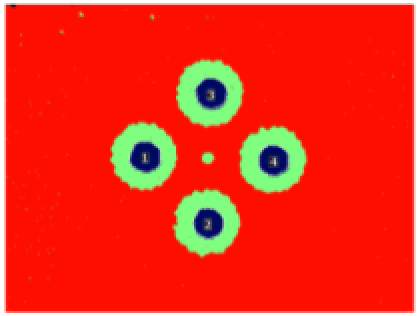
- ***Automated CD inspection of Cu trace widths, heights***
- ***UBM diameters, Cu pillar heights***
- ***Cu Roughness***
- ***Film thicknesses during process***

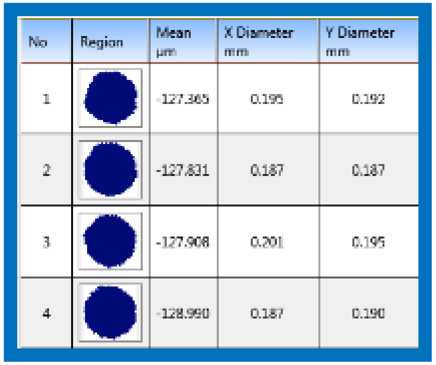
Copper Pillar / Solder Bumps Height / Width and PR (photo resist) Thickness





No	Region	Mean µm	X Diameter µm	Y Diameter µm
1		-60.841	401.050	414.784
2		-59.439	403.797	406.544
3		-61.694	406.544	406.544
4		-58.657	74.167	68.673
5		-60.558	406.544	403.797



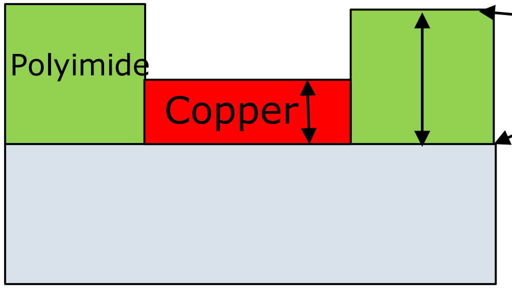


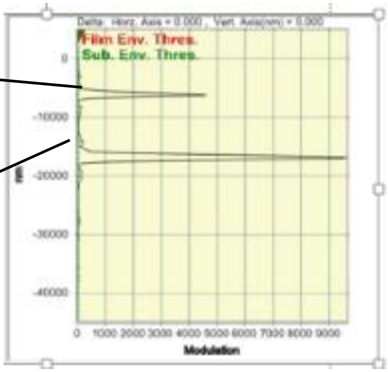
No	Region	Mean µm	X Diameter mm	Y Diameter mm
1		-127.365	0.195	0.192
2		-127.831	0.187	0.187
3		-127.908	0.201	0.195
4		-128.990	0.187	0.190

One measurement, multiple analyses done simultaneously

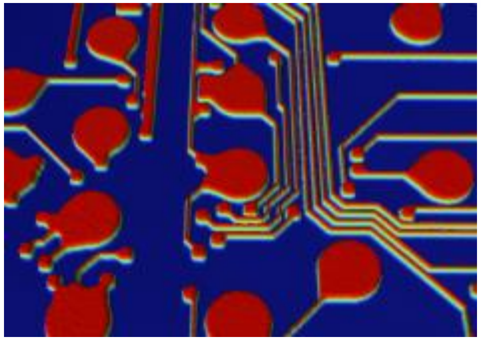
RDL – Redistribution Layer

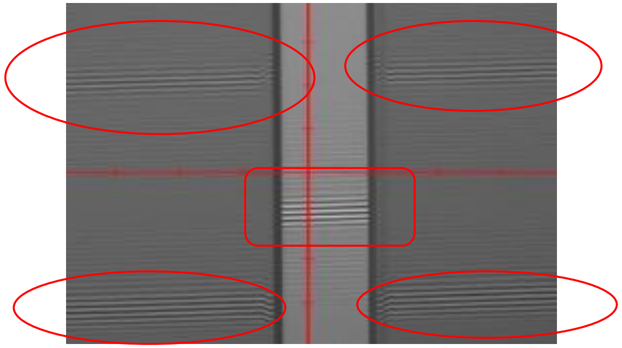
Film Measurement capability separates two signals and measures the thickness without a step height

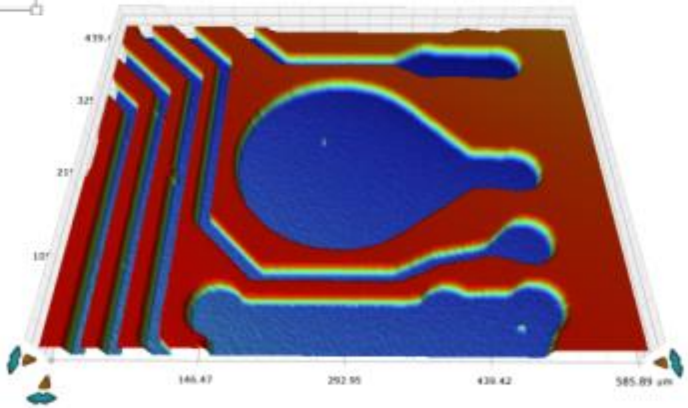




Copper Thickness



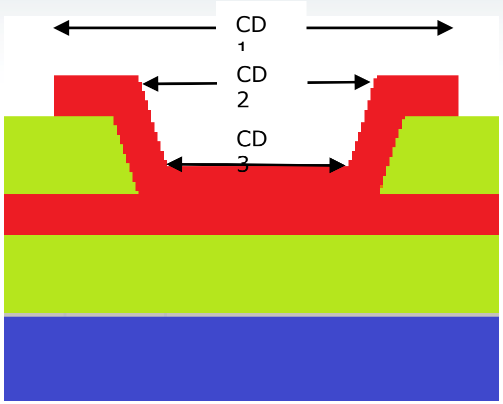


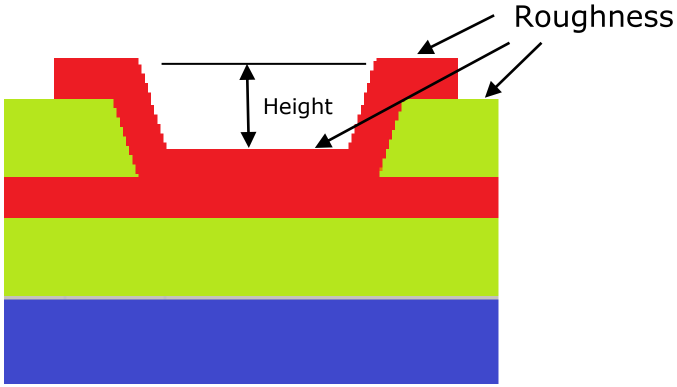


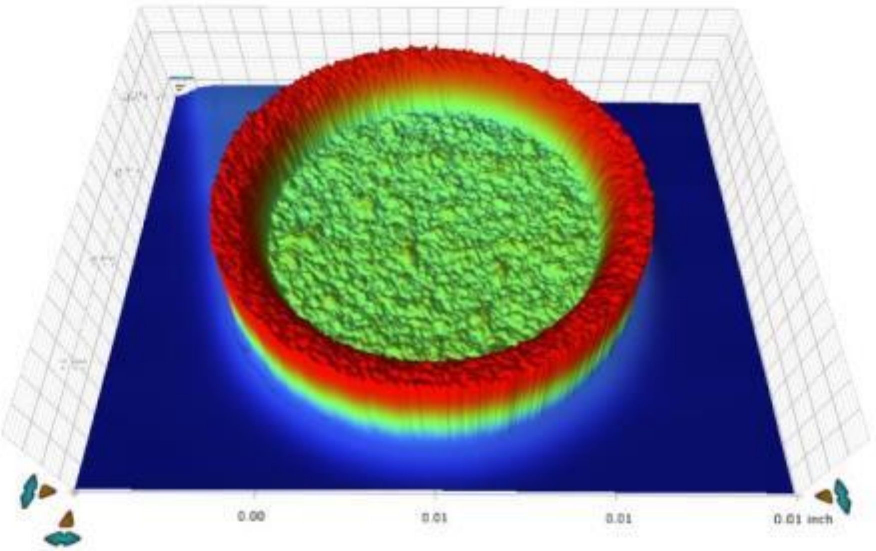
Polyimide Thickness

Both Copper and Film thickness in a single measurement

UBM - Under Bump Metallization

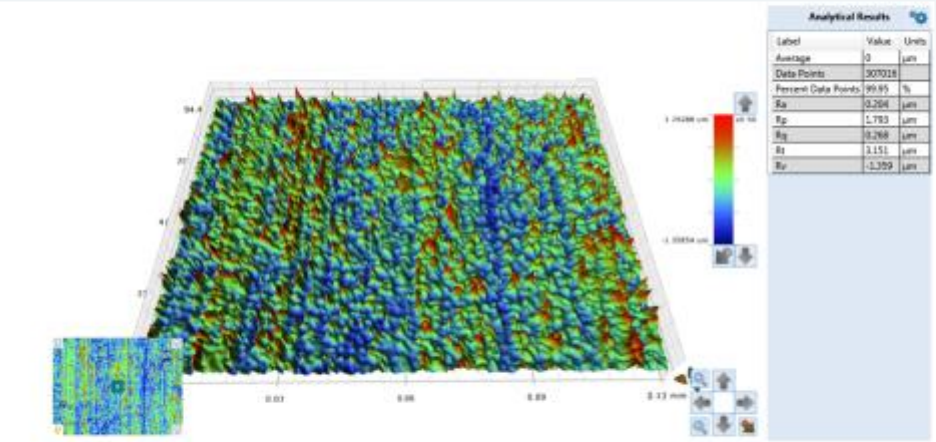






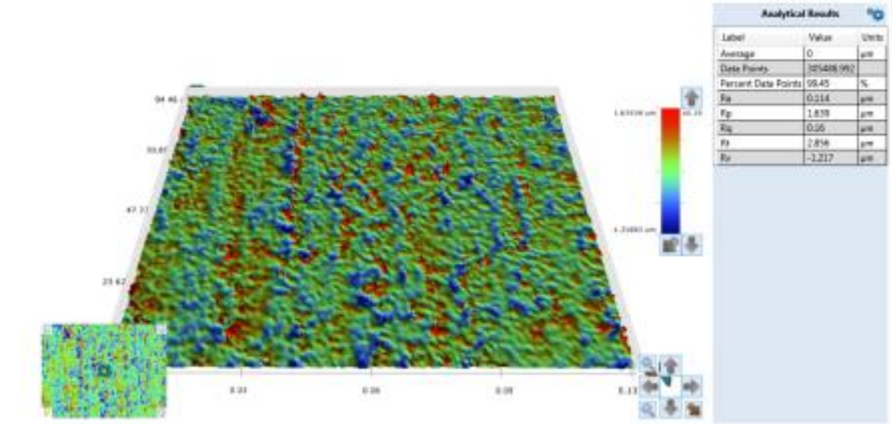
CD/Width, Height and Roughness of UBM in a Single Measurement

Lead Frame Roughness
Before and After Process



Analytical Results

Label	Value	Units
Average	0	µm
Data Points	307018	
Percent Data Points	99.95	%
Ra	0.204	µm
Rp	1.793	µm
Rq	0.268	µm
Rt	3.151	µm
Rv	-1.359	µm

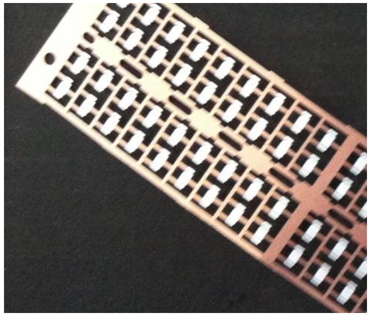


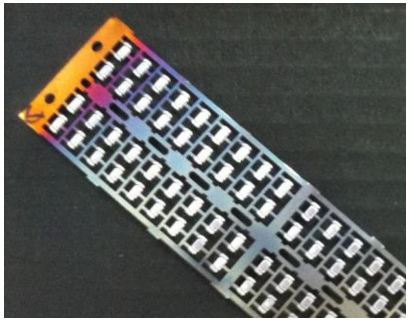
Analytical Results

Label	Value	Units
Average	0	µm
Data Points	305406.992	
Percent Data Points	99.45	%
Ra	0.114	µm
Rp	1.639	µm
Rq	0.16	µm
Rt	2.856	µm
Rv	-1.217	µm

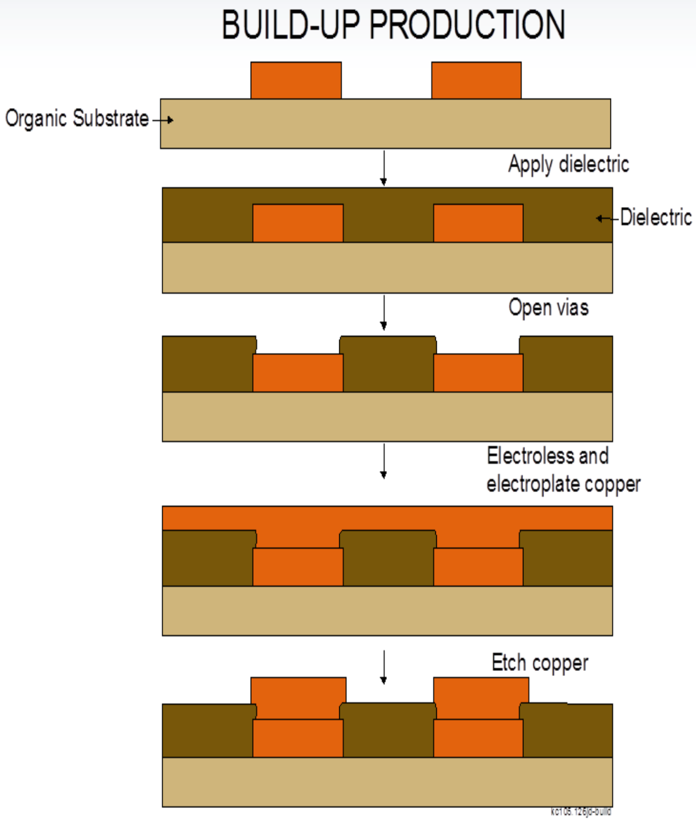
Ra: 204nm

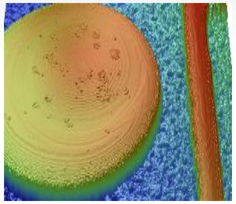
Ra: 114nm



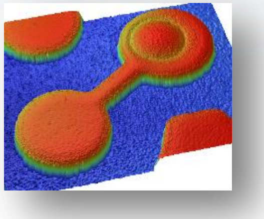


HDI PCB Substrate Metrology

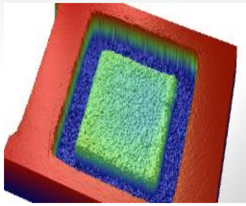




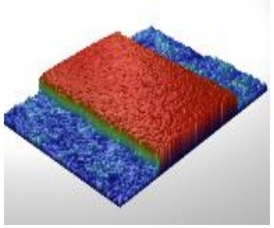
Pad Clearance



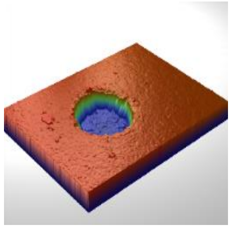
Circle Connect



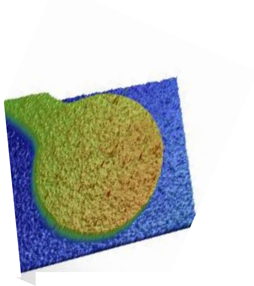
Overlay



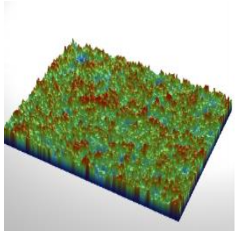
Trace



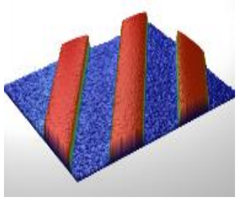
Complex Via



Auto Alignment & CD



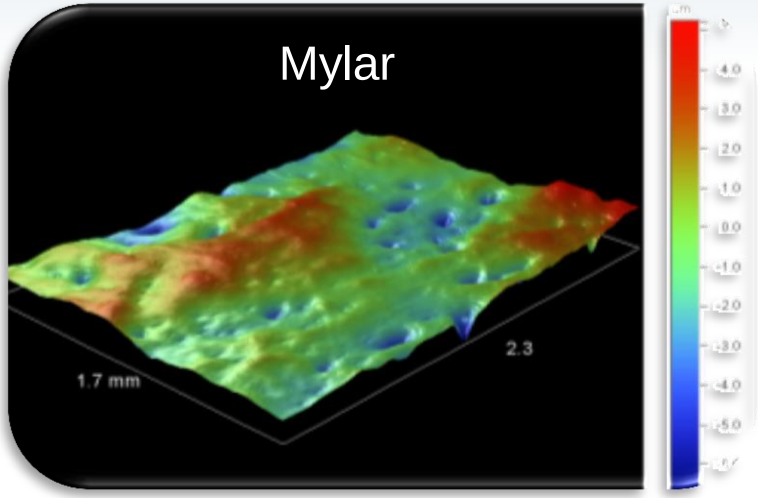
Surface Roughness

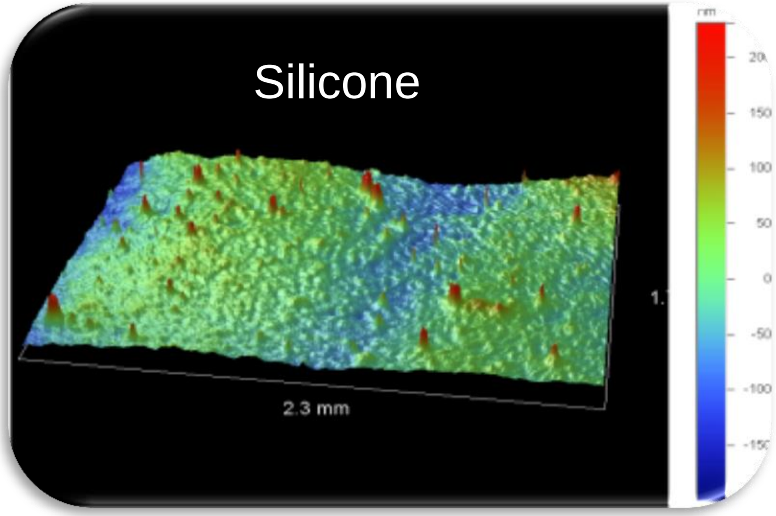


MultiTrace

Defects and CD Variations of Any Layer Can Decrease Performance, Lower Yields, and Increase End of Line Scrap and Product Cost

Polymer substrates
Roughness & waviness measurements

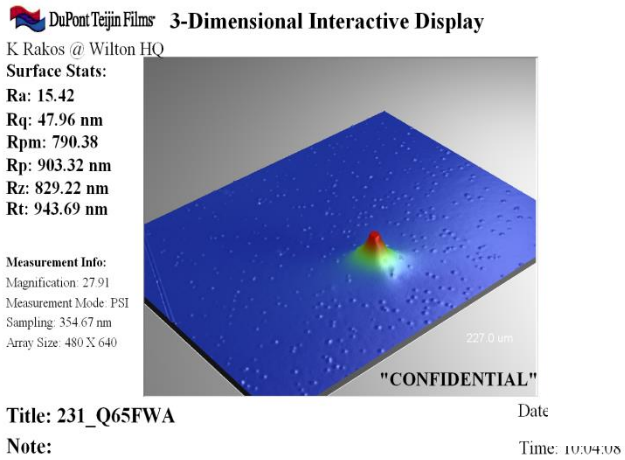

Mylar


Silicone

- Fine features and large waviness affects:
  - Adhesion of deposited film
  - Longevity of deposited film

- Requirements:
  - Fast
  - Large field of view
  - Vertical resolution below 1nm

Defect Detection and Analysis on Flexible Film



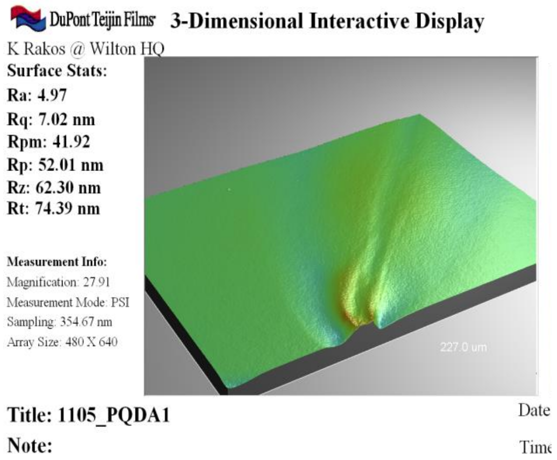
DuPont Teijin Films **3-Dimensional Interactive Display**

K Rakos @ Wilton HQ

Surface Stats:
Ra: 15.42
Rq: 47.96 nm
Rpm: 790.38
Rp: 903.32 nm
Rz: 829.22 nm
Rt: 943.69 nm

Measurement Info:
Magnification: 27.91
Measurement Mode: PSI
Sampling: 354.67 nm
Array Size: 480 X 640

Title: 231_Q65FWA
Date
Note:
Time: 10:04:08



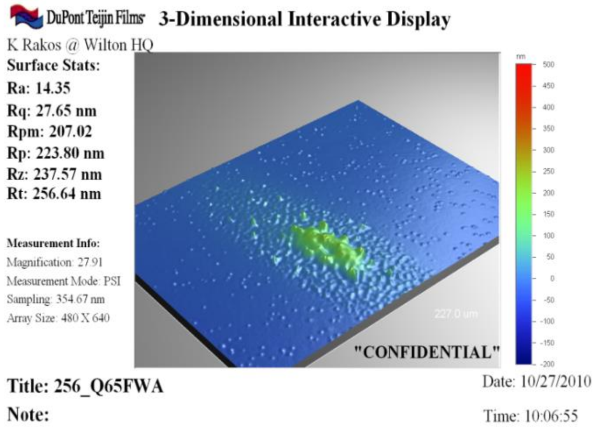
DuPont Teijin Films **3-Dimensional Interactive Display**

K Rakos @ Wilton HQ

Surface Stats:
Ra: 4.97
Rq: 7.02 nm
Rpm: 41.92
Rp: 52.01 nm
Rz: 62.30 nm
Rt: 74.39 nm

Measurement Info:
Magnification: 27.91
Measurement Mode: PSI
Sampling: 354.67 nm
Array Size: 480 X 640

Title: 1105_PQDA1
Date
Note:
Time



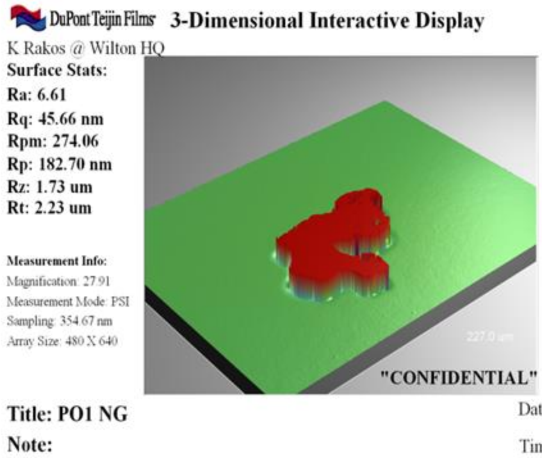
DuPont Teijin Films **3-Dimensional Interactive Display**

K Rakos @ Wilton HQ

Surface Stats:
Ra: 14.35
Rq: 27.65 nm
Rpm: 207.02
Rp: 223.80 nm
Rz: 237.57 nm
Rt: 256.64 nm

Measurement Info:
Magnification: 27.91
Measurement Mode: PSI
Sampling: 354.67 nm
Array Size: 480 X 640

Title: 256_Q65FWA
Date: 10/27/2010
Note:
Time: 10:06:55



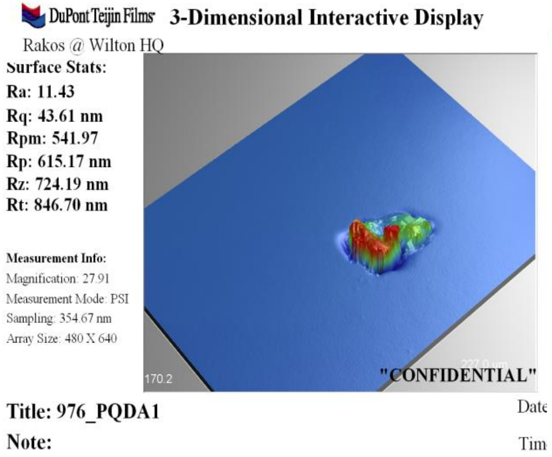
DuPont Teijin Films **3-Dimensional Interactive Display**

K Rakos @ Wilton HQ

Surface Stats:
Ra: 6.61
Rq: 45.66 nm
Rpm: 274.06
Rp: 182.70 nm
Rz: 1.73 um
Rt: 2.23 um

Measurement Info:
Magnification: 27.91
Measurement Mode: PSI
Sampling: 354.67 nm
Array Size: 480 X 640

Title: PO1 NG
Dat
Note:
Tin



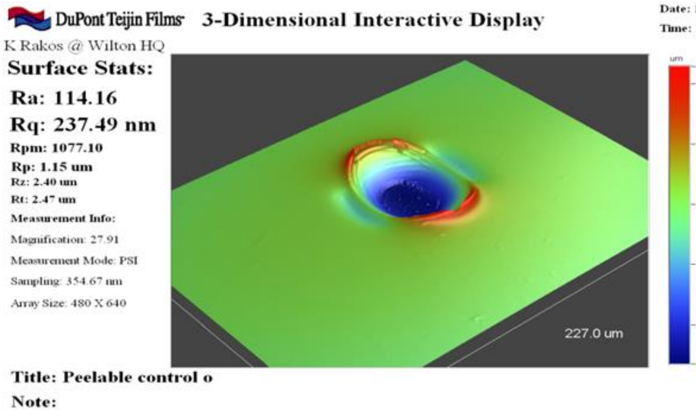
DuPont Teijin Films **3-Dimensional Interactive Display**

Rakos @ Wilton HQ

Surface Stats:
Ra: 11.43
Rq: 43.61 nm
Rpm: 541.97
Rp: 615.17 nm
Rz: 724.19 nm
Rt: 846.70 nm

Measurement Info:
Magnification: 27.91
Measurement Mode: PSI
Sampling: 354.67 nm
Array Size: 480 X 640

Title: 976_PQDA1
Date
Note:
Tim



DuPont Teijin Films **3-Dimensional Interactive Display**

Date:
Time:

K Rakos @ Wilton HQ

Surface Stats:
Ra: 114.16
Rq: 237.49 nm
Rpm: 1077.10
Rp: 1.15 um
Rz: 2.40 um
Rt: 2.47 um

Measurement Info:
Magnification: 27.91
Measurement Mode: PSI
Sampling: 354.67 nm
Array Size: 480 X 640

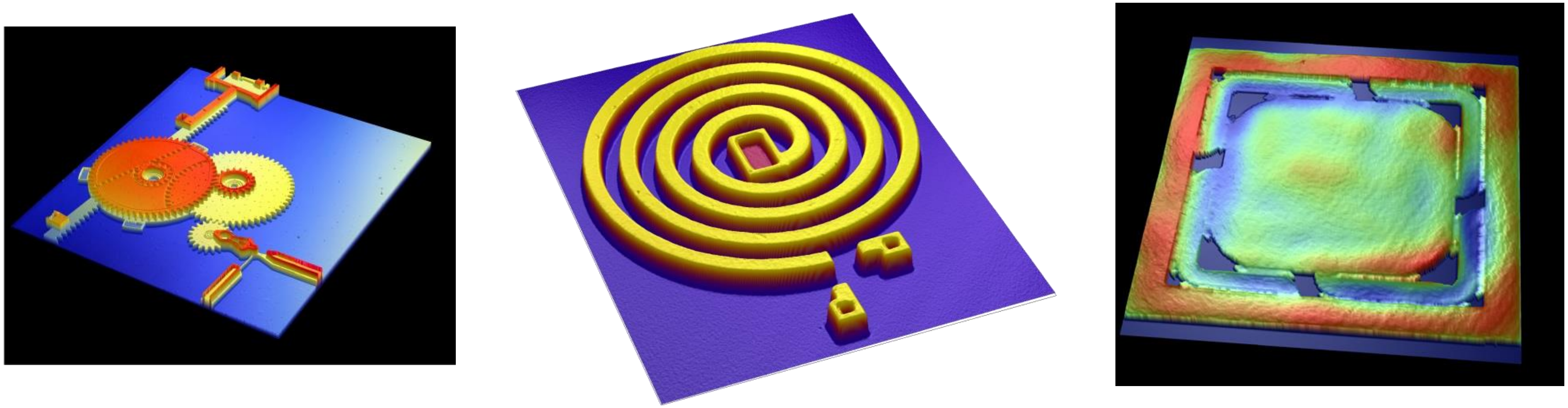
Title: Peelable control o
Note:

Courtesy of Karl Rakos, DuPont Teijin Films

MicroElectroMechanical Systems (MEMS)

- Manufactured using techniques similar to those of semiconductors
- Feature sizes typically 1-100µm
- Applications: automotive sensors,

  optical network switches, displays, projectors, medical devices, etc.

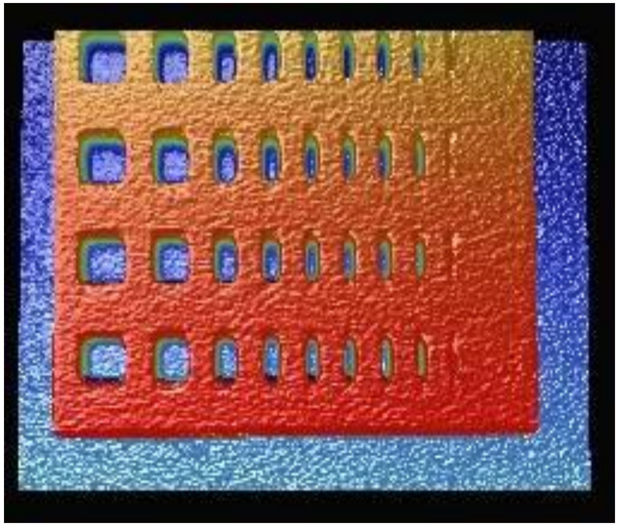


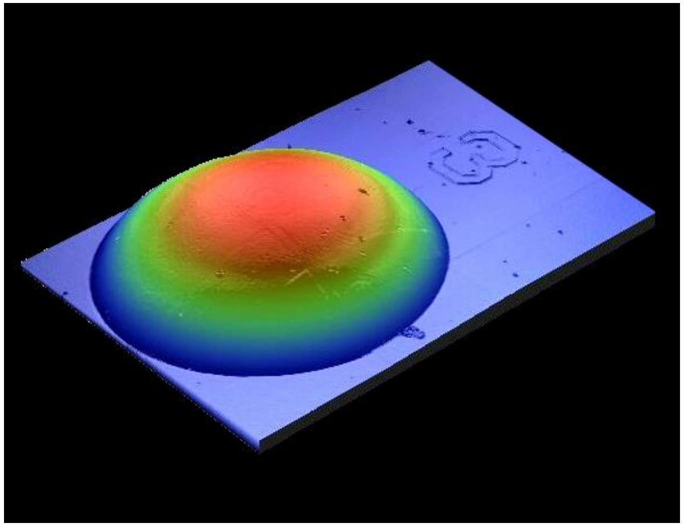
Optical Profiling Advantages for MEMS manufacture

- 3D visualization of part performance
- Non-contact—will not deflect or deform structures
- High vertical resolution captures optical-grade surface roughness
- Vertical range for large steps and thicknesses
- Lateral resolution and feature-tracking software for critical dimension analysis
- Static and dynamic measurement provide comprehensive analysis in a cost-effective, single platform
- Rapidly image entire device, and analyze multiple features, at high vertical resolution

Roughness Measurement

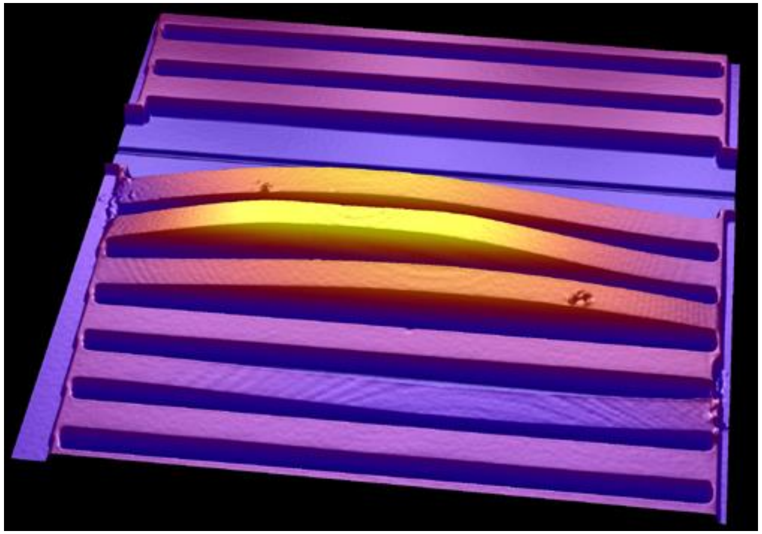
- Characterize surfaces from super-smooth to very rough
- 3D parameters provide directionality, periodicity, peaks vs troughs, etc—far more than just average roughness
- Control film deposition processes

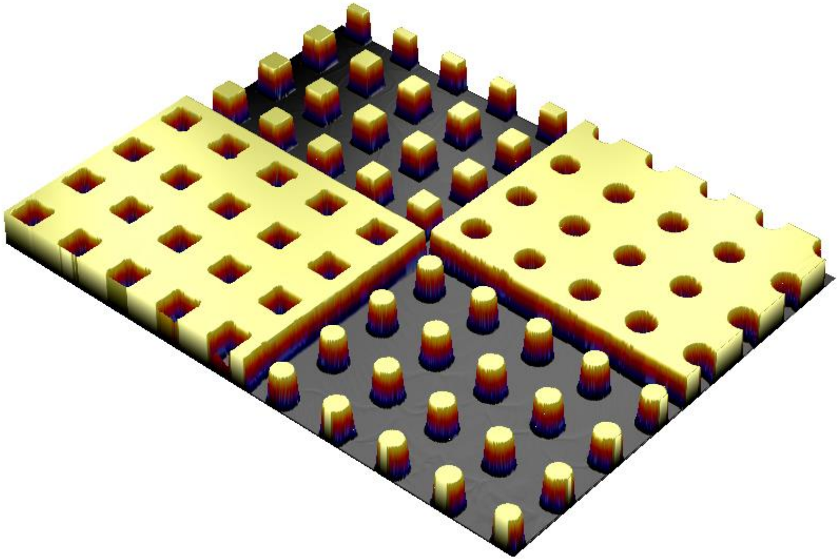




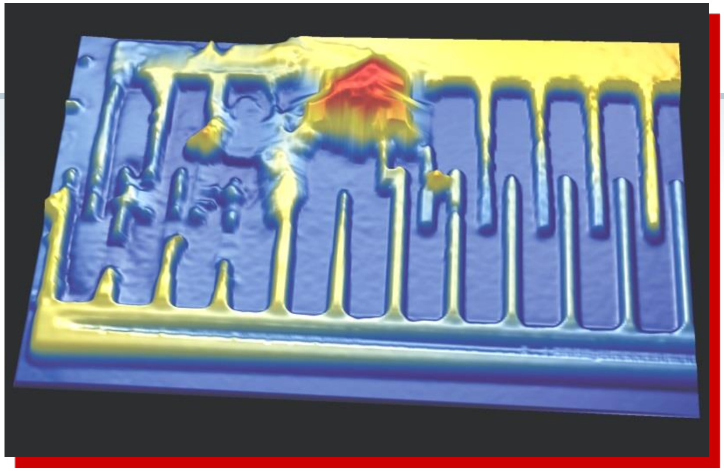
Step Height Measurement

- Measure Step heights from nanometers to 8mm
- Determine thickness of films and resists
  for process control
- Monitor deposition and etch processes

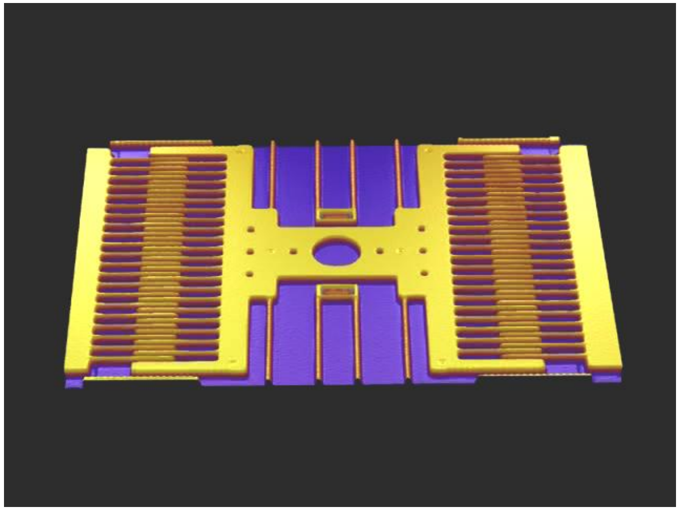




Dynamic Measurement (DMEMS)



Static measurement of ESD-damaged resonator (Courtesy CNRI MEMS Exchange)



Dynamic measurement of resonator (Courtesy Sandia National Labs)

- Static measurement quantifies individual features and films
- Dynamic measurement lets you visualize and quantify true device functionality during actuation

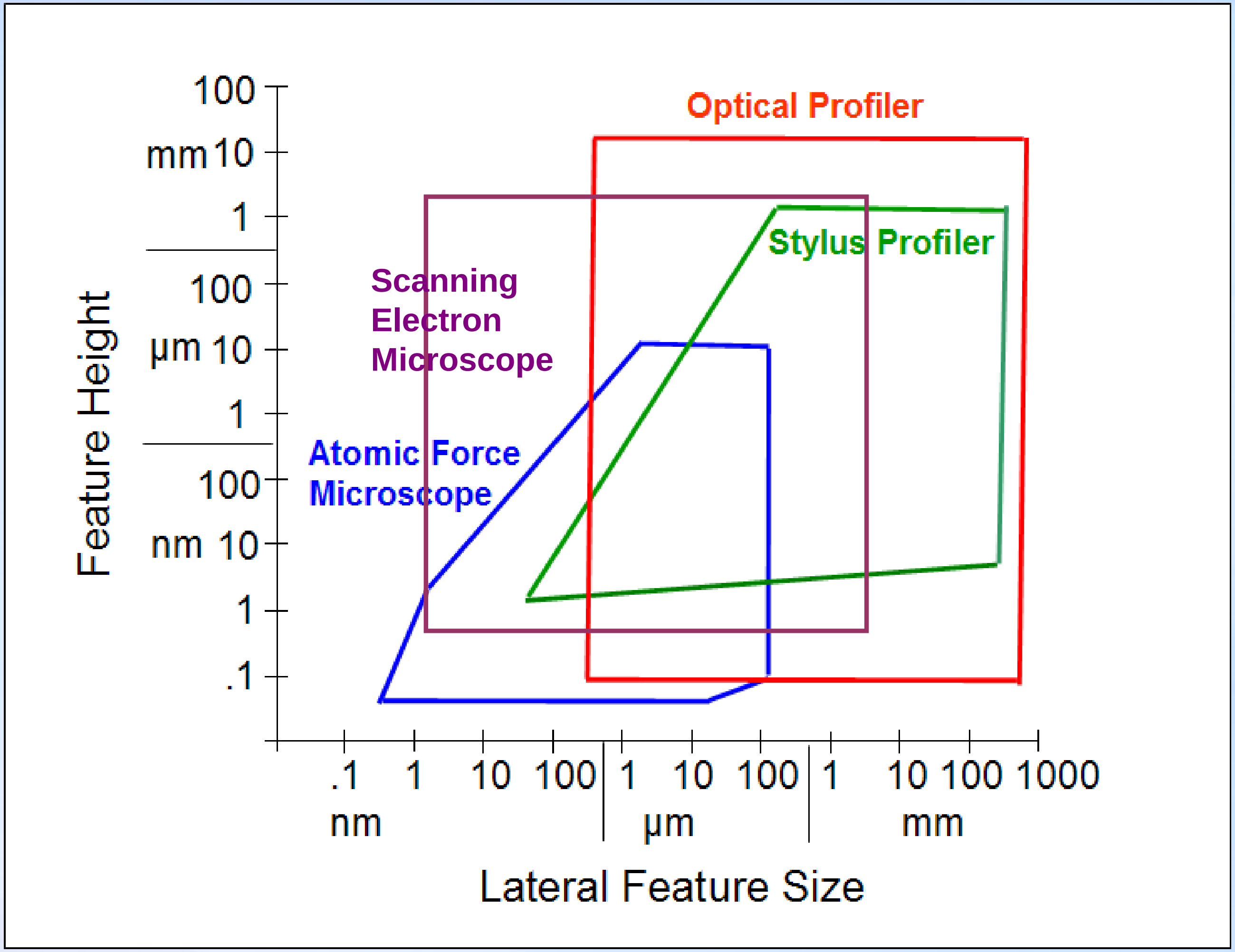
MEMS

Comparison of Metrology Techniques

	Optical Interferometry	Stylus	AFM	SEM
3D Measurement	Quantitative	Quantitative	Quantitative	Qualitative
Sample Interaction	Non-contact, Non-destructive	Contact	Intermittent Contact, Non-destructive	Non-contact, Electron bombardment
Acquisition Speed	< 5 secs/area	5 secs/line	0.5 sec/line	20 – 320 seconds/image
Vertical Measurement Range	Up to 10 mm	1mm	20 um	~10um depth of field
Vertical Resolution	<1 A	<5A	<1 A	2nm – 10nm
Lateral Resolution	0.2 um	>1um	<5nm	2nm – 10nm

Price	$80K-$200K	<$50K	>$100K	$80K - $500K

Metrology Analysis Ranges



Optical And Stylus Systems are Complementary

- Stylus
  - Sub-nm vertical resolution
  - 1mm vertical range
  - Rapid single traces
  - Insensitive to material effects
  - Accurate and repeatable
  - Variable lateral resolution
  - Slower for 3D
  - Requires contact with surface
- Optical
  - Sub-nm vertical resolution
  - 10mm vertical range
  - Rapid, full-field 3D measurements
  - Sensitive to material effects
  - Accurate and repeatable
  - Variable lateral resolution
  - Constant vertical resolution
  - Handles transparent materials

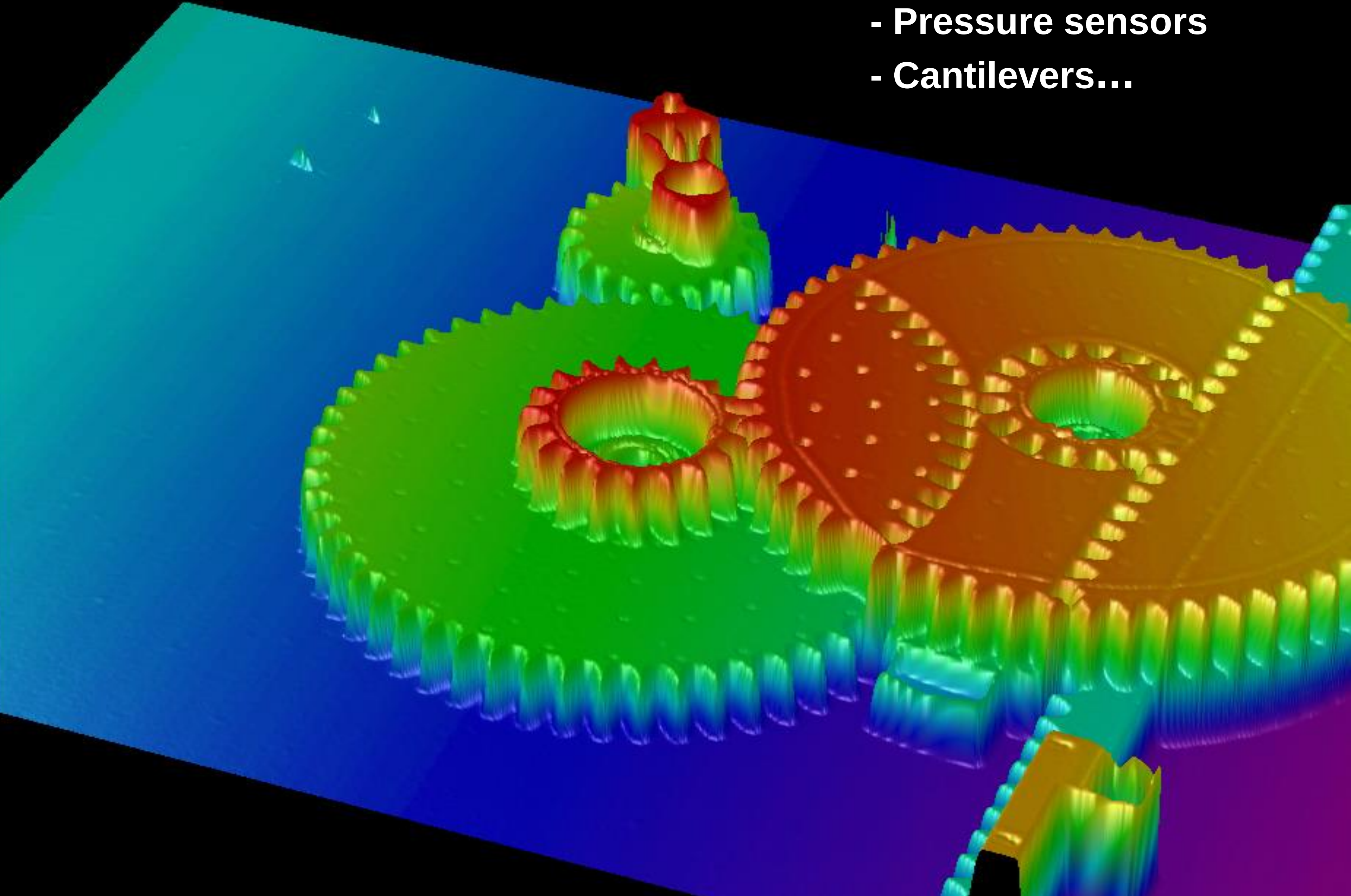
Challenges

- **Manufacturing environment may introduce noise in the measurement**
  - **Mechanical vibration**
  - **Acoustic noise**
  - **Temperature fluctuation**
  - **Contamination**
- **Equipment self heating may cause thermal drift of the system**
- **Complex sample geometry and material combination may cause artifacts in measurements**

Summary

- Metrology tools will play an important role in the emerging technology advancement.
- Optical interferometers are widely used as process motoring tools because they can quickly cover a large area, and are very versatile. They are best to be used for critical dimension, film thickness, and roughness measurements. They can also be used for defect detection and analysis.
- Stylus profilers are also very useful tools because they are low cost and easy to use. They are best to be used as monitoring tools for step height and roughness measurements.
- AFM is the ultimate metrology tool for resolution in the sub nanometers. It can also measure material properties in the nanometer scale. High speed AFM opens opportunities for understanding of new technologies.

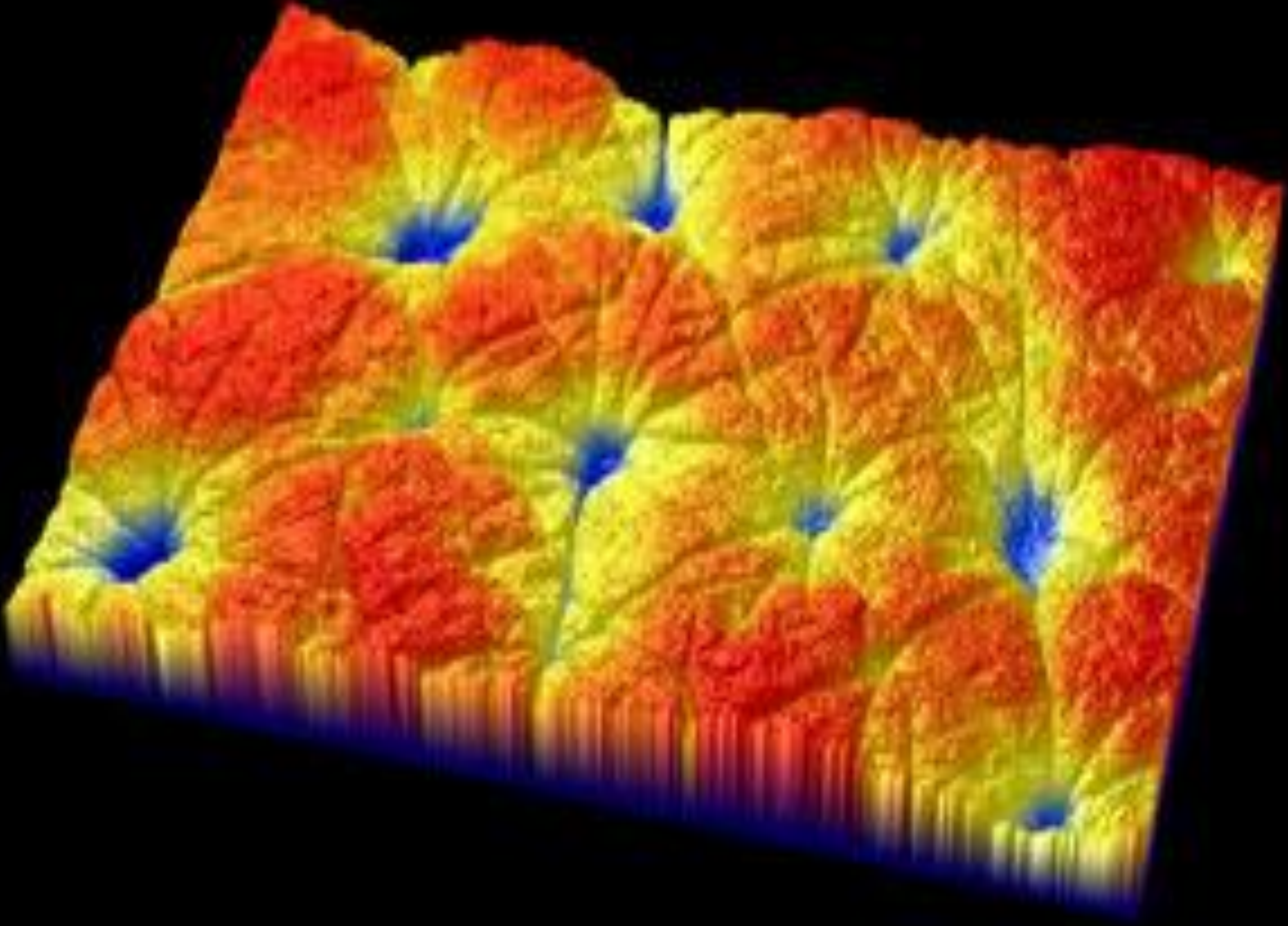
- **Let’s have some fun now …**



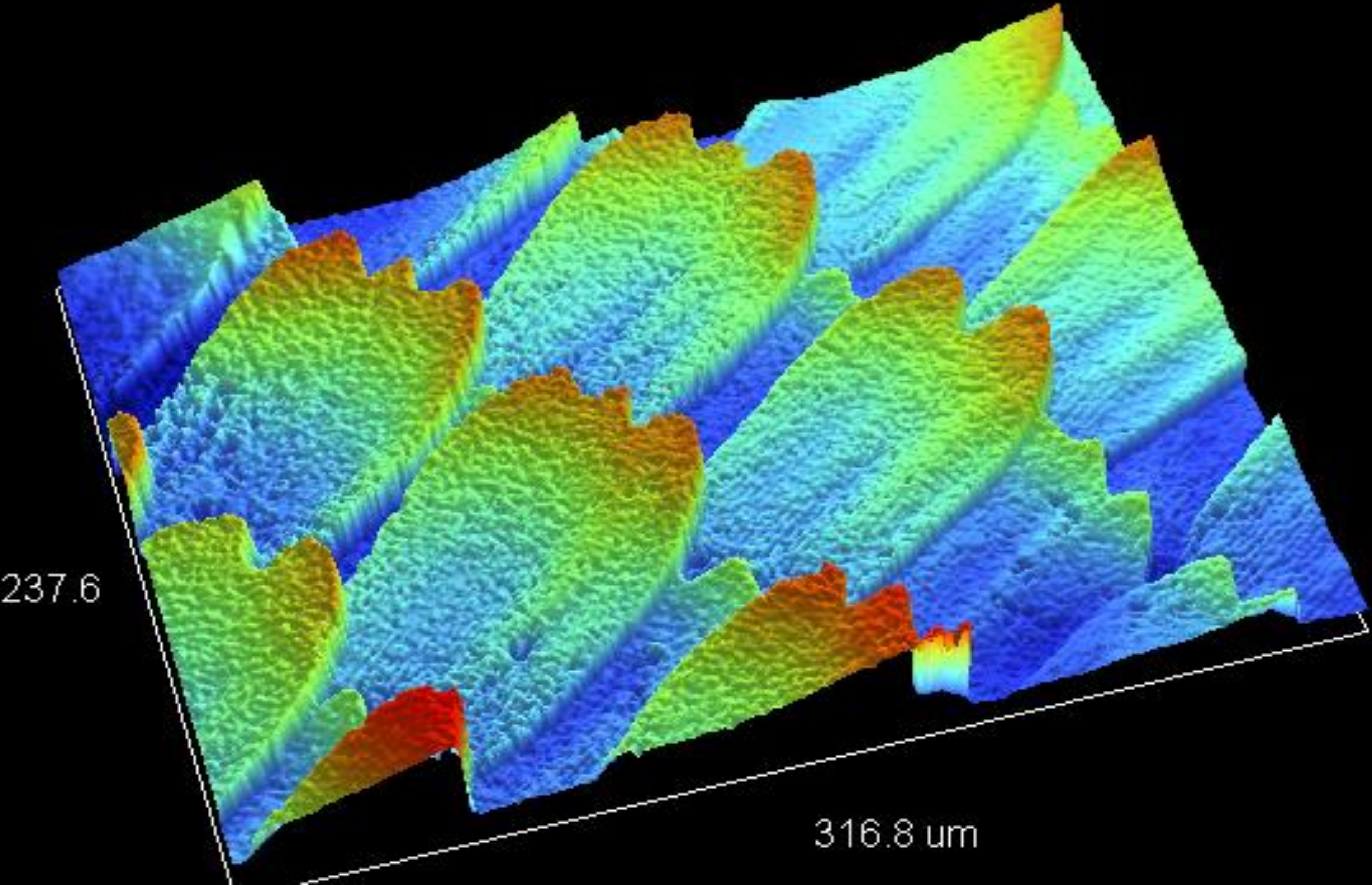
MEMS Gear

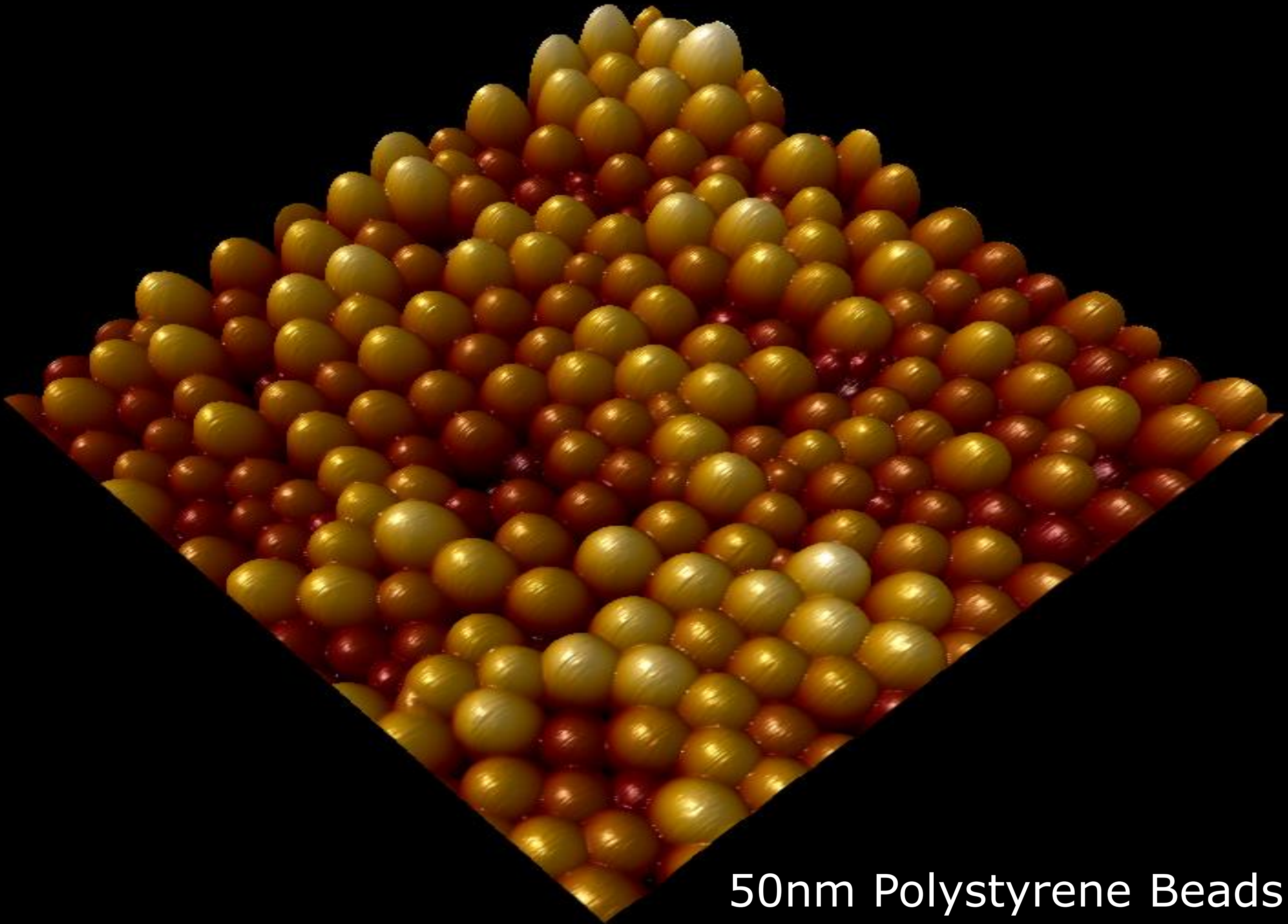
- Miniaturized machines
- Pressure sensors
- Cantilevers…

Human Skin Cells

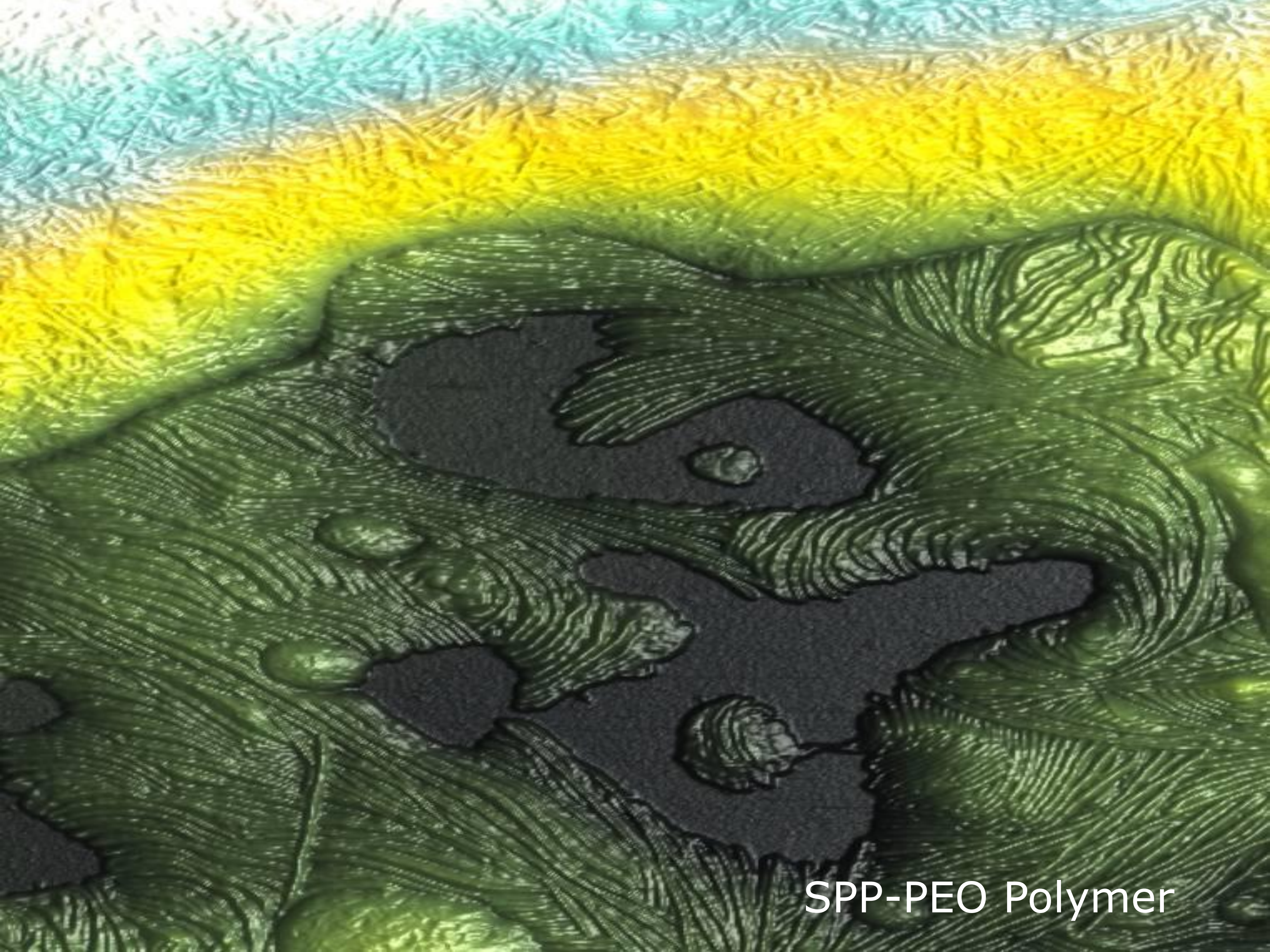


Butterfly Wing

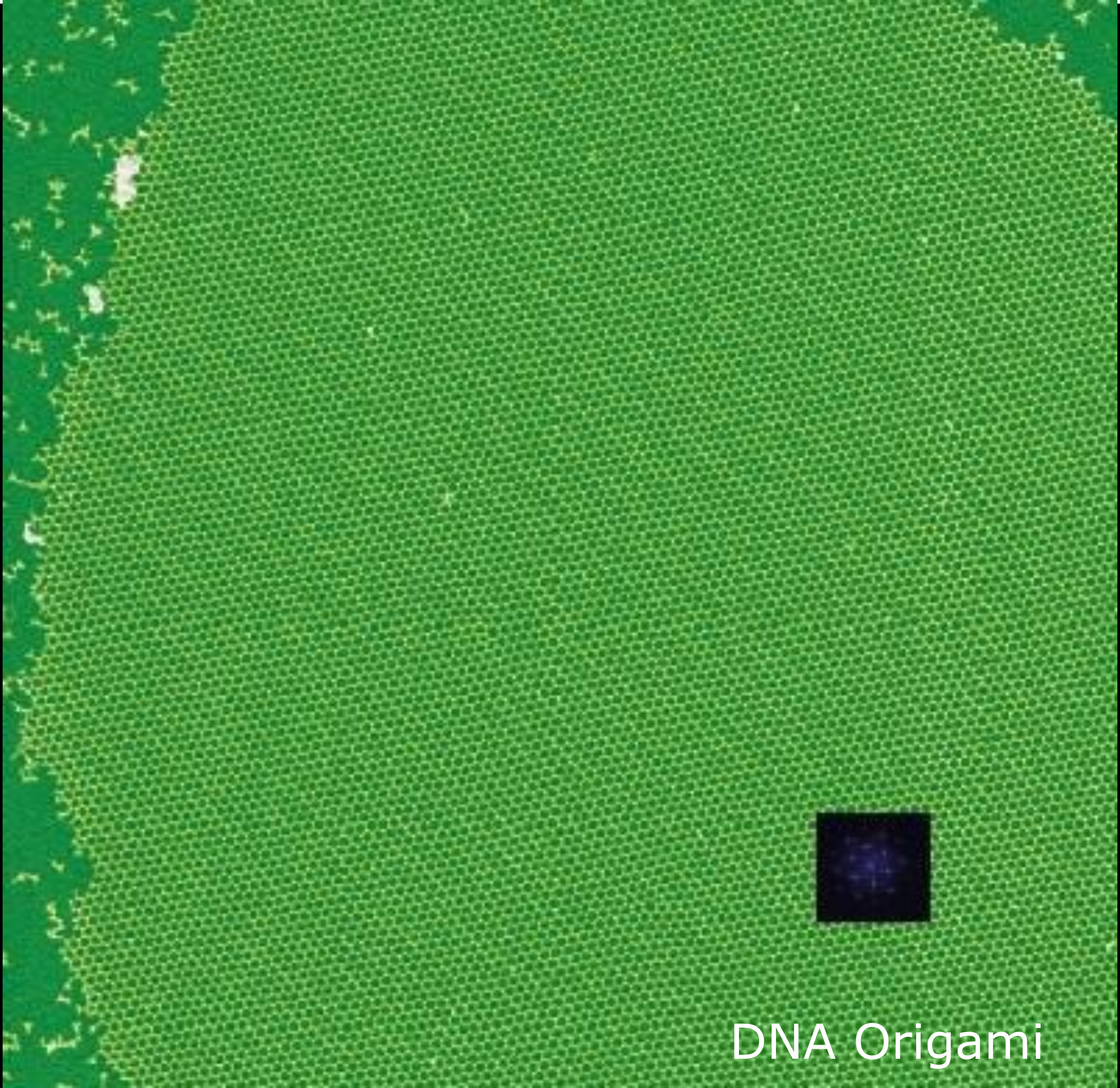




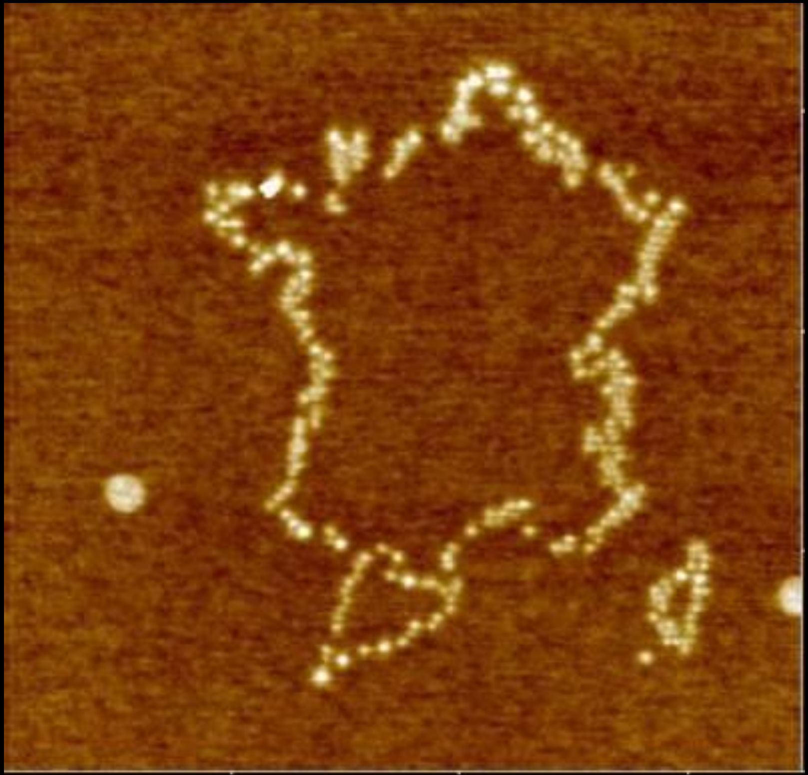
50nm Polystyrene Beads



SPP-PEO Polymer

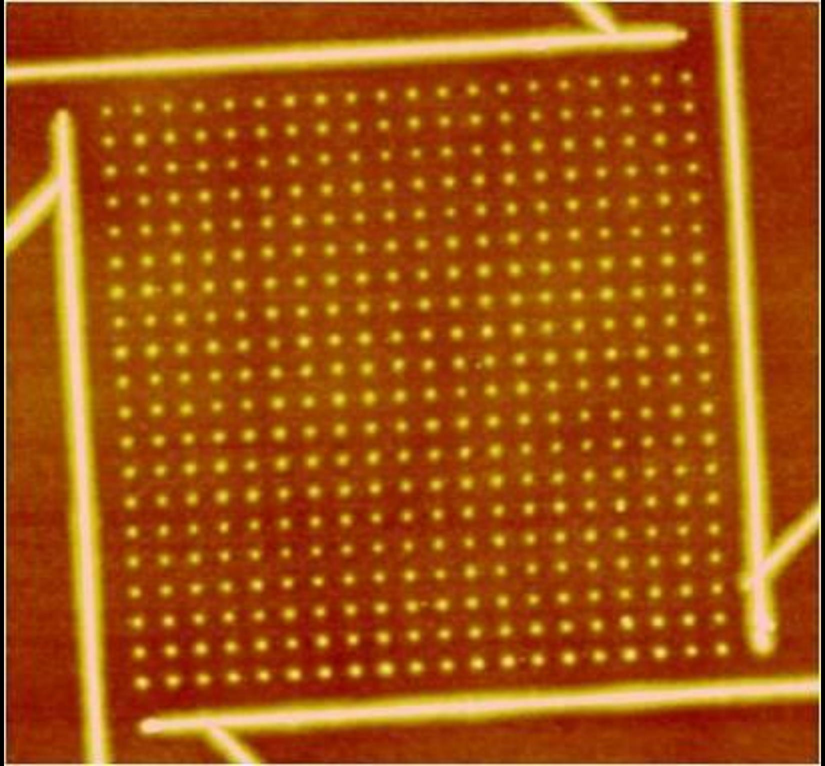

DNA Origami

Courtesy: F. Perez, CNM Barcelona



nm-scale Map of France

Courtesy: A. Dorn, ETH Zurich



Antidot Pattern on GaAs

Created with AFM ‘Nanolithography’