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College of Optical Sciences

6.0 Measurement of Surface Quality

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- 6.1 View transmitted or reflected light
- 6.2 Mechanical Probe – Stylus Profilometry
- 6.3 AFM – Atomic Force Microscope or SPM – Scanning Probe Microscope
- 6.4 Lyot Test (Zernike Phase Contrast)
- 6.5 FECO – Fringes of Equal Chromatic Order
- 6.6 Nomarski Interferometer - Differential Interference Contrast (DIC)
- 6.7 Interference Microscope

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Introduction

- Surface quality refers to surface finish, which includes
  - Pits
  - Scratches
  - Incomplete or “grey” polish
  - Stain
  - Etc

- With the exception of incomplete polish, factors are beauty effects except
  - when the surface is near a focal plane, or
  - system is especially sensitive to stray radiation, or
  - systems such as high-energy laser systems where laser damage may occur.

Scratch and Dig

The scratch and dig standards of mil spec MIL-0-13830, published in 1954, are widely used in the industry. For example

80 – 50 means

the apparent width of the scratch is 80 microns and the diameter of permissible dig, pit, or bubble in hundredths of a millimeter (i.e. 50 means 0.5 mm diameter).

Scratch and Dig Numbers

The total length of all scratches and number of pits also limited by the spec. In practice, the size of a defect is judged by a visual comparison of graded defects.

80 – 50 relatively easily fabricated

60 – 40

40 – 30 command a small premium in cost

40 – 20

20 – 10 reserved for field lenses or reticle blanks

10 – 5

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ISO 10110-7

- A key issue with MIL-O-13830 is that it cannot be used to specify defects that fall below the smallest comparison standards – size 10 for scratches and size 5 (50 μm diameter) for digs.
- ISO 10110-7 published in 1996 defines precise sizes and frequency of occurrence for acceptable defects over a given area. This allows for the specification of smaller defect levels and makes the surface inspection process more quantitative and less prone to operator error. It does not indicate how measurements should be performed.

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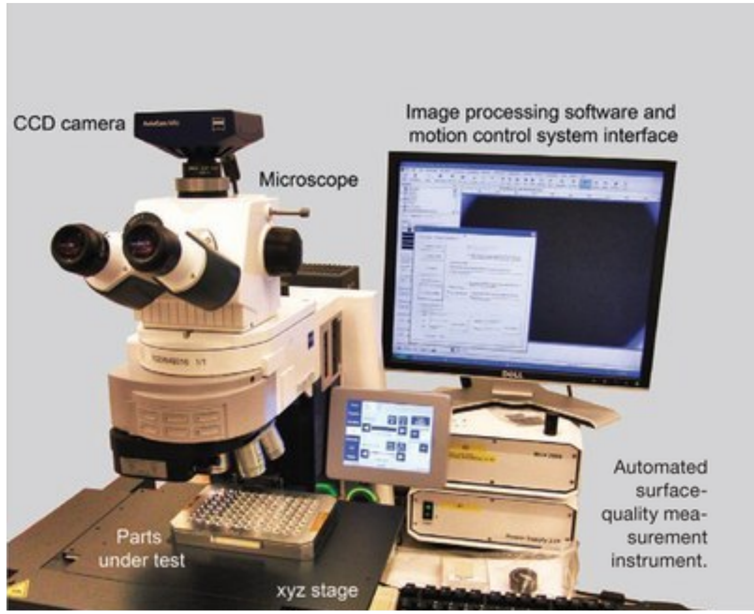
Ref: OPN, July/August 2012, p. 15-16

Automated Quality Measurement



[Microscope optics parameters]

Objective Lens Magnification	2.5X	5X	10X	20X	50X
Objective NA	0.06	0.13	0.2	0.4	0.7
Field of View (mm)	5.84	2.92	1.46	0.73	0.29
Objective Resolution (µm)	5.59	2.58	1.68	0.84	0.48
Minimum Sizeable Imperfection (µm)	20.48	10.24	5.12	2.56	1.02
Camera Adapter Magnification (M)	0.63X				
Pixel Spacing (µm)	6.45				
Sensor Size (mm)	9.2				
Center Wavelength of Illumination (nm)	550				

Ref: OPN, July/ August 2012, p. 15-16

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6.1 View Transmitted or Reflected Light

References

Ref: Elson, Bennett, and Bennett, "Scattering from Optical Surfaces", Vol. 7 of Applied Optics and Optical Engineering", Shannon and Wyant, Ed.

Stover, "Optical Scattering – Measurement and Analysis", SPIE Press Monograph, 1995.

Orange Peel

- If a surface is not sufficiently polished, or if felt or paper polishing is performed, the surface often has a rough texture.
- If the surface is illuminated with a bright point source and either the transmitted or reflected light is viewed a few inches away from the surface, intensity variations that have a texture like the peel of an orange will be observed.
- The sensitivity of the test for looking at reflected light is approximately four times greater than for transmitted light (n=1.5).

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Observing Surface Pits

- Pits in the surface can be observed by edge illuminating the sample and looking at the scattered light. The eye or camera should image on the surface. Often the resulting image is compared with standards.
- Instead of using edge illumination, it is possible to simply focus a bright filament onto the surface and look at the scattered light. (Make sure that direct light is not being observed.)
- A Schlieren system can also be used to observe light scattered by the surface pits.

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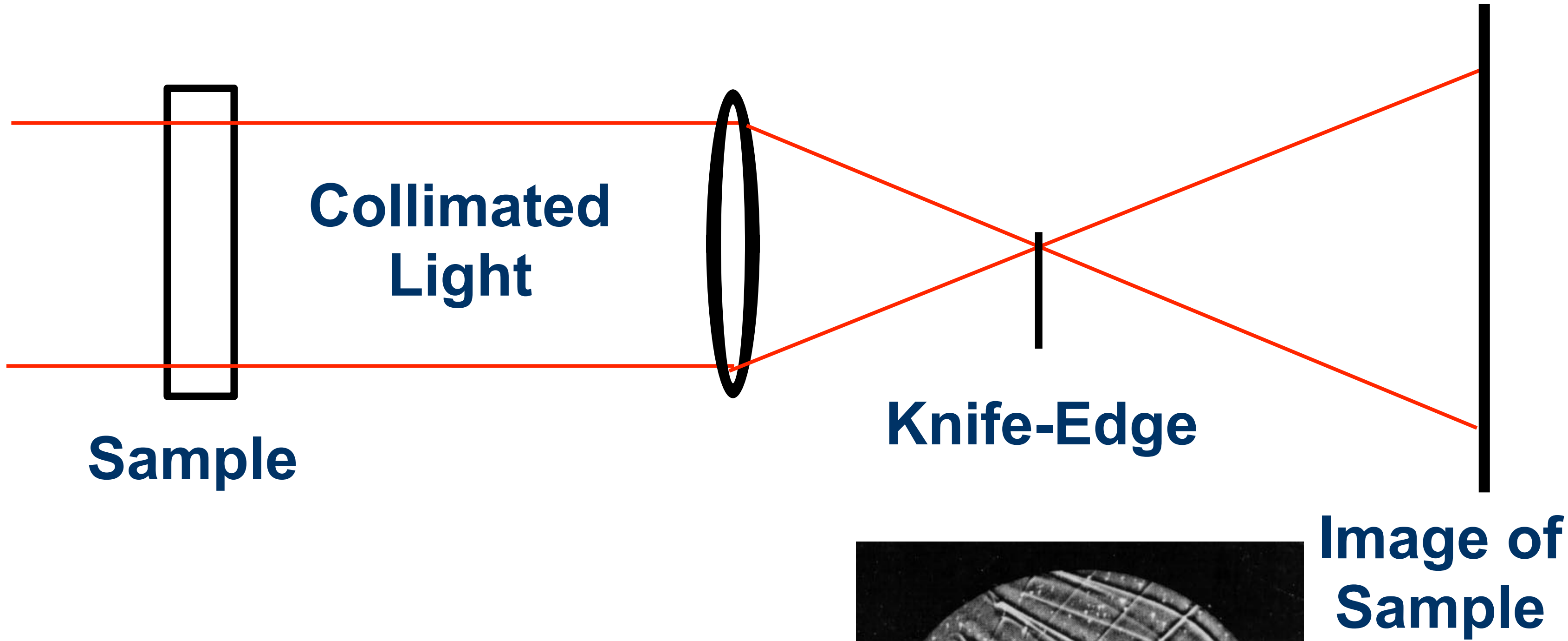
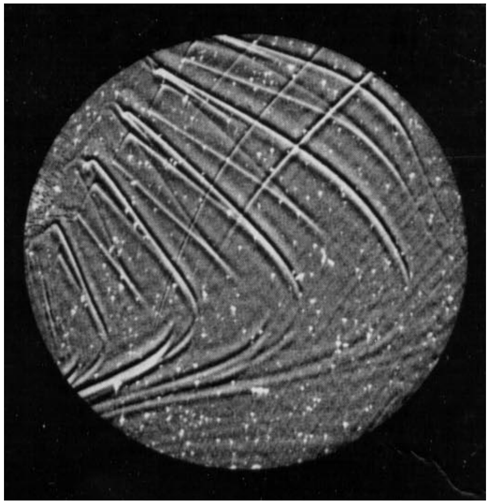
Schlieren System

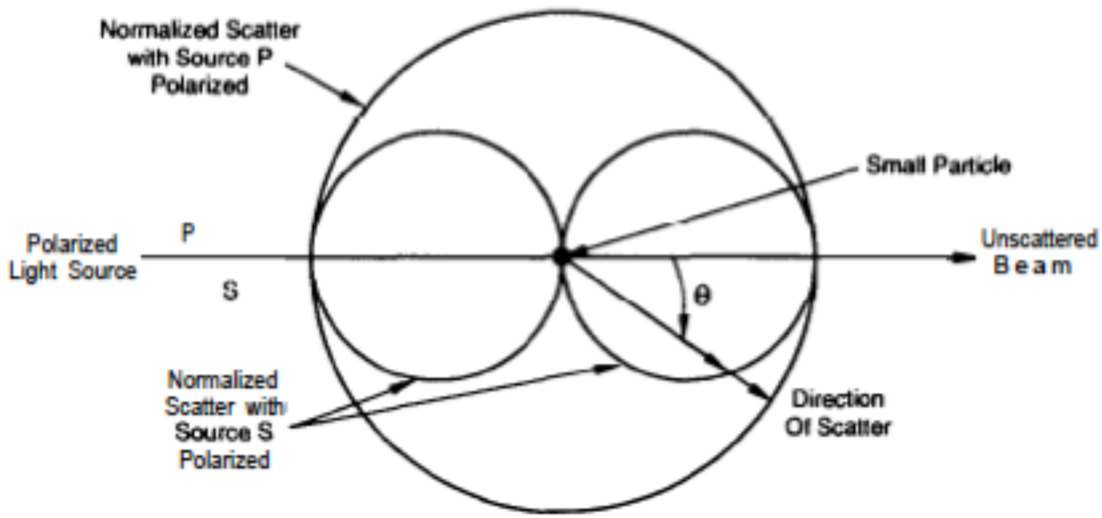




Bidirectional Scatter Distribution Functions

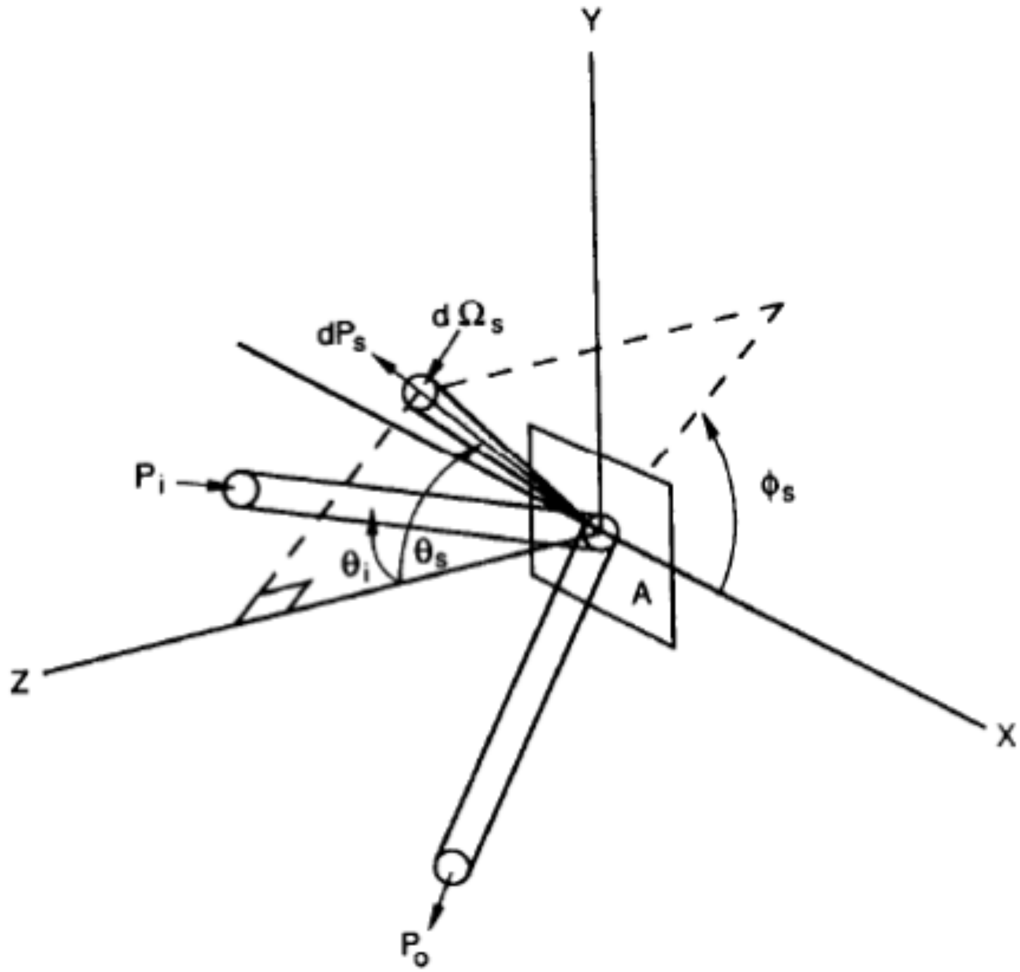
Reference:

Optical Scattering by John C. Stover



Scatter pattern changes dramatically with polarization of the incident beam.

Bidirectional Reflectance Distribution Function (BRDF)



BRDF

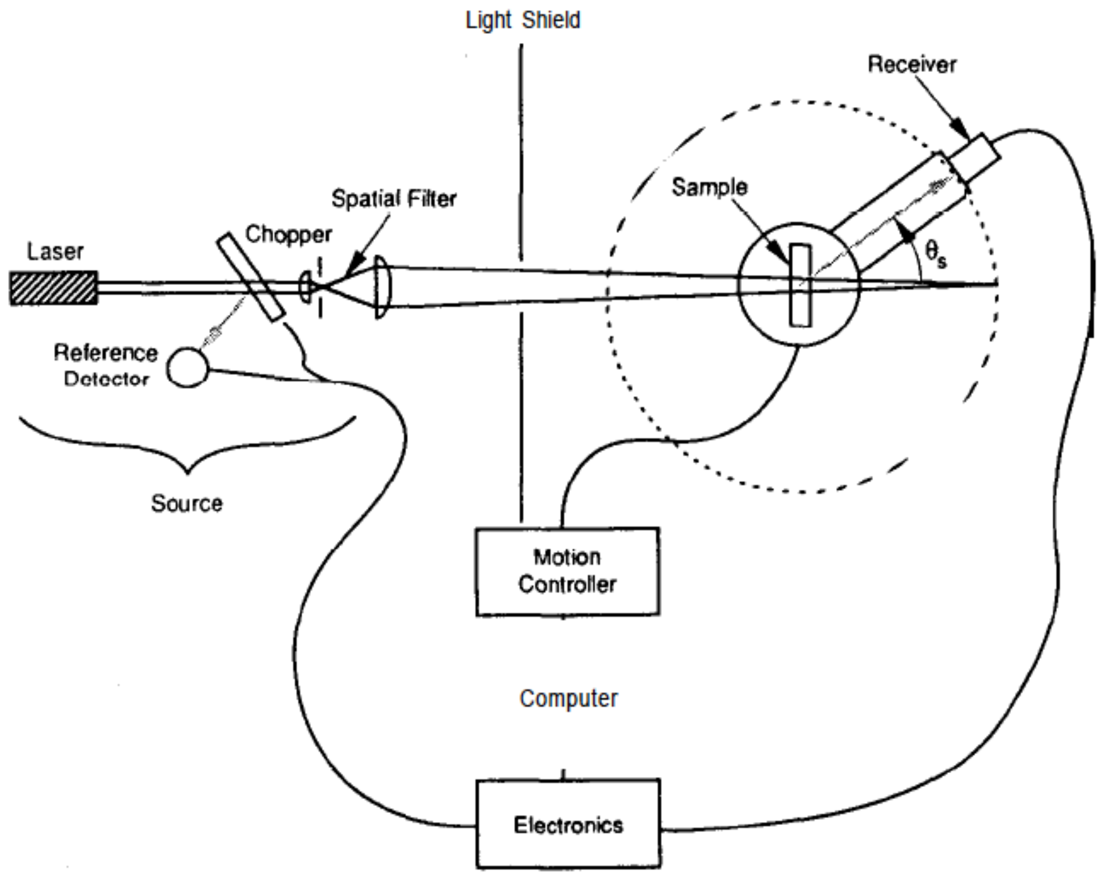
$$BRDF = \frac{\text{differential radiance}}{\text{differential irradiance}} = \frac{dP_s / d\Omega_s}{P_i \cdot Cos(\theta_s)} \cong \frac{P_s / \Omega_s}{P_i \cdot Cos(\theta_s)}$$

Surface irradiance is flux (watts) per unit illuminated surface area

Scattered surface radiance is flux scattered through solid angle per unit illuminated surface area

Cos factor is correction to adjust illuminated area to apparent size when viewed from scatter direction

BSDF Scatterometer



Lambertian Sample

A common assumption is that for a diffuse sample the scattered radiance is a constant. This means the scattered power/unit solid angle falls off as Cos(θ_s). Samples which scatter in this manner are known as Lambertian samples.

$$BRDF = \mathrm{F} = \frac{dP_s / d\Omega_s}{P_i \cdot Cos(\theta_s)} = \mathrm{Constant} = \frac{R}{\pi}$$

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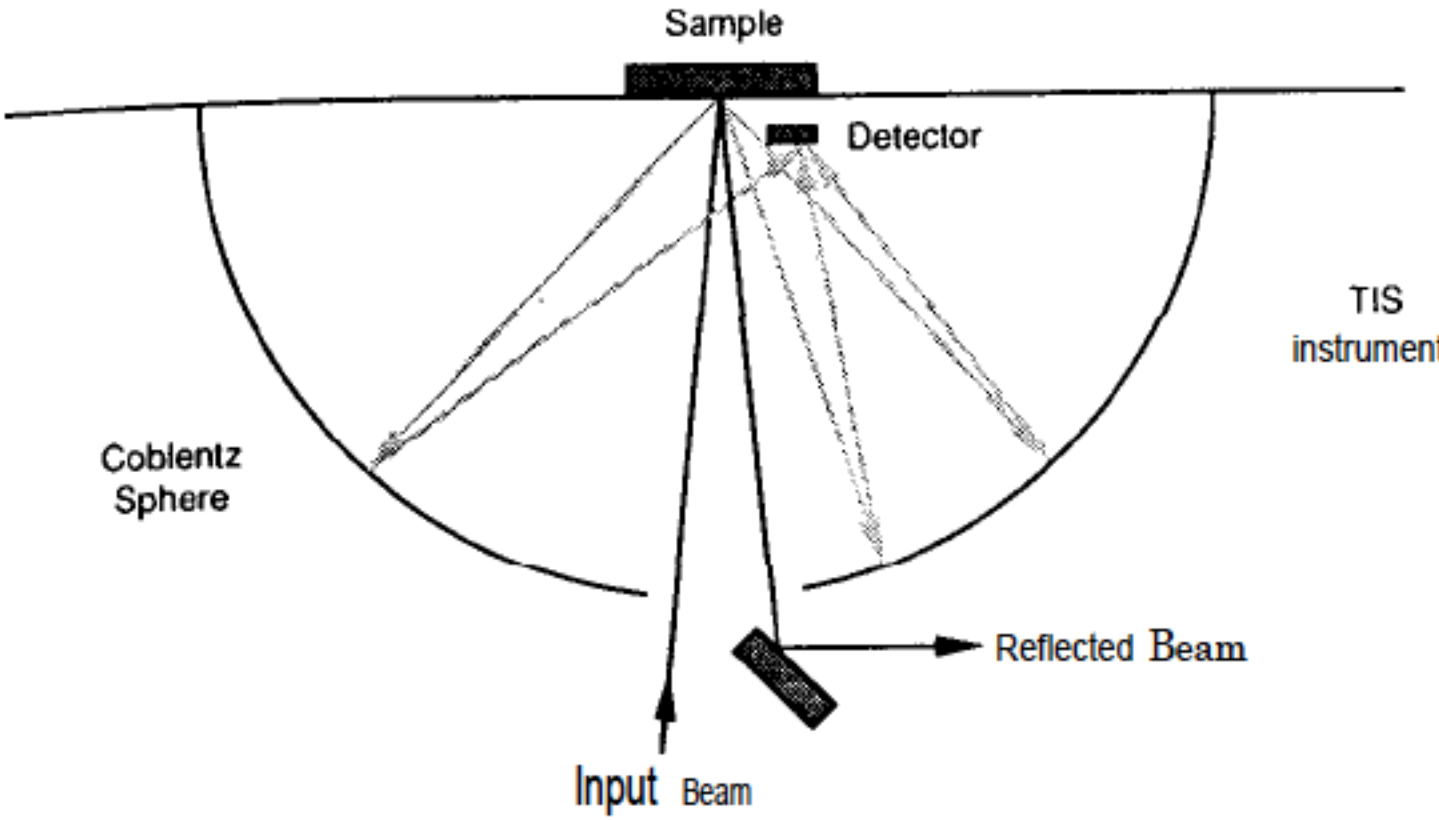
Total Integrated Scatter



$$TIS \equiv \frac{P_s}{R \cdot P_i} = \frac{P_s}{P_o} \approx \left(\frac{4\pi\sigma \cdot Cos(\theta_i)}{\lambda} \right)^2$$

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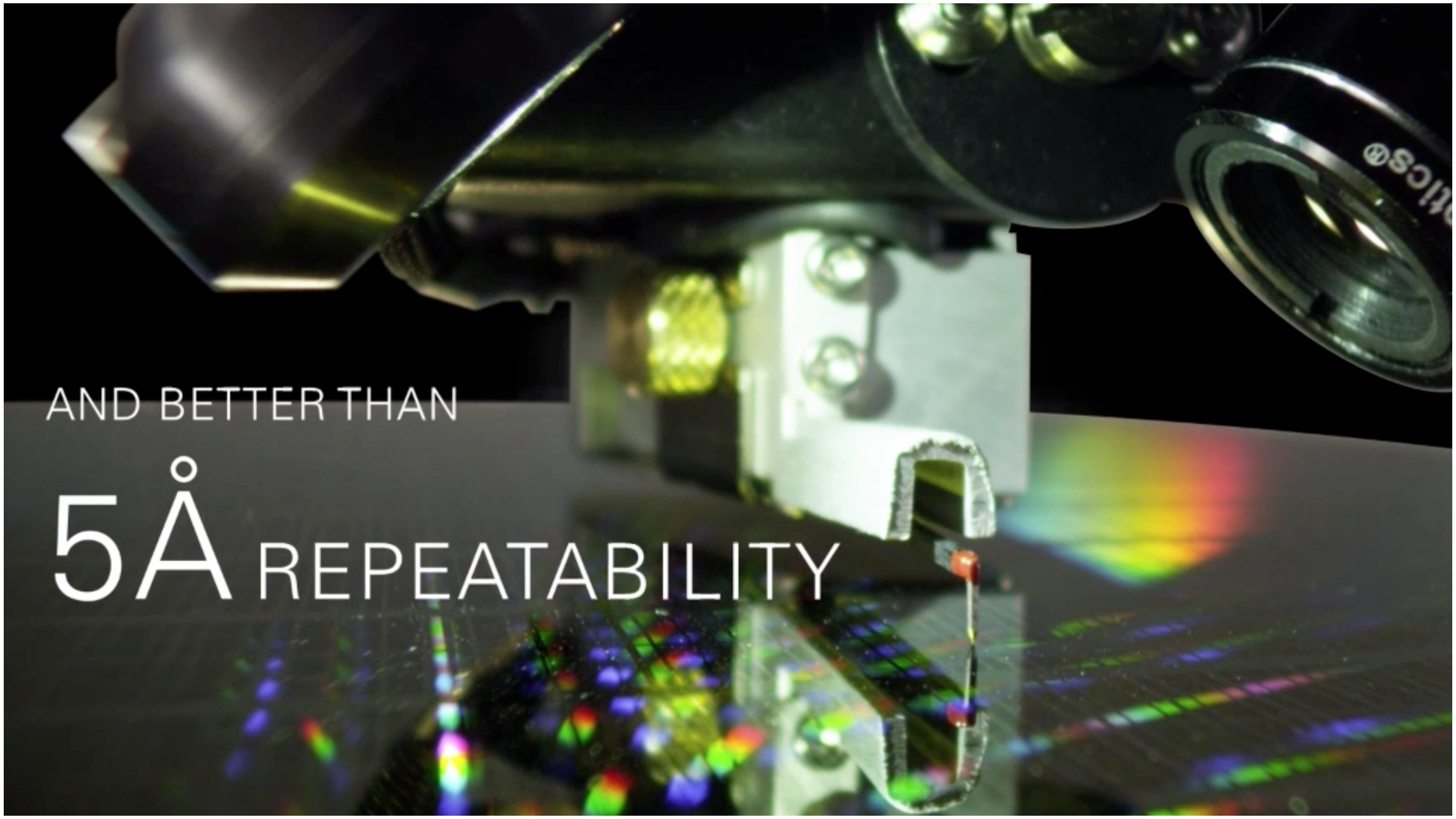
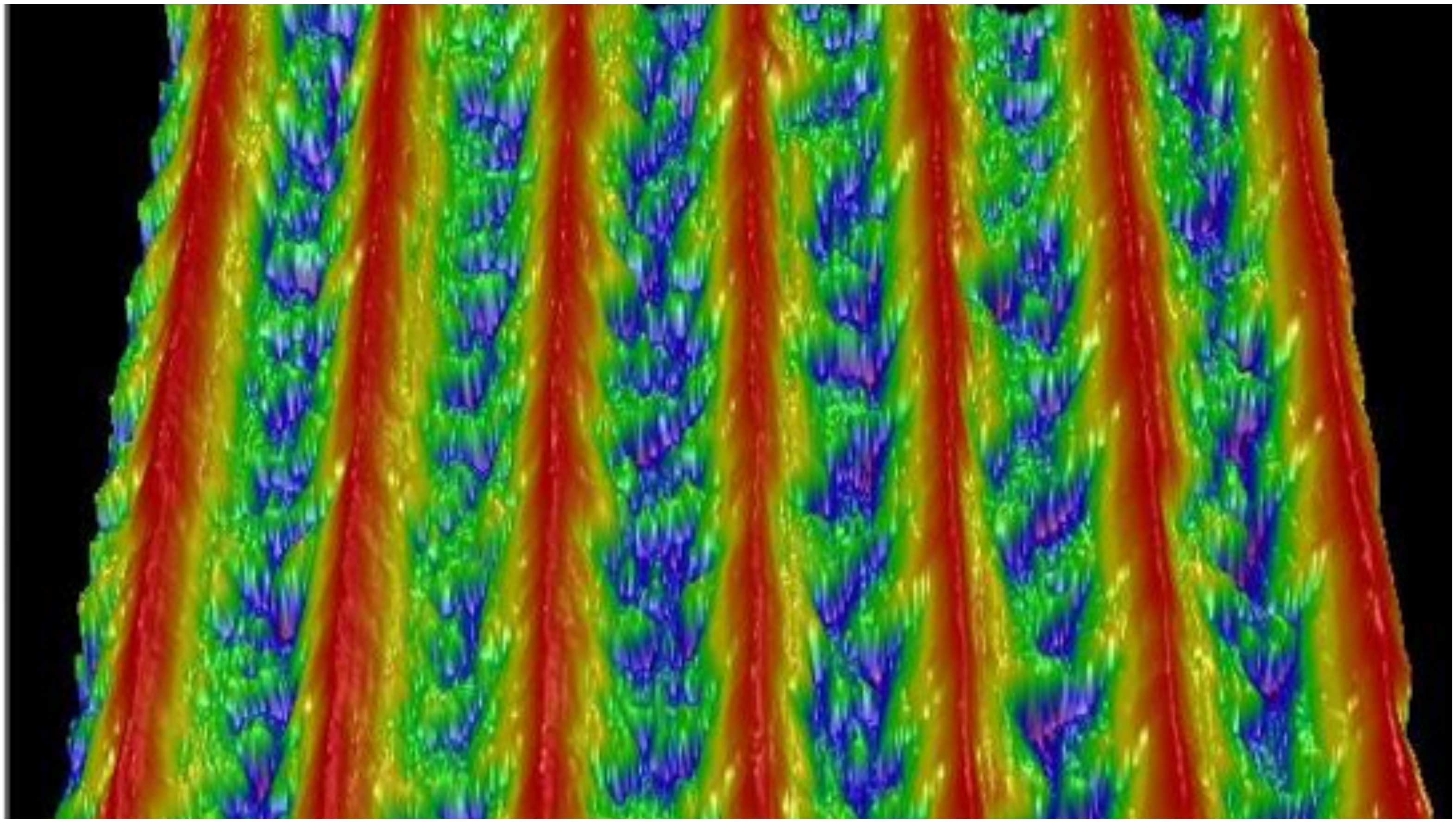
6.2 Mechanical Probe - Stylus Profilometry (contact measurement)



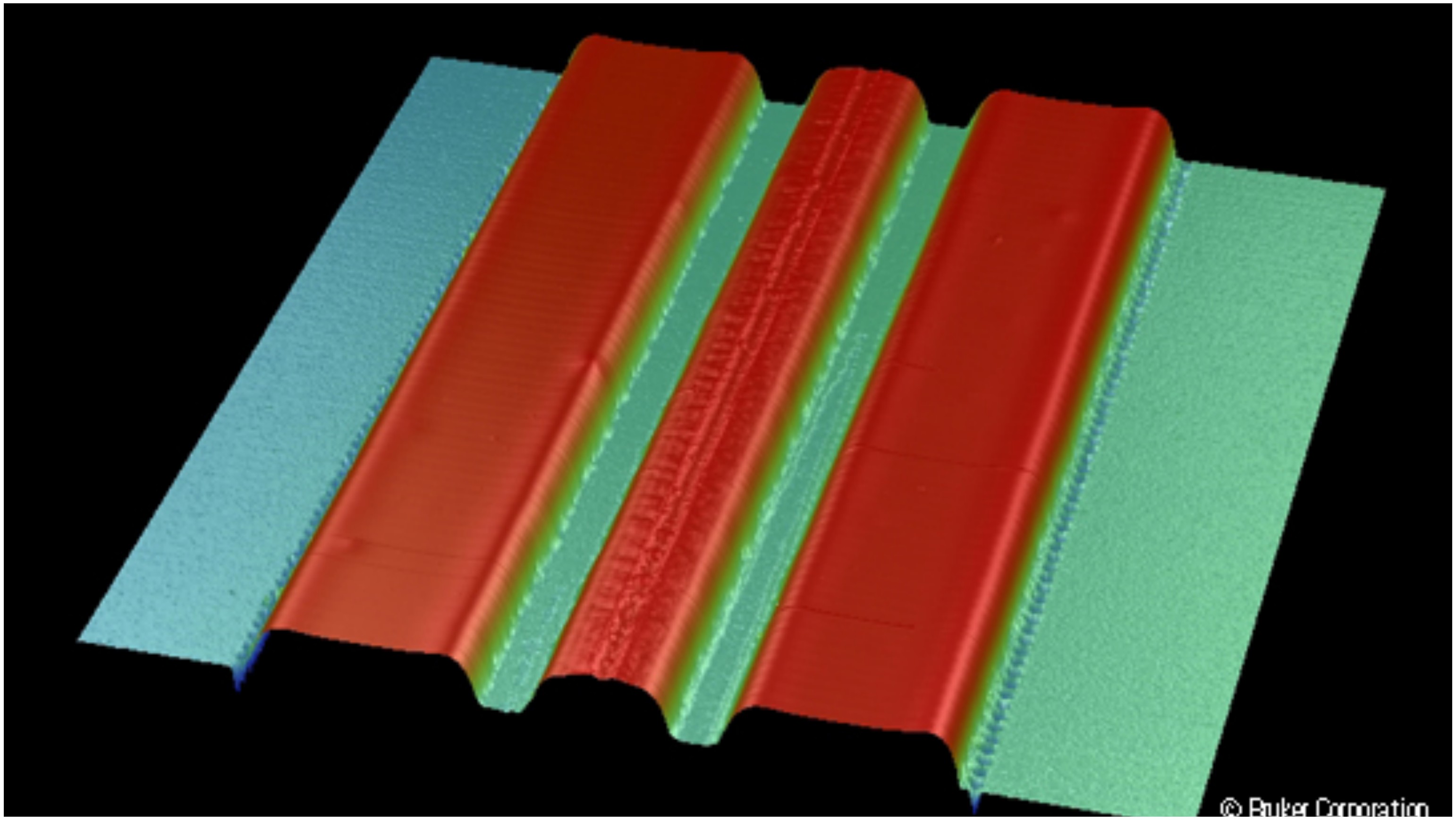
Stylus force – 1 to 15 mg, Stylus radius – 50 nm to 25 μm
Vertical range 1 mm, Vertical Resolution 1Å, Scan length 55 mm

Measurement Obtained Using Stylus (Machining Standard)



Ref: Bruker

Measurement Obtained Using Stylus (Metal Traces)



Ref: Bruker

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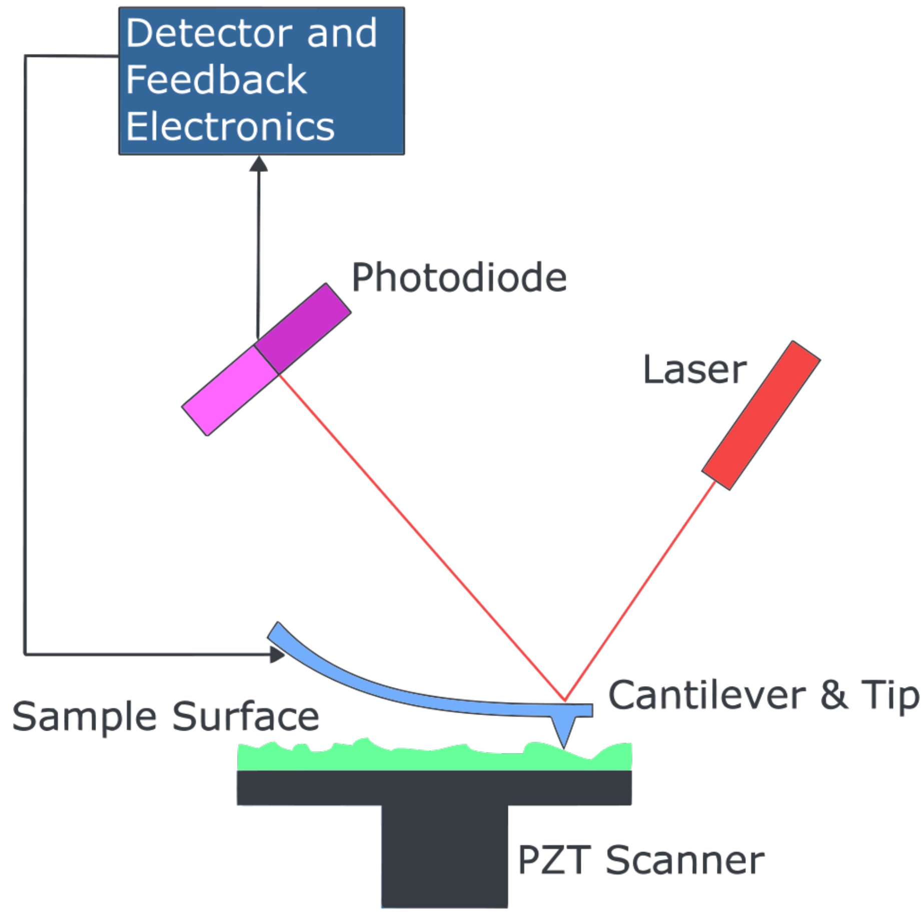
6.3 AFM – Atomic Force Microscope or SPM – Scanning Probe Microscope



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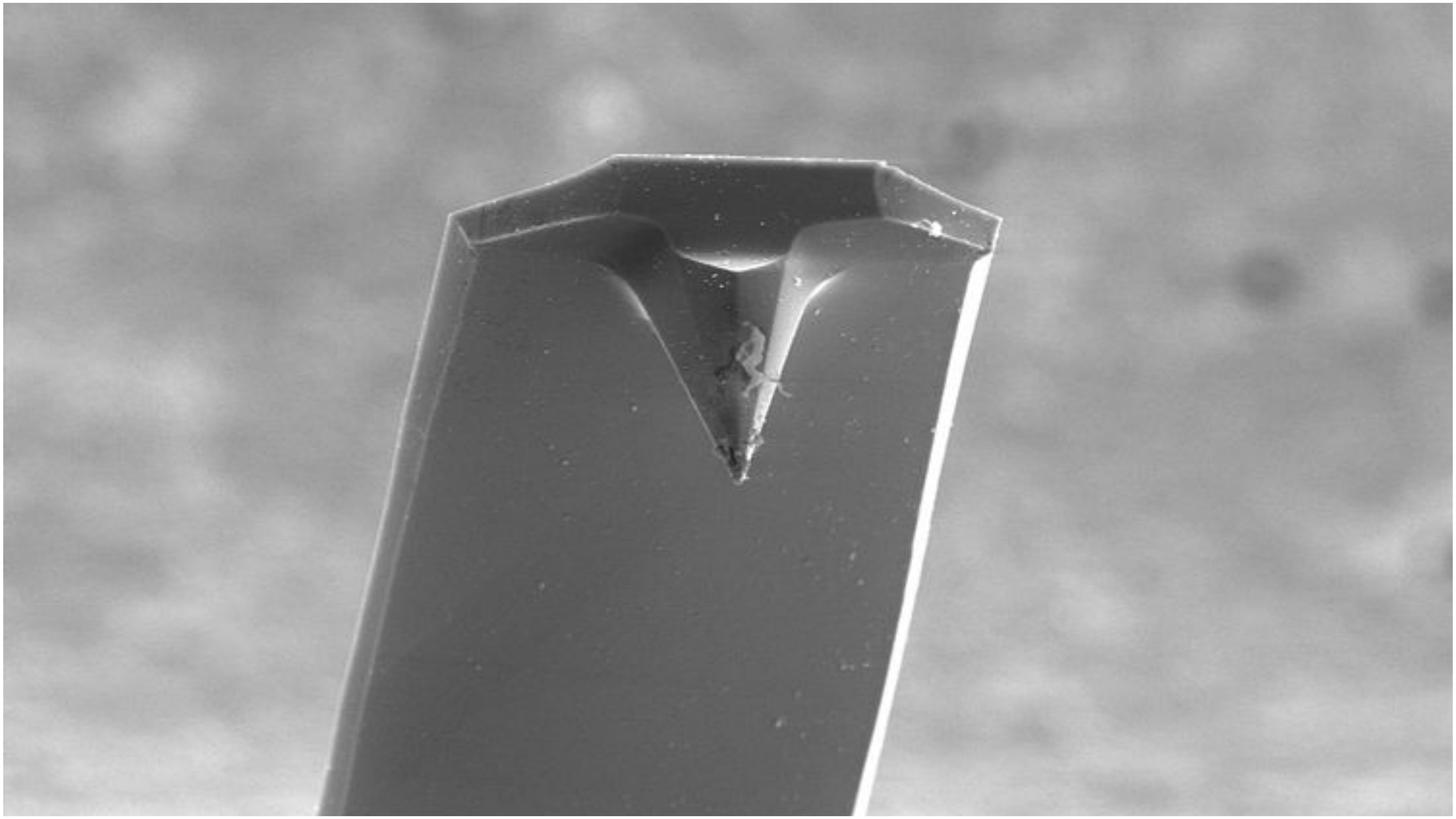
Basic Principles of AFM

- The AFM consists of a cantilever with a sharp tip.
- The cantilever is typically silicon or silicon nitride with a tip radius of curvature on the order of nanometers.
- When the tip is brought into proximity of a sample forces between the tip and the sample lead to a deflection of the cantilever.
- Typically, the deflection is measured using a laser spot reflected from the top surface of the cantilever into an array of photodiodes.

Electron Micrograph of Used AFM Cantilever



Width ~ 100 µm

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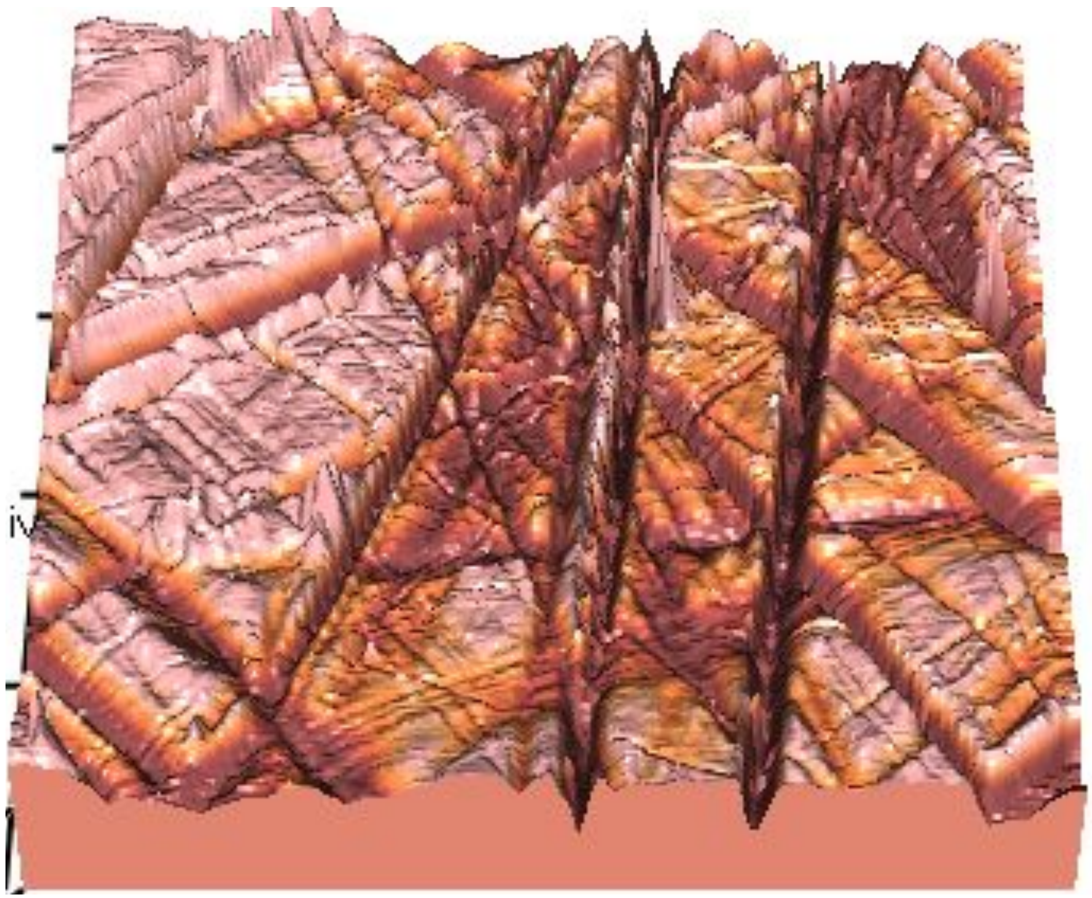
Commercial AFM

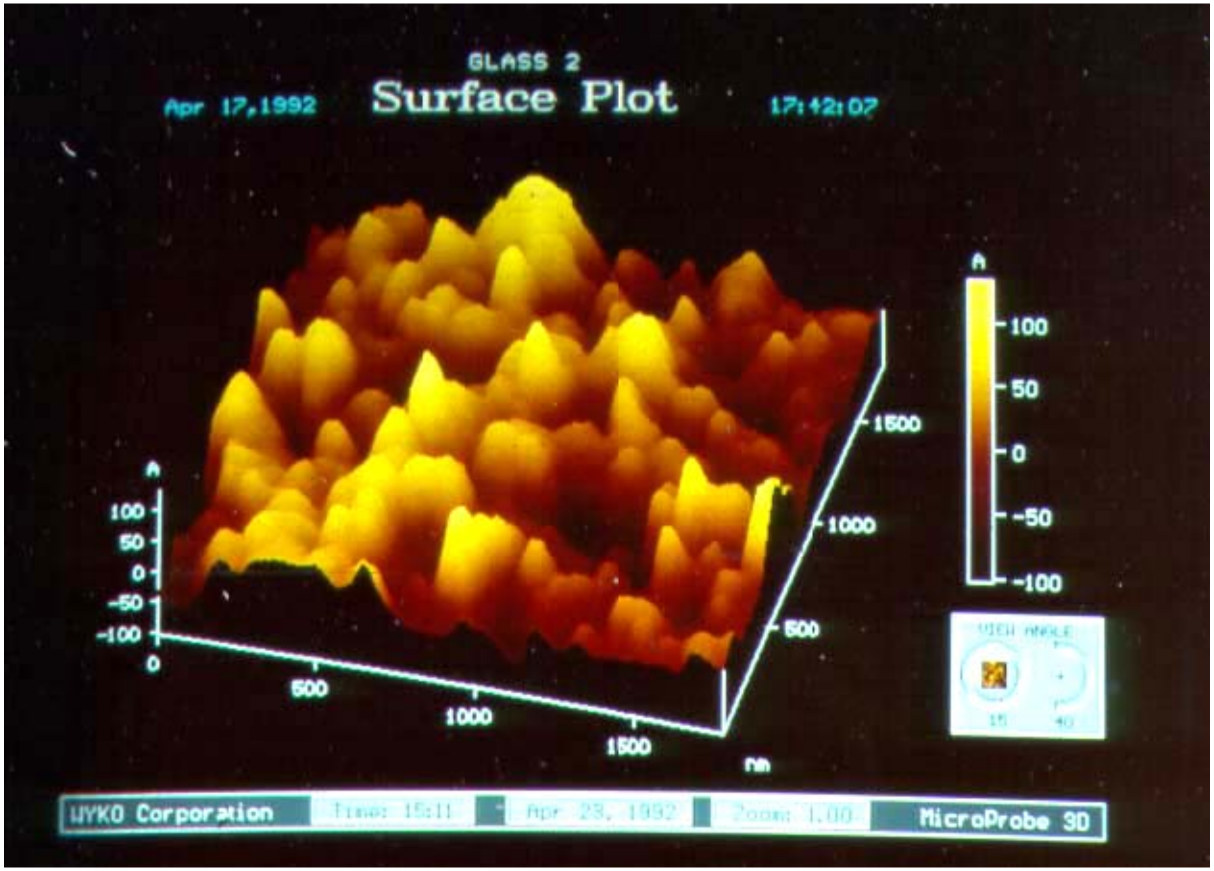
AFM Scan of 20 μm x 20 μm Glass Sample



Ref: Bruker

WYKO AFM (1991)

Glass Sample - RMS 3.4 nm



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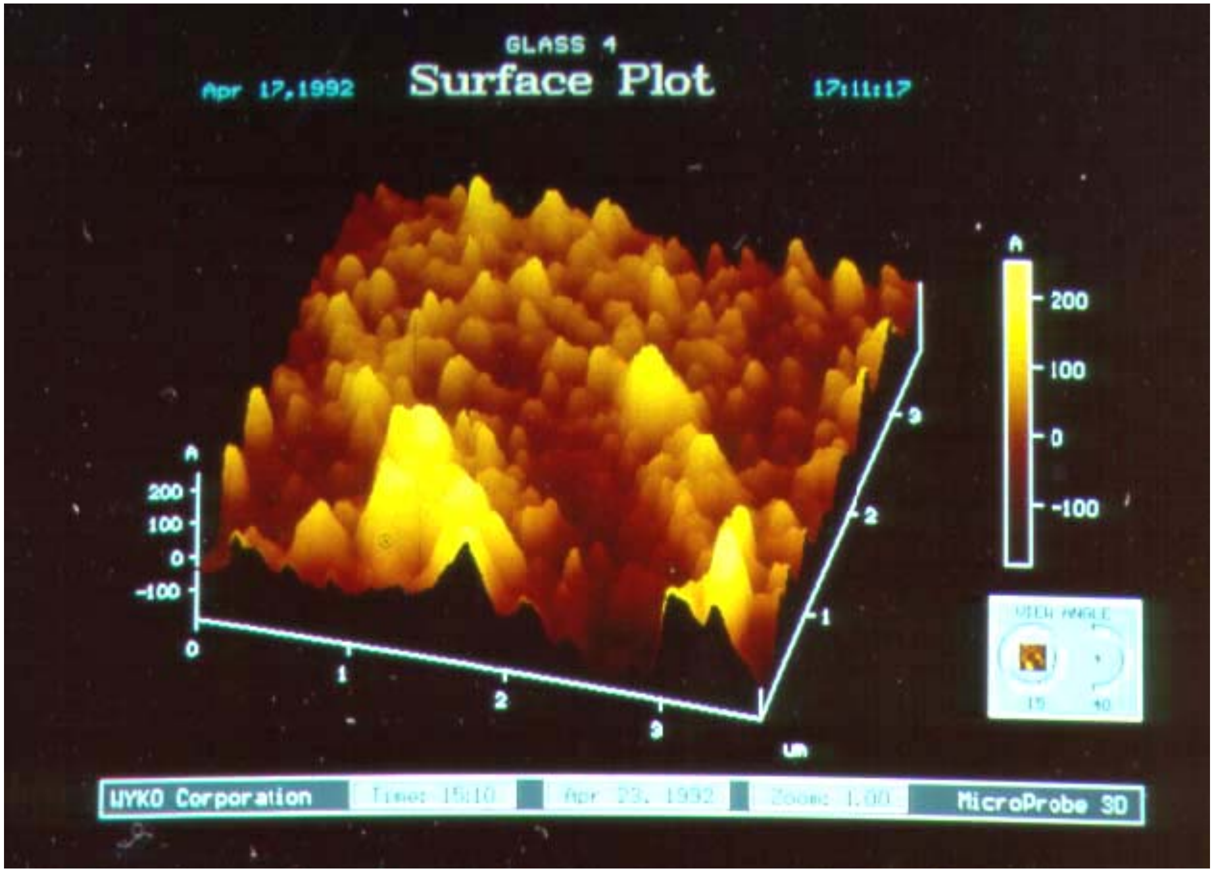
Glass Sample - RMS 5.8 nm



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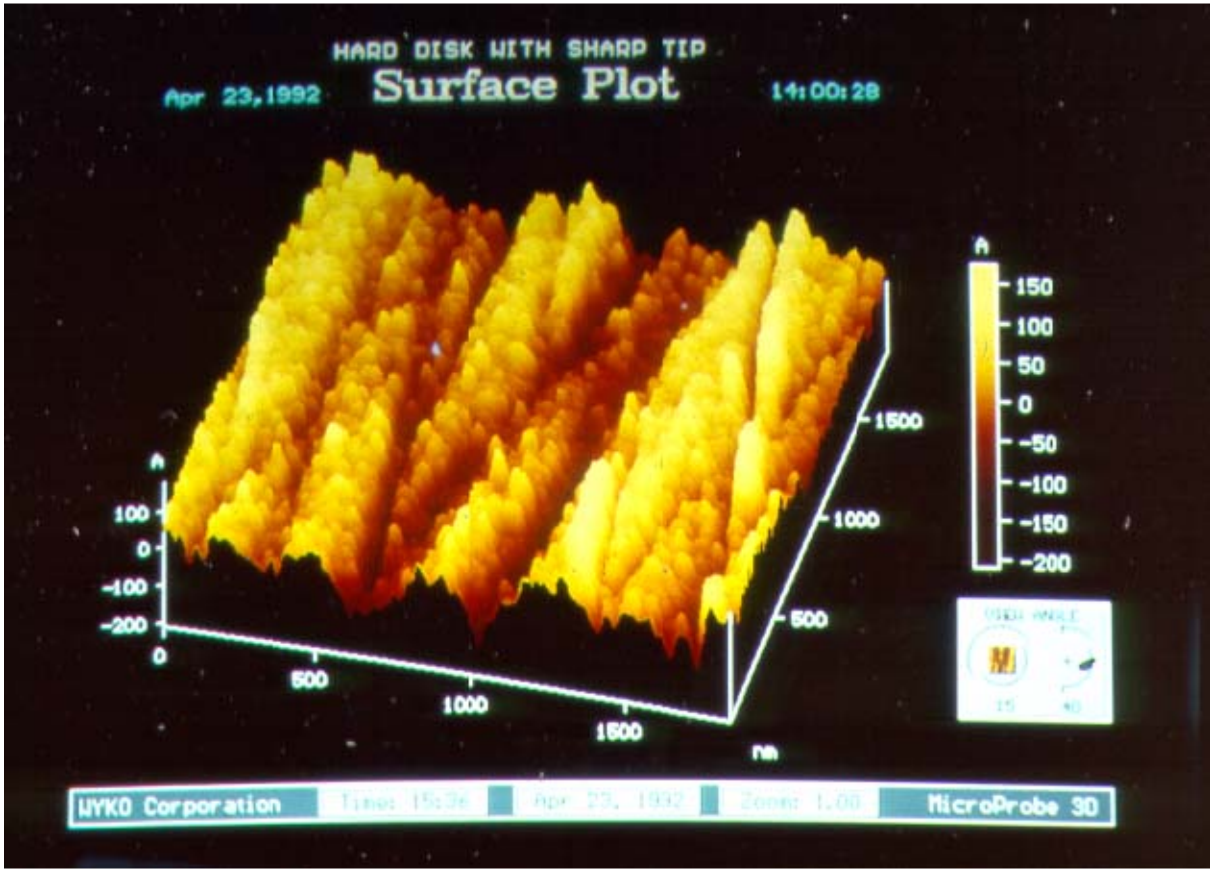
Magnetic Hard Disk



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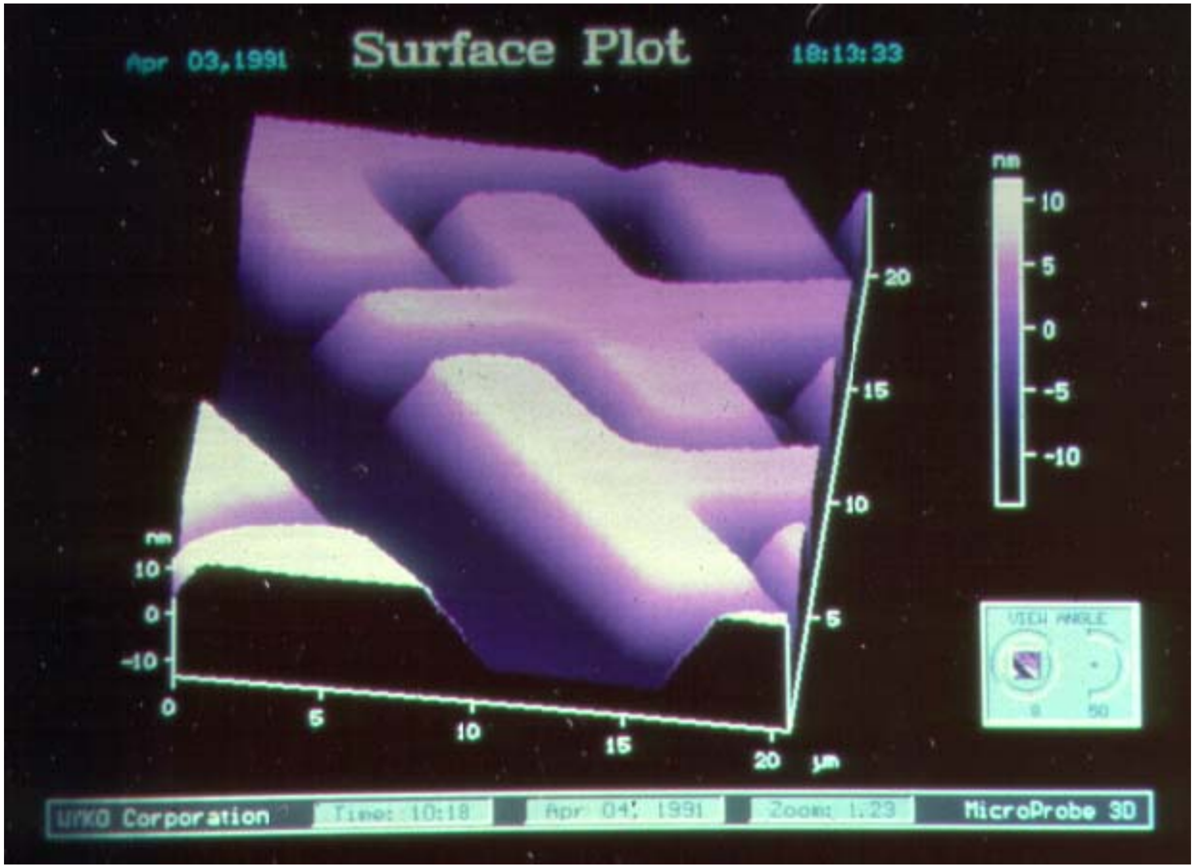
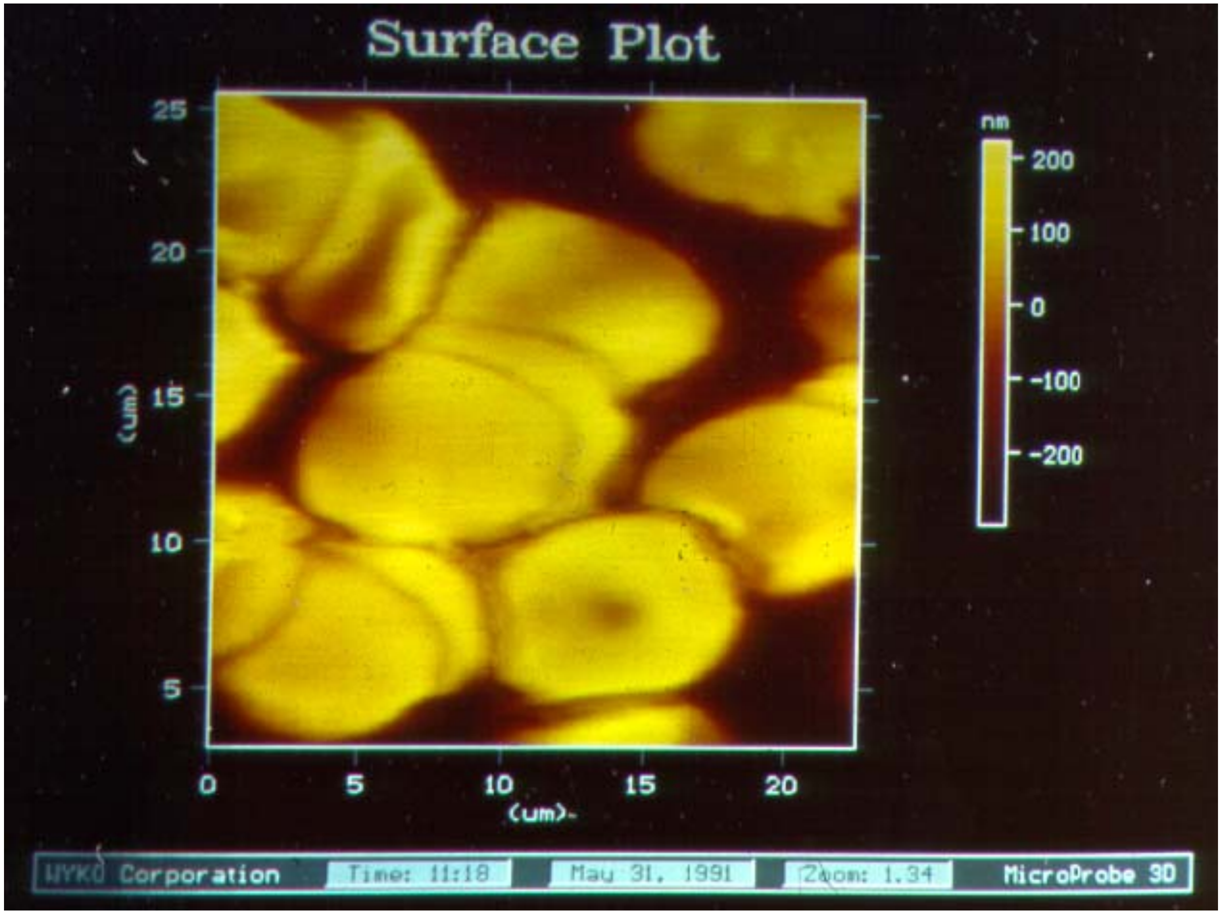
Integrated Circuit



Blood



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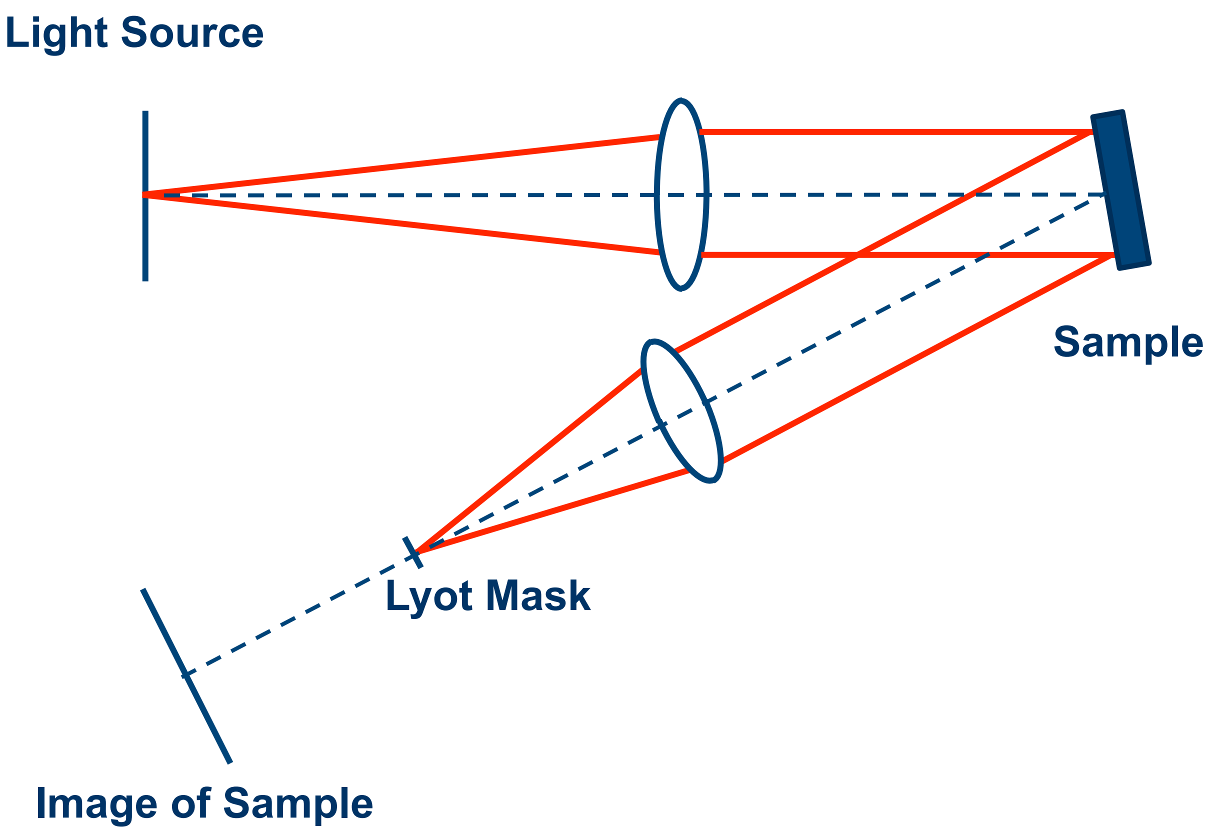
6.4 Lyot Test (Zernike Phase Contrast)



Lyot Mask

- Mask
  - Intensity transmittance of a^2 for the region within the first dark ring of the Airy disk focused on the mask
  - Essentially 100% transmittance for the region outside the first dark ring of the Airy disk
  - Retards the phase of the light falling within the first dark ring of the Airy disk 90^o (positive contrast) or 270^o (negative contrast)
- If z(x,y), the height variation of the test sample surface, is a small fraction of a wavelength of the light used, the amplitude of the light reflected from the sample at normal incidence can be written

$$e^{i\frac{2\pi}{\lambda}2z(x,y)} \approx 1 + \frac{2\pi}{\lambda}2z(x,y)i$$

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Irradiance Distribution in Image Plane

For unit magnification and positive contrast the irradiance distribution, I(x,y), in the image plane of the sample tested in reflection at normal incidence is given by

$$I(x,y) = t_o^2 \left| ai + \frac{4\pi}{\lambda} z(x,y) i \right|^2 =$$

$$t_o^2 a^2 \left[1 + \frac{4\pi}{\lambda} \frac{z(x,y)}{a} \right]^2 \approx$$

$$t_o^2 a^2 \left[1 + \frac{8\pi}{\lambda} \frac{z(x,y)}{a} \right]$$

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Linear Relationship Between Irradiance Distribution and Height Variations

If $4\pi z(x,y)/\lambda << a$, the irradiance is linearly related to the height variations of the surface.

As an example let z =10 Angstroms and λ=633 nm. Density, D, is defined as

$$D = \log\left[\frac{1}{a^2}\right]$$

D	0	0.5	1	1.5	2
a	1	0.56	0.32	0.18	0.10
$1+\frac{8\pi}{\lambda}\frac{z(x,y)}{a}$	1.04	1.07	1.13	1.22	1.40
$\left[1+\frac{4\pi}{\lambda}\frac{z(x,y)}{a}\right]^2$	1.04	1.07	1.13	1.24	1.44

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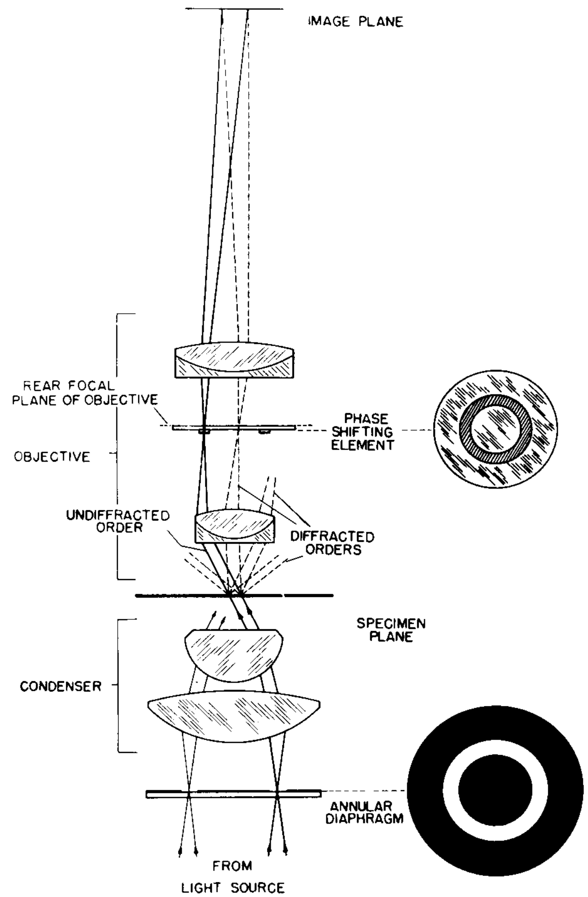
Phase-Contrast Microscope



To increase the resolution and the amount of light, the light source and mask are often annular.

R. Kingslake, "Applied Optics and Optical Engineering", Vol. IV, p.68, (1967).

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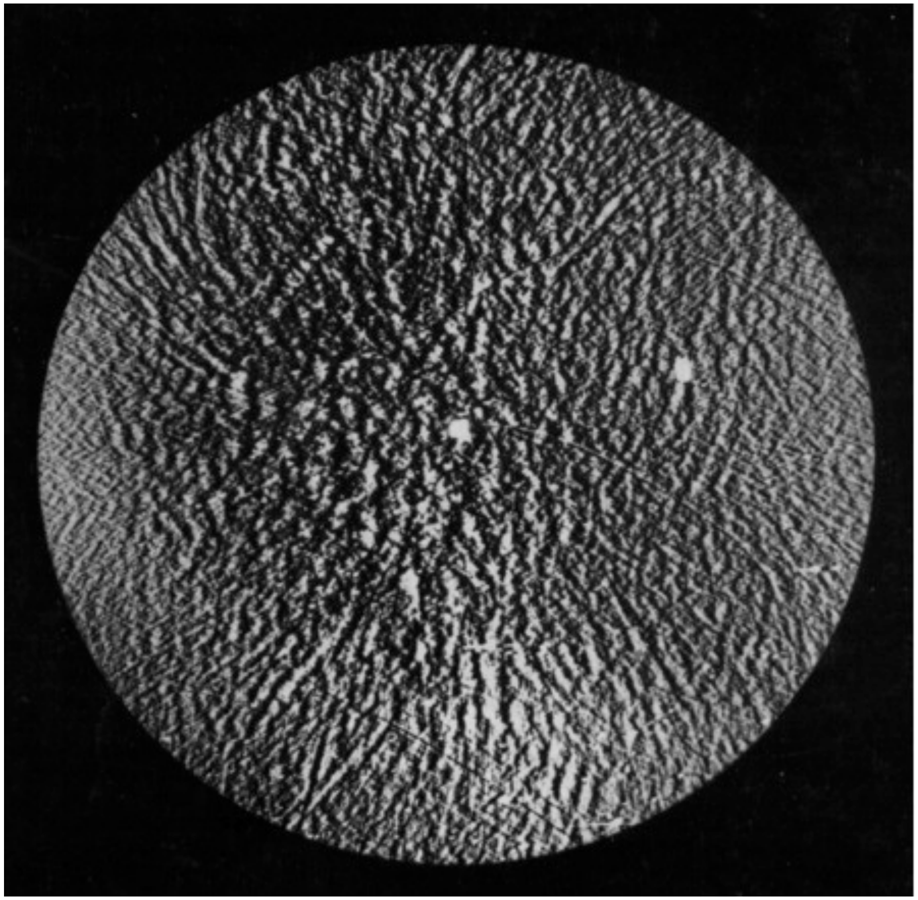
A Pitch Polished Lens Surface



Ref: "Atlas of Optical Phenomena", Vol. 1 by Cagnet, Francon, and Thrierr

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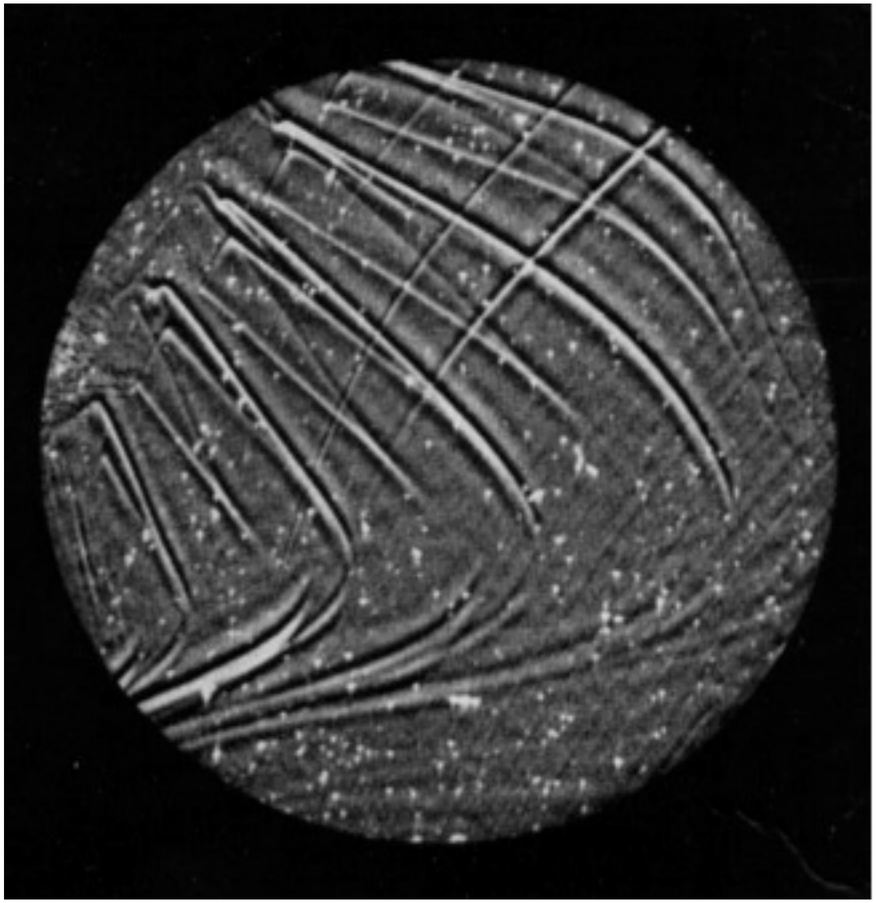
Inhomogeneities in Glass (Schlieren Method)



Pits in Glass (Schlieren Method)

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Herbert Highstone's Comments on Lyot Test

My phase plates are made from colloidal carbon, which is a fancy name for candle soot. First I smoke a glass plate with a candle flame, and then I use a straight edge and a scraper to form the phase shifting element or "phase strip" which can be from 1 mm to 8-10 mm in width. The glass plate can be a surplus "filter element" or even a nice piece of float glass from a high quality picture frame.

The phase contrast setup also acts as an image processor that can emphasize or even delete various spatial frequencies on the glass surface. As the source slit width is reduced, and the geometric image of the slit is moved closer to the edge of the phase strip, the low image frequencies analogous to the "Foucault shadows" are boosted. (HHighstone@cs.com)

Reference - 1

- Pluta, M. "Non-Standard Methods of Phase Contrast Microscopy," in Advances in Optical and Electron Microscopy, Volume 6, Ed. R. Barer and V. Cosslett (London and New York, Academic Press, 1975).

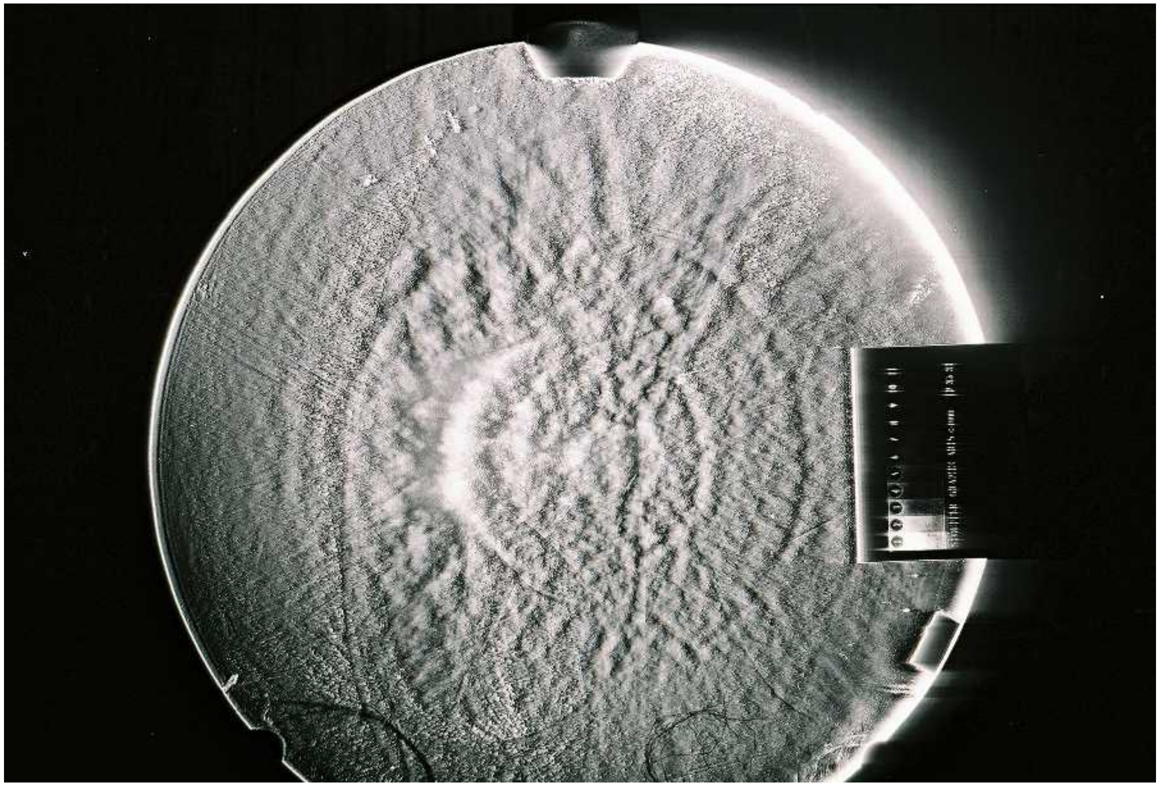
- As Pluta suggests, the soft film of soot can be "fixed" by very gently flowing 99% isopropyl or drug store alcohol over it. Then the film is much more resistant to mechanical damage, and it will also form a smoother edge (as demonstrated by Pluta's micrographs) when shaped with a scraper.

Reference - 2

- Boyd, W.R., "Achieving Smoothness of Optical Surfaces," Applied Optics Vol. 10 No. 6, p. 1478, June 1971.

- Boyd found that phase contrast was quite useful to keep track of the process of polishing supersmooth optical surfaces. It's a quick and robust test method, and cheap enough to implement wherever it's needed.

Badly Polished 6-inch Newtonian Primary Mirror



6.5 FECO – Fringes of Equal Chromatic Order

- **The FECO interferometer**
  - Multiple-beam interferometer
  - White light source
  - Test sample is focused onto the entrance slit of a spectrograph
  - Each fringe gives the profile of the distance between the test surface and the reference surface for the line portion of the surface focused onto the entrance slit.

For multiple-beam interference the transmission is given by

$$I_t = \frac{I_{\max}}{1 + F Sin[\delta/2]^2} \quad \text{where } \delta = \frac{2\pi}{\lambda_o} 2ndCos[\theta] + 2\phi$$

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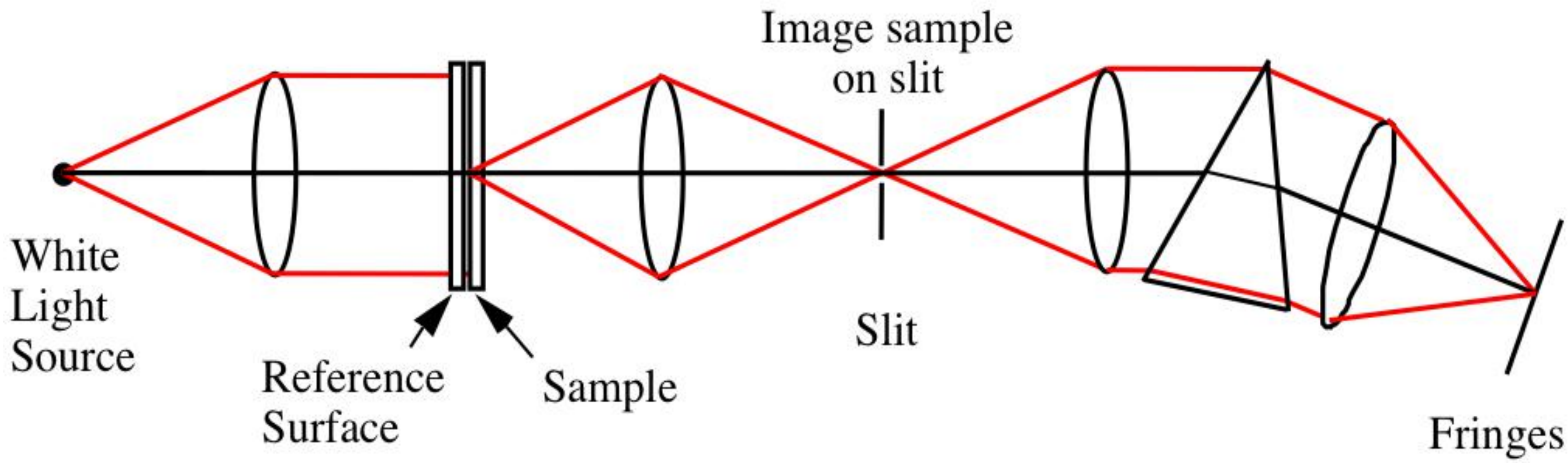
Schematic Diagram of FECO Interferometer



If n = 1 and θ = 0° for a bright fringe of order m

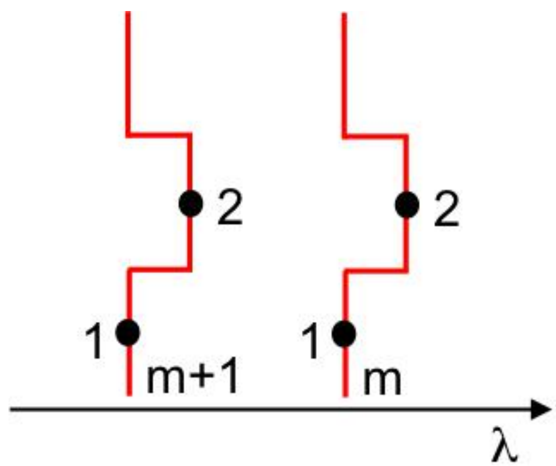
$$\frac{\phi}{\pi} + 2\frac{d}{\lambda} = m$$

It should be noted that for a given fringe d/λ= constant and

$$\lambda_m = \frac{2d}{m - \frac{\phi}{\pi}}$$

FECO Output

The drawing shows two fringes in the FECO output. The goal is to find the surface height difference between points 1 and 2.



$$d = \left(m - \frac{\phi}{\pi}\right)\frac{\lambda}{2} \quad \text{and} \quad d_2 - d_1 = \left(m - \frac{\phi}{\pi}\right)\left(\frac{\lambda_{2,m} - \lambda_{1,m}}{2}\right)$$

Determining Height Difference

For point 1 and fringe orders m and m + 1

$$\left(m-\frac{\phi}{\pi}\right)\lambda_{1,m}=\left(m+1-\frac{\phi}{\pi}\right)\lambda_{1,m+1}$$

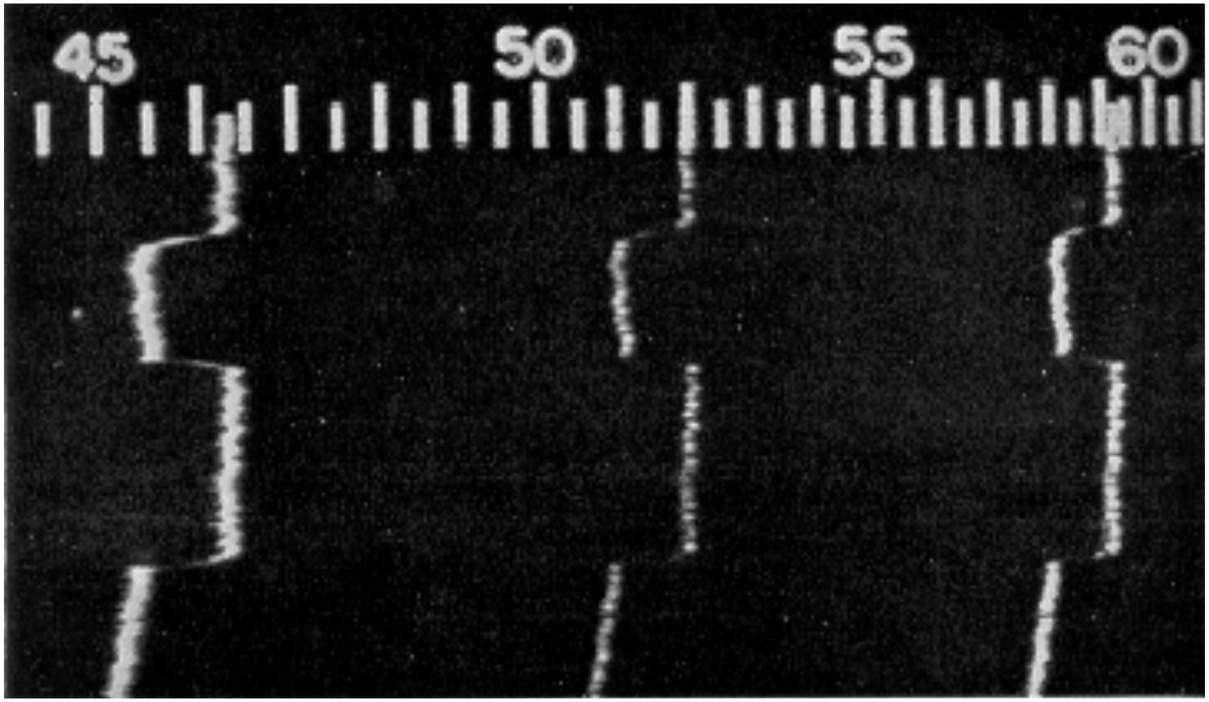
Thus

$$\left(m-\frac{\phi}{\pi}\right)=\frac{\lambda_{1,m+1}}{\lambda_{1,m}-\lambda_{1,m+1}}$$

and

$$d_2-d_1=\frac{\lambda_{1,m+1}}{\lambda_{1,m}-\lambda_{1,m+1}}\left(\frac{\lambda_{2,m}-\lambda_{1,m}}{2}\right)$$

FECO Results for Section of a Diamond Crystal Surface (Ref: Born & Wolf)



Scale is wavelength in hundreds of Angstroms.

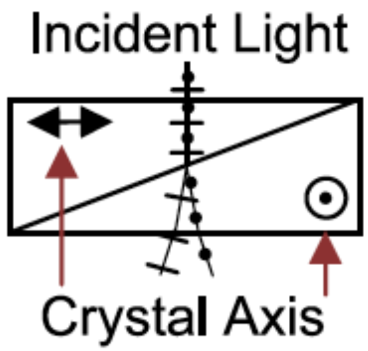
Since d_2-d_1 is proportional to $\lambda_{2,m}$-$\lambda_{1,m}$, the profile of the cross-section of an unknown surface is obtained by plotting a single fringe on a scale proportional to the wavelength.

Comments on FECO

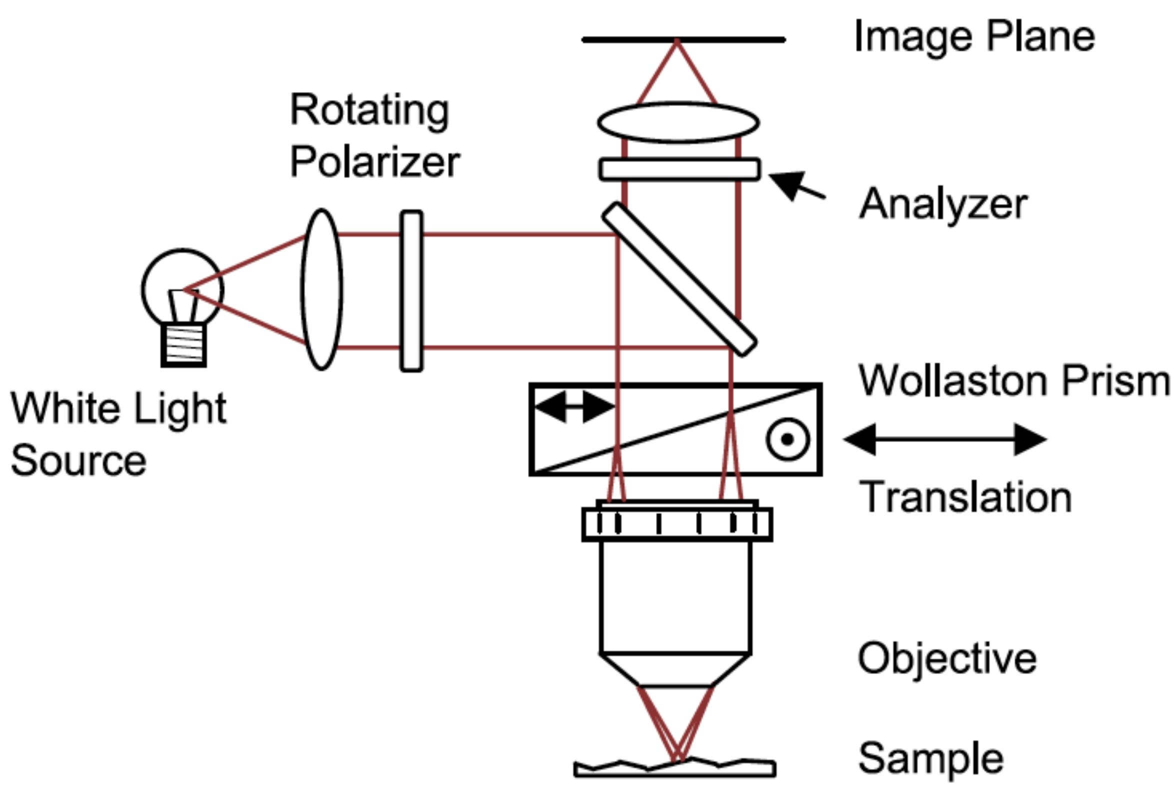
- The slit selects a narrow section of the interference system and each fringe is a profile of the variation of d in that section since there is exact point-to-point correspondence between the selected region and its image on the slit.
- Small changes in d are determined by measuring small changes in λ. There are no ambiguities at a discontinuity or whether a region is a hill or a valley. Surface height variations in the Angstrom range can be determined.

Two disadvantages are
1) we are getting data only along a line and
2) the sample being measured must have a high reflectivity.

6.6 Nomarski Interferometer - Differential Interference Contrast (DIC)



Wollaston Prism



Sometimes called polarization interference contrast microscope

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Nomarski Interferometer – How does it work? Part I.

- A polarizer sets the angle of polarization.
- The Wollaston splits the light into two beams having orthogonal polarization, which are sheared with respect to one another.
- After reflection off the test surface the Wollaston recombines the two beams and undoes the shear in the beam so source spatial coherence is not required.
- A fixed analyzer placed after the Wollaston transmits like components of the two polarizations and generates an interference pattern.

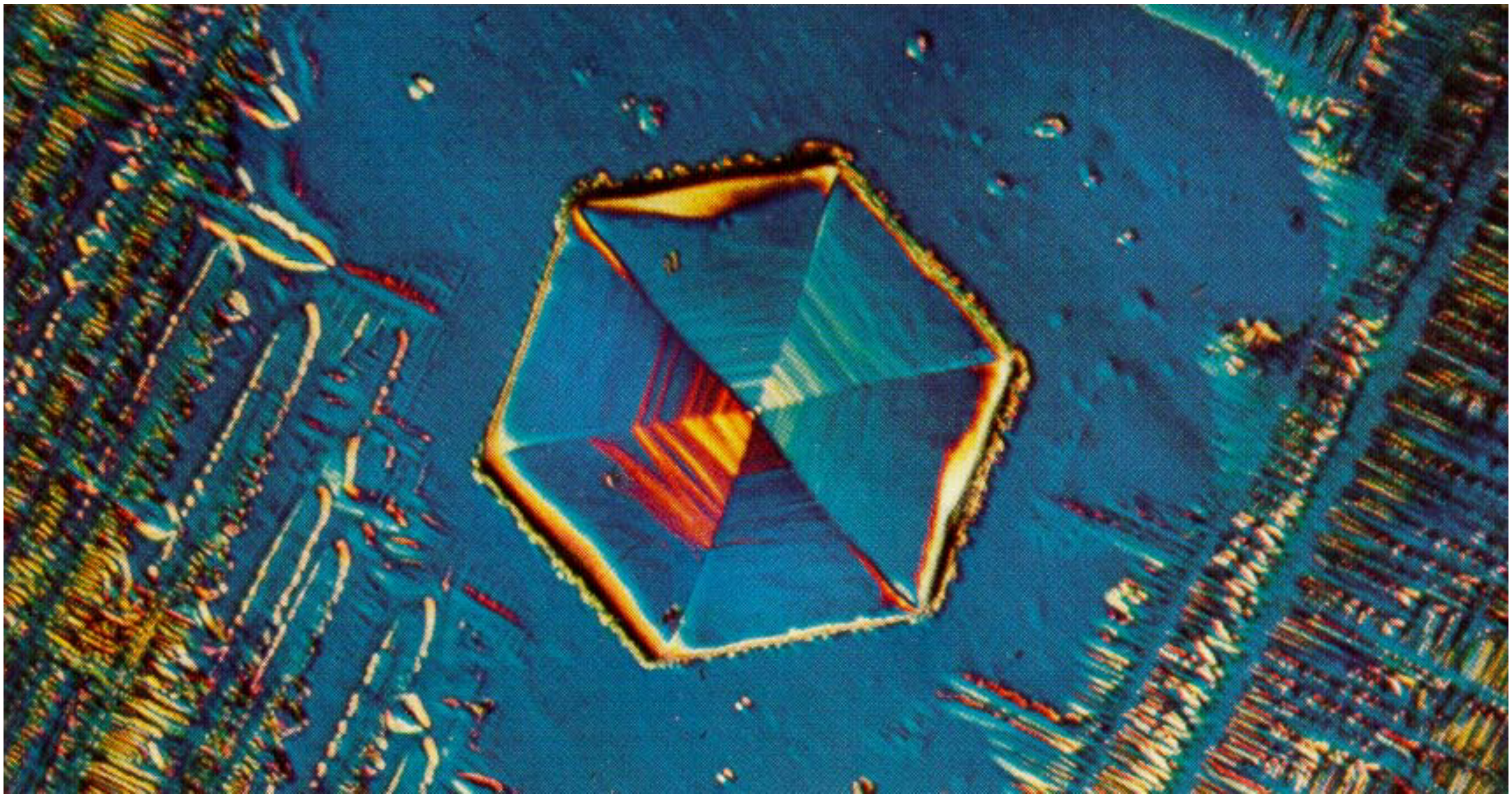
Nomarski Interferometer – How does it work? Part II.

- **The resulting image shows the height difference between two closely spaced points on the test surface.**
  – The point separation (shear at the test surface) is usually comparable to the optical resolution of the microscope objective so only one image is seen.
  – The image shows slope changes. Like all shearing interferometers, only slope changes in the direction of the shear are seen.
- **The path difference between the two beams is adjusted by laterally translating the Wollaston prism.**
  – If the axes of the polarizer and analyzer are parallel and the prism is centered, the path lengths are equal and white light is seen for a perfect test surface with no tilt.

Nomarski Interferometer – How does it work? Part III.

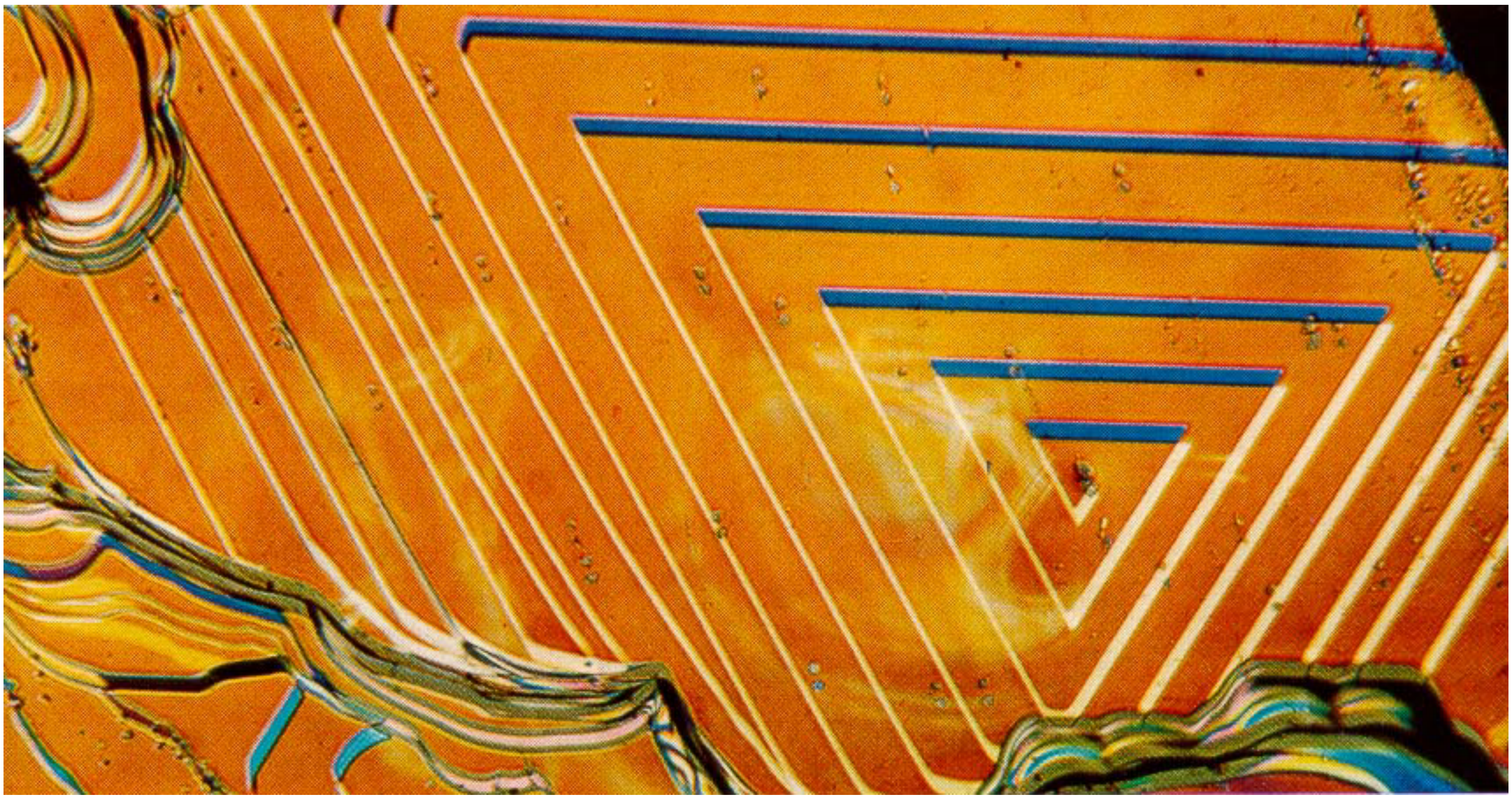
- If polarizer and analyzer are crossed and the prism centered, no light gets through.
- If the prism is translated sideways
  – Two beams have unequal paths and different colors are seen
  – Color for a specific feature on the test surface depends upon the path difference between the two beams
  – A constant slope will give a constant color. A color change indicates a change in the surface slope.
- If the polarizer before the prism, or the analyzer before the detector, is rotated
  – Relative intensities of the two orthogonal polarized beams change
  – Colors and contrast change.

Crystals of ammonium alum seen with differential polarization microscope



Ref: "Atlas of Optical Phenomena", Vol. 2, Francon etal.

Crystals of silicon carbide seen with differential polarization microscope



Ref: "Atlas of Optical Phenomena", Vol. 2, Francon etal.

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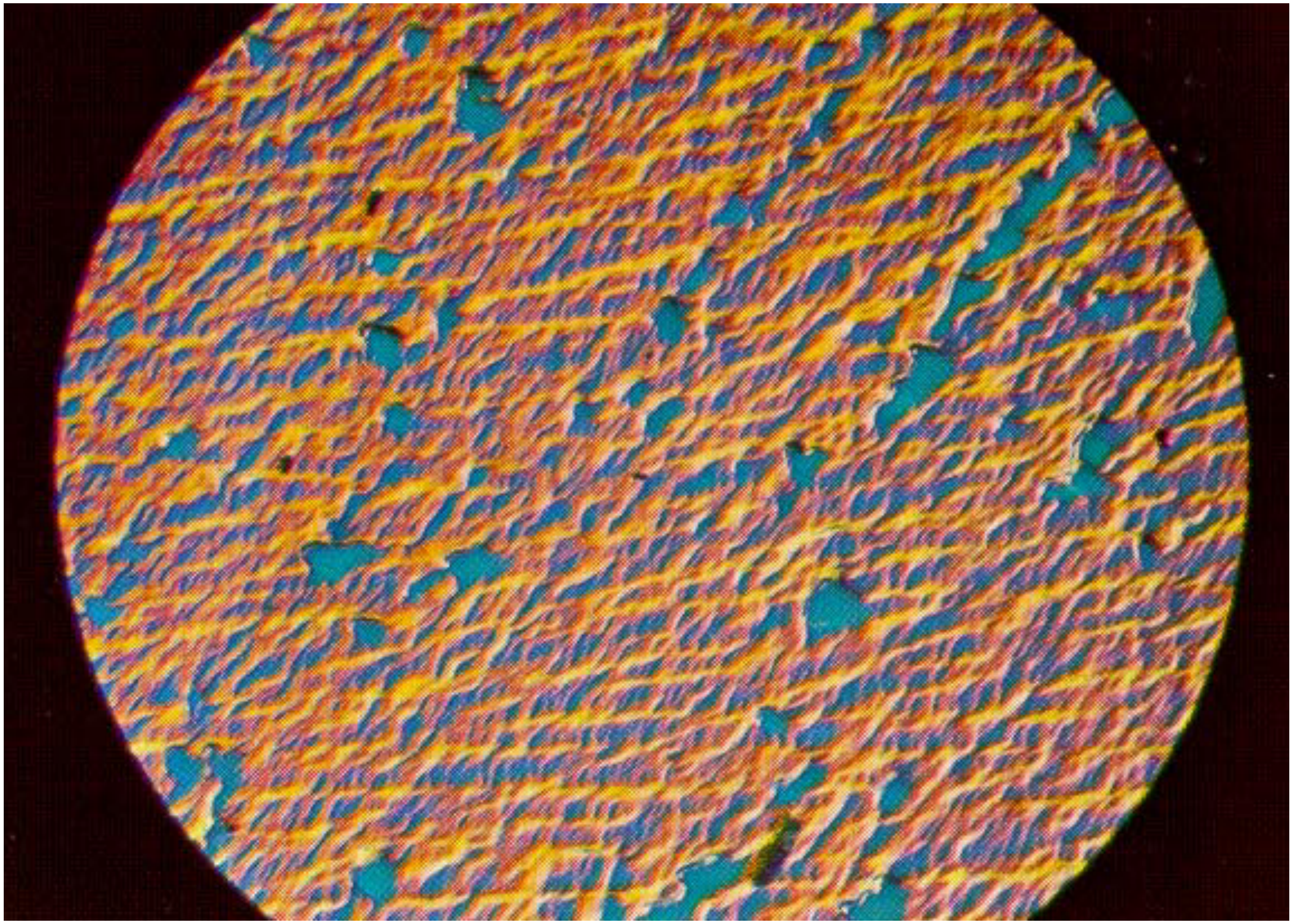
Defects of germanium plate seen with differential polarization microscope



Ref: "Atlas of Optical Phenomena", Vol. 2, Francon etal.

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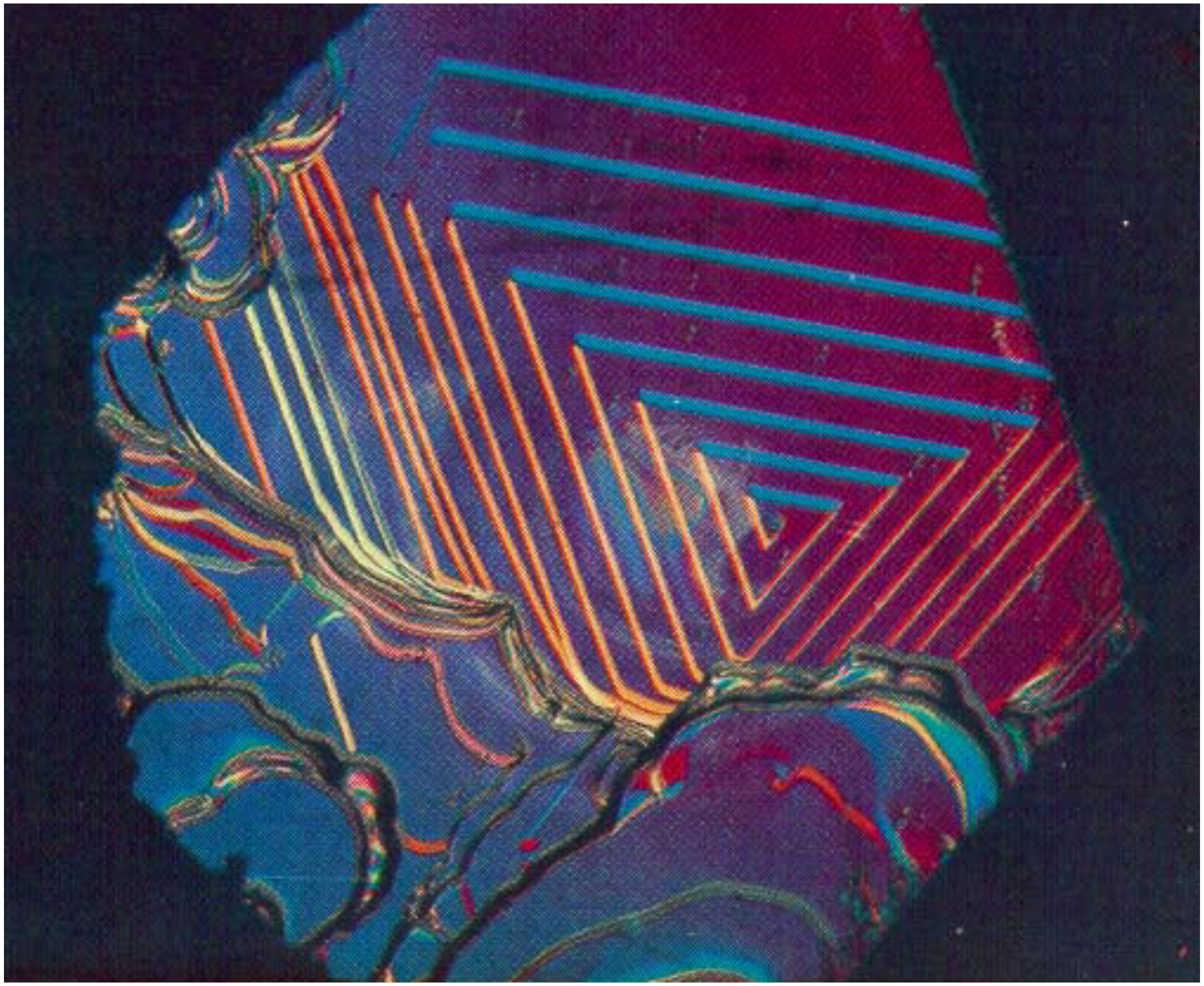
Silicon carbide crystal seen with differential polarization microscope



Ref: "Atlas of Optical Phenomena", Vol. 2, Francon etal.

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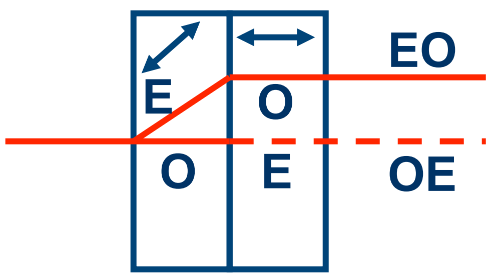
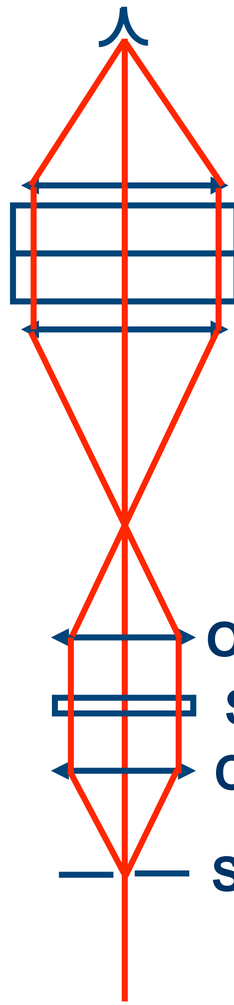
Francon Interference Eyepiece



Savart Plate



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6.7 Interference Microscope

- Non-contact measurement
- 2D or 3D surface topography
- Visual qualitative surface inspection
- Vertical resolution suitable for super-polished optics
- Fast measurement and analysis

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Advantages of White Light over Laser Light

- Lower noise
  - No spurious fringes
- Multiple wavelength operation
  - Measure large steps
- Focus easy to determine

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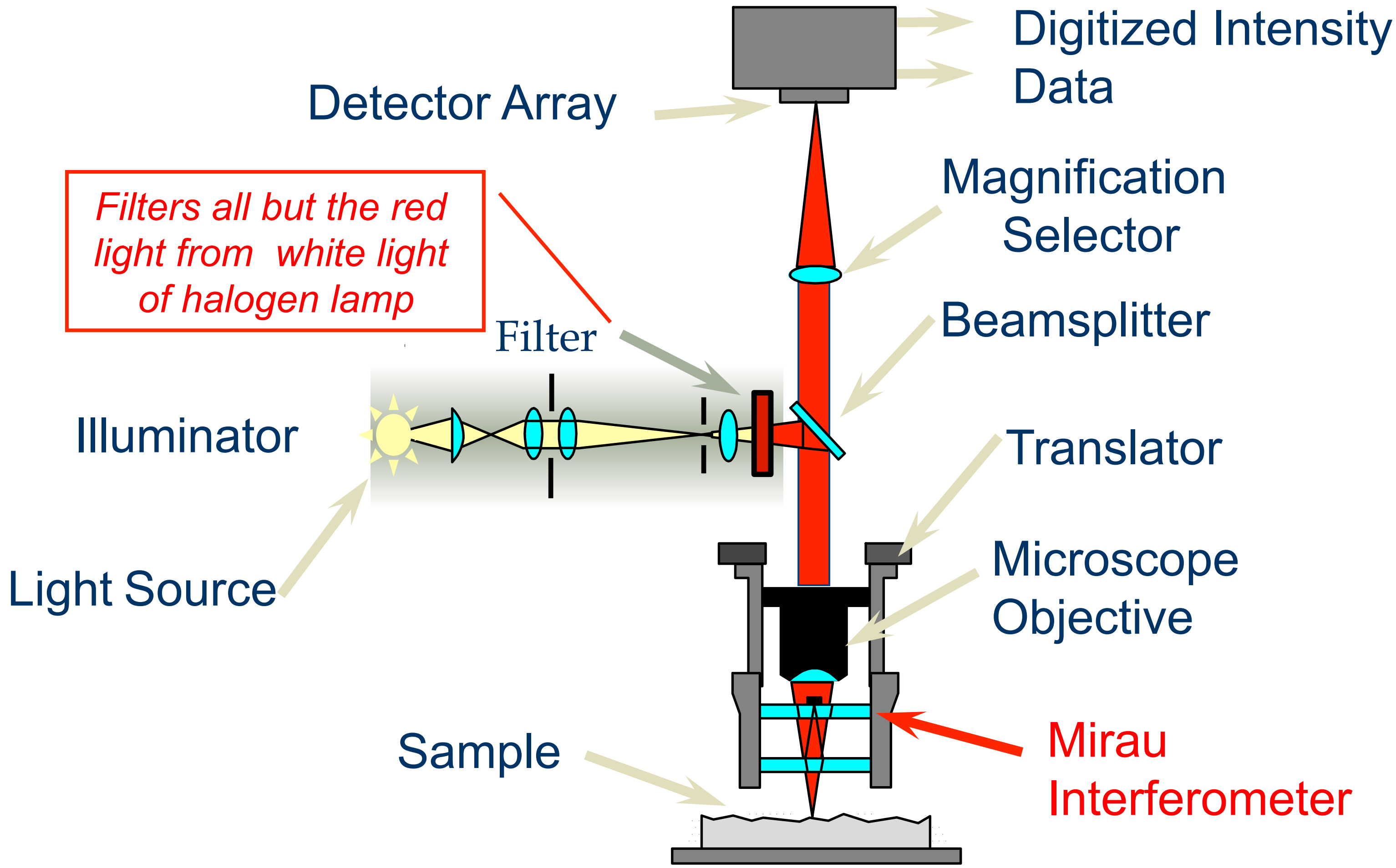
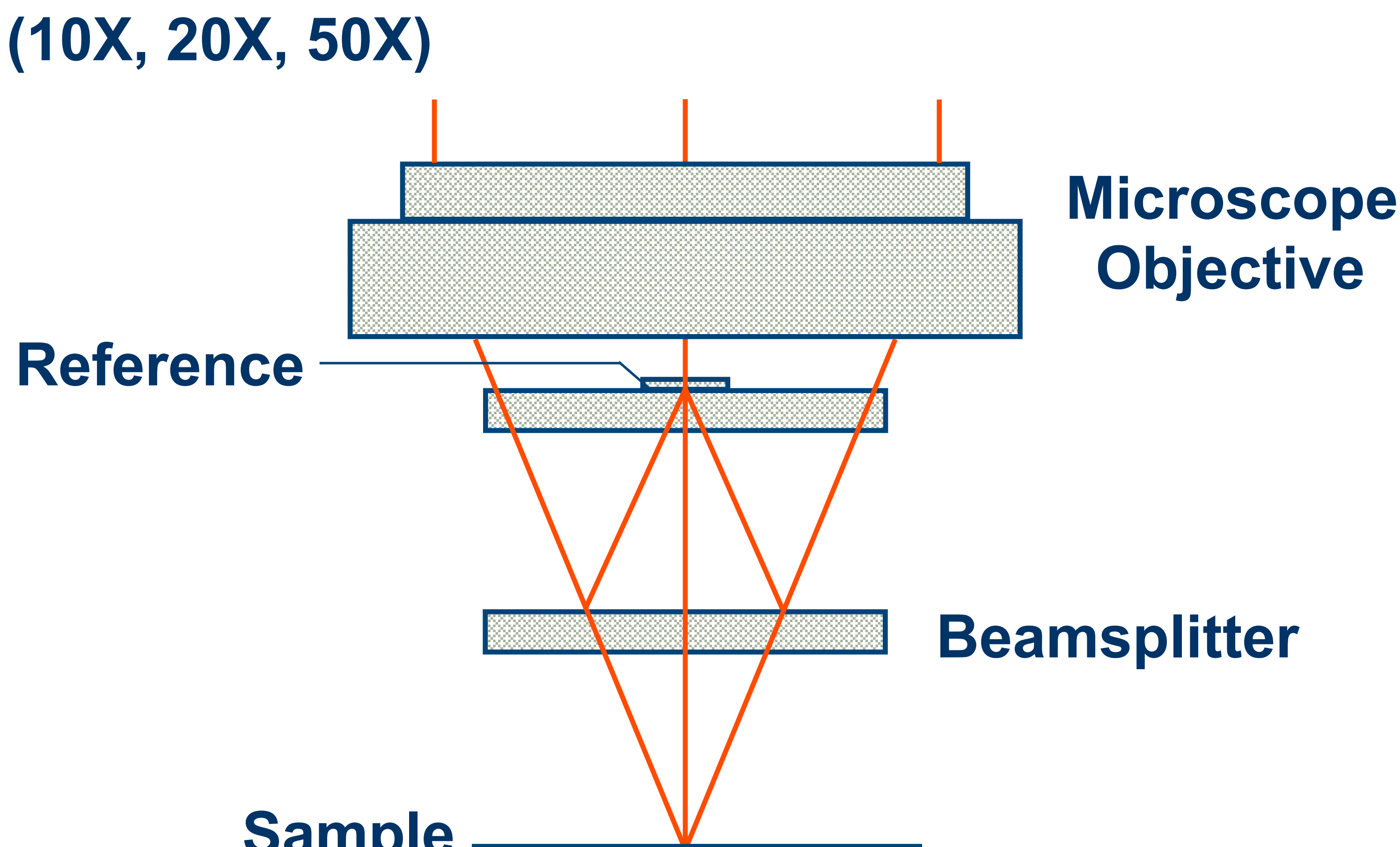
Interference Microscope Diagram

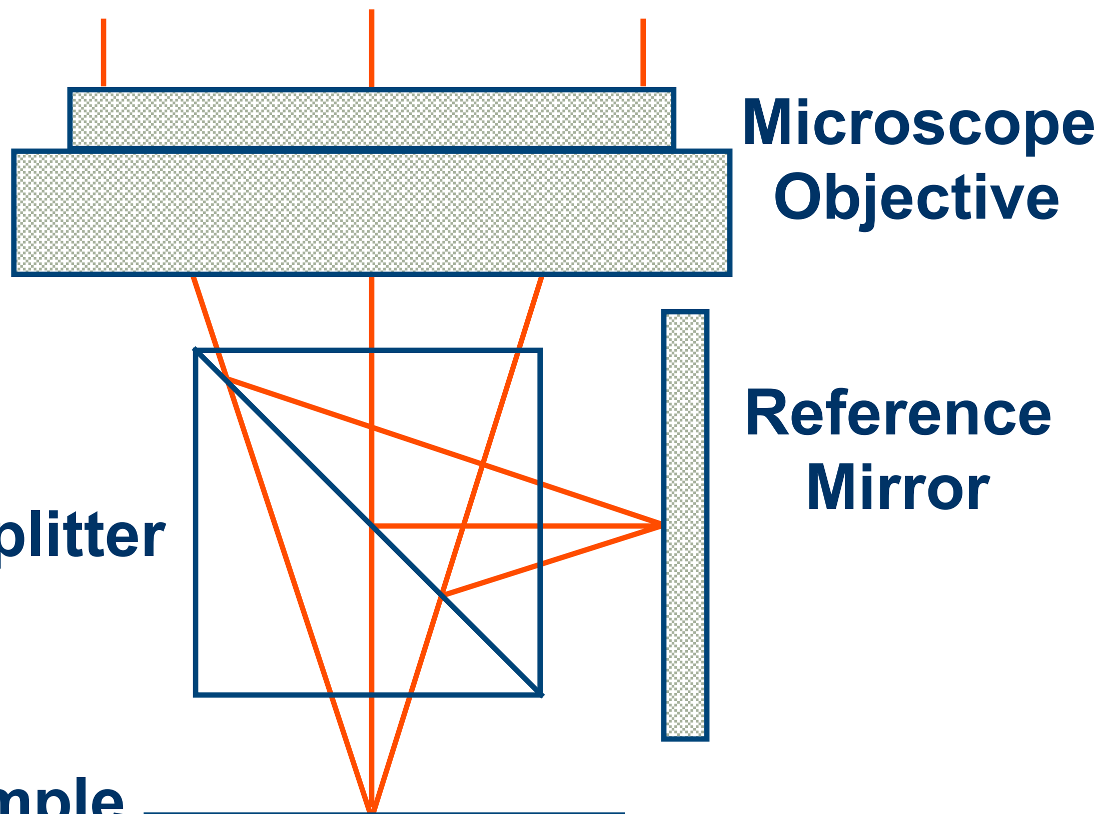


Mirau Interferometer

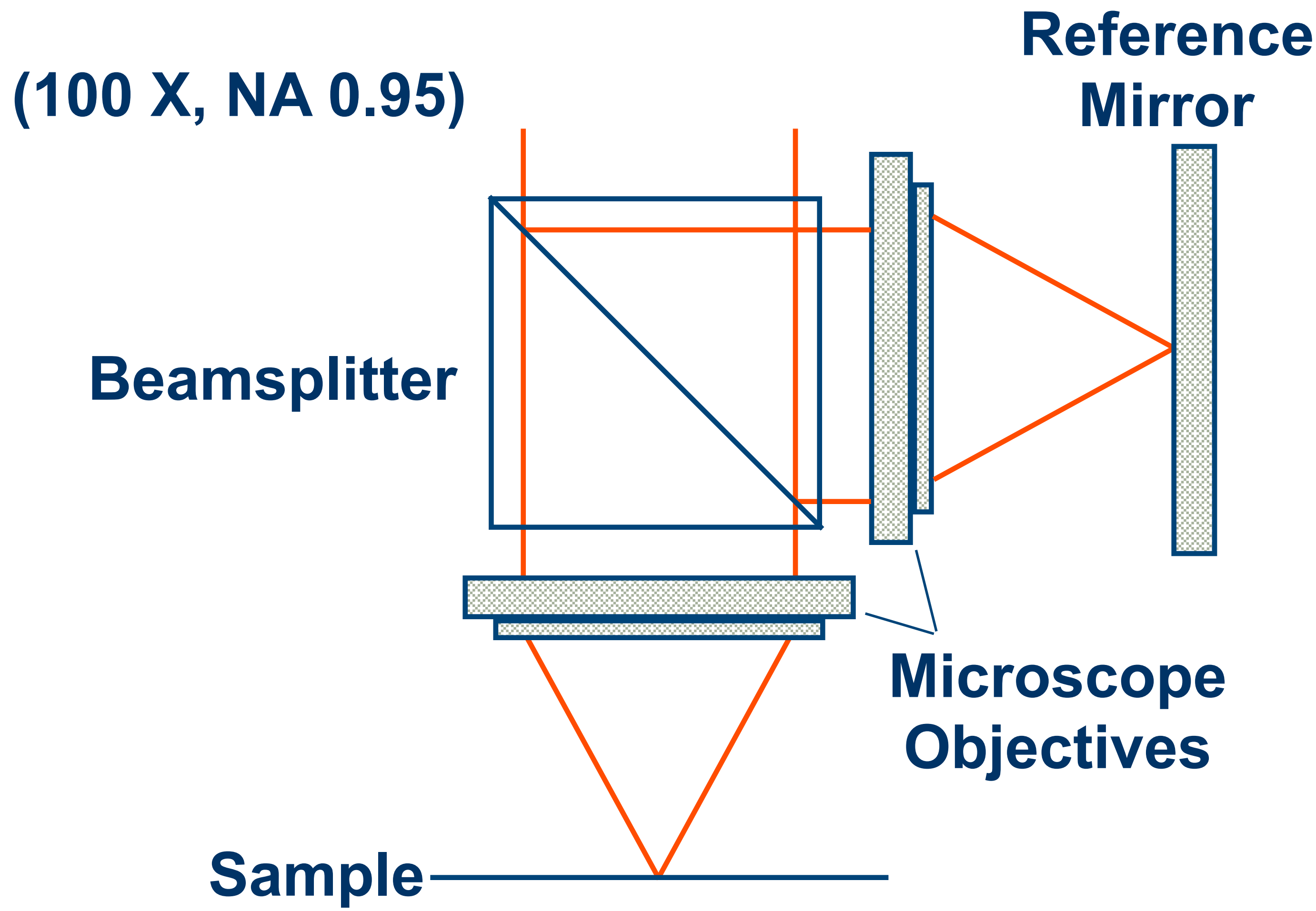


Michelson Interferometer

(1.5X, 2.5X, 5X)



Linnik Interferometer



Interference Objectives

- **Mirau**
  - Medium magnification
  - Central obscuration
  - Limited numerical aperture
- **Michelson**
  - Low magnification, large field-of-view
  - Beamsplitter limits working distance
  - No central obscuration
- **Linnik**
  - Large numerical aperture, large magnification
  - Beamsplitter does not limit working distance
  - Expensive, matched objectives

Optical Profiler

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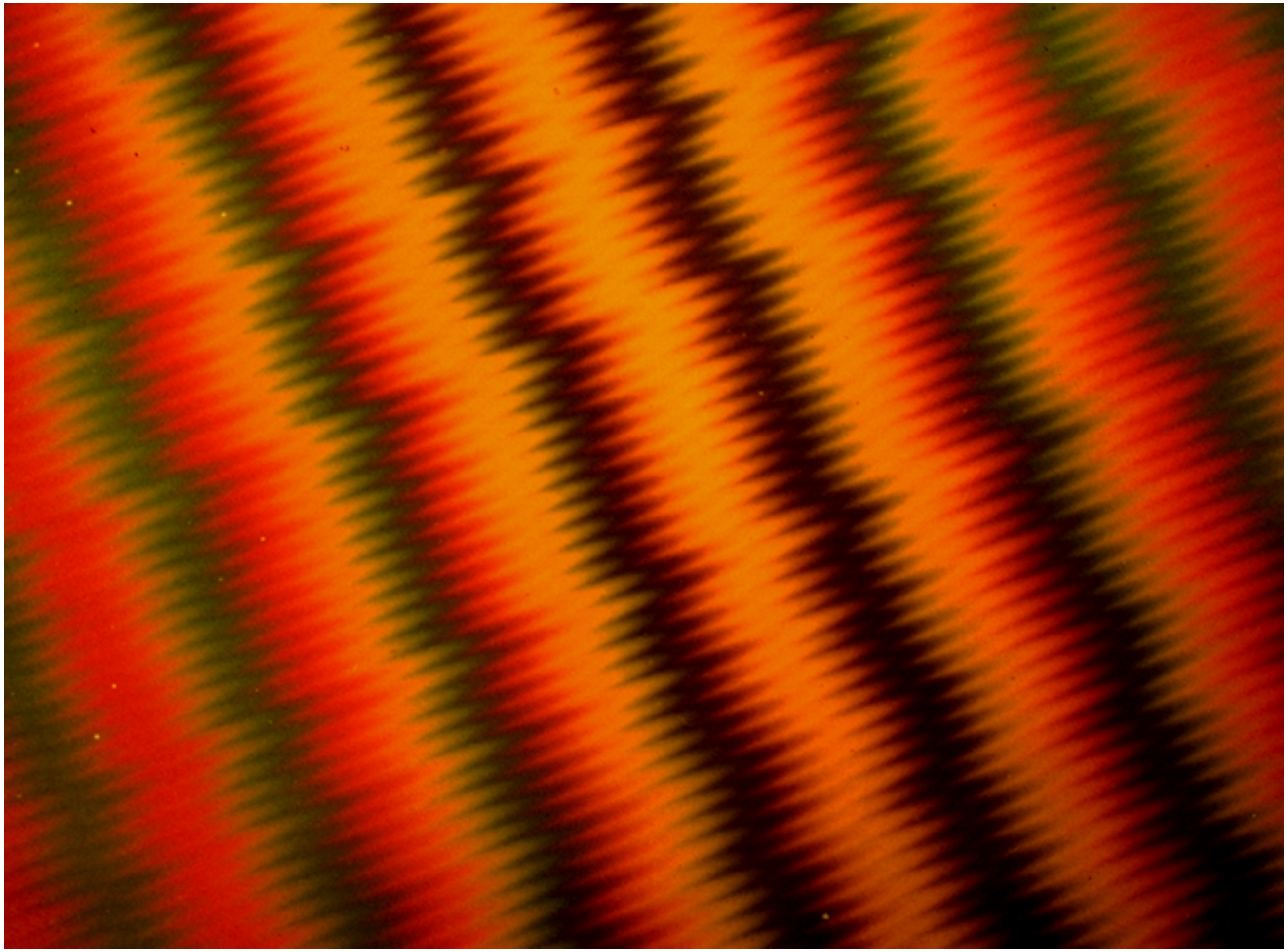
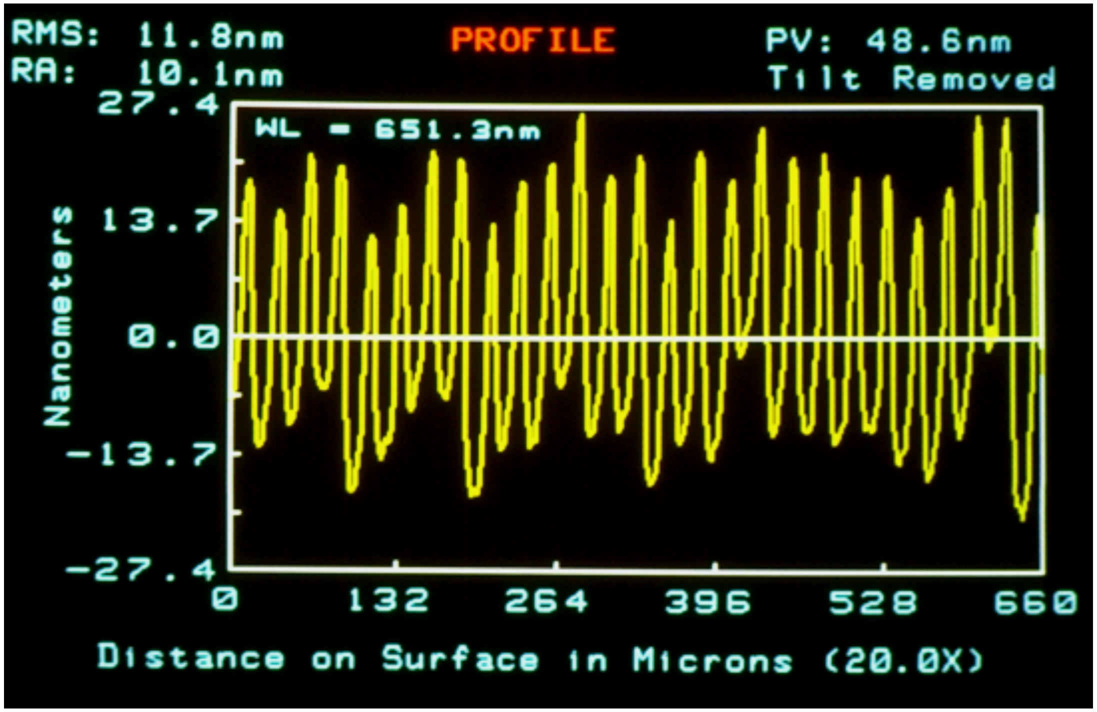
White Light Interferogram



Profile of Diamond Turned Mirror



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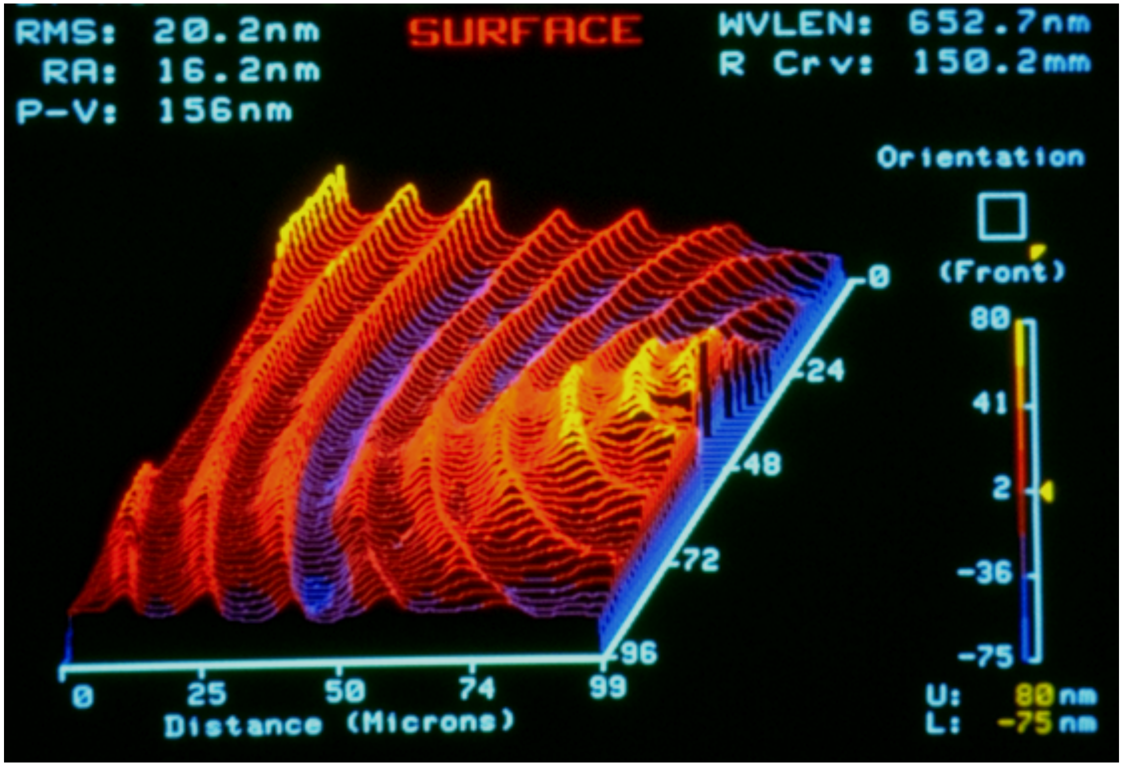
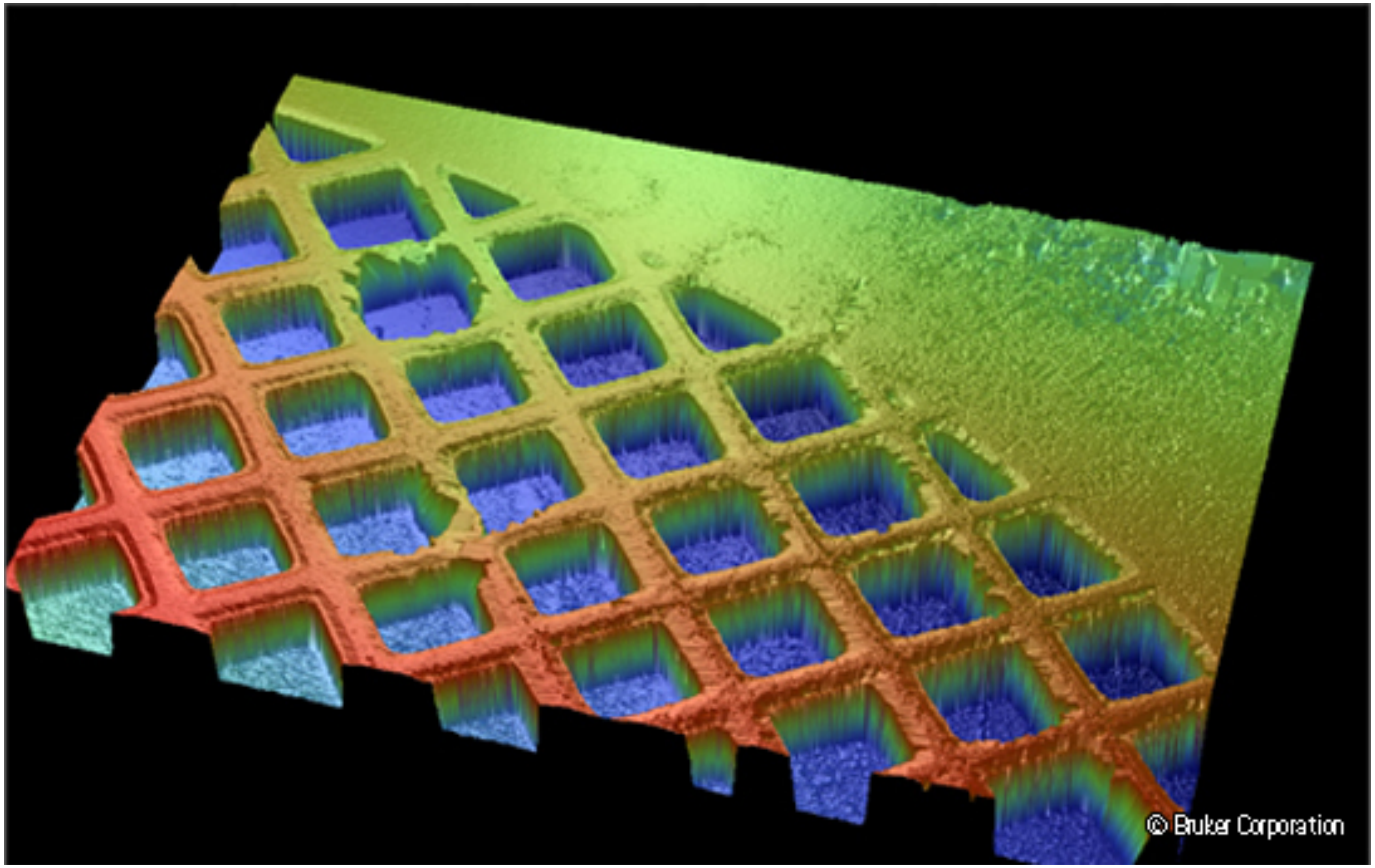
Diamond Turned Mirror

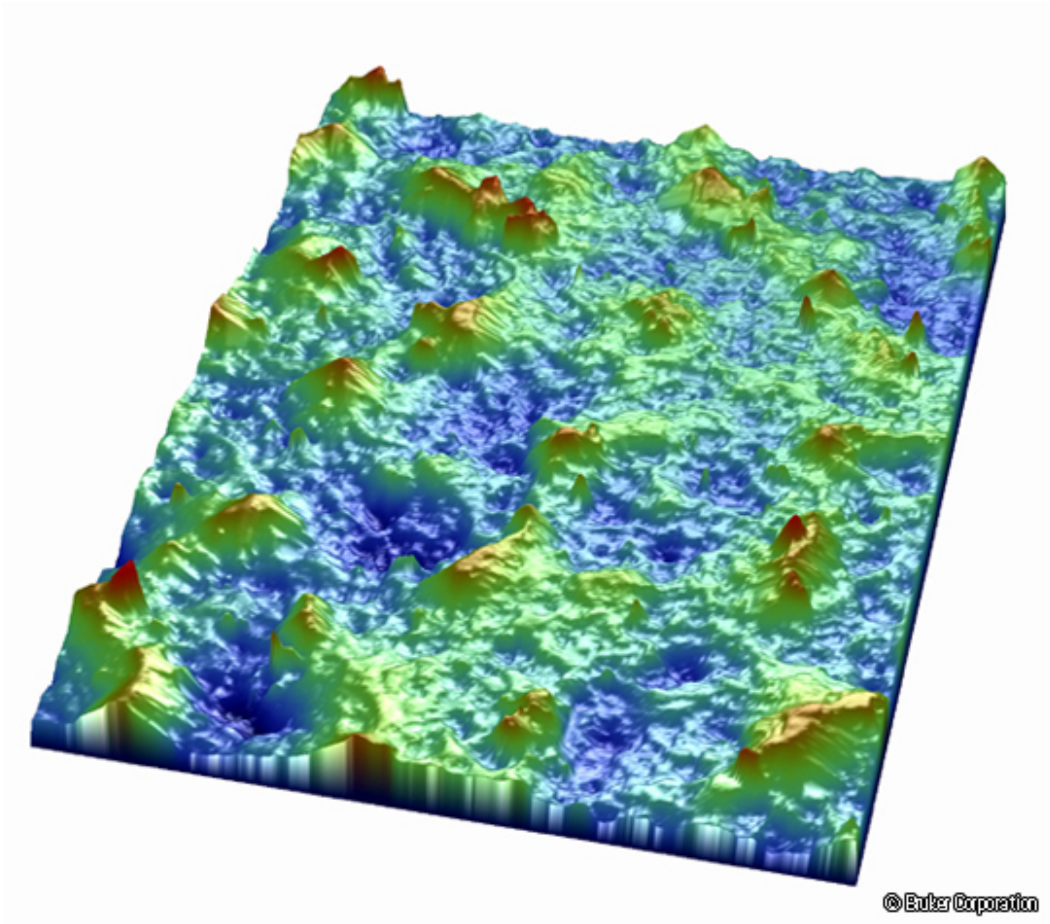


Grating



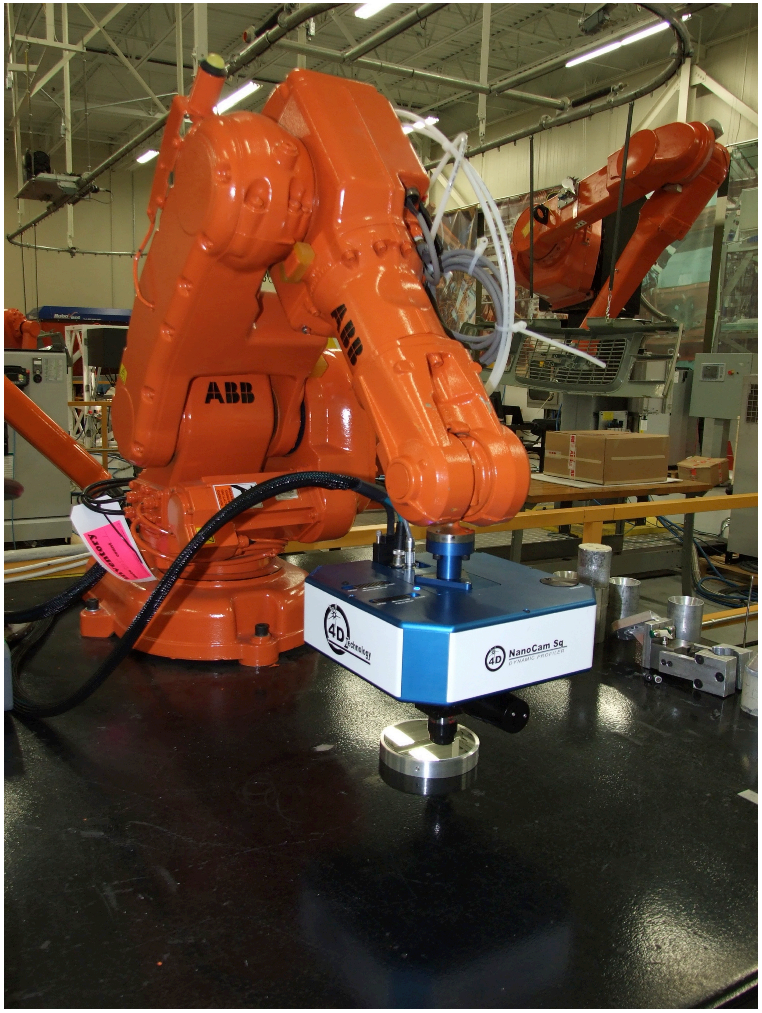
Ref: Bruker

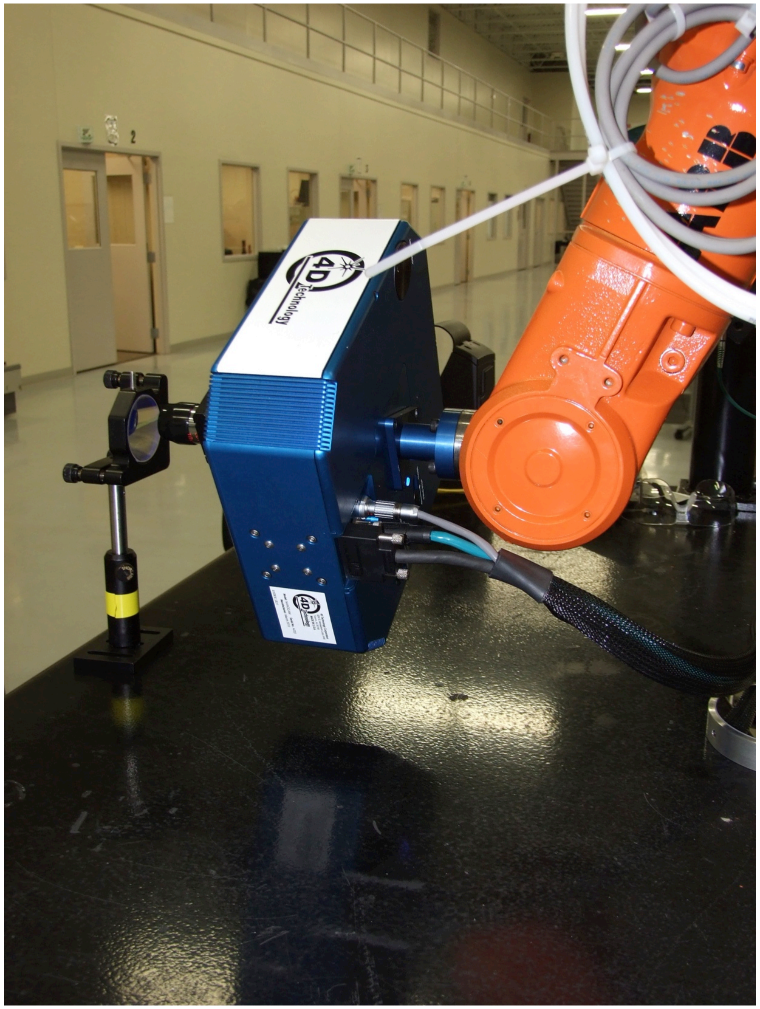
Diamond Film



Ref: Bruker

Mounting Optical Profiler on Robot





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