Inspection and metrology 1
Optical microscopy: Inspection and dimension measurement

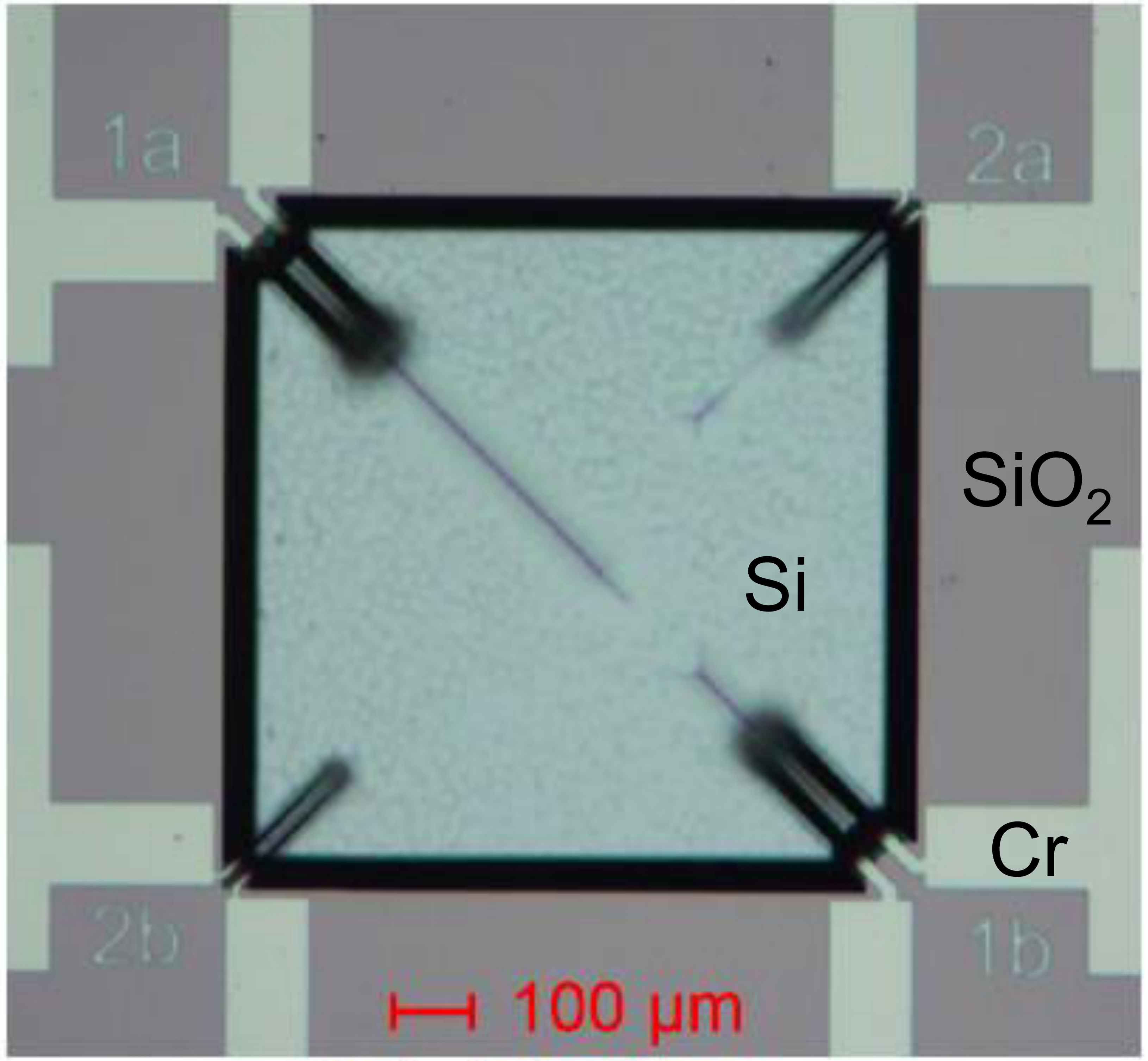
Micro and Nanofabrication (MEMS)

Prof. Jürgen Brugger & Prof. Martin A. M. Gijs

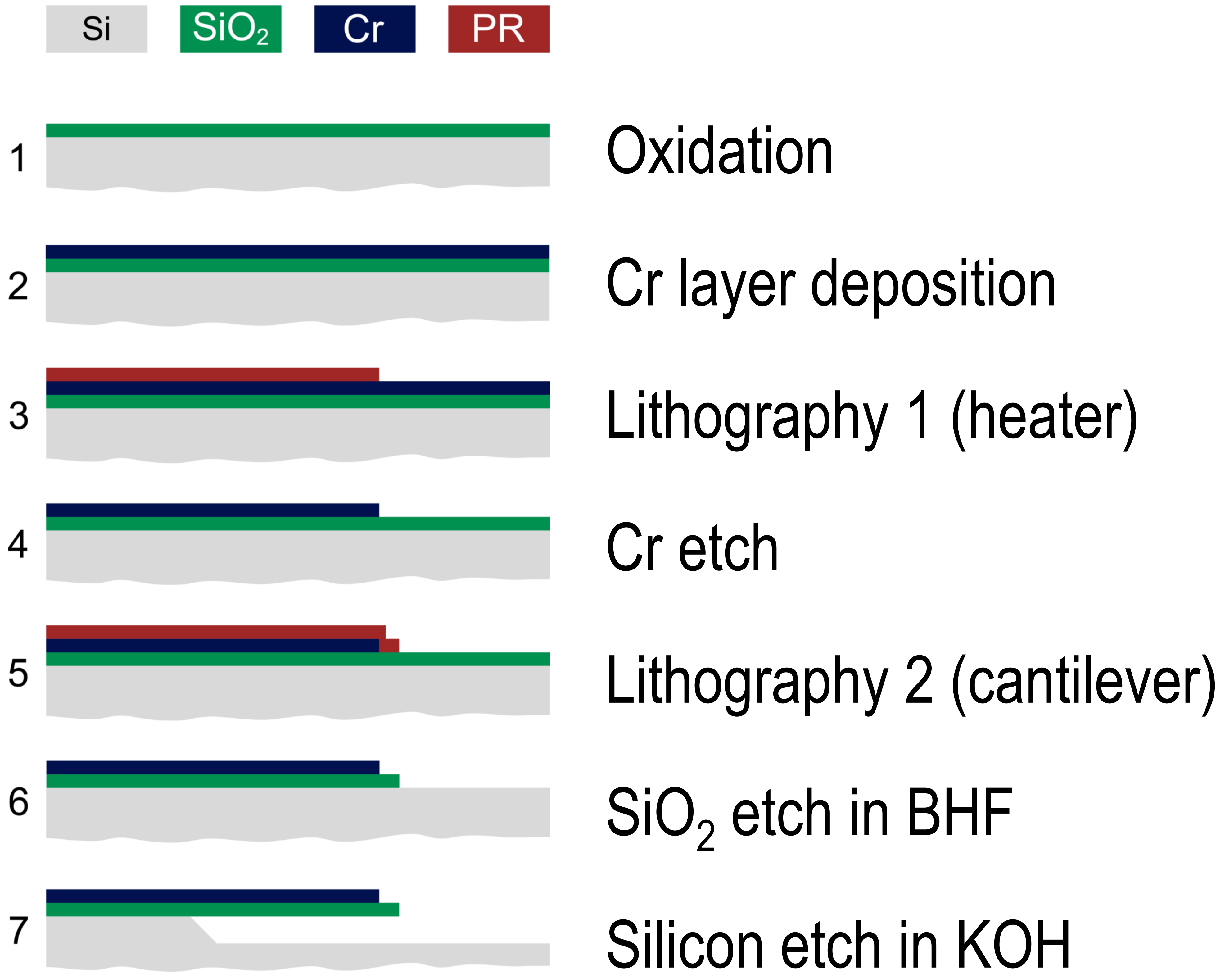
Optical microscopy

- Optical microscopy variations
  - Bright field (BF) and Dark field (DF)
  - Differential Interference Contrast (DIC)
  - Others
- Inspection under different modes
- Dimension measurement (XY & Z)
- Calibrated metrology

Bi-morph thermal actuator



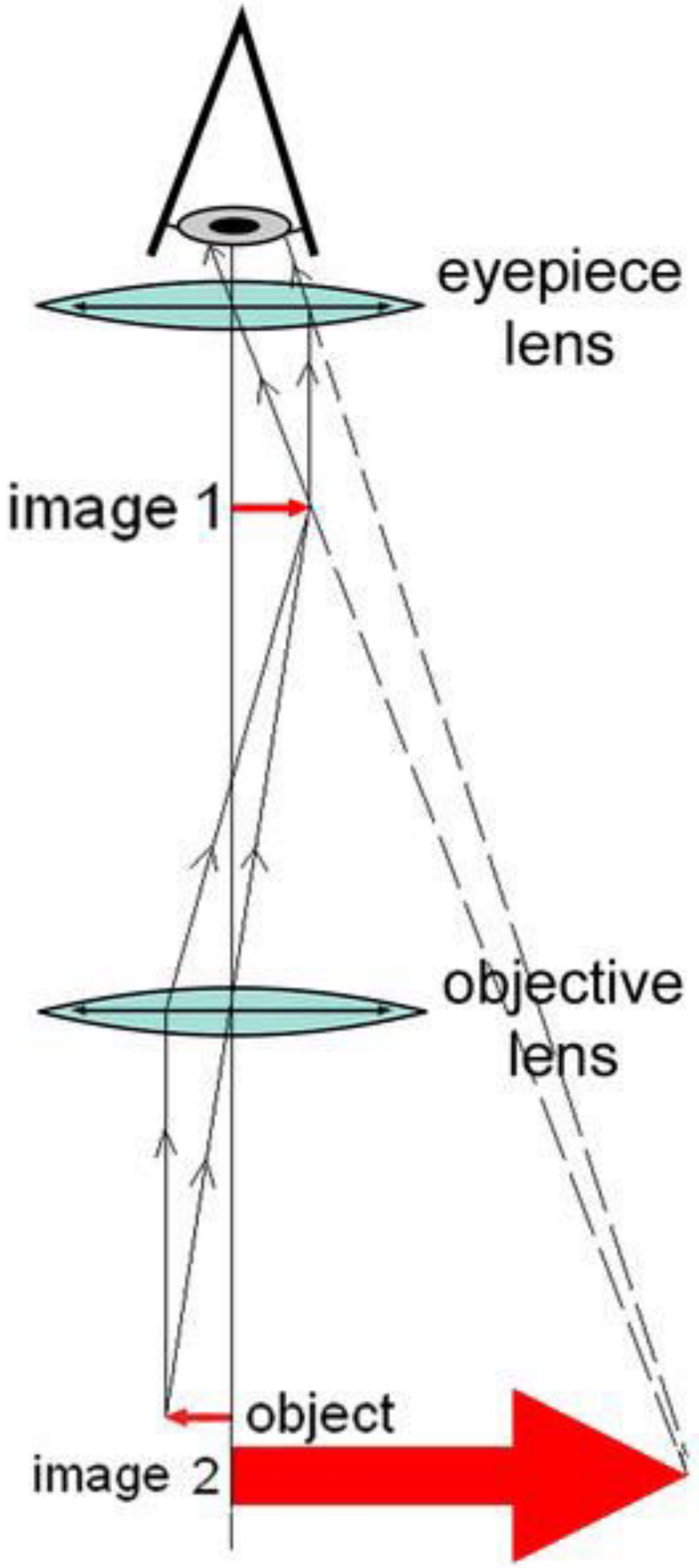
Optical microscope



How to check the process result?

Basics of an optical microscope

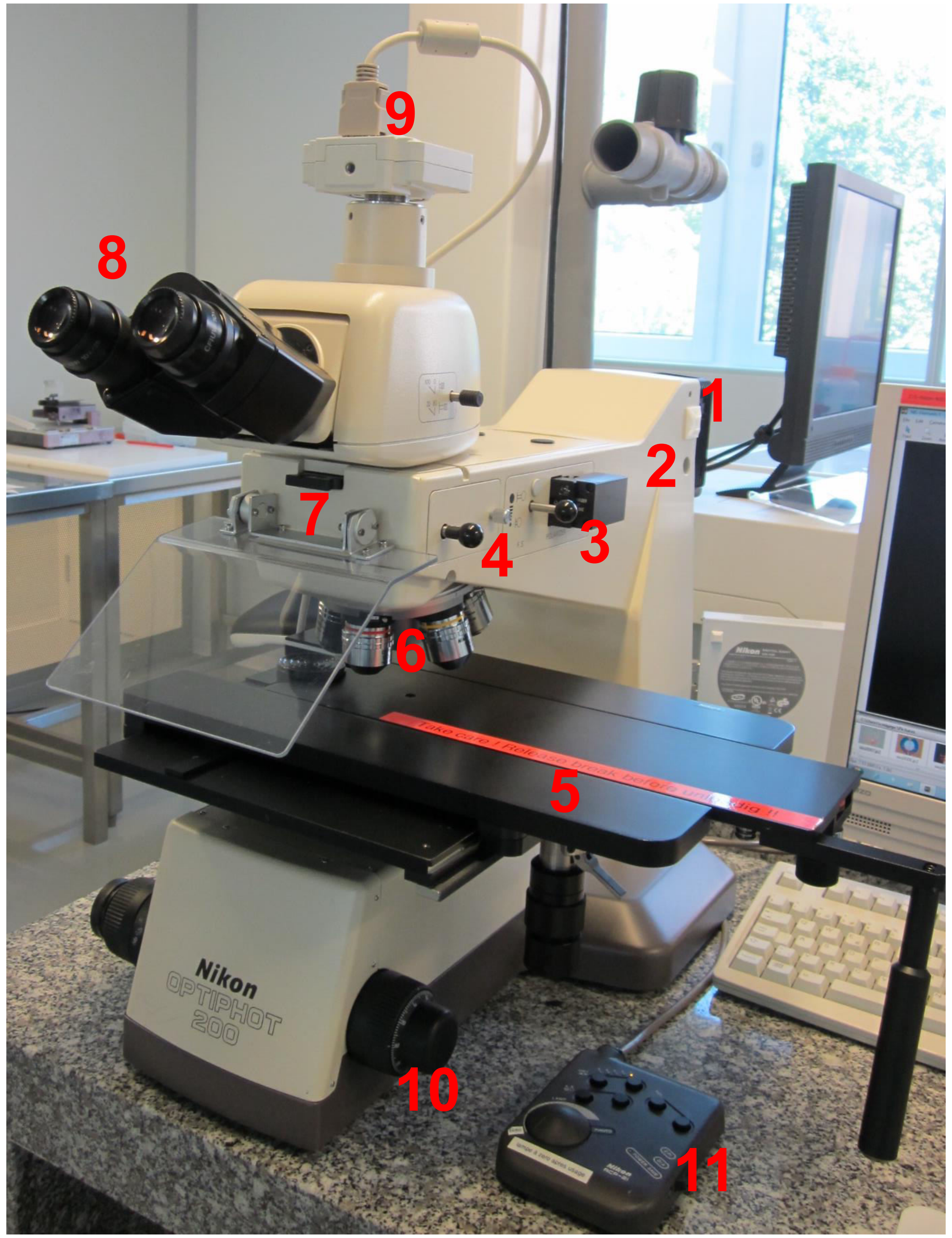
- Compound lenses to magnify the object
- Total magnification = (magn. of eyepiece lens) x (magn. of objective lens)
  - Magn. of eyepiece: 5x, 10x (the most common), 15x, 20x
  - Magn. of objective lens: 5x-100x
- Transmitted light for transparent specimen
- Reflected light for opaque specimen

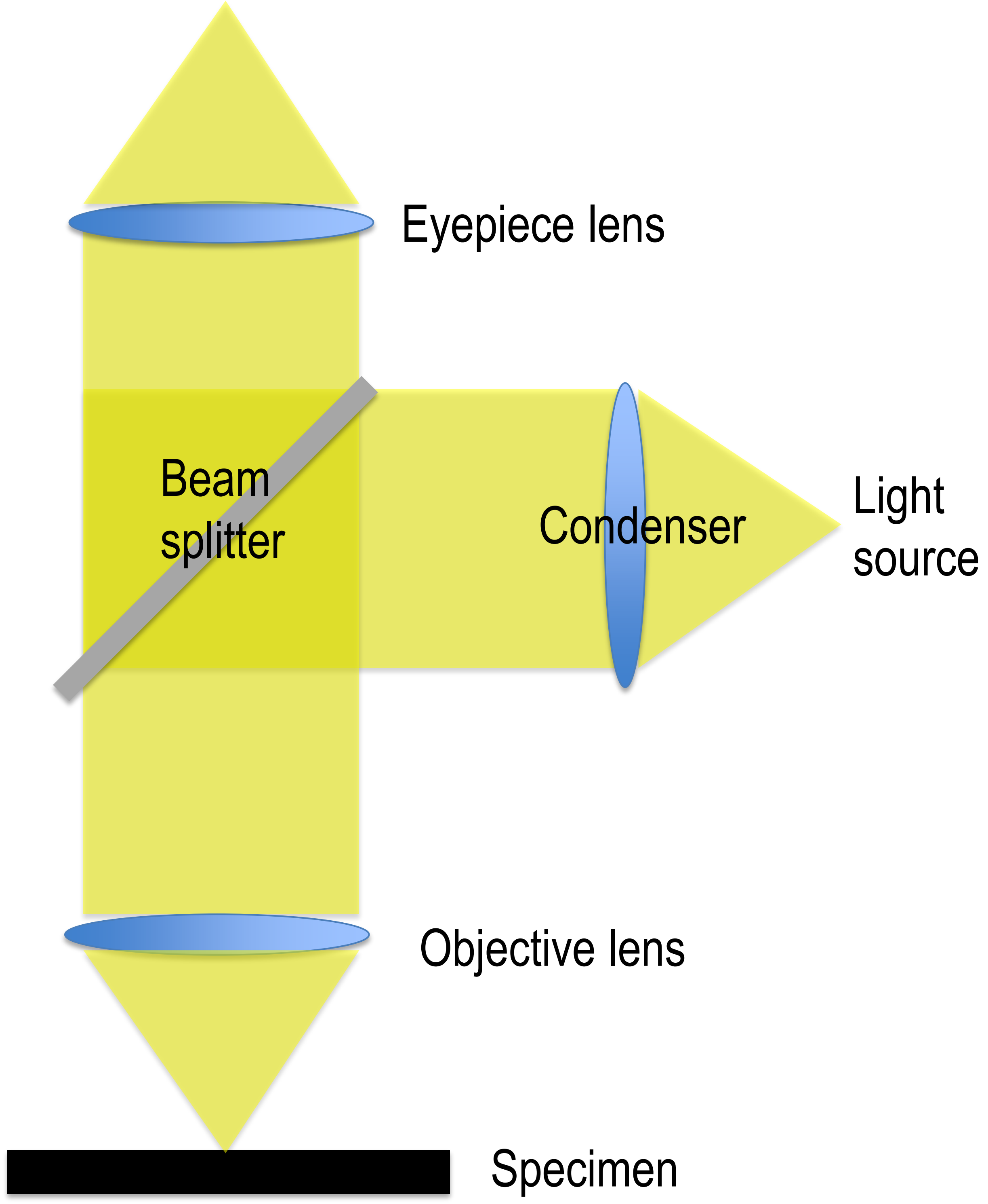


https://commons.wikimedia.org/wiki/File:Microscope_compound_diagram.png

Optical microscope configuration

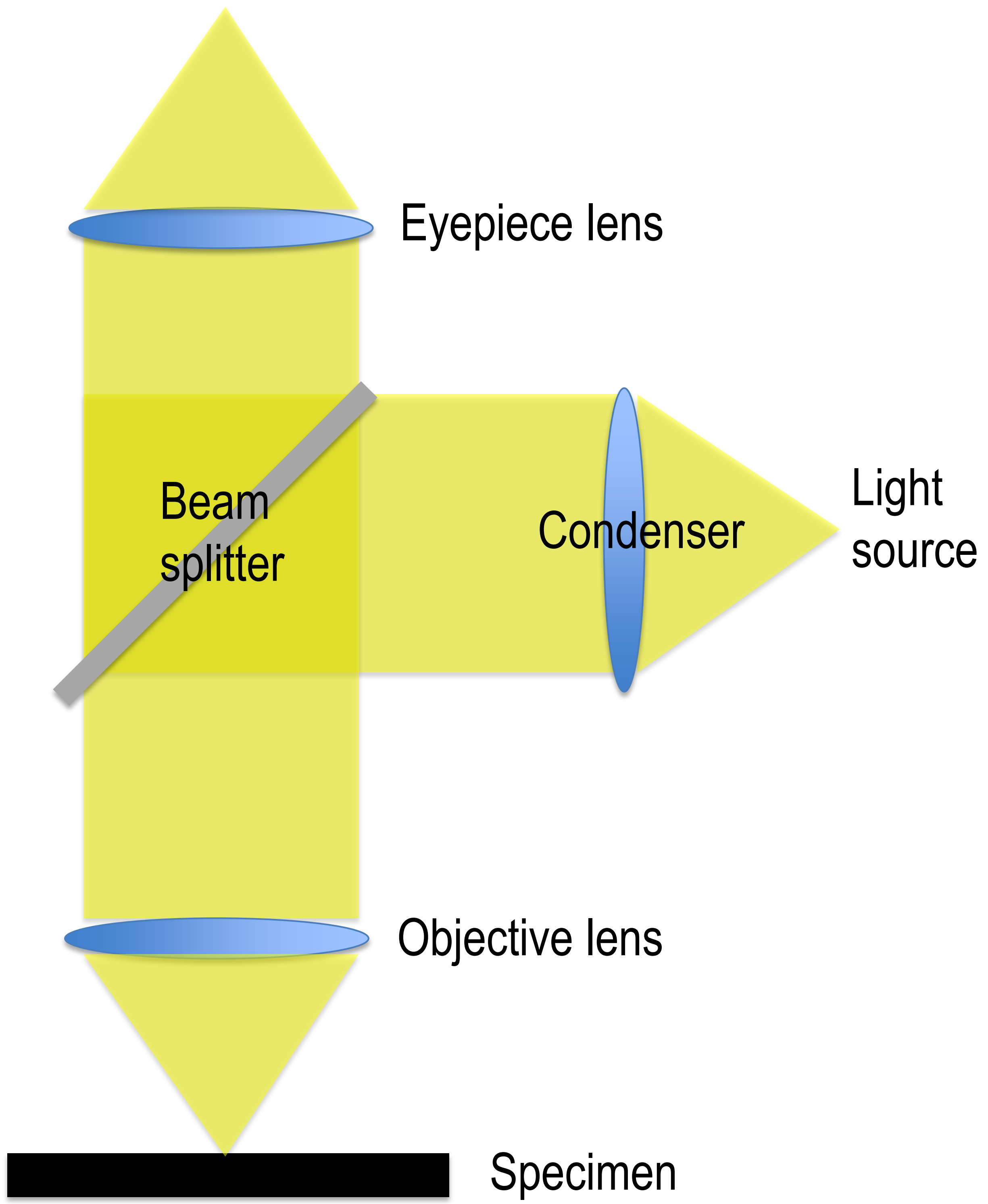
1) Light source
2) Condenser
3) DIC polarizer slider
4) Bright/dark field knob
5) XYZ specimen stage
6) Objective lenses
7) Analyzer slider
8) Eyepieces
9) CCD camera
10) Focus knob
11) Controller





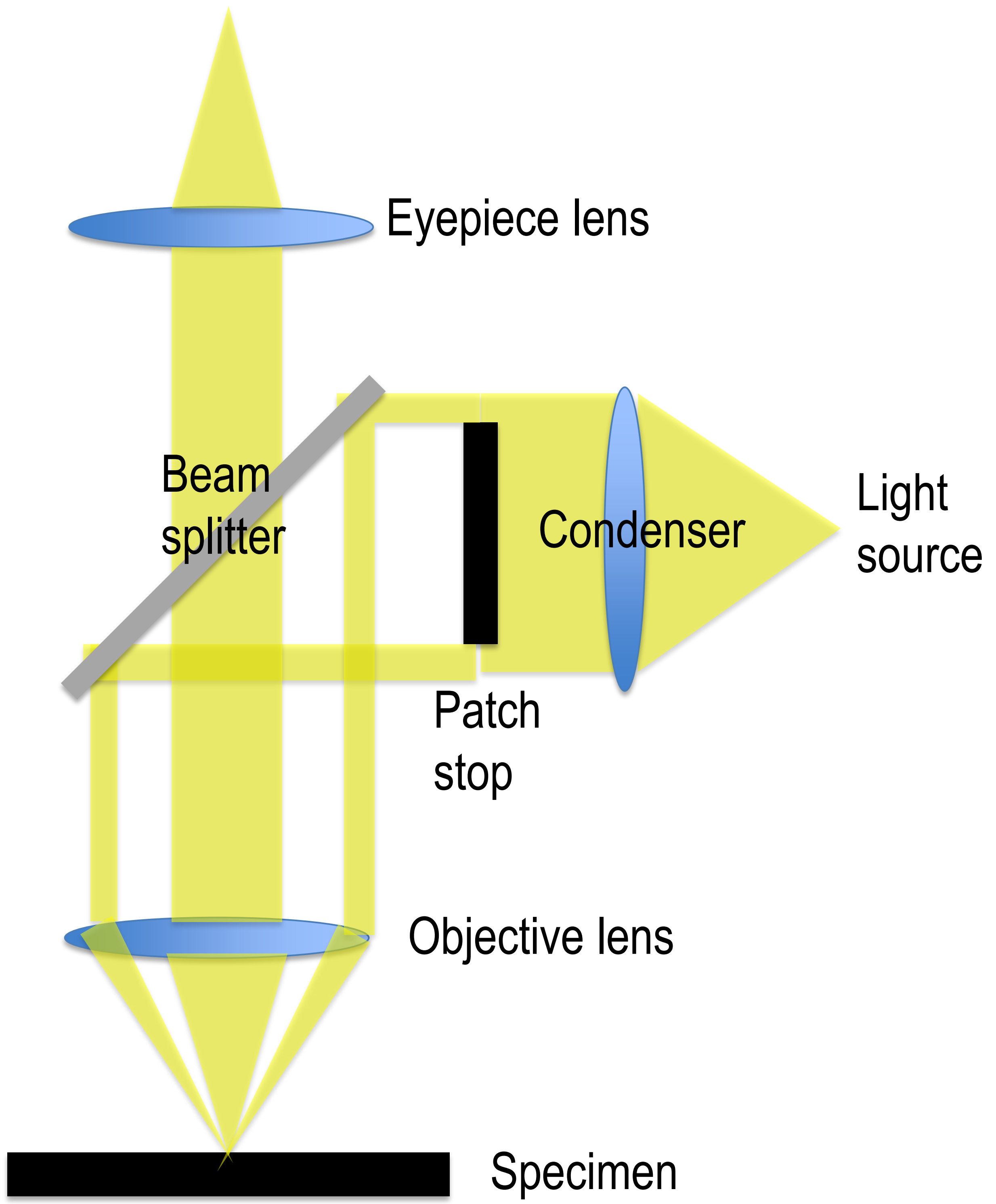
Bright field optical path

Optical microscopy variations



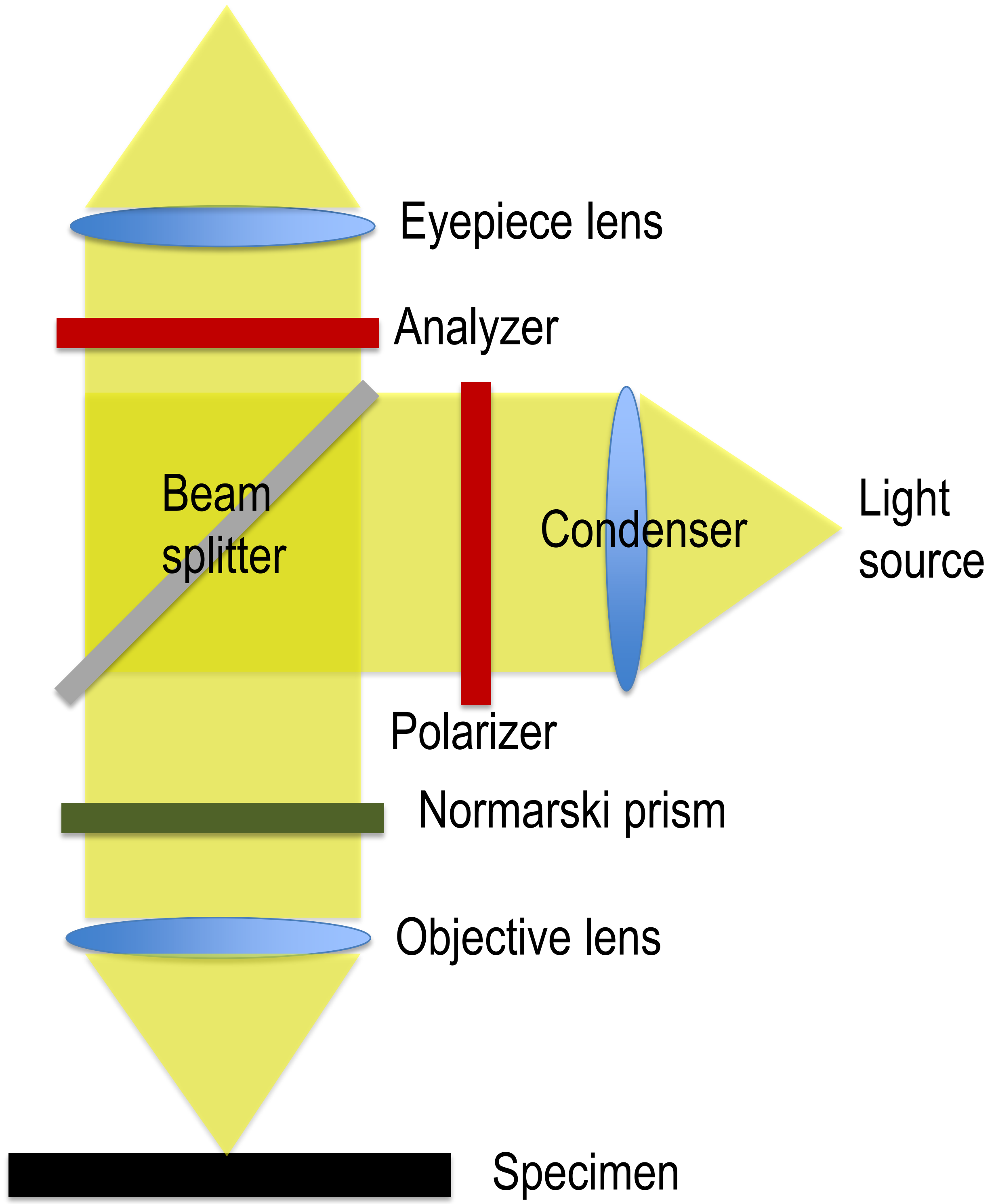
Bright Field (BF)

- Contrast caused by attenuation of light
- Common mode



Dark Field (DF)

- Contrast caused by intensity of scattered light
- Edge enhancement

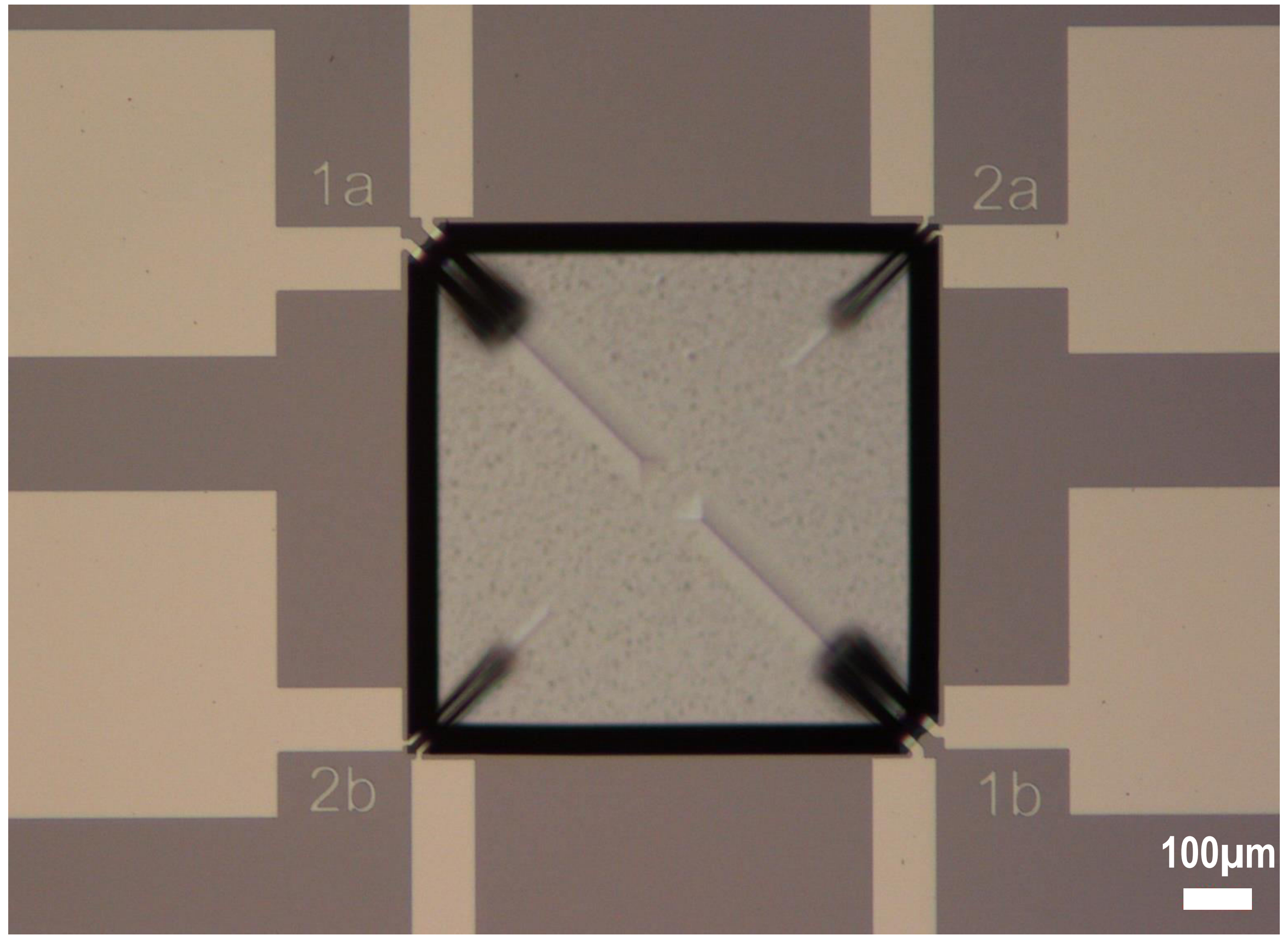


Differential interference contrast (DIC)

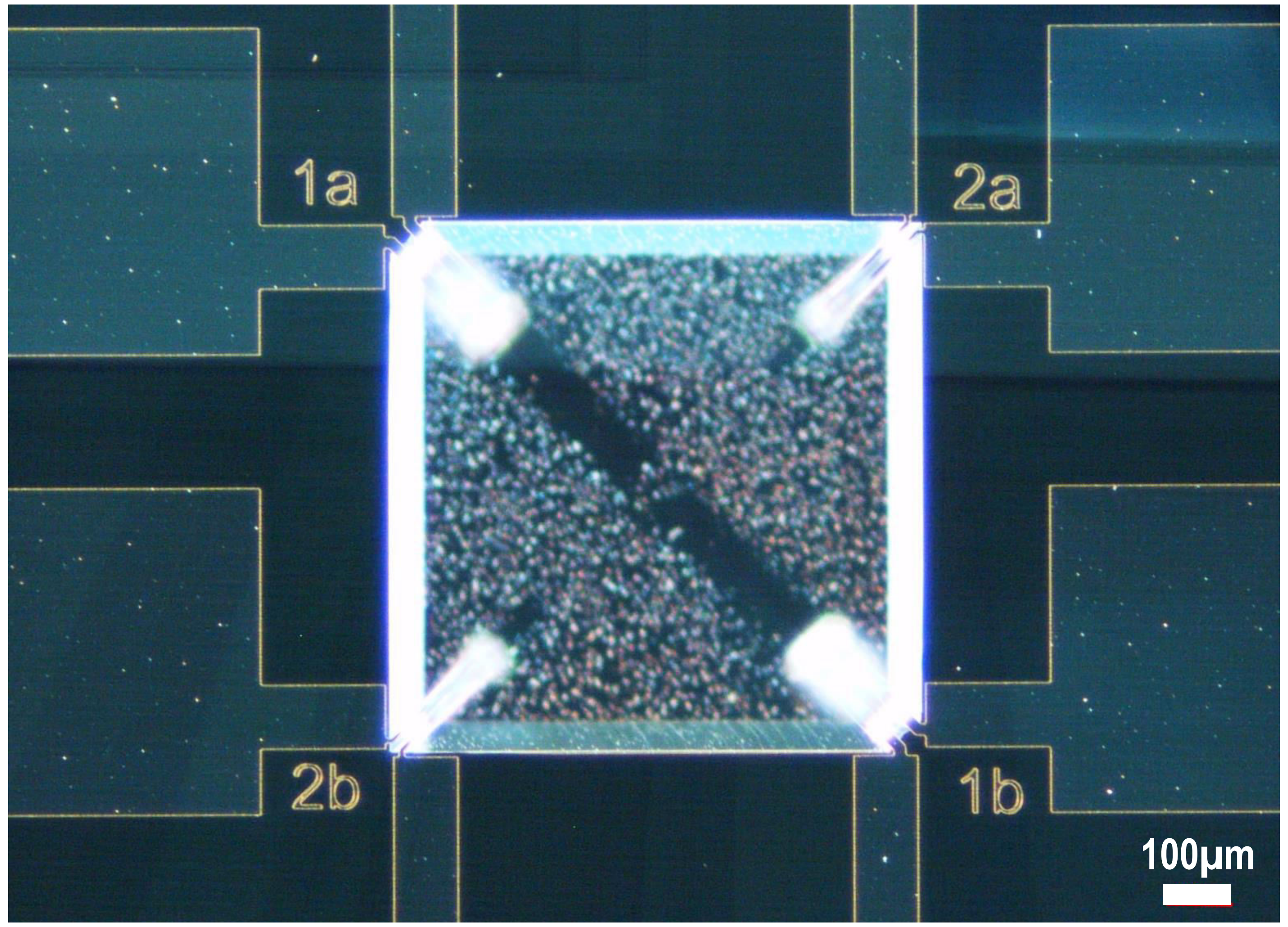
- Contrast caused by intensity of interfered light
- 3D appearance

Optical microscopy variations

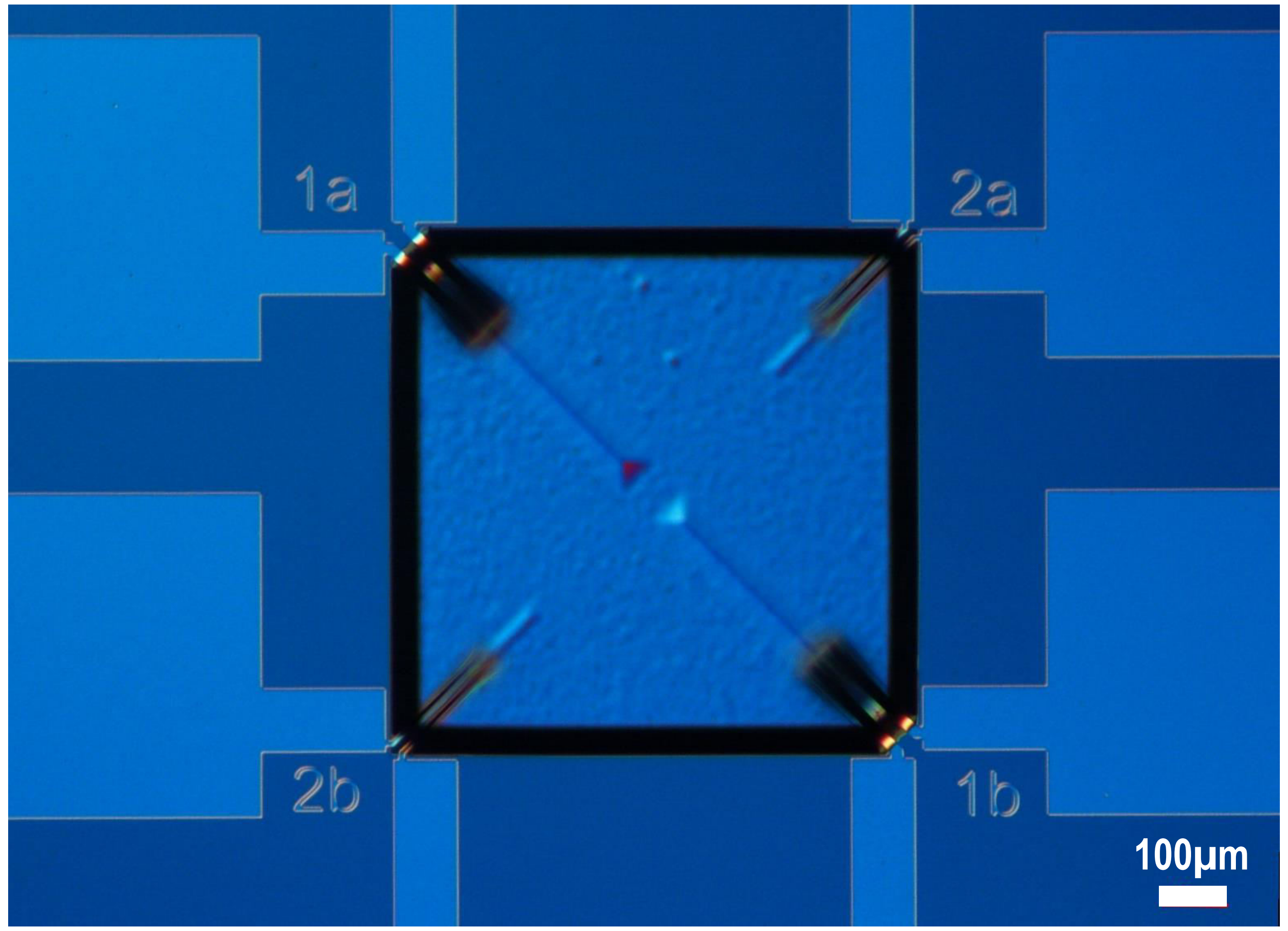
- Bi-morph actuator optical microscope inspection



Bright field



Dark field



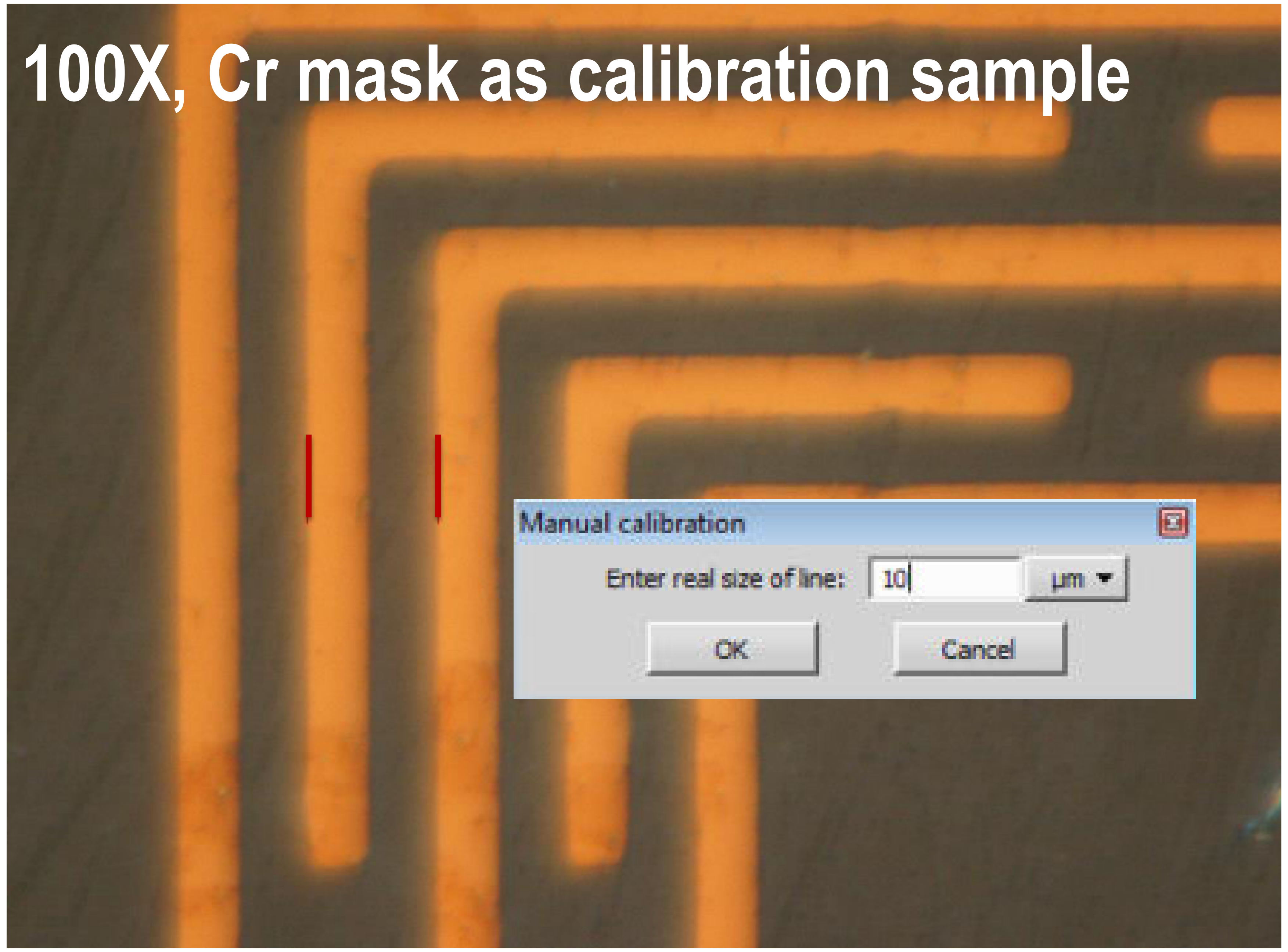
DIC

Optical microscopy variations

Method	Features	Main Areas of Use
Bright field	• The most common mode • Entire field illuminated	• Commonly used
Dark field	• Observing the scattered light • Edge enhancement	• Defect inspection
DIC	• Enhance the topography • 3D appearance	• Topographical inspection • 3D structure inspection
Phase contrast	• Contrast from interference due to phase shift	• Transparent sample • Live cells observation
Polarizing	• Contrast from specimen birefringence	• Mineral crystals observation
Fluorescence	• Observing fluorescent light	• Cells/tissues labeled with fluorescent dye • Auto-fluorescence

Dimension measurement: XY

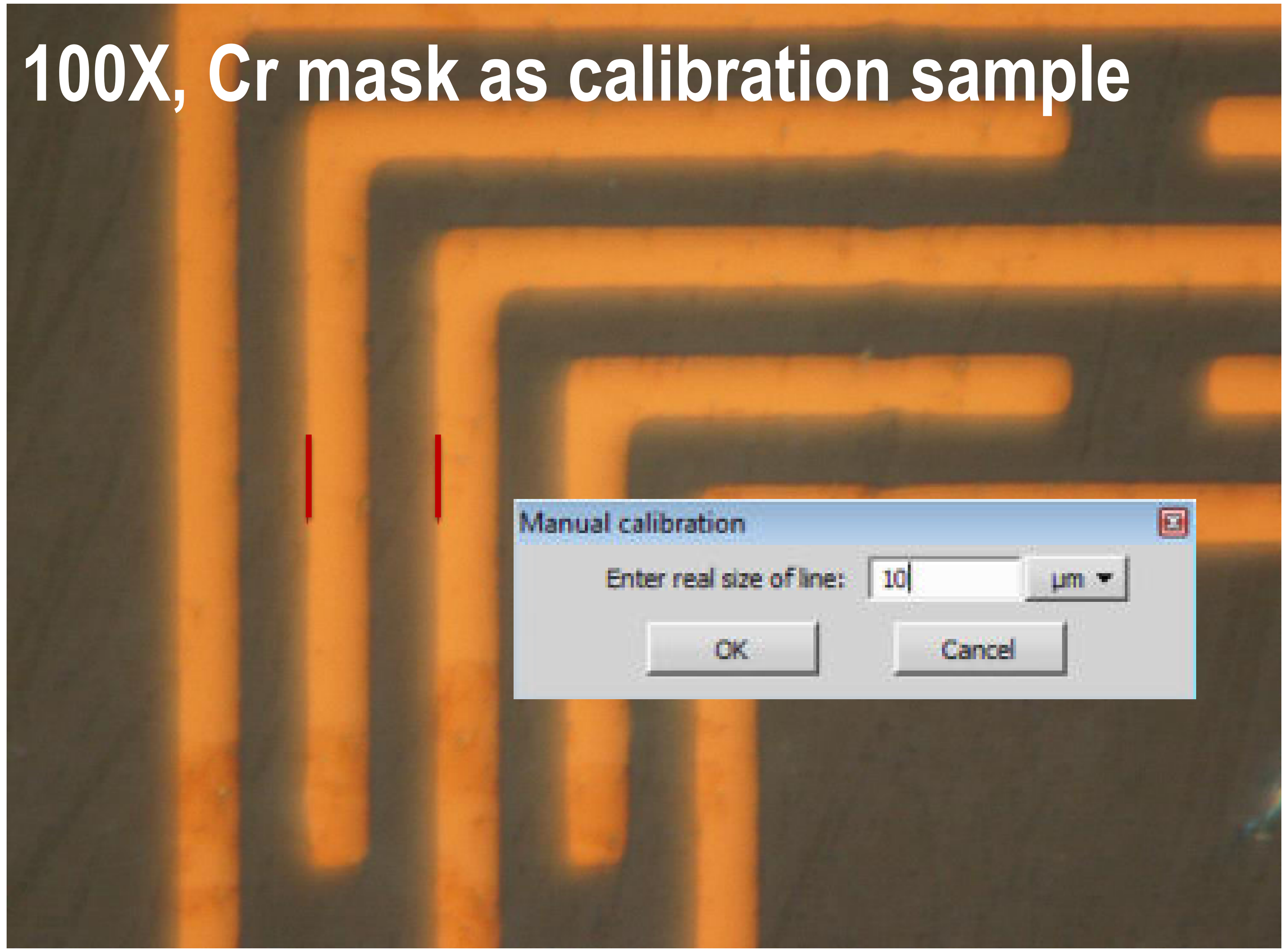
- CCD camera ➔ standard sample with known dimension ➔ how many µm per pixel ➔ calibrate the scale bar in the CCD image



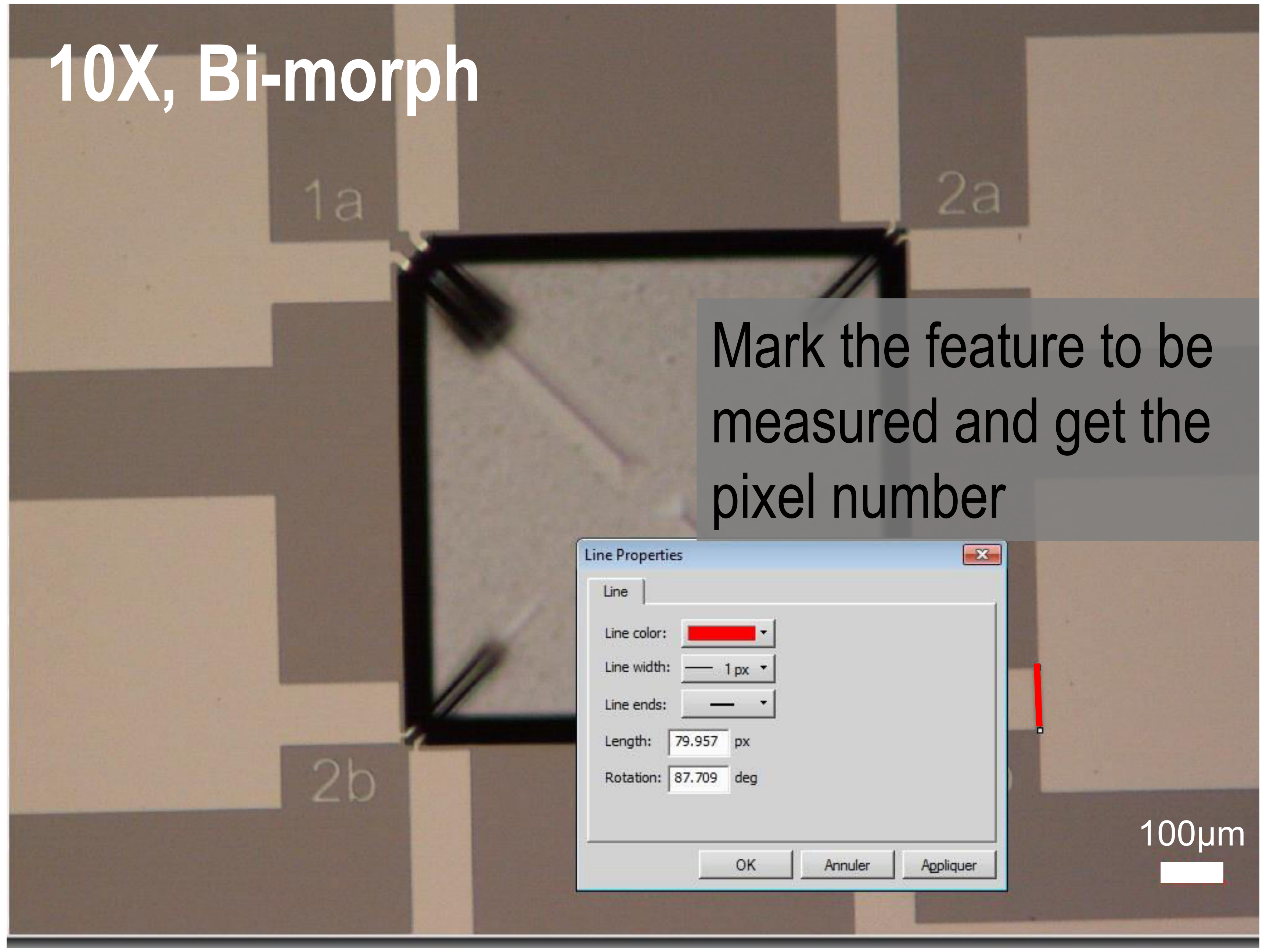
Mark the feature with known dimension and calibrate
1 pixel = 0.1243µm in 100x image

Dimension measurement: XY

- CCD camera ➔ standard sample with known dimension ➔ how many µm per pixel ➔ calibrate the scale bar in the CCD image ➔ use the scale bar as a ruler
- Resolution limitation: ~0.5µm



Mark the feature with known dimension and calibrate
1 pixel = 0.1243µm in 100x image

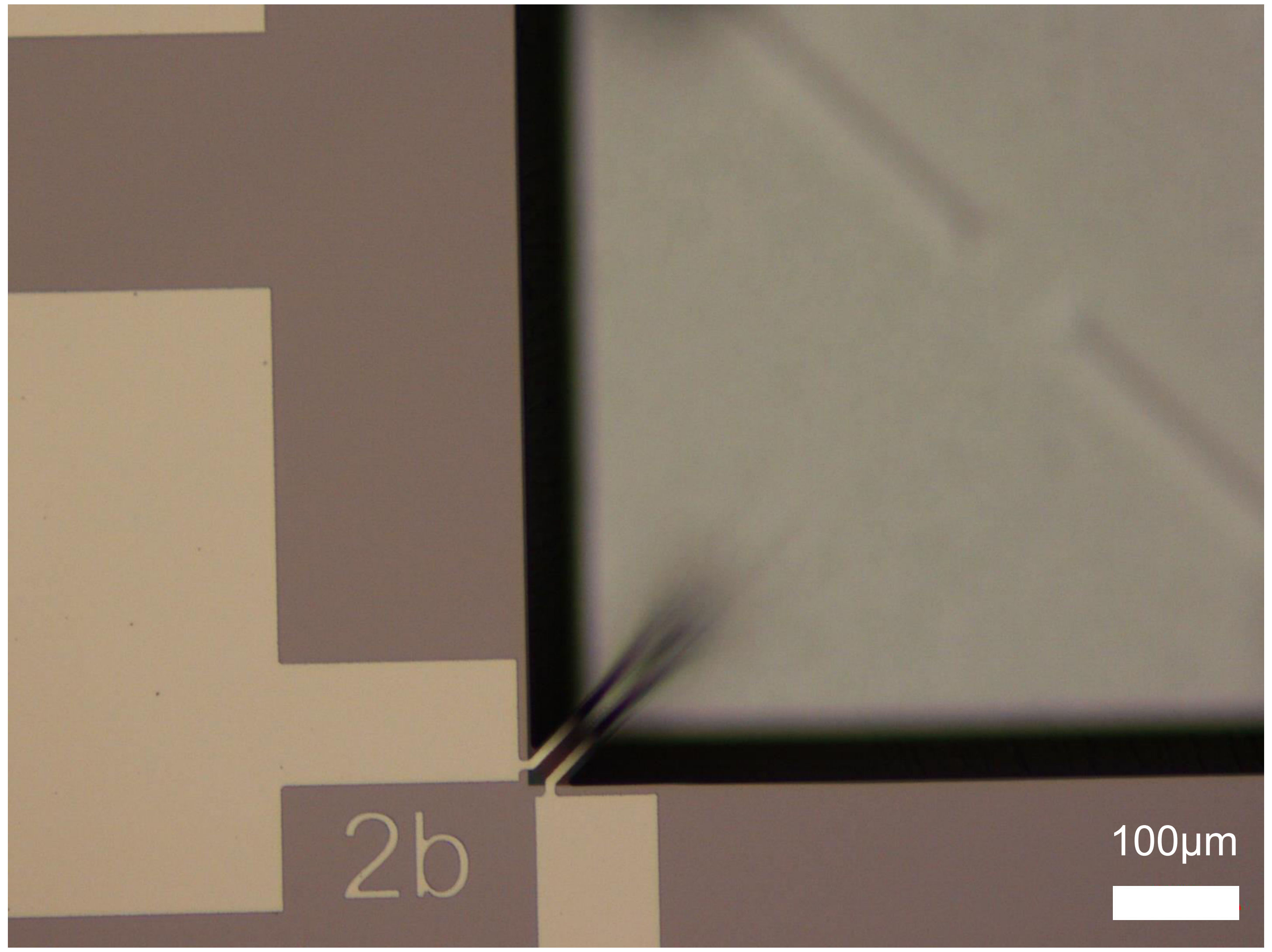


Cr line width=79.957 pixels, 1 pixel = 1.243µm in 10X image
➔ 79.957 x 1.243 = 99.4µm (100µm in design)

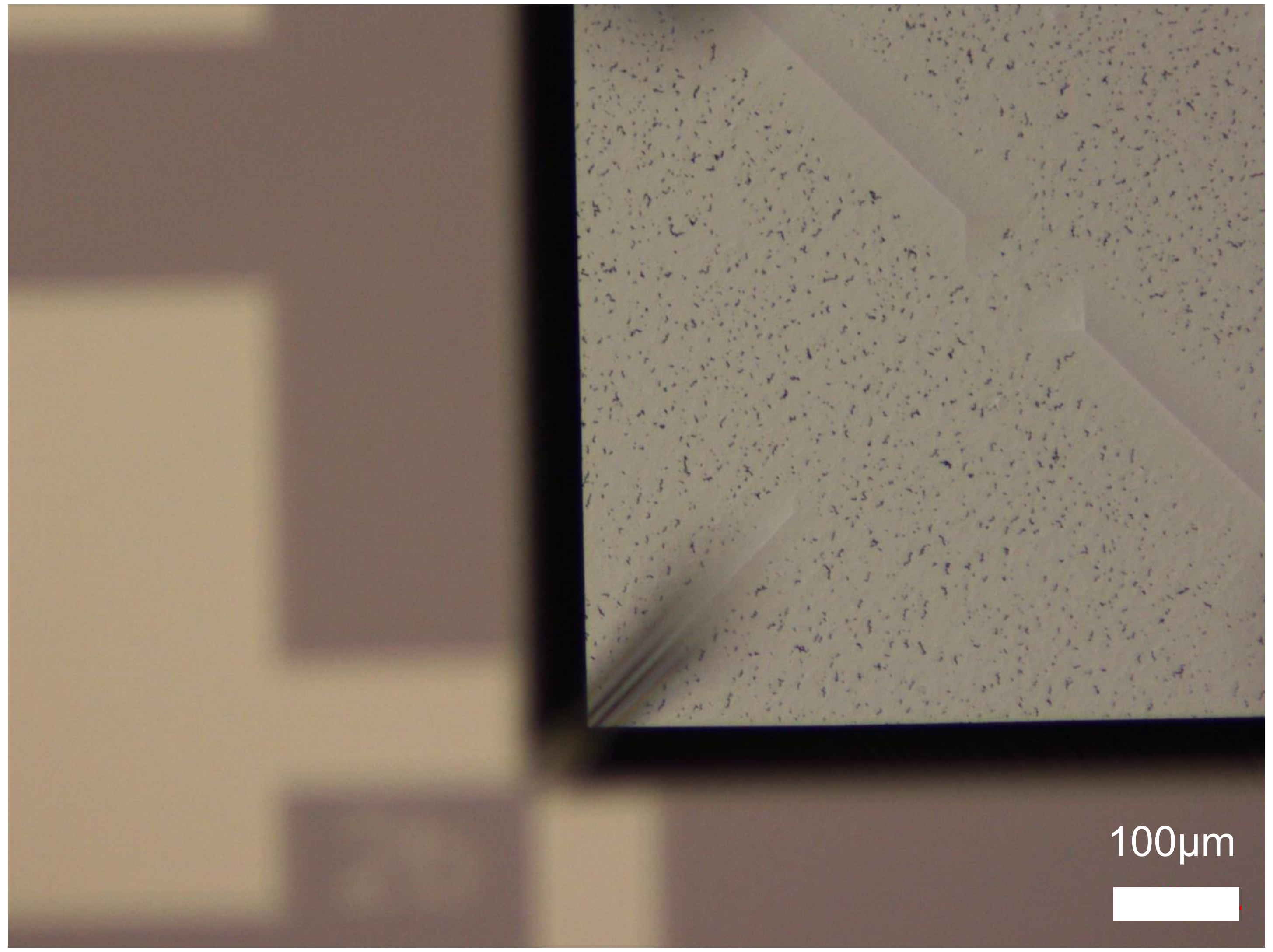
Dimension measurement: Z

- Calibrate the scale on focus knob ➔ focused on top surface ➔ focused on bottom surface ➔ read the focus knob scale difference ➔ estimate the Z-dimension

Focus knob with scale



Focused on top surface



Focused on bottom of Si cavity

Estimated cavity depth is ~70µm

Summary

- Easy, fast and cost effective method for inspection and dimension measurement
- Multiple modes for specific purpose
- Non-contact, non-invasive
- Works for both opaque and transparent specimens
- Workhorse for sample inspection

Inspection and metrology 2
Optical thin film thickness measurement

Micro and Nanofabrication (MEMS)

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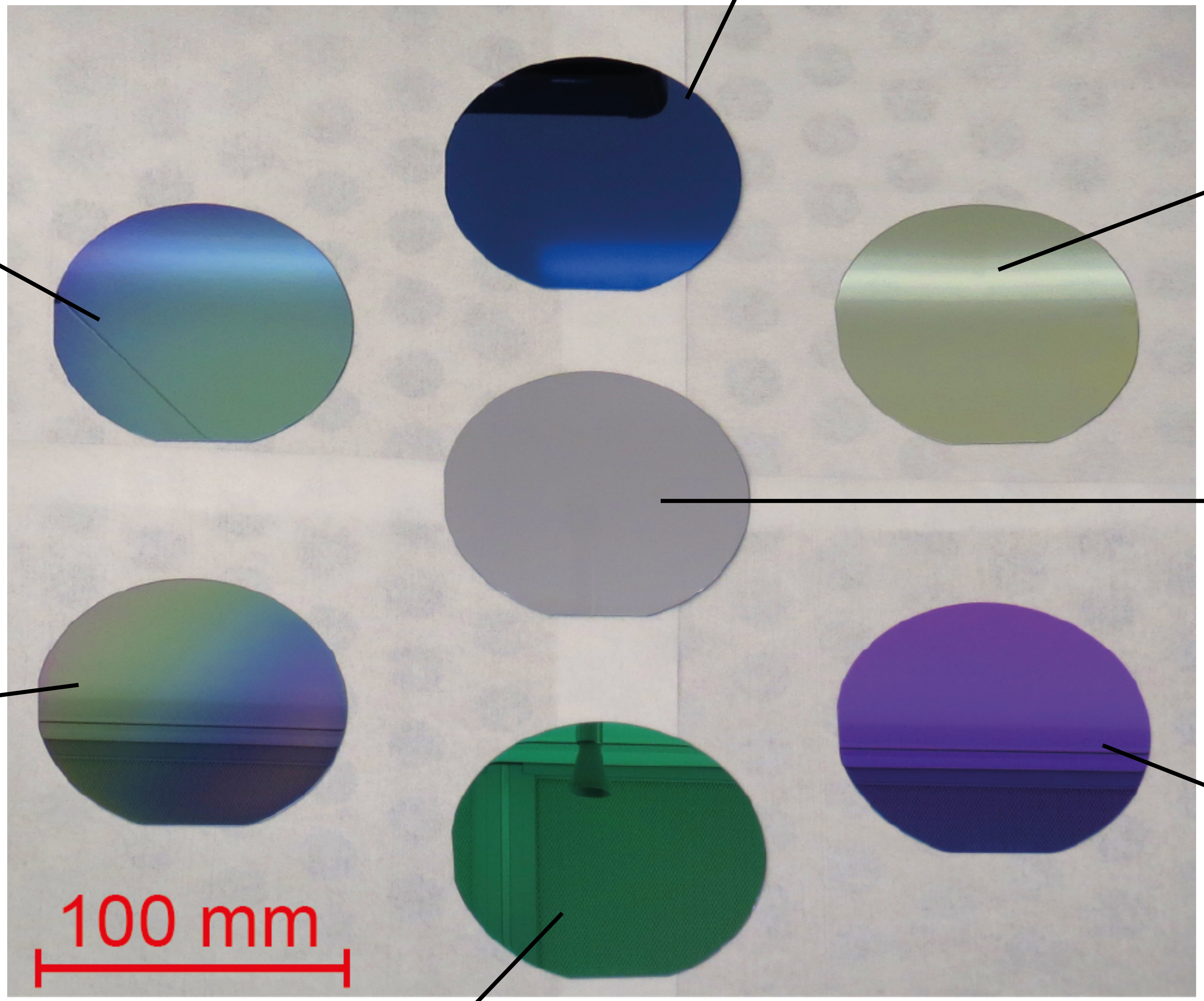
Optical thin film thickness measurement

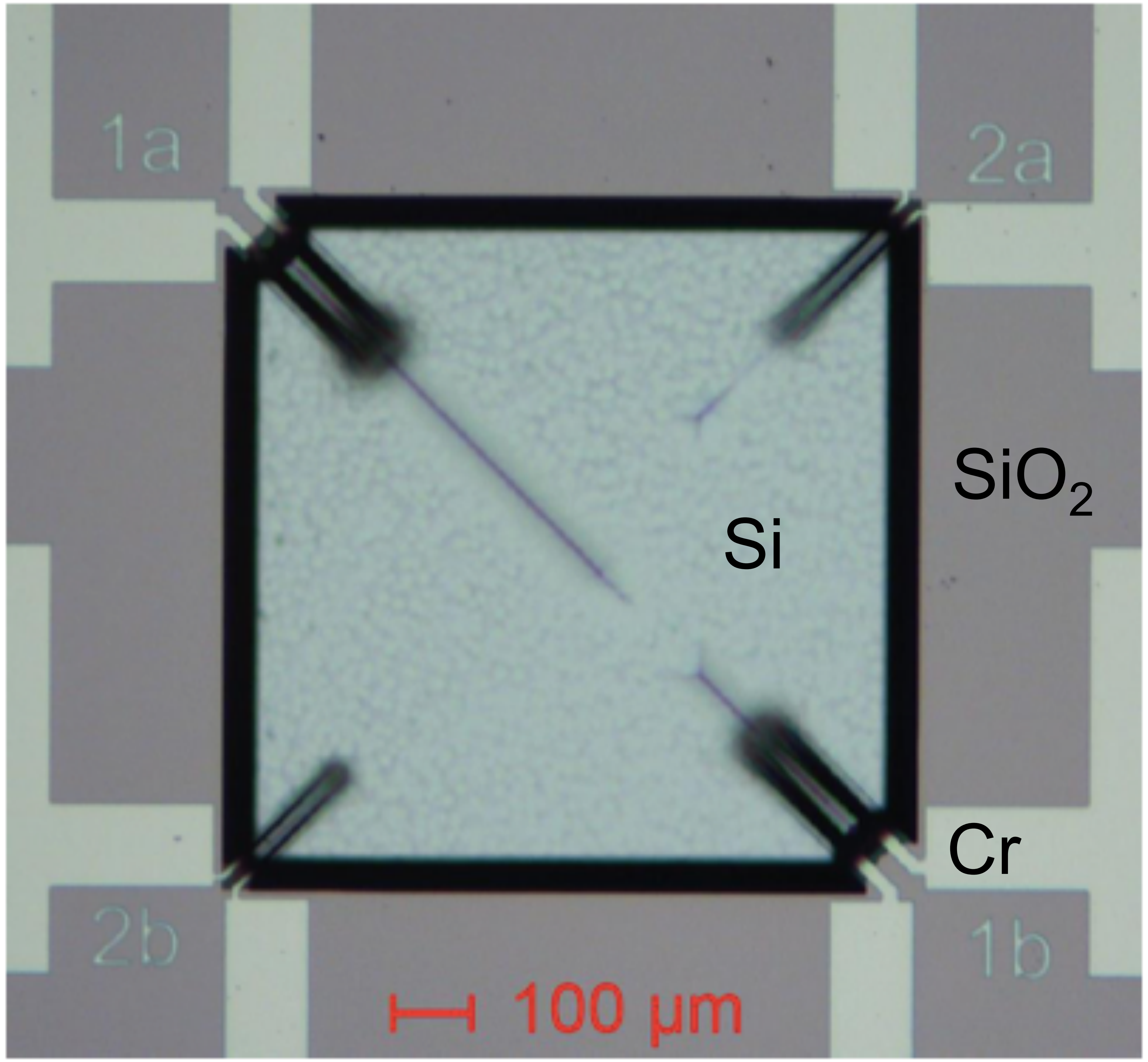
- Physical principle
- Variations
  - Reflectometer & transmittometer
  - Ellipsometer
- Bi-morph SiO_2 thickness measurement

Color change in SiO_2 thin film

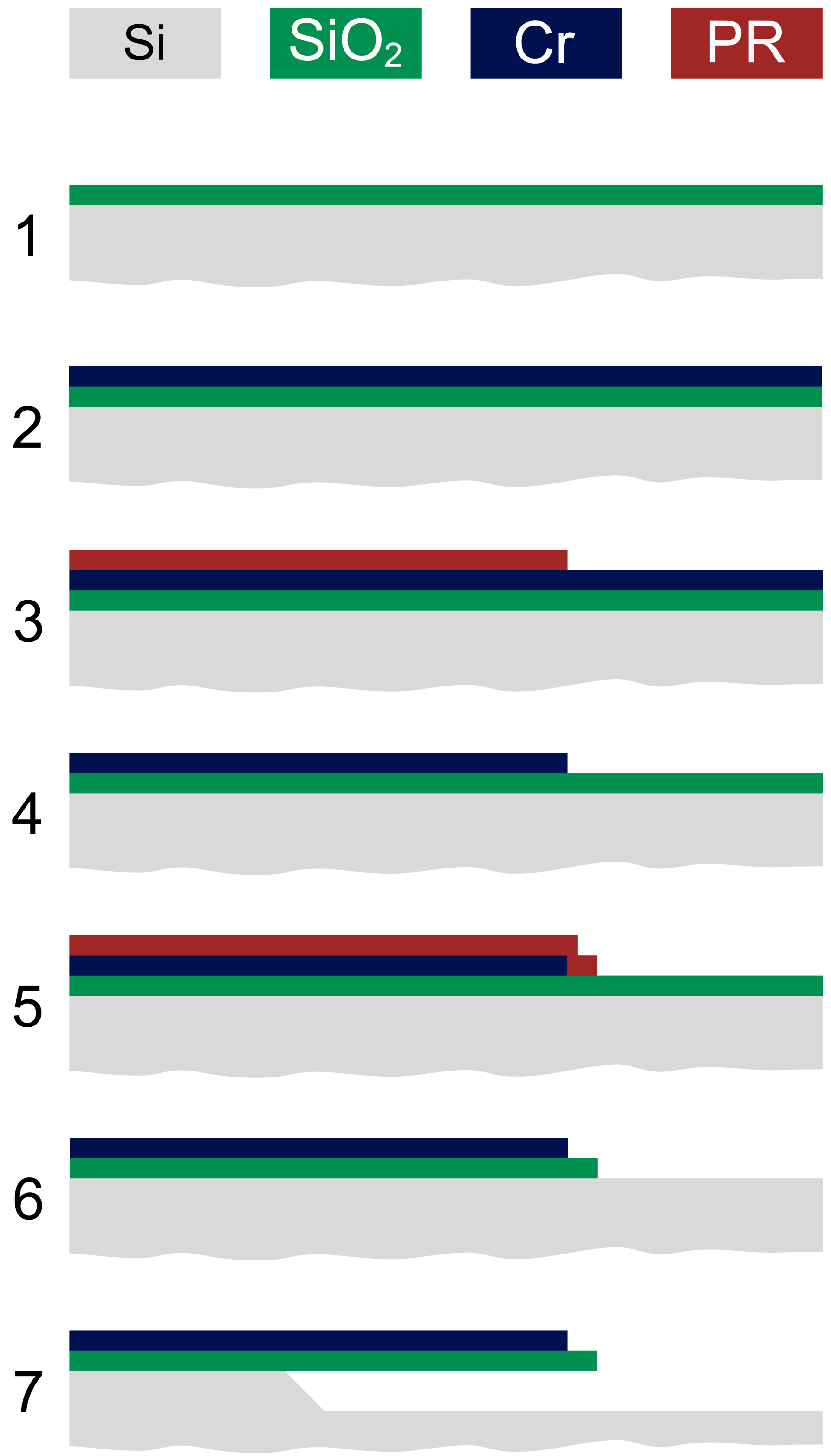
SiO_2 on silicon



Bi-morph SiO_2 thickness measurement



Optical microscope

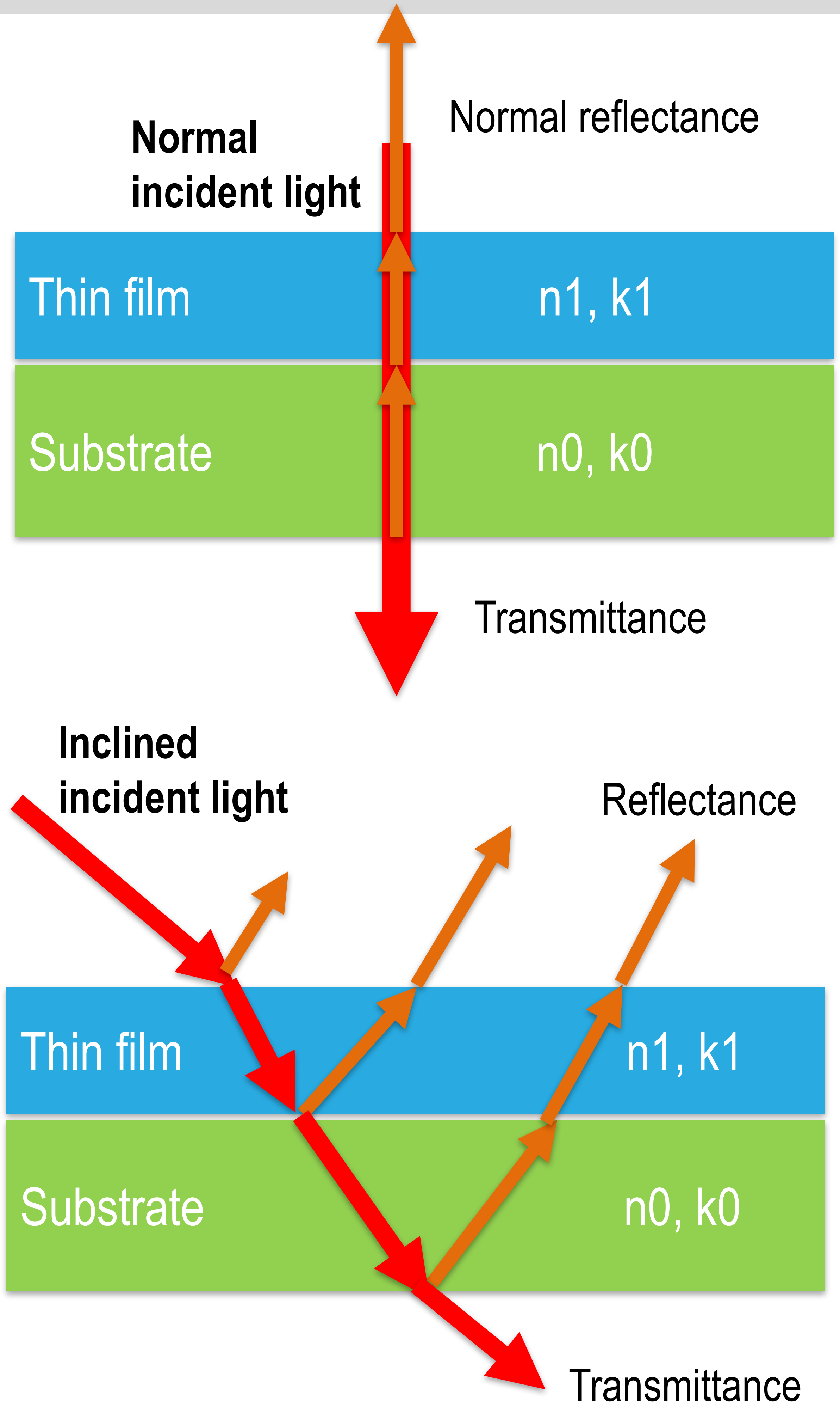


1. Oxidation
2. Cr layer deposition
3. Lithography 1 (heater)
4. Cr etch
5. Lithography 2 (cantilever)
6. SiO_2 etch in BHF
7. Silicon etch in KOH

How to measure the thickness of SiO_2?

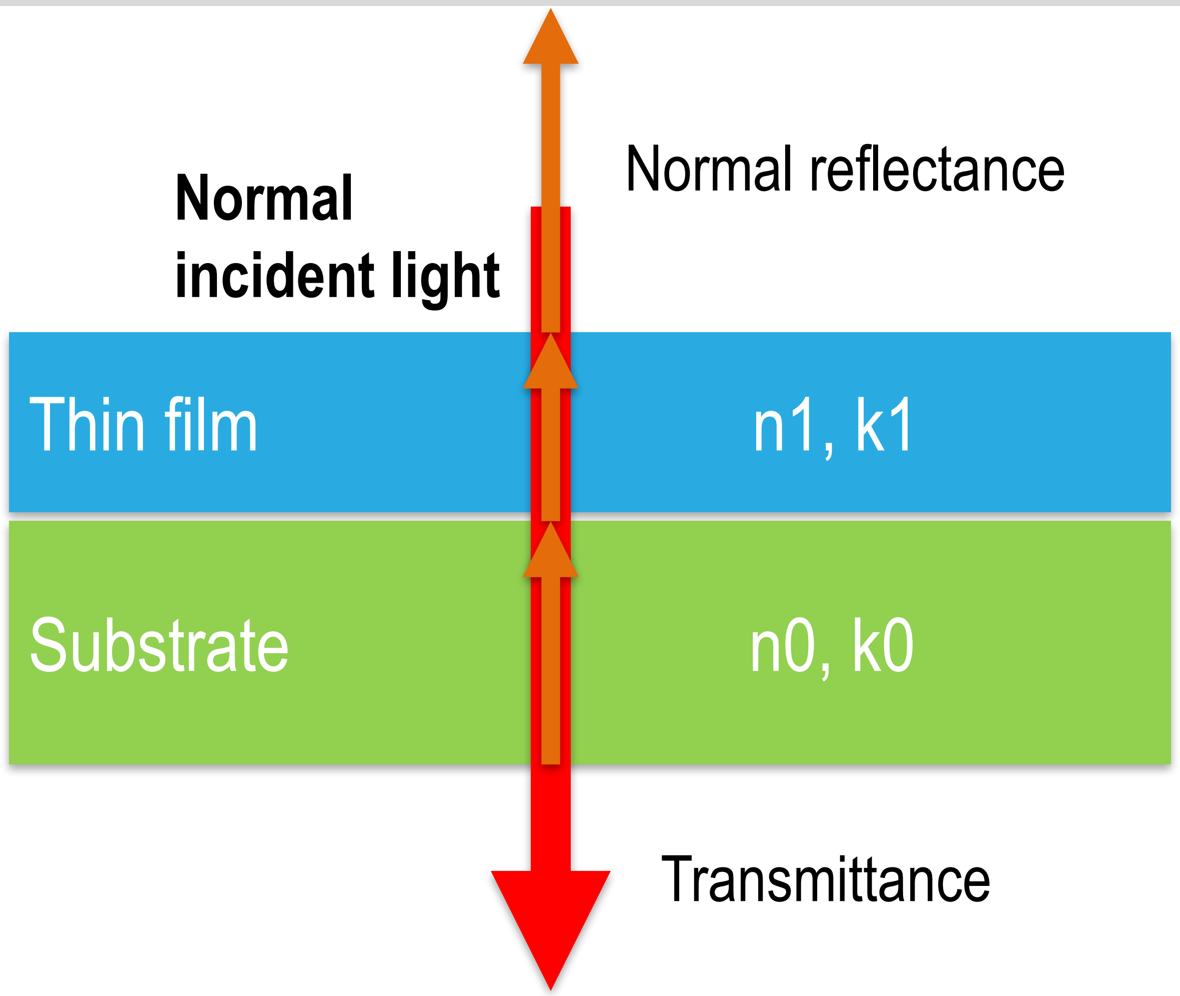
Physical principle

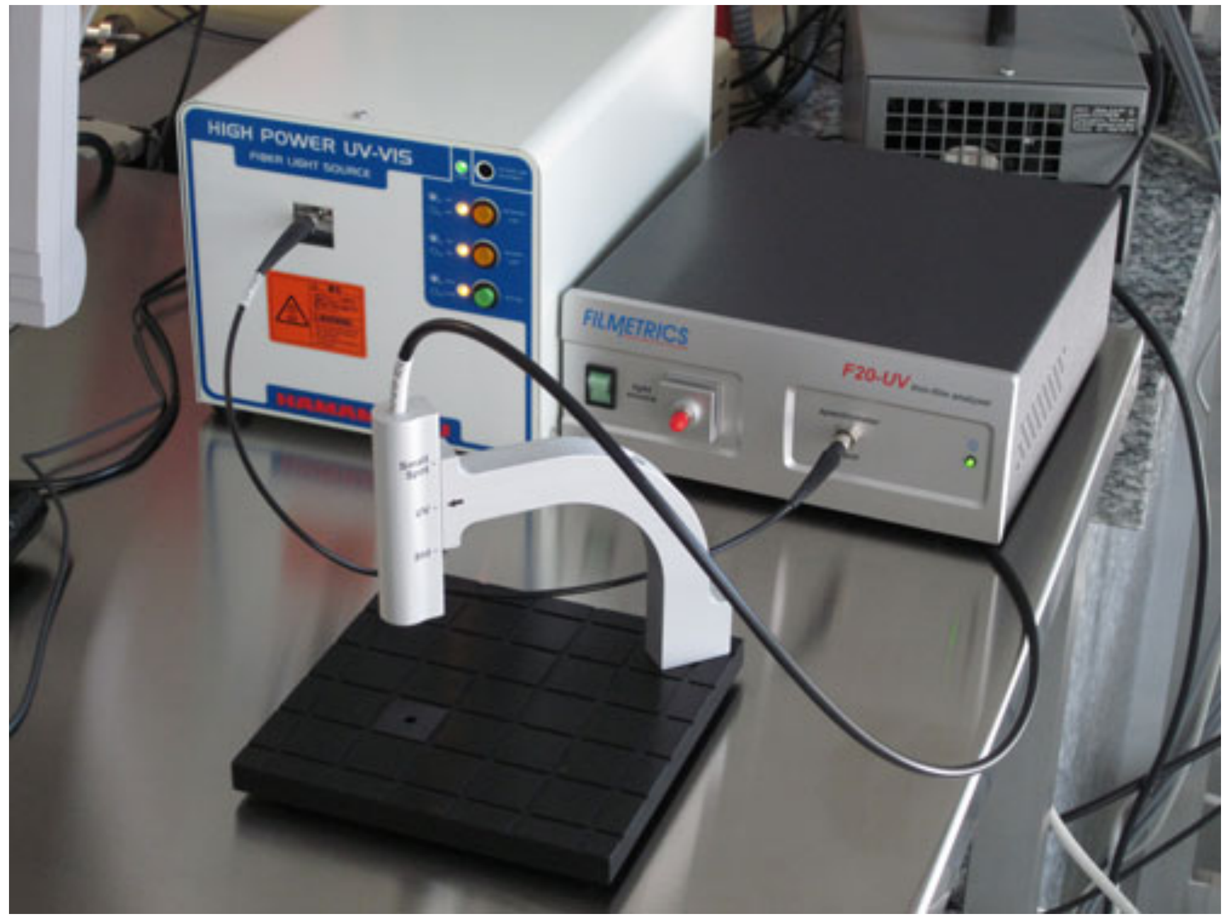
- Polychromatic incident light ➔ reflectance/transmittance spectrum ➔ thin film thickness with the best spectrum fitting
- The light properties change of reflected/transmitted light is correlated to the thin film thickness
- Thin film has to be “transparent” to incident light
- Measurement for multiple thin film layers is also possible
- Non-destructive measurement



Reflectometer & transmittometer

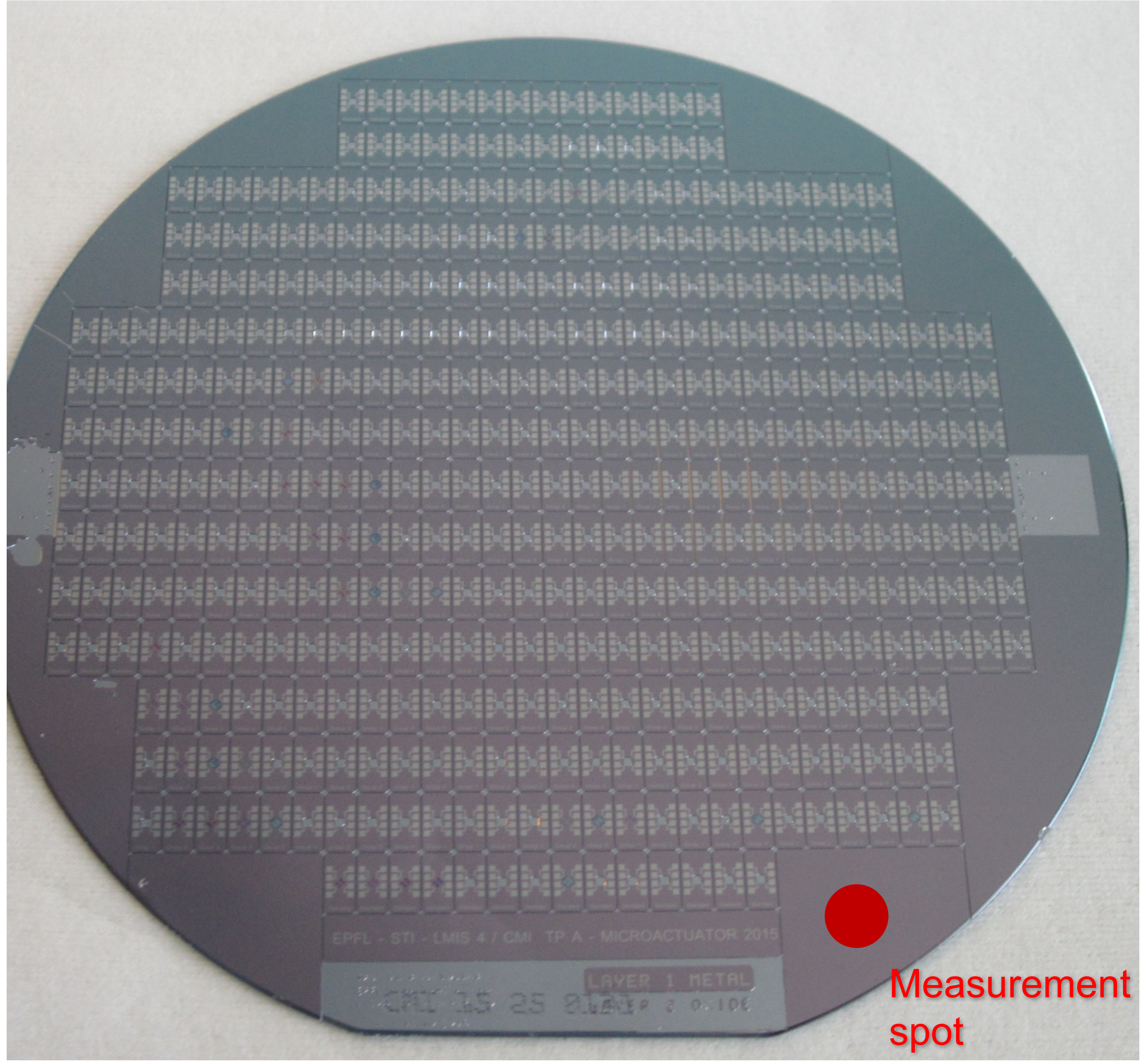
- Normal incidence
- Signal: change in intensity over the wavelength
- Light source: deuterium lamp + halogen lamp (wavelength: 200nm to 1100nm)
- Beam spot size: 1.5mm
- Film thickness range: 1nm to 40µm
- Thin film material: photoresist, SiO_2, Si_3N_4 and other polymer, dielectric films
- n, k measurement is also possible





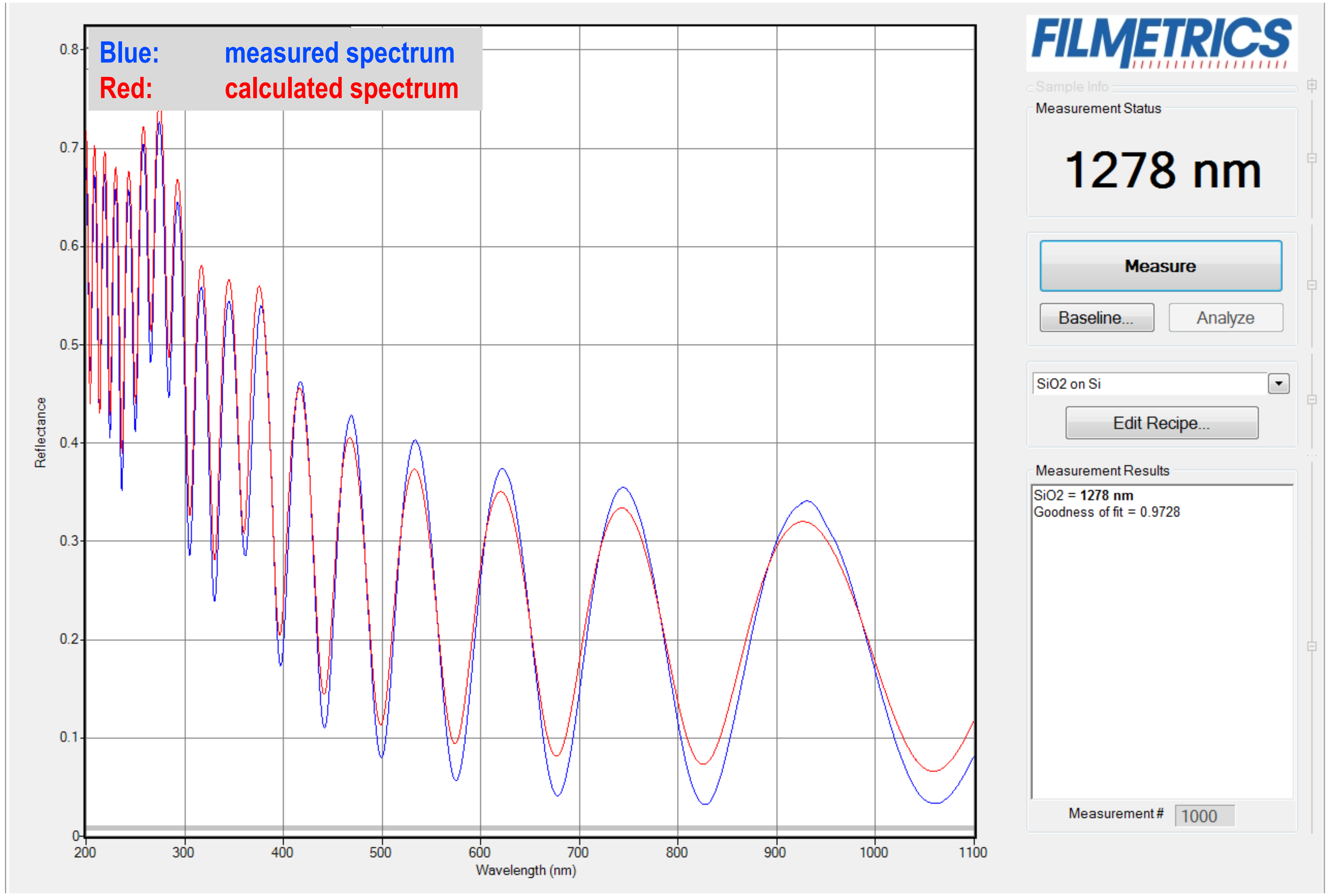
Bi-morph SiO_2 thickness measurement

Bi-morph wafer



Spot size is too large to measure the SiO_2 in the Bi-morph die

➔ measure the SiO_2 at wafer edge

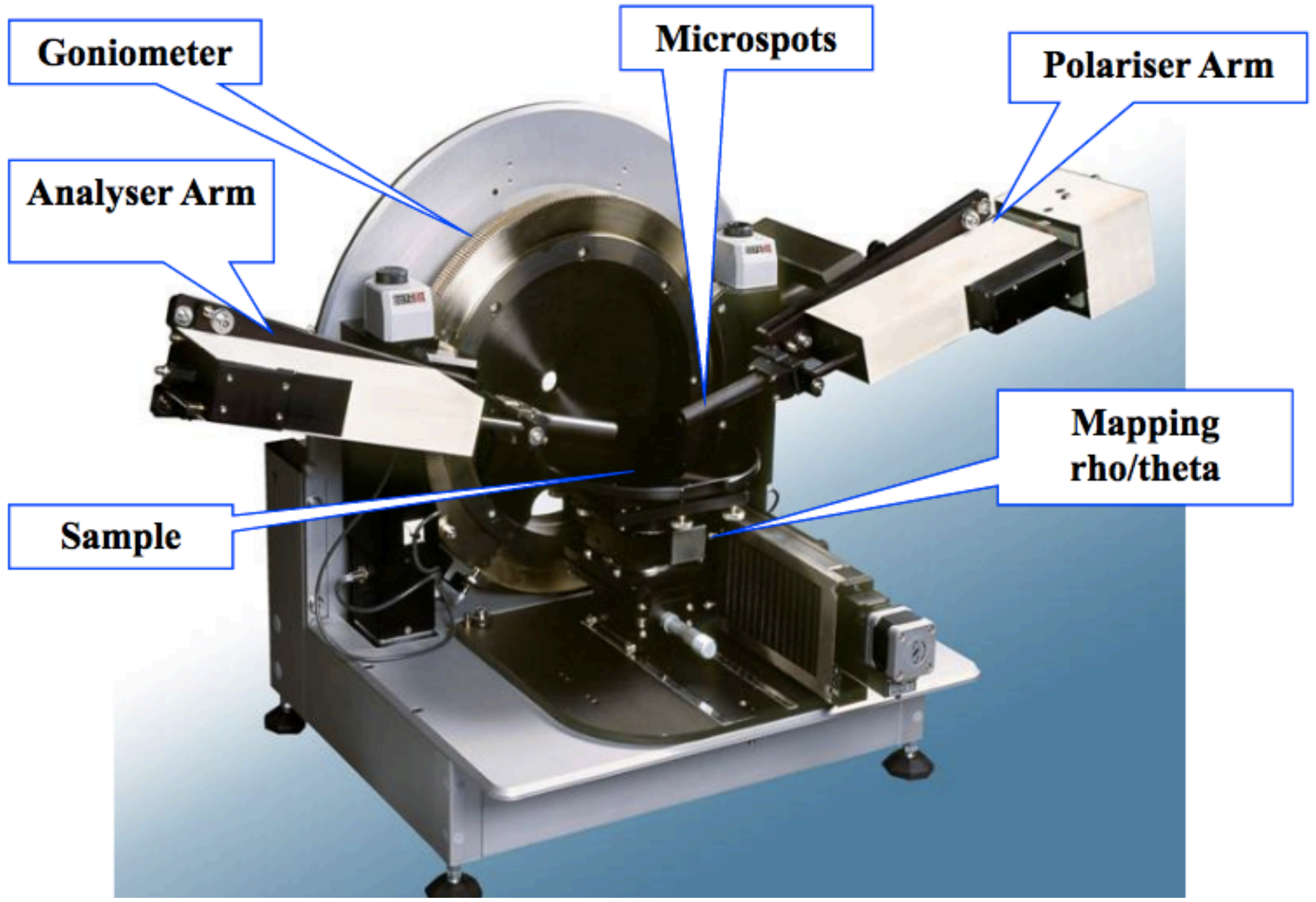


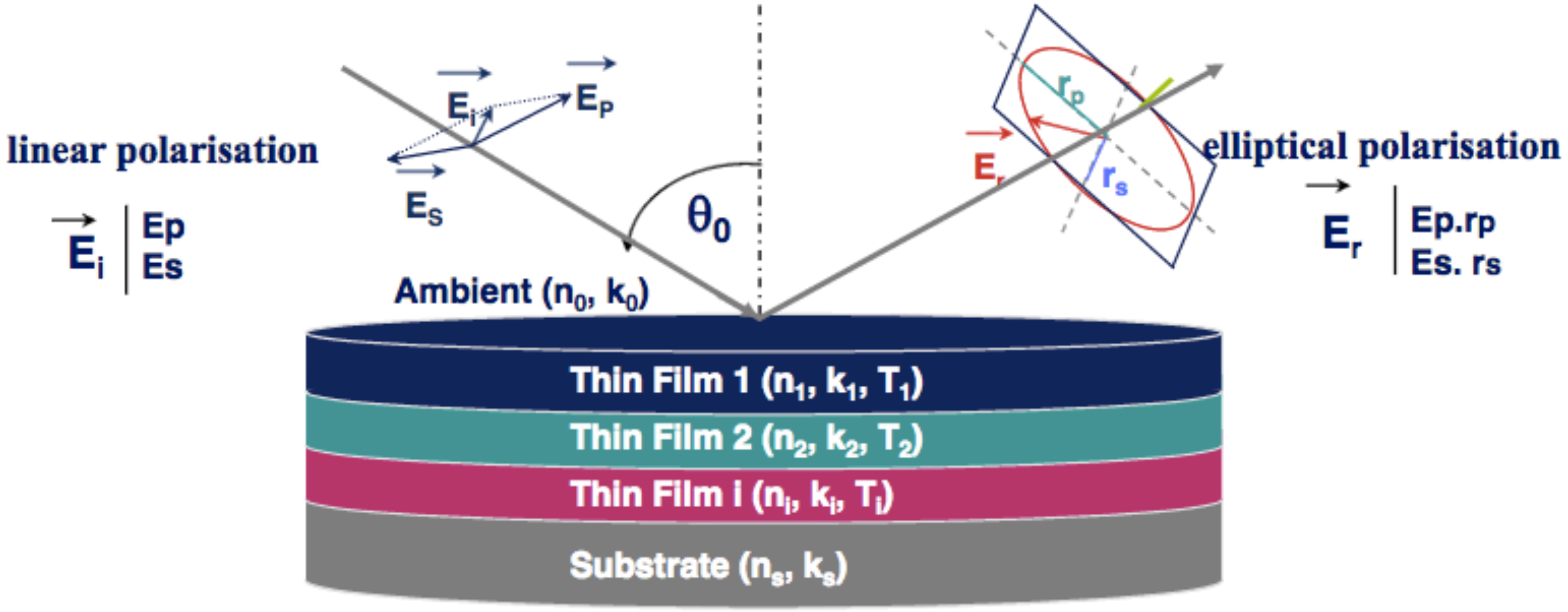
SiO_2 thickness: 1278nm (1500nm in design)

Goodness of fit: 0.9728 (1 means perfect fitting)

Spectroscopic ellipsometer

- Inclined incidence
- Change in polarization after reflection
- Spot size: 400µm
- Wavelength range: 190nm to 2000nm
- Film thickness range: few Å to 50µm
- Other properties of thin film:
  - Composition
  - Roughness
  - n, k value
- ZnO, Pbs, PbSe, TiO_2, Al, Ag, Au, SiN, SiC, Si, CdTe, CdS…

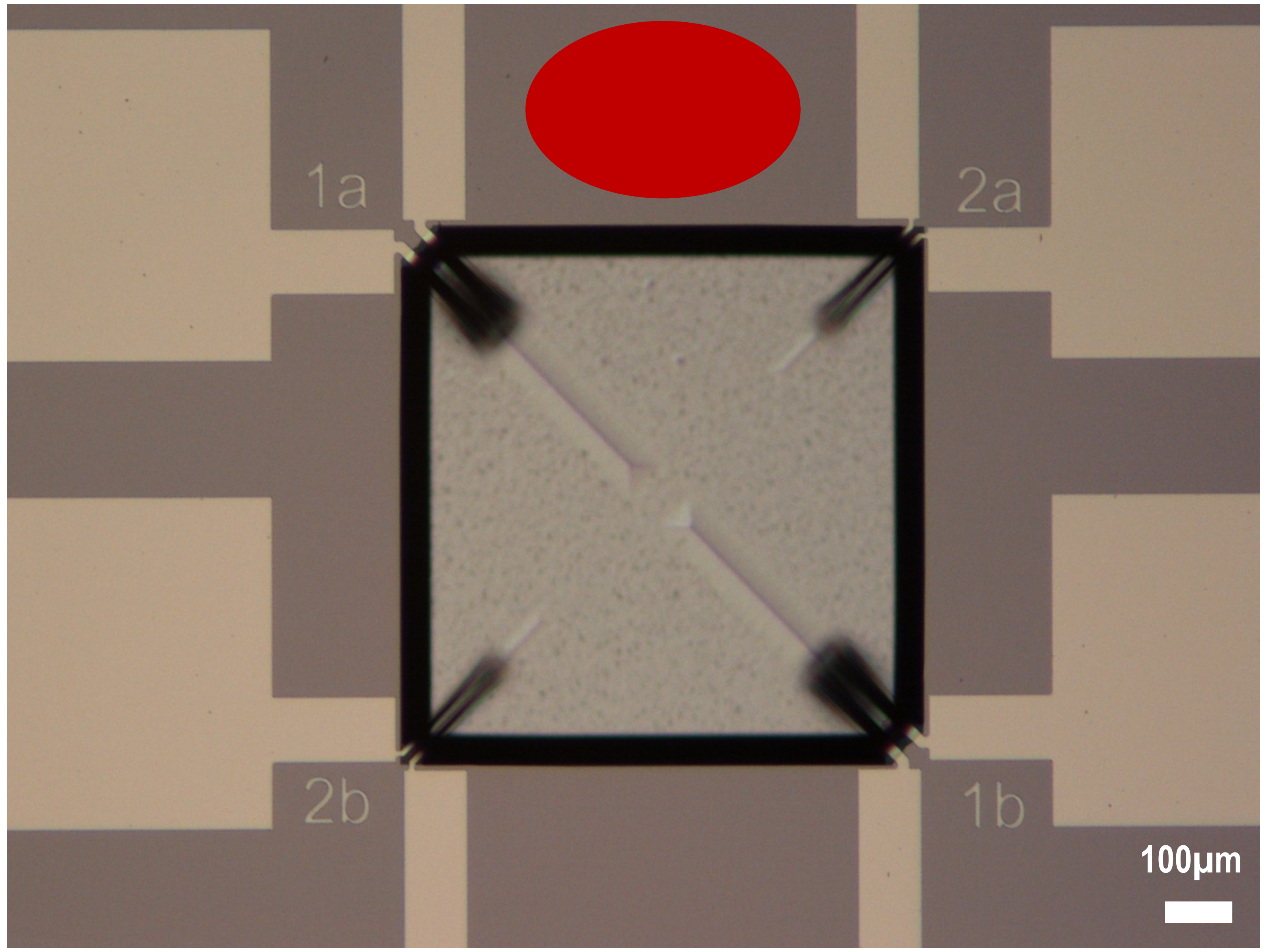


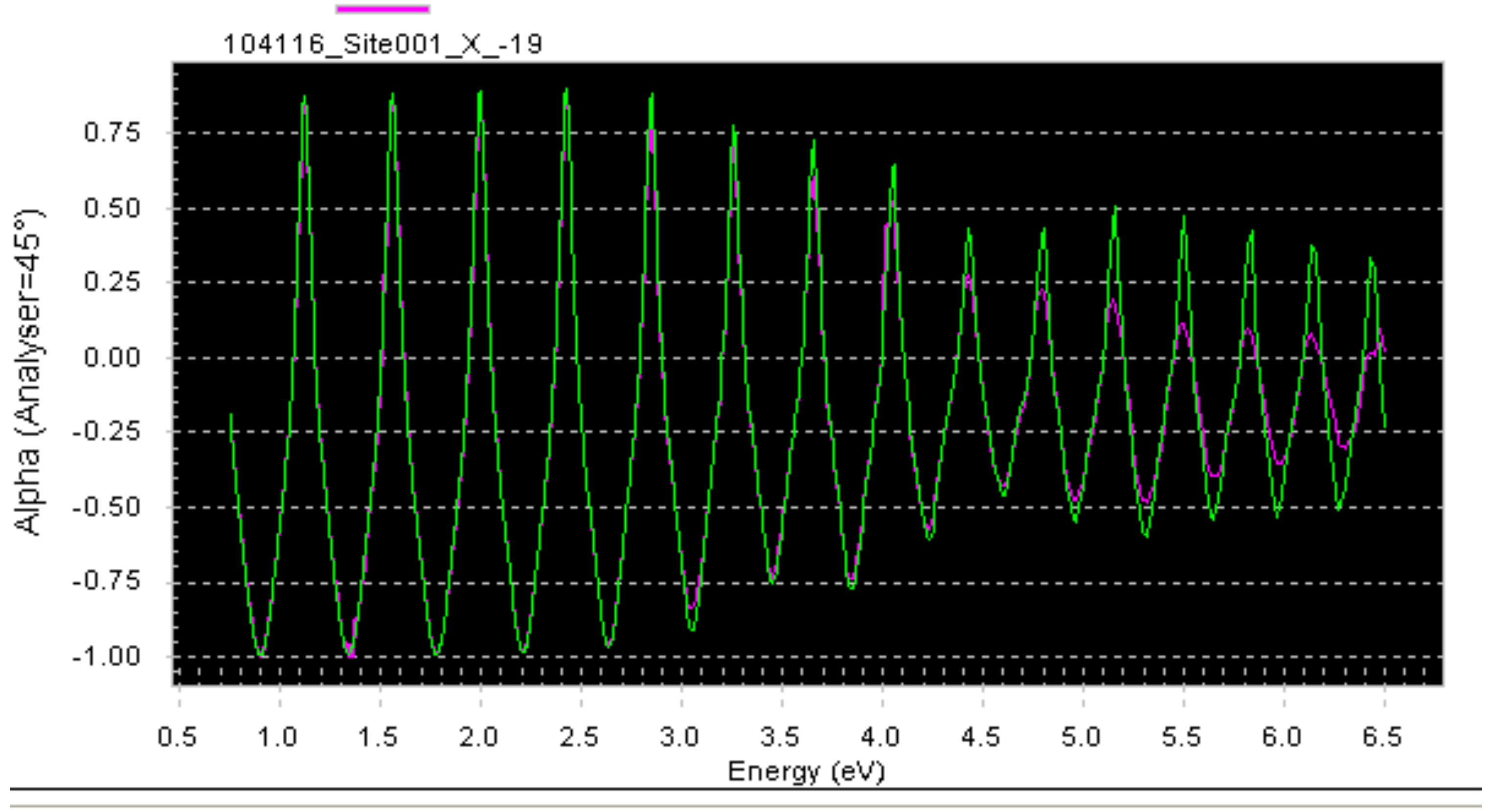


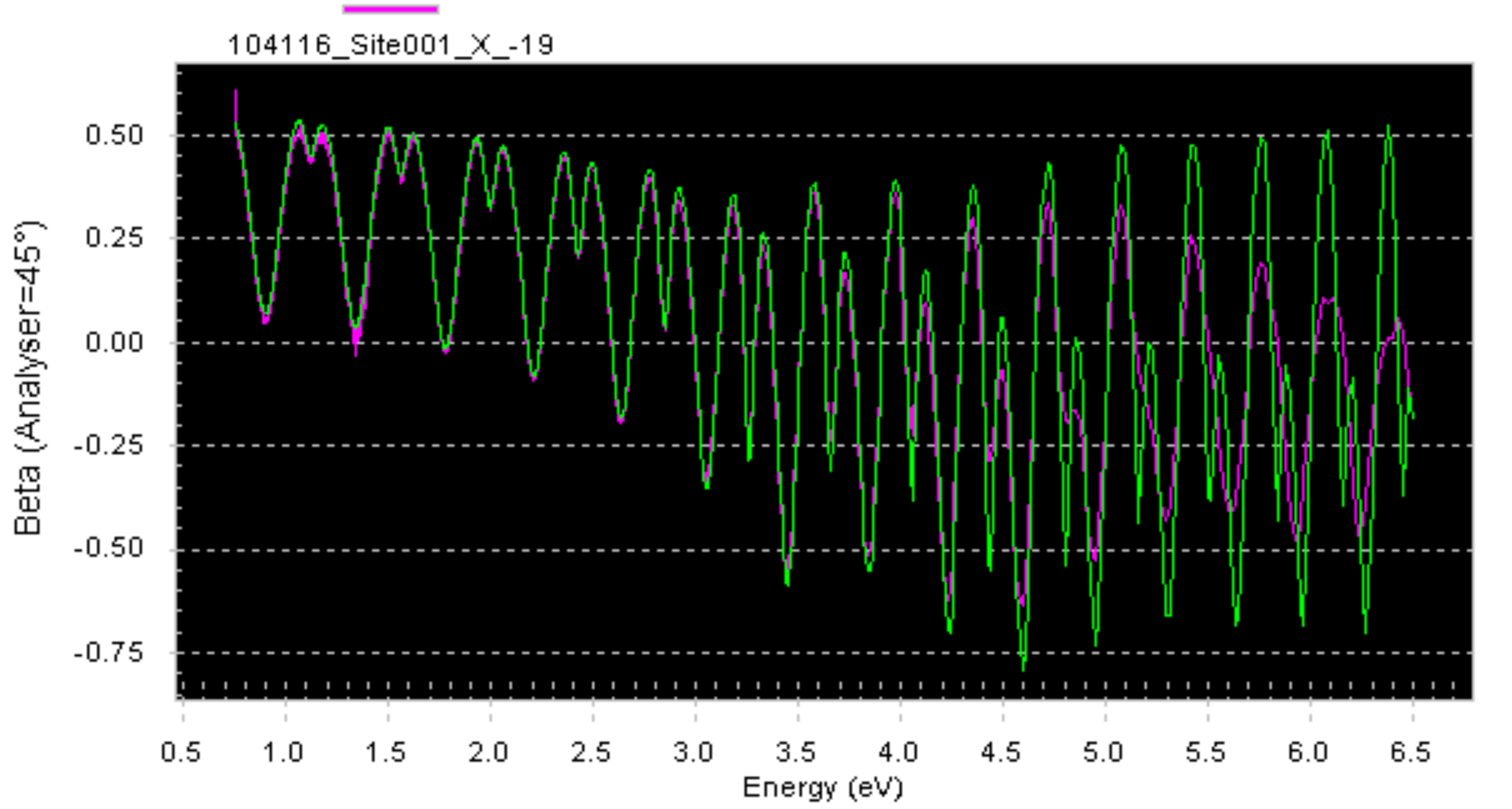
Bi-morph SiO_2 thickness measurement

- Use ellipsometer to measure SiO_2 in the Bi-morph die

Measurement spot







SiO_2 thickness: 1282nm (1500nm in design)

Goodness of fit: 0.9585 (1 means perfect fitting)

Summary

- Reflectometer & Transmittometer
  - Rapid measurement of thin film thickness
  - Large beam spot size
- Ellipsometer
  - Smaller beam size and higher accuracy
  - More complicated methodology
- Both are non-contact, non-invasive
- No sample preparation needed

Inspection and metrology 3
Optical surface profile measurement

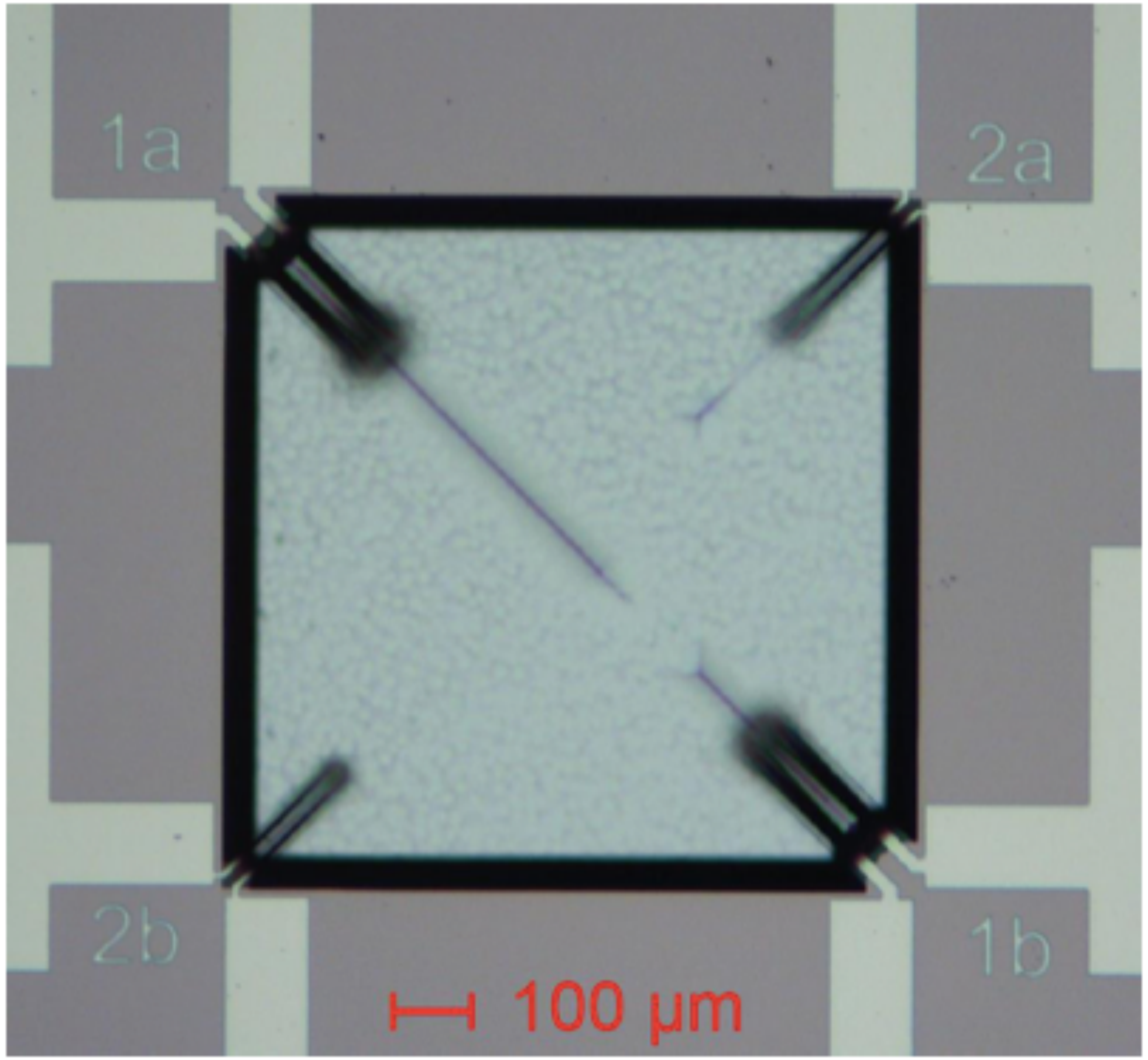
Micro and Nanofabrication (MEMS)

Prof. Jürgen Brugger & Prof. Martin A. M. Gijs

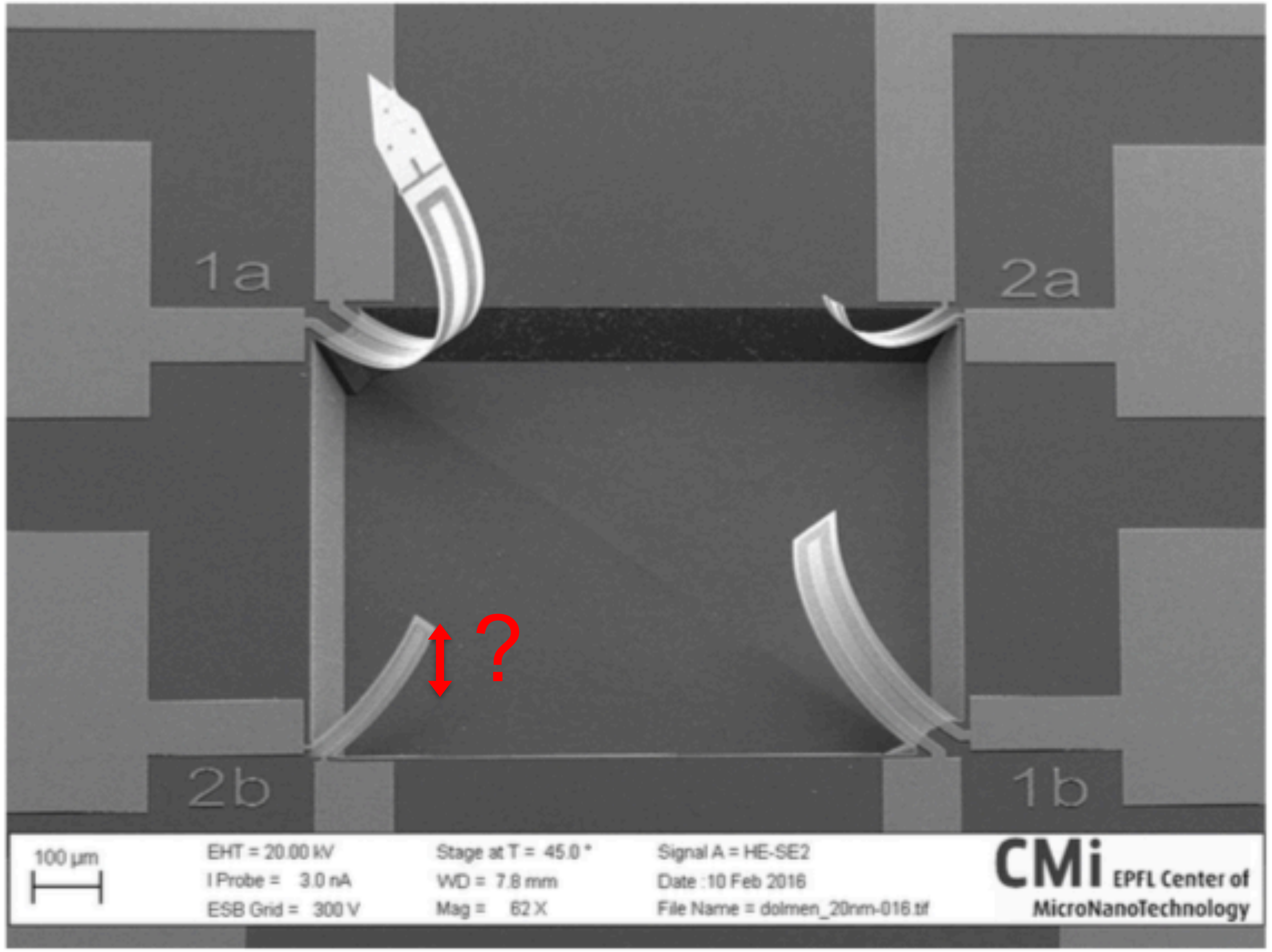
Optical surface profile measurement

- White light interferometric (WLI) surface profiler
- Bi-morph measurement with WLI
- Laser beam surface profiler
- Thin film stress measurement

Bi-morph surface profile measurement



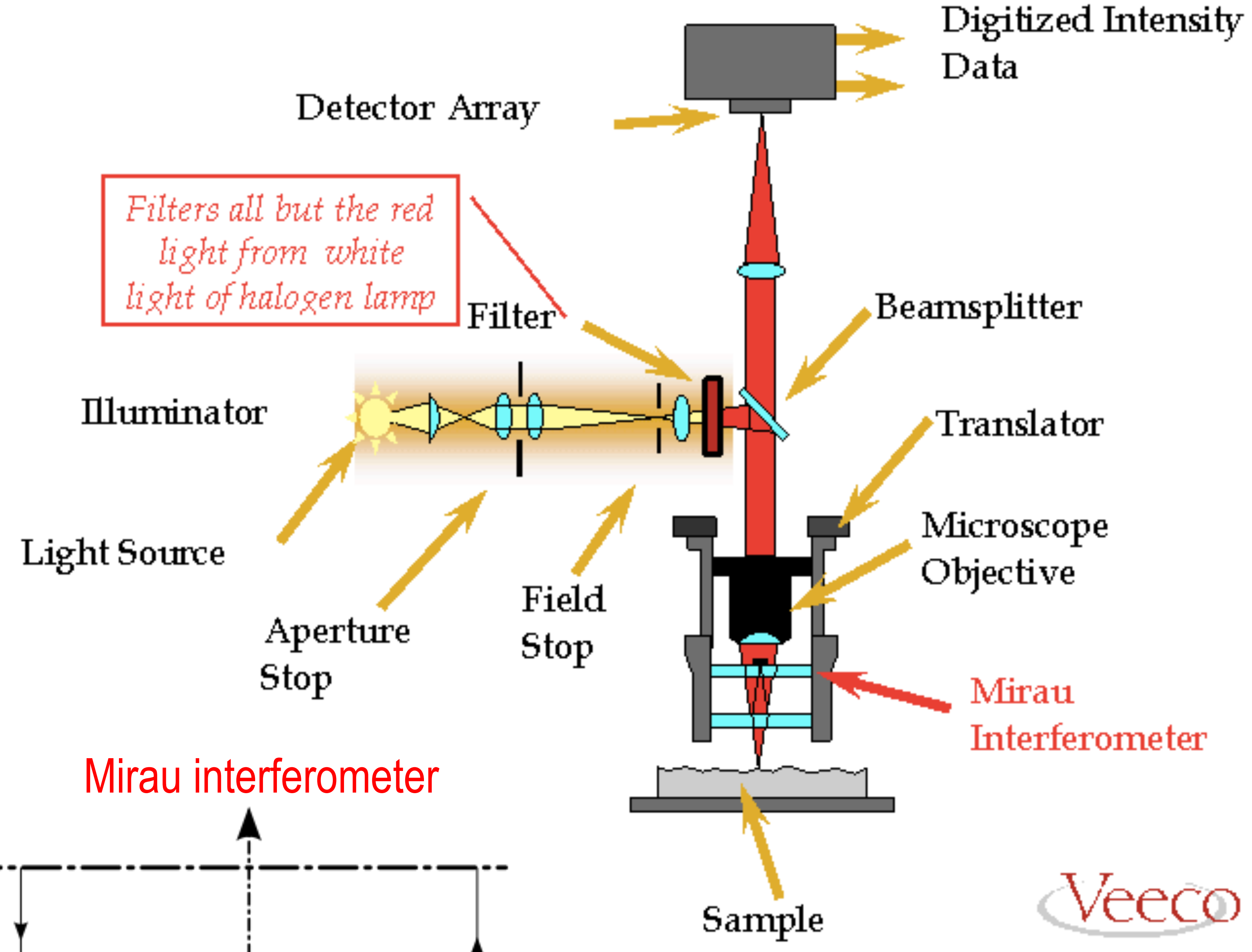
Optical microscope



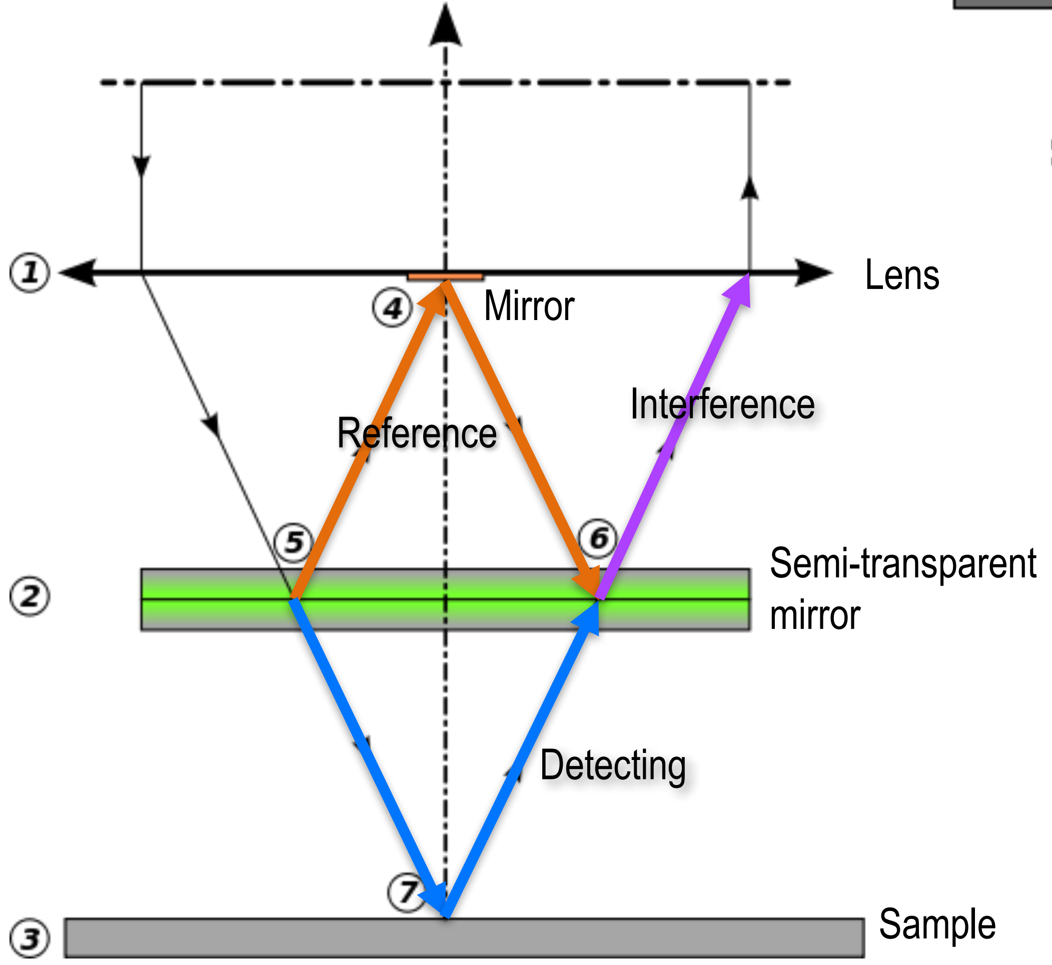
How high is the cantilever bending upwards?

White light interferometric surface profiler

- Mirau interferometer embedded objective lenses
- Surface topography ➔ optical path change ➔ interference change
- Scan in vertical direction to obtain 3D surface profile
- Field of view: up to 2.5mm x 1.9mm
- Vertical resolution: < 1nm
- Vertical scan range: 1mm
- Non-contact, non-destructive



Mirau interferometer



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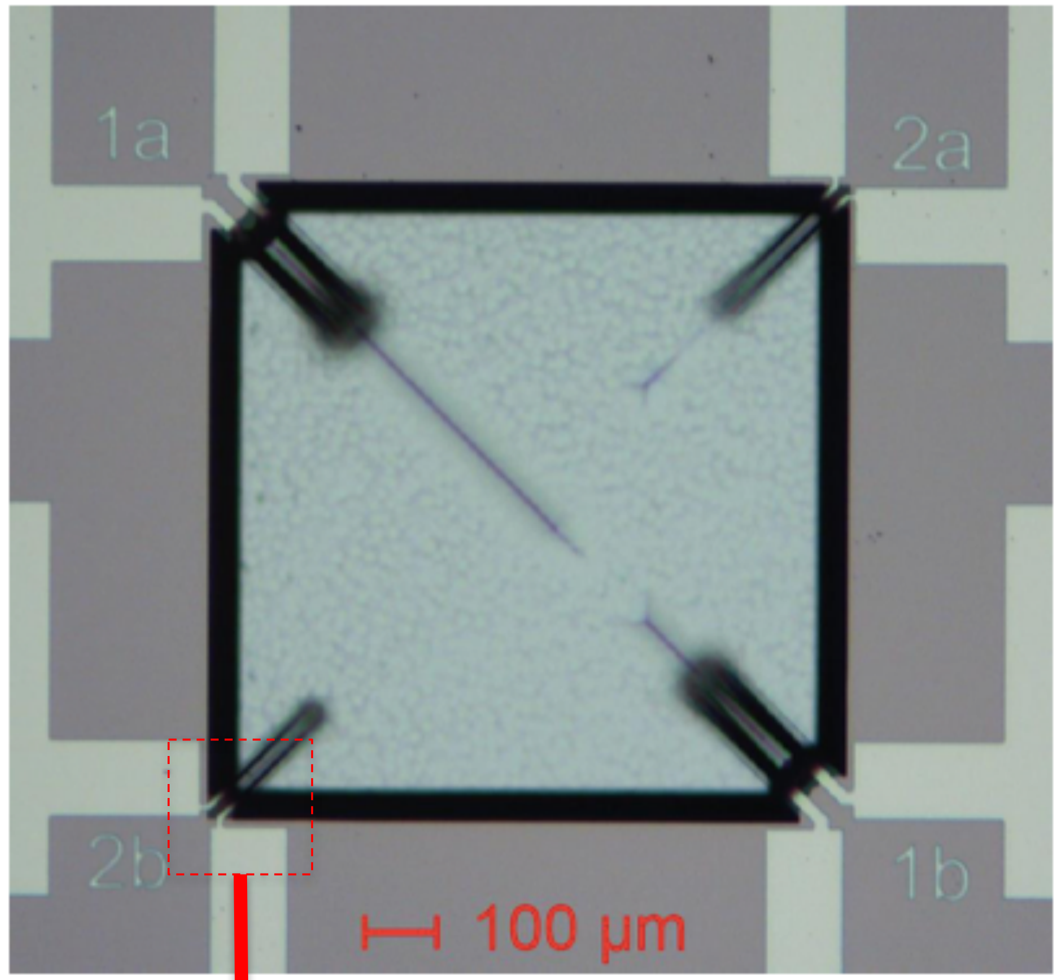
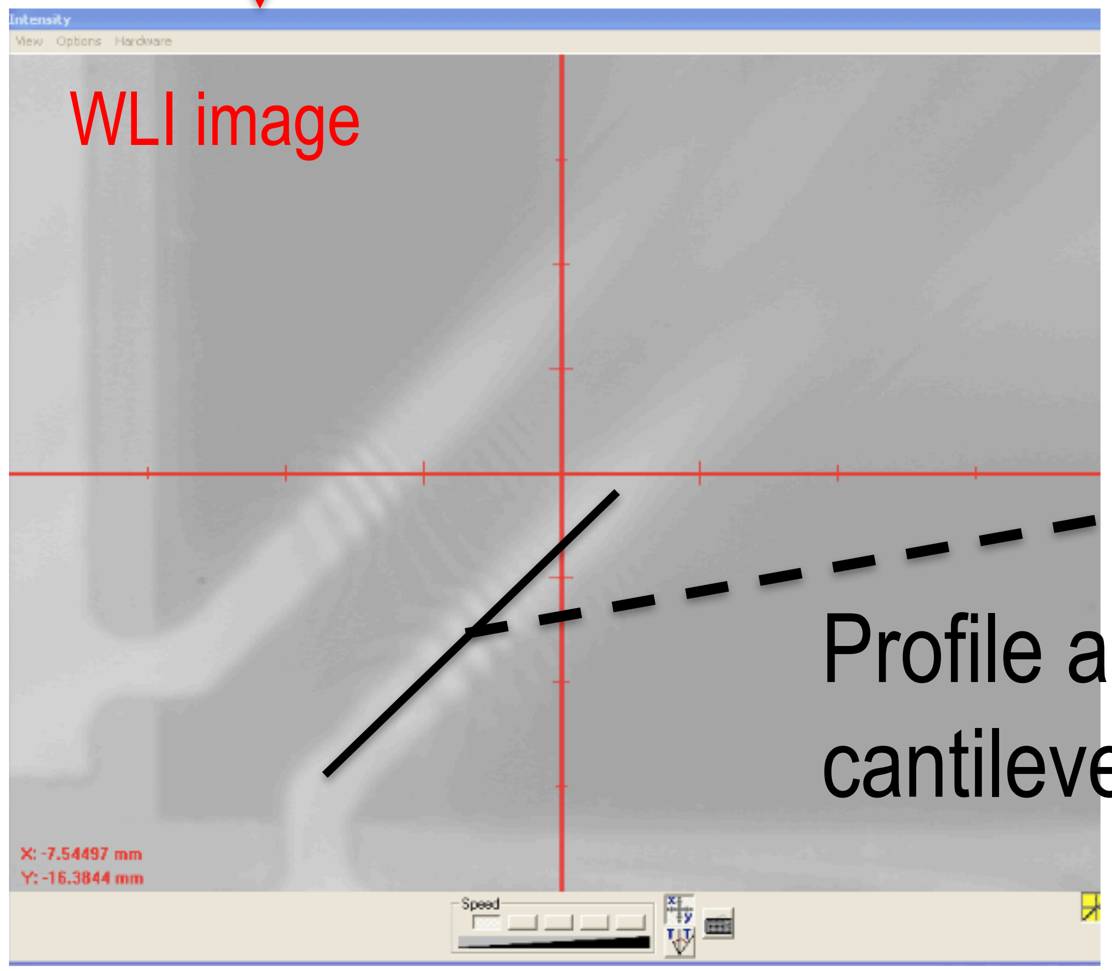
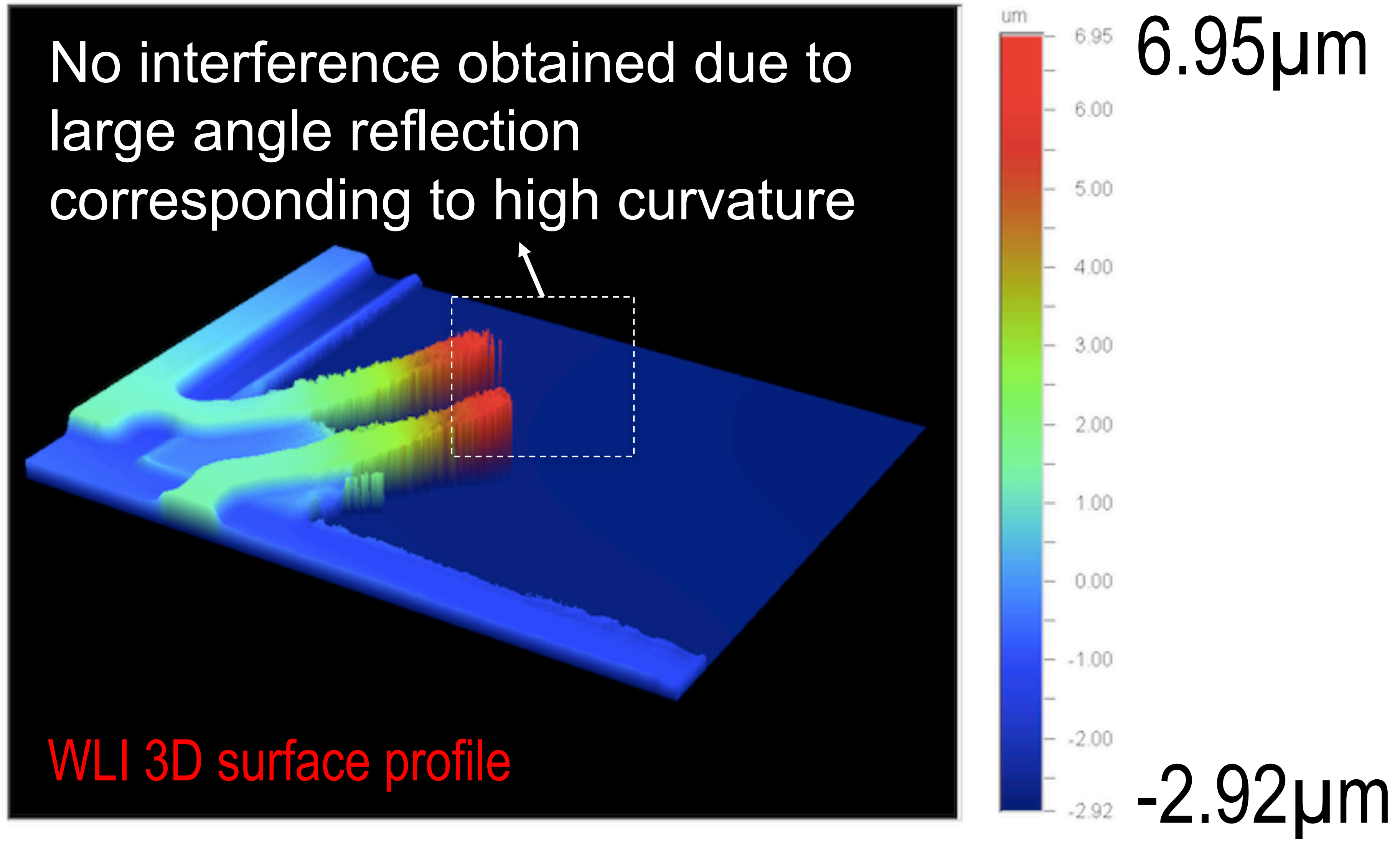
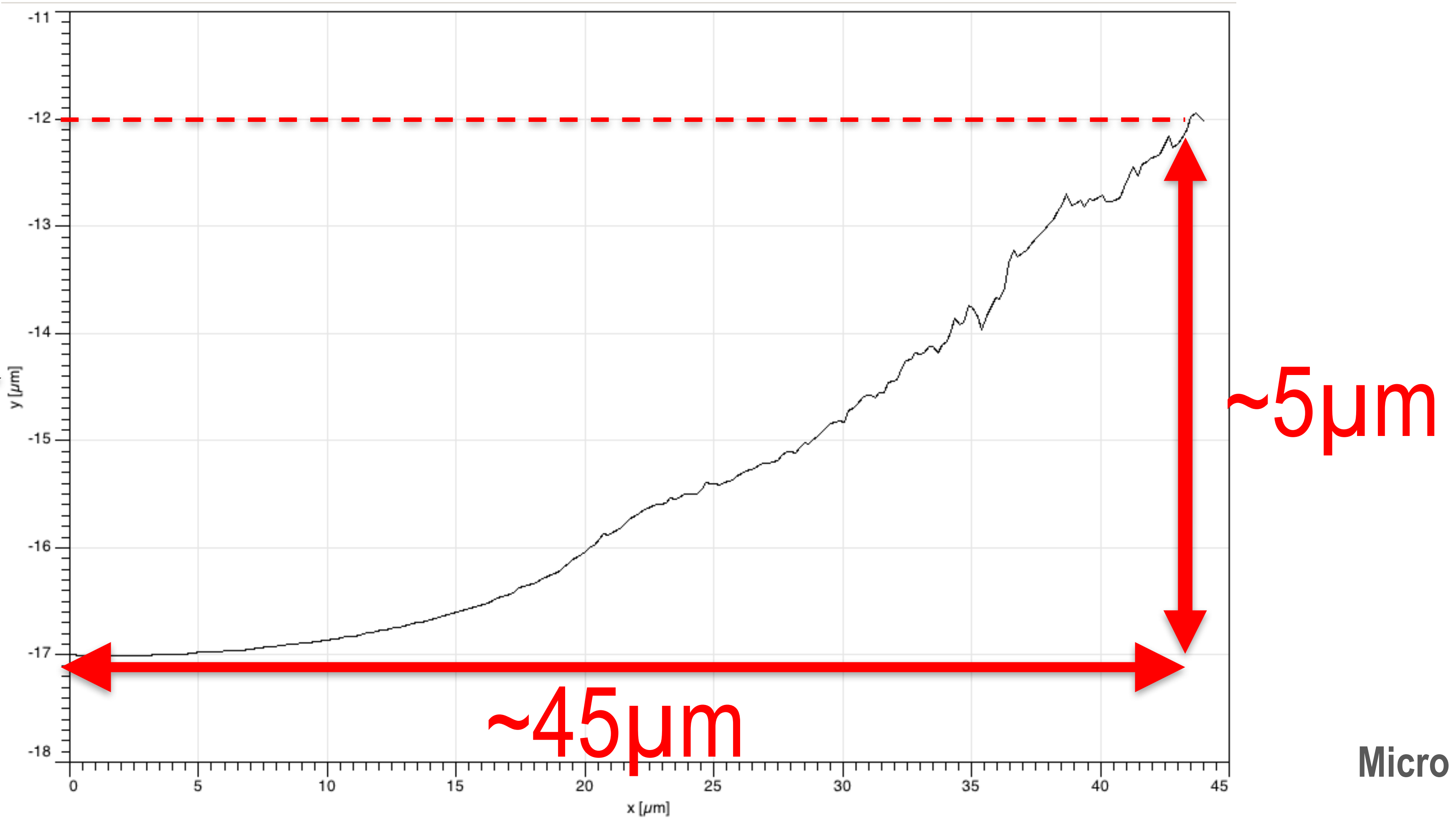
Bi-morph measurement with WLI



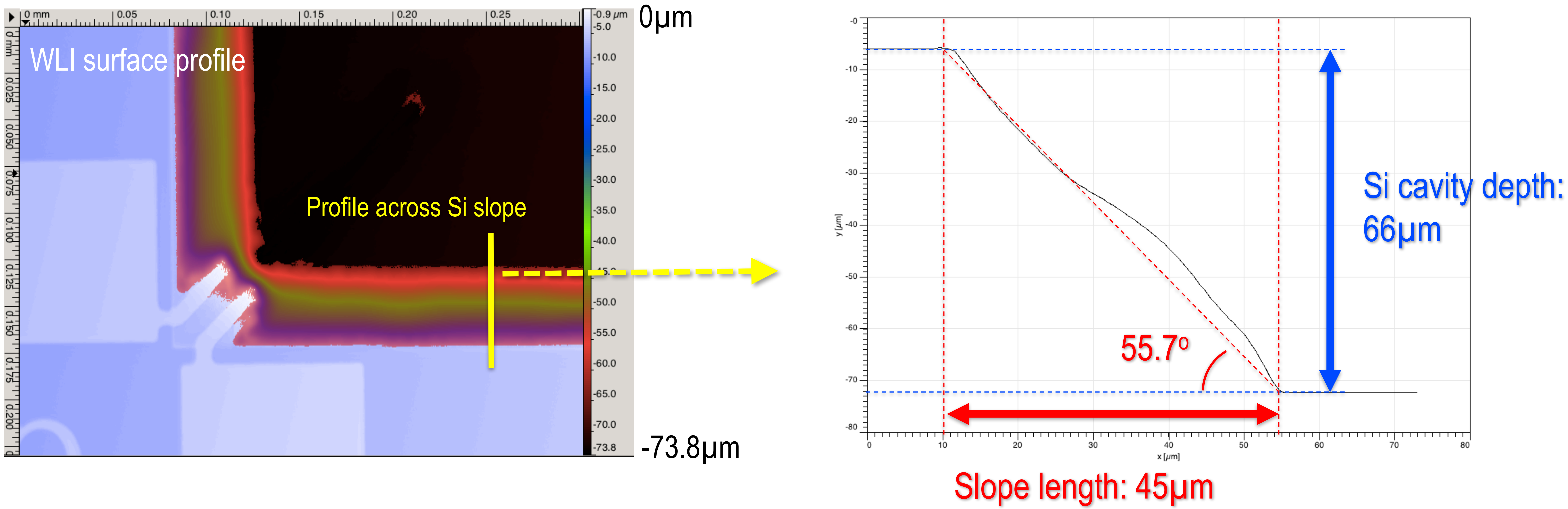
Optical microscope



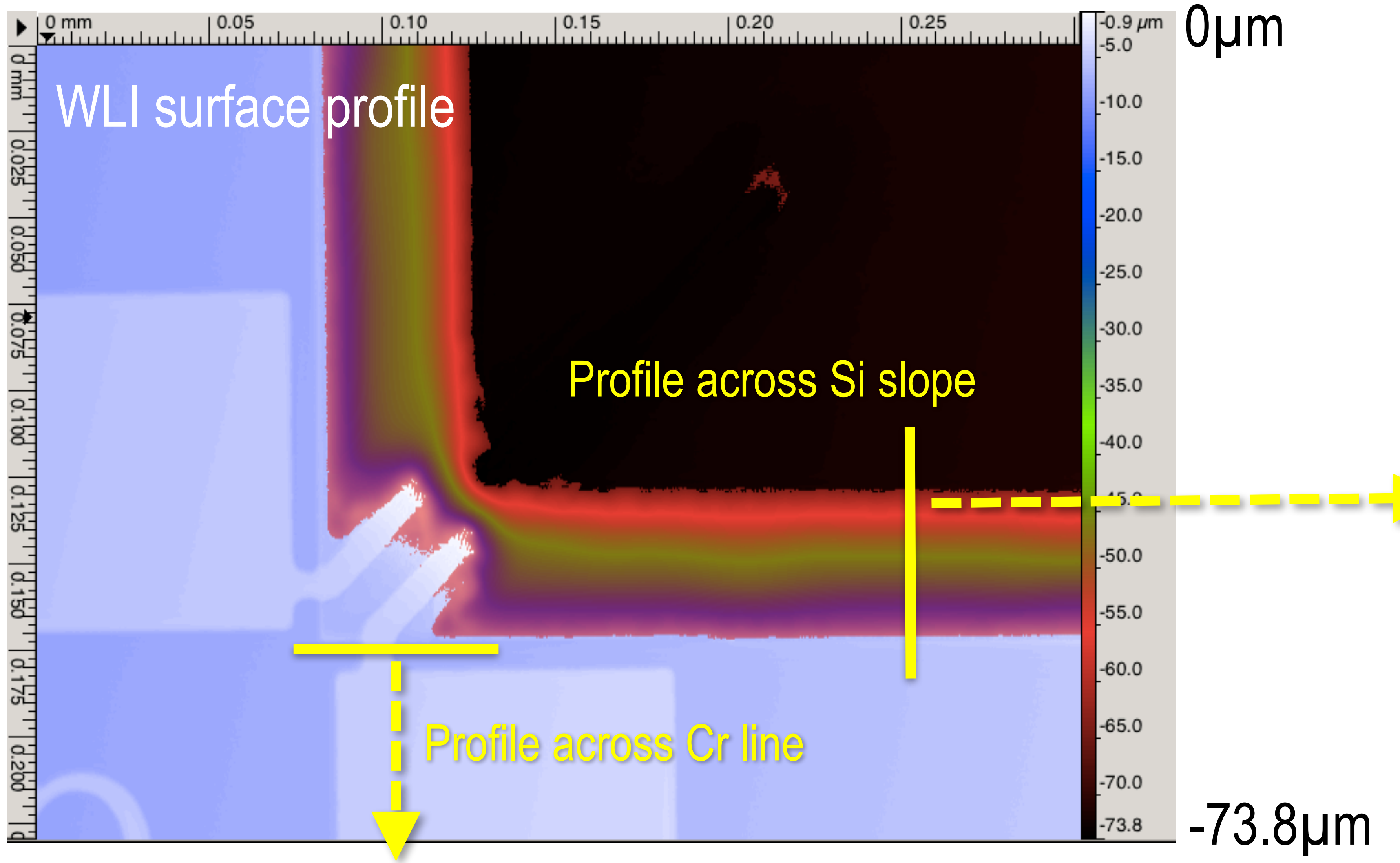


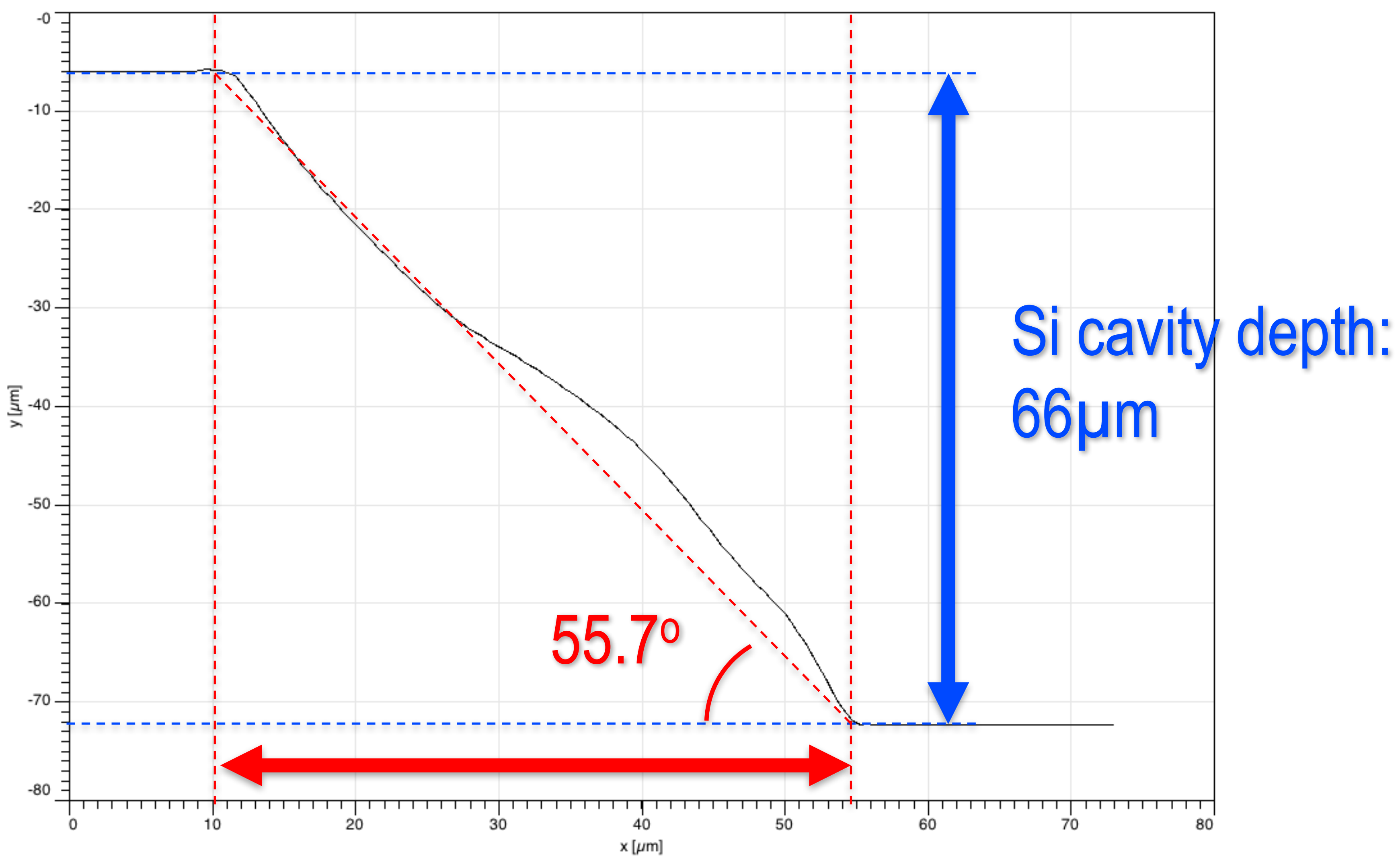


Bi-morph measurement with WLI

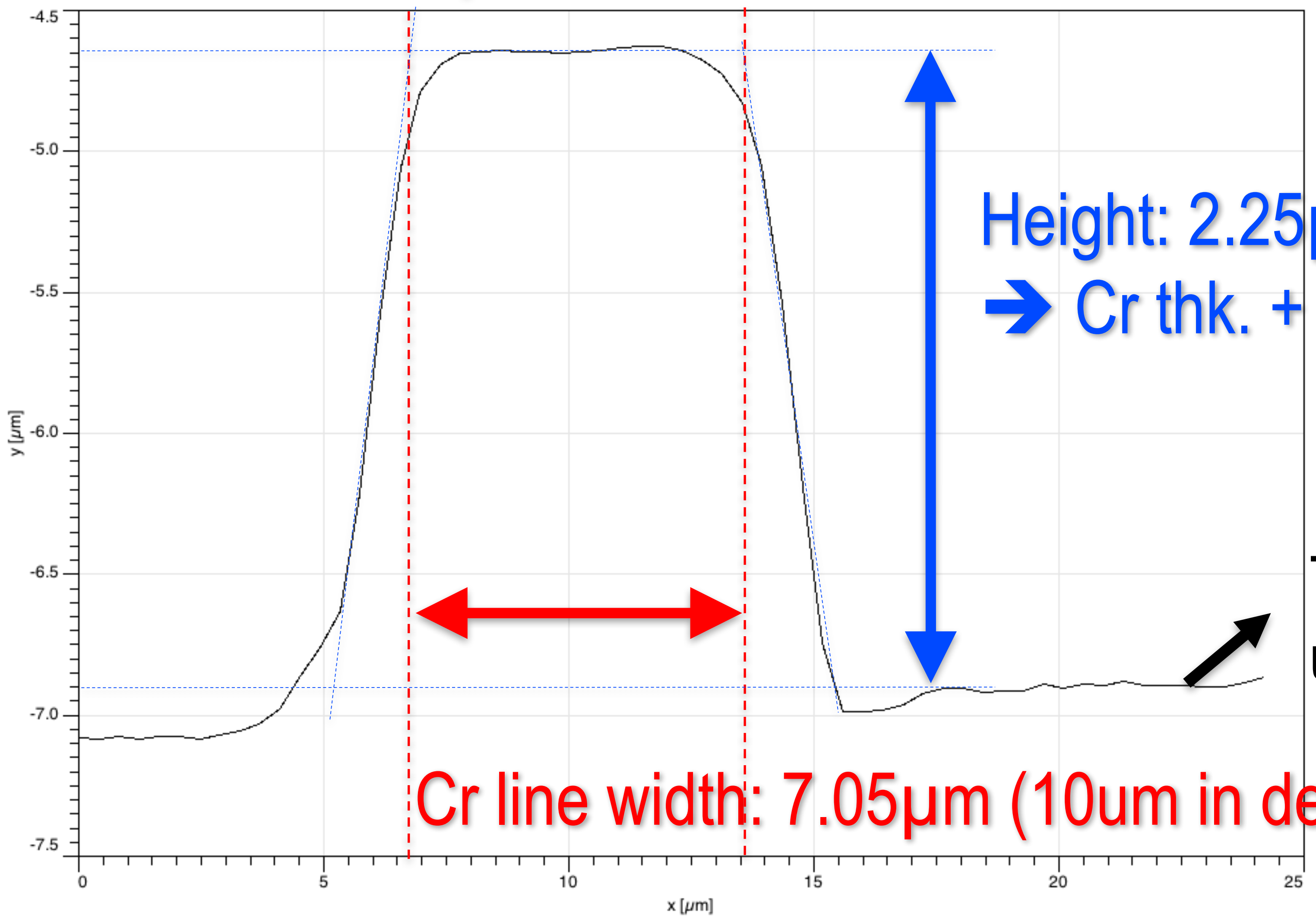


Bi-morph measurement with WLI





Slope length: 45µm

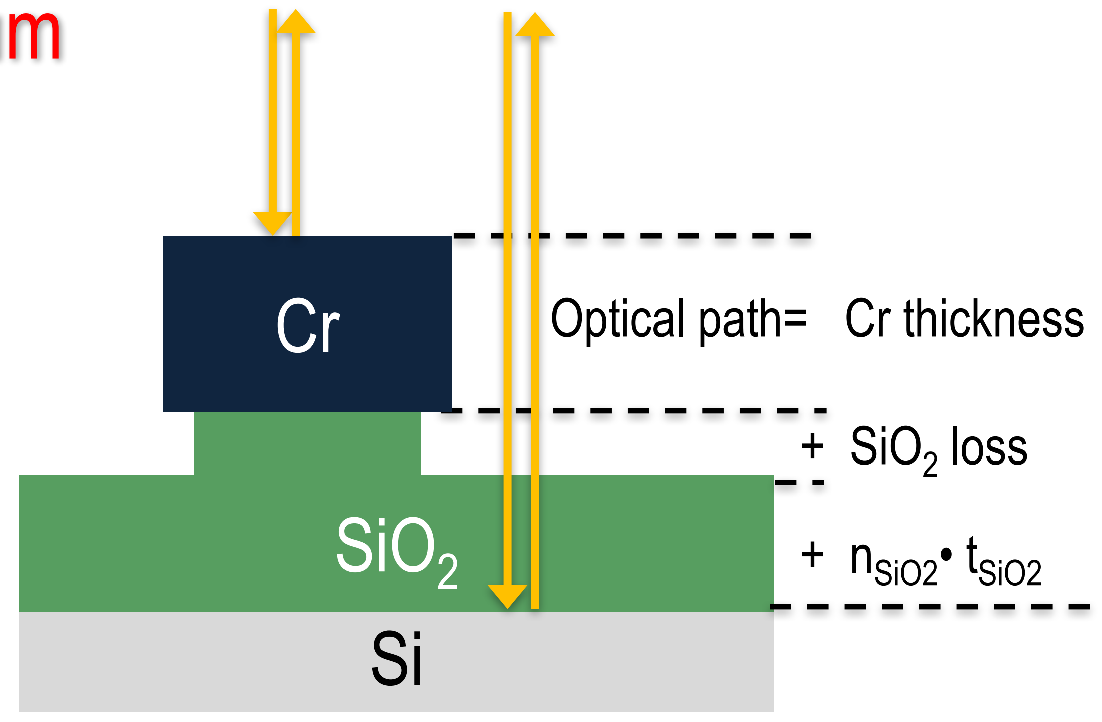


Height: 2.25µm >> process target Cr thk.: 500nm

➔ Cr thk. + SiO_2 loss + SiO_2 effective thk. ($n_{SiO2} \cdot t_{SiO2}$)

This should be Si surface under SiO_2

Cr line width: 7.05µm (10um in design)



Bi-morph cross section

Stresses in thin films

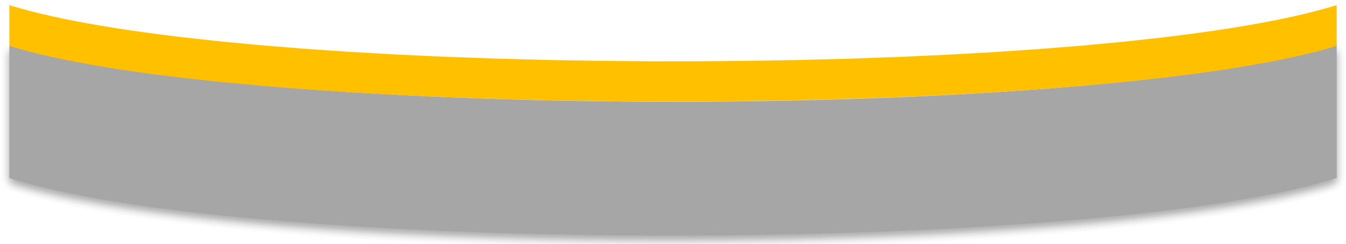
The thin film stress causes wafer bending!

Film growth or deposition

Bare silicon wafer is almost flat

Compressive stress

or

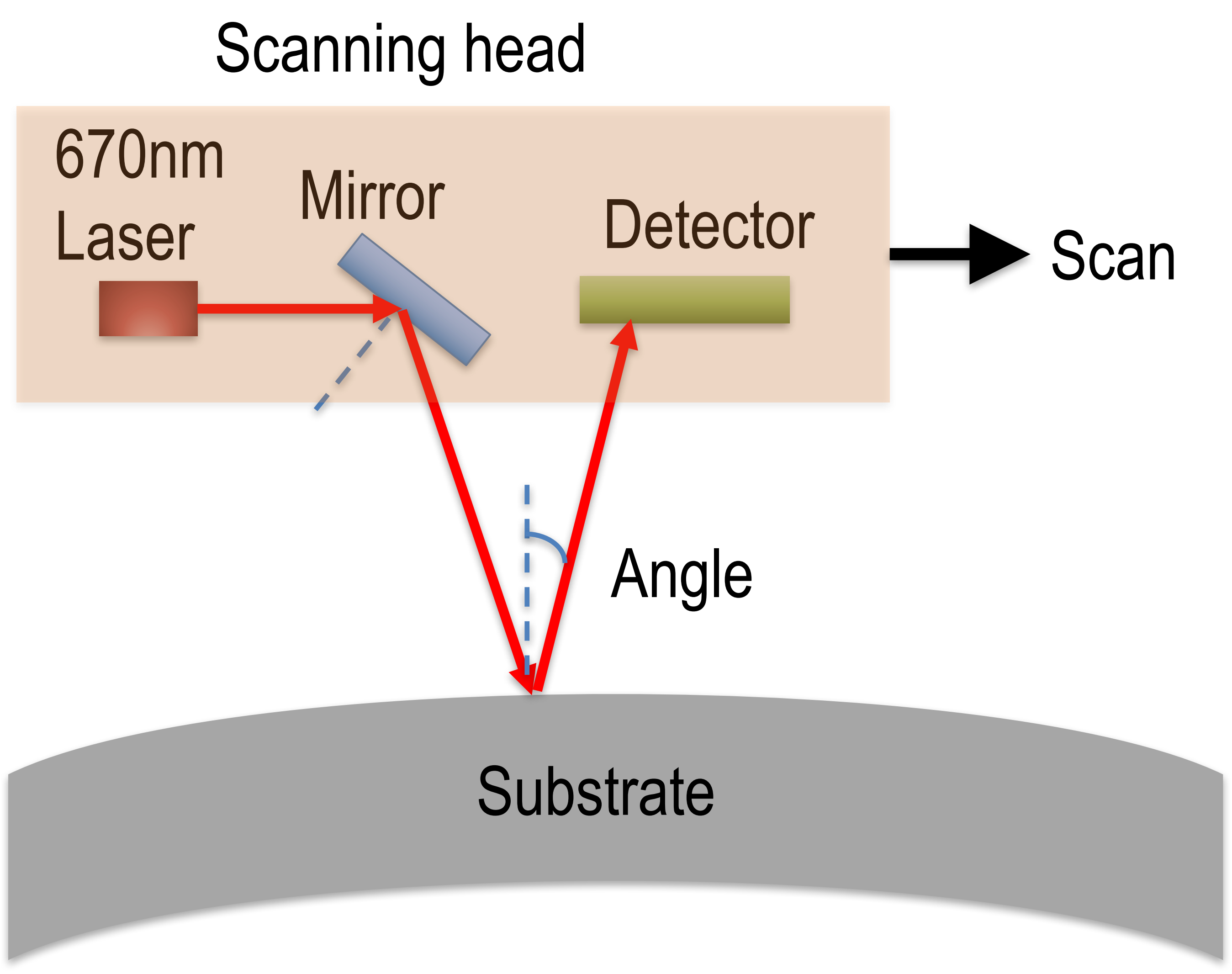


Tensile stress

How to measure the thin film stress level?

Laser beam surface profiler

- Laser beam to detect the entire wafer surface profile → curvature
- Too large wafer curvature will affect fabrication process
- Wafer curvature → thin film stress level

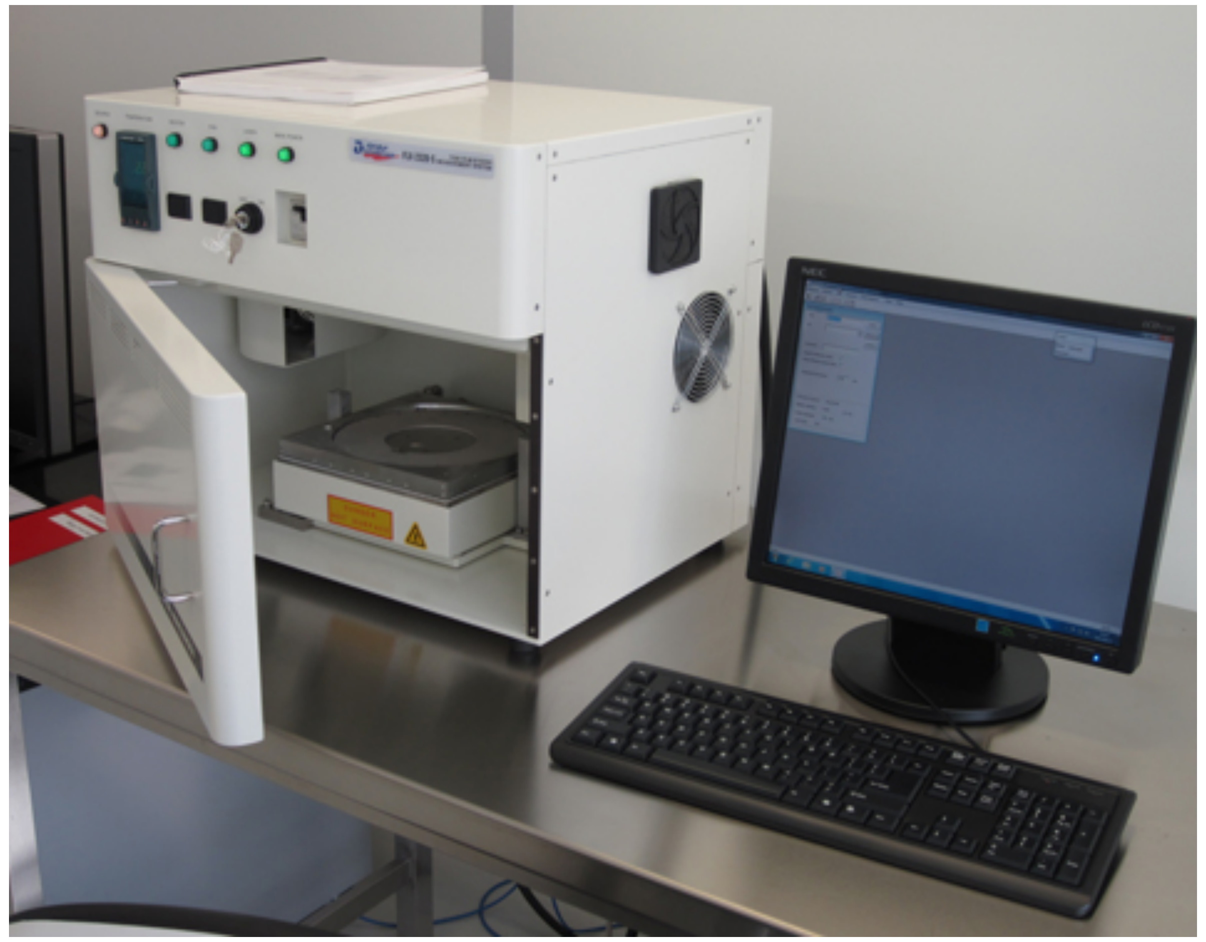


- Stoney equation:

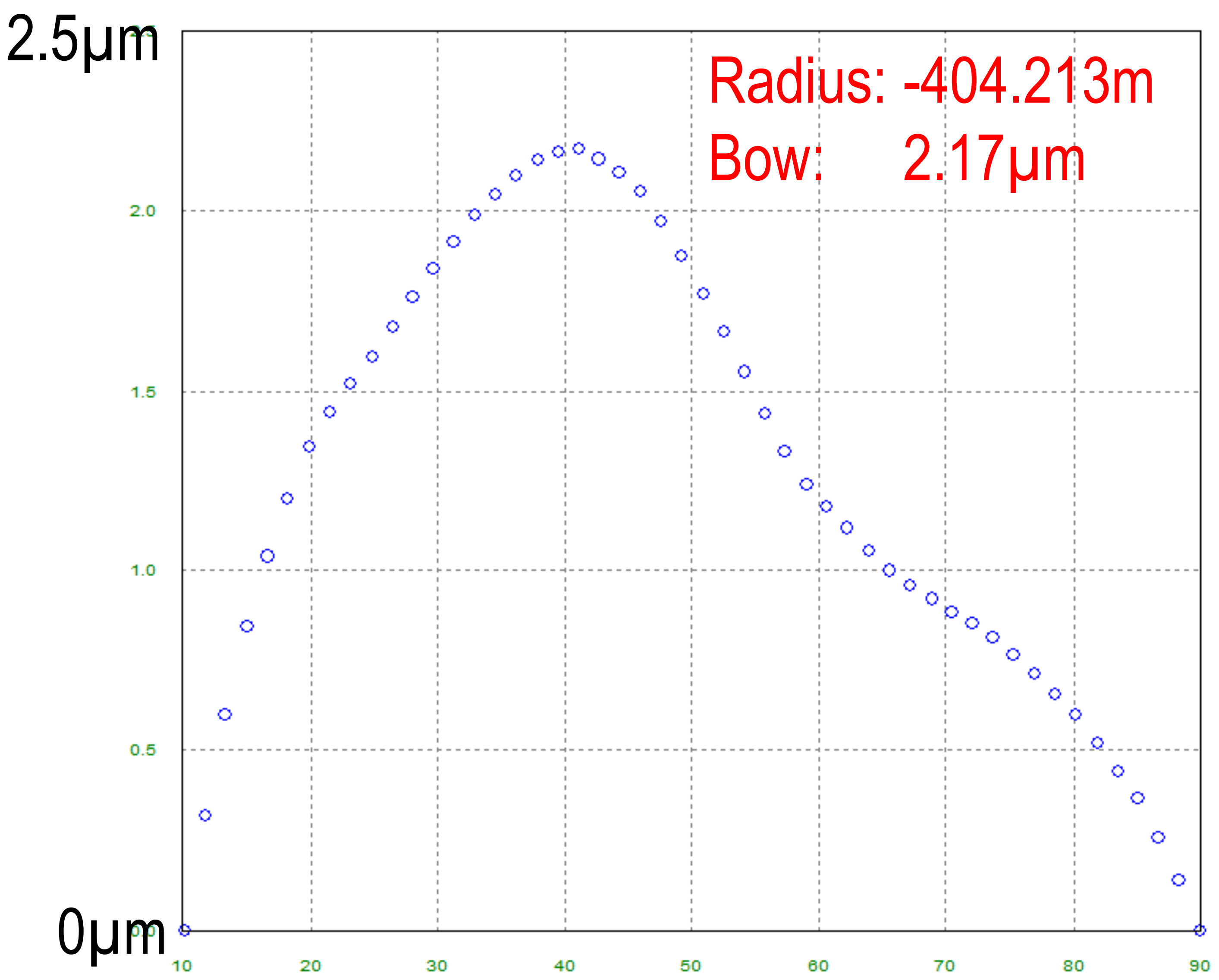
$$\sigma_f = \frac{E_s}{6(1-\nu_s)} \cdot \frac{t_s^2}{t_f} \left(\frac{1}{r_{sf}} - \frac{1}{r_s} \right)$$

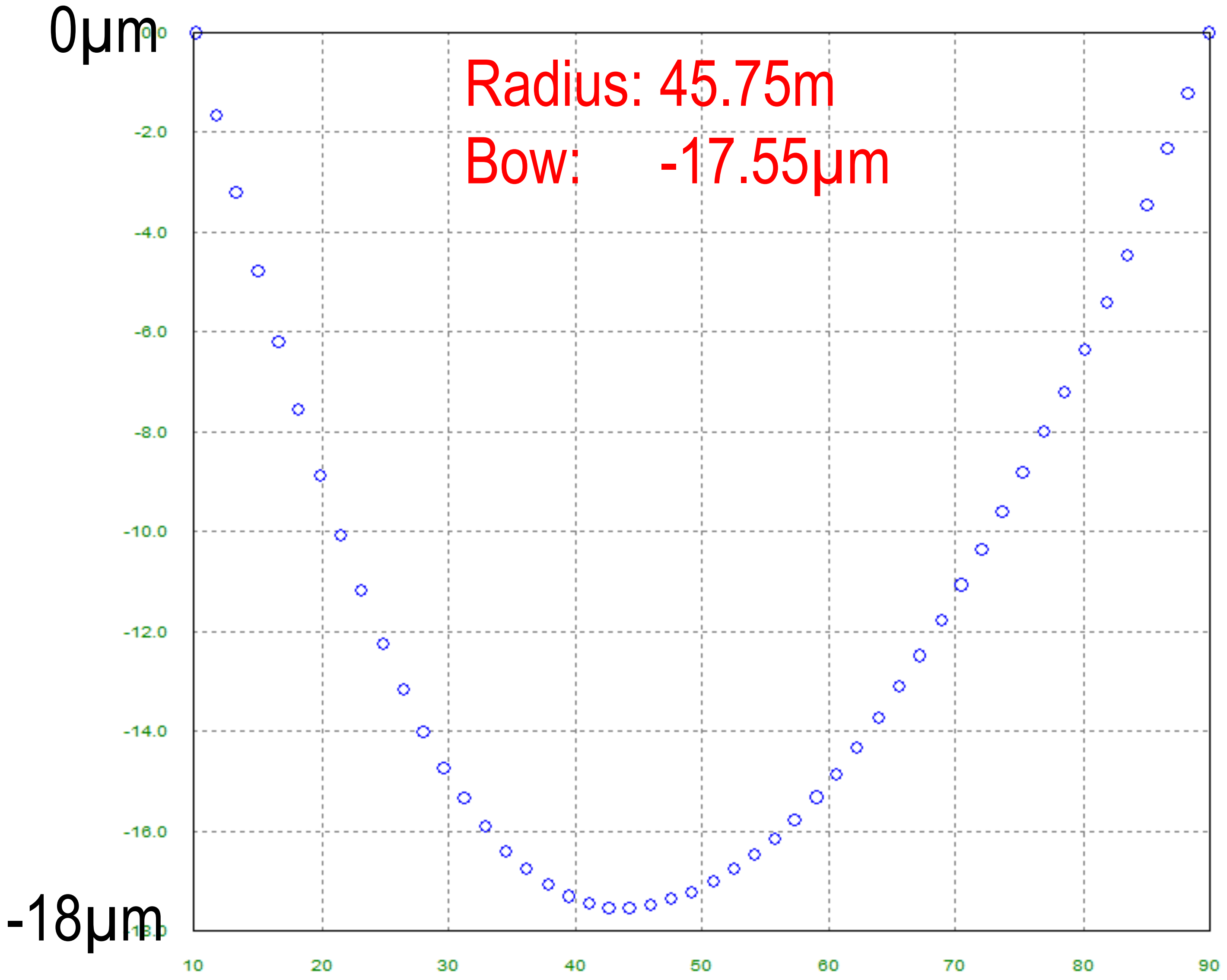
σ_f = stress in film in [Pa], by convention negative stresses are compressive
E_s = substrate Young's modulus in [Pa]
ν_s = Poisson ratio of the substrate
t_f and t_s = film and substrate thickness in [m]
r_{sf} = radius of curvature of the substrate with the thin film in [m]
r_s = radius of curvature of the substrate before deposition in [m]

Thin film stress measurement

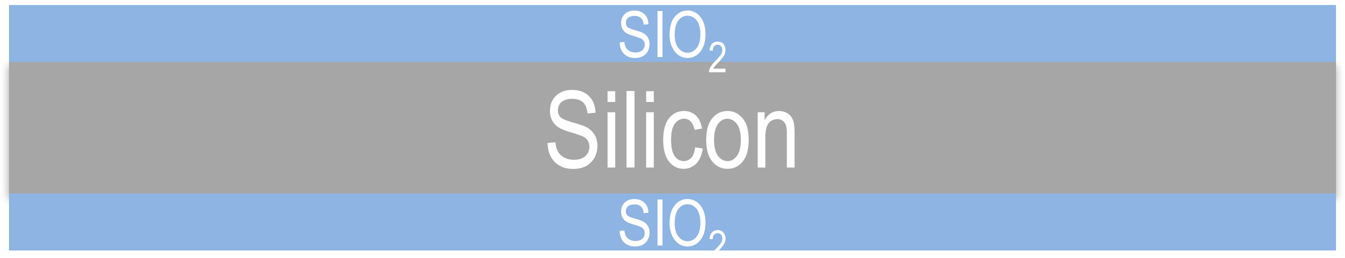


Laser beam surface profiler

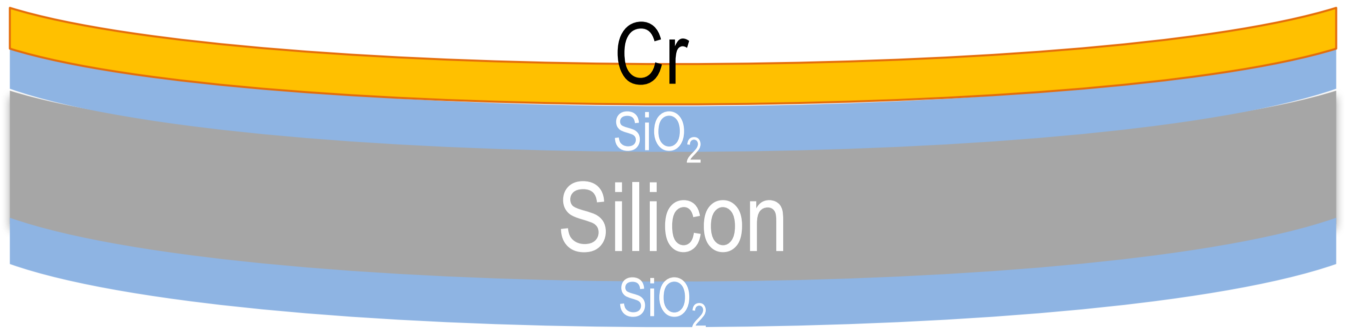




Bi-morph wafer:



Before Cr deposition



After Cr deposition

$$Cr\ \ film\ \ stress = \frac{185GPa}{6(1-0.06)} \cdot \frac{(525 \cdot 10^{-6}m)^2}{0.5 \cdot 10^{-6}m} \left(\frac{1}{45.75m} - \frac{1}{-404.213m} \right) = 0.44GPa = 440MPa\ \ (tensile)$$

Summary

- WLI surface profiler
  - XYZ dimension measurement
  - Released structure measurement
- Laser beam surface profiler
  - Wafer curvature
  - Thin film mechanical stress
- Non-contact, non-invasive
- No sample preparation needed

Inspection and metrology 4
Mechanical surface profile measurement

Micro and Nanofabrication (MEMS)

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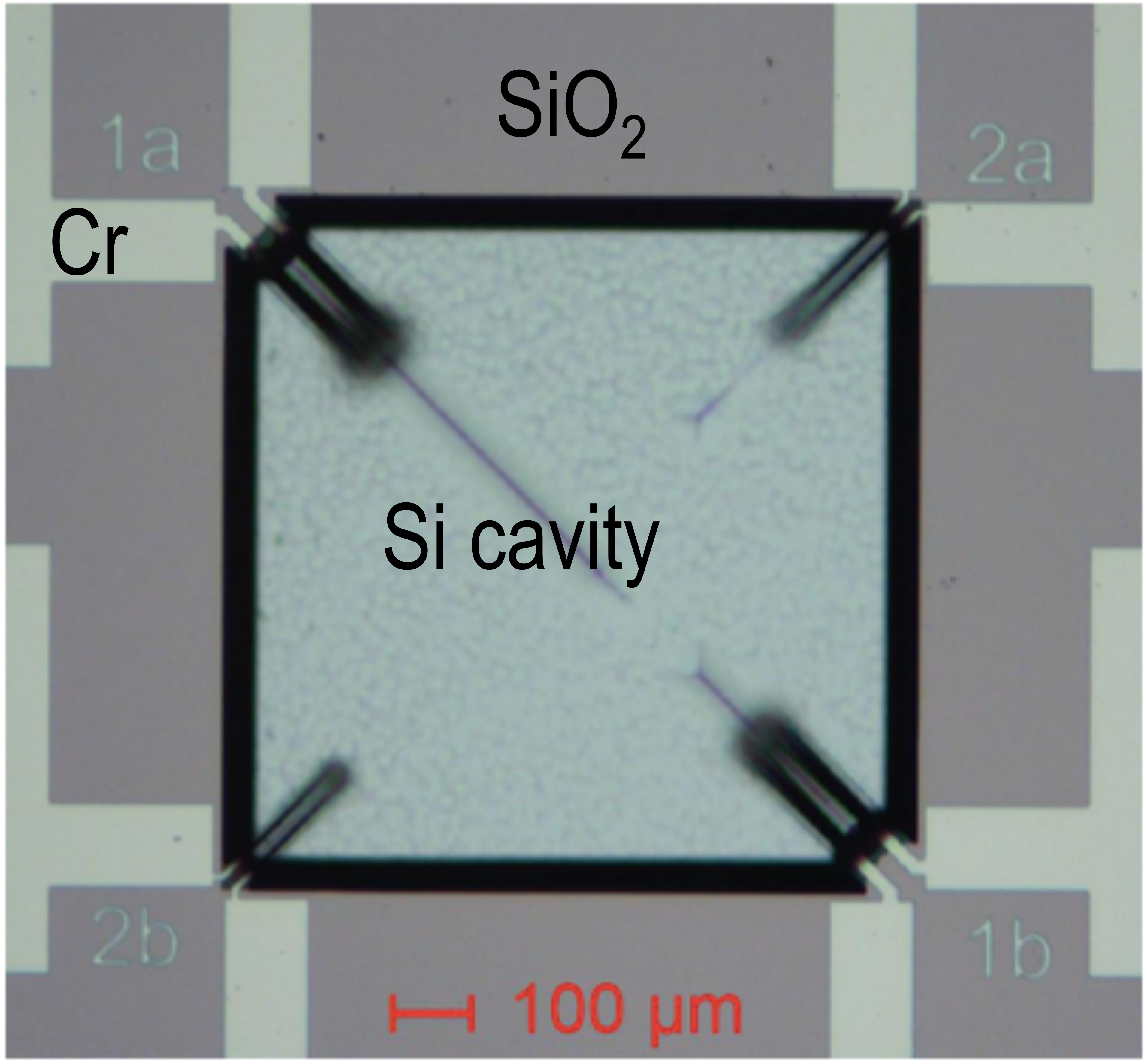
Mechanical surface profile measurement

- Mechanical surface profiler
- Bi-morph surface profile measurement
- Atomic force microscopy
- Bi-morph surface roughness measurement

Bi-morph surface profile measurement

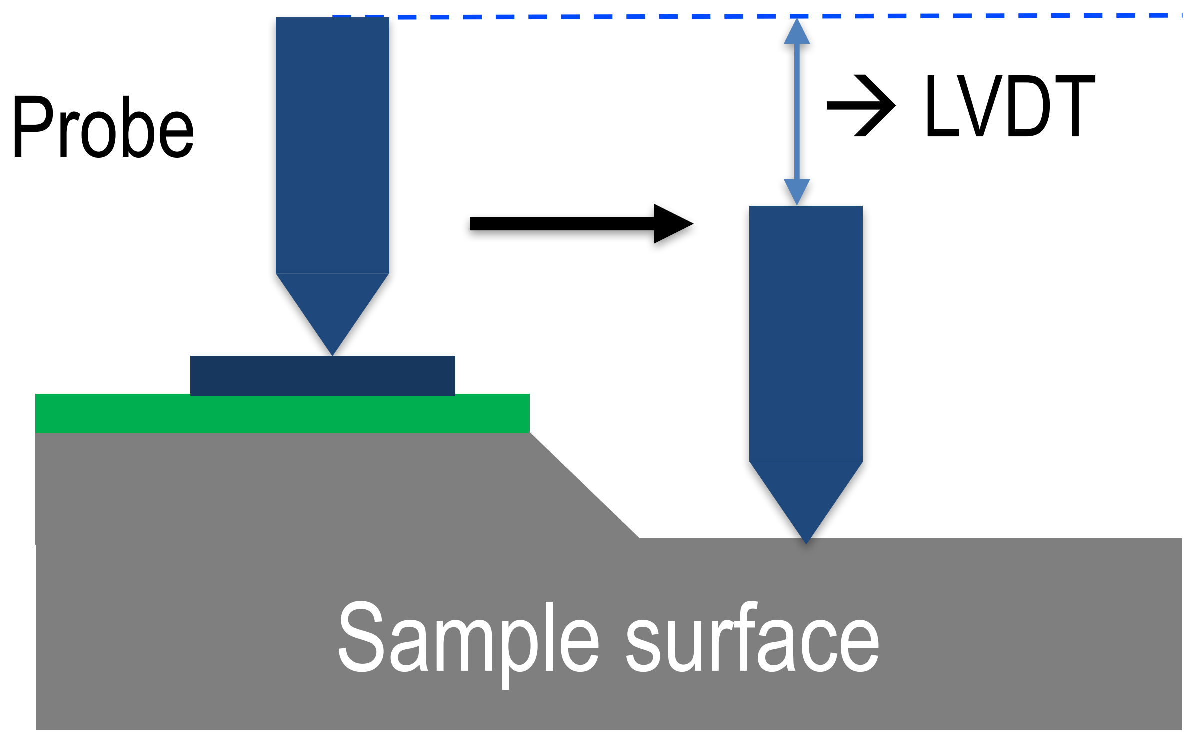
- Cr thin film thickness
- Cr and SiO_2 thin film surface roughness



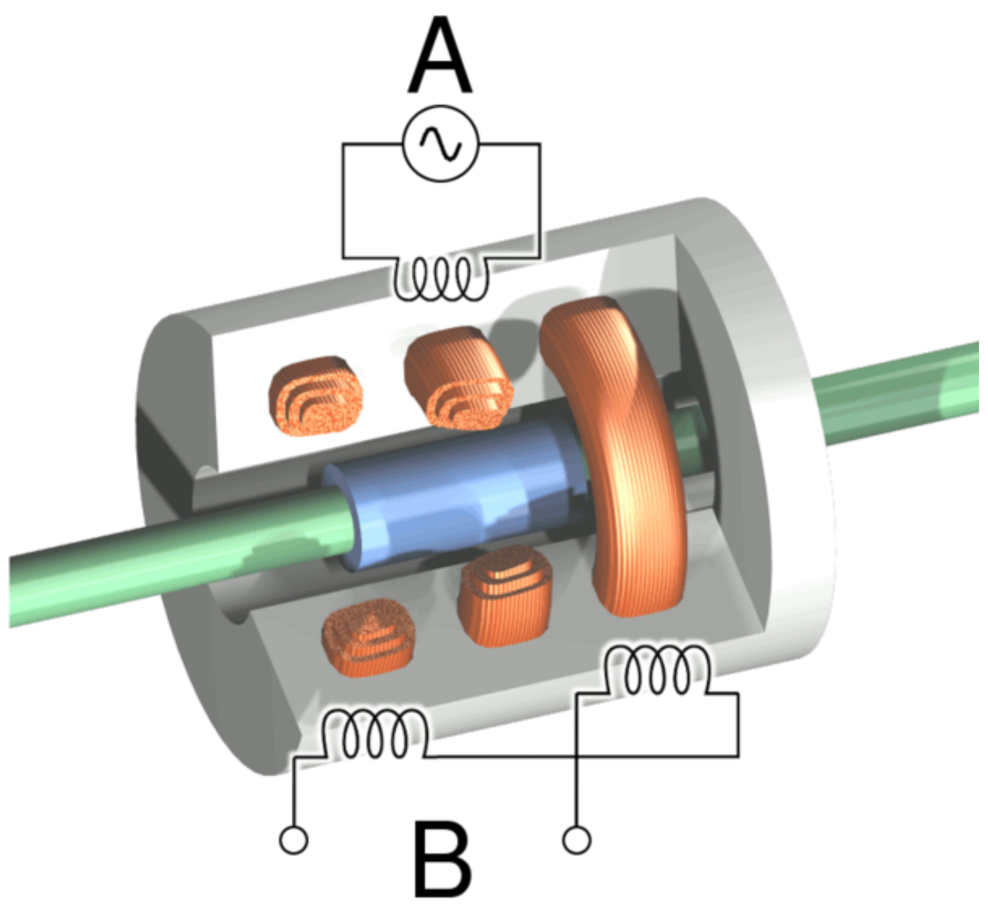
Optical microscope

Mechanical surface profiler

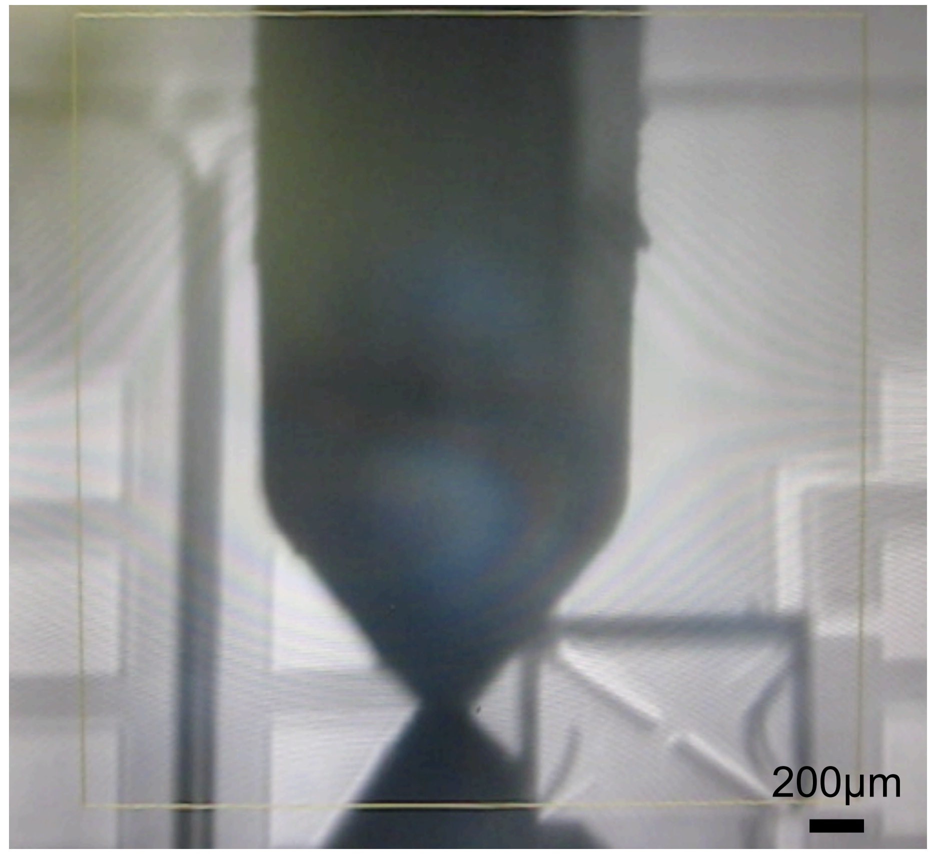
- Diamond probe scans the surface
- Surface height ➔ probe position ➔ electrical signal
- Resolution in Z: ~1nm
- Measurement range in Z: up to 1mm
- Scan length up to 55mm
- Risk to damage the probe or sample



LVDT

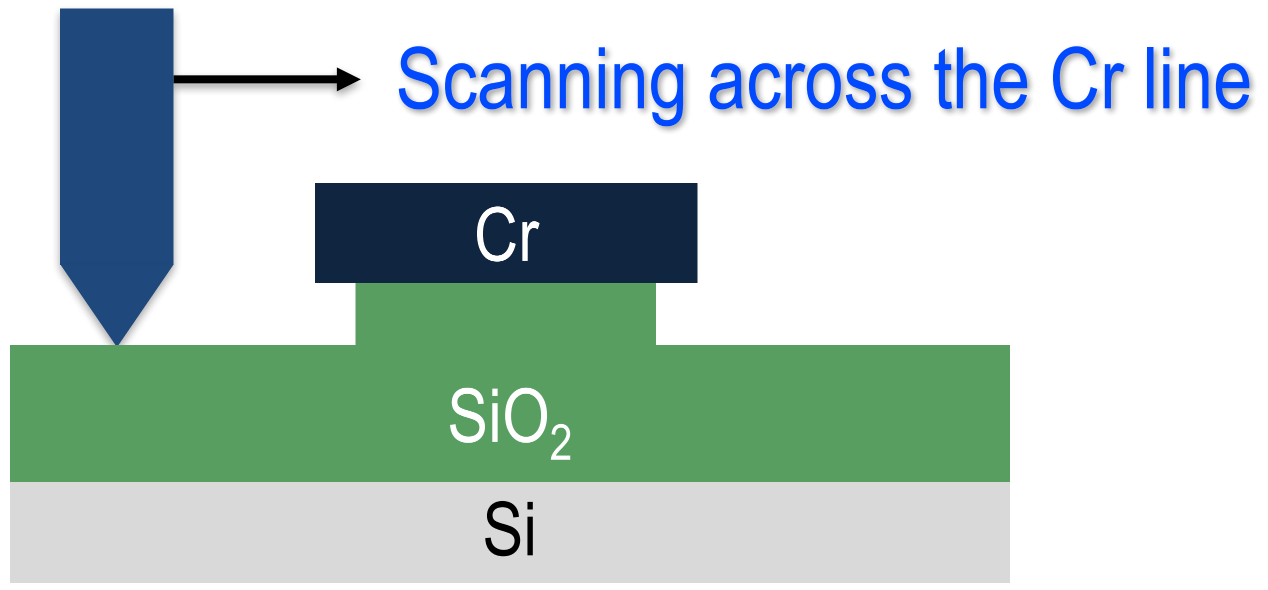


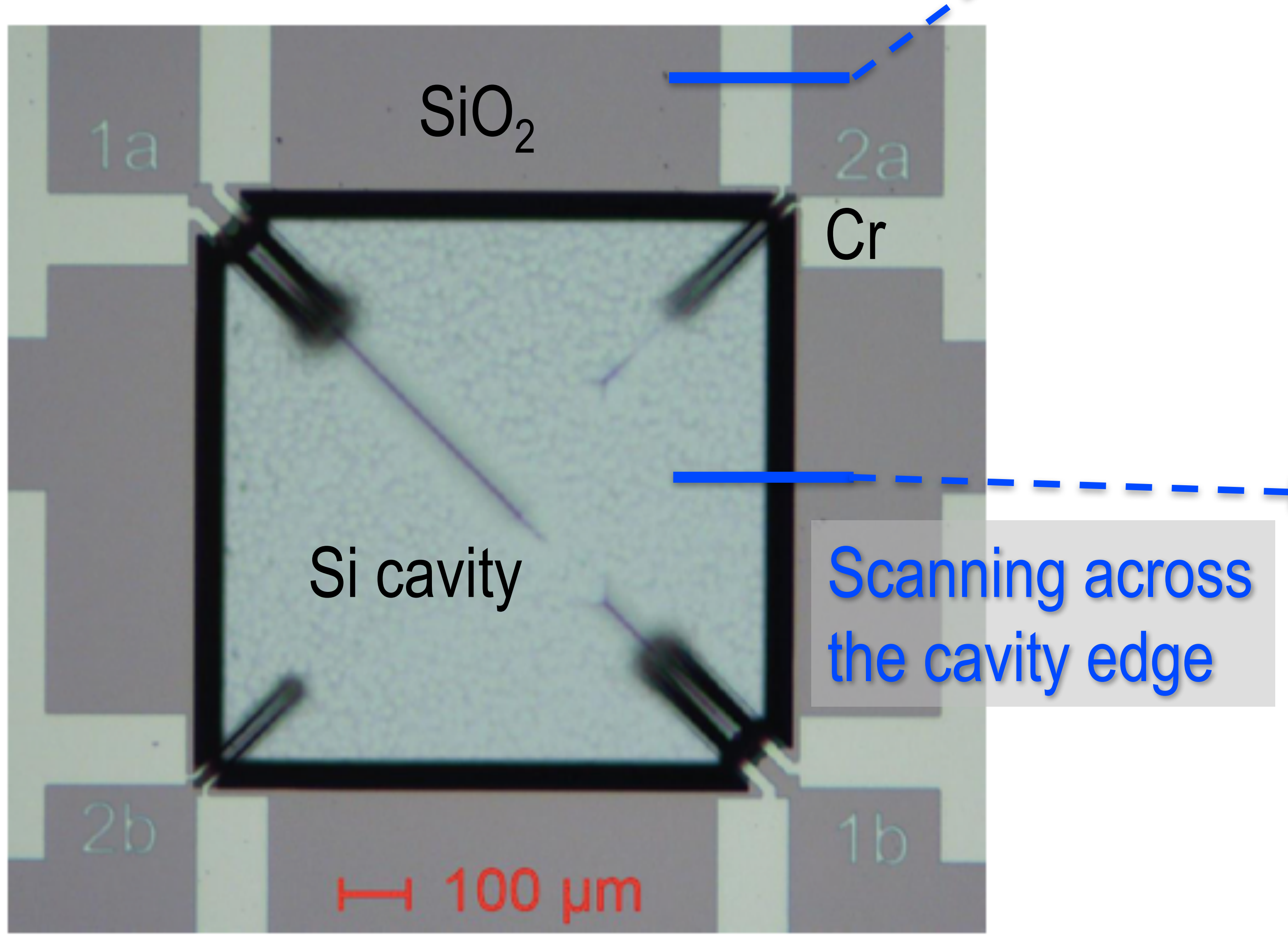
https://commons.wikimedia.org/wiki/File:LVDT.png



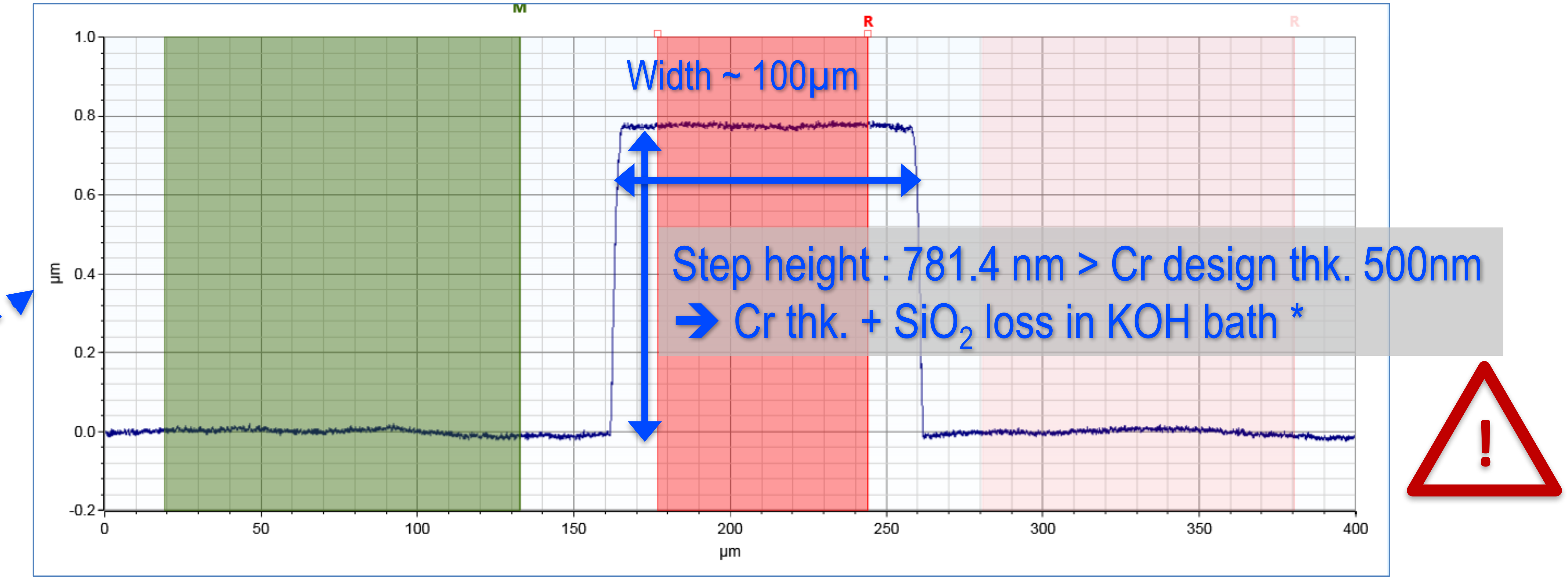
LVDT = linear variable differential transformer

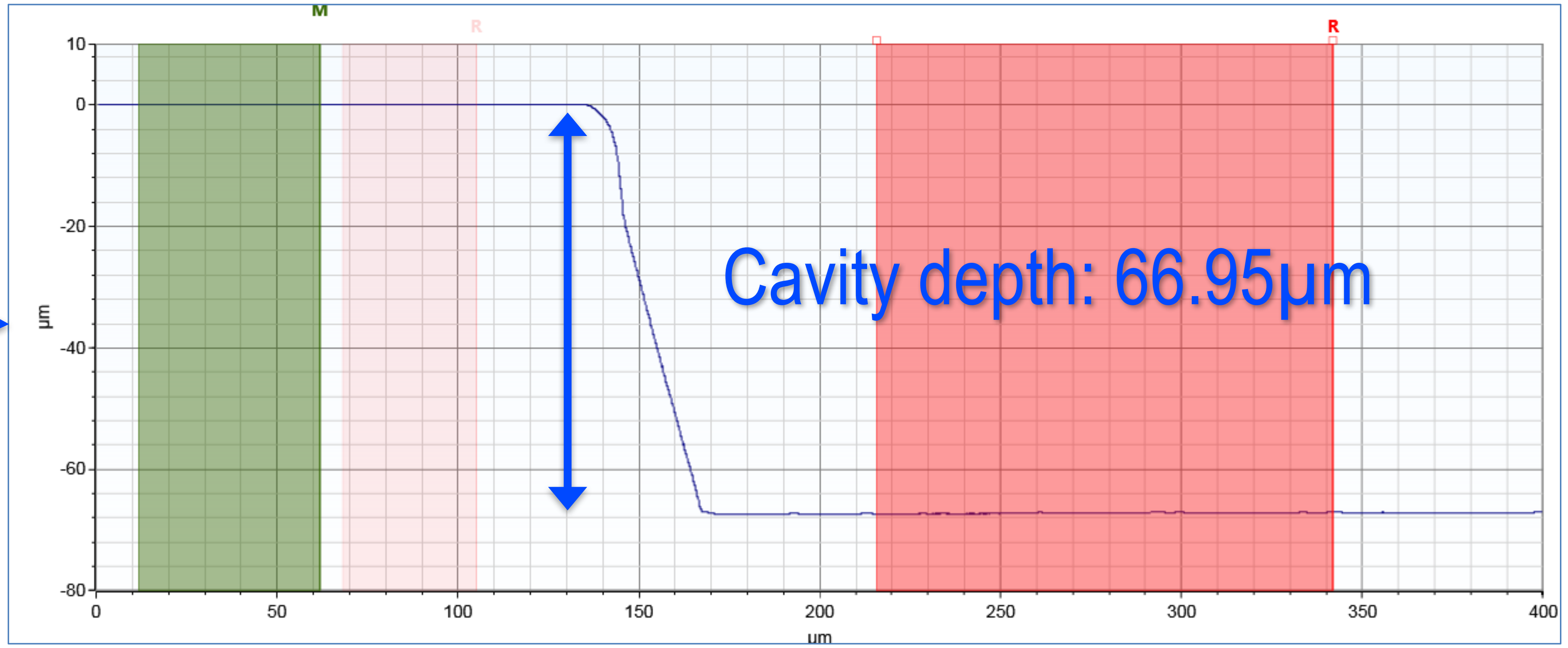
Bi-morph surface profile measurement





Optical microscope

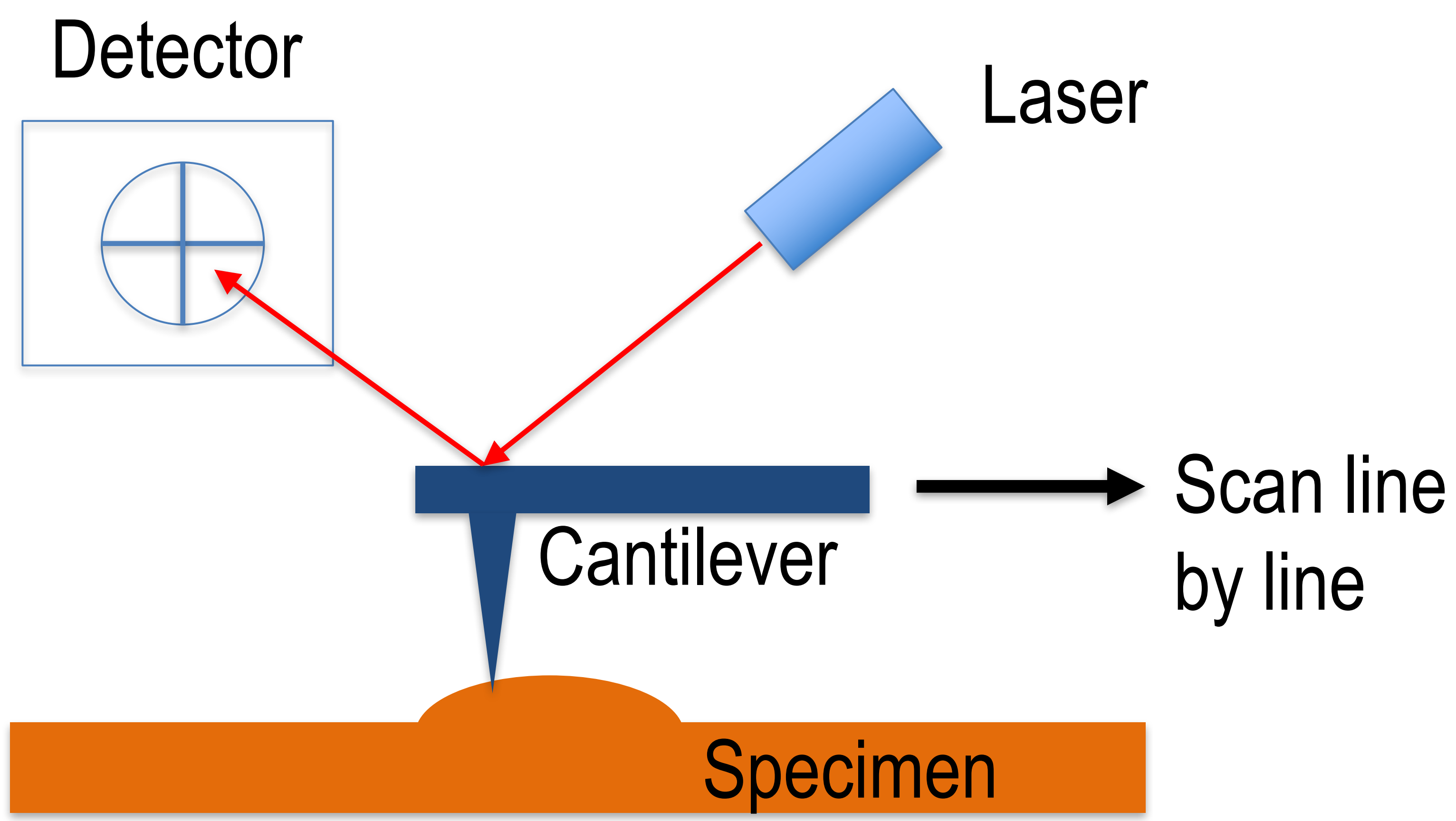


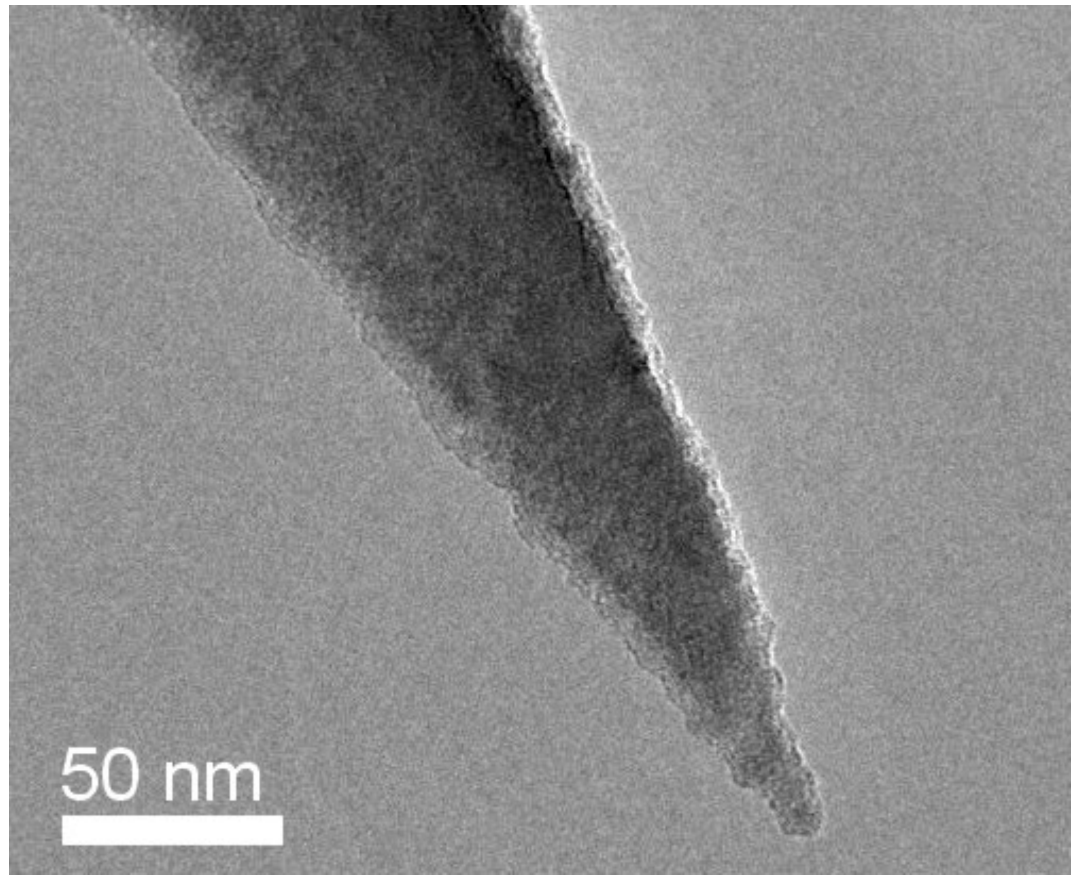


* Please refer to the previous module: **Case study: thermo-mechanical micro-actuator**

Atomic force microscopy

- A cantilever probe to touch and scan the surface
- Surface height ➔ probe position ➔ laser signal
- Probe is consumable
- Z resolution: ~ 0.1nm
- XY lateral resolution: < 10nm
- Nano scale 3D surface profile map
- Surface roughness measurement

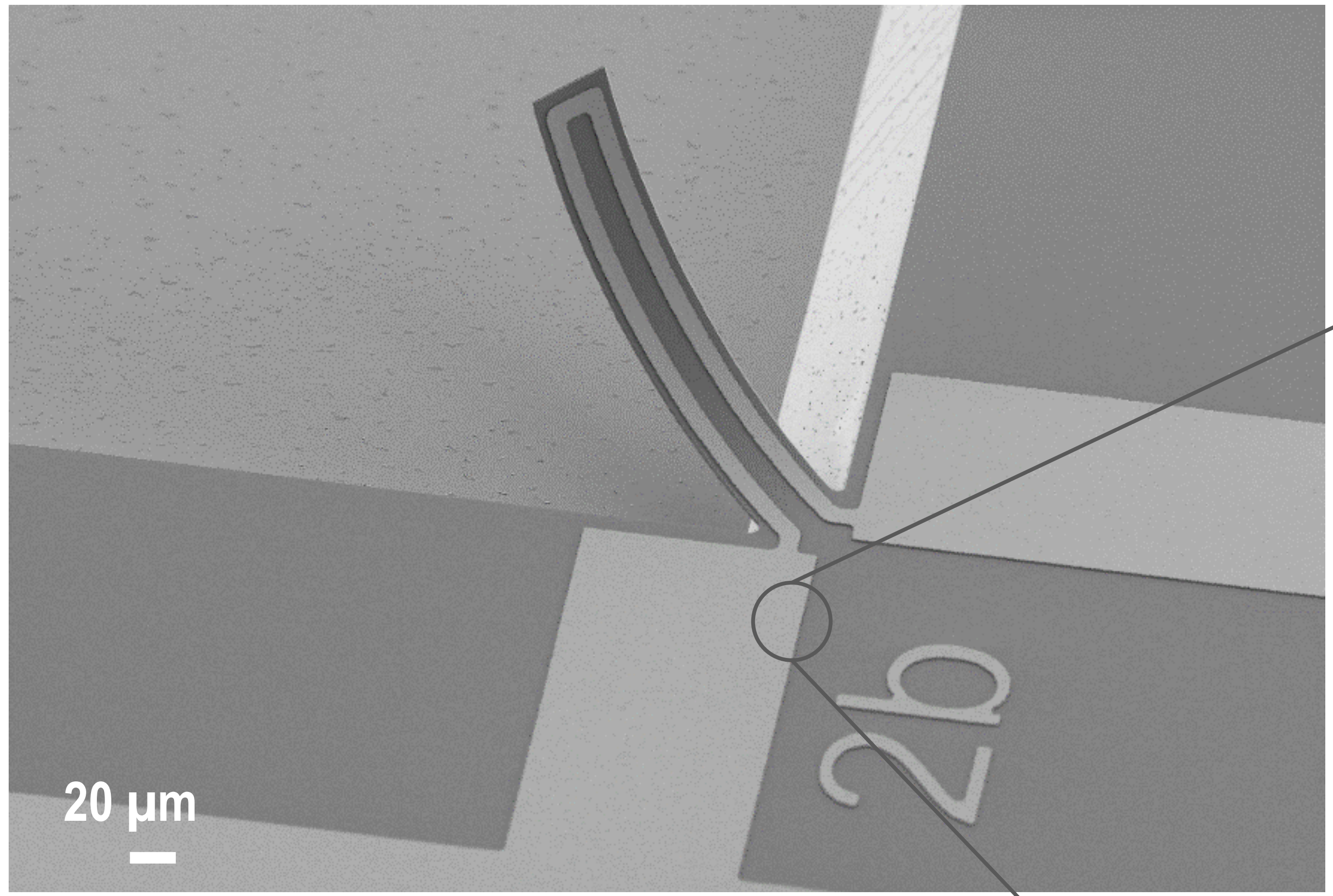




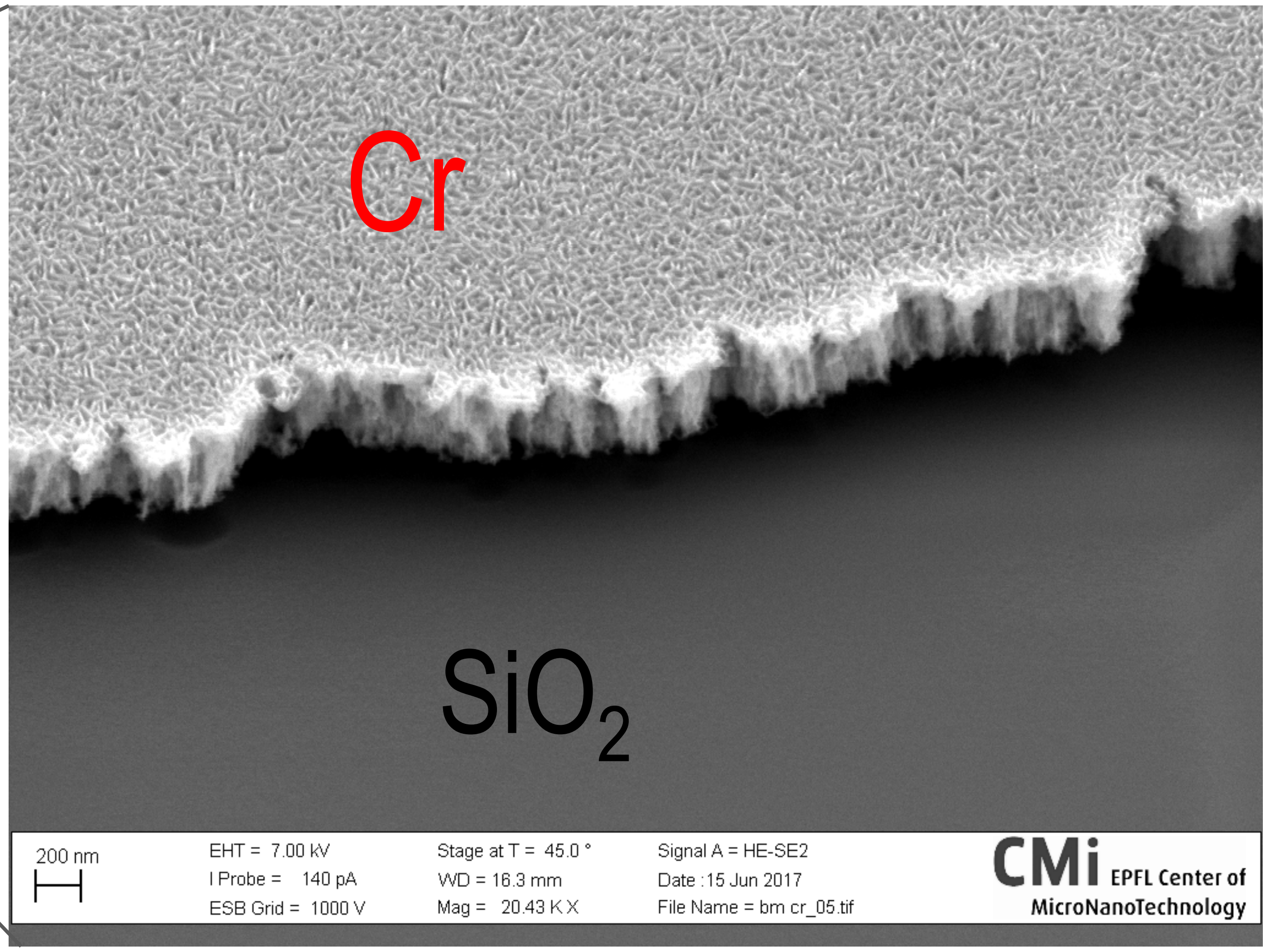
TEM image of NANOSENSORS PointProbe Plus AFM tip
Courtesy of NanoWorld AG

Bi-morph surface roughness measurement

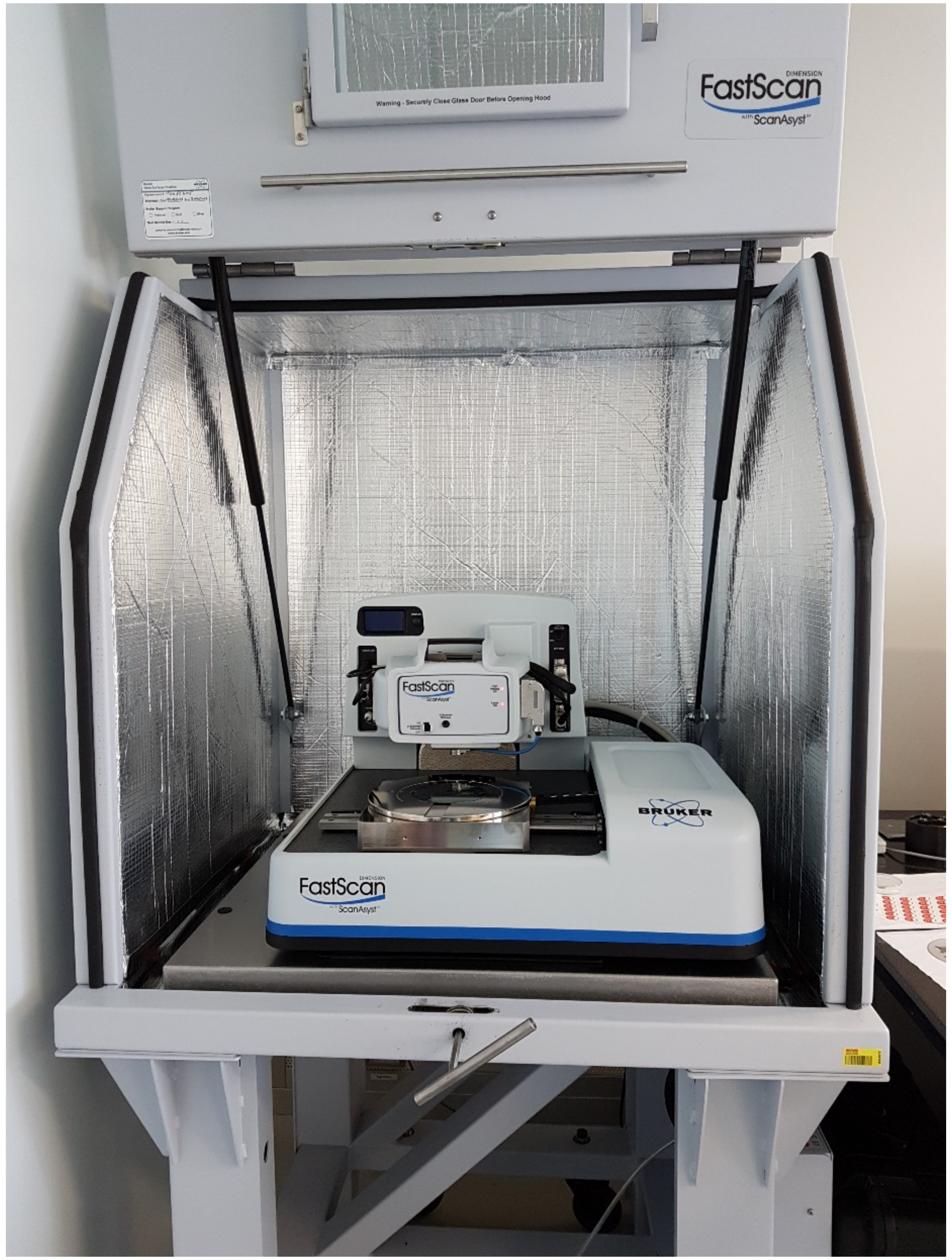
- To measure the surface roughness of Cr and SiO_2



SEM image of the bi-morph @ 3 keV and 45 degrees tilt



SEM image to indicate where the surface roughness is measured



Bi-morph surface roughness measurement

- AFM VIDEO

Bi-morph surface roughness measurement

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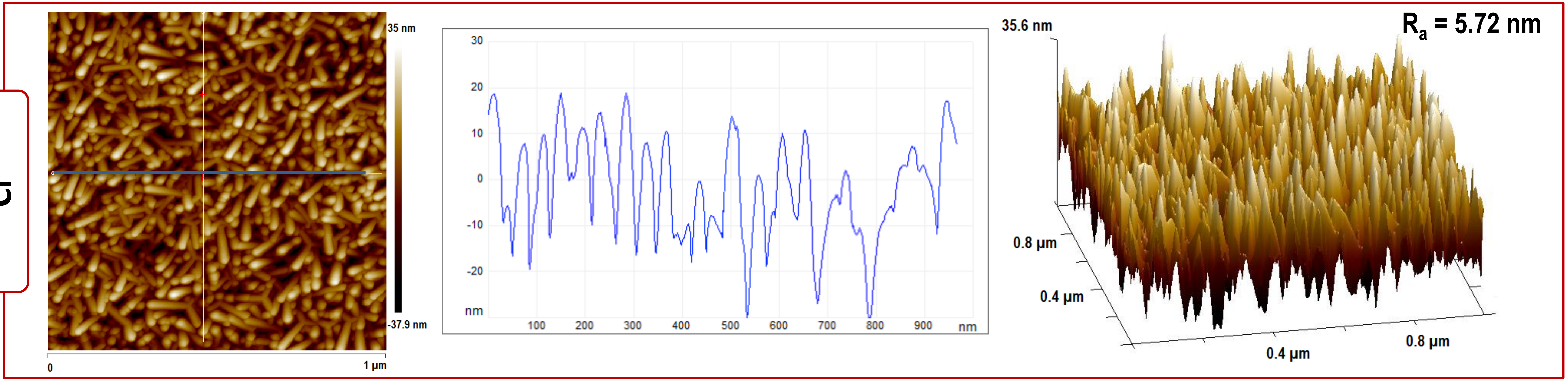
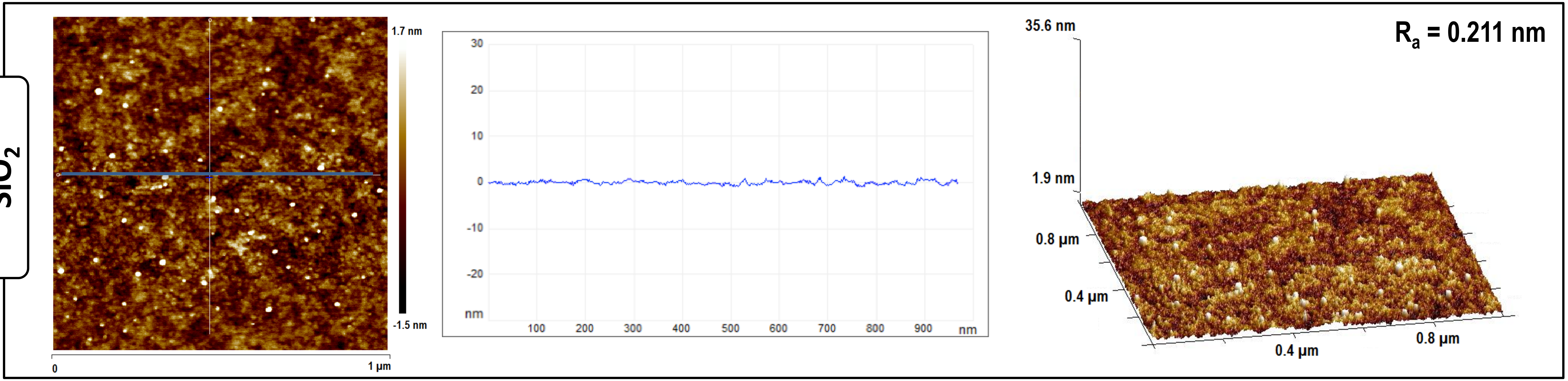
Cr

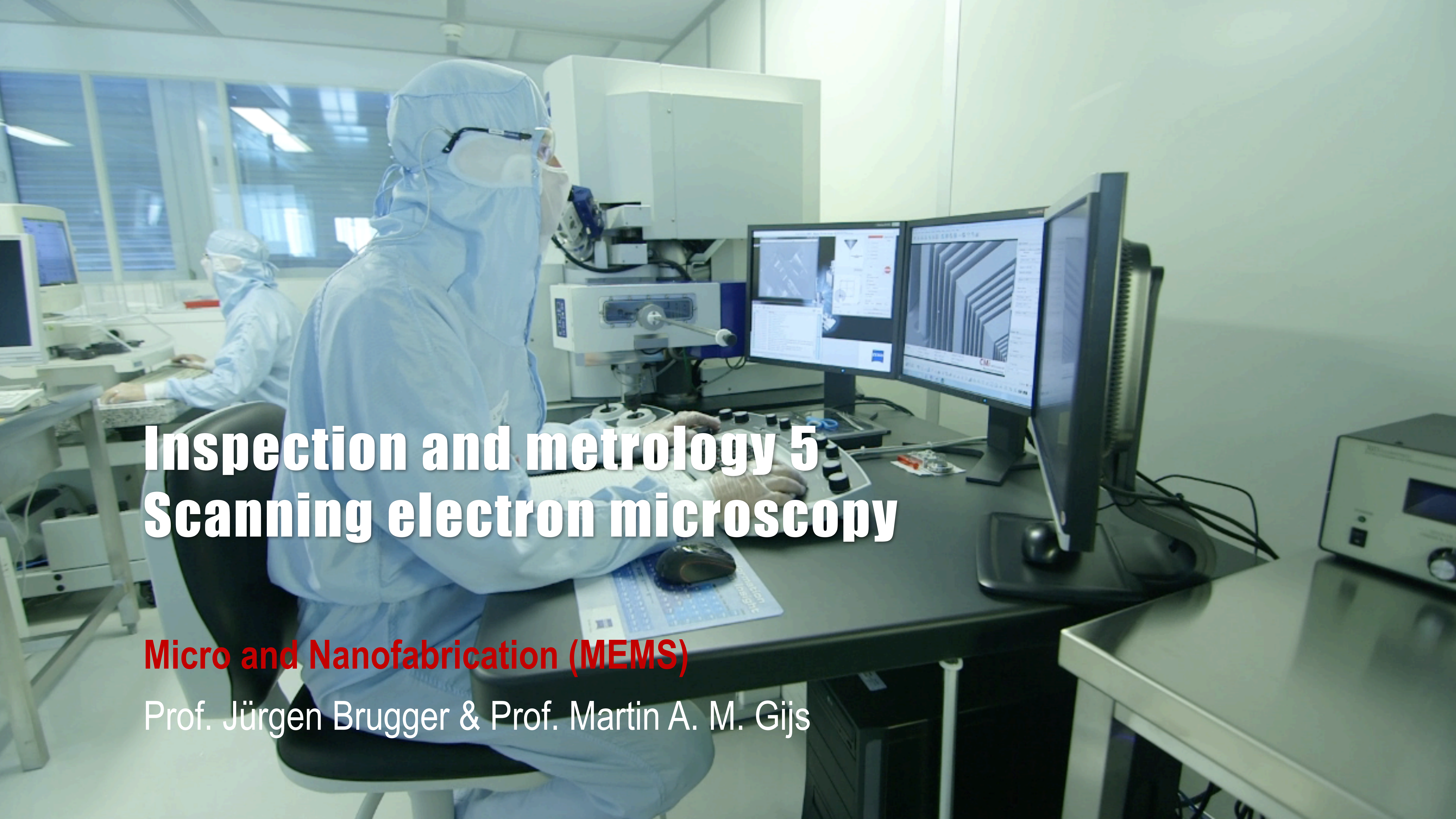


SiO_2



Summary

- Physical contact
- Opaque film thickness measurement
- AFM for nano scale image
- Conductive / non-conductive samples



Inspection and metrology 5
Scanning electron microscopy

Micro and Nanofabrication (MEMS)

Prof. Jürgen Brugger & Prof. Martin A. M. Gijs

Scanning electron microscopy

- Physical principle
- Inspection with different electron signals
- Charging issue
- Dimension measurement

Scanning electron microscopy

Why use electrons instead of photons?

- Overcome the optical diffraction limit:

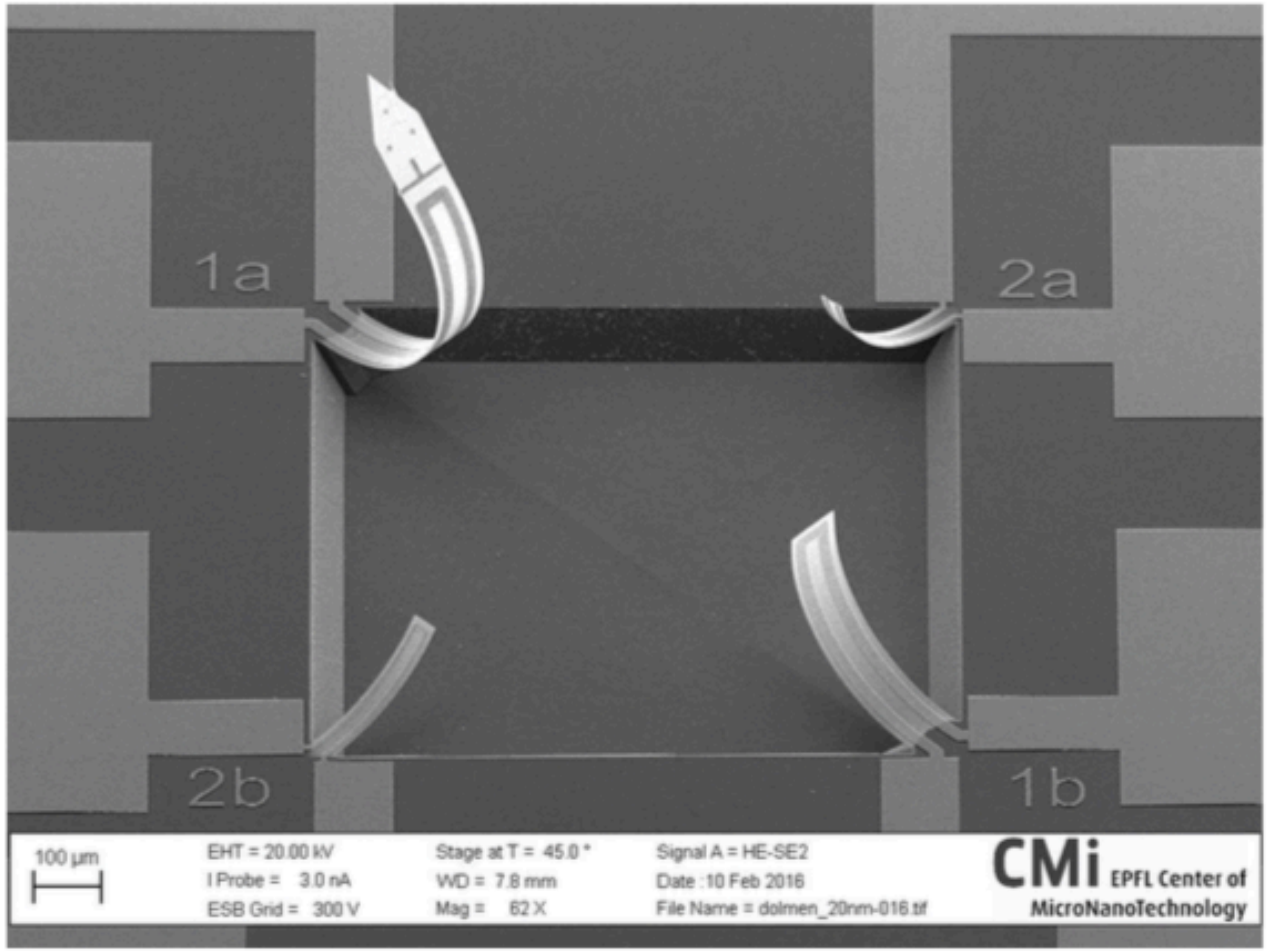
$$\sim\lambda/2$$

- Electron wavelength, De Broglie equation

kV	1	10	100
nm	0.038	0.012	0.0038

$$\lambda_e = \frac{h}{p}$$

λ: wavelength
h: Planck's constant
p: momentum

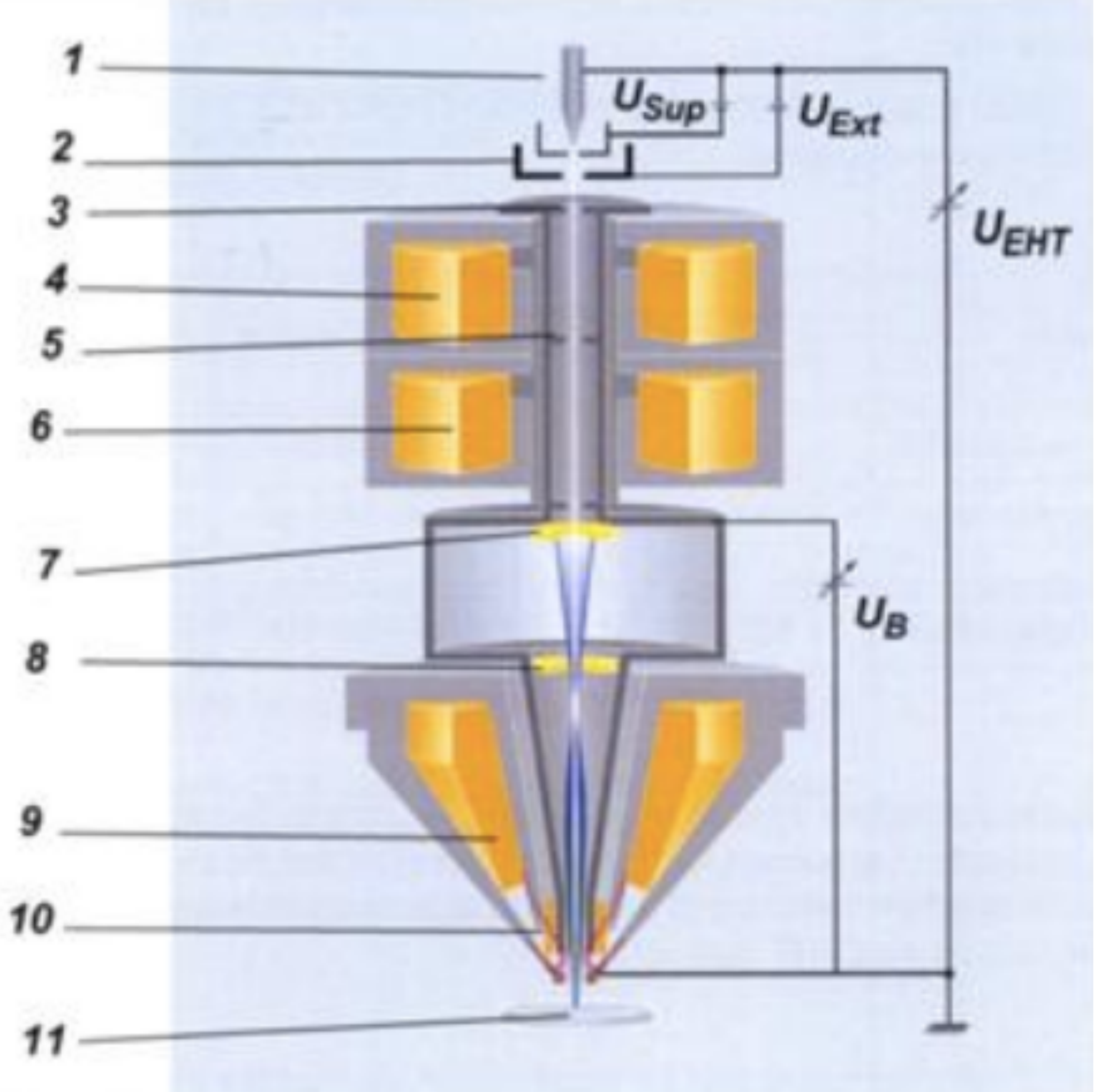


Using electron results in higher resolution compared to visible light

Schematics of SEM system

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

- System similar to EBL:
  - E-gun: 0.02 – 30 kV
  - Electromagnetic lenses
  - Vacuum system
- Electrons ➔ detectors ➔ image
- Morphology & compositional analysis
- Resolution: ~1nm
- Accuracy: +/-3%
- Conductive samples required for high quality imaging

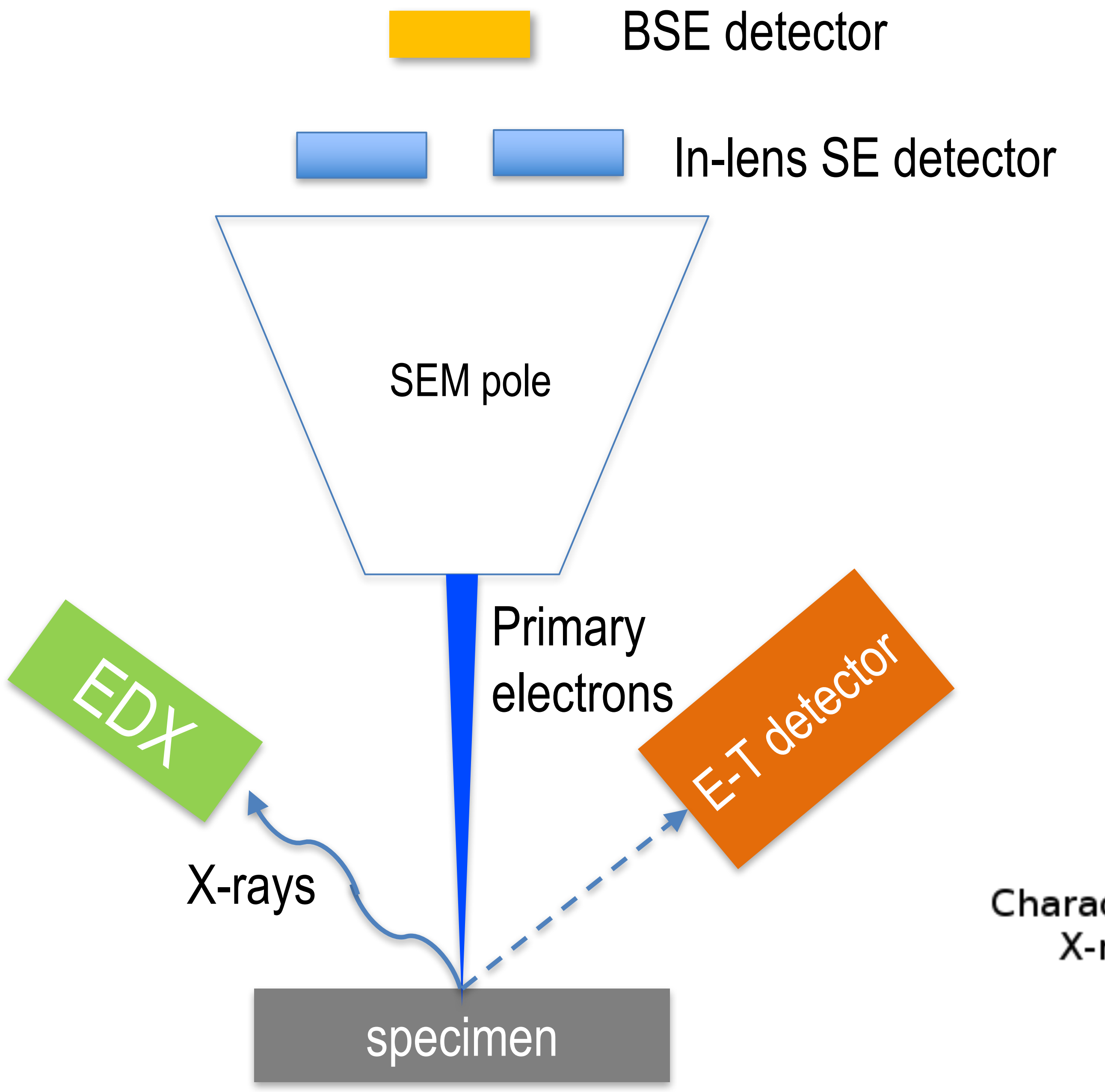


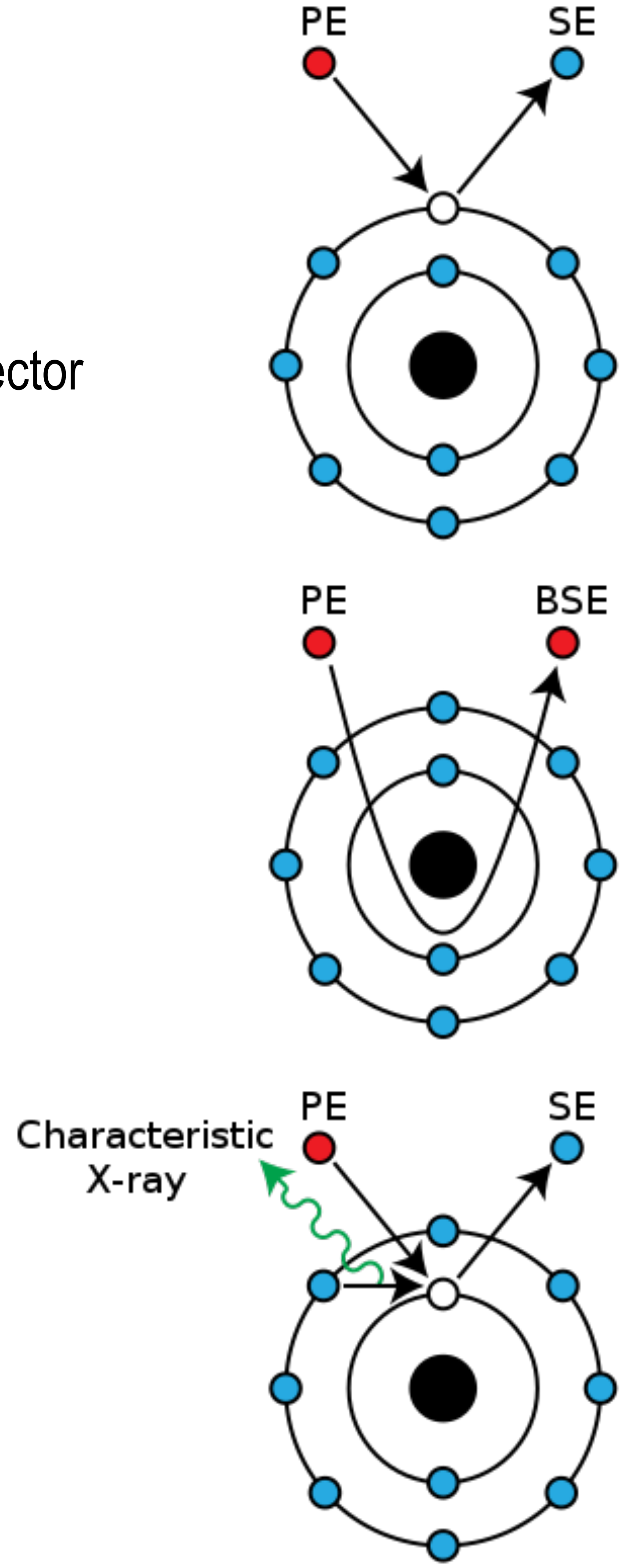
Zeiss The GEMINI II column

1. Gun
2. Extractor
3. Anode aperture
4. Upper condenser
5. Single hole aperture
6. Lower condenser
7. BSE detector
8. In-lens SE detector
9. Objective lens
10. Scanning coils
11. Specimen

Inspection with different electron signal

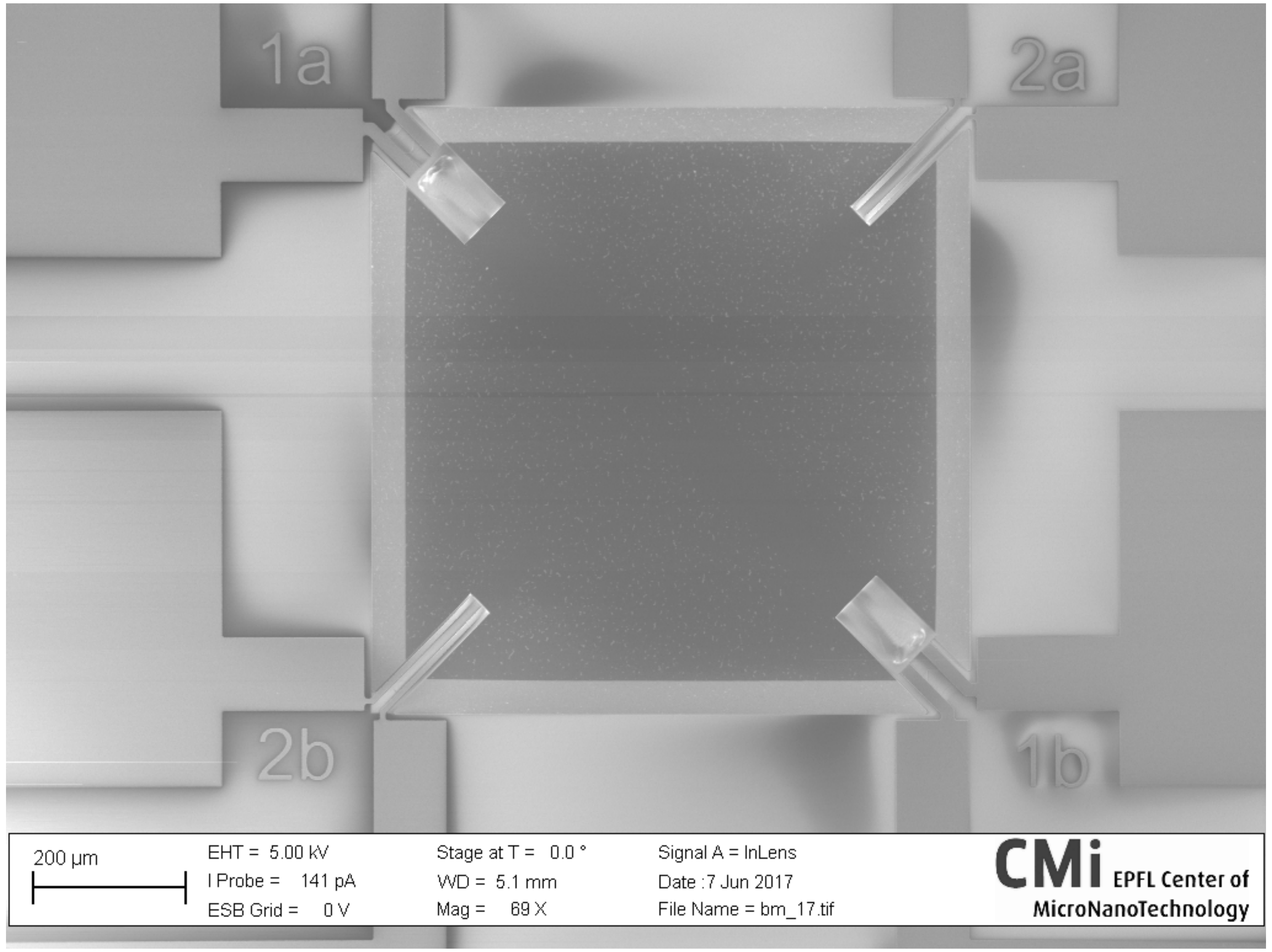
- Secondary electron (SE) imaging
  - Surface structure
- Backscattered electron (BSE) imaging
  - Atomic number ↑ , BSE ↑ ➔ material contrast
- High efficiency SE (HE-SE2) imaging
  - Topography and edge enhancement
- Energy-dispersive X-ray (EDX)
  - X-ray detection
  - Spectroscopic compositional analysis



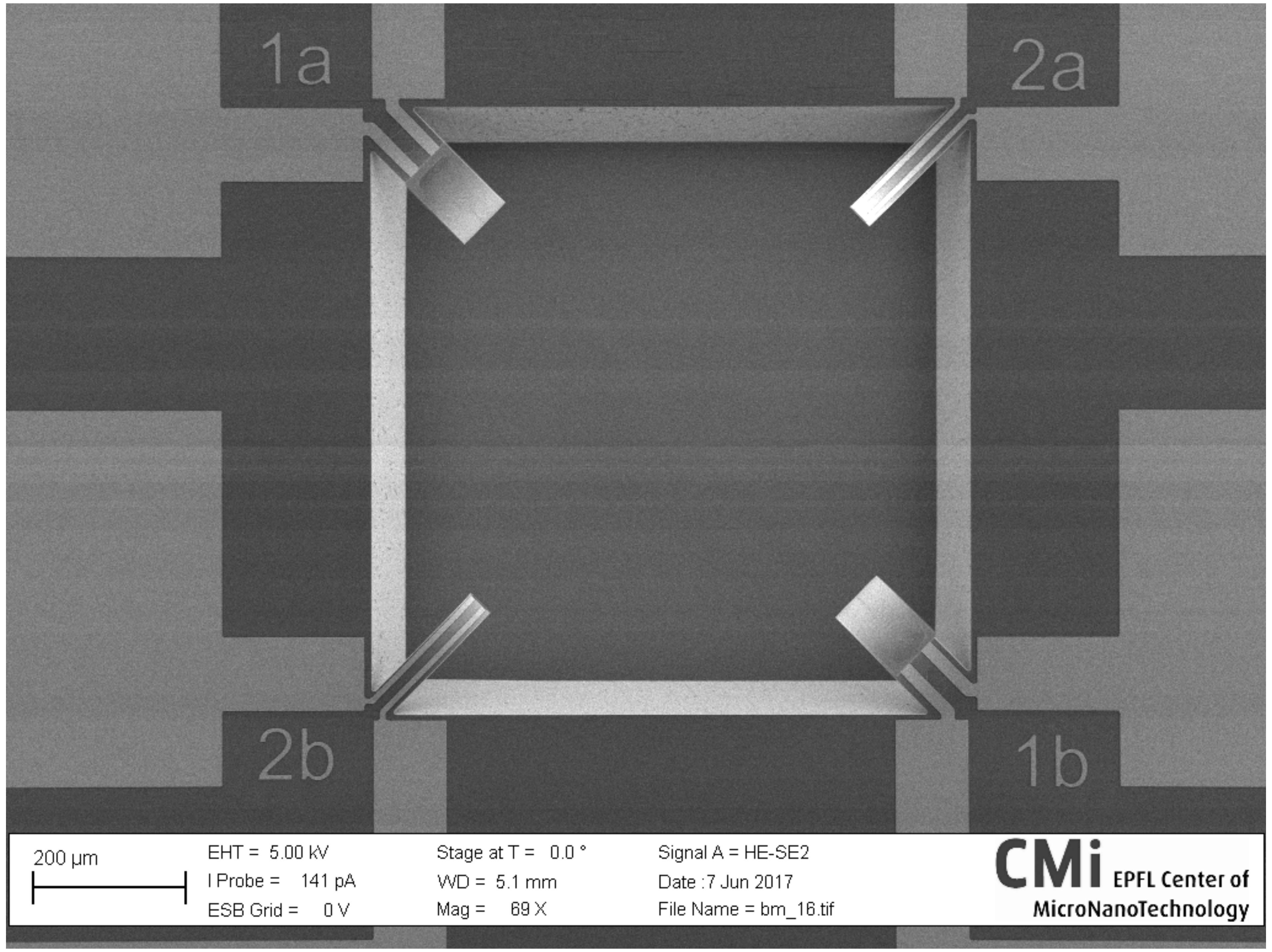


https://commons.wikimedia.org/wiki/File:Electron_emission_mechanisms.svg

Inspection with different electron signal

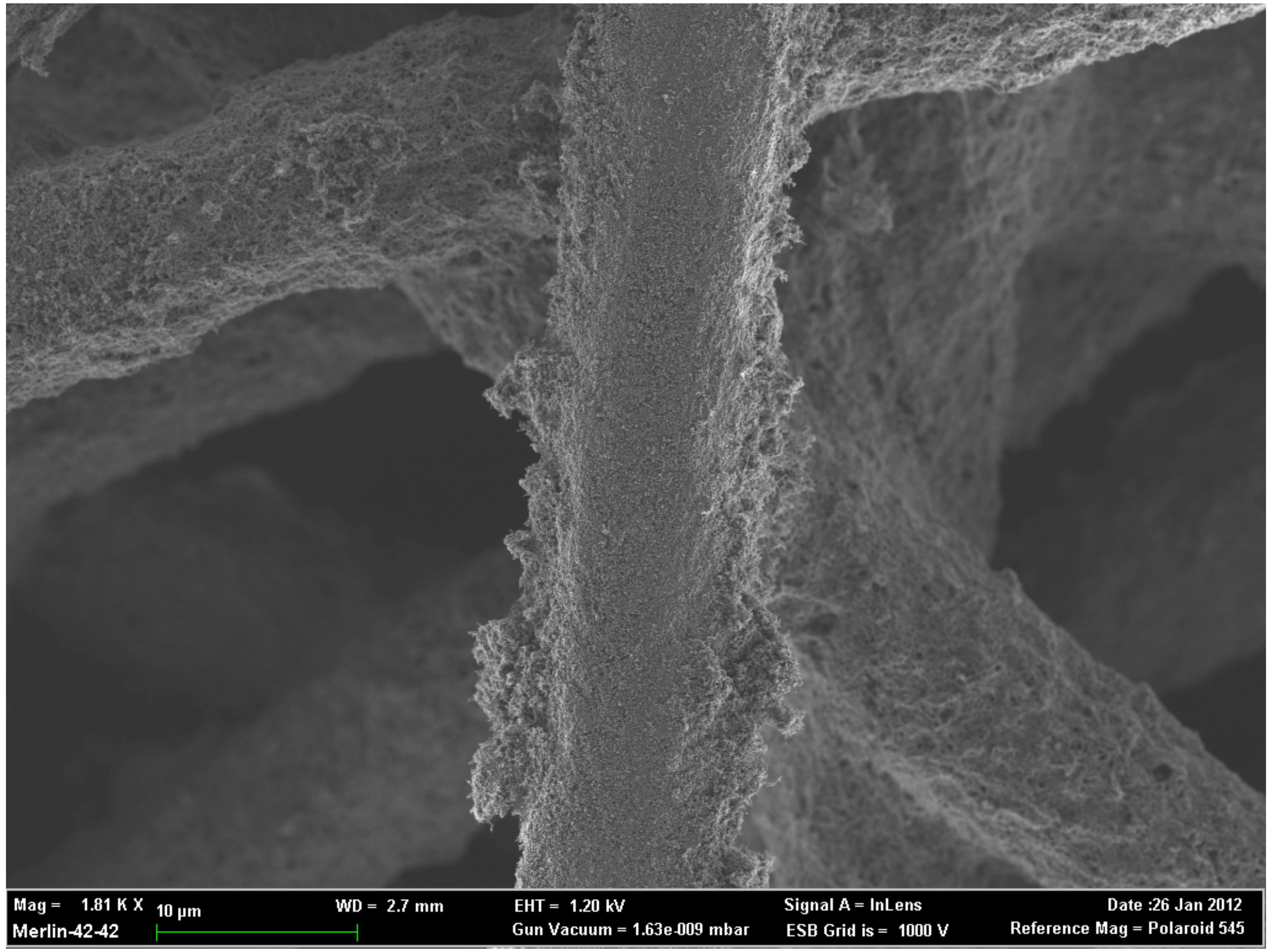


InLens-SE
SEM image of Bi-morph

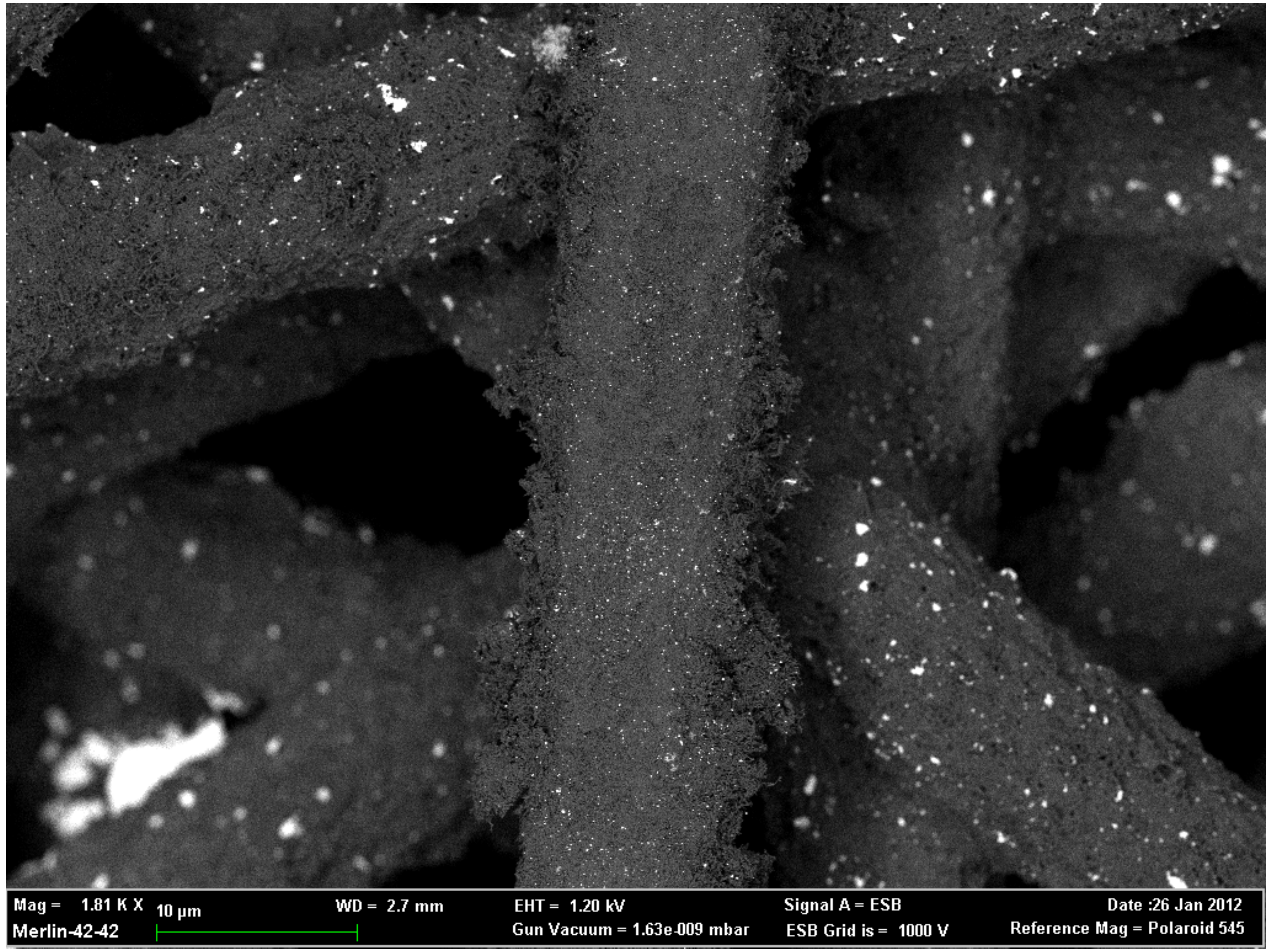


HE-SE2
SEM image of Bi-morph

Inspection with different electron signal



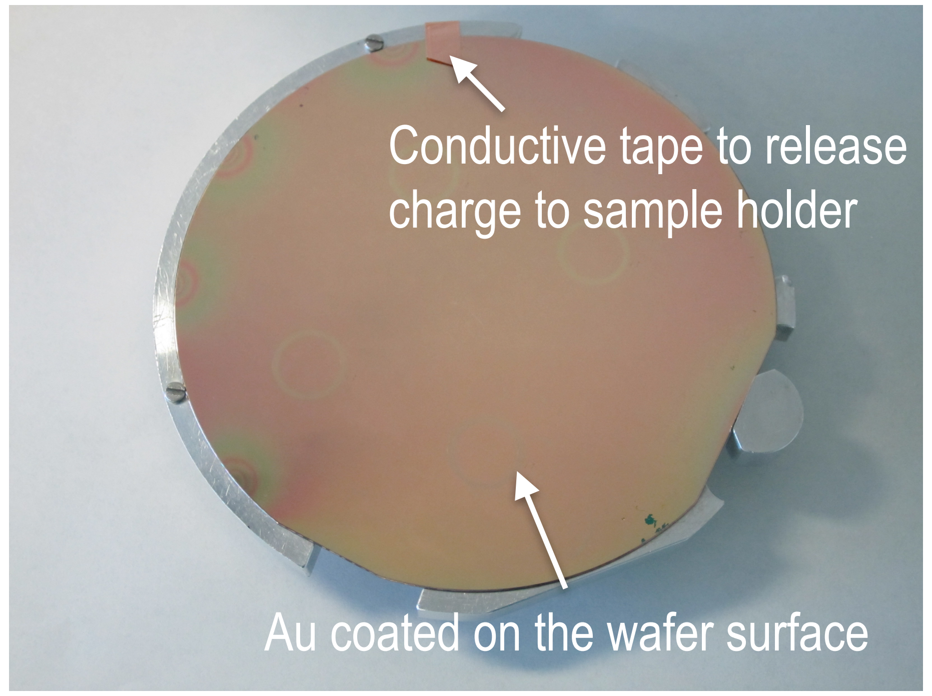
InLens-SE
SEM image of carbon nano tube bundle

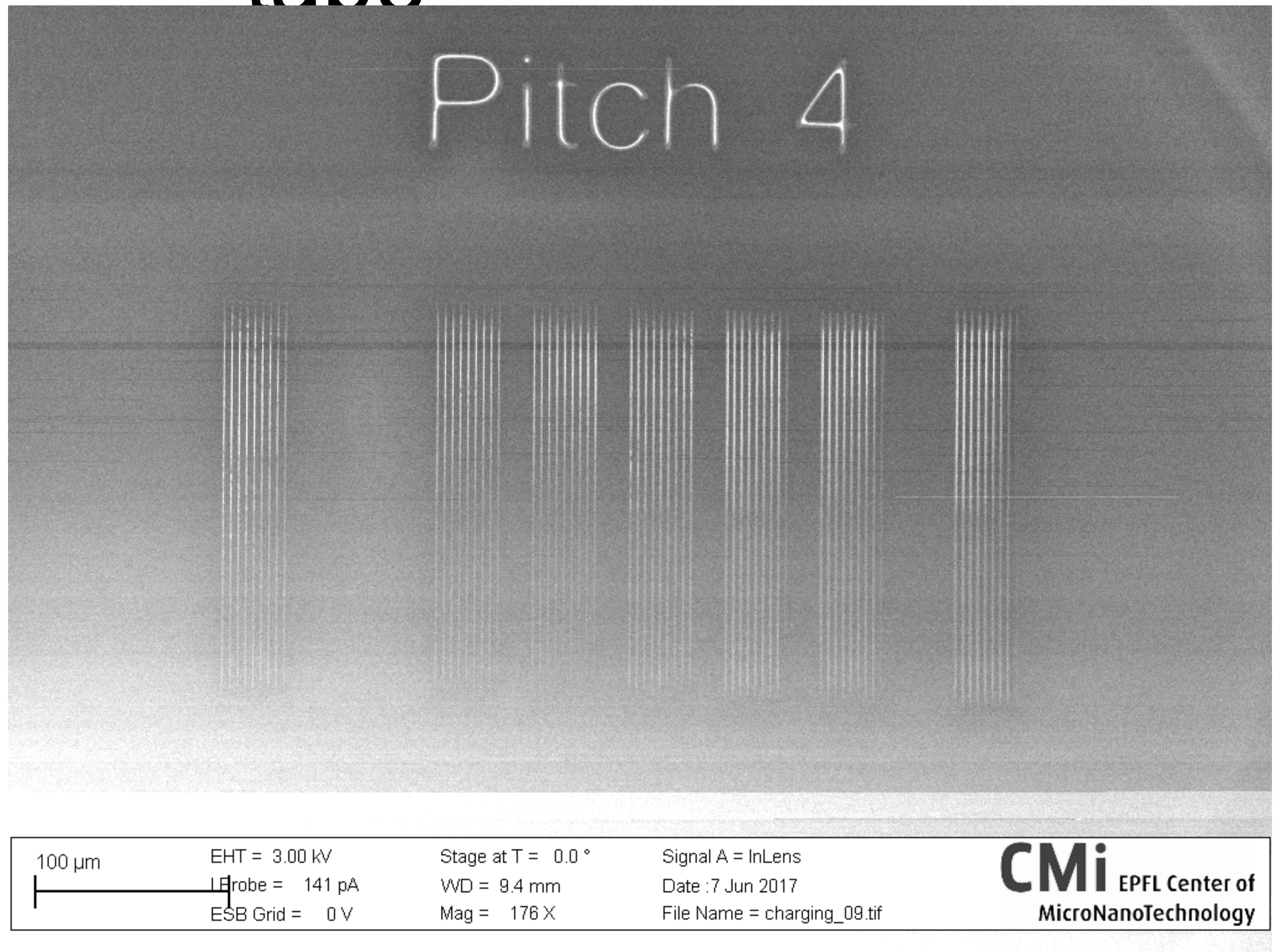


BSE
SEM image of carbon nano tube bundle

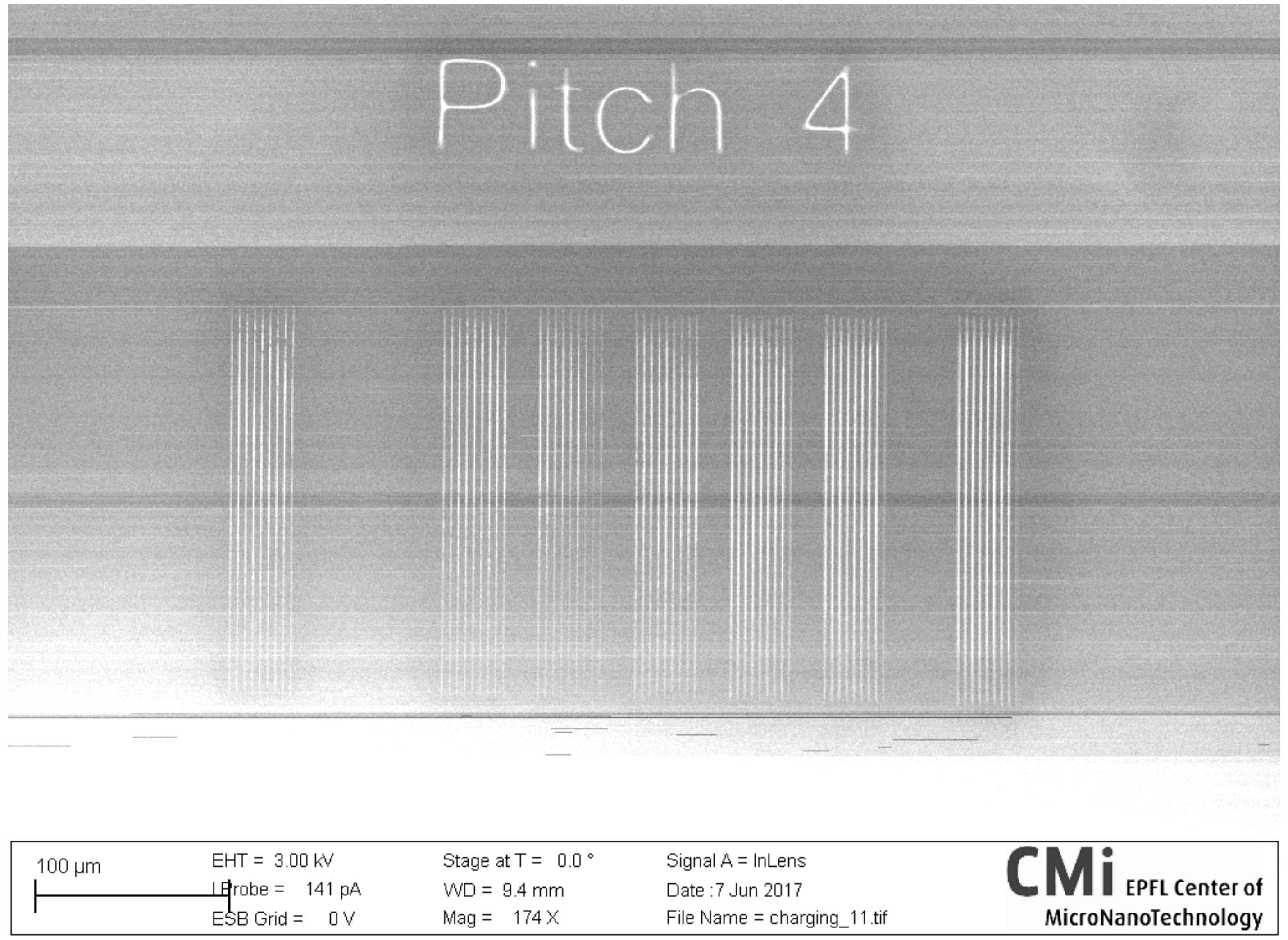
Charging issue

- Electron charges accumulate on the sample and repulse other electrons if the sample is not conductive
- Solution: metal coating (e.g. 20nm Au) + conductive tape

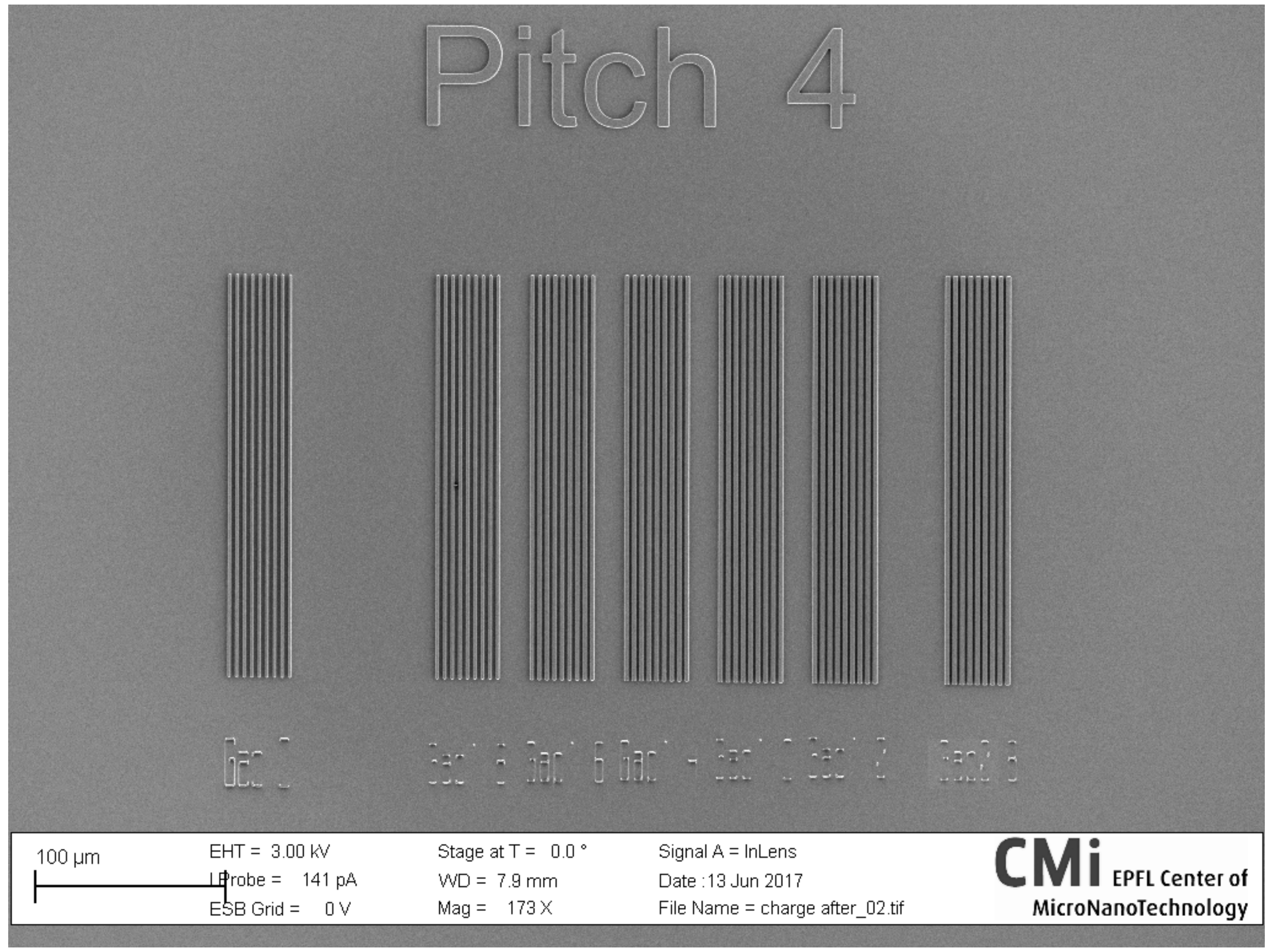




Poor image due to charging
(PR on SiO_2)



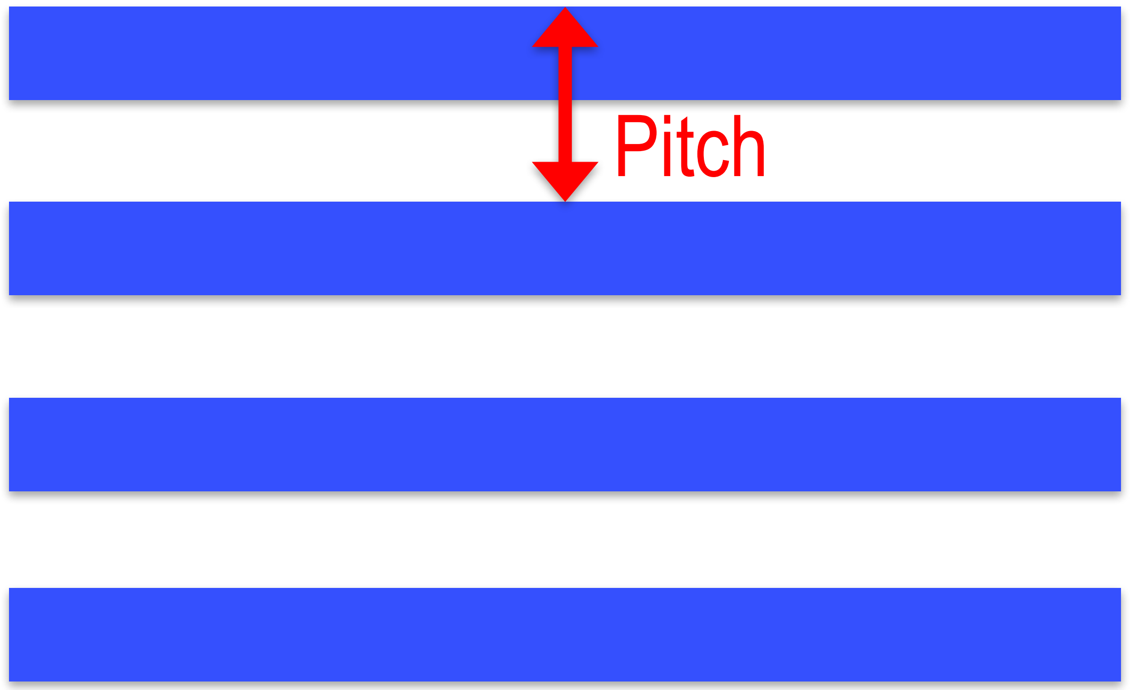
Even worse over time
(PR on SiO_2)



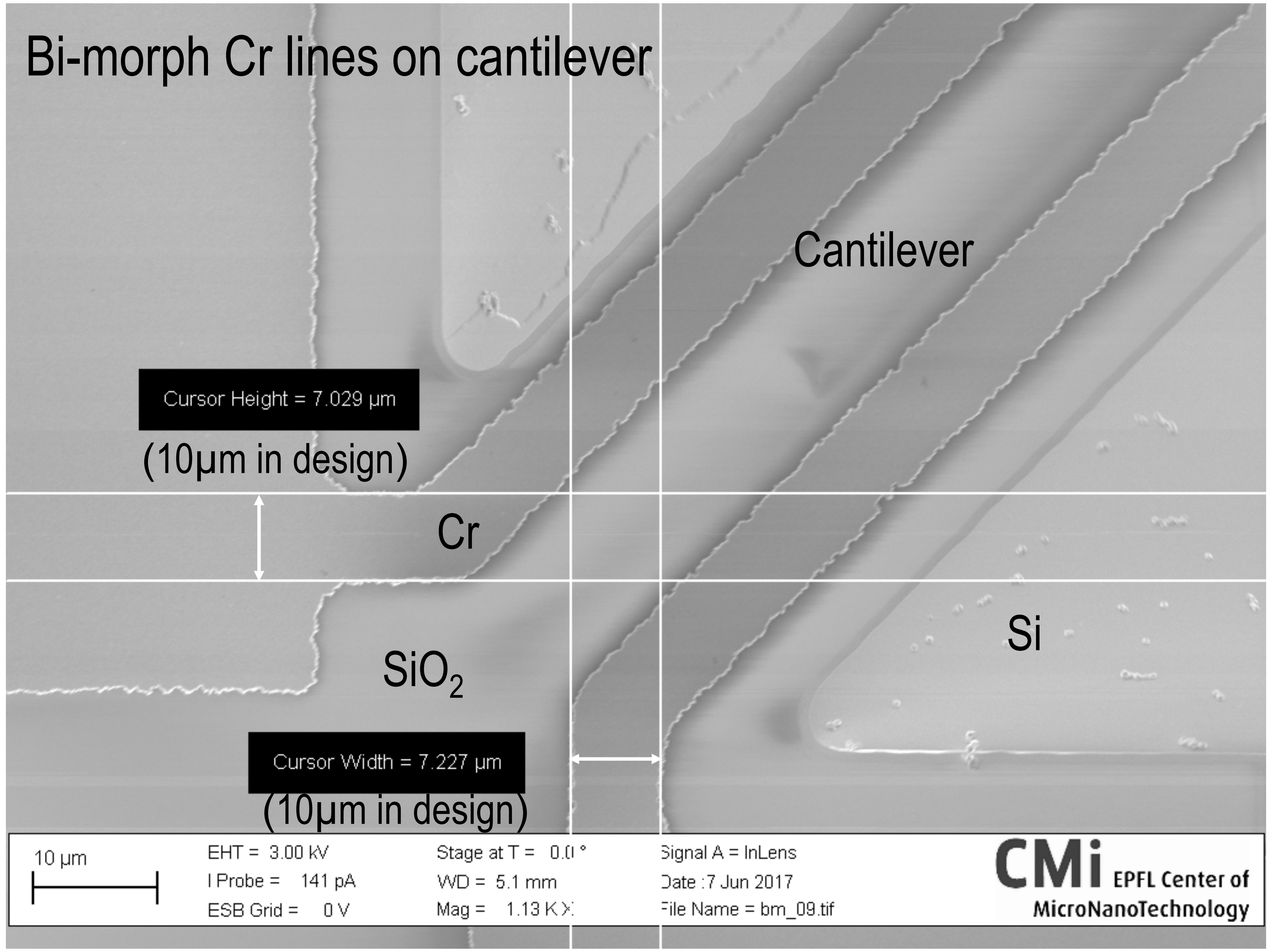
With Au coating

XY lateral dimension measurement

- Standard sample with known dimension ➔ how many µm per pixel ➔ scale bar calibration
- Use the scale bar to measure XY lateral dimensions



Periodic pattern fabricated by EBL as standard sample for calibration, the line width may vary but **the pitch** is highly accurate



Scanning electron microscopy

- SEM VIDEO

Summary

- Magnification up to 500,000X
- Accurate dimensional measurement
- Nano scale inspection (tilting possible)
- Soft samples could be slightly damaged by high energy electrons

Inspection and metrology 6
Focused ion beam: Local cross sectional inspection and measurement

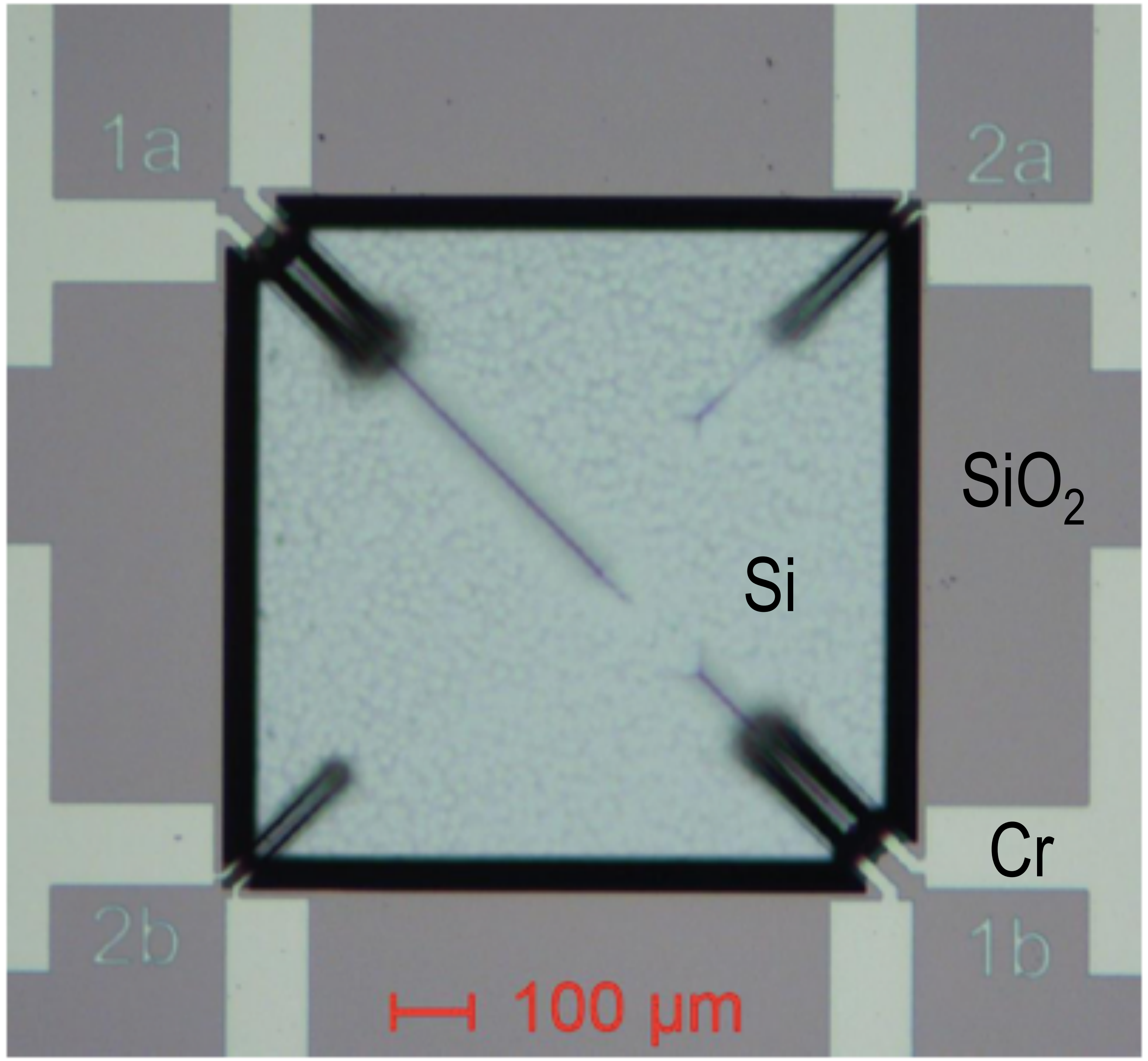
Micro and Nanofabrication (MEMS)

Prof. Jürgen Brugger & Prof. Martin A. M. Gijs

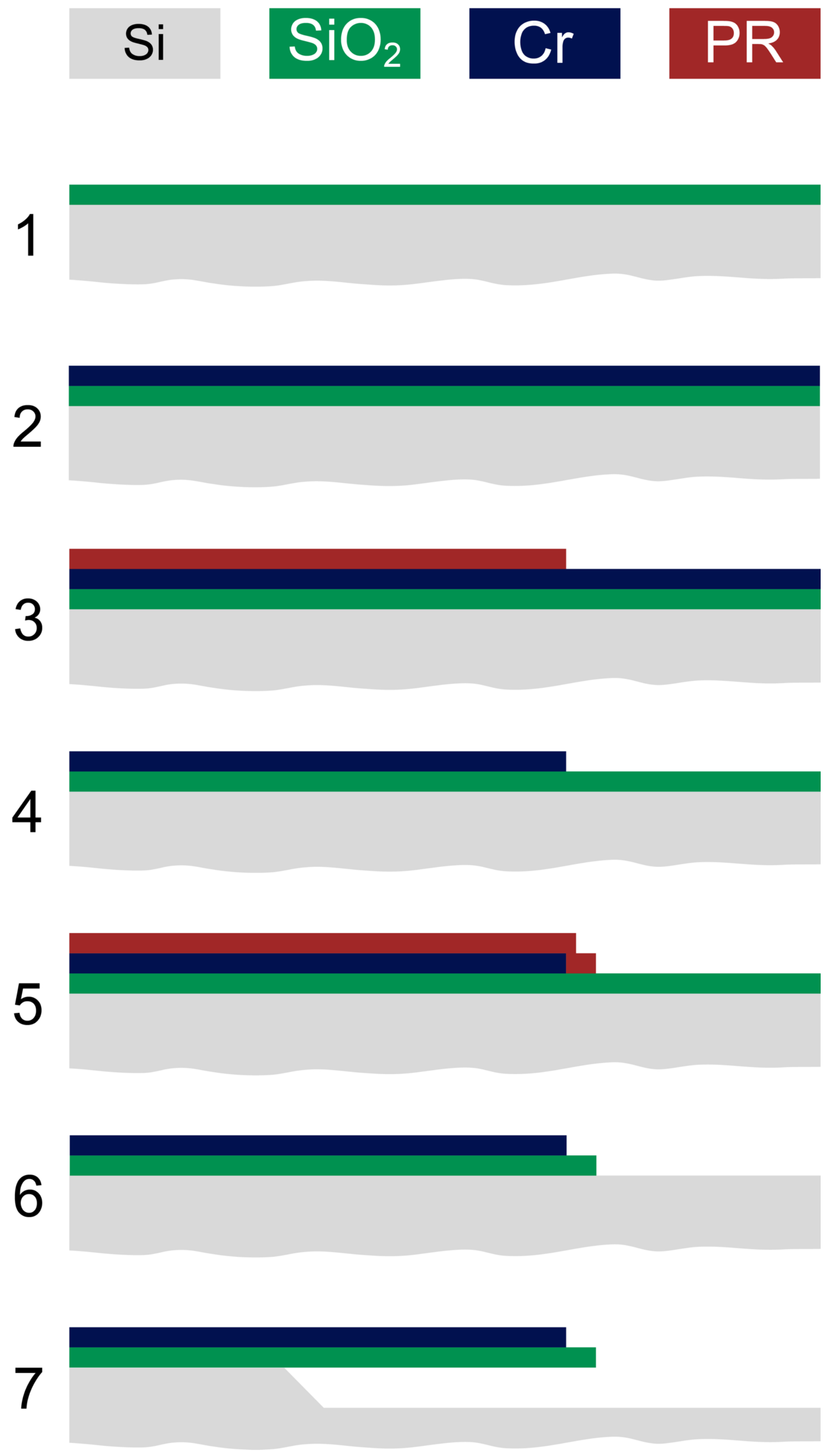
Focused ion beam

- Basic principle
- Focused ion beam imaging
- Local cross sectional inspection
- Z-dimension measurement

Bi-morph thermal actuator



Optical microscope

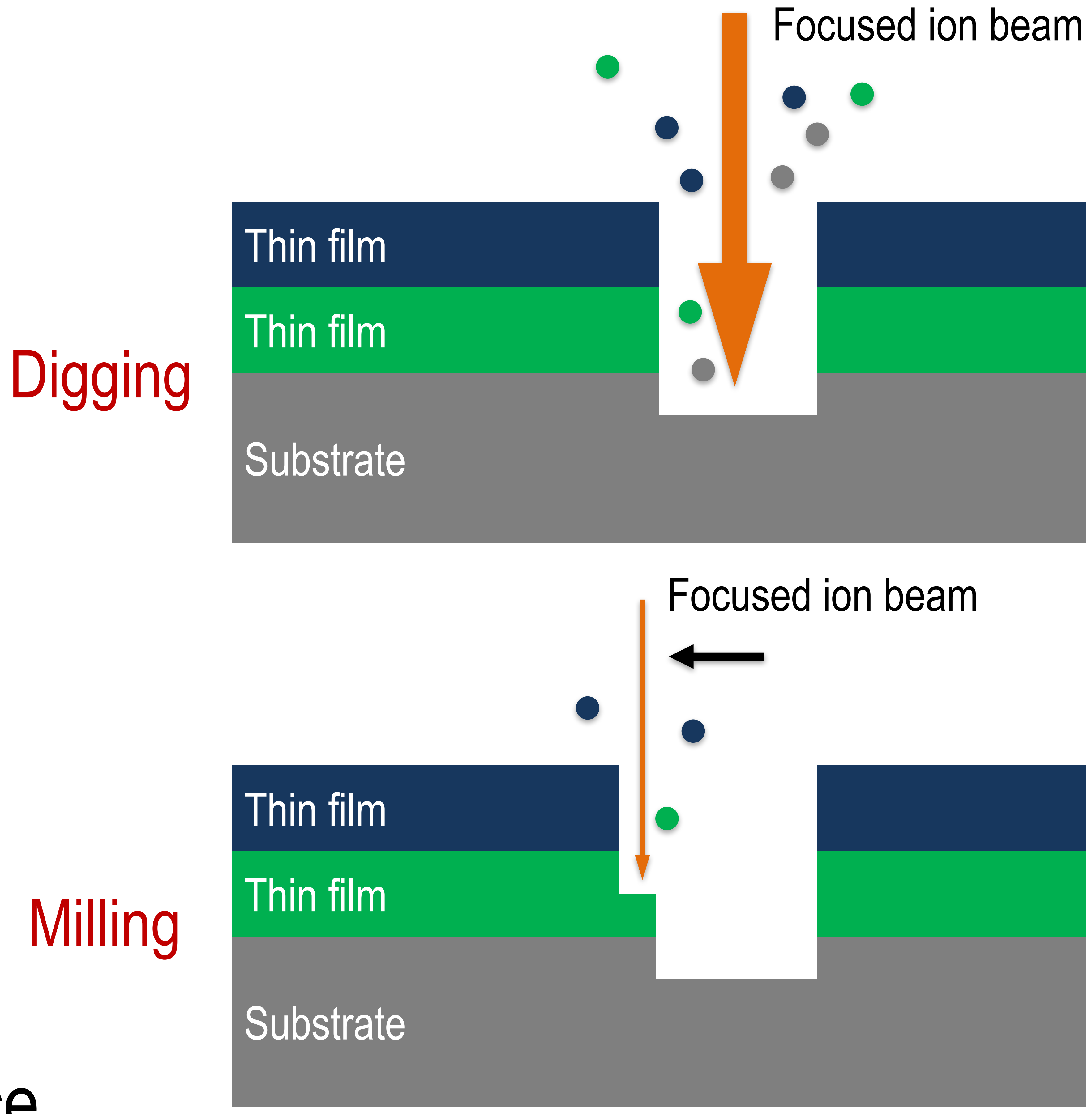


1. Oxidation
2. Cr layer deposition
3. Lithography 1 (heater)
4. Cr etch
5. Lithography 2 (cantilever)
6. SiO_2 etch in BHF
7. Silicon etch in KOH

How to check the device cross section without breaking the wafer?

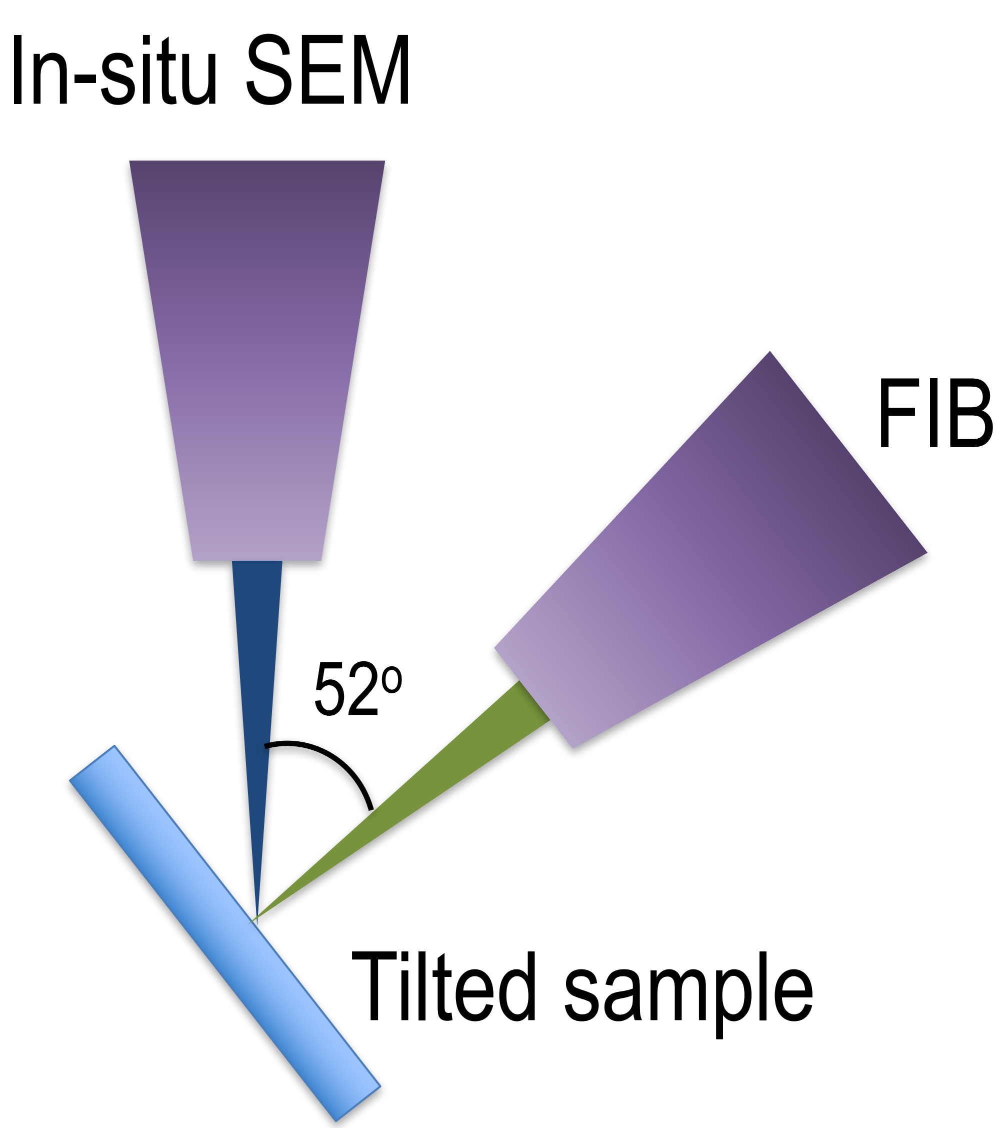
FIB basic principle

- Ion imaging:
  - System similar to SEM: Ions (Ga+) instead of e^-
  - Resolution: < 10nm
  - Damages the sample surface
- Sample sputtering & milling
  - Sub-µm spatial resolution
  - Depth up to hundreds of µm
- Localized deposition
- Embedded SEM (Dual-beam system)
- Conductive samples for better performance

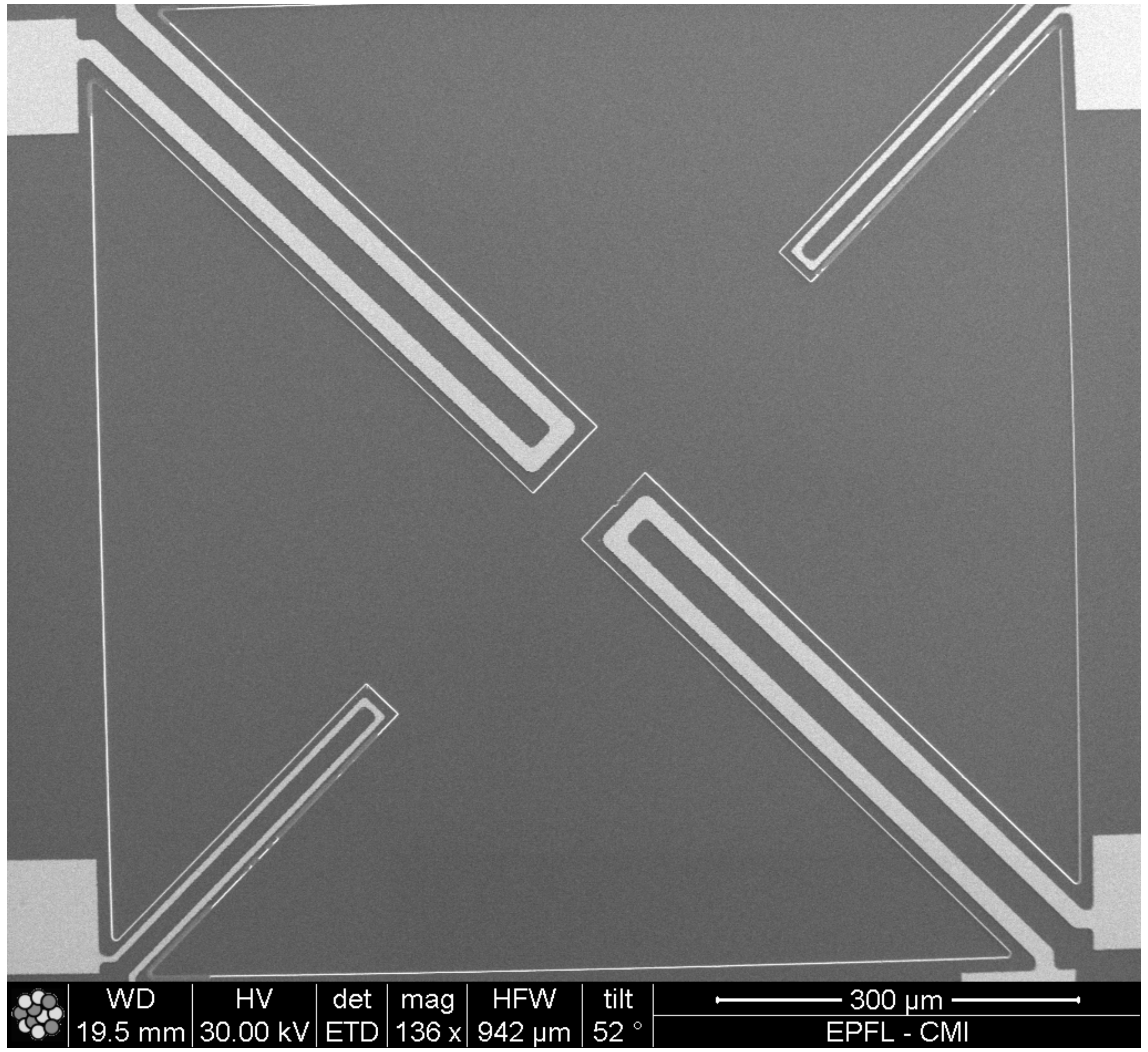


Focused ion beam imaging

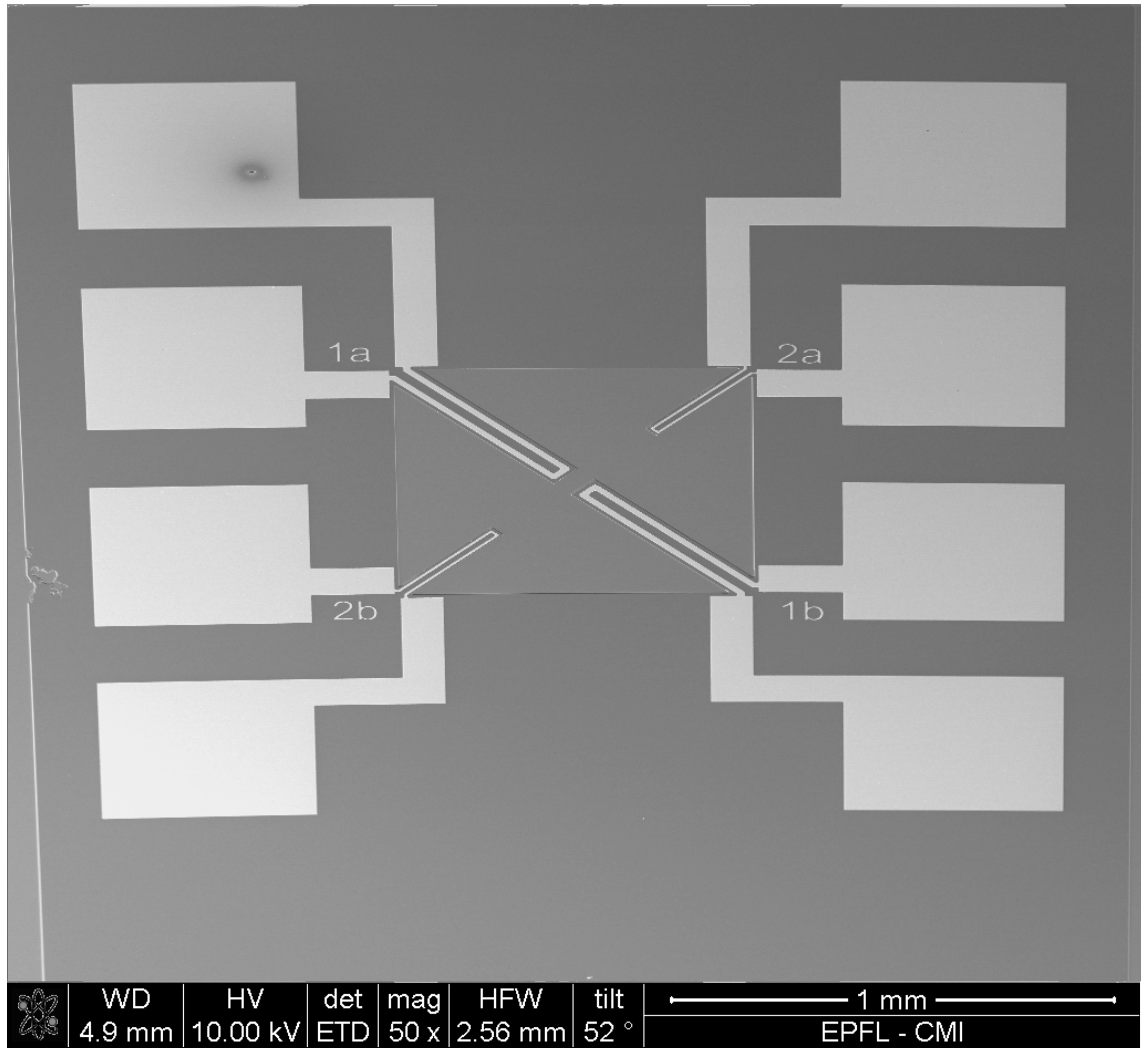
- Sample: bi-morph wafer before KOH wet etch (20nm Cr coated to reduce charging)



Dual-beam system



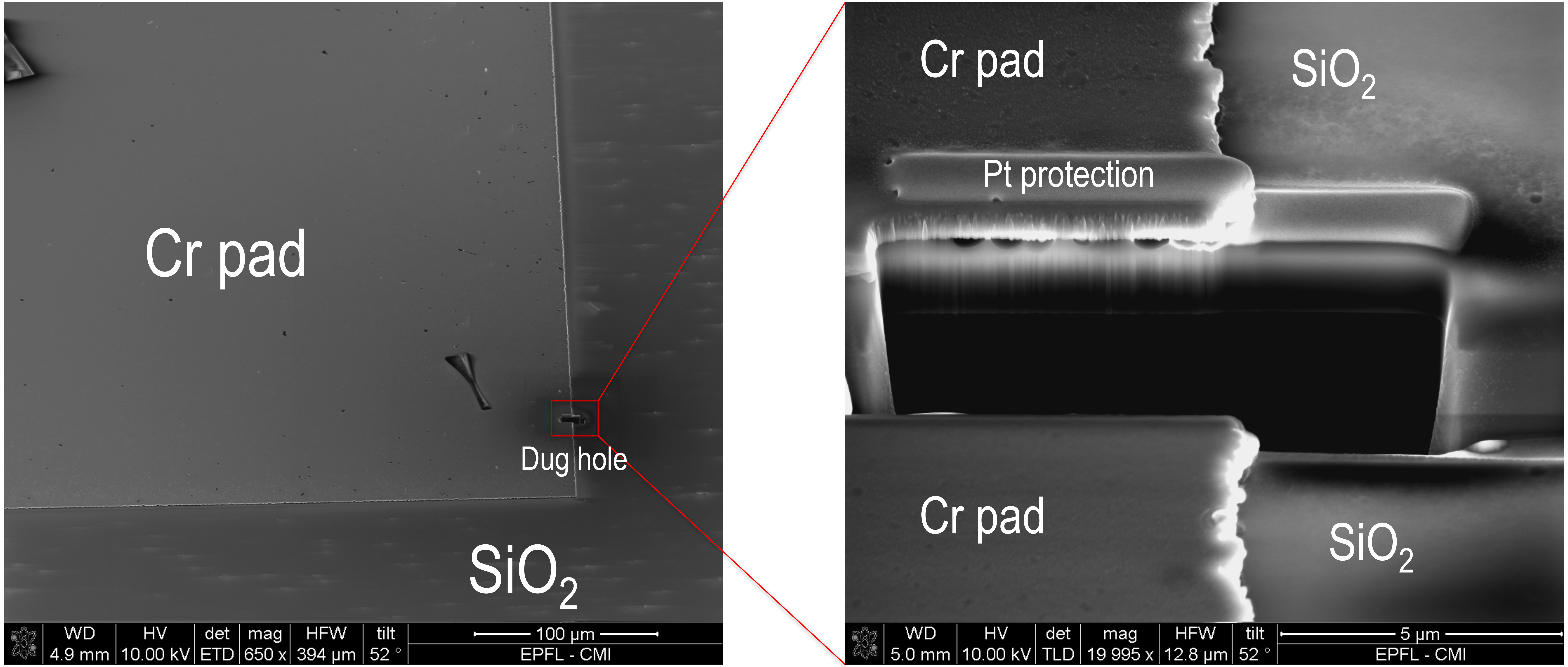
Ion imaging
(Top view)



In-situ SEM
(Tilted view)

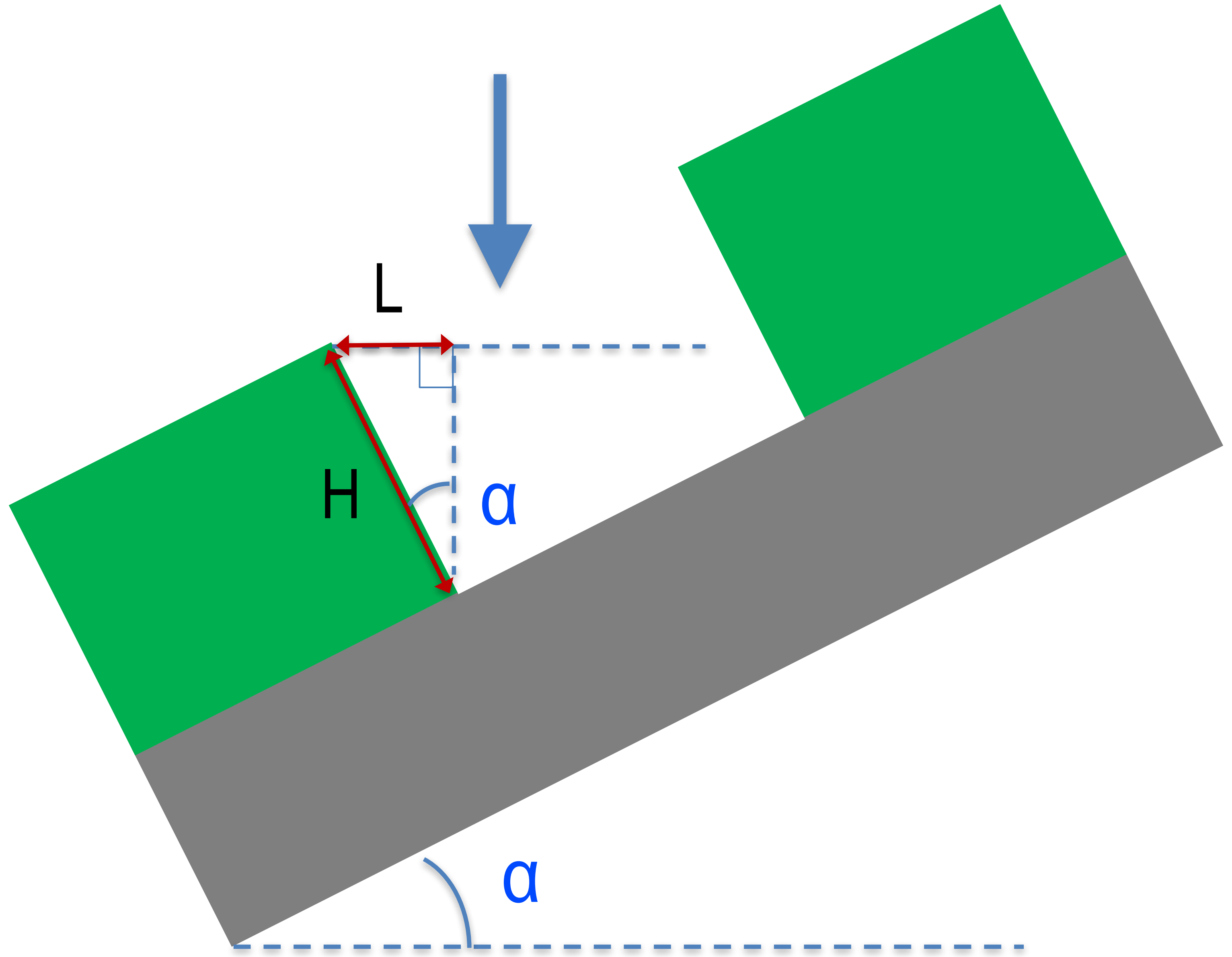
Local cross sectional inspection

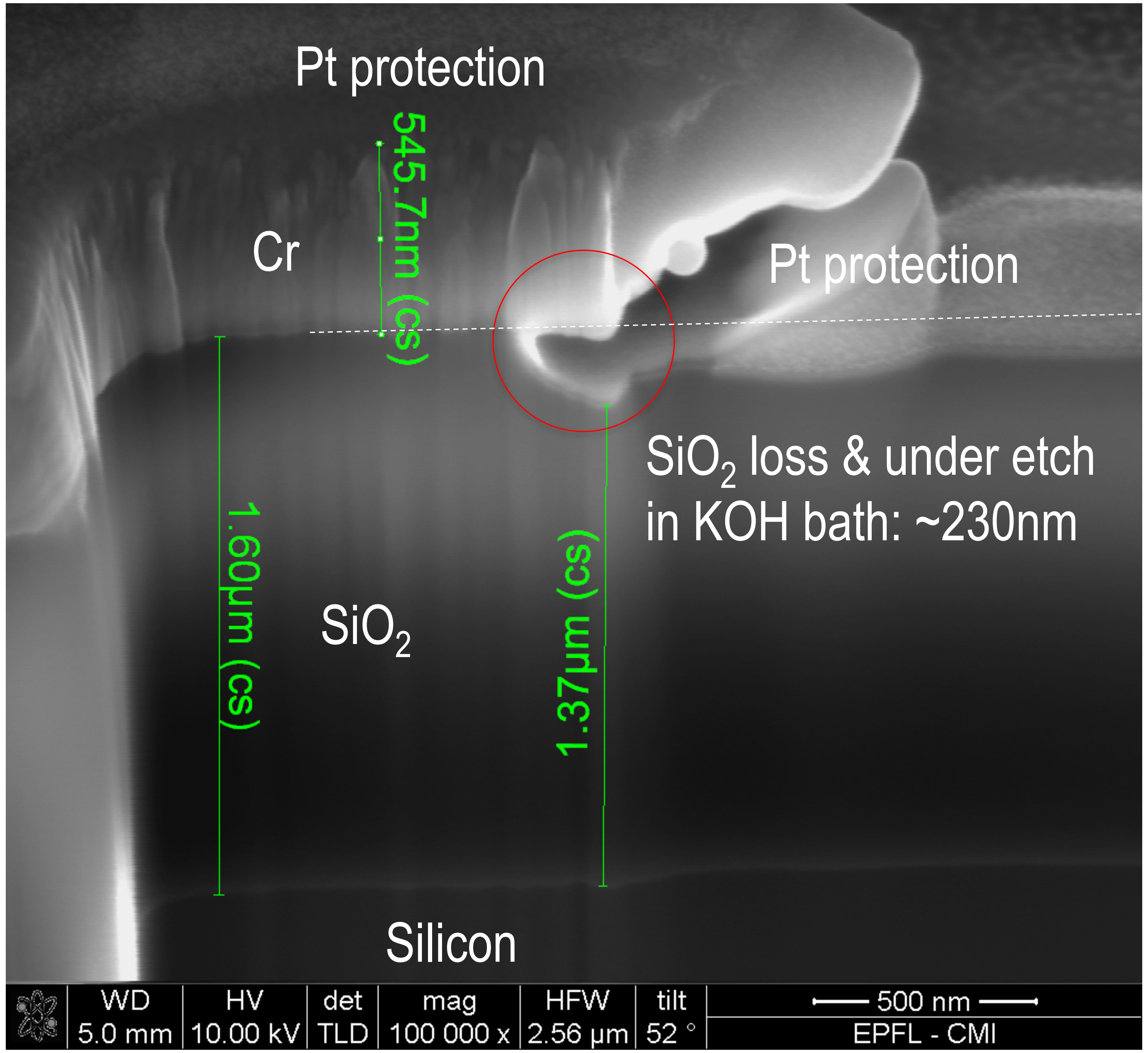
- Sample: Bi-morph wafer after KOH wet etch, without extra Cr coating
- In-situ Pt deposition ➔ FIB digging ➔ FIB milling



Z-dimension measurement

- Sample tilting is needed for better cross sectional view
- Z dimension compensation: $H = L / \sin(\alpha)$





Magnified cross section after milling

Summary

- Ion imaging will damage sample
- In-situ SEM
- Locally destructive cross sectional inspection & measurement

Inspection and metrology 7
Electrical characterization

Micro and Nanofabrication (MEMS)

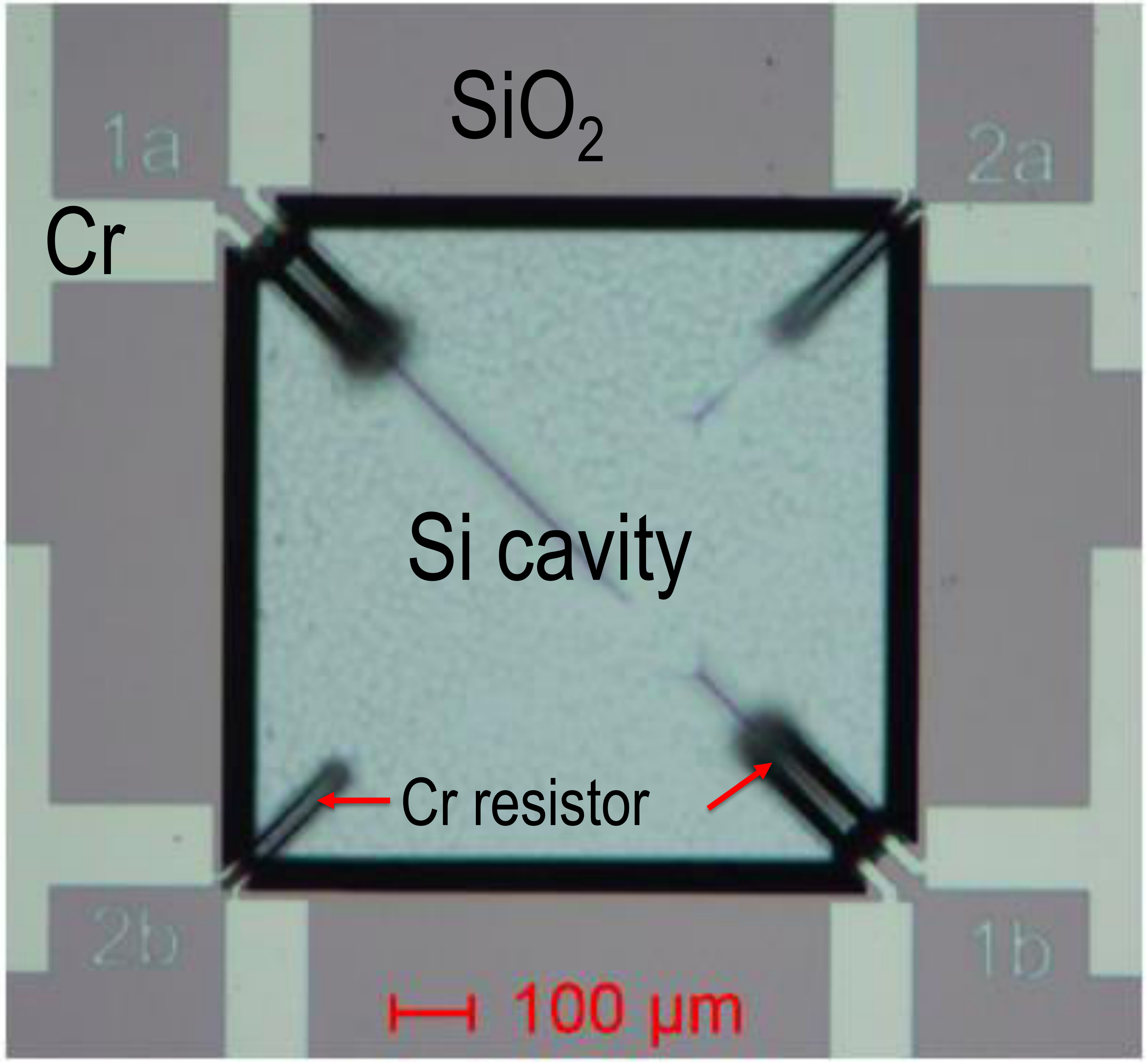
Prof. Jürgen Brugger & Prof. Martin A. M. Gijs

Electrical characterization

- Resistivity meter
- Bi-morph Cr resistivity measurement
- Prober station
- Bi-morph actuation and measurement

Bi-morph electrical characterization

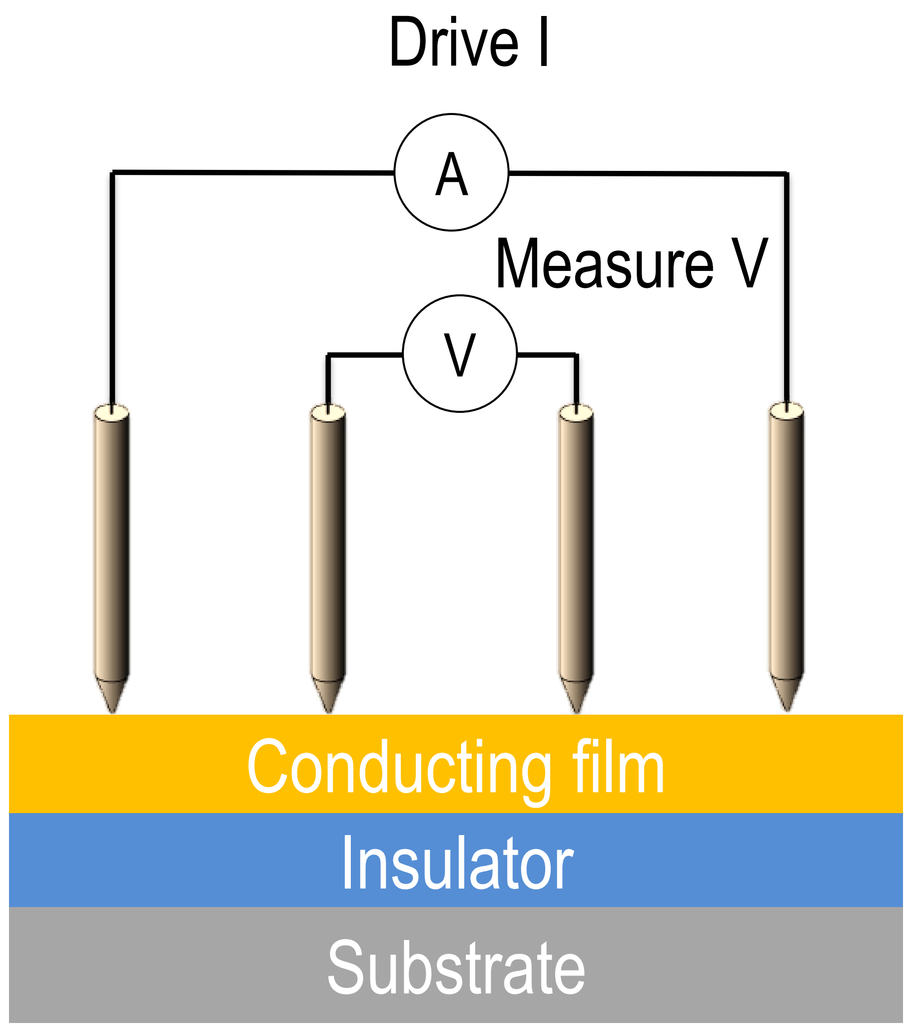
How to evaluate the Cr film quality and determine the resistance of the Cr heaters?



Optical microscope

Resistivity meter

- To evaluate the metal film quality
- Van der Pauw 4-point measurement
- Probe spacing: ~ 1mm
- Unpatterned film with known thickness on an insulator
- Accuracy: +/- 0.5%

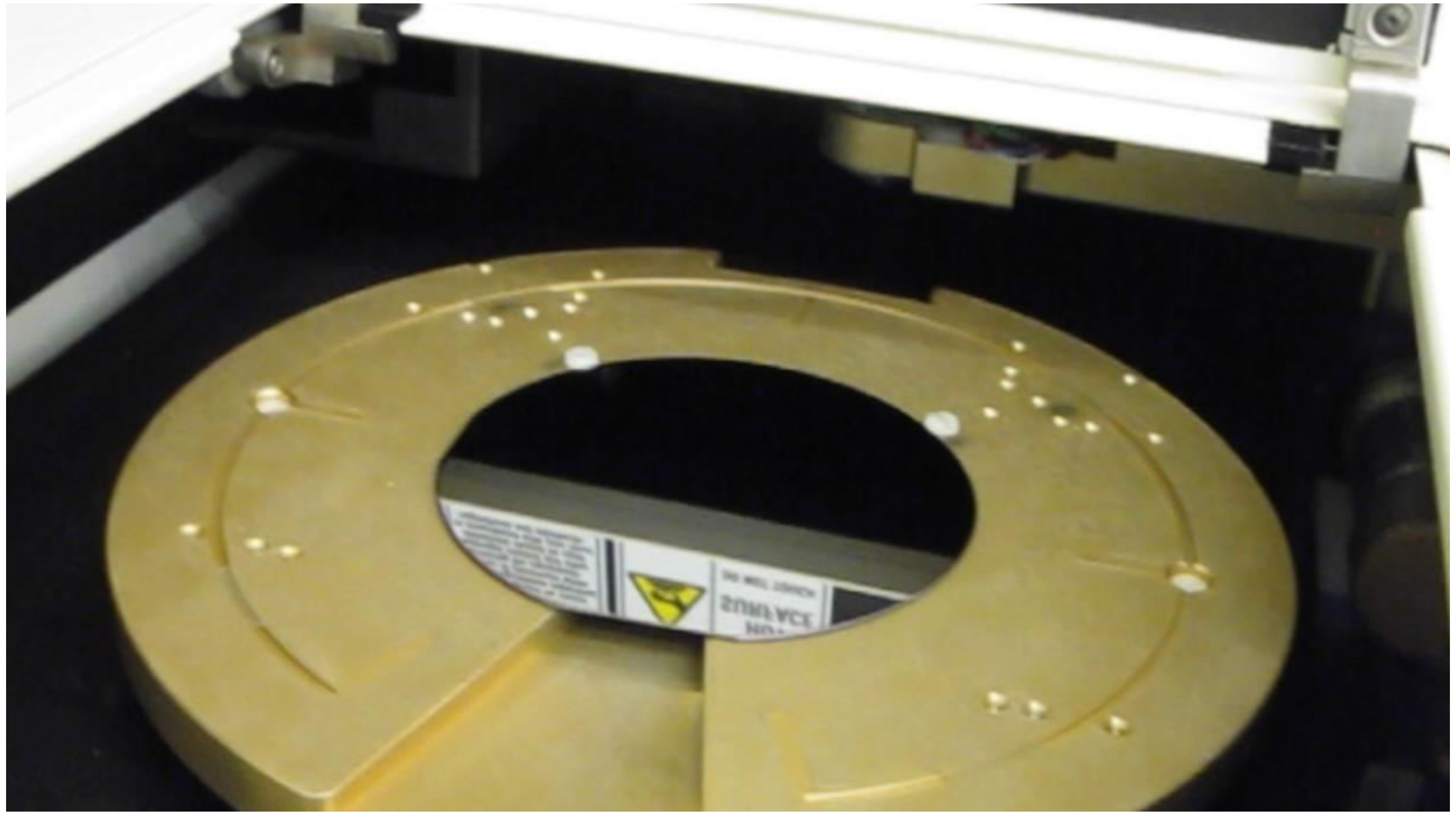


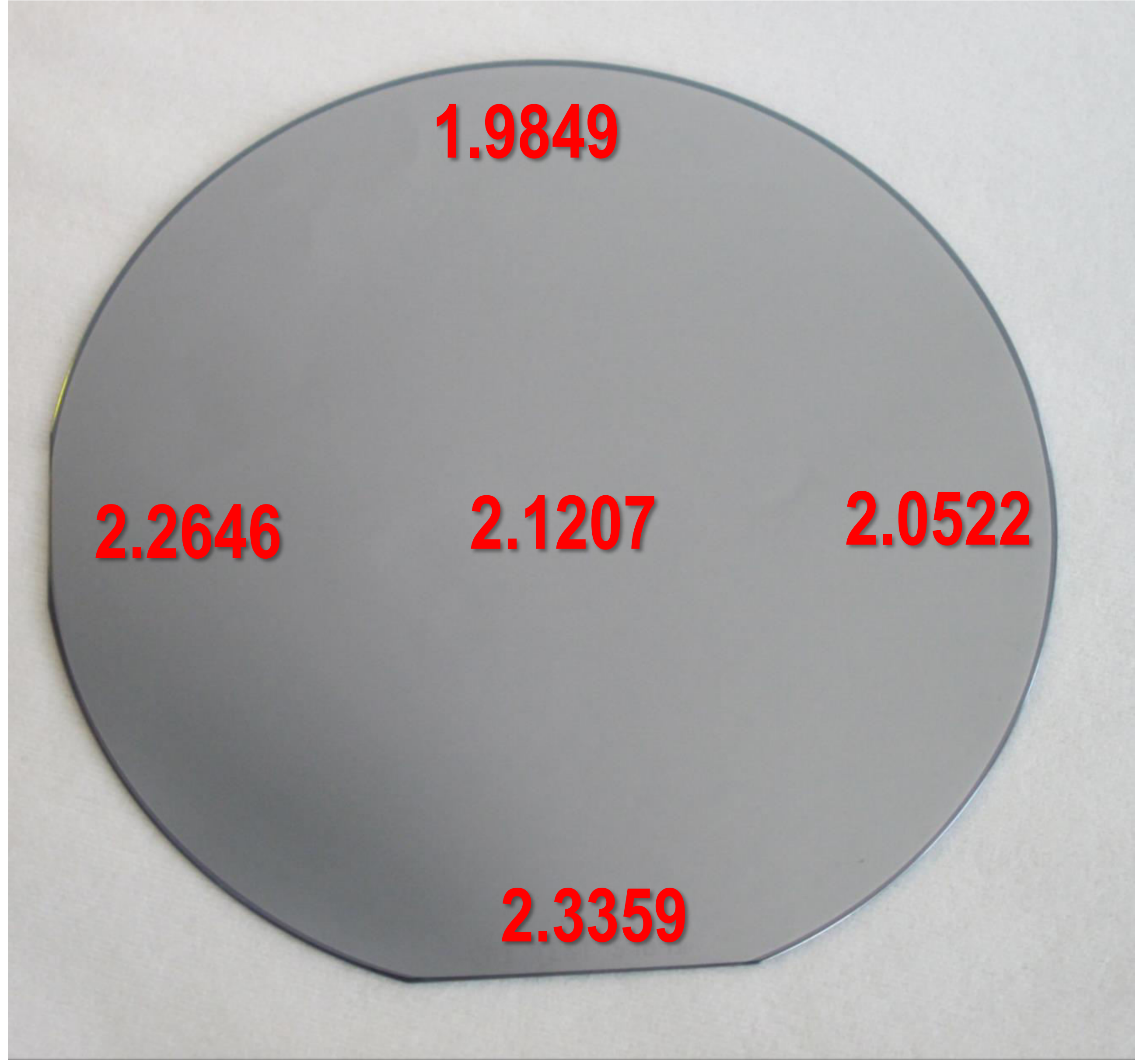
Van der Pauw formula for 4-point measurement: $$R_s = \frac{\pi}{ln2} \cdot \frac{V}{I}$$

Calculate resistivity: $$\rho = R_s \cdot t$$

R_s : Sheet resistance (ohm/sq)
V : Voltage (V)
I : Applied current (A)
ρ : Resistivity (ohm•m)
t : Film thickness (m)

Bi-morph Cr resistivity measurement





$\rho = R_s \bullet t$

R_s mean value = 2.152 ohm/sq

t_{Cr} = 500nm

➔ The resistivity of Cr = $R_s \bullet t_{Cr}$ = 2.152 x 500 x 10^{-9} = 1.076 x 10^{-6} ohm•m

5-sites R_s data (ohm/sq) of bi-morph wafer after Cr deposition

Bi-morph Cr resistance calculation

$$R = \rho \frac{L}{tW} = R_s \cdot sq. \quad where \quad R_s \equiv \frac{\rho}{t} \quad sq. \equiv \frac{L}{W}$$

R : Resistance (ohm)
ρ : Resistivity (ohm•m)
L : Resistor length (m)
t : Resistor thickness (m)
W : Resistor width (m)
R_s : Sheet resistance (ohm/sq.)
sq. : Square number

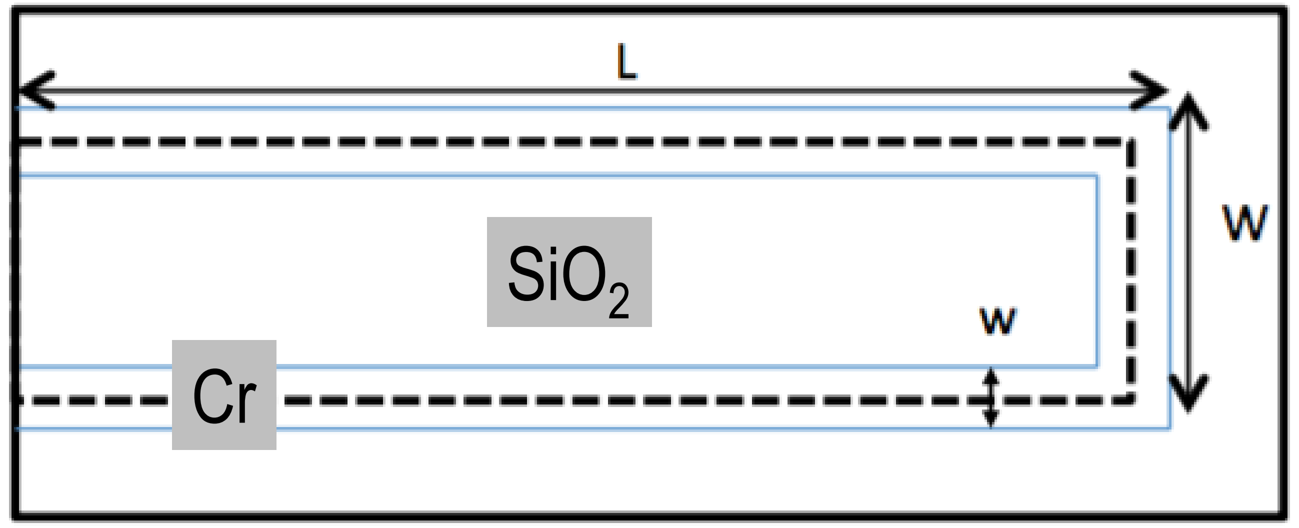
For Cr resistor:

R_s = 2.152 ohm/sq.

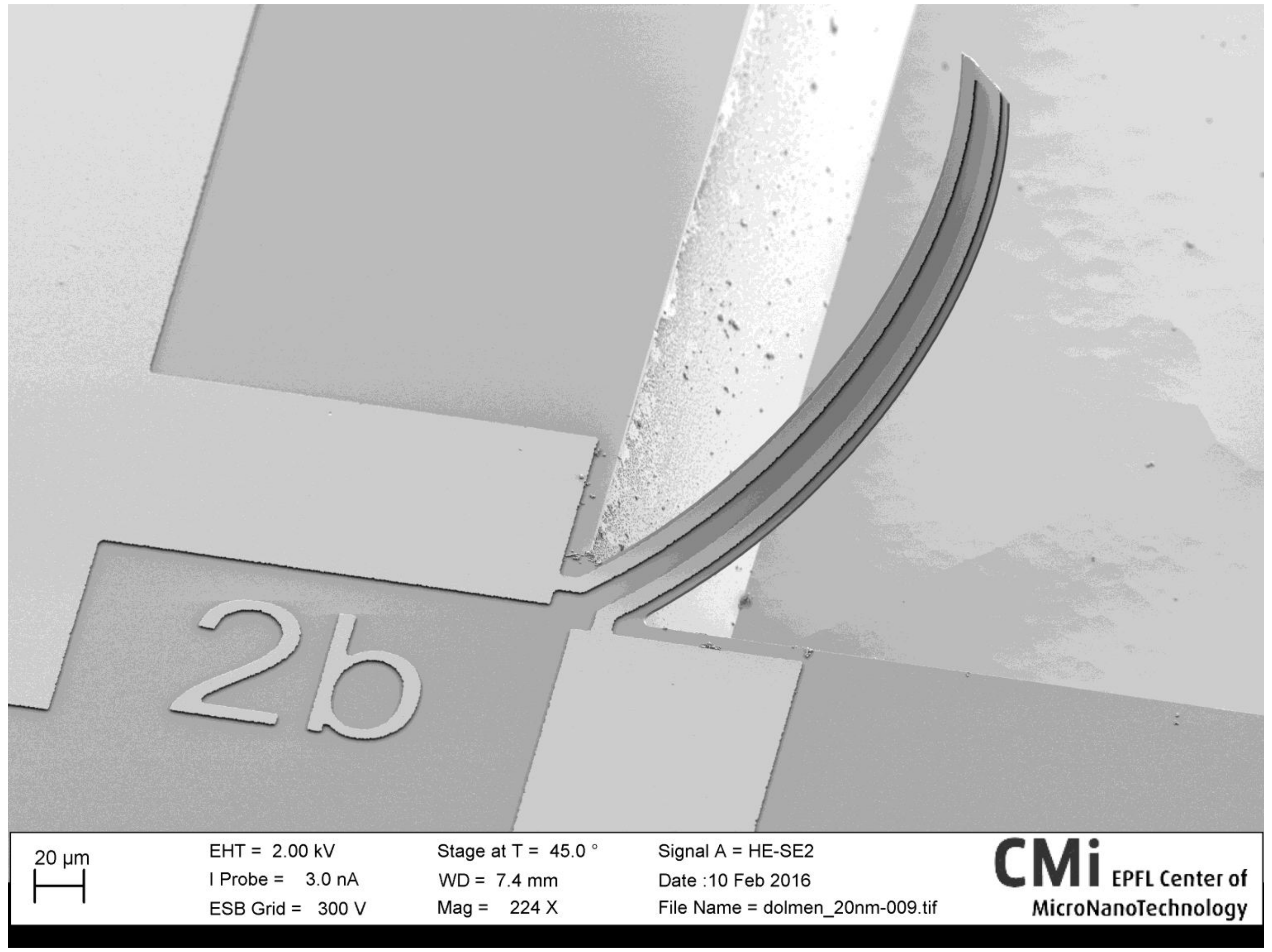
L = L_{eff} = 640 µm

W = 7.13 µm

The resistance of Cr = 2.152 x (640 / 7.13) = 193.2 ohm

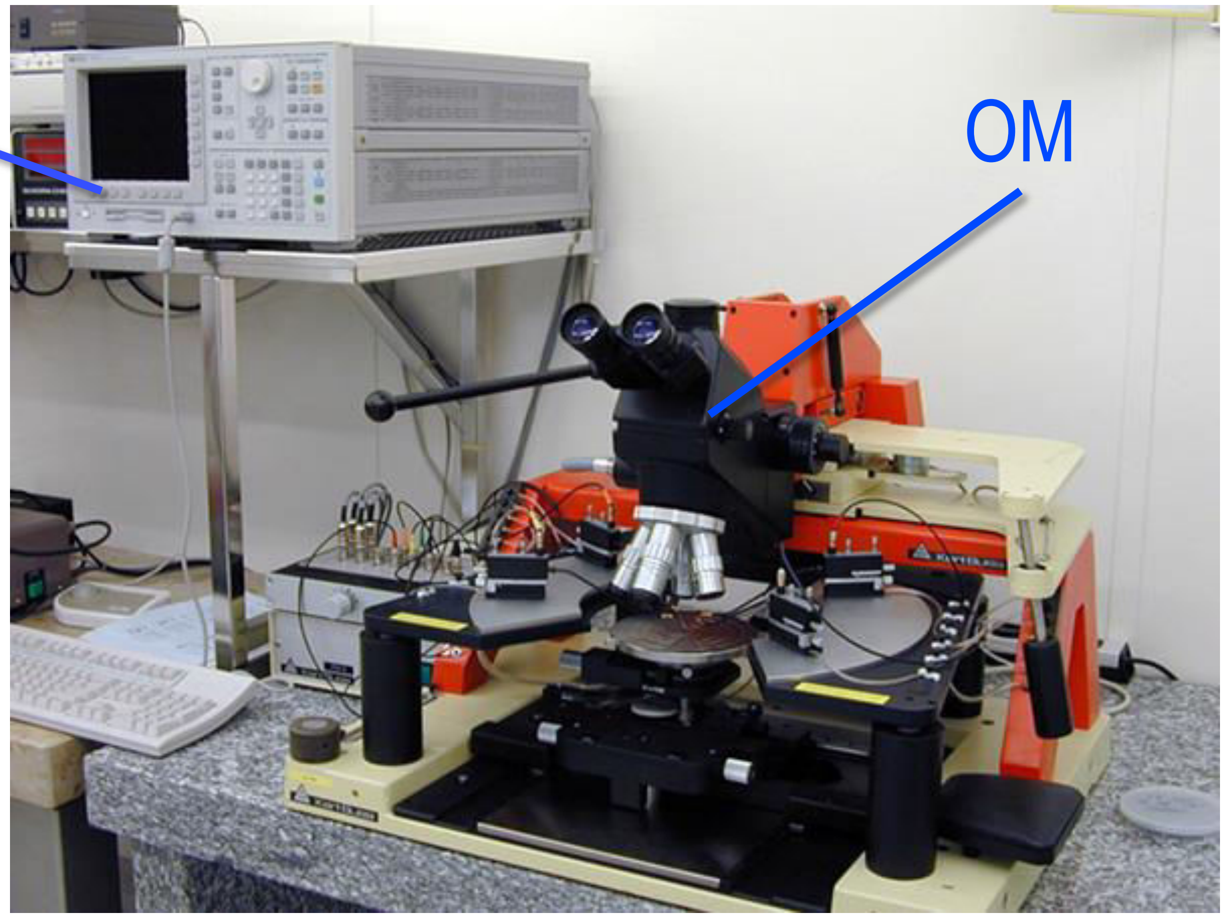


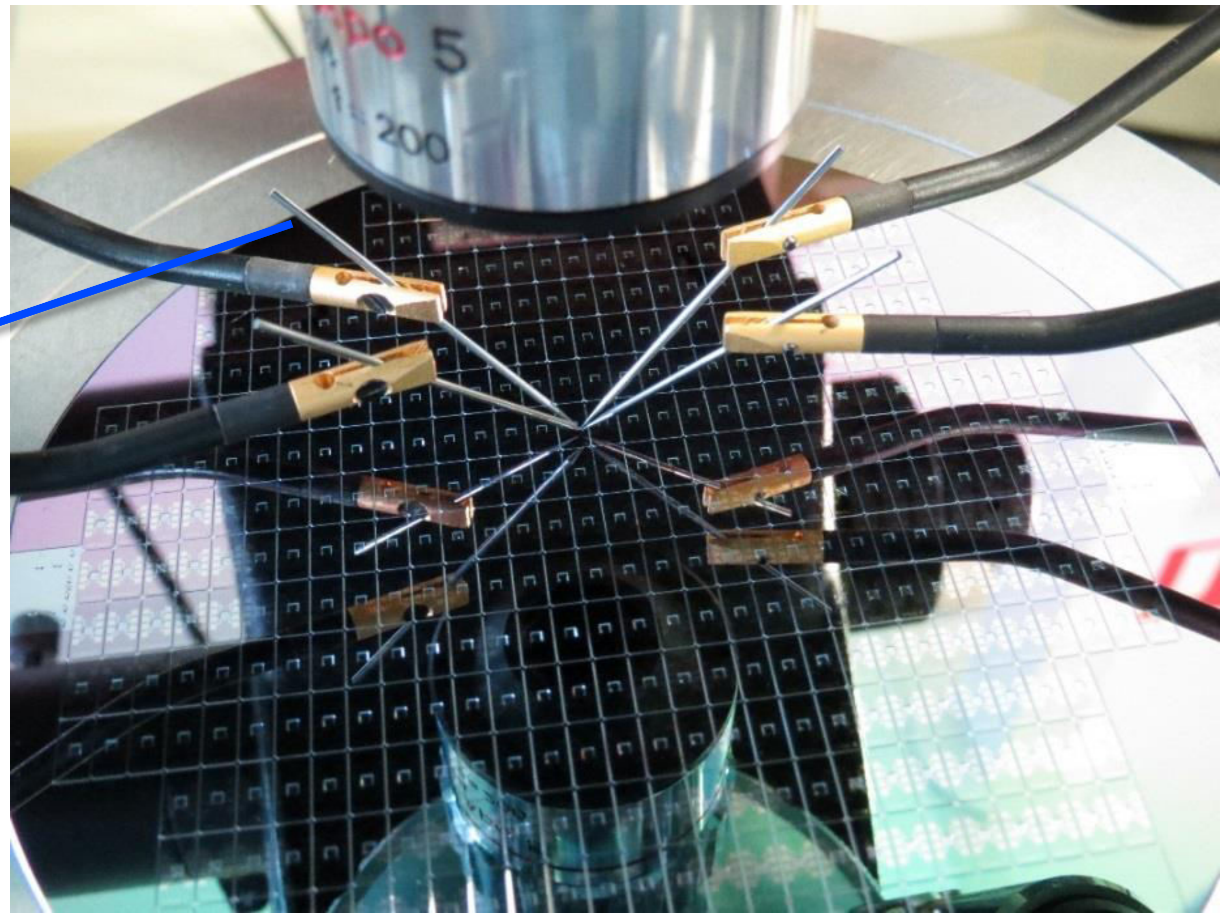
$$L_{eff} = 2\left(L - \frac{w}{2}\right) + W - w$$



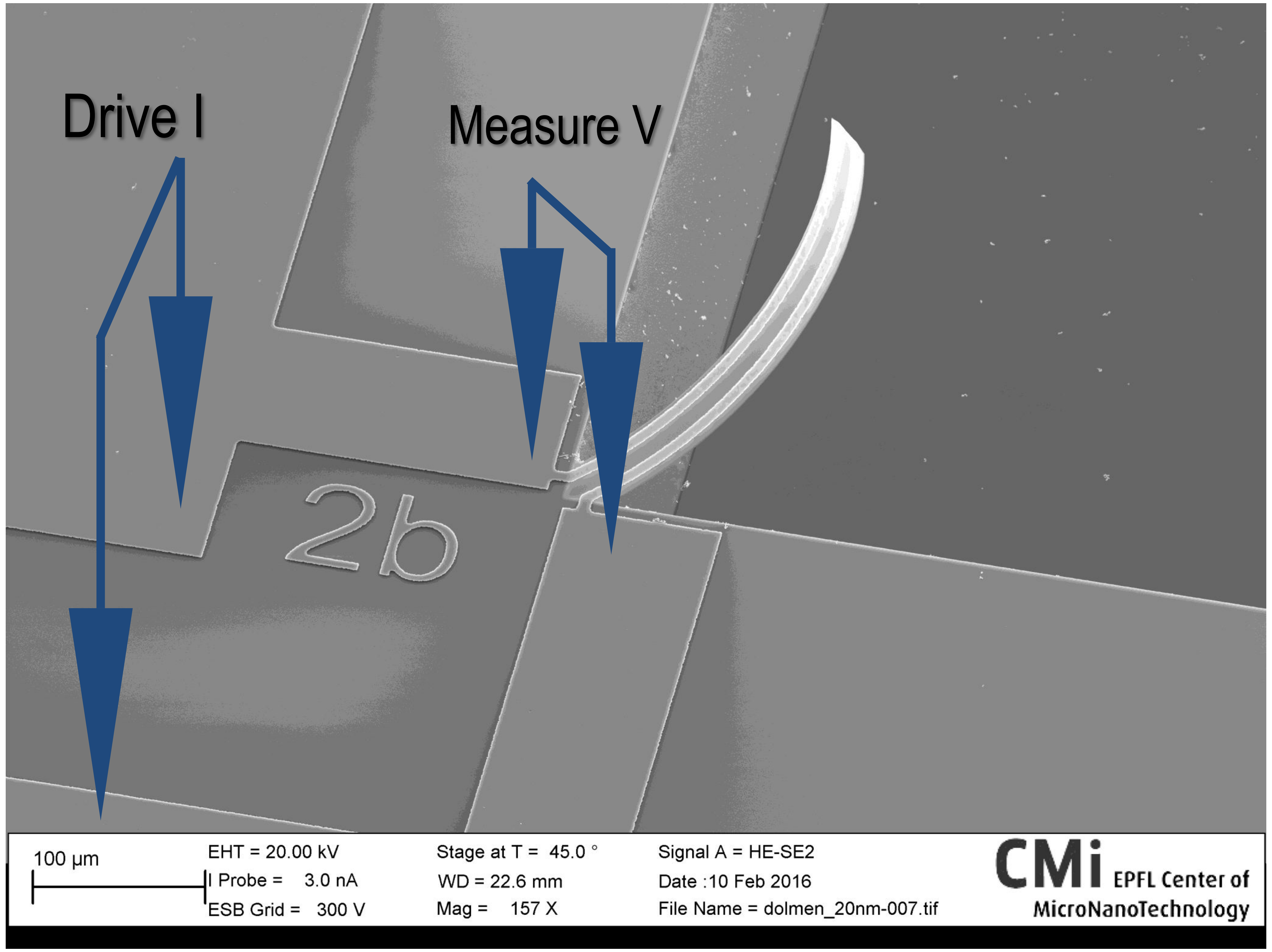
Prober station

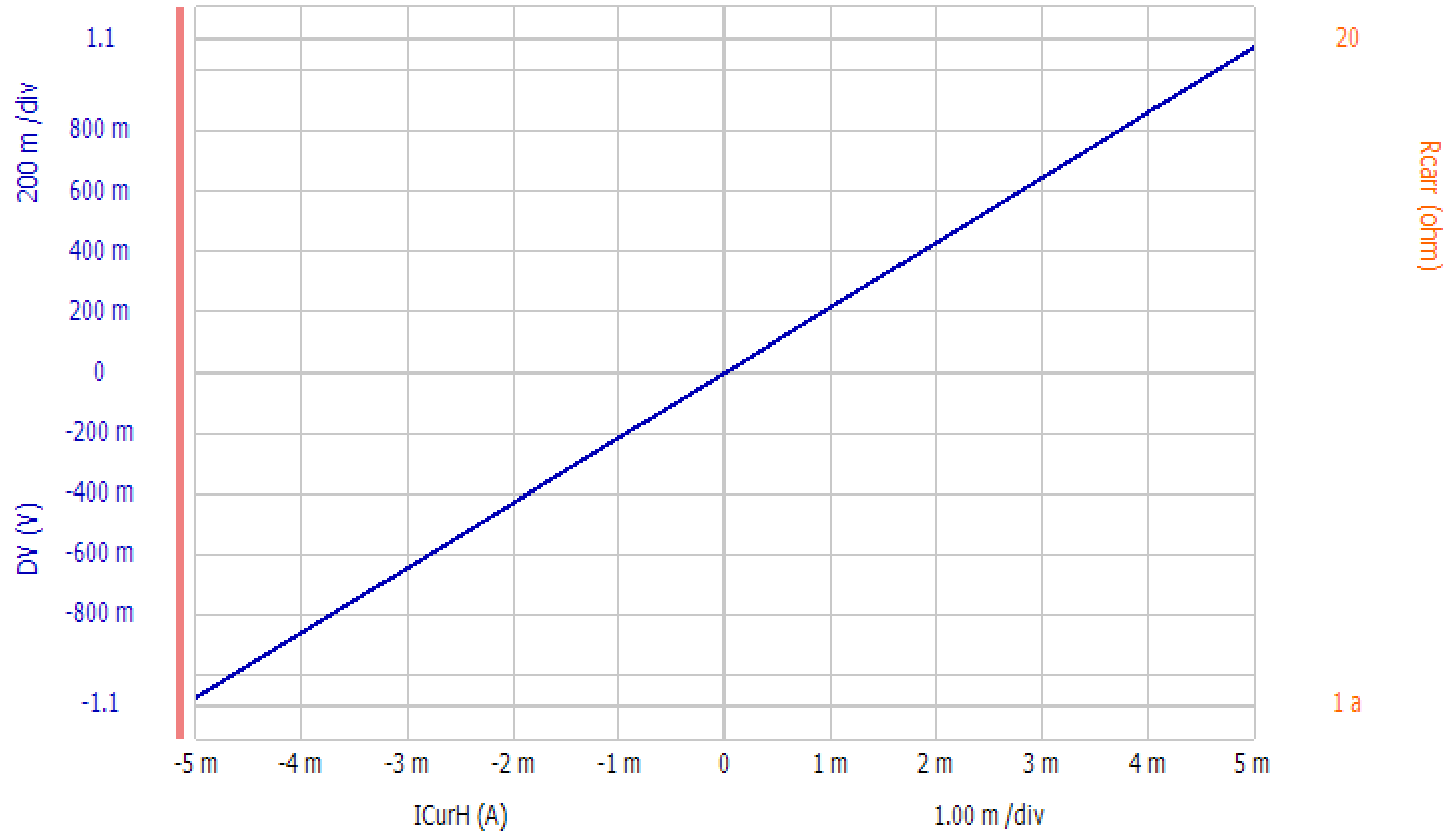
- OM + tungsten micro probes + multimeter & power supply
- Metal pads needed: > 50 x 50 μm^2
- Electronics characterization
  - Current (0.1 fA – 1 A), voltage (0.5 μV – 200 V)
- I-V, C-V, C-f, C-t curves
- MEMS resonant frequency





Bi-morph Cr resistance measurement





Cr resistance = 215 ohm
(Calculation: 193.2 ohm)

Summary

- Proper test pattern design
- Risk to burn out the device
- Always make the pads big enough
- Ohmic contact